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# The Design and Construction of a Telescope Mount for a Wide Field Polarimeter.

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A thesis submitted to the University of Durham for the degree of MSc.

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Department of Physics

September 1998



11 MAY 1999

# Abstract

This thesis describes the design, construction and operation of a prototype wide field polarimeter to be used in large scale polarisation studies of the sky.

A personal computer controls the stepper motors which drive an equatorial mount arrangement, whilst a lap top computer controls the CCD camera software.

The third, fourth and fifth chapters describe the initial design process. The sixth chapter describes in detail the final design of the telescope mount. The seventh chapter gives an insight into how the structure was fabricated.

Finally, the thesis describes the commissioning and operation of the telescope mount, with a section incorporating some results obtained from observing Jupiter.

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# 1. Polarimetry in Durham

## 1.1 Background

Astronomy comprises the observational and theoretical study of celestial bodies including: planets, comets, stars, galaxies, clusters of galaxies and cosmology. It is one of the oldest sciences and has developed with the speed of improvements in instrumentation, technology and other scientific advances within the last two decades.

It is possible, using various astronomical techniques, to measure the radiation emitted from astronomical objects. Using the data gathered by these methods, astronomers attempt to answer questions about the nature and history of stars and the universe.

The subject of interest here is optical polarimetry, where light from astronomical objects is used to investigate the geometry and composition of material within the region around the light source and in the intervening medium. Astronomical polarimetry is used in the study of stars, nebulae, galaxies, the interstellar medium and of planets.

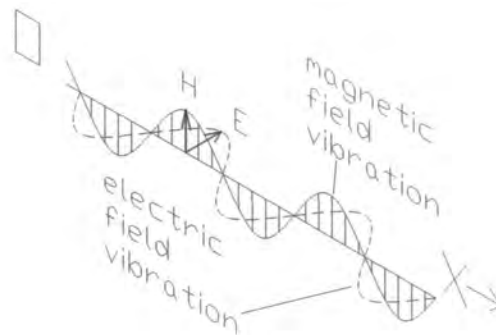
Polarisation occurs for various reasons, the mechanisms being scattering, dichroic extinction, synchrotron radiation, reflection and the Zeeman effect. The instrument used to measure the level and position angle of linear polarised light is a polarimeter.

There have been four polarimeters built at Durham, each one improving upon the success of previous models, and utilising improved components. The Durham Polarimeter measures linearly polarised light from the blue to infra red wavebands.



### 1.1.1 Polarisation of light

A light wave can be considered to act similarly to a sinusoidal wave. The vector which represents this wave does not rotate about the axis about which it oscillates, it keeps the same relative angle with respect to its direction of travel. When large numbers of atoms emit light, the position angles are usually randomly distributed; they are unpredictable with respect to time, this is termed unpolarised light.



**Figure 1-1 A single light wave**

With reference to Figure 1-1, the light vector, travelling in the direction towards X, can be considered to consist of two vectors, electric field and magnetic field, travelling perpendicular to one another, and to its direction of propagation. The size and orientation of the electric field vector is measured to determine the degree of polarisation of the light wave.

In the example shown in Figure 1-1, by standing at the point X, and observing the electric field vector, E, a straight line would be traced horizontally perpendicular to the line O-X. This is called linear polarisation.

Most emitted light is unpolarised, but if it passes through certain materials, or is reflected from a surface, the electric field vector aligns preferentially in one direction giving partially polarised light. If the oscillation of the electric field vector rotates

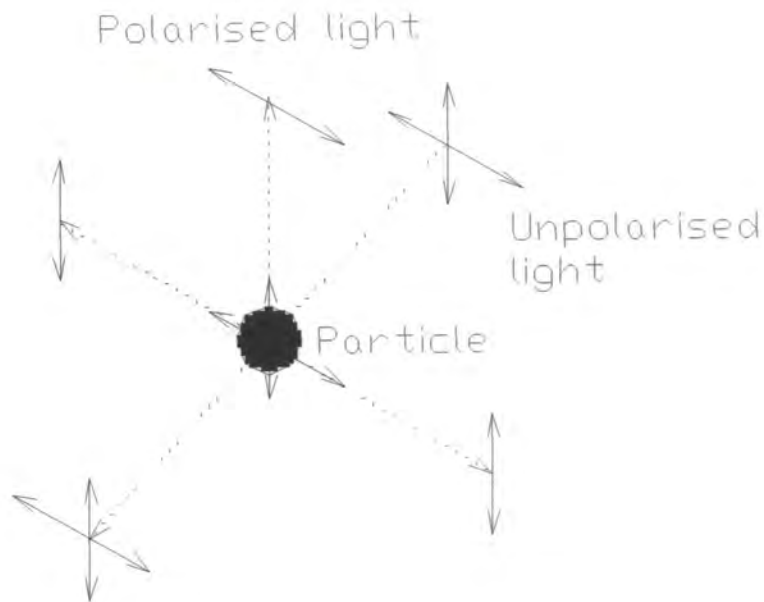


such that its endpoint traces a circular pattern, then this is known as circular polarisation. Rotation of the electric field vector can also trace an ellipse called elliptical polarisation.

There are three main polarisation mechanisms: scattering, extinction and the synchrotron effect.

**Scattering** is the deflection of light from the direction of travel as a result of interaction with particles, such as atoms, molecules or dust in the medium through which it is travelling. The degree of polarisation induced by scattering is a function of the scattering angle. The direction and magnitude of the scattering are dependant upon the fact that the incoming photon causes the scattering medium to radiate dipole radiation in directions non-parallel to the oscillating dipole.

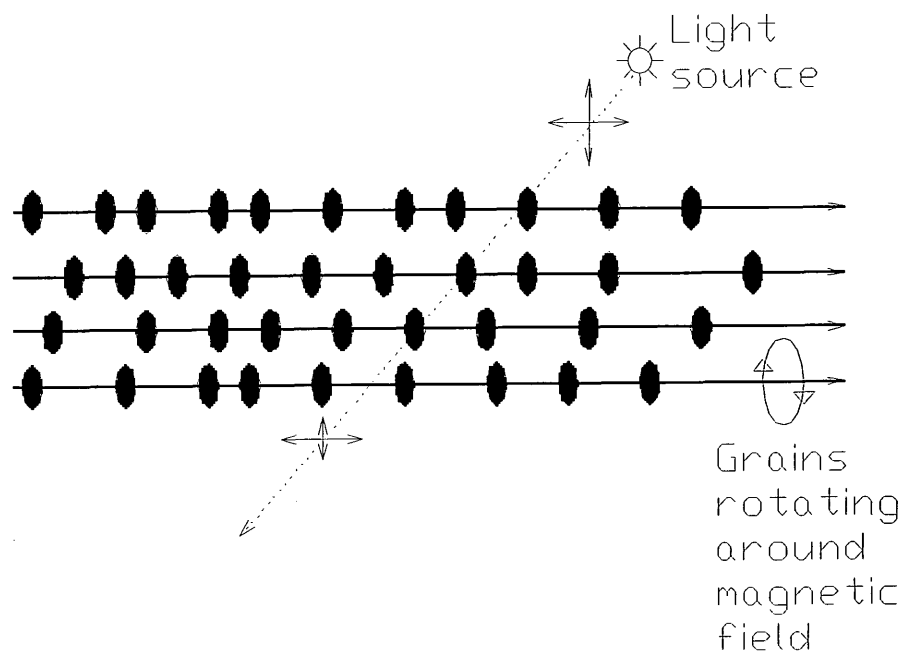
Measurement of linear polarisation can help to identify the scattering material, its geometric relationship to the light source, and also some of the properties of the light source. Scattering is illustrated in Figure 1-2.



**Figure 1-2 Scattering**

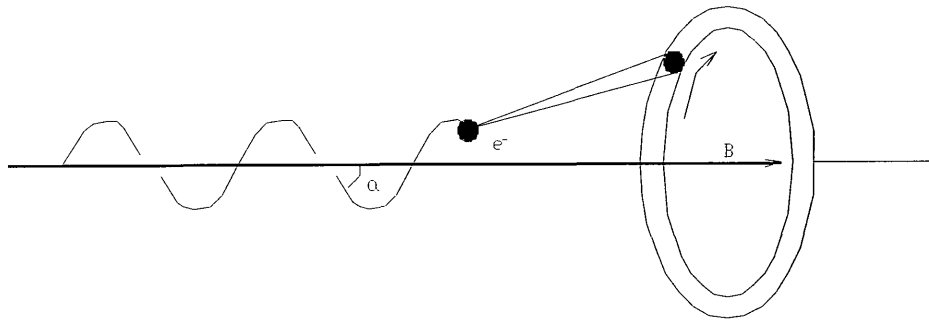
**Dichroic extinction.** This is a result of differential extinction of light wave components. When light from an astronomical object passes through magnetically aligned (non-spherical) grains of interstellar dust, there is a tendency for light passing along the length of the grain to absorb more light than that perpendicular to it.

Non-spherical particles of interstellar dust can induce a preference for the orientation of the light wave with respect to the magnetic field. This gives rise to a net excess of light polarised perpendicular to the direction of grain alignment. The degree of polarisation is related to the size of grain, the magnetic field strength and the distance to the light source. There should be a greater degree of polarisation for a light source positioned farther away than one close. Figure 1-3 illustrates the principle of extinction.



**Figure 1-3 Dichroic Extinction**

**Synchrotron radiation.** When high energy electrons move in a magnetic field they give off electromagnetic radiation, causing polarisation of the light. An electron moving in a magnetic field follows a helical path. Acceleration of the electron in a circular path causes it to radiate electromagnetic waves, illustrated in Figure 1-4.



**Figure 1-4 Synchrotron radiation**

Figures 1-2, 1-3 and 1-4 are courtesy of Dr D. P. Stockdale.

## **2. The Durham polarimeter.**

The history of the Durham polarimeter has been covered in detail by several authors, Pallister (1976), Axon (1977), Warren-Smith (1979), Rolph (1990) and Stockdale (1996). It is designed to mount onto ground based telescopes and to analyse the characteristics of astronomical objects. The current system uses a CCD detector to collect the light image electronically so that it can be studied at a later date.

For the purpose of this research, the Mark 3 polarimeter was updated and used.

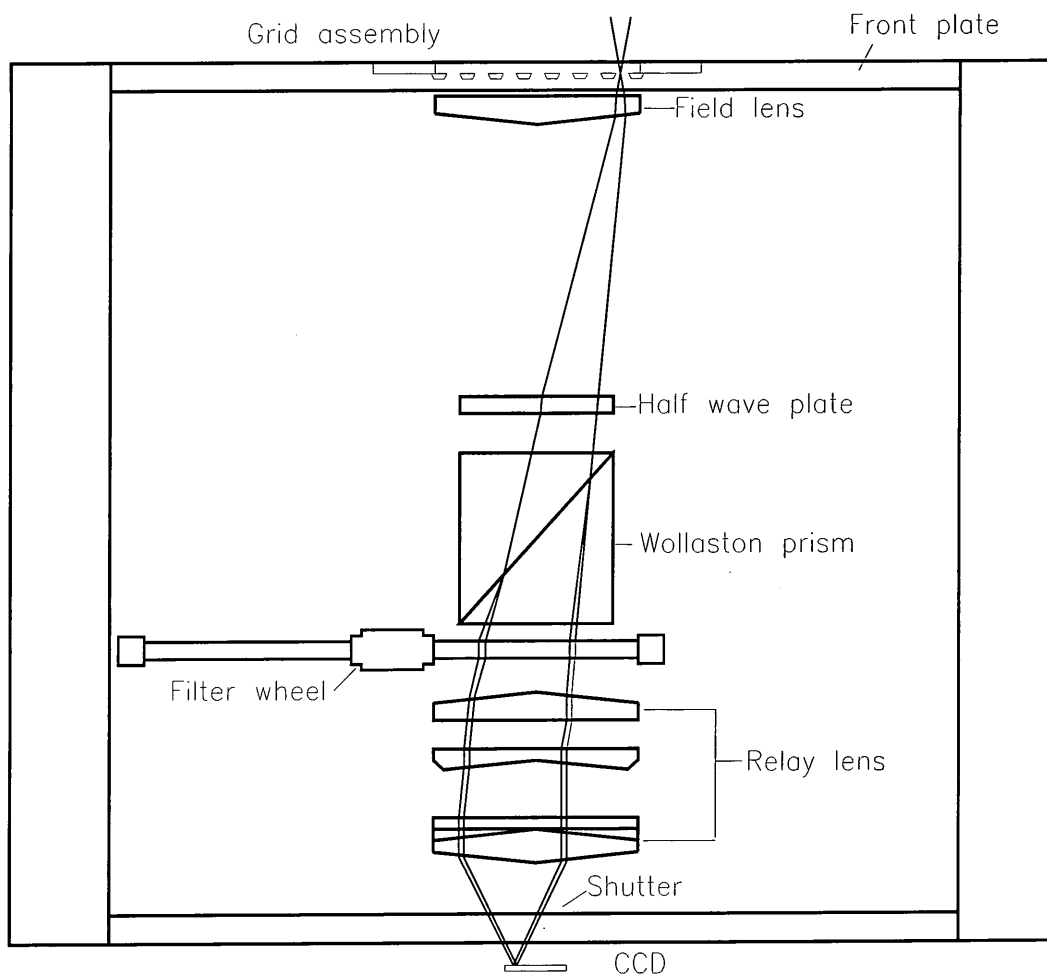
### **2.1 Polarimeter structure**

The polarimeter is shown schematically in Figure 2-1. It is essentially a sealed box, containing optical components which pass light to a CCD camera, so obtaining an electronic image. It's body is predominantly constructed from aluminium alloy (HE30TF), using 38mm square bar as support struts to separate 18mm thick front and back plates.

Traditionally, the polarimeter mounts onto a telescope using a connector plate fastened to the polarimeter front plate. The connector plate is spaced according to the telescope, ensuring that the grid mask lies in it's focal plane.

Reflected light is kept to a minimum by sealing the polarimeter from external light sources, and by colouring internal surfaces matt black where possible.

The optical components are positioned using stepper motors controlled by computer. Each of the units, the half wave plate, filter wheel, polarimeter focus and the grid mask are driven using gears connected to the stepper motors. Position sensors are used to control the position of the components relative to their desired location.



**Figure 2-1 A schematic illustrating the polarimeter**

## 2.2 The Polarimeter - how it works

The Durham polarimeter is an imaging device which uses a **Wollaston prism** to split incident light into two perpendicularly polarised beams.

A minimum of two readings are required to determine the state of polarisation, and so a device called a **half wave plate** is used to rotate the plane of polarisation.

The half wave plate introduces a phase difference of  $180^\circ$  between the parallel and perpendicular components of the polarised light. By rotating the half wave plate through an angle  $\theta$ , the plane of polarisation is rotated through an angle  $2\theta$ . It is rotated by  $22.5^\circ$  between exposures, thus rotating the plane of polarisation by  $45^\circ$ . Four readings are taken by rotating the half wave plate four times through  $22.5^\circ$ , effectively giving readings at  $0^\circ$ ,  $45^\circ$ ,  $90^\circ$  and  $135^\circ$ . By taking readings at four positions instrument errors can be removed from the final data.

Because the incident light splits into two beams, the CCD would see a double image, and so a **grid** is placed at the focal point of the telescope to block half of the image, see Figure 2-2. The CCD detector can pick up both the parallel and perpendicular polarisation states. The missing portion of the image is collected by moving the telescope twice over one third of a grid width and the resulting images pieced together to give a complete image of the object.

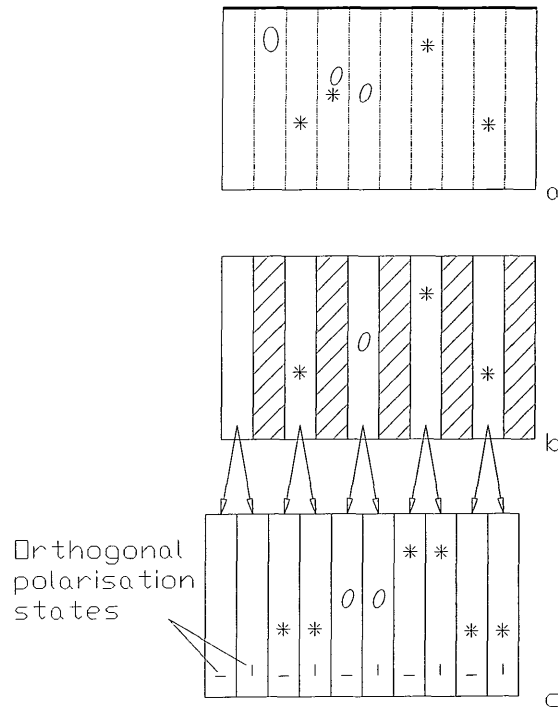
Two lenses focus light from the telescopes primary mirror onto the CCD detector. The **field lens** focuses an image of the telescope's secondary mirror onto the half wave plate. The light passes through the remaining optical components and it enters the **relay lens** which focuses the light onto the CCD detector. This provides an image of the object as it would appear at the telescope focus, i.e. the grid mask.

A **filter wheel** provides eight apertures located between the Wollaston prism and the relay lens. Five of the apertures hold filters each of which are used to remove particular wavelengths of light from the beam, allowing the operator to concentrate on one known wavelength. The remainder can be used to hold specific filters for observing a particular object.

Fitted to the back plate of the polarimeter is a **CCD camera**, detector size  $512 \times 512$  pixels, which is used to detect the light passing through the polarimeter. This converts the incoming signal into a form which can be read and used by a computer.

Cooling of the CCD provides a stable signal with minimal noise from sources other than the detected image. This is achieved by filling the camera body with liquid nitrogen, the temperature is stabilised at approximately  $-140^{\circ}\text{C}$  by means of a vacuum surrounding the stored nitrogen.

A typical image as seen by the polarimeter can be seen in Figure 2-2.



**Figure 2-2 A view of the sky through the polarimeter.**

The image collected by the telescope is shown in Figure 2-2a, the image which passes the polarimeter grid mask is seen in Figure 2-2b, and the image collected on the CCD camera is shown in Figure 2-2c.

The part of the image shown as hatched lines in Figure 2-2b, is collected by moving the telescope twice over one third of a grid width as described previously.

In Figure 2-2c each element of the double image hold the data relating to either the horizontal or vertical polarisation vectors.

## 2.3 Wide field polarimetry.

Large scale polarimetric studies of large objects are rarely done due to the time limitations found on telescopes, and the area which can be studied within its field of view. The field which can be imaged using the polarimeter is determined by the size of the telescope, typically  $\sim 10$  arcmin on a one metre telescope. There are a number of objects which although having polarimetric properties cannot be studied because they are larger than the imaging field.

Some examples of possible studies include mapping of :-

large nearby galaxies (e.g. M31, M81) These galaxies have detailed radio polarisation observations. Optical polarisation data could be used alongside this data to investigate the structure in galactic magnetic fields.

the polarisation of the stars in the whole of Milky Way. This could build on previous work undertaken by Mathewson and Ford, to include details such as more stars and use all of the BVRI wavebands.

large scale nebulosities such as Orion Nebula, M18, M8. This would lead to the discovery of many illuminating sources and indicate the relationship between the sources and the geometry of the nebulae.

By manufacturing a telescope mount to support an existing polarimeter it would be possible to transport it to suitable observing sites and operate it almost continuously. As a consequence a prototype wide field polarimeter was proposed.



### 3. Telescope requirements

The new instrument should operate in the same way as a conventional telescope, although there would be limitations because of its portable nature. The instrument must have the capability to be set level and true to the latitude of the observing site, to ensure accurate tracking of objects.

Physically, the polarimeter could not be altered, and so the new instrument must accommodate it, the CCD cryostat, and a liquid nitrogen filler pipe. The motor control unit, which would normally attach to the side of the polarimeter whilst it was mounted on a telescope, can be separated for use on the wide field polarimeter. Cables could be prepared to run between the polarimeter and control unit.

The tracking rate is fixed due to the rotational speed of the earth and so the drive mechanisms must be capable of the necessary tracking speeds, with provision for fast slewing. It would be advantageous when initially positioning the telescope mount on to the desired object to be able to move quickly across the sky, which would also be useful when after tracking objects for a long period it would be possible to move quickly onto an object of different Right Ascension, rather than waste observing time.

Any image collected on the CCD must be stable in the same way as it would on a telescope. This implies that the instrument must be capable of providing smooth tracking of objects with no significant drift, without system vibration but with the provision of a variable tracking rate. A well balanced instrument will ensure that there should be no sudden uncontrolled movement, which would affect the quality of the data. The drive mechanism should also ensure that tracking is in a controlled fashion, and so accurate monitoring of the motor, and drive shaft rotation would be useful.

In addition to the operational requirements of the new instrument it is also important to consider the instrument characteristics with respect to the technical ability of its users. It should be an instrument that anyone, with limited technical

knowledge, will be able to take to an observing site, assemble and use without danger to the operator or damage to the instrument. To do this, then the design should be simple, and adjustments kept to a minimum.

## 4. Design Proposals

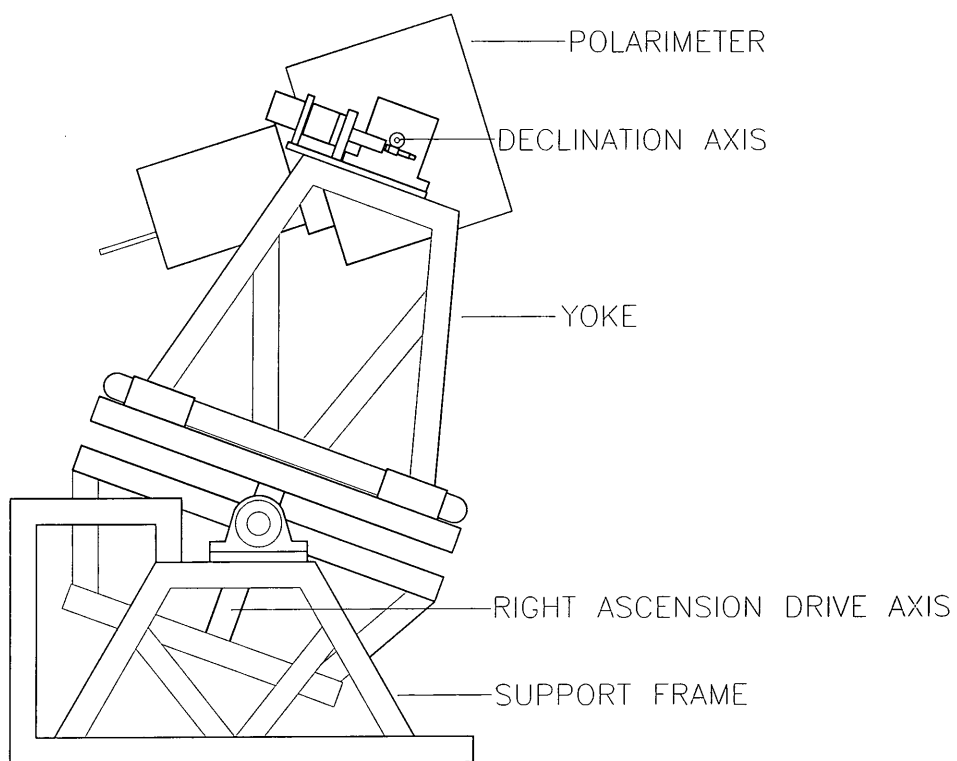
Two methods of providing a telescope support were considered, these were equatorial mounting, and alt-azimuth. The equatorial mount gives movement in Right Ascension and declination, with tracking of an object possible with movement of one axis. Alt-azimuth requires both a tilt and pan motion to track an object, with a variation in the drive rate dependant upon the altitude of the object.

Alt-azimuth suffers from field rotation when time exposure is attempted. To reduce the data to an understandable form may take some time to modify current procedures and may introduce the need for having two reduction methods, one for standard telescopes, and one for the wide field polarimeter. For this reason and for the relative ease with which an Equatorial mount can be controlled meant that an Equatorial mount was the preferred option of holding the polarimeter.

A yoke would support the polarimeter in declination, a second axis would provide the drive and control mechanism of the yoke, and a third axis would enable changes in elevation of the yoke base relative to the latitude of the observing location.

## 4.1 Scale Model

After considering several options for the instrument design a quarter scale model of the support framework was built from mild steel tube. By doing this it was possible to see potential problems with the design, and to give indications as to the best way of manufacturing the instrument.



**Figure 4-1 Instrument design**

The principle of this design was, that the polarimeter would be supported in bearings on a yoke, allowing its rotation in declination. A drive mechanism would provide accurate motion control. The yoke would be supported on a drive shaft

extending from a supporting table, and housed in bearings. The Right Ascension drive would be housed at the bottom of the table section, providing rotation of the yoke.

A support framework would hold the table within bearings, providing elevation of the instrument to suit observing location. The whole instrument should be level, and so a means of levelling would be provided in the bottom section. An alignment mechanism would also be required to ensure accurate setting to the true North.

Using the model, it became apparent when rotating the yoke that clearances between elements had not been considered carefully enough, and that the instrument would not work if built to this particular specification. By altering the elevation framework and increasing the clearance between the yoke and table this problem was rectified. The clearance between yoke and elevation framework were checked by rotating the table from the horizontal through  $70^\circ$ , using the Autocad drawing package. By doing this the clearances could be clearly seen, and adjusted accordingly.

It was also suggested that in order to make assembly of the instrument easy, another stage should be added between the Right Ascension drive shaft and the yoke. Rather than try to fit the yoke directly onto the drive shaft, a mid stage which was permanently fastened to the shaft would be preferred. The yoke could then be placed directly onto a flat surface, and four bolts fitted through it into the yokebase.

The base which would be in contact with the ground was initially designed to rest directly onto the ground with no fixing. This was changed so that the base was clamped directly onto a concrete pad prepared especially for the instrument, resulting in a reduced base length, which would give easier access to the front of the instrument, and greater stability of during operation.

From this, a more detailed design developed, resulting in the manufacture of the telescope mount described.

## 4.2 Telescope drive mechanism

One of the first stages in the selection procedure was the way in which the telescope mount would be driven. A worm drive was selected for both axes, both for ease of motor attachment, and also for the quiet operation for which they are typical. A stepper motor was preferred to a synchronous motor, primarily due to cost, and so a spreadsheet program was derived in which various parameters could be input, and a suitable motor and gear configuration selected to enable tracking at the sidereal rate of one rotation in 23 hours 56 minutes 4 seconds.

Using a stepper motor with  $1.8^\circ$  steps, iteration resulted in a step rate of 1000 step/ sec, the resolution was found to be of the order 0.01 arc sec/ step, from a gear ratio of 43200:1

In order to achieve this gear ratio with standard components, a gear box of ratio 308:1 was selected for each axis, both would drive worm gears. A standard worm wheel of 150 teeth for the Right Ascension axis gave a final reduction ratio of 46200:1, whilst the Declination axis uses a standard worm wheel of 70 teeth to give a ratio of 21560:1.

The slew rate for the declination axis was accepted to be one half of that on the Right Ascension drive axis because it was expected that the polarimeter would normally be expected to rotate through  $180^\circ$ , and so by slewing both axes at the same rate, it should take the same time for their maximum traverse.

## 5. Detailed Design

The mark III polarimeter (Warren- Smith) had been superseded by an updated version described by Stockdale (1996), as a result, it was to be used in the development of the wide field polarimeter.

The dimensions of the polarimeter can be best approximated by a cube of 400mm side length, whilst the CCD can be considered as a cylinder of length 400mm, and diameter 240 mm. The combined weight of polarimeter and CCD is 65 kg.

In the process of designing an instrument to mount the polarimeter, consideration should be given to modifications to the way in which the polarimeter would operate on this new instrument. Mounting the polarimeter would be difficult if the same procedure were followed as that for a conventional telescope, and so a means of modifying the polarimeter to support itself within rotating bearings was developed.

It would require protracted calculations to determine the exact centre of gravity of the polarimeter assembly, made more difficult because there would be additions to the polarimeter structure in the course of instrument development, and so the polarimeter was modified to accept two stub shafts placed at its physical centre, and the instrument would be balanced prior to use.

In addition to the physical characteristics of the polarimeter, its control should be considered, and as a consequence it was decided to remove the motor control unit which effectively drives all components within the polarimeter. It was decided that the control unit should be separated and suitable cables routed to an external location. It was envisaged that the control unit would eventually sit within a control room along with computer controls.

Finally, the optics which feed light to the polarimeter should also be considered during the design process, so that when modifications were made to the polarimeter to

add support stubs, any additional components to fit optics could also be made at the same time.

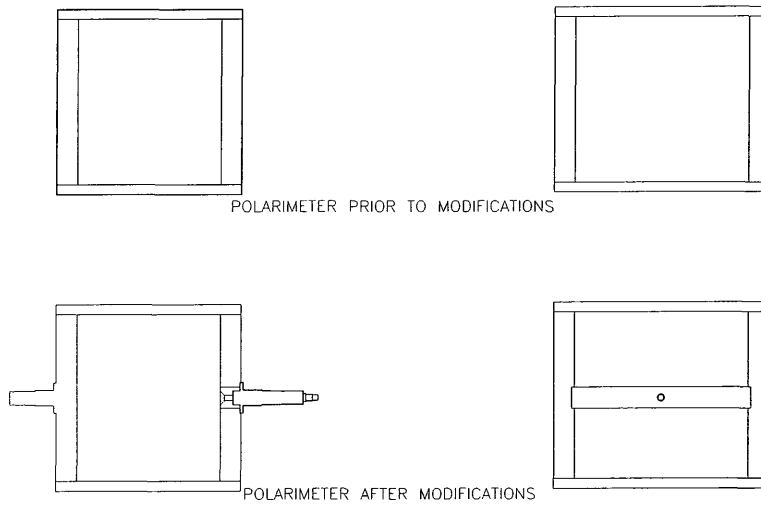
Initial thoughts for providing optics to gather light for the polarimeter were to use a Celestron spotting scope. This would initially involve making an adapter to connect it to the polarimeter front plate. Once the wide-field polarimeter was working properly then a different arrangement may be considered to improve on the quality of the image captured by the polarimeter. If this were to happen then the changes to the optics may facilitate some more modifications to the polarimeter body, although the operation of the polarimeter would not change.

## **5.1 Modifications to the polarimeter.**

In order to support the polarimeter within bearings two stainless steel stub shafts were added to provide what was effectively a shaft running through the instrument. To do this two horizontal supports were placed between the corner columns of the polarimeter.

The polarimeter carcass is illustrated in Figure 5-1. The original polarimeter configuration is illustrated in the top section of the figure, the bottom section shows the modifications.





**Figure 5-1 The polarimeter carcass**

The Figure illustrates the location of the additional horizontal supports, and the positioning of the support stubs.

The corner columns of the polarimeter were made from 38 mm square section aluminium. The deflection of this section under the given loads was calculated using the standard deflection formula for a beam fixed at both ends with central loading.

$$Y = \frac{W * x^3}{192 E I}$$

**W = beam load**

**x = distance between supports**

**E = Young' Modulus**

**I = moment of inertia**

Applying a factor of safety of 2, the load became 130 kg, the distance between supports was 322mm, E for aluminium is  $70 \text{ GN/m}^2$ , and I for this section is  $1.738 \cdot 10^{-6} \text{ m}^4$ .

The **deflection** was found to be in the region of **0.002 mm**, and so this material could be seen to be more than adequate for its purpose.

The support struts were fixed to the polarimeter by machining rebates into the corner columns and held in place using two M6 cap screws per end, ensuring positive location and fixing.

The stubs were designed to fit into a counterbore in the centre of the support struts, and were held in place by a single M10 countersunk screw fastened from within the polarimeter body, and two M6 button head screws fastened through a flange to the outside of the support struts.

The stub dimensions were found in the same way as that used for the polarimeter supports, with the final geometry determined once the drive mechanism had been finalised. The torque requirements of the shafts in question can be assumed to be negligible due to the operating conditions of the polarimeter, and so the stub diameters were selected with reference only to resistance to bending.

Assuming the stubs to be a continuous shaft through the polarimeter, simply supported in bearings and the load at its centre, the shaft diameter can be found using the equation:

$$\sigma = \frac{W * x}{4 * Z}$$

$\sigma$  = Max. allowable stress

$W$  = load

$x$  = distance between supports

$Z$  = section modulus

The maximum allowable stress, was 100 MN/m<sup>2</sup> (MegaPascals), the load 130 kg, the distance between supports 400mm, and  $Z$ , the section modulus is a value dependant upon the shaft diameter. The section modulus is a value found by dividing the Moment of Inertia by the distance from the neutral axis of the section to its outer limits.

$Z$  was calculated to be  $0.637 * 10^{-6} \text{ m}^3$ , and using the relationship  $Z = 0.098 * d^3$  the stub shaft diameter was found to be 23.5 mm. To accommodate available bearing sizes this value was increased to 25mm, this would have the effect of reducing the stress in the stubs.

The polarimeter relies on controlled exposure to light entering the polarimeter, and so with the modifications described the existing side covers could not be used. This resulted in new side panels being manufactured from 1.6 mm aluminium sheet. A step was machined in the corner columns of the polarimeter framework to accept the sheet aluminium keeping the top surfaces flush. Holes were added to provide secure fastening around the panel.

The remaining sides also had covers made, using 2.5 mm aluminium sheet. One cover, considered to be reasonably permanent, had a cut out machined to provide easy access to the upgraded control wiring connections. This was screwed onto the polarimeter using existing holes. The remaining cover had four quick release DZUS fasteners fitted so that quick and easy access was afforded to the polarimeter optics.

In order to attach the telescope optics to the front plate of the polarimeter, four holes were drilled into the front plate to accept four screws that would hold down the optics support ring. The optics are described more fully in section 6.7.

Two 12 mm aluminium plates were screwed to the front plate of the polarimeter to attach lifting bars and balance weights. M6 tapped holes were positioned along the length of the plates. Four aluminium bars, each with two M6 clearance holes, could then be attached to make loading of the polarimeter onto the mount easier and safer.

The front plate of the polarimeter had holes drilled to fasten onto the telescope connector plate, these holes were redundant for the wide field polarimeter, and so a cover was made to block light from entering through them.

## 5.2 Drive requirements

Initially, a means of slewing and tracking using two separate drive mechanisms was considered but this could create problems of control during operation, and so a system which would fulfil both requirements was preferred. Using two methods would introduce problems such as two motor drives, and/ or gear drives or complex transfer between a fast and slow transmission.

In order to find suitable motor, gearbox and worm gears, slewing times which were acceptable had to be first chosen. Because system torque is directly proportional to acceleration, then acceleration should be reduced to keep torque to acceptable levels. In order to determine these factors, it was assumed that the system would be balanced during use, and so by determining the polar moment of inertia of the system, it would be possible to control torque by altering slewing rates.

### 5.2.1 Drive torque

The torque limits of the drive mechanism, on both axes, could be found using the formula:-

$$T = I * \alpha$$

**T = Torque**

**I = moment of inertia**

**$\alpha$  = angular acceleration**

It can be clearly seen that, with a system of fixed inertia, the maximum torque will occur at a point where acceleration is a maximum.

The first step in finding the system torque was to find the inertia of the driven elements. The acceleration could be varied using the motor control system.

In order to determine the polar moment of inertia for the yoke, and hence the Right Ascension drive mechanism, the yoke was approximated to be a pyramid. Using the formula:-

$$I = M * (A^2 + B^2) / 20$$

**I = moment of inertia**

**M = Mass**

**A , B = base lengths**

the inertia was found to be **4.22 kg/m<sup>2</sup>**. This was calculated with a mass of 75kg, which was the approximate combined weight of the polarimeter and the yoke. The yoke had a square base of length 0.75 metres.

Similarly, for the declination axis the polarimeter was approximated to be a rotating cube and so using the formula:-

$$I = M * (A^2 + B^2) / 12$$

the inertia was found to be **2.0 kg/m<sup>2</sup>**. Again the mass used was 75 kg, to introduce a factor of safety, and the polarimeter was approximated to a square of length 0.4 m.

### **5.2.2 System operating times**

A spreadsheet program was used to determine, using Newton's Laws of Motion, a reasonable blend between torque limitations and operating times. Preliminary calculations enabled selection of a motor, gear box and worm drive components capable of fulfilling the system requirements.

The worm wheel teeth have a module of 0.4, from which can be described their physical size, and their maximum torque is limited to 0.36 Nm. The motor has a torque curve which depends on the operating speed, with a minimum torque of 0.125 Nm, as the motor increases speed to 10,000 steps/ sec, with a maximum torque of 0.28 Nm. The gear box has a torque capacity of 50 Nm.

The stepper motor operates at 1.8° step intervals, and so 200 step/ revolution was used calculate the operating speeds. The tracking speed and resolution of the instrument, fixed the gear ratios at 46200:1, and 21560:1 for the Right Ascension and declination axes respectively, see section 4.2.

In order to slew in Right Ascension at reasonable rates, the maximum operating conditions were applied. The maximum speed of the motor is 10000 steps/ sec, equivalent to 314.1 rad/ sec (50 rev/ sec). If the time taken to reach this speed, from rest, was 60 seconds then the acceleration of the motor can be found using

$$V = \alpha * t$$

This equates to an increase in the motor step rate of 167 step/ s<sup>2</sup>, an acceleration of 5.23 rad/ s<sup>2</sup>. The acceleration of the yoke is a function of the gear ratio of the drive mechanism and so it would be 1.13 \*10<sup>-4</sup> rad/ s<sup>2</sup>.

The distance covered in this time can be calculated using

$$S = 1/2 \alpha * t^2$$

and found to be 0.203 radians.

The same conditions would apply in slowing the system down, and so the remaining distance must be covered at the maximum slewing speed. With the yoke

rotating at 0.0068 rad/ sec, the remaining 5.877 radians will be covered in 865 seconds (about 14.5 minutes). This gives a slewing time of about 16.5 minutes.

The torque of the system is a maximum of  $4.77 * 10^{-4}$  Nm, well within the capabilities of the motor and gear drive assembly. By increasing the step rate, the system slew time can be reduced.

A similar theory can be followed for the declination axis, this would give a maximum acceleration of  $2.43 * 10^{-4}$  rad/ s<sup>2</sup>, which corresponds to a maximum torque of  $4.85 * 10^{-4}$  Nm. The time taken to turn through 180° would be around 5 minutes.

There would be no point in rotating the polarimeter into position so quickly if the Right Ascension was not in place, and so the declination slew speed can be reduced to conserve component life.

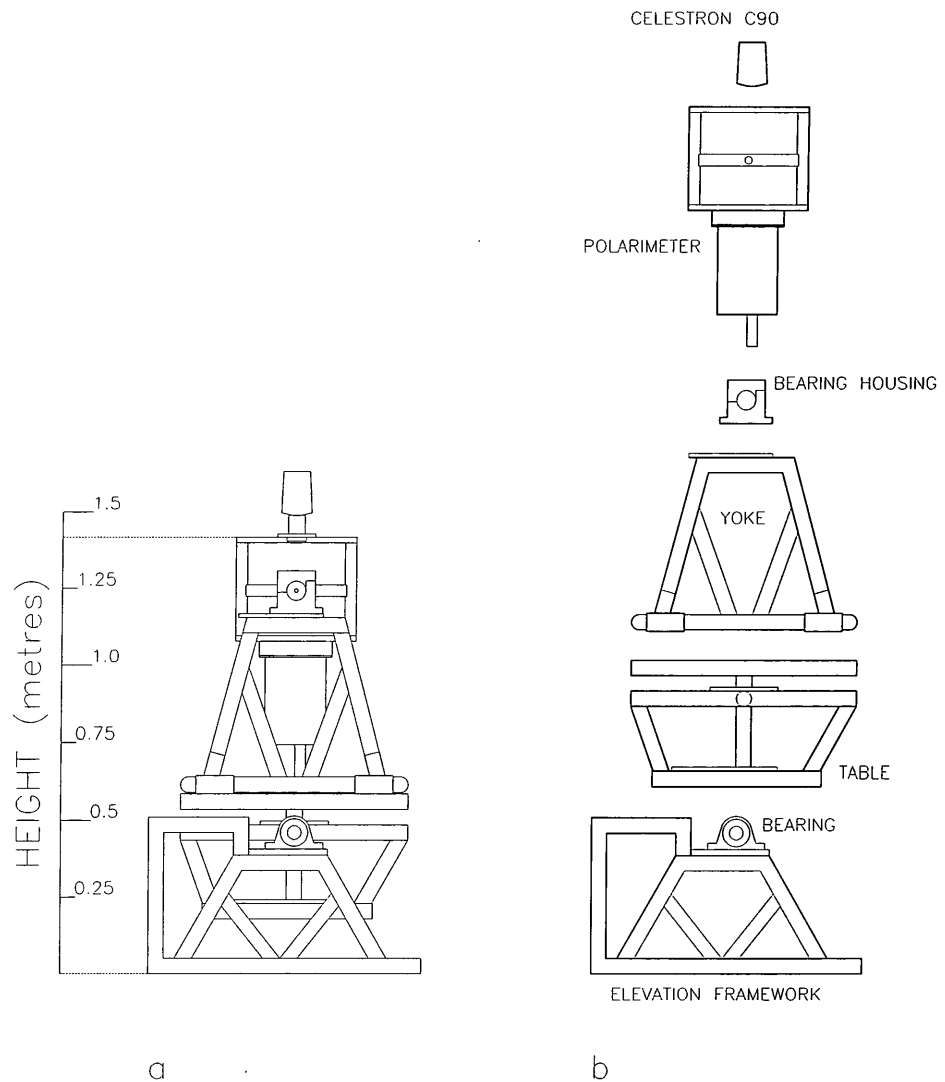
The tracking speed of the Right Ascension axis can be theoretically calculated. One turn of the yoke is required in a sidereal day, this being a period of 86164 seconds. The gear ratio of 46200 means that the motor therefore rotates once in 1.865 seconds. Because we know the motor has 200 steps/ rev, we can therefore say that the required step rate of the motor is in the region of 107 steps/ sec.

When using gear trains to move an object there are inherent losses within the system. The greater the number of elements within the system, then the greater will be the losses. The efficiency of worm gears can range from 46% to 98%, depending upon the operating conditions. This can include the material used to manufacture the gear components, the gear geometry, type of lubrication and the speed of operation. As a consequence, the theoretical step rate of the motor can only be used as a guide because there is no indication as to the efficiency of the transmission system, and so the actual tracking rate can only be found once the instrument is tested.



## 6. Telescope mount design

An illustration of the final design of the telescope mount is shown in Figure 6-1. This provides a side elevation of the basic support structure. Parts of the control mechanism have been removed for clarity, but these are illustrated subsequently.



**Figure 6-1 A side elevation of the telescope mount**

Figure 6-1a illustrates the assembled telescope mount, Figure 6-1b shows it broken down into constituent parts.

Working from the top of Figure 6-1, a Celestron C90 spotting scope was attached to the front plate of the polarimeter to provide a means of focusing light onto the grid mask. This will be used until the system is proven to work, although there is the intention in future to obtain dedicated optics designed for the wide field polarimeter.

The polarimeter sits within a pair of bearings housed on top of the yoke. The declination axis drive assembly is fitted to the side of the yoke below the bearing housing assembly.

The yoke is bolted to an intermediate stage which fastens onto the Right Ascension drive shaft. This intermediate stage is intended to be permanently attached and can be prevented from rotating, by fitting a metal strap between the table and yoke base.

The yoke is driven in Right Ascension by a mechanism housed within the base of the table.

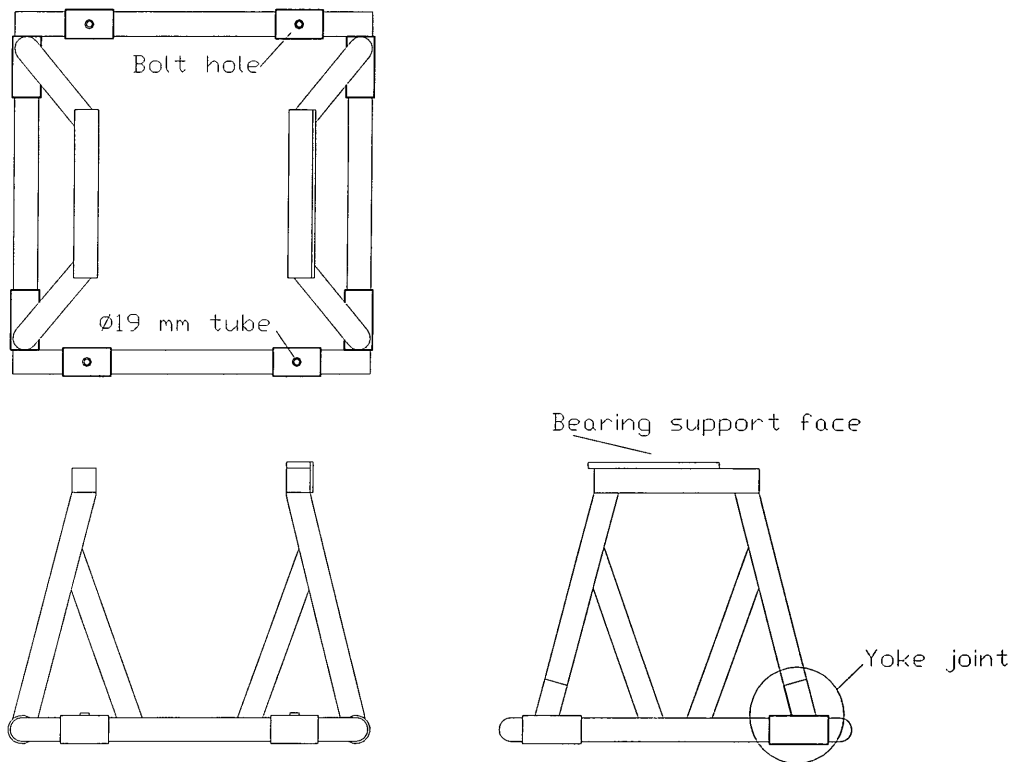
The elevation framework has a pair of bearings opposing each other, these support the table framework which rotates to suit the latitude of the observing site. A mechanism attaches below the bearing on the elevation framework to allow accurate control of changes in the elevation angle.

The elevation framework sits onto an aluminium base, not illustrated, using a central spigot as location. This allows alignment of the telescope axis to north or south, using steel studding to drive the elevation framework around on its support.

A framework bolted to the ground provides a solid base from which to level, and then clamp the entire structure onto taking into account ground that is not level.

## 6.1 Yoke design

The yoke was designed to accept the polarimeter, allowing side and base clearance. It was based around a pyramid trying to combine rigidity with light weight. This led to the framework illustrated in Figure 6-2, a fabricated structure built principally from round aluminium tube.



**Figure 6-2 Illustrates the design of the instrument yoke.**

Square tube was used to support the declination bearing housings, with two M12 threaded inserts welded into each tube to accept the housing fasteners. A 12mm aluminium plate was welded onto the top surface of the square tube to provide location for two 6mm dowels used to obtain positional repeatability of the bearing centres.

More aluminium plate was welded onto one side of the yoke to provide a mount for the declination drive mechanism. Three M6 tapped holes fasten the drive carrier plate, and two dowel holes ensure gear centre distances remain constant.

Aluminium plates, with M6 holes tapped in them, were welded to the corners of the square tube so that balance weights could be added to the yoke.

The yoke is bolted to the intermediate stage via the four bolt points positioned as shown in Figure 6-2. These were cut in the 50 mm tube to provide clearance for 19 mm diameter tube, which was subsequently welded into position. The bore of the 19 mm tube provided clearance for the M12 bolts used to hold the yoke and its base together. The tube provided a flat clamp face for the bolt head and prevented crushing of the main tube caused by clamping of the bolts. The bottom of the 50 mm tube had a 12 mm clearance hole only, so that the 19 mm tube would not rely on the weld quality for its clamp strength.

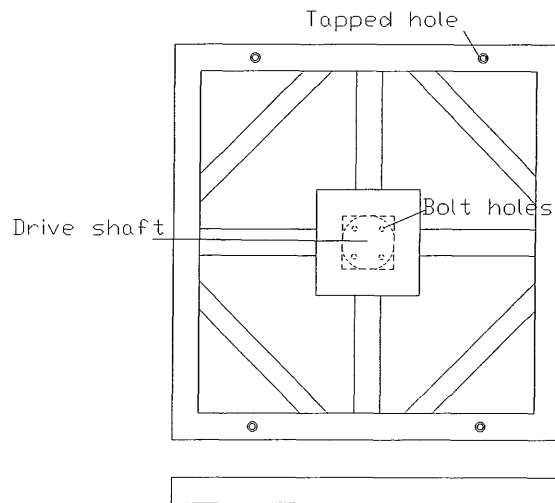
The joints which form the sides of the yoke were made with 50mm internal diameter tube which fits over the 50mm tube used in the construction of the remainder. The same tubes are used around the clamp holes to provide a solid interface. The manufacture of these joints is described fully in section 7.3.

Rigidity of the structure was improved by welding 44mm diameter tube between the sloping faces of the yoke and the base.

Power to the declination axis motor, and for the alignment camera, was fed through plastic conduit fitted up the side of the yoke. A die cast aluminium connection box was fitted to the side of the yoke below the motor. The electrical connections were made within this box, which was sealed with a neoprene gasket.

## 6.2 Yoke base

Figure 6-3 illustrates the yoke base. The dashed lines in the centre of the figure show the top of the Right Ascension drive shaft, with the bolt hole positions shown. A hole through the centre allows the electrical supply cables through to the top of the yoke.



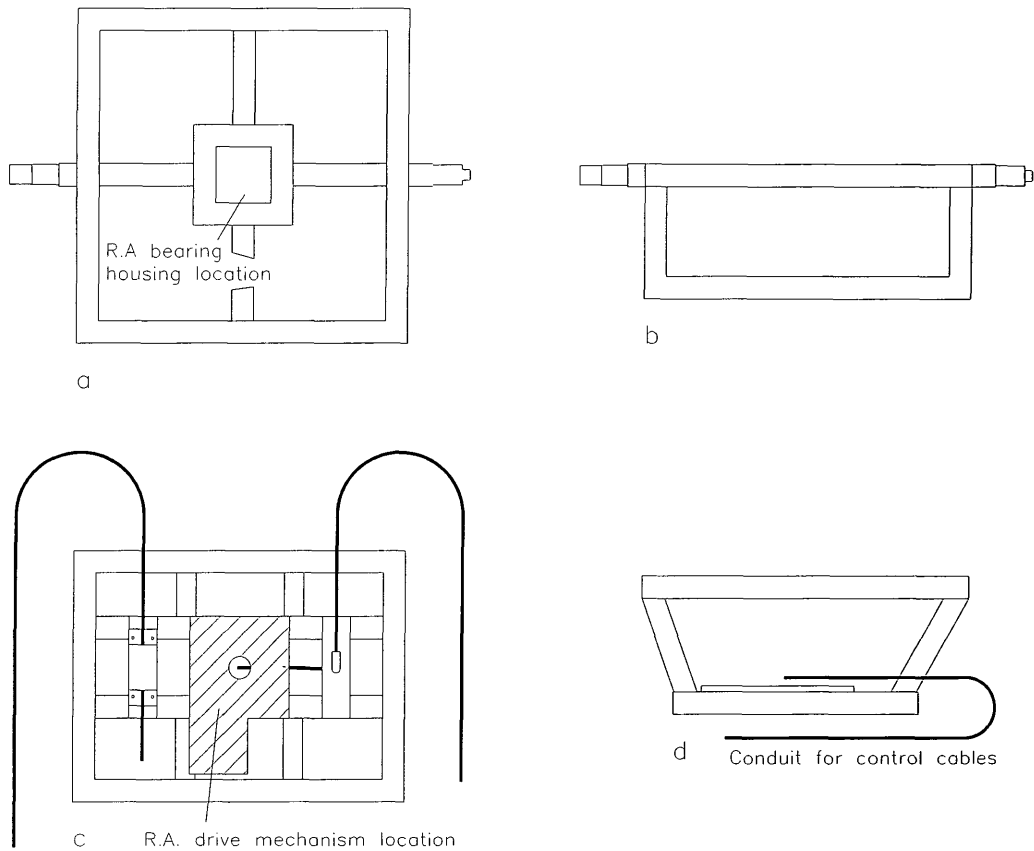
**Figure 6-3 The yoke base**

The four holes which connect the yoke to the yoke base, were provided by welding four threaded aluminium inserts into the square aluminium tube. A clearance hole was cut into the top of the tube to accept M12 bolts which held the inserts prior to welding.

The squares formed by the framework were done using 50 mm square aluminium tube. The cross which forms the connection between the inner and outer squares was made up of 50mm round tube welded onto the framework, in the manner described fully in section 7.1. Tube was welded across the corners to add strength.

## 6.3 Table

The table, shown in Figure 6-4, houses the components for the Right Ascension drive axis. Figure 6-4c shows the bottom section of the table, a 12mm thick plate, shown by hatched lines, carries the drive motor and gear box, see section 6.6.



**Figure 6-4 Illustration of Table section**

Square section aluminium tube was used to manufacture the framework. The thick black lines which loop around from the table base illustrate the path of the conduit carrying the drive cables.

Thrust bearings are used to support the drive shaft within housings located within the top and bottom faces of the table, allowing smooth rotation, ensuring that there is no movement in the plane of the drive shaft axis. The first bearing is located within a

housing in the square shown in Figure 6-4a, whilst the second is located below the plate shown hatched in Figure 6-4c.

Both housings are fastened in place onto aluminium plates welded into the respective locations. The housings have levelling screws to ensure alignment of the bearings once the shaft is in position. Four screws hold the housings in position.

The two stub shafts which support the table are held in pillow block bearings. These are used to rotate the instrument to the elevation angle and also to lock it in that position. The shaft to the left of Figure 6-4a, serves to clamp the table in position whilst the shaft to the right has a spur gear attached to provide fine adjustment in elevation.

The stub shaft diameter was designed to withstand the effect of bending due to the weight of the polarimeter and the telescope framework. The total mass,  $M = 150$  kg, supported over length,  $l = 0.9\text{m}$ , with maximum allowed stress,  $\sigma = 75 \text{ MN/m}^2$ , the diameter  $d$  was found using the equations shown:-

$$Z = \frac{M \cdot 9.81 \cdot l}{4 \cdot \sigma}$$

$$Z = 0.098 \cdot d^3$$

The diameter of stub shaft was found to be 35.6 mm. To allow for unknown or unexpected loads, the shaft diameter was increased to 45 mm, a convenient size for standard pillow block bearing.

The sloping front and rear faces of the table were to provide vertical and horizontal faces when the polarimeter was being used at its extreme latitudes, it would provide better access to the base of the table during operation.

To counterbalance the turning effect of the yoke and polarimeter, weights were built into the table. This was not expected to be the definitive solution to counterbalancing of the polarimeter and yoke but would provide a useful means of hiding necessary balance weights without taking up external space. These weights were taken into account in the calculation of shaft diameter.

Power to the drive motors was provided via cables passing through plastic conduit below the table. The declination drive cable passed through the centre of the Right Ascension drive shaft to conduit positioned on the yoke.

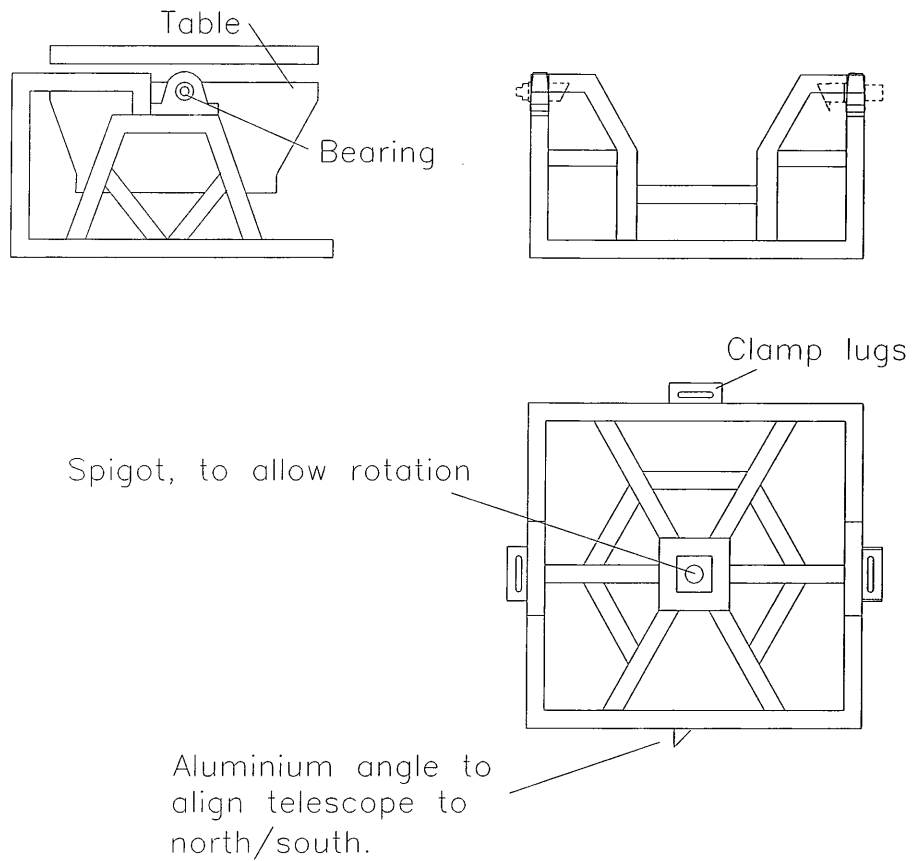
A die cast aluminium box was attached to the base of the table, and the Right Ascension drive cables connected within.

Two aluminium plates were added to the framework; one held the conduit end, whilst the other held the Right Ascension connector box in place.



## 6.4 Elevation axis

A means of setting the telescope mount to the desired angle of latitude was achieved using the cradle illustrated in Figure 6-5. Two bearings were fitted to the square section tubular framework to provide smooth rotation over the range  $0^{\circ}$  to  $70^{\circ}$  from vertical.



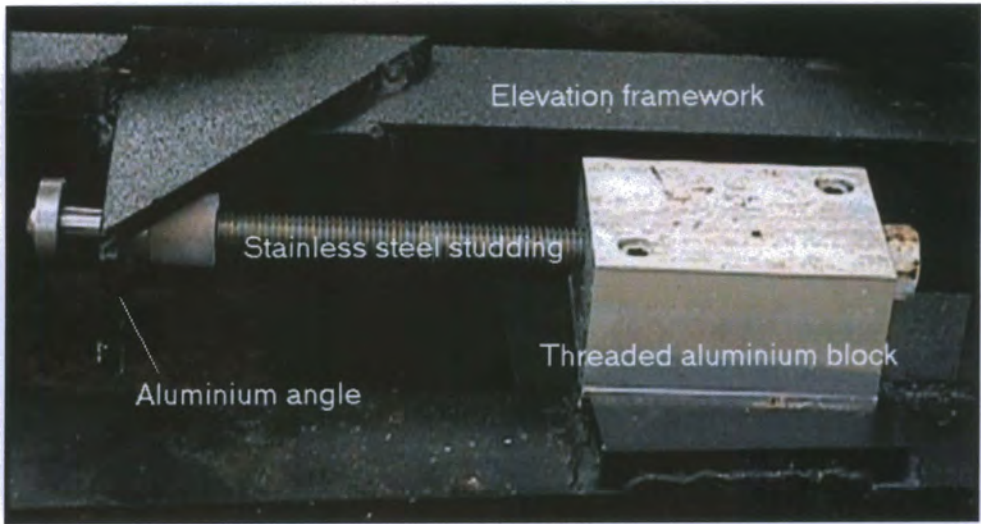
**Figure 6-5 Elevation framework**

To allow alignment of the instrument in the North - South plane, rotation was attained using a stub extending vertically downward into a bearing supported in the groundbase. Motion in this plane was achieved using, the mechanism illustrated in Photograph 1. A length of studding screwed through a threaded aluminium block,

pushing onto a piece of aluminium angle, shown as a triangle at the very bottom of Figure 6-5. Alignment should be done without the polarimeter in place.

The framework is held in place using three slotted clamping points which can be locked once alignment is complete, Photograph 2. PTFE pads were fitted to the groundbase to reduce sliding friction.

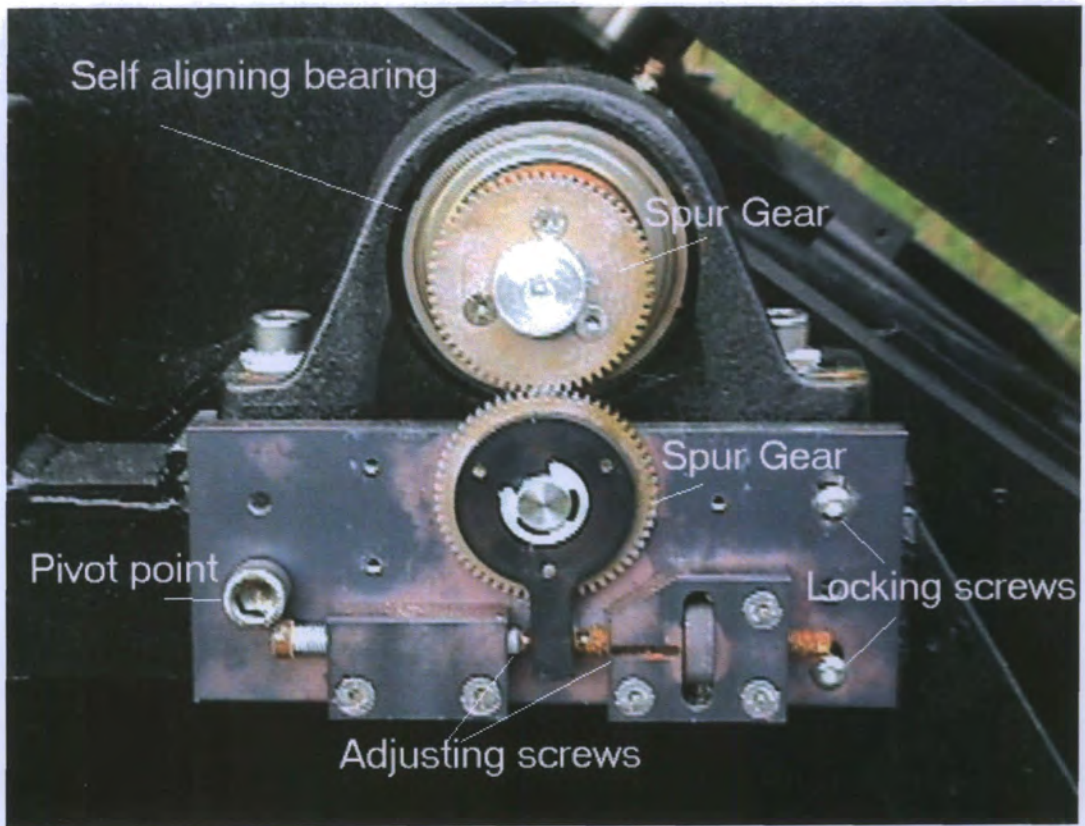
The power cables originate from a single box located at the rear of the elevation framework. The cables feed from the bottom of the box, through plastic conduit, to the front of the framework, forming a loop to return to the centre of the table. The declination drive cable passes on the right of the framework, the Right Ascension on the left.



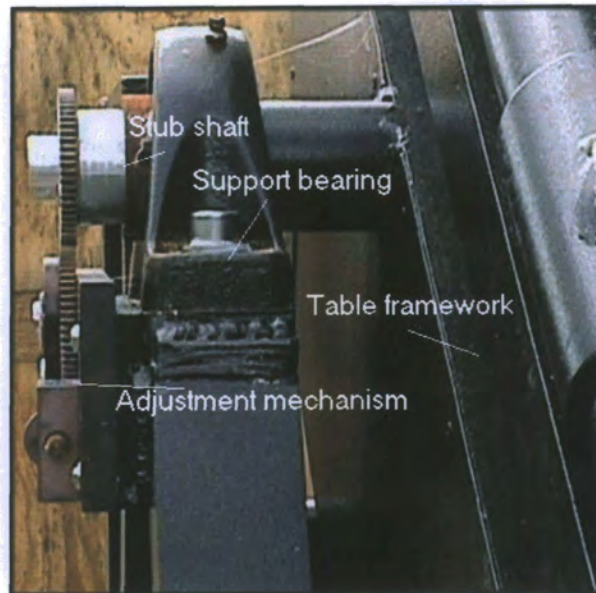
**Photograph 1 North-South alignment mechanism**



**Photograph 2 Adjustment of elevation framework**



**Photograph 3 Elevation fine adjustment mechanism**



**Photograph 4 Side view of elevation adjustment mechanism**

### **6.4.1 Setting the telescope elevation angle**

It was intended that the system should be balanced prior to altering the elevation angle. Without balancing, the instrument could become unstable resulting in either damage to the instrument or possible injury to the user.

Setting of the elevation is done manually, preferably with two operators. The mechanism illustrated in Photograph 3, is disconnected by removing two 6mm dowel pins, and loosening two M6 screws from the carrier plate. This allows the plate to drop on the slots, with a dowel bolt acting as pivot, disengaging the drive, and allowing the table and yoke to be rotated to approximately the correct angle, measured on a graduated scale fitted to the clamp block.

The carrier plate is repositioned, re-engaging the two spur gears. The lower spur gear can then be rotated on its pivot by moving a thumbscrew to push on the lever to obtain fine adjustment of the elevation. The lever is made from aluminium and is machined to accept the spur gear, which can then be screwed in place using the three screws as illustrated.

Whilst setting the elevation the polarimeter will not be in place and so balance weights need not be excessive. A small CCD camera (SBIG ST-6) can be mounted between the declination axis bearing housings to aid in the set up of the telescope.

Balancing of the telescope is described more fully in section 9.3.

### 6.4.2 Friction locked joints

In order to lock the elevation axis, a friction locked joint was employed, it can be defined using the formula below K. Gieck, and with reference to Figure 6-6.

$$F_n = \frac{T v}{\mu d}$$

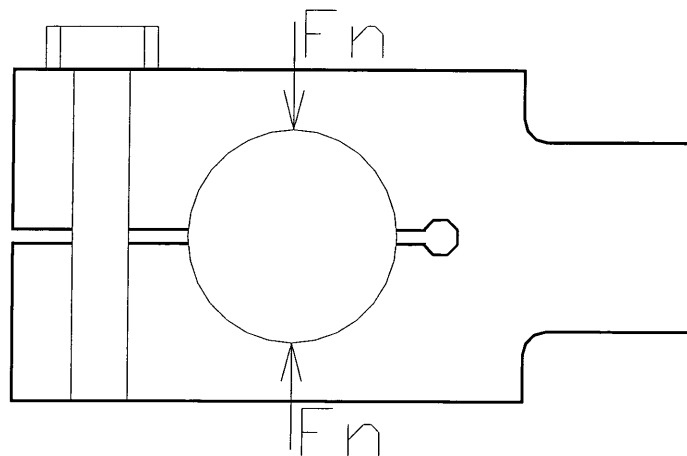
**$F_n$  = Normal force**

**$T$  = Torque**

**$v$  = Factor of safety**

**$\mu$  = coefficient of friction**

**$d$  = shaft diameter**



**Figure 6-6 Friction locked joint**

The friction locked joint works by clamping the stub shaft within a mating orifice increasing friction by the addition of the clamp load. With reference to the above formula, the torque would be calculated from the turning moments created by the weight of the polarimeter (75kg) at a distance from the table pivot (0.785m), this value was found to be 577Nm . The factor of safety can be any value but was initially

left at 1, whereas the coefficient of friction is 1.35 for dry aluminium to aluminium contact. The shaft diameter was calculated to resist bending and set at 45 mm, (section 6.3).

From this the **normal force** required on the table shaft was found to be 9.5 kN, assuming no counterbalance of the polarimeter on the table.

The area of bolt which can withstand this load can be found from:-

$$A_{\text{bolt}} = \frac{F_n}{\sigma_p}$$

$A_{\text{bolt}}$  = Area of clamp bolt

$\sigma_p$  = Permissible stress

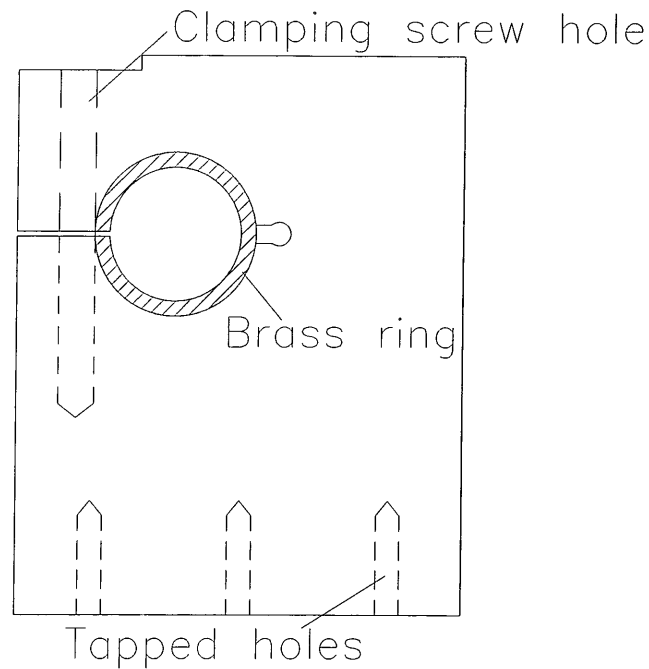
If the permissible stress in the bolt was limited to 100 MPa, the diameter of bolt would be calculated to be 11 mm. This is not a standard size bolt, and so a M12 bolt was selected, bearing in mind that in calculating these figures no account was taken of the counter balance effect that the weights built into the table framework would have. Indeed the ideal would be to determine a suitable amount of counterbalance weight which could be added to reduce the turning effect of the polarimeter to a smaller value.

### 6.4.3 Elevation clamp block

In order to hold the table at the elevation angle, a clamp block was manufacture from aluminium. This is illustrated in Figure 6-7, and is shown in Photograph 5.

With the table fitted to the elevation framework, the block is slid over the table stub. Three countersunk screws fasten through a plate on the elevation framework into the bottom of the block.

Initially, the aluminium block clamped directly onto the stub shaft on the table. This created a problem of localised welding of the two aluminium components. This was rectified using a split brass ring, shown hatched, fitting within the clamp block, on the stub, to allow easy removal of the assembly upon dismantling the instrument.

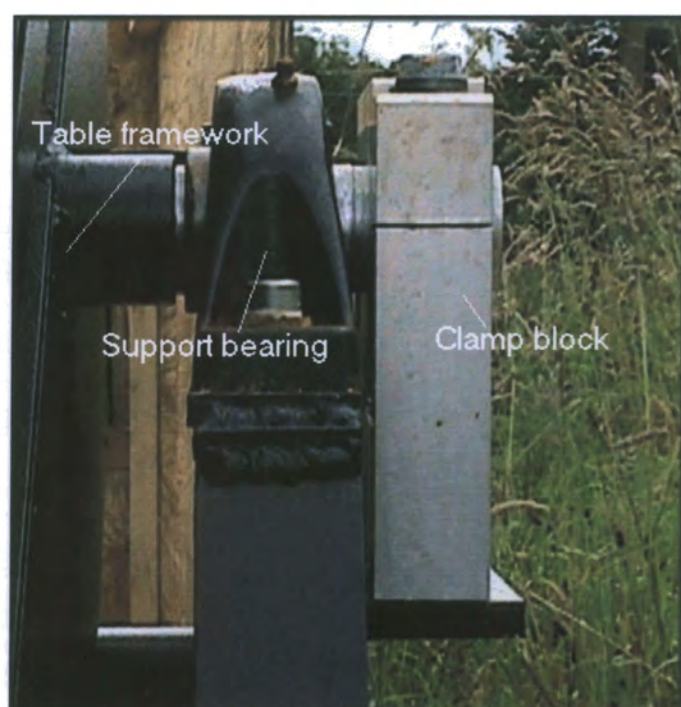


**Figure 6-7 Elevation clamp mechanism**

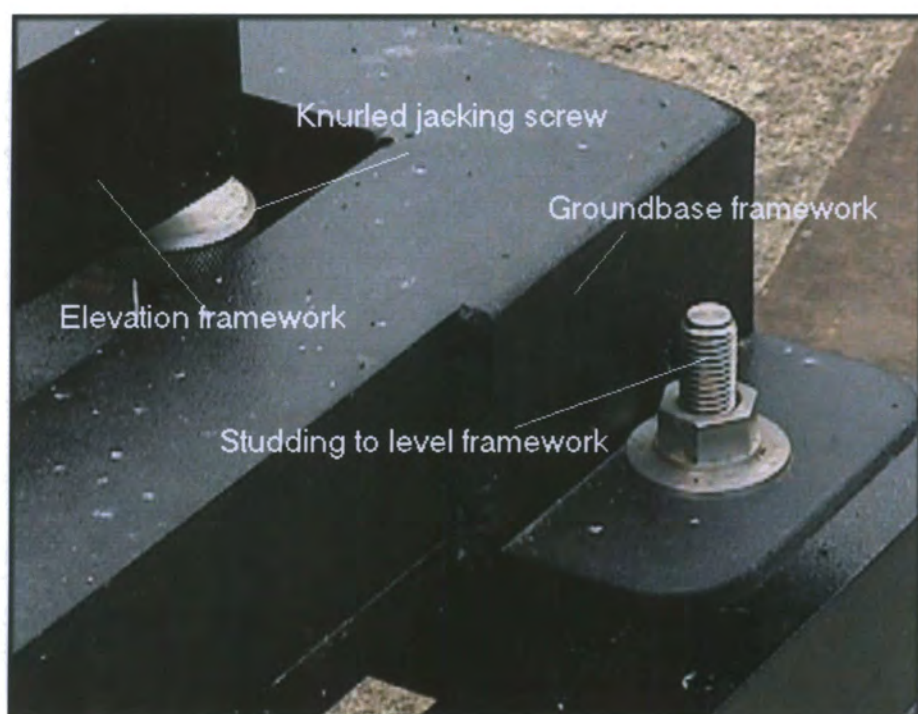
A 12 mm bolt passes through a clearance hole above the open slot on the block into a tapped hole, this can be seen by the fine dashed lines. By tightening the screw, the gap is closed causing the stub shaft to be gripped by the clamp block.

This clamp bolt should be loosened prior to moving the telescope mount in elevation, and prior to adjusting the elevation as described previously.





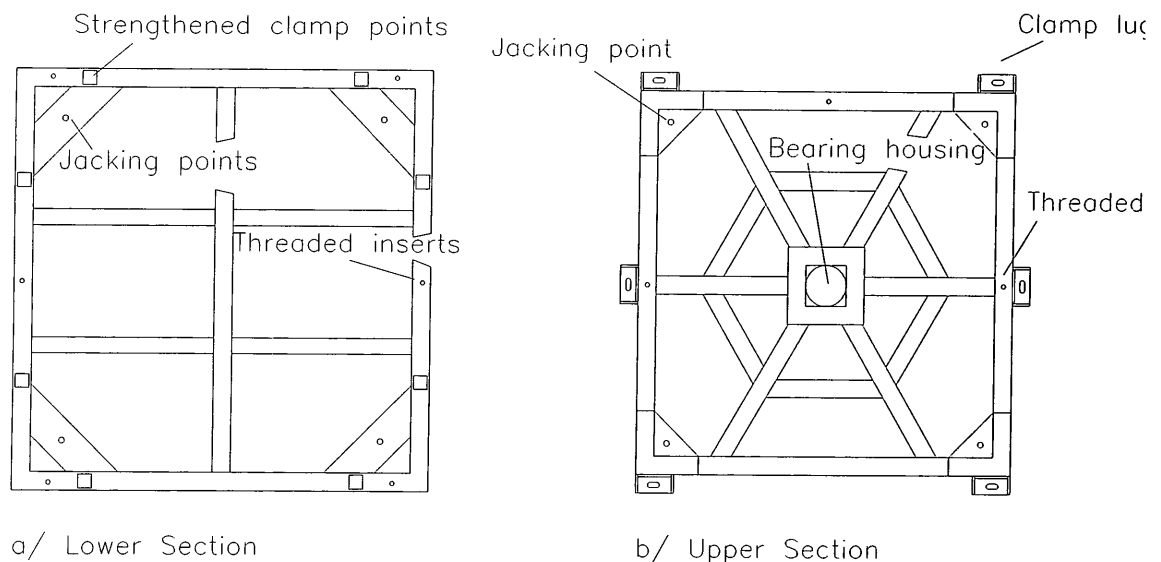
**Photograph 5 Front elevation of clamp block**



**Photograph 6 Levelling of telescope mount**

## 6.5 Groundbase

Levelling of the telescope mount is done using the frameworks illustrated in Figure 6-8. The section shown in Figure 6-8a, is designed to clamp to a solid flat surface, and the section shown in Figure 6-8b is used to level the telescope mount in relation to the lower section using jacking screws located in each of the four corners. Both frameworks were built from 50mm square section aluminium tube.



**Figure 6-8 Groundbase/levelling framework**

The lower section had blocks welded within the tubes to provide points, where the instrument could be clamped to a concrete pad without crushing the tube, these pads can be identified by 3mm plate welded to the tube above the blocks. The corners had 12mm aluminium plate added to provide a solid jacking point for the levelling section.

The upper section had 19mm thick aluminium plates welded into each corner to provide material in which the stainless steel jacking screws could be screwed. The jacking screws have radiused ends to ensure contact even when the two frameworks

do not lie parallel to one another. Photograph 6 illustrates the mechanism used to level the telescope mount.

The thread does not extend to the end of the screws so that it will not be damaged in use. A knurled end is used to turn the screws, although a hexagon was added in case adjustment was required when the telescope mount was assembled, and consequently the load on the screw would be greater.

Stainless steel studding was screwed into the lower section to enable clamping of the two sections when levelled with the jacking screws. A locking nut was placed above and below each of the six clamp lugs illustrated in Figure 6-8b.

A ball bearing was housed in the upper section to allow the elevation framework to pivot freely around the groundbase . This enabled setting up of the instrument in the North-South plane.

PTFE pads were added to the top of this section to reduce sliding friction between sections. Three tapped holes in the top face of the upper section are used to clamp the elevation section in position on the groundbase, once alignment was complete.

## **6.6 Drive assembly.**

In order to drive the telescope in both Right Ascension and Declination it was decided to utilise standard components. Applying this philosophy, suitable motor and gearbox arrangements were found.

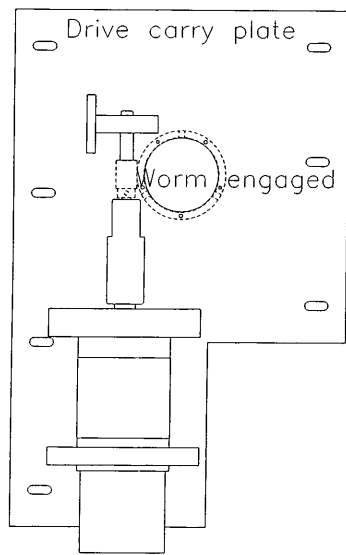
### **6.6.1 Right Ascension axis**

The Right Ascension drive mechanism is illustrated in Figure 6-9. Figure 6-9a is a plan view of the drive with worm and wheel engaged, Figure 6-9b shows elements of the design in side elevation.

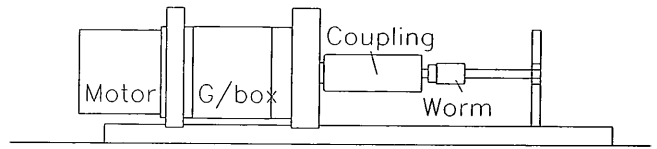
The motor and gearbox assembly are standard components supplied by McLennan Servo supplies, the stepper motor 23HS-108 connected to a P62 series planetary gear head. A planetary gear head was used to enable a large gear ratio to be attained within a small space.

The worm, W04S-6S, and wheel, W04B65-S150, are standard components supplied by Reliance Gear company. The stepper motor is rated at 200 steps/ rev, and the overall gear ratio for the drive is 46200:1.

The centre of the worm wheel was machined to be a good sliding fit over the Right Ascension drive shaft. A collar was fitted to the worm wheel, which fastened it onto the drive shaft. Three screws fasten through the collar into the shaft, with five screws and a dowel fastening the gear onto the collar. Figure 6-10 illustrates the way in which the worm wheel was attached to the drive shaft. It was not possible, due it's size, to attach it directly.

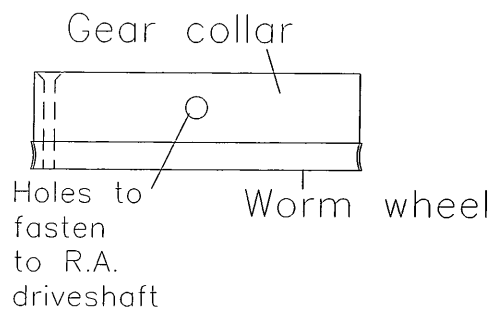
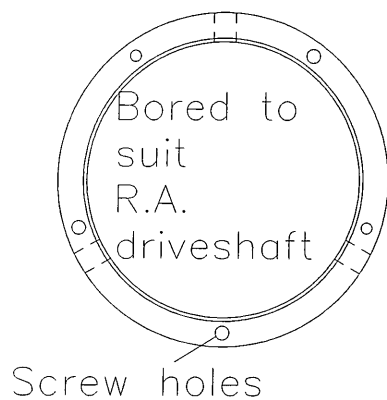


a/



b/

**Figure 6-9 The Right Ascension Drive Mechanism**



**Figure 6-10 Right Ascension drive gear**

An aluminium collar was manufactured to attach the gear, a series of screws hold the gear to the collar, and three screws around the collar fasten it to the drive shaft.

The worm was positioned centrally on the worm wheel using aluminium supports to hold the motor, gear head and worm shaft. The motor and gear box assembly was fastened to the front support using four M5 countersunk screws into holes located in the front of the gear head, a second support was used at the rear of the gear head.

A solid coupling was manufactured, and connected to the gear box output shaft using a square, parallel key, the other end holds the worm shaft. A grub screw holds the coupling in place on the key, whilst two further grub screws hold the worm shaft in the coupling. The free end of the worm shaft is supported in a bearing housed in an aluminium support. The worm was securely held on the shaft using two grub screws positioned perpendicularly.

The whole drive assembly was fastened onto a 3.2 mm aluminium plate with countersunk screws. Each of the components were fitted to the plate in their respective positions prior to finally tightening the screws.

The complete assembly, Figure 6-9b, can then be mounted onto the bottom level of the table framework. The support plate was manufactured from 12 mm thick aluminium plate, machined to accommodate the drive support plate, so that the top of both plates lie flush. This plate was welded into position at the bottom of the table framework.

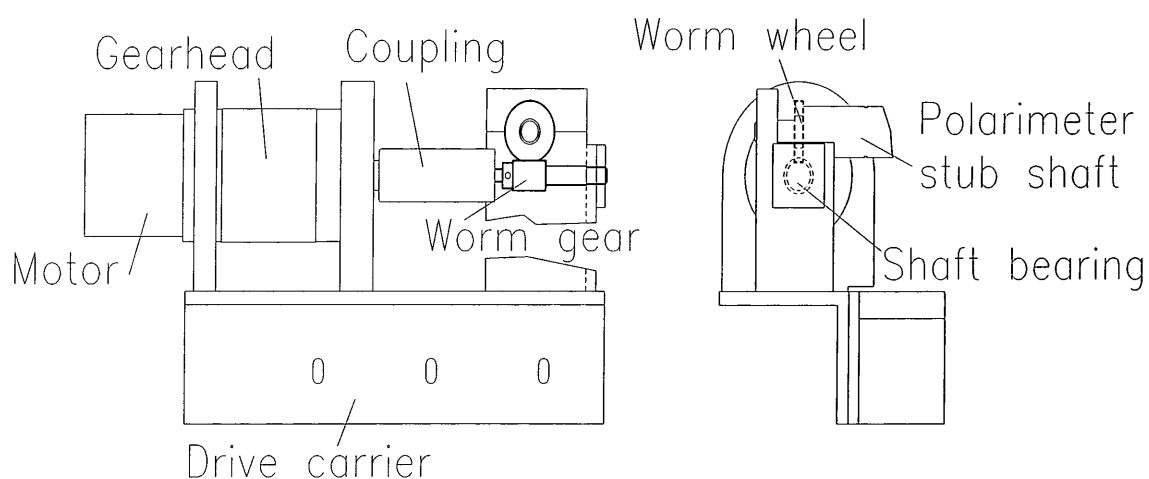
A series of slotted holes around its perimeter fasten the drive assembly to the support plate. The drive can be connected by loosening the screws which hold the mounting plate in position, and sliding it across to engage the gear teeth.

### **6.6.2 Declination axis**

The declination axis uses the same motor, gear head and worm as the Right Ascension axis. The worm wheel differs only in size, it has 70 teeth, W04B65-S70.

The worm wheel was machined to slide onto the end of the polarimeter stub shaft and a dowel inserted. A brass nut tightens the gear up to the stub shoulder.

The motor and gearbox assembly are mounted similarly to the mechanism used on the Right Ascension axis, see Figure 6-11, with the centre support height to suit the polarimeter stub shaft. The drive assembly is mounted on a piece of aluminium angle which is screwed onto the side of the yoke. Once in place, the mount is slid up to engage the worm with the wheel, dowels are put in place.



**Figure 6-11 Declination drive mechanism**

The gear ratio on the declination axis is 21560:1.

## 6.7 Polarimeter optics.

Under normal operating conditions light would pass to the polarimeter through a telescope, and so, this was replaced using a Celestron C90 spotting scope mounted onto the front plate of the polarimeter to focus the image onto the grid mask.

The Celestron C90 uses a combination of mirrors and lenses, arranged using the Maksutov-Cassegrain design, to produce an image. The technical specification of the C90 is listed:

<b>Optical System</b>	<b>Maksutov-Cassegrain</b>
<b>Aperture</b>	<b>90 mm</b>
<b>Focal length</b>	<b>1000 mm</b>
<b>Useful Power Range</b>	<b>25x to 210x</b>
<b>Linear field of view</b>	<b>16 metres</b>
<b>Angular field of view</b>	<b>1.0°</b>
<b>F/ratio</b>	<b>f / 11</b>

The grid spacing within the polarimeter is 4mm per grid, the focal length of the Celestron C-90 is 1000mm, this equates to 13' 45" of the sky per grid.

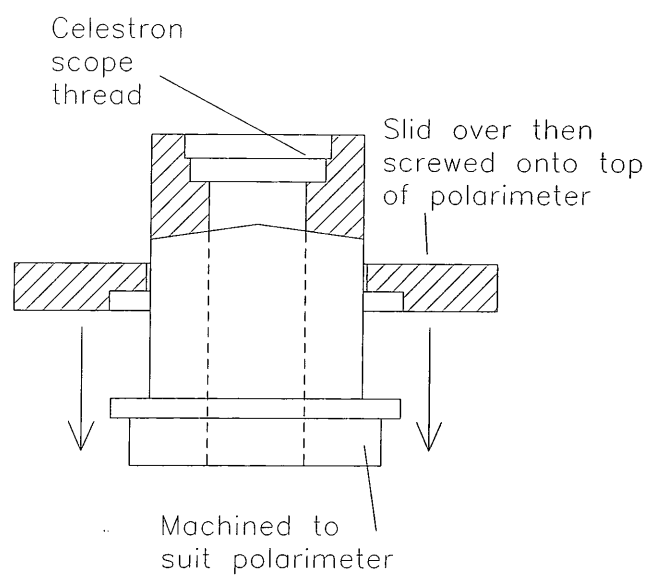
The spotting scope is attached using the adapter illustrated in Figure 6-12. The C90 screws into the thread at the top of the adapter, and locks.

The adapter locates within a counterbore in the front plate of the polarimeter. A sliding fit was achieved, to reduce lateral movement of the C90 on the polarimeter.



The clamp ring was slid over the adapter prior to mounting the C90, holding it securely in place on the front of the polarimeter. Four screw holes at the corner of the clamp fix the adapter in place on the front of the polarimeter.

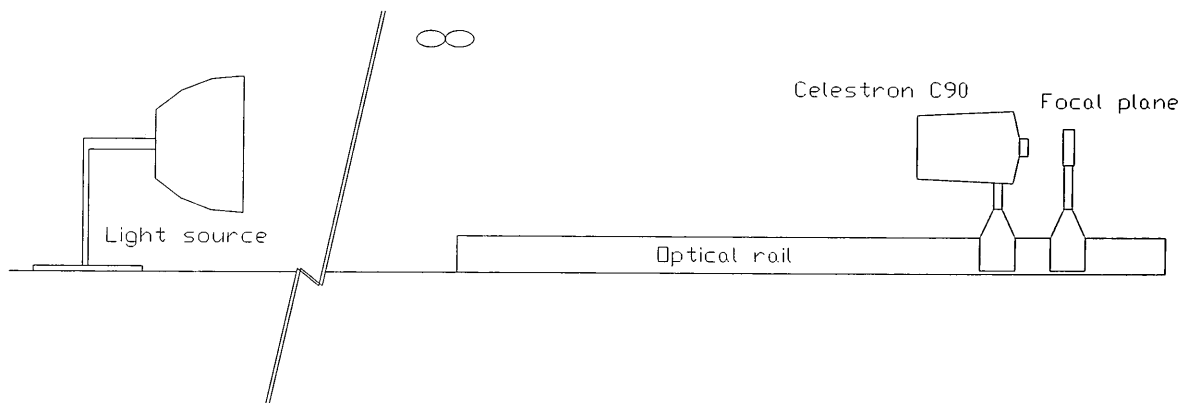
The hole passing through the centre of the adapter has a fine screw thread cut along its length to reduce reflected light. The adapter was anodised matt black.



**Figure 6-12 Celestron C90 Optics Adapter**

### 6.7.1 Determination of Celestron C90 focal length.

The focal length of the C90 was found using standard optical components to mount the instrument on an optical bench, see Figure 6-13, whilst directing a light beam toward the C90 in a dark room.

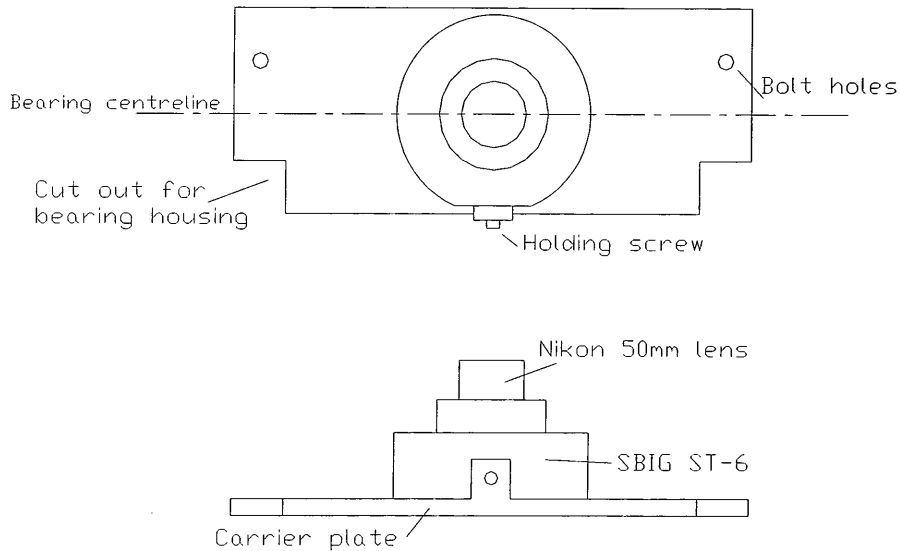


**Figure 6-13 Determining the focal length of the Celestron C90 spotting telescope.**

A plain piece of white card was attached to a second optics stand. This stand was moved, relative to the C90, so that a sharp image appeared. The distance between the image and C90 was measured and used to determine the length of the optics adapter shown in Figure 6-12.

## 6.8 Recording device

In order to align the telescope to an object, a CCD camera was mounted onto the declination axis bearing housings on the yoke framework. The camera mount can be seen in Figure 6-14.



**Figure 6-14 CCD mounting plate**

A Santa Barbara Instrument Group ST-6 air cooled CCD was used; a mounting plate was manufactured, to fasten the camera to the yoke bearing housings quickly and easily. A standard Nikon 50 mm Lens was fitted, using an adapter, to focus light onto the CCD chip. A lap top computer was used to operate the camera software.

Once aligned on a known astronomical object, then the CCD mount can be removed and the polarimeter fitted.

Under normal conditions of use, the polarimeter would be fitted with an evacuated and cooled CCD dewar to record the light images. Because of the remote

nature of the test site it was decided to replace this mechanism temporarily with the SBIG ST-6, which is powered electrically, but self cooling.

In order to fit this to the polarimeter a mounting flange was made. This consisted of a piece of 12.5 mm aluminium plate, machined to fit within the counterbore on the polarimeter. A hole was machined centrally, in which was cut a thread corresponding to that on the camera itself, M42 \* 0.75 mm pitch. The camera was held in place by a threaded insert screwed into the camera, which in turn was screwed onto the mounting plate, which locked the two items together. A counterbore was machined in the centre of the plate to bring the focal point of the polarimeter onto the CCD chip.

#### **6.8.1 The SBIG ST- 6 CCD camera.**

In order to reduce unwanted noise on the CCD chip, it is important that the camera is cooled. This camera is cooled using a two-stage thermoelectric cooler to cool the CCD. The camera has a temperature sensing thermistor to monitor the temperature keeping it at the user defined value.

The pixel size of the ST-6 camera is 23 \* 27 microns, arranged into 375 \* 242 pixels. The size of the array is 8.63 \* 6.53 mm.

## 7. Manufacture

The telescope framework consists of aluminium tube with material thickness of 3mm, the material was strengthened locally with the addition of aluminium plate, or aluminium inserts. Stainless steel was used where increased component strength was required, such as driveshafts and fasteners.

Both materials were selected for their corrosion resistance, and ready availability.

### 7.1 Manufacturing practices

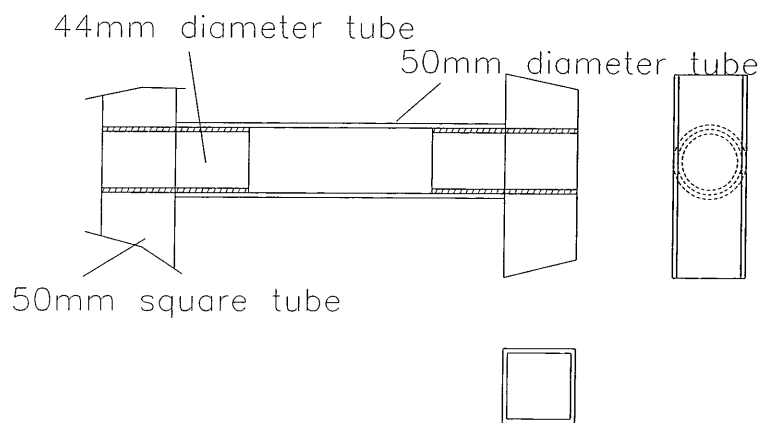
Many components on the framework were duplicated, and, so stops were fitted to the table of the milling machine to ensure repeatability and to speed up manufacture. This included mitres to form enclosed squares for items such as the yoke base, hole positions ready for inserts, and, to machine components to length.

All tube was cut and then machined to length either on a milling machine or lathe to ensure accuracy and good surface contact prior to welding. It is easier to weld two pieces of material where there is a consistent gap between them, otherwise there is a tendency for the heat caused in the welding process to blow the parent metal away.

Welding of the aluminium was done using a MIG welding machine using a 1mm diameter filler wire. The Right Ascension drive shaft was made from stainless steel, and had a flange welded onto the main shaft using a TIG welding machine.

## 7.2 Joint manufacture

Several sections of framework have a common structure which can be seen from a plan view of the telescope mount. A typical joint assembly is illustrated in Figure 7-1, this shows how the components were assembled prior to welding. This arrangement would be typical of the yoke base, the top of the table, the bottom of the elevation framework and the levelling framework.



**Figure 7-1 An illustration of joint construction for the framework.**

Referring to Figure 7-1 two lengths of 50 mm square aluminium tube lie vertically, joined by a length of 50 mm diameter tube. A tube 44 mm diameter, shown by hatched lines, fits into the round tube, then through a hole machined in the square tube. After assembling the components in this way, each joint was temporarily welded, and then checked to ensure that geometrical accuracy remained. After ensuring no movement had occurred as a result of the heat input upon 'tack' welding, the framework was welded to produce a permanent fixture.

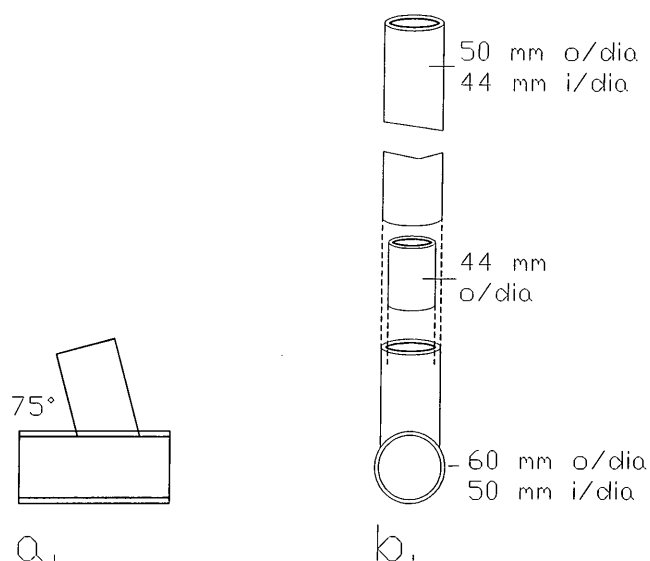
All external joints had excess weld removed using a sanding disc fitted to an angle grinding machine.

By forming the joints in this manner, the structure proved easier to assemble for welding, providing dimensional accuracy and increasing strength in the region of the joints.

### 7.3 Yoke construction

The yoke assembly was constructed from round tube. This would reduce weight and provide an easy method of assembling the components prior to welding. Round tube of similar strength to that of square tube weighs less. It was easier to prepare round tubes which would slope in two directions than it would have been to accurately cur square tube to do the same.

The joints which formed the yoke are illustrated in Figure 7-2.



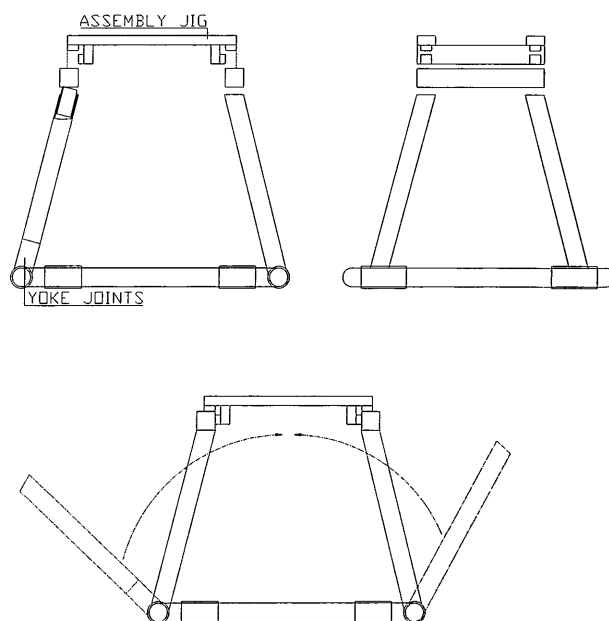
**Figure 7-2 Yoke joint construction**

Figure 7-2a illustrates a sectional view of the construction of the corner supports for the yoke sides. This consists of 60 mm diameter tube, bored to 50 mm diameter, with

a 50 mm hole machined through its wall at an angle of 15°, into which was welded 50 mm diameter tube. The sloping tube fits over the 50mm diameter tube which forms the bottom of the yoke, and so to provide good contact its end was machined at 15°, to achieve the corresponding radius on its end, see Figure 7-4.

Figure 7-2b shows an exploded view of one leg of the sloping yoke sides. Here, 50mm section tube was joined together using tube of outside diameter 44mm. Similarly, tube was fed into the top to locate within the square tube which formed the bearing support faces.

With reference to Figure 7-3, it is possible to describe how the yoke was assembled from these components.



**Figure 7-3 Assembly of the yoke prior to welding**

The bottom of the yoke consists of four pieces of 50 mm diameter tube, mitred at 45°, with the corners welded after assembly.

The yoke joints, Figure 7-2, were slid into place with plain 60 mm diameter tube slid over the front and rear sections of the base of the yoke, allowing the corners of the yoke to be welded. The plain tube had holes drilled to accept 19mm tube used to accommodate the bolts which hold the yoke onto the yoke base. When fastening the



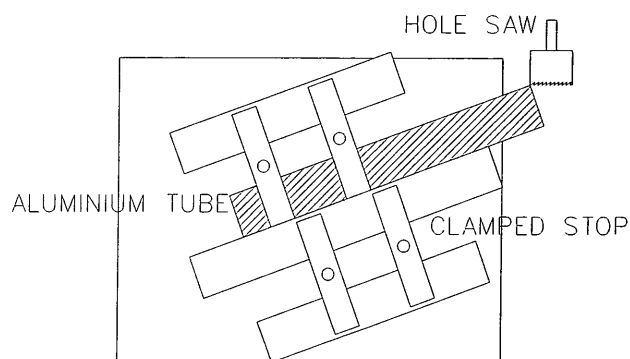
yoke to its base, the 60mm tube would resist any bending force which may be likely due to the gap created by the yoke joints.

The tube which makes up the corners of the yoke were assembled, as shown in Figure 7-2b, onto the yoke joints and swung up until they fed into the holes machined in the bottom of the square tube. The square tube was held securely using the jig, as illustrated in Figure 7-3, until checked for accuracy and then welded together.

Once the main structure of the yoke was welded together the remaining strengthening pieces could be added to provide the final object.

### 7.3.1 Preparing the tubes for assembly.

In order to cut the ends of the tubes for the yoke, a hole saw was used to form a radius passing through the end of the tube, Figure 7-4. By cutting the tube end in this way it enabled a closer fit between mating components whose interface would otherwise leave gaps so increasing weld difficulty.



**Figure 7-4 Machining of round tube to form joints**

The tube was clamped onto an engineers block, and a datum point defined relative to the vertical face. Using a hole saw the excess material was removed using a slow speed and feed.

## 8. Engineering design.

In order to design the support frame to withstand the weight of the polarimeter, it was important to consider several physical properties of materials suitable for the designed structure. In this instance it was considered that aluminium's general properties would be suitable. Its price was not excessive, it has reasonable strength to weight ratio, it is easy to machine and weld and is widely available. In addition there are several finishes which can be applied to the completed structure each of which could be provided locally.

### 8.1 Mechanical properties of metals.

Destructive tests are conducted, in a controlled manner, to determine the mechanical properties of a metal in order to predict what may occur under given conditions. Commonly, tensile strength is sufficient for calculating a component's suitability because many other properties can be gauged from this. By introducing a factor of safety a known value of tensile strength should not be exceeded and a component becomes inherently safe.

The allowable stress in a material must therefore be below the elastic limit thus:-

$$\text{Allowable stress} = \frac{\text{yield strength}}{\text{Factor of safety}}$$

The yield point of a material occurs where there is a large increase in strain with little or no increase in the stress, indicating that the material has elongated plastically and permanently. It is generally accepted that this value is not exceeded in designing components.

It should be noted that when loading a material, a gradually applied static load is preferable to a shock load which can have the effect of doubling the applied load causing premature failure at what was thought to be a safe design load.

### **8.1.1 Aluminium**

Aluminium alloy is widely used for structural and mechanical applications. It has a low relative density,  $2700 \text{ kg m}^{-3}$ , coupled with reasonably high tensile strength when used as an alloy. Other properties include ease of machining and good corrosion resistance.

Aluminium readily oxidises protecting from corrosion. Corrosion resistance can be further enhanced by anodising, a process which artificially thickens the oxide layer. A porous surface results enabling the use of dyes to colour the surface layer. Subsequent to colouring, the surface is sealed to render it impermeable. A matt black colourant was chosen to reduce the effect of reflected light on small components. On larger components, such as the support framework, the treatment was matt black powder coated paint.

In this instance the aluminium used throughout was 6082 T6. The material was bought from Smiths Metal Centres who have their own coding system, this was HE30TF.

The tensile strength of a 6082 aluminium alloy ranges from 155 MPa in the annealed state to 220 MPa when aged naturally, and 325 MPa when precipitation hardened. In aluminium the yield stress is referred to as the proof stress, this figure is approximately 30-50% of the tensile strength. A value of 75 MPa was used throughout for the maximum permitted stress.

### **8.1.2 Stainless steel**

Stainless steel was used to manufacture components where higher strength was required. This was so in the drive shafts and support shafts for each of the drive mechanisms. The grade used was 303 stainless steel available from standard stockists, and was chosen for its ease of machining.

Typical mechanical properties would give a tensile strength of 620 MPa, and a yield strength of 240 MPa. For purposes of calculating the size of components the maximum permissible strength of the stainless steel components were limited to 100 MPa.

## 8.2 Structural considerations

Material properties are of prime concern in the design and manufacture of frameworks, strength and stiffness especially so. Without strength and stiffness the framework would fail in its primary task of supporting the polarimeter.

These properties can be altered by the design of the structure. With reference to a typical deflection formula:-

$$Y = \frac{W * x^3}{192 E I}$$

to obtain minimal deflection Young's Modulus, E, and moment of inertia, I, should be large, and where possible load and length as small as possible. The load cannot be reduced, although the other properties can be controlled.

Typical arrangements to reduce the deflection of a loaded beam include:-

- 1 reducing section length by an amount  $x_1$ , reduces deflection by a factor  $x_1^3$
- 2 increasing the second moment of area i.e. change material section
- 3 change the material to one with high modulus of elasticity
- 4 use diagonal bracing to introduce triangular sections, an inherently rigid shape
- 5 improve joint design to add strength

It was not practical to consider changing the material to one of a higher modulus of elasticity because of factors such as cost and ease of manufacture.

### 8.3 Bearing selection

Bearing selection can be a detailed process taking into account many different factors. For this instrument the bearings were selected for load carrying capacity and direction of loading. The speed of rotation and number of cycles will be negligible in relation to other, more typical uses, and were therefore ignored.

In general, the rotation of the telescope mount would induce both radial and axial loads, although this will occur to varying degrees. A common, readily available bearing is the single row deep groove, which withstands axial loading in both directions, a fair radial load capacity and will withstand some slight misalignment of shafts. It was therefore decided that where possible these bearings would be used unless some other property was required and a more suitable bearing could be selected.

On the declination axis, because alignment could not be guaranteed, a self aligning bearing was chosen to seat the polarimeter drive shaft end. The shaft was determined to withstand the load of the polarimeter, and so the internal bore of the bearing was fixed. The weight of the polarimeter was known, and so the bearing selected to withstand this load both radially and axially.

The Right Ascension drive shaft has a large axial load caused by the combined weight of yoke, polarimeter and associated parts. Its radial load was not so great and so the bearings selected to support the shaft were a pair of thrust bearings. The upper bearing was of larger diameter than the lower for ease of assembly, although both have sufficient capacity to support the weight. In these bearings, a means of applying load in both directions is required. For one direction the weight of the yoke etc. provides sufficient load, whereas a screw thread with locknut were used at the bottom of the Right Ascension drive shaft. This keeps the two bearings tightened onto their housings and prevents movement of the shaft within their housings, see Figure 9-1.

The other type of bearing selected for the telescope mount were self aligning bearing units called plumber blocks. These are essentially a cast housing into which are located a bearing which can withstand angular misalignment of the two bearing faces. These were selected because of the difficulty in fabricating a framework to precise dimensions as would be required of standard single row deep groove, and that they were a self contained unit which are screwed onto a flat face. These units were doweled into place so that if removed they would return to the same place. The actual size of plumber block used was determined by the shaft size on the table framework, and the load which would be carried by them.

## 9. Commissioning the telescope

In order to obtain data regarding the effectiveness of the design, it was decided to site the telescope mount at the University Observatory. Prior to it being moved to this site, the telescope mount was assembled in the laboratory, and some simple tests conducted.

### 9.1 Laboratory tests.

Manufacture of the framework was closely controlled to ensure that it was the correct size and shape. This would ensure that the axis through the centre of the Right Ascension driveshaft was coincident with the centre of the yoke framework. During initial assembly of the framework an aluminium plate with a 2mm central hole was placed across the declination axis bearing housings. A weighted string was lowered through the hole; its centre was checked against the centre of the yokebase driveplate to determine the concentricity of the framework centres. This was shown to be accurate, although no finite figure could be given below 1mm.

In order to obtain accuracy in the plane parallel to the top of the table support bearings, it was known that the frameworks were welded whilst fixed to a flat metal surface. This ensured that by measuring the gap between the yokebase and the table framework and obtaining consistent measurements that the rotation of the yokebase to the table framework was parallel.

The yoke was welded and then stood on a flat table. A height gauge was used to measure the different height of the bearing support surfaces. There was approaching a 0.5mm height difference and so the aluminium plates to be welded to the top of the bearings were machined accordingly.



With the polarimeter in place in the declination axis bearings a dial gauge was used to measure the accuracy of rotation of the polarimeter. The sides of the polarimeter were found to run parallel with the sides of the yoke.

The remaining tests included simple balancing, and attaching of a computer in order to drive the telescope in Right Ascension. Once completed the whole structure was moved to the external location.

## **9.2 Setting up the telescope mount**

After conducting preliminary tests within the laboratory, a site was prepared at the University Observatory. A concrete pad previously the site of a gamma ray telescope was used to build the wide field polarimeter, it was assembled during daylight hours, and then finally aligned at night time. An approximate North was found during daytime using a compass, and a steel framework bolted to the concrete pad so that it's centre was pointing towards magnetic North. This was a fairly crude way of aligning the mount, although it was considered close enough for initial set-up. Having found the approximate magnetic North, the final adjustment of the framework was done at night with the CCD camera attached. Once Polaris was centred on the computer, the framework was re-positioned to align on true North.

The ground base framework was sited onto the steel base, and clamping bolts used to hold the two together. This provided a solid base on which to build the telescope mount, although in future it is anticipated that the steel framework would not be used. M12 studding was screwed into the ground base, and a locking nut screwed down each piece of studding onto the top of this framework.

The levelling framework was added to the ground base lowering the support lugs over the studding, fitting the remaining locking nuts onto the studding. Jacking screws located in each of the four corners of the levelling framework were turned until it was

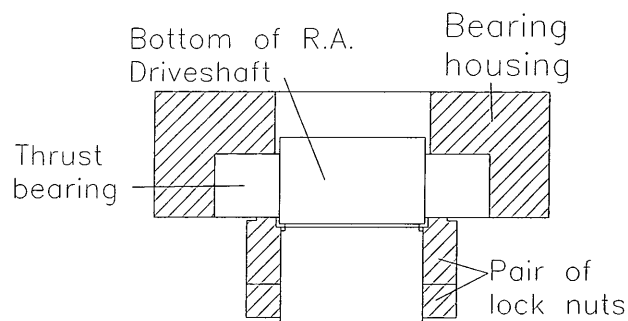
level in all directions. This was checked using a spirit level. The locking nuts were hand tightened up to the support lugs and locked in place using spanner and socket wrench.

The elevation framework was lowered onto the levelling framework ensuring that the central spigot located into the bearing within the lower framework. Screws were fitted through the clamping lugs into the levelling framework. The north-south adjustment block was positioned onto the front of the framework, and screwed in place. At this stage this section was positioned centrally on the levelling framework, but the locking screws were not tightened. The spirit level was placed across the bearing support faces to ensure that the elevation framework was still level.

The table framework was positioned within the elevation framework and support bearings doweled into place and screws tightened. The clamp block was positioned onto the elevation framework, and over the table shaft and screwed into place without the clamp bolt being tightened. The elevation adjustment mechanism was fitted to the shaft at the other side of the table. Again this was not locked into position until the yoke was placed onto the top of its drive shaft. This provided better access to the Right Ascension drive mechanism beneath the table during assembly, making it possible to tilt the assembly to a comfortable position.

The bearing housings for the Right Ascension drive were positioned within the table framework ensuring that the levelling screws aligned with radiused seats machined into the central support plates, without tightening them firmly. The drive shaft was lowered through the upper bearing and held whilst the Right Ascension drive gear was fed up onto it. The shaft was then lowered through the lower bearing. The upper lock nut which applies the load on the thrust bearings was put in place and hand tightened Figure 9-2.

The yoke base was lowered onto the end of the drive shaft, and all four screws tightened. The lock nut on the Right Ascension drive shaft bearings was tightened until no axial movement was felt, but still so that the yoke base could be rotated freely, a second nut was tightened up to the first and the pair locked. The bearing housings had their levelling screws tightened into their seats on the table and locknuts attached. The four holding screws on each bearing housing were tightened.



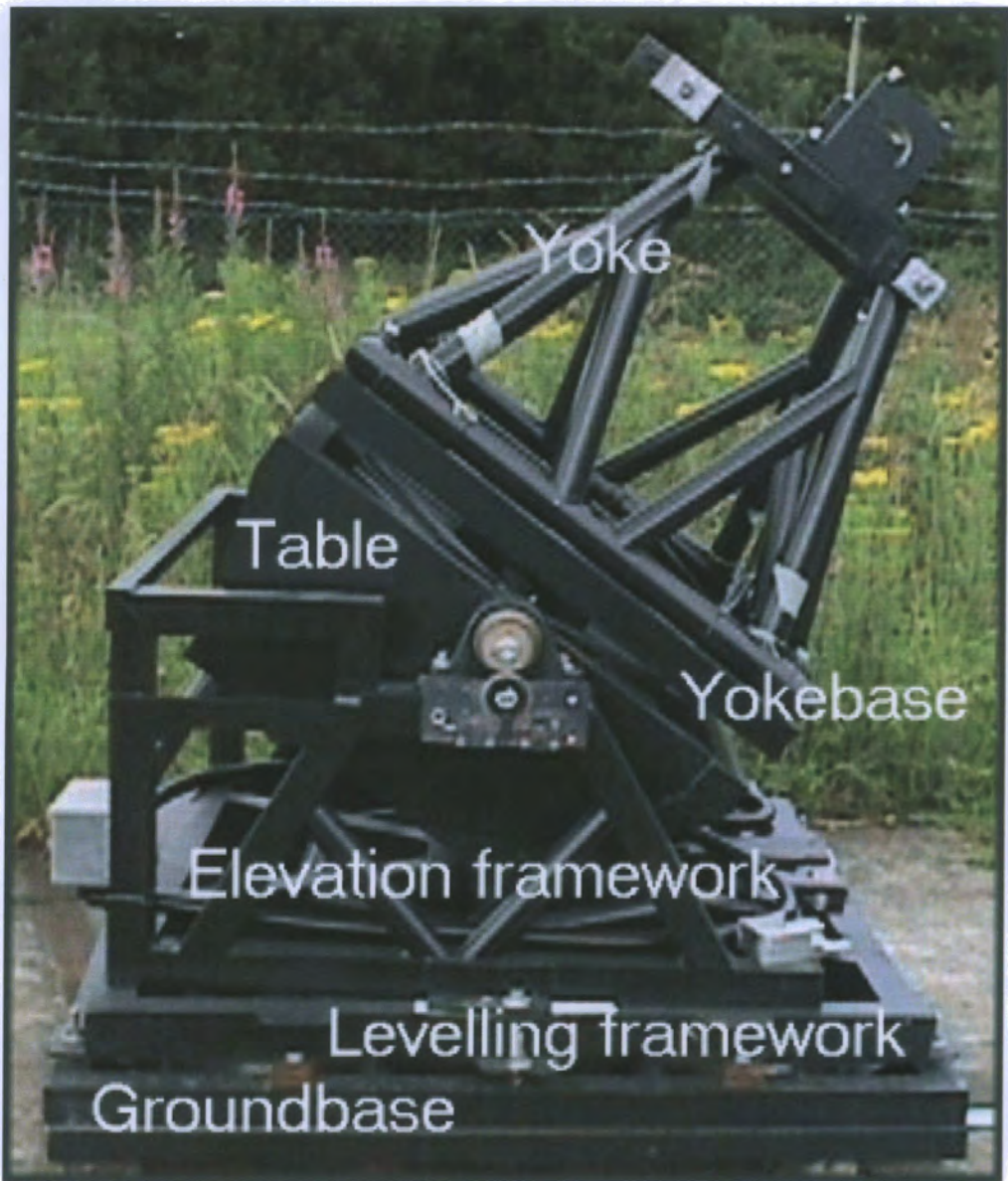
**Figure 9-1 Applying thrust to right ascension drive**

The yoke was lowered onto the yoke base with four M12 bolts holding it in place, through the 19 mm tube welded in place on the yoke. The polarimeter support bearing housings were placed onto the yoke, doweled and screwed into place.

Once assembly of the structure was complete, the elevation axis was set using a piece of wood cut to the desired angle, this being approximately  $56^\circ$ , held against the framework, and a spirit level used to check for accuracy. Once confident of the angle, the clamp block was tightened against the table shaft to hold it in place. The elevation adjustment mechanism was positioned and locked in place, as a further means of holding the framework. From this it was possible to balance the framework.

Photograph 7 shows the framework assembled at the University Observatory site. This is a side elevation without the polarimeter mounted.

Photograph 8 is a front elevation of the mount with the CCD carrier plate fitted between the declination support bearings.



**Photograph 7 Side elevation assembled telescope framework**



**Photograph 8 Front elevation of telescope mount with SBIG ST-6 carrier plate fitted**

## 9.3 Balancing

In order to operate the telescope effectively, it was important to achieve near perfect balance. This was important because out of balance forces put excessive strain on parts of the system which have not been designed to withstand them, and also to ensure smooth, continuous rotation around the cycle.

After balancing the telescope, the lead weights which were used were melted together to form one solid piece dedicated to a particular point. A colour coding and numbering system was employed to identify the position of each weight for future reference.

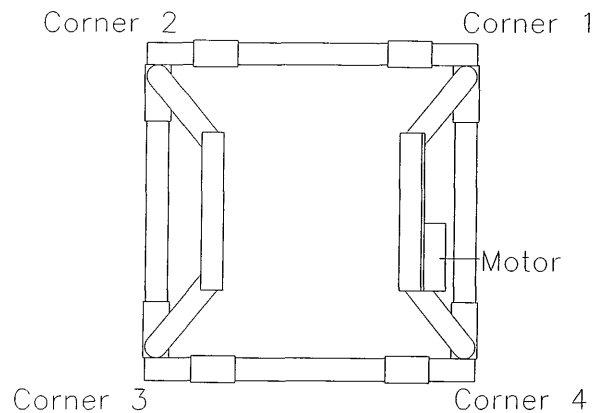
### 9.3.1 Balancing of the yoke

In order to obtain tracking images using the SBIG ST-6, the telescope was assembled as described in section 9.2. The camera support plate was attached across the polarimeter support bearing housings, and the declination axis motor assembly fitted to the top of the yoke. The motor's electrical supply cables, and connector boxes were also fitted. Stainless steel studding was screwed into the aluminium pads welded onto the top of the yoke, and the corners were numbered 1 to 4, as illustrated in Figure 9-2.

Taking into account the weight of the declination drive motor, a large lead weight was made to fit to corner no. 2. Subsequent weights were added to the corners to counteract the effect of the motor on the yoke. The weights were initially roughly cut pieces of lead with clearance holes to accept the M6 studding.

The yoke was allowed to move freely, and once it appeared close to balance, a loop was attached to each corner, and a digital force gauge used to determine the load required to rotate the yoke in each direction for each corner. A record was kept of the

effect of adding weights to any corner, and as a consequence it was possible to reduce the out of balance forces.



**Figure 9-2 Yoke corner numbering for balancing**

Table 9-1 gives an indication of the way in which the loads were applied to the yoke. In the table, the addition of a weight is illustrated by for example, +3, indicating a weight was added to corner number 3. The resulting change in the force gauge readings are then listed below that.

	Change	START	+3	-3, +2	-2, +1	+1, +3	+1, +3
FORCE	weight						
GAUGE	Corner 1	4.9	5.9	4.4	5.3	3.9	2.4
READING	Corner 2	4.9	6.8	6.8	3.9	3.9	2.9
(Newton's)	Corner 3	2.4	0.9	4.4	0.9	1.9	2.4
	Corner 4	2.4	3.9	3.4	1.4	2.4	0.9

**Table 9-1 An illustration of the addition of balance weights to the yoke**

It was found, in general, that by adding weight to opposing corners the out of balance forces were reduced. Therefore by adding weight to corner 2 the turning effect of the motor was reduced, although the addition of weights to corners 1 and 3 had a similar affect. By adding and subtracting weights to corners 1, 2 and 3, the telescope became balanced in Right Ascension. At each addition of weight, the force meter was attached to the loop at each corner of the yoke. The force required to lift that corner to align the yoke frame square to the table was recorded and weight added or subtracted to the appropriate corner. Once a consistent reading was found for each corner the telescope was considered to be balanced.

The same process was carried out when the polarimeter was added to the yoke.

It became apparent whilst balancing that the cables which run through the centre of the Right Ascension drive shaft were themselves creating a torque on the system. This would need to be rectified once the telescope mount was returned to the laboratory.

### **9.3.2 Balancing the polarimeter**

In order to control the polarimeter in the same way as the telescope, it too was balanced once all components had been attached. This included the Celestron C-90 spotting scope and the SBIG ST-6 CCD camera.

The polarimeter was balanced in the yoke whilst it was held by a fixing strap connecting the yokebase with the table. The CCD was fitted to the bottom of the polarimeter by removing the split clamping ring, positioning the CCD carrying plate within its housing, and replacing the clamp strip. The spotting scope was attached to the polarimeter via the adapter as described in section 6.7.



From this stage, weights were added to the top surface of the polarimeter via M6 studding fastened into tapped holes along the length of the aluminium strips secured to the top of the polarimeter. Large lead weights were initially placed front and back of the top face of the polarimeter, smaller weights were added to this until the polarimeter could be moved easily and left in position without movement, thus indicating balance.

## 9.4 Drive set-up

Initial tests within the laboratory were used to gauge the difficulty of balancing the mount and to assess the drive mechanisms whilst within close proximity to services.

To engage either drive, the motor assembly should be slid toward the worm wheel ensuring positive engagement of the gear teeth.

The motors are controlled via a standard PC, and the step rates are controlled on screen. Initial testing of the motors proved that the Right Ascension drive did not have coincident centre heights for the worm drive, and consequently the worm was trying to re-cut the wheel teeth, apparent with flaking of the brass from the worm wheel. The problem was rectified by lowering the height of the motor assembly in relation to the worm wheel. In addition it was noted that the head of the screws which hold the Right Ascension lower bearing housing in place protruded slightly, raising the drive support plate slightly. This was rectified by machining some material off the top of the screw heads.

Tests were done using a theoretical step rate of 107 step/sec, with acceleration of 100 steps/ sec<sup>2</sup>. Each of the tests were done for a period covering approximately one quarter revolution of the yoke, and timed. In each instance the time taken to complete this distance was approximately twice that expected, and so the step rate was doubled.

The telescope mount was left, in a room, with the yoke tracking at a rate of 216 steps/ sec for a period of 18 hours, i.e. from one afternoon until the next morning. Again the rotation appeared to be slightly out and so the tests were repeated where the telescope mount was left to run at varying speeds, for periods in the region of 24 hours. Over a period of five days, it was found that the closest available step rate was 214 steps/ sec.

This fulfilled five complete revolutions in a period of 119 hours 46 minutes, which should in theory have been closer to 119 hours 40 min., a small error which could not be rectified, it was only possible to use integer values. The tracking rate of the telescope would need to be altered during observing runs should trailing of images become evident on the CCD detector. The intention was that over a long tracking period the step rate would be varied between 213 and 214 steps/ sec.

## **9.5 Aligning the telescope mount**

Initial operational tests involved setting up the telescope mount as described in section 9.2. The camera was mounted across the yoke bearing housings, and its cable fed down the back of the yoke, through the elevation framework, and into the computer.

A series of test exposures were taken to determine exposure time for the camera for the light conditions. This resulted in obtaining an image of Polaris, although the image was badly out of focus. By increasing the length of the adapter the image became more out of focus with the camera lens set to infinity, suggesting that the adapter needed to be reduced in length, to bring the focal point of the lens closer to the CCD chip.

This image was of use, however, in that it enabled the alteration of the elevation angle, and the north alignment. The blurred image at first appeared on screen at the

bottom right of the computer monitor, by tilting the telescope mount down on the elevation axis, the image moved up the screen. It was finally locked with the image set approximately central within the display. The same was true of the north alignment, moving the telescope to the right when viewed from the rear also moved the image to the centre of the display. In this sense we were fortunate to centralise in this plane because initial set up was just within the  $5^\circ$  tolerance which had been allowed. This suggested a better initial set up technique be followed for future observing runs.

In order to determine the true North-South plane it would be appropriate to find a more accurate manner of determining the Pole position. It was in fact fortunate that the method employed of holding an orienteering compass to determine North for this site and then setting up on this projected line yielded a result which was within the adjustment range of the mount.

Once the image was centralised on the computer monitor, the altitude and azimuth of the telescope mount was considered to be set. There was no means of determining how accurate this actually was and so it was done by measuring the image position within the computer screen.

## 10. Operating the wide field polarimeter

The date on which the following data was recorded was the morning of 15th August 1998, the sky was clear.

The images illustrated in Figures 10-1, and 10-2 were taken to obtain evidence as to the tracking ability of the telescope mount. The SBIG ST-6 camera was mounted as described in section 6.8. These exposures were for a period of 5 minutes each with an interval between exposures of 5 minutes which gave a total tracking time of 15 minutes. There does not appear to be any trailing around these objects when comparing the two images.

It was found that the sky coverage using the SBIG ST-6 camera was in the region of 60° West to East, and 40° North to South.

After taking these images, the telescope mount was set up as described in section 9, the clamp strap was fitted between the table and yoke to hold it in place during set up.

The Right Ascension drive motor was positioned within the table, the drive was not engaged. The declination axis motor was fitted to the side of the yoke, and fastened so that the gears would not engage when the polarimeter was fitted. In both instances the cover was removed from the connector boxes, and the electrical connections made.

The polarimeter was fitted with four lifting bars, each attached using two M6 screws. The declination axis bearing housings were split to enable the polarimeter to be lifted into position with one person at each side. It was held until the housing covers were replaced, and two M12 bolts were screwed into place. The internal covers which protect the polarimeter optics during transit were removed, as were the lifting bars.

The SBIG ST-6 camera had its threaded insert screwed home, and this assembly screwed into the camera support plate. The control cable was connected to the camera and fed across the yoke to its control box. A lap top computer was used to operate the camera software. Using the polarimeter grid spots as a reference, the camera was rotated to align the spots with the CCD chip.

The Celestron C-90 was screwed into its adapter which in turn was lowered into the counterbore on the front plate of the polarimeter. The four retaining screws were fastened. A small finder scope, normally attached to the C-90, was fitted to the side of the polarimeter to aid in positioning the telescope mount.

M6 studding was screwed into the plate at the top of the polarimeter and the balance weights added. The cables which control the polarimeter were connected between polarimeter and control box.

The polarimeter was assessed for balance. It was found that the cables attached to the CCD camera and the polarimeter were inducing force onto the polarimeter. Additional weights were added but the effect depended on the orientation of the polarimeter and on the length of available cable. By coiling the cable, the effect was lessened, although this was not always possible because of the orientation of the mount in relation to the polarimeter control box.

The polarimeter and telescope mount were connected to a personal computer. Once the control links had been made, the strap which held the yoke to the table was removed allowing the yoke to rotate freely. The cables were found to interfere with the Right Ascension balance, and so weights were added to try to alleviate the problem. This reduced the forces sufficiently to enable the motor to drive the yoke.

The telescope mount was rotated manually to align on Jupiter. This was the most visible known object in the sky at that time, and so the mount was aligned so that it

appeared centrally within the finder scope. The drive assemblies in both Right Ascension and declination were engaged, and locked.

The SBIG ST-6 camera was set to focus, obtaining a continuous readout to produce an image on the lap top computer display screen. After some time determining the correct direction of rotation of the motor's to track an object, the image of Jupiter appeared to the top right of the screen.

The finder scope was adjusted so that it was again centred on Jupiter making it easier to position the telescope mount on an object should the subject change or a problem occur in tracking.

The camera exposure time for each image of Jupiter was 4 seconds, with tracking of the object occurring over the period 02.24 to 02.55. After obtaining a set of images of Jupiter moving the half wave plate to four positions, the half wave plate was returned to it's start point and the process repeated; no filters were used.

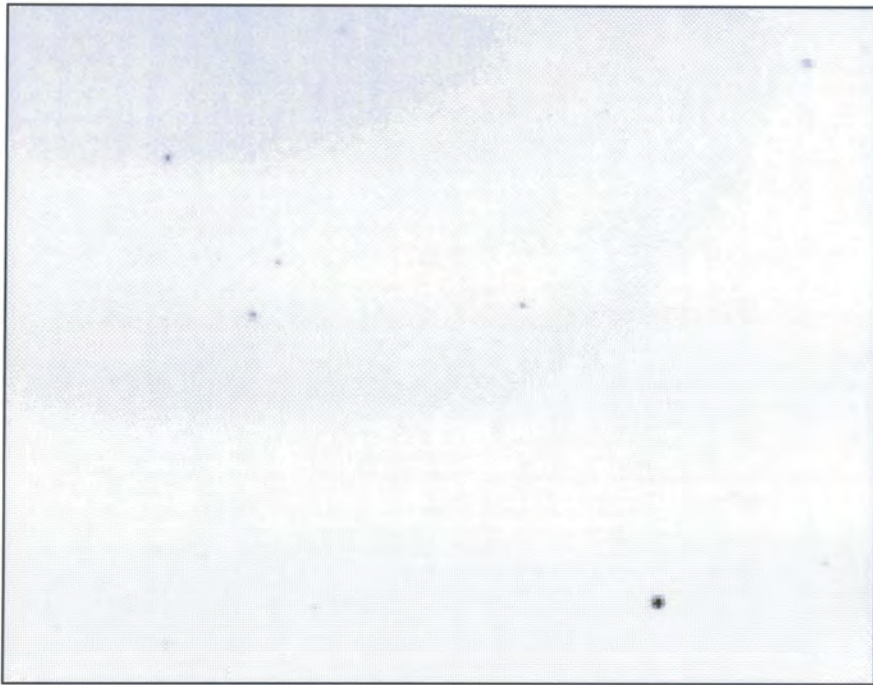
Figures 10-3, 10-4, 10-5, and 10-6 are the images collected on the SBIG ST-6 of Jupiter at the four half wave plate positions. These are raw images taken using the polarimeter, they have not been reduced to obtain a polarisation map. The exposure time was short, and therefore there can be no evidence of trailing. The images were later found to be badly out of focus.

The grid spacing within the polarimeter equates to 13' 45" of the sky per grid. There were 12 grid elements and so the sky coverage is in the region of 165 arcmin, or 2.75 degrees.

By measuring across the image it was found that there were 30 pixels per grid. Each pixel equates to 0.46 arcmin or 28 arcsec/pixel.

These images were the only ones possible due to cloud appearing. The equipment was then returned to the laboratory. This was the only clear night for which data could

be gathered prior to the optics and control equipment being despatched to South Africa for one year.

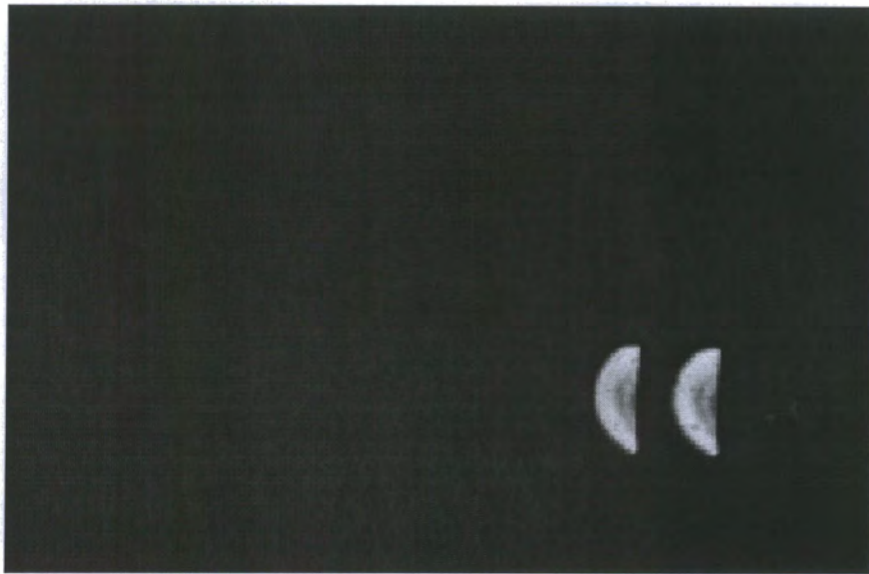


**Figure 10-1 Image of a star field (scale 60° E-W, 40° N-S)**

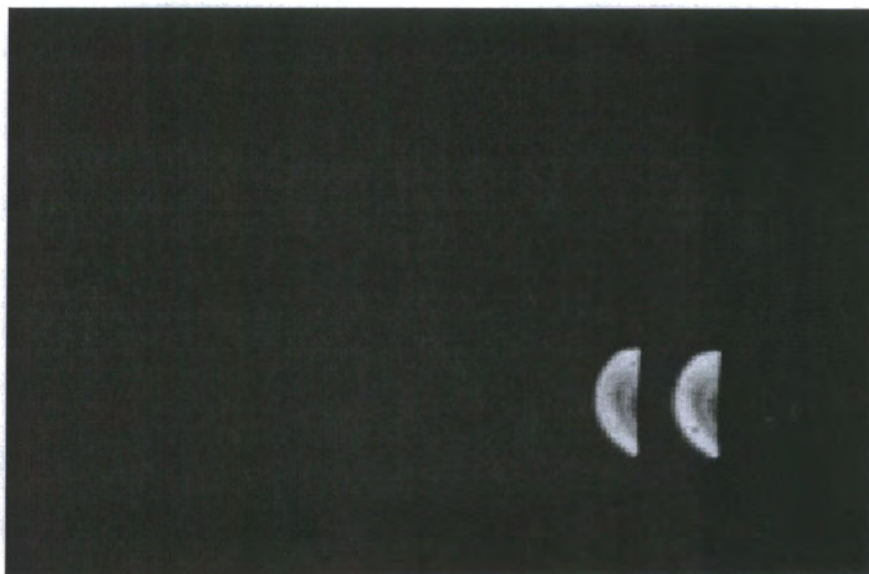


**Figure 10-2 Image of a star field (scale 60° E-W, 40° N-S)**

The image scale for Figure 10-3 to 10-6 is approximately 165 arcmin West to East, and 105 arcmin North to South.

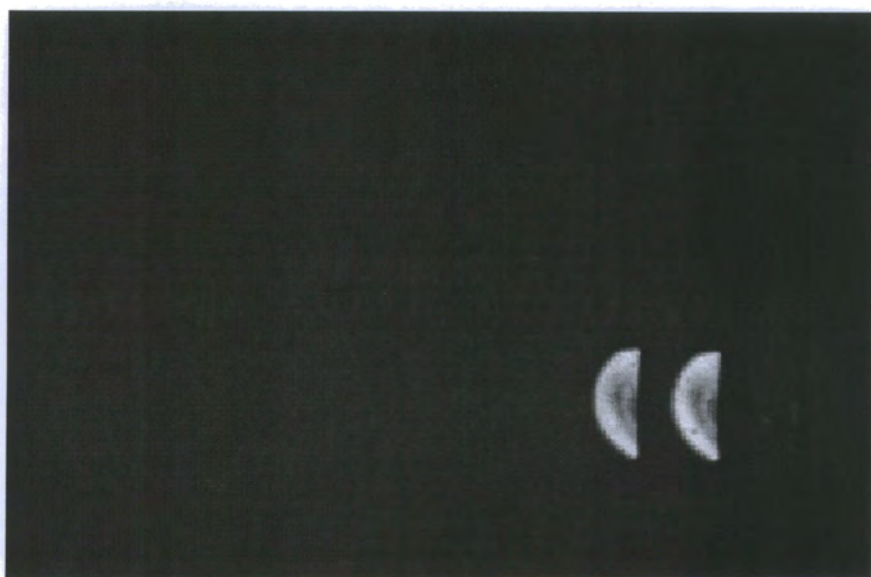


**Figure 10-3 Unfocused image of Jupiter with half wave plate @ 0 deg**



**Figure 10-4 Unfocused image of Jupiter with half wave plate @ 22.5 deg**





**Figure 10-5 Unfocused image of Jupiter with half wave plate @ 45 deg**



**Figure 10-6 Unfocused image of Jupiter with half wave plate @ 67.5 deg**

## 11. Discussion

In order to analyse the success of the telescope, its operation should be broken down into several elements.

### 11.1 General

The site chosen to position and test the telescope mount was not ideal, although there was no alternative site locally.

The concrete pad which had previously been installed for a Gamma Ray Telescope provided a solid base from which to build this instrument. A central raised area was too small to support the framework without manufacturing additional support. A steel framework was welded to enable secure fastening of the mount to the concrete pad. The pad did not align to the North, and so to enable adjustment within  $\pm 5^\circ$  the support framework did not lie square to the concrete pad.

There was no security at the site, due to its remote location, and lack of suitable fencing, and so it was not possible to leave equipment unattended. As a result it was necessary to take equipment to the site on every occasion that work was being done. This became tedious when weather conditions changed resulting in an end to work, or when it was only possible to set equipment up in the available daylight prior to observing. Access to the site was approximately 150 metres down a grassy slope, which was in turn 1.5 km from the main departmental buildings.

It would be preferable due to the observing conditions to move to a better site were there was less local lighting, and a greater prospect of good observing conditions. In trying to obtain suitable images for this thesis several weeks passed were it was not possible to attempt observing.

## 11.2 Support framework

The framework was easy to assemble, with only the levelling of the elevation framework taking any great time. The concrete base was not level, it was not orientated to a particular direction, and it was not the correct size for the ground base framework. In the future it would be better to build the instrument from a dedicated concrete base, allowing room around the framework upon which to walk, and with suitable site access.

The table framework had counterbalance weights built into it to counteract the moments caused by the weight of the polarimeter and the yoke. After assembly, it was realised that some of the weights within the table were quite ineffective, their position lay too close to the pivot point of the table adding weight without any real counterbalance effect. Subsequent frameworks should have this weight redistributed or removed so that the effect of the weight would be as it was initially intended to be or removing it from the structure to reduce the strain on components.

When adding the combined weight of the polarimeter, the CCD dewar and optics to the yoke, there appeared to be some deflection of the yoke base causing interference between one corner of the yoke base and the bolt used to clamp the elevation axis. This problem was rectified by filing the corner off the top of the bolt, although this can only be considered to be a temporary solution. It did not appear to be such a problem with the SBIG ST-6, and so this suggests that weight is the major problem.

The deflection of the yoke was probably caused by misaligned drive bearings which has the effect of running the shaft eccentrically, giving the impression of varying height between table and yoke base. Adjustment of the bearing housings and checking the gap between yoke and table without load would eliminate this. If, however, there were deflection the instrument may benefit from the addition of spherical ball support bearings. These would be attached to the top of the table

framework, and screwed out to touch the bottom of the yoke base framework whilst it was in a state of rest, with no weight attached.

A larger drive shaft and central bearings would provide greater stability, although this would increase the cost for bearings, shaft material, and gear components.

### **11.2.1 Elevation mechanism.**

Using the SBIG ST-6 CCD camera fitted as described in section 6.8, it was possible to obtain an image on the computer monitor. This was a bright spot at the bottom right hand side of the screen. By adjusting the elevation mechanism, it was easy to move this object to a point within the centre of the screen.

The mechanism worked quite well, although it was necessary to add a little pressure to remove some of the force on the thumbscrew. Additional counterbalance weights on the table would allow easier adjustment.

The screw threads used to drive this mechanism were zinc plated steel rather than stainless steel which resulted in them corroding badly. The table support bearings were a type of carbon steel and also suffered badly from corrosion. These elements should be replaced with stainless steel components.

### **11.2.2 North - South alignment**

Again with the SBIG ST-6 camera fitted as described in section 6.8, it was possible to alter the North - South alignment mechanism, and see the image move across the screen. In this instance, with a badly focused image, it was possible to move the image across half the display area. This should approximate to a 5° rotation of the elevation framework. Movement was easy and smooth although it was at the extent of the mechanism's travel.

A better means of initially aligning the centre of the instrument should be found in future, for example more accurate setting with a compass. Final alignment of the instrument to the Pole could then be achieved more easily and within the limits of the adjustment mechanism. The mechanism worked well, and because the polarimeter was not fitted there was little weight to move.

## **11.3 Drive mechanisms**

### **11.3.1 Right Ascension drive**

This was the first element of the instrument to be used in its operational state. The system was approximately balanced in the laboratory as described in section 9.3.

After testing the drive without load at slow speeds to ensure that it was capable of driving, the speeds were increased to that which would be required for slewing. It was noted at these speeds that some flaking occurred from the brass worm wheel, leaving a fine brass dust on the drive carrier plate. The centre height of the drive components was checked, and found to be inconsistent. This was modified, but the problem was still found to exist. Further examination illustrated that the countersunk screws which hold the lower bearing housing in place were slightly raised above the level of the aluminium plate, which in turn raised the drive carrier plate. By removing the excess screw material, the plate was allowed to sit correctly on the bottom of the table.

Once rectified, the motor speed was decreased and the telescope operated at the theoretical tracking speed. The tracking speed was found to be too slow, because the yoke had not completed one full revolution in 24 hours. Subsequent tests found that the required rate of rotation of the motor was in the region of twice the theoretical rate, and so the step rate was increased accordingly.

After moving the mount to the Observatory site it was balanced correctly, however, it was found that the hole provided through the centre of the drive shaft did

not have sufficient clearance for the size of cable used. This resulted in a torque being placed on the drive shaft which had to be overcome during operation. Without care being taken during use, this cable would become twisted, and in severe cases could cut through exposing bare wires, which could destroy the link between motor and controller.

In order to obtain some experimental data, care was taken, but upon moving the instrument back to the laboratory, the intention was to increase the size of this hole to a more appropriate size, and fit bearings into the ends so the cables will tend not to wear against a sharp corner. The centre of the bearing should simply rotate if the cable is held against it.

### **11.3.2 Declination axis drive**

The declination axis suffers from backlash in the gears when reversing the drive of the motor. This should be accounted for when tracking an object to ensure that the polarimeter is only driven in one direction, but could be monitored with the addition of positional encoders. One further problem which can be foreseen is that whilst tracking an object in Right Ascension, the orientation of the polarimeter is such that the backlash between gears allow the polarimeter to move, and so a simple braking/holding mechanism should be employed.

## **11.4 System optics**

### **11.4.1 Celestron C-90**

It is hard to say how effective the C-90 was, although it did appear to give a clear image of the object being studied. There was a problem of condensation on the lens as atmospheric temperature dropped below the dew point.

It is anticipated that in future the C-90 will be replaced by some optics designed specifically for this instrument.

Upon returning to the laboratory, the data obtained on the SBIG ST-6 was analysed, and found to be incredibly out of focus. At this point there was nothing which could be done because the equipment was no longer in Durham.

#### **11.4.2 Recording device**

First attempts at using the optics were in obtaining an image of a star using the SBIG ST-6, mounted as described in section 6.8. This resulted in a blurred image which could not be focused using the Nikon lens. This caused some frustration as the instrument had been set up to track objects, and was defeated due to the length of a camera adapter. This simply required a reduction in it's length so that the lens lay closer to the chip within the CCD camera.

After modifying the adapter, the camera was taken outside merely to focus on an object without it being connected to the telescope framework. Once a clear image was attained, a locknut was tightened onto the camera body ensuring that the focus position could be easily repeated.

Even though the camera could not be focused, it was possible to determine the effectiveness of the alignment mechanisms.

The images which were collected on the SBIG ST-6 were adequate for testing the operation of the mount, however, it is unlikely that it would be used for future observations, due to the relative areas of the CCD chip on the ST-6 and the usual CCD camera. The additional weight caused by the replacement of CCD camera could produce problems in the operation of the Right Ascension drive as described in section 11.2, the yoke could deflect under load.

## 11.5 Operation of the wide field polarimeter

During set up of the instrument it became apparent that the control cables from the yoke to the computer which controls the instrument should be re-routed. The cables exerted forces onto the polarimeter which proved difficult to resolve.

One way in which this problem could be rectified would be to increase the length of the cables, introducing a coil effect within them, which could increase or decrease depending upon declination. The remaining cables could then be passed at the most convenient point through the yoke to the control boxes. In actual fact, however, even this may not entirely cure the problem. The cables should ideally pass through the centre of the Right Ascension drive shaft in the same way as the motor controls do, although presently this would not be possible. The hole through this drive shaft is currently too small for its existing cables, and so it would need to be even greater than is presently needed. This may not be possible with the current arrangement, because the shaft may be physically too small.

Slewing of the telescope mount was slow, which could be a problem. What seemed to be an acceptable time in theory, in practice appears to be a lifetime, and so by disconnecting the motors, and moving the instrument manually, the wasted time was reduced. Once this mount were used fully operationally, then this may not be a problem as slewing to a start position may only be done once in a night, and then the instrument set to its tracking rate.

## 11.6 Test data

The data collected and illustrated in Figures 10-1 to 10-6 show that the telescope mount was capable of collecting data. There was little evidence of trailing on any of the images, although it would be unlikely that any would occur for the very short exposures used on Jupiter.



Whilst attempting to reduce the images of Jupiter to obtain polarisation maps, problems were encountered in being able to match one set of images with another. The short exposure time required for such a bright object was too short to obtain reference stars, and as a result it was difficult to overlay the three sets of images obtained. As a result of this artificial guide stars were overlaid onto the images, but these proved difficult to place with accuracy.

The resulting attempt at producing a polarisation map therefore only represented the images shown in Figures 10-3 to 10-6, and a second set of images of the same sector of Jupiter. Unfortunately, after spending some time examining this data, and obtain dubious results, it was considered that the Celestron C-90 was too out of focus to have produced images that were of use. There is no question, however, that the polarimeter and it's associated software works.

## 12. Conclusions

### 12.1 Telescope mount

The site which was used to test the wide field polarimeter was not suitable for a long term project. There was no security, and so, all equipment had to be transported to and from the site for each attempt at observing. The set up time involved each time was approximately one hour, the same to pack up, although this did involve transportation time. As a result of this there were several occasions which involved setting up the instrument and the weather conditions changed preventing observations. Relocation of the instrument to a good astronomical location would yield useful results because of improvements in weather conditions and environmental conditions.

There would be reduced set up times as a result of the typically remote location which brings with it better security, allowing the instrument to be left during daylight hours. A dome to house the mount, or a box which could be moved around it would help to protect from the weather, whilst providing a cover to protect the instrument when not in use.

The cables which control the polarimeter and camera need re-routing. If they passed through the centre of the mount they would not interfere with the motion of the yoke. Repositioning of the polarimeter control cables to leave the polarimeter through the it's sides, would mean that the cables would turn with the instrument rather than against it. This would reduce the turning effect which occurs at present. If the cables were lengthened then some way of coiling them to prevent them from trying to drive the polarimeter should be found.

The strength of the wind was an important factor in the instrument's use. Any wind seemed to affect the mount causing it to move within the backlash of the gears, which can affect the image quality. By fitting a brake mechanism to the declination

axis, it could be controlled to hold the polarimeter steady. A brake would need to be electronically controlled and linked to the drive mechanism. The right ascension axis could not be controlled in the same way, and so some way of loading the drive to ensure positive contact with the gears should be considered.

The Right Ascension drive shaft should be increased in size. This need not be for structural reasons, but to allow more of the control cables to pass through it, so removing the problem of cables trailing over the yoke. Once the bundle size were accurately known, then a suitable bore size could be selected for a larger drive shaft. This would require some redesign of the table framework to accept increased bearing sizes, and would obviously require different gears to drive the mount.

There was a often a fear whilst using the instrument that some-one would exert excessive force on the yoke when touching it and that the gears would be damaged. Whilst the gears did the job required of them, and are adequate for the intended purpose, perhaps they should be replaced by more substantial gears so that they will withstand excessive forces.

In order to accurately monitor the position and tracking rate of the telescope mount it would be useful to incorporate some sort of positional encoders, which if possible could be used to set a park position for the mount, and so keep track of the area of the sky being studied.

## **12.2 Test data**

The images in Figure 10-1, and 10-2 illustrate a longer exposure than was necessary for Jupiter. These images do not shown any trailing. If the CCD camera were replaced with a one producing better resolution then the image quality would be improved, and consequently the quality of the image would improve.

The readings taken using the polarimeter were of short duration, because of the intensity of the light emitted from Jupiter, that they would not produce any trailing anyway. As a result of the short exposure it also proved difficult to reduce the images to obtain polarisation maps. There were no stars visible on the images which could be used to match up the three sets of images taken.

After attempting to analyse this data, it would have proved useful to return the equipment to the test site, and perhaps select a different set of objects that would have been easier to reduce, unfortunately because of circumstances there was no opportunity to do this. Observing conditions were poor for much of the summer, and after the only attempt with the polarimeter, it's optics, and control electronics were sent to South Africa with another polarimeter.

The fact that the images of Jupiter were not of sufficient quality to obtain polarisation maps are not as a result in deficiencies in the telescope mount, polarimeter or the reduction process. It was merely a function of the time scale with which the test data was gathered. The weather was not sufficiently good to spend time obtaining large amounts of data with which to work, and equipment used to operate this mount had to be sent to South Africa for use at the SAAO.

The main data which was of use was that shown in Figure 10-1 and 10-2, which illustrates that the telescope mount can track objects. The fact that there was experimental deficiency in taking images suitable for reduction was not a fault of the telescope mount.

## 12.3 Scope for future work

Whilst operating this mount as a wide field polarimeter, it was possible to see improvements which could be introduced for second generation instruments. Changes which can be foreseen are:-

1. Improved observing location, with the site specific to the mount
2. Reconsider the balance weights within the table framework, improving balance whilst reducing weight.
3. Adding spherical ball type bearings to ensure a consistent gap between table and yoke base.
4. Increase the radial dimensions of the right ascension drive shaft. This would provide a greater area for cables passing through, and would increase stability of the yoke in relation to the table.
5. As a consequence of changes to the right ascension drive shaft, it's gears would need to be replaced. These should be replaced by more substantial gears which will withstand greater loading.
6. Add a clutch mechanism to the declination axis to hold it in place whilst tracking. This would reduce strain on the gears and ensure accurate retention of declination angle.
7. Add positional encoders to the moving elements of the drive mechanisms.
8. Replace the SBIG ST-6 with a different CCD which would give a larger chip size. This would require a supply of liquid nitrogen.
9. In time, replace the Celestron C-90 with optics specifically designed for this instrument.

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