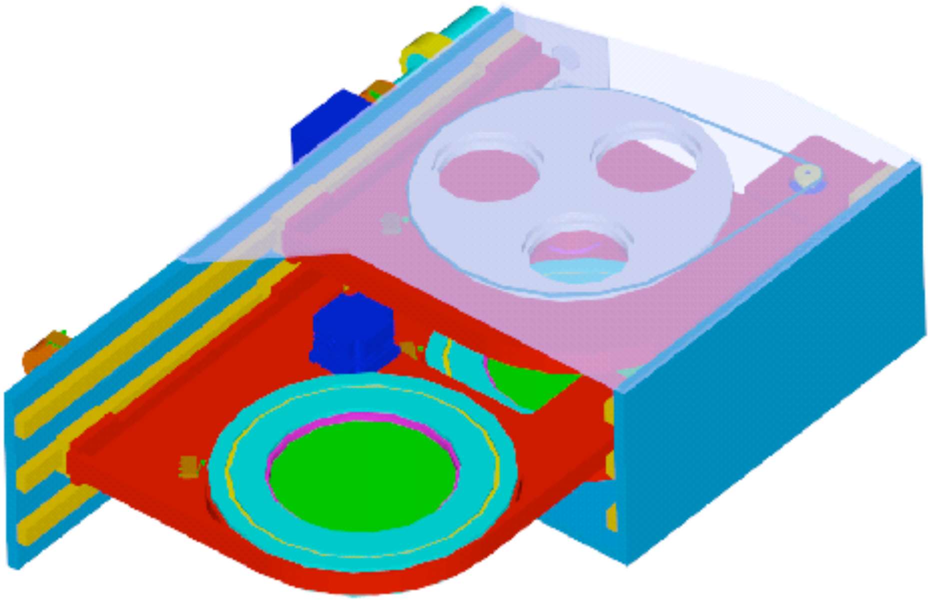
Papers for the
Gemini Polarisation Unit
Critical Design Review



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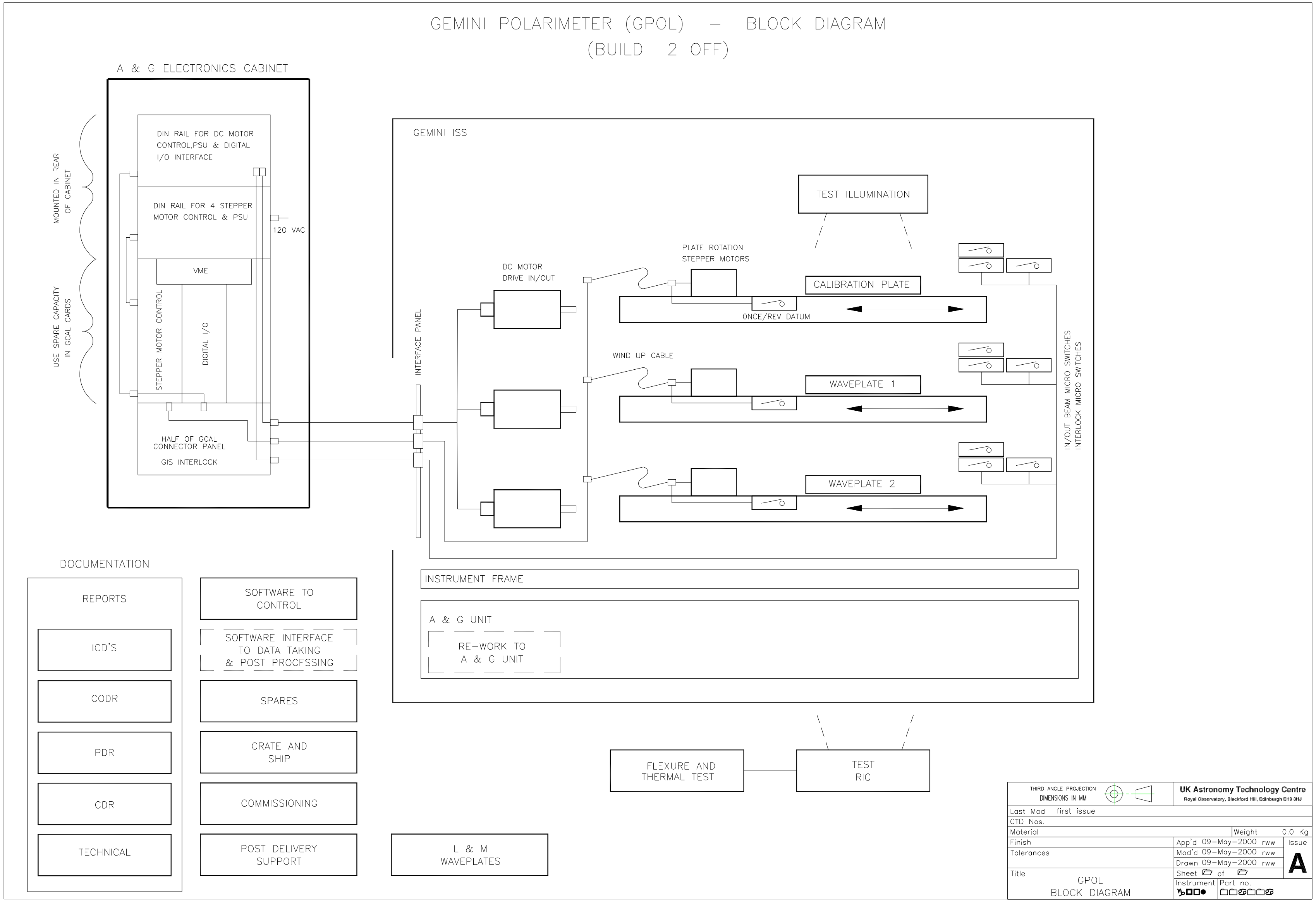


Gpol Block Diagram

Figure 1

1. INTRODUCTION

1.1 Purpose of Document

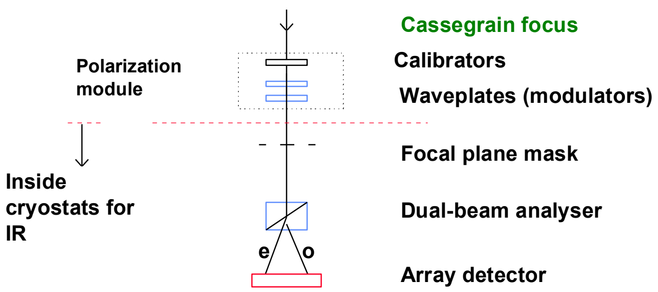
This document contains the design data developed for the Critical design review (CDR) of the Gemini Polarisation Unit (GPOL). It references several design documents including the Operational Concept Definition Document (OCDD) and the Functional and Performance Requirements Document (FPRD).

The purpose of the document is to provide the information necessary to review the design and to act as a reference for the completion phase of the project.

1.2 Brief Description of Gemini Polarisation Unit

It is proposed that polarimetry observations on Gemini are achieved, for all instruments operating between 0.3 and 5μm, using a polarisation module that will be placed in front of the up-looking ISS port. The module will contain a minimum of two waveplates, which can be used in series, and a calibration capability. Implementation must be remotely retractable and allow for unvignetted use of the bottom port over a minimum 7 arcmin diameter science fov with a goal of 10 arcmin. The fov of the waveplates must be a minimum of 0.5 arcmin with an extended fov for the OIWFS. Single waveplates should cover 0.3 to 1.2μm and 1 to 2.5μm, with a goal of covering 0.3 to 2.5μm with a single waveplate. The L band will be covered with a first order waveplate.

Analysers, which should be two-beam polarisers, will be the responsibility of the instrument teams.



Basic Polarimetry System

Polarisation measurements are made by recording images or spectra at a number of specified angular positions of the waveplate. When a dual-beam analyser is used both orthogonal components of polarisation are recorded simultaneously.

2. SCIENCE CASE

2.1 Science Case

There are few, if any, areas of astronomy where polarimetry does not or could not play a key role, ranging from planetary surfaces to distant active galaxies. This applies to observations covering the whole of the electromagnetic spectrum.

2.1.1 Producing polarised flux

Intrinsic mechanisms:

• Electrons with low values of v/c in a magnetic field produce cyclotron radiation (circularly polarised)

• relativistic electrons produce synchrotron radiation (linearly polarised), with $\underline{E}$ perpendicular to $\underline{B}$

• in *emission* aligned grains (grain short axis parallel to the local magnetic field) produce polarisation with $\underline{E}$ perpendicular to $\underline{B}$

• Zeeman-split spectral lines are circularly polarised.

Secondary mechanisms:

• scattering off electrons or dust grains produces linear polarisation with $\underline{E}$ perpendicular to the scattering plane for electrons and for dust grains whose size is small compared to the wavelength of radiation

• scattering of linearly polarised radiation off non-Rayleigh particles produces circular polarisation

• scattering of radiation (of any state) off aligned grains produces circular polarisation

• radiation passing through a medium of aligned dust grains (grain short axis parallel to the local magnetic field) produces polarisation by dichroic *absorption* with $\underline{E}$ parallel to $\underline{B}$.

2.1.2 Polarimetry as a diagnostic tool

Polarimetry can provide the following information:

- presence of synchrotron radiation (linear polarisation) for core-dominated radio sources
- doppler-boosted emission from relativistic jets, characterised by high and variable polarisation
- presence of cyclotron radiation (circular polarisation) produced by electrons in a magnetic field with most power generated at the gyration frequency for electron speeds that are low, relative to the velocity of light, while higher harmonics are produced as the velocity increases
- scattering (linear and circular polarisation)
    - ◊ view usually obscured regions
    - ◊ study the geometrical and velocity relationship between source, scatterer and observer without spatially resolving the source
    - ◊ comparison of total and (scattered) polarised provides views of a source from different angles
    - ◊ whereas linear polarisation is dominated by the last scatter, circular polarisation usually depends on the polarisation state of the last-scattered photon and hence provides information on the previous history of that photon
    - ◊ grain properties can be determined from the wavelength dependence of linear and/or circular polarisation.
- magnetic fields

  - ◊ linear polarisation, produced in absorption by the passage of radiation through aligned grains, or produced in emission from aligned grains, gives the direction of the magnetic field, as projected on to the sky plane
  - ◊ circular and linear polarimetry of Zeeman-split lines can give magnetic field strengths and directions, with the latter parallel to the line of sight

- spectral components
  - ◊ different components can be separated as they usually have a different spectral dependence of polarisation and different polarisation position angles
  - ◊ the polarised flux spectrum gives directly the spectrum of a polarised source diluted with unpolarised flux (e.g. a blazar with starlight from a host galaxy).

A number of more detailed examples of the science that can be carried out with Gemini polarimeters is included in Annexe A of the OCDD.

2.2 OCDD and FPRD

The OCDD is at revision 3.0. The purpose of this document is to develop the science case into a document defining the overall science concept. This document was developed by the project scientist in collaboration with the project manager and IGPO staff. It is the under pinning document that the design must comply to.

The FPRD is at revision 3.0. The purpose of the FPRD is to provide engineers with the requirements for the design of GPOL. The FPRD is the specification derived from the OCDD. If the requirements of the FPRD do not match the concepts in the OCDD, the OCDD takes precedent. The design must meet the requirements in the FPRD completely. Every design feature must be traceable to the FPRD.

3. OPTICAL DESIGN

3.1 Waveplate Design

Waveplates have the advantage that it is possible to make the plates achromatic, or even superachromatic, by using combinations of plates and by using different materials. The nomenclature can be confusing: superachromat is a term commonly applied to plates that cover 0.3 to 1.1μm, although it is possible to make plates achromatic form 0.3 to 2.5μm; the term achromat has been used to describe plates covering 1.0 to 2.5μm. Waveplates will accept a wide angular beam (e.g. the polarisation efficiency of a superachromat is still $\geq$ 98% for a f/16 beam), and generally have good transmission although careful cementing or the use of optical matching oils is needed when multiple plate retarders are used.

Any waveplate will have some departure from a true $\lambda/2$ or $\lambda/4$ retardance. For the case of a superachromat, covering 0.3 to 2.5μm, the maximum departures from a $\lambda/2$ or $\lambda/4$ retardance are 5% and 10% respectively (B Halle design), which leads to a reduction in polarisation efficiency (see below), which can be easily measured and accounted for in data reduction. The effect of the change in the orientation of the optic axis with wavelength of a few degrees, that occurs with (super) achromatic waveplates, can be easily corrected in the data reduction.

(i) a $\lambda/2$ retarder

For a 5% error in retardance, the modulation efficiency is reduced by only ~0.9%. A potentially more significant problem is that in the presence of a 100% circular polarisation, a spurious linear polarisation of ~9% would be measured. Apart from AM Her binaries, objects usually have much higher linear than circular polarisation and thus the cross-talk is unlikely to be a problem in practice.

(ii) a $\lambda/4$ retarder (note that quarter-wave retarders are not in the baseline)

For a 10% error in retardance, the modulation efficiency is reduced by only ~1.5%. As noted in section 4, a non-perfect $\lambda/4$ retarder does not in itself cause any linear polarisation to be measured as circular.

3.1.1 Image wander

The main disadvantage of waveplates is that they have to be mechanically rotated and this can lead to image wander:

(i) when the plates have an error angle φ in plane parallelism, plate thickness d, distance to focus of D, then the radius of the error circle r at focus is given by:

$r=D\ \varphi\ (n-1)+d\varphi(1-1/n)$; second term applies only if the tilt is on the upper surface. For a goal of r<0.050 arcsec (f/16 focus, plate scale 1.6 arcsec/mm, r~30μm), D ~750mm, d~20mm and n~1.5 (see section 7.2), φ < 30arcsec. Note that the second term is negligible.

(ii) when the rotation axis is not normal to the plate, with an error of φ:

r=dφ(1-1/n); giving a requirement of φ< 16arcmin for the same constraint.

(iii) when the rotation axis is not parallel with the telescope axis, the image shift at focus is the same as (ii) above, but it is fixed after the insertion of the plate and is independent of rotation.

Alternatively, for step-and-stare mode, any image wander can be corrected for in real-time by moving the telescope by offsets that have been previously calculated for each of the waveplate positions.

3.1.2 Polarisation ripple

Another problem when using waveplates for spectropolarimetry is the occurrence of a ripple in the polarisation spectrum at moderate to high spectral resolutions. Multiple interference between the different surfaces of composite waveplates appears to be responsible, with the beats occurring through interference effects at slightly different optical spacings (the ripple spacing is proportional to λ^2). The effect is most marked at UKIRT where the waveplates have air spacings resulting in larger reflections at each interface. The plates were not cemented as this was thought to be difficult for plates with a diameter of 95mm. A possible remedy is to include an optical oil between the plates to provide better optical matching.

At present the ripple is removed by doing a Fourier Transform of the spectrum, removing the power at the ripple frequencies and then doing the inverse transform. This process works well but it would be sensible to minimise the effect or to have an algorithm which automatically removes the ripple from the data. Although the cause of the effect appears to be understood in general terms, a detailed analysis of the effect for particular waveplates needs to be carried out.

3.1.3 Absorption bands

Hydrocarbons in the cements used in the construction of waveplates and Wollaston prisms can produce significant absorptions in the near-infrared. For example using CGS4+IRPOL, on UKIRT, produces a deep absorption band between 3.35 and 3.4 μm.

3.1.4 Range and size of waveplates

Separate retarders are usually needed to cover 0.3 to 1.1μm, 1.0 to 2.5μm and each of the L and M bands. However, single retarders can be produced to cover 0.3 to 2.5μm, with polarisation efficiency greater than 99%. The L and M retarders should be first-order plates which act as a single order plate with respect to the variation of retardance with wavelength ($P_\eta \sim \sin(\pi/2.\lambda_o/\lambda)$, temperature and angle of incidence. Multiple order plates should be avoided.

The free aperture of the waveplates should ideally cover the field of view of all the instruments. In practice this may not be possible, at least not with single crystals. For these, the maximum diameter plates for 1-2.5μm and for the L and M bands, are ~95mm, and probably no more than ~65mm for 0.3 to 1.1μm or 0.3 to 2.5μm[1]. However, mosaics can be made and B Halle have constructed a 3x3 mosaic for the ESO VLT, with each section 45x45mm. The dead-space between each section is ~2mm. In principle even larger mosaics could be constructed. The fovs of the instruments are shown in Table 1. Waveplates of 65mm clear aperture would be sufficient for the finest scale of NIRI, for 88% of the long camera slit and 55% of the short camera slit of NIRS, for 88% of the HROS slit, and for 28% of the long-slit mode of GMOS. Waveplates of 95mm clear aperture would be sufficient for

[1] a 0.35μm to 2.5μm λ/2 single piece waveplate, with clear aperture of 95mm, is being constructed for Hough by B Halle for a different project, although delivery (as of Jan 7 2000) is delayed

all but the coarsest scale of NIRI, for the whole slit of the long camera and most of the slit of the short camera of NIRS, for HROS, and for 40% of the long-slit mode of GMOS.

Instrument	Fov (arcsec)	fov (mm)	Notes
NIRI	20, 50, 120	57, 74, 113	pixel scales 0.02, 0.05, 0.12 arcsec
NIRS	50 (long camera) 150 (short camera)	74 129	
HROS	60	79	long-slit mode
GMOS	330x330	229x229	long-slit mode
OIWFS	210	163	

Figure 2: Fields of view of the Gemini instruments.

The diameter of the fov in mm is calculated assuming a distance of 0.73m from the focal plane, and a scale of 1.8 arcsec/mm. At this distance a diameter of 46mm is required for an unvignetted fov for a point source.

Also shown in Figure 2 is the fov of the OIWFS. In order to maximise the opportunity of finding field stars for the tip-tilt secondary the full fov of the OIWFS, with a clear aperture of ~165mm diameter, is required. As single crystal plates of this size are not available either mosaics must be used or the waveplates must be surrounded by a transparent ring (possibly fused silica) of diameter 165mm. Because of the large size, the thickness of this size of ring may need to be larger than the thickness of the waveplate, requiring the use of a compensating additional glass plate (fused silica) to equalise the optical depths of the waveplate and the ring. Unequal optical depths would produce significant dead-space as the unvignetted diameter of a point source is 46mm at the position of the polarisation module. In this case the ring would contribute no additional fov as the width of the ring is less than the image size.

3.2 Instrument Requirements

Each instrument has to include a polarisation analyser and a focal plane mask. Although these are the responsibility of the instrument teams it is useful to include the requirements here.

3.2.1 Analysers

Two types of polarising prism are commonly used: calcite blocks, that produce a translational displacement between the e- and o-rays, and Wollaston prisms that produce an angular separation of the two beams.

Calcites have been used in a number of optical spectrographs placed below the spectrograph slit, with a beam displacement which is ~0.1 x the calcite thickness. A simple calcite has the disadvantage that the two beams have different optical path lengths and therefore a different focus. This can be overcome by using a Savart plate, as in the ISIS spectropolarimeter on the WHT (Tinbergen 1992). Calcites cannot be used beyond 2.0μm because of their large opacity to the o-rays.

Goodrich (1991) describes a modified Glan-Taylor calcite polarising beam splitter that produces a beam separation equal to the beam diameter, although the two beams have unequal path length.

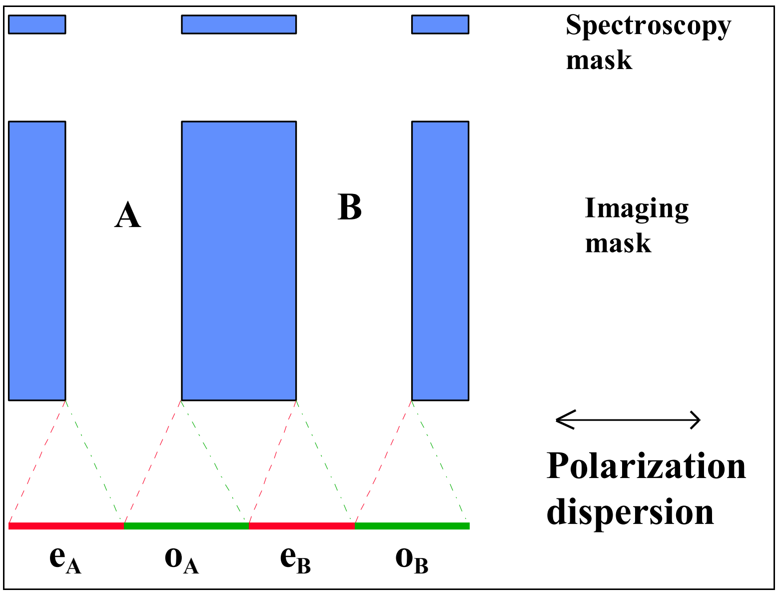
Wollaston prisms have been used in the collimated beams of IR cameras and spectrometers (Hough et al 1994, 1996). The deviation of the 2 beams is given by $\delta eo = 2\ (n_e\text{-}n_o)\ \tan\Omega$, where Ω is the prism angle, and (e.g. n_e, n_o) is the material birefringence. Double Wollastons, with twice the thickness and angular dispersion, can also be produced. Oliva et al (1996) give the separation of the two beams in arc seconds, expressed in sky-projected angles as $2063(n_e\text{-}n_o)\ \tan\Omega.DpDtel^{-1}$, where Dp is the diameter of the pupil image inside the instrument (in centimetres) and Dtel is the telescope diameter in metres.

In selecting a material consideration has to be given to: transmission, the required beam separation and birefringence of materials, wavelength dependence of birefringence (images can become elongated in the polarisation dispersion direction when using broadband filters), the ability to cement the (two) components of a Wollaston prism, and the ability to operate at low temperatures for infrared instruments. **Appendix C** of the OCDD gives information on possible materials for each instrument.

When using reflection gratings a problem can arise when the polarisation state of one of the beams is crossed with the polarisation axis of the grating, leading to significant loss of light and an imbalance between the two beams. There are two ways to reduce the effect. First, to have the polarisation states of both beams at 45 degrees to the polarisation axis of the grating, thus ensuring that the beams are balanced. Second, to use a quarter-wave retarder after the analyser, with its fast axis at 45 (and 135) degrees to the two orthogonal polarisations. This will convert the linear to circular polarisation.

3.2.2 Masks

A focal plane mask is required so extended objects can be observed without overlapping the two beams from the dual-beam analyser. Below is shown a mask for imaging and for spectroscopy, used with a dual-beam analyser which gives a beam separation of one-quarter of the array. The separation of beams is a compromise between possible optical aberrations produced for large separations and cross-talk for too small a separation. Large separations are convenient as extended objects may be fully covered by one of the mask gaps and observations can be made with a single setting of the telescope.



4. MECHANICAL DESIGN

4.1 Design trade-off

4.1.1 Gemini A&G Unit Space Envelope Considerations

The GPOL must fit into the Gemini A&G Unit. Space in this unit is very cramped and there are several goals and requirements the design must meet:

- There is a requirement to minimise any disruption to the A&G systems
- There is a goal to cause no disruption to the A&G systems
- There is a requirement to not vignette the 7 arc-minute science beam
- There is a goal to not vignette the ten arc-minute science beam
- While height is restricted there is a requirement for two waveplates and a calibration plate, each independently deployable.
- While height is restricted there is a goal for three waveplates and a calibration plate, each independently deployable.

This results in the space envelopes defined in ICD 1.6/1.12 and reproduced as

Figure 3 and Figure 4.

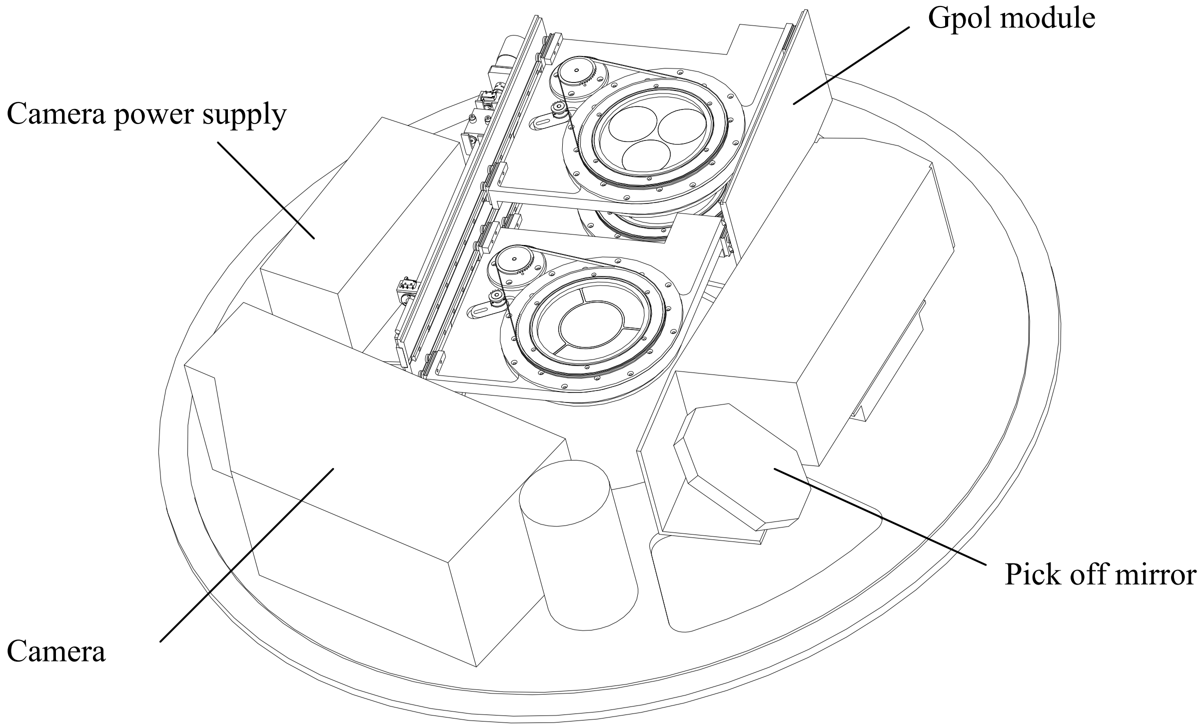


Figure 3 View of A&G module 1 showing Gpol position

Diagrams show the lid and rear connector panel removed for clarity

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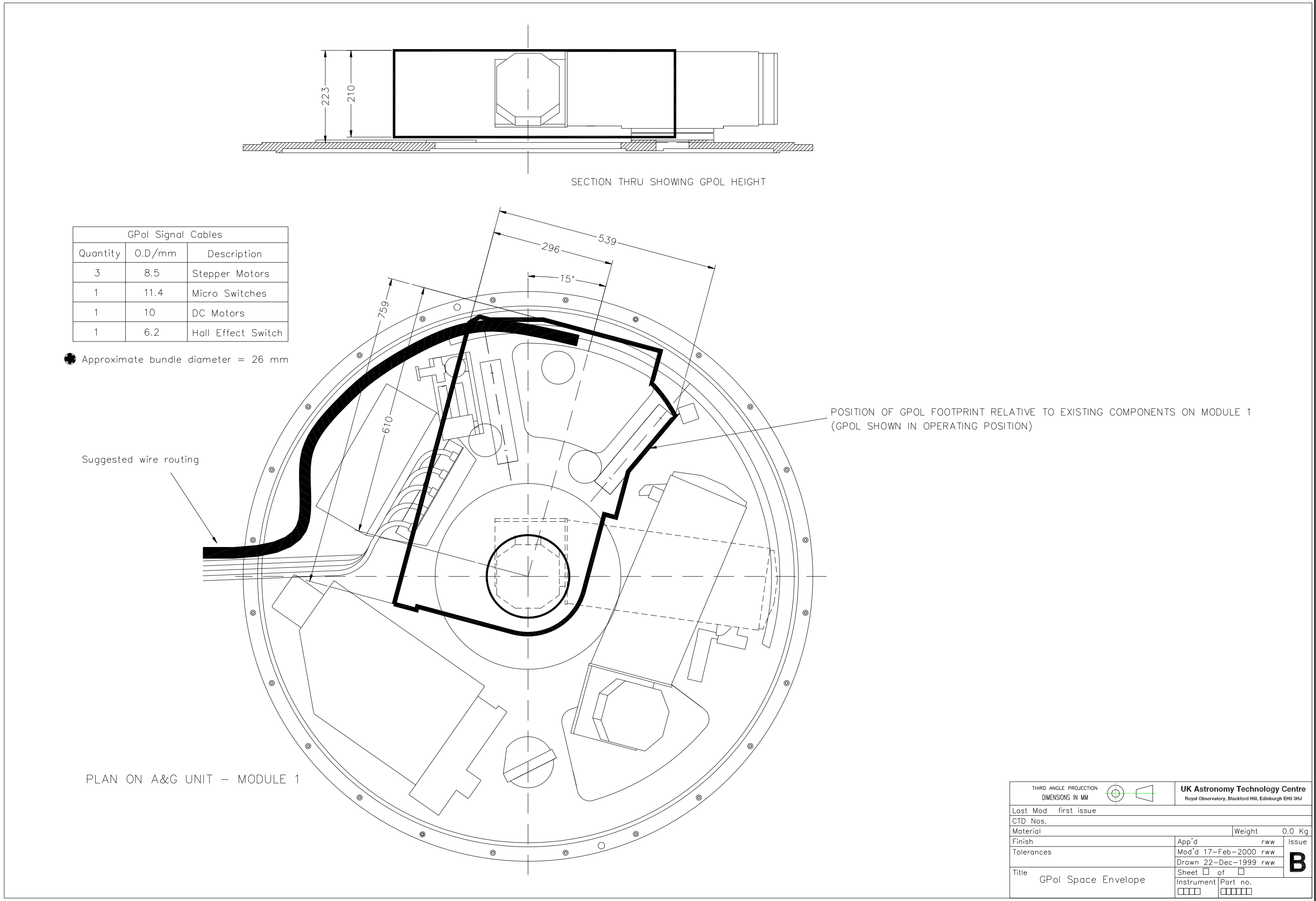


Figure 4 Gpol space envelope

4.1.2 Linear Drive Design

In this arrangement, the waveplates and calibrator are driven along Hepco linear slides. The tracks are stacked above each other.

The major advantages are:

i. The space envelope is suited to the existing A&G arrangement. In particular, the CCD controller is not moved. The connector block and cooling manifold require relocation.

ii. The use of two linear slides, one of which spans the aperture, minimises flexural problems.

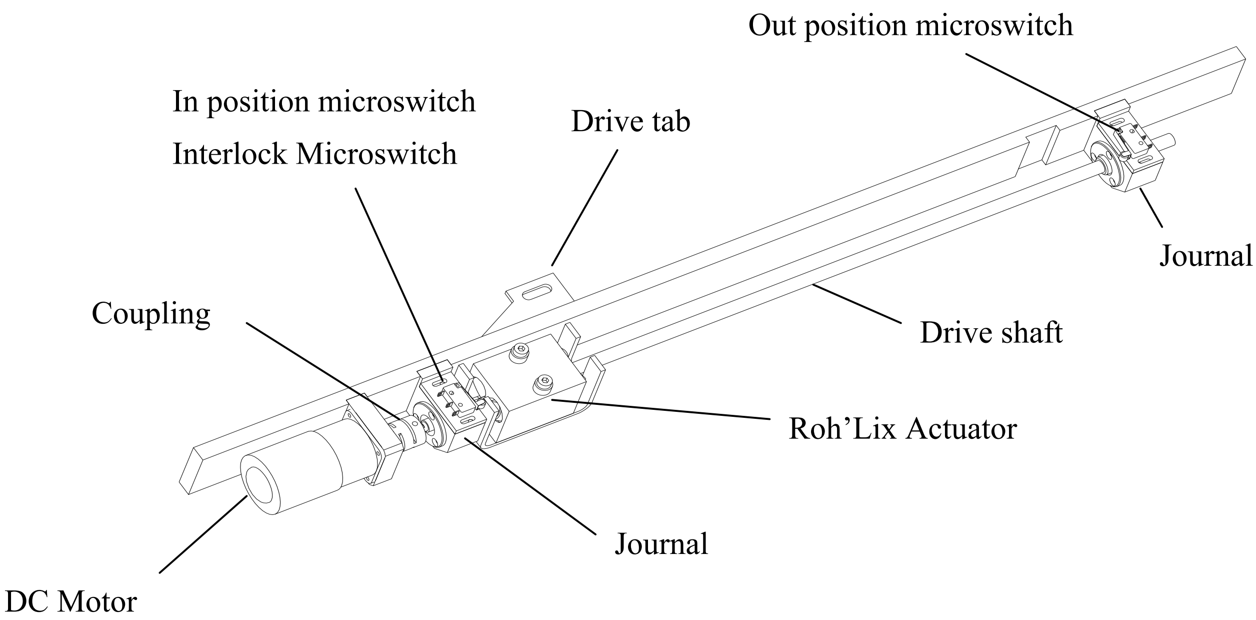


Figure 5 View of Linear Drive Mec hanism

4.2 Linear Drive Mechanism

The waveplates and calibration source carriers are moved independently on linear slides as shown in Figure 6 and Figure 7 below.

The linear drive is achieved using a Roh'lix actuator mechanism. The mechanism converts rotary motion into linear travel using a helical bearing layout. A DC motor rotates the shaft through a flexible coupling and the waveplate carrier is moved linearly into the beam. The shaft is supported through two journals each having twin bearings. A micro-switch at each end of the travel detects whether the carrier is in or out.

The Roh'lix bearing is spring loaded and will act as a slipping clutch if its movement is impeded. The enables the controlling software to drive the motor for a fixed time into a hard end stop if required.

The drive mechanism assembly is common to all carriages. The shorter travel distance required for the calibrator being accommodated by moving the out journal and microswitch.

The motor RPM and pitch of the actuator combine to give a linear speed of 10.5mm/second. The total deployment time being calculated at 40 seconds. The torque required to insert the waveplate blade is calculated at 0.3 NM. The stated motor torque is 0.6 NM.

Due to the possibility of contact with the Acquisition Camera pick-off mirror a park switch will be interlocked with the A&G system. This is achieved by activation of a microswitch in the home position.

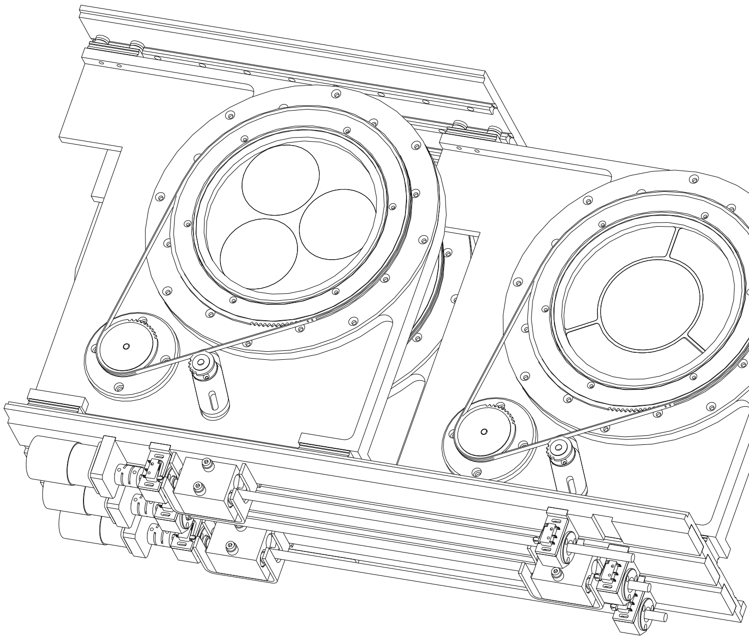


Figure 6 Linear Drive Design Showing Waveplate Deployed

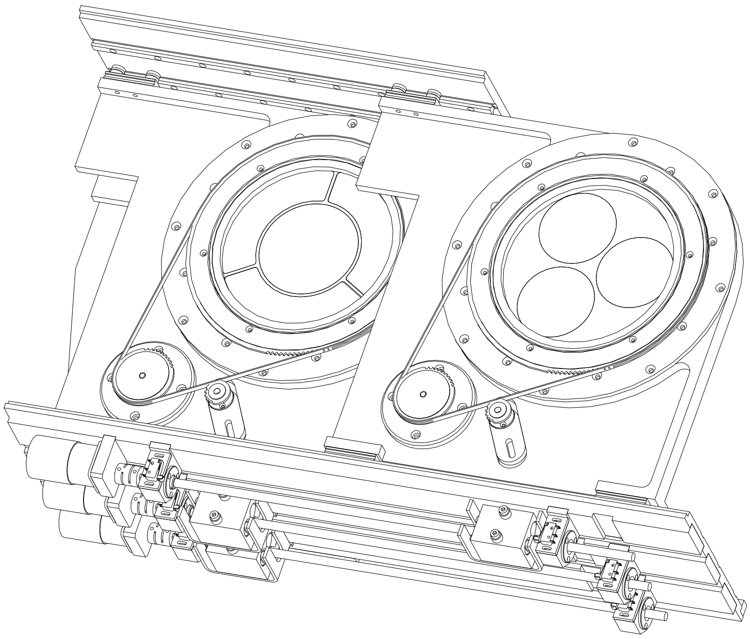


Figure 7 Linear Drive Design Showing Calibration Plate Deployed

4.3 Waveplate Rotary Drive

Each waveplate carrier is mounted in a rotator. The rotator consists of three main components as shown in Figure 9:

i. The Rotator drive assembly:

A stepper motors revolves the carrier using a sprocket and belt drive arrangement. The drive ratio being set at 6:1. A sprung idler sprocket maintains the belt tension. The torque required to drive the rotator assembly is calculated at 0.06 nm. The stepping motor maximum torque is 0.127 nm.

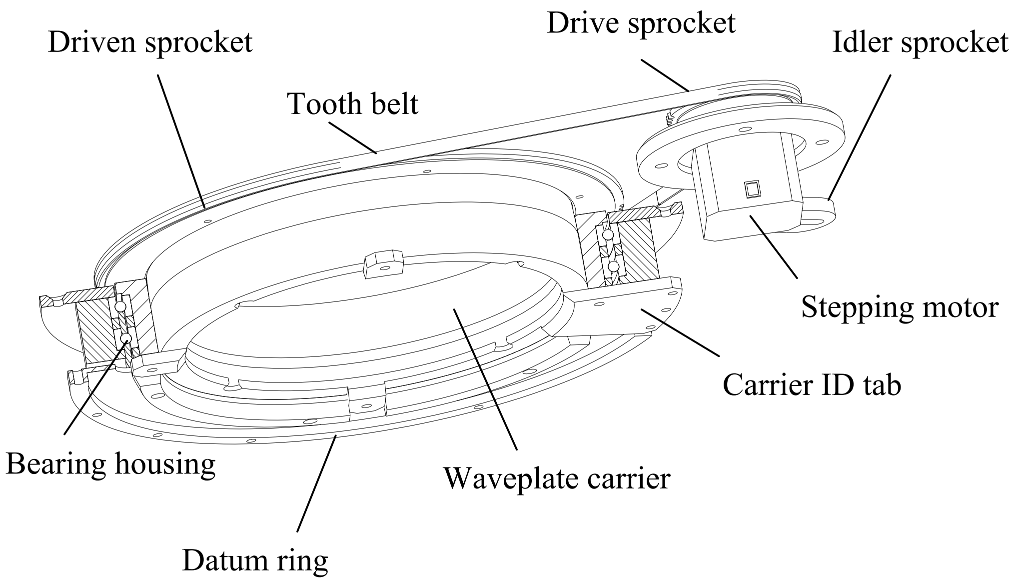
ii. The bearing housing:

The housing contains two Kaydon slim bearings, the driven sprocket, and carrier identification tab. The maximum radial and axial run out stated for the Kaydon bearings is 0.03mm.

iii. The datum ring:

The datum ring contains the sensor for zero position and the operating positions of 22.5, 45, 67.5, 90 and 135 degrees.

Figure 8 Rotator Drive Assembly



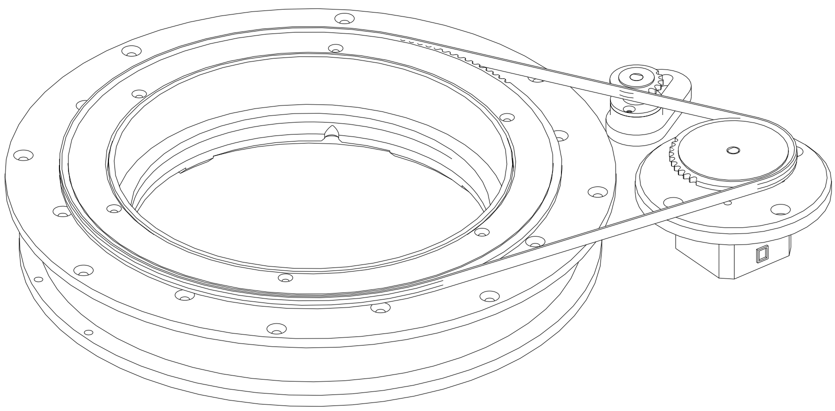


Figure 9 **Rotator Drive Assembly with carrier removed**

4.4 Waveplate Mounting and Interchange

A tool is required to allow the waveplates and calibration source (mounted within carriers) to be inserted or extracted into the carriage mechanism. Access to the carriage would be through the lower port of the ISS using the tool in a vertical position.

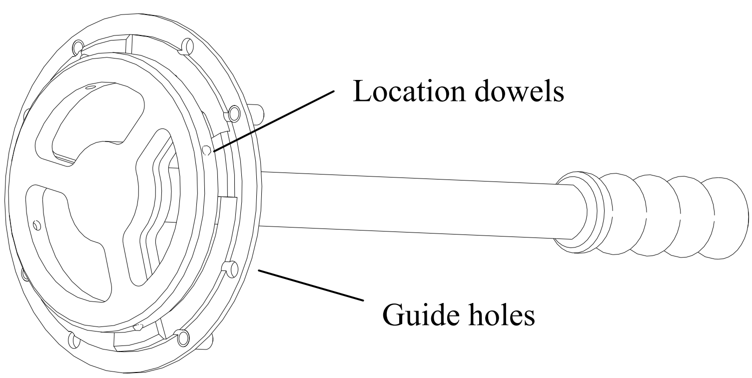


Figure 10 Waveplate Insertion and Extraction Tool

The proposed method of extracting the carrier from the carriage being outlined below

i. The tool is inserted into the base of the carrier. The four holes in the rim of the tool are aligned with the four screws holding the carrier to the rotator. The dowels locate into holes on the carrier and a short turn of the tool clockwise engages them (bayonet fitting).

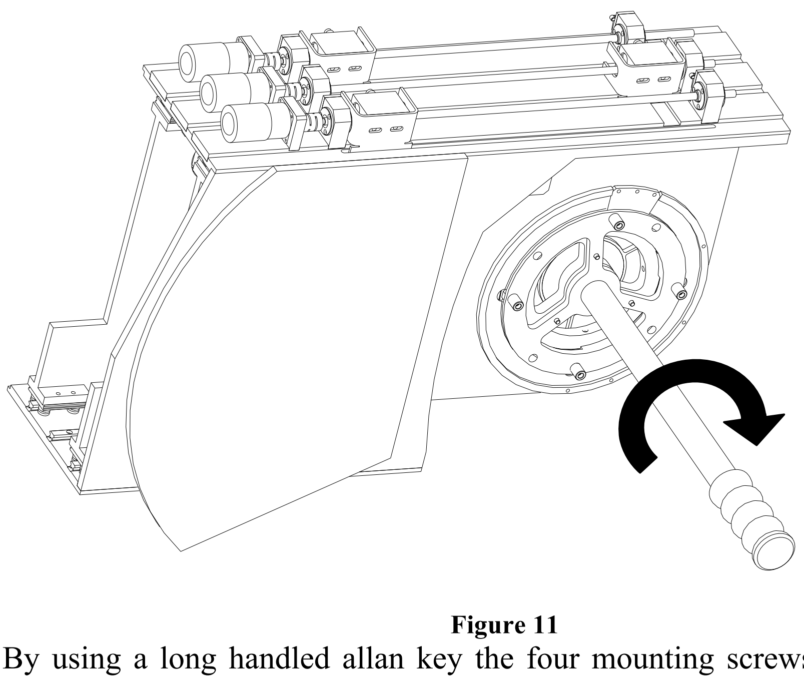
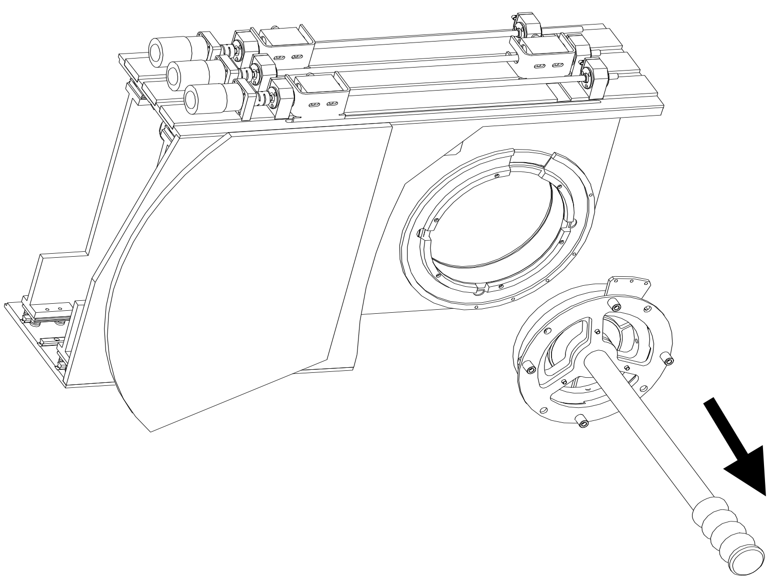


Figure 11

ii. By using a long handled allan key the four mounting screws on the carrier can be removed.

Figure 12



iii. The screws will remain captive within the tool. The carrier can be slowly removed from the rotator down through the ISS.

iv. The carrier and waveplate can now be stored in box. The box would contain a pocket and four threaded holes. Only when the carrier is placed in the pocket and the screws engaged could the tool be removed by twisting anti-clockwise.

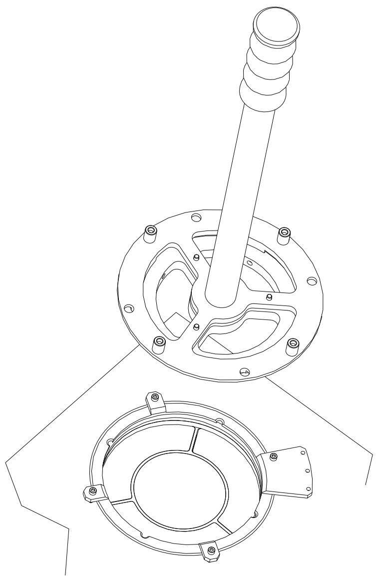


Figure 13 Storage of waveplate carrier in a box

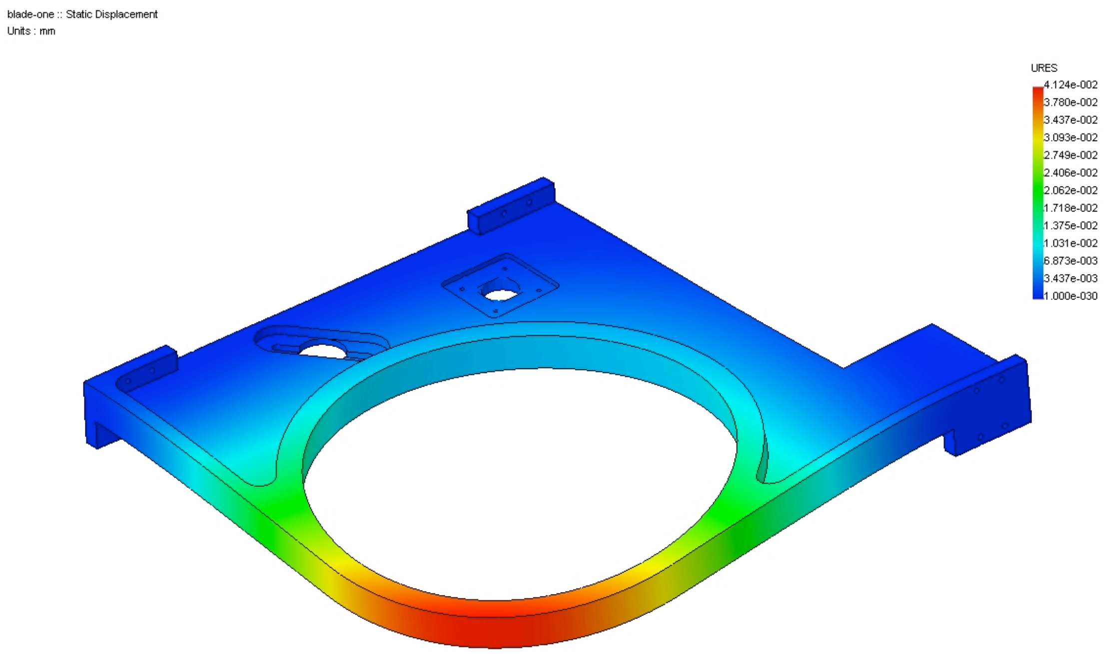
4.5 Weight analysis

Initial estimates show the full assembly weight to be 52 Kgs. Lifting eyes will be fitted to the casing to allow removal from the A&G module.

4.6 Flexural Stability

The initial flexure analysis of a populated waveplate blade shows a deflection of 0.04 mm at the radius edge of the waveplate carrier (telescope at zenith). Further measurements will be taken using dial gauges following build.

Figure 14 Flexure Analysis



Mounting to the A&G Module

The A&G unit has two rectangular upstands incorporating two threaded holes each. It is proposed to mount the GPol base plate to the upstands using the existing holes and adding two new M8 threaded holes per side. The GPol module is then fixed to the base plate by M10 screws through three machineable pads. Clearance is allowed on the rear two mounting screws to allow GPol to rotate around the front pad for angular positioning. The pads are individually machined to level the module as required. Once positioned, dowels are fitted through two of the pads into the base plate. Gpol can be removed from the A&G module by removing the lid and undoing the M10 screws through the pads. The base plate and dowels remain in position.

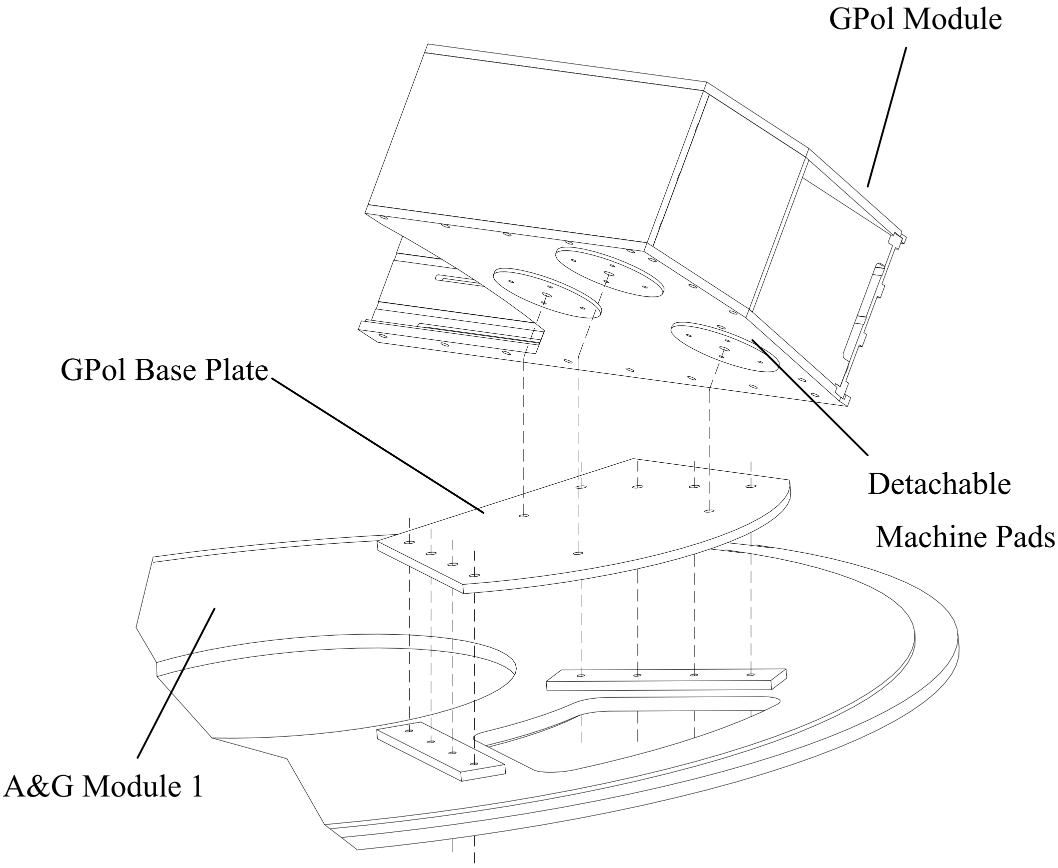


Figure 15 GPol Mounting

5. CONCEPTUAL DESIGN COMPLIANCE MATRIX

A matrix of requirements from the FPRD is shown below identifying compliance or non-compliance of the Conceptual Design.

Requirement	Description	Compliant y/n	Non-compliance
Requirement 1.1	For highest precision (P≤ 0.05%), the polarisation module should be before any non-symmetric reflections	Y	
Requirement 1.2	When not in use the polarimetry module must not vignette a 7 arcmin diameter fov.	Y	
Goal 1.2	When not in use the polarimetry module should not vignette a 10 arcmin diameter fov.	N	9 arcmin
Requirement 1.3	The waveplates should retract into a dust cover when not deployed.	Y	
Requirement 1.4	minimal disruption to the A&G hardware as defined in ICD 1.6/1.12	Y	
Goal 1.4	No disruption to the A&G hardware	N	
Requirement 1.5	The control hardware will be mounted external to the ISS	Y	

Goal 1.5	The WFS control hardware will be utilised to drive the various mechanisms		
Goal 2.1	A single (superachromatic) waveplate to cover 0.3 to 2.5μm	Y	
Requirement 2.1	A single (superachromatic) waveplate to cover 0.3 to 1.1μm and a single (achromatic) waveplate to cover 0.9 to 2.5μm; first-order plate to cover the L band (M-band plates are not in the baseline)	Y	
Requirement 2.2	Waveplates to provide λ/2 retardances (quarter-wave retarders - for circular polarimetry - are not in the baseline).	Y	
Requirement 2.3	A set of 3 non-rotating calibration plates, that cover the wavelength range of Gemini polarimeters and be automatically deployable	Y	
Requirement 2.4	The GPOL will need to operate two waveplates together.	Y	
Goal 2.4	GPOL should contain at least three waveplates that can be accessed and operated remotely	N	
Requirement 2.5	Waveplate clear apertures to be minimum of 95mm.	Y	
Requirement 2.6	Wedge angle of the waveplates to be less than 0.5 arcmin	Y	
Requirement 2.7	Rotation axis of waveplates to be normal to the waveplate to within 16		

	arcmin		
Requirement 2.8	Clear aperture of rotating assembly to be 165mm. Optical thickness of waveplate and clear aperture to be uniform to 1%.	Y	
Requirement 3.1	Waveplates should be introduced and withdrawn with the minimum disruption	Y	
Requirement 3.2	The on-axis centering should be better than ±0.5mm.	Y	
Requirement 3.3	Waveplate identification to be electronically encoded	Y	
Requirement 3.4	Waveplates must not be able to rotate in their holders.	Y	
Requirement 3.5	The waveplate optical axes to be aligned in the same direction with a precision of a quarter degree.	Y	
Requirement 3.6	Waveplates to be rotated continuously or in step-and-stare mode	Y	
Requirement 3.7	Sensors, attached to the rotating assembly, should be used to define the usual operating positions: 0, 22.5, 45, 67.5, 90 and 135 degrees.	Y	
Requirement 3.8	The sensors should be magnetic or, if optical, should be powered off when the operating position has been reached.	Y	
Requirement 3.9	Rotate one or two waveplates, either in continuous or step and stare mode.	Y	
Requirement	Sense of rotation should be switchable	Y	

3.10	in engineering mode, but always default to the same sense in observing mode.		
Requirement 3.11	Any angular position, in steps of a half-degree or less, should be available by offsetting from the 0-degree position.	Y	
Requirement 3.12	Each of the set waveplate positions should be accurate to better than 0.2 degrees relative to the zero-degree position	Y	
Requirement 3.13	Intermediate waveplate positions should be accurate to better than 0.2 degrees relative to the zero-degree position	Y	
Requirement 3.14	The minimum rotation period (τ_{min}) should be an integral number of half-seconds..	Y	
Requirement 3.15	τ_{min}<5 sec	Y	
Goal 3.15	τ_{min} to be 4sec	Y	
Requirement 3.16	Rotation periods should be programmable with τ ranging from to τ_{min} to $10\tau_{min}$ in steps of $0.5\tau_{min}$	Y	
Requirement 3.17	Continuous rotation should be uniform to 1 part in 200 and with a long-term precision of 1%.	Y	
Requirement 3.18	Motors to be in standby mode when stationary, but to retain sufficient torque to stop any slippage.	Y	
Requirement 3.19	Waveplates and rotating assembly to produce beam-wander of less than		

	0.050arcsec at the focal plane		
Requirement 5.1	In step-and-stare mode any beam wander resulting from the rotation of the waveplate can be corrected for by offsetting of the telescope		
Requirement 5.2	The Gemini Cassegrain focus must be capable of increasing by up to 15mm.	Y	
Requirement 5.3	The PWFS focus needs to be mechanically adjustable by up to 15mm or a glass plate, or plates, of suitable optical thickness can be placed in the PWFS filter wheel		
Requirement 5.4	Online data reduction to give Stokes parameters for individual integration and running average (with uncertainties)	Y	
Requirement 5.5	The TCS and OCS must inform the relevant instrument when the GPOL is in position to make and observation.	Y	
Requirement 5.6	The TCS must provide the top level control of GPOL	Y	
Requirement 5.7	The WFS must provide the top level VME processing and control hardware for the GPOL.	Y	
Requirement 6.1	System must conform to ICD-G0013 Gemini Environmental Requirements	Y	
Requirement 6.2	Mechanisms that are passively cooled must not raise the	Y	

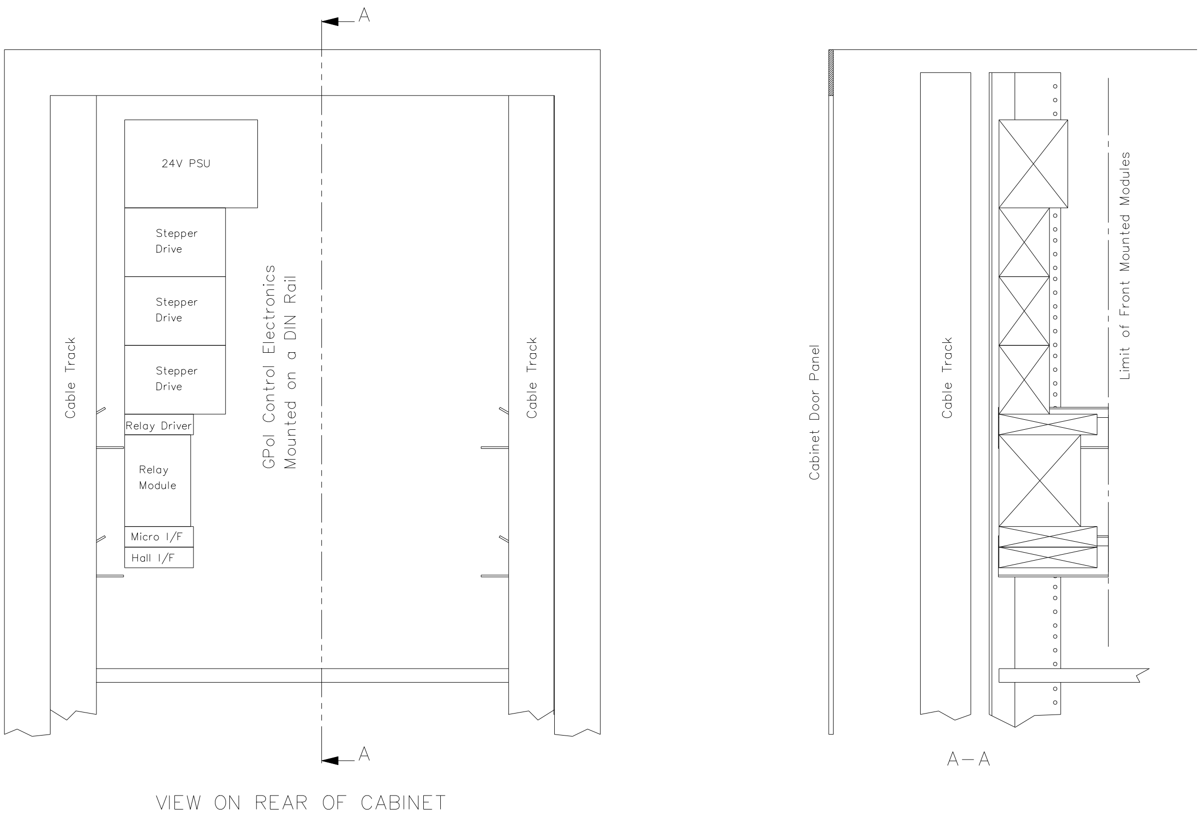
	surrounding A&G structural temperature by >2° C		
Goal 6.2	Mechanisms should be powered off when not in use.	Y	By switching off mains power in Cabinet
Requirement 6.3	Handling equipment to be provided for safe lifting and movement of the unit and sub-assemblies (e.g. waveplate installation/removal jig).	Y	
Requirement 6.4	Mauna Kea available power is 120 V 60 Hz AC	Y	
Requirement 6.	Cerro Pachon available power is 110 V 50 Hz AC	Y	

6. ELECTRONICS

6.1 Introduction

The enclosed Gpol electrical block diagram Figure 17 (89-UKATC-7000-50m00e) details components and connectivity from the mechanical chassis to the control electronics in the A&G wavefront sensor cabinet.

Accommodating the Gpol electronics within the A&G wavefront sensor cabinet is a problem. Insufficient front panel space remains and the proposal is to mount the control electronics on a DIN rail in the upper part of the rear of the cabinet, Picture 1 shows a scaled representation of the Gpol electronics within the cabinet. Proprietary power supplies will be used with specialist packaging reserved for the stepper motor drives and digital interface electronics. The control interface to the computer system will be via the spare capacity in the Gcal VME electronics. The cables leaving the cabinet will make use of space available on the Gcal connector panel. Provision for Gpol connector panels has been made as part of the Gemini calibrator (Gcal). The Gcal VME panel (89-UKATC-5000-26m50e) will require modification to introduce the additional control signal lines for the Gpol stepper motors and digital I/O signals.



Picture 1 A&G wavefront sensor cabinet

6.2 Functions

6.2.1 The electronics systems will perform the following functions:

- Control of 3 DC motors for waveplate carriage insertion/extraction, with datum sense of in and out beam position (using microswitches)
- Control of 3 stepper motors, one mounted on each waveplate carriage for rotation of the waveplate carrier.
- The waveplate carriage will have a Datum and waveplate identification sensor. Additional sensing will identify preferred operating positions (22.5, 45, 67.5, 90 and 135 degrees). A total of 7 states will be sensed per plate using 2 Hall effect sensors with targets mounted in the rotating plate. One Hall effect sensor is dedicated to detecting the datum position, the other sensor identifies all other positions. Figure 16 illustrates identification zones.

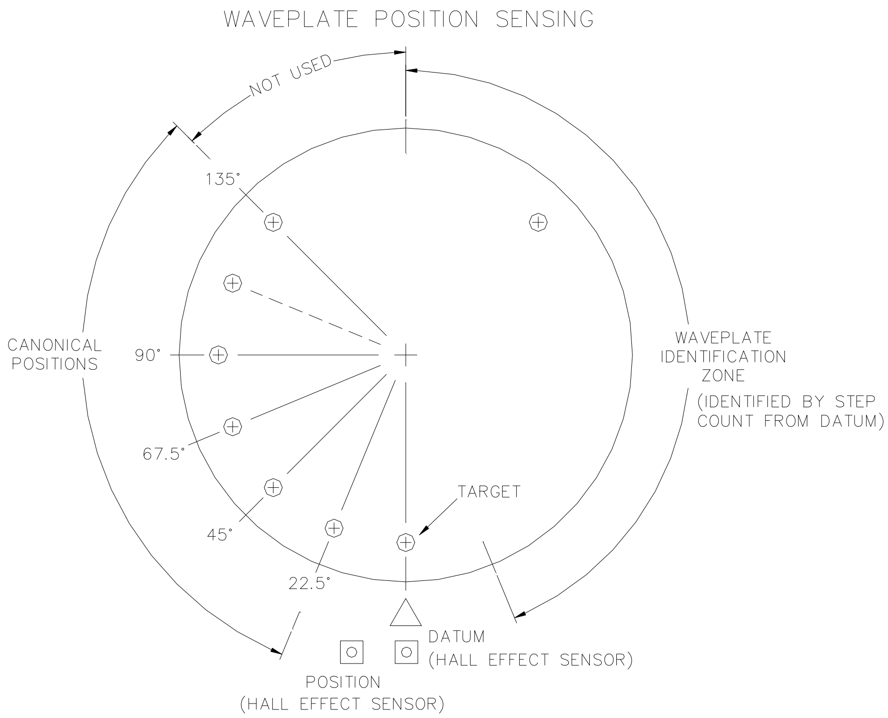


Figure 16 Waveplate identification zone

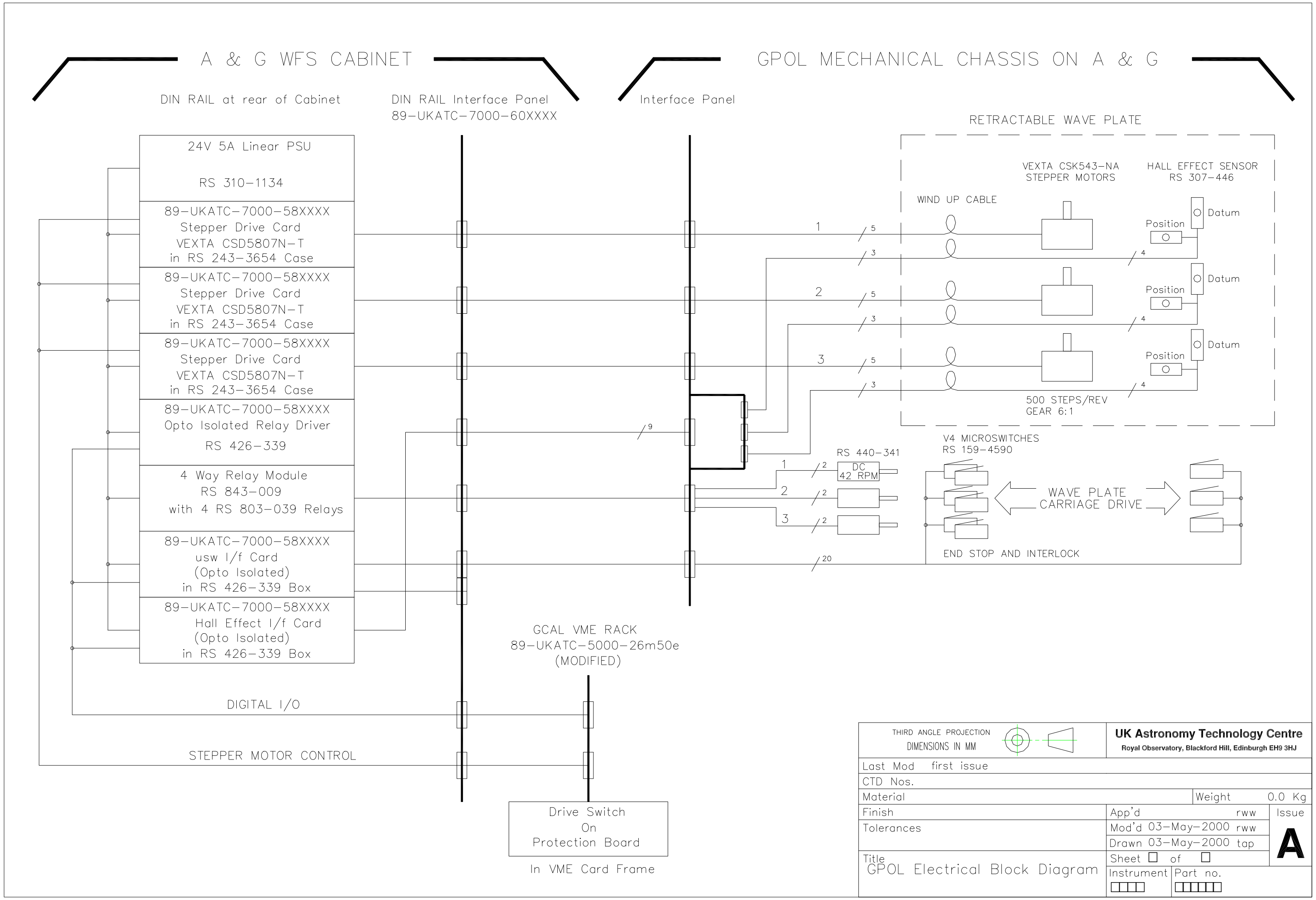


Figure 17 electronic Block Diagram

6.3 VME Rack.

GPol will use spare capacity on the following Gcal cards:

- Oregon Microsystems stepper motor controller VME8
- Xycom digital I/O card XVME-240.

6.4 Interlock

The power supply for Gpol is derived from spare capacity on the Gcal mains connector block. Switching off the master switch on the front panel prevents any mechanism from moving and so provides safe access.

A 2 pin connector is provided on the Gpol interface panel (rear of A&G wavefront sensor cabinet). The connector is wired directly to 3 microswitches on the home (or "in garage") position of the waveblades. The microswitches are wired is series such that normally closed (NC) is registered while all 3 waveblades are at Home. Should any waveblade move then an open contact is measured (NO).

6.5 Power Dissipation

Quiescent power dissipated by the Stepper motors mounted on Gpol will not greatly exceed 5 Watts. Within the cabinet the principal source of power dissipation will be the power supplies and this could be estimated to be of the order 75 watts. The waveplate blade area (0.18m^2) gives an effective heatsink of at least 0.75 C/W resulting in a temperature rise of 5C for continuos running of the motor (will be lower when waveplate carrier is included). No cooling of the waveplate blade is necessary.

6.6 Software requirements.

A software interface will need to be developed to allow the user to perform the following functions.

Drive and position the 3 polarisor carriage wheels using an Oregon Microsystems standard VME motor control card. The control methodology to be employed should kept simple as follows. There will be one datum position on the wheel (figure 14), each subsequent target position will be located by motor steps and confirmed by activation of the 2nd Hall effect sensor. Waveplate identification will be done by encoding the number of steps from datum to a unique position confirmed by activating the sensor.

Controlling the wave plate carriers will be done by utilising the digital outputs on the Xycom VME digital I/O card to select 1 of 3 carriers then to engage a DC power supply to drive the carrier motor for a fixed time. Direction of travel will be controlled by reversing the polarity of the DC supply to the motor through a suitable interface connected to the digital I/O card.

7. SOFTWARE

7.1 Scope

The scope of the software provided with Gpol shall generally be as provided for other Gemini instruments or telescope subsystems. However because Gpol must be used with other instruments, it places requirements on other Gemini systems.

The software provided with Gpol shall be that necessary to control its mechanisms. The Gpol control system will be a subsystem of the Telescope Control System, since it affects the beam before it enters an instrument. This simplifies the system by removing the need to include Gpol control software in any instrument with which it is used. It ensures that one instrument cannot affect the beam entering another and is consistent with the philosophy that the TCS is responsible for controlling the telescope beam before it enters an instrument.

In order to make effective use of Gpol, some other systems must be modified:

Observatory Control System (OCS)	▪ Include Gpol data in configuration data sent to TCS ▪ Sequence Gpol and data acquisition ▪ Control on-line data analysis ▪ Store additional data in FITS header
Telescope Control System (TCS)	▪ Send command to Gpol as instructed by the Observatory Control System or a TCS console. ▪ Modify pointing in response to corrections received from Gpol
Instrument Component Controller	▪ LUTs should include details of analysers and focal plane masks
Instrument Detector Controller	▪ Four read-out windows required on CCD
Instrument Sequencer	▪ Store additional information in FITS header
Data Handling System	▪ On-line data reduction for data quality assessment
Interlock System	▪ Disable telescope motion if GPOL gets into a position where damage could result from such motion (probably not required) ▪ Prevent damage caused by GPOL and A&G mechanisms colliding (probably not required)
A&G opto-mechanical system	▪ Check that GPOL is not in way before inserting HRWFS probe

7.2 Gpol Control Interface

Gpol will be controlled as a subsystem of the TCS and so the interface must conform with ICD7b. The TCS/Gpol interface will be defined formally in an ICD, but it is expected the commands will be based on the following.

7.2.1 Commands

Commands are defined by CAD (Command Action Directive) records and responses by CAR (Command Action Response) records. These and other Gpol records will be identified by the prefix *gpol:*.

Command (CAD) gpol:	**Fiel d**	**Attribute**	**Type**	**Description**	**Response (CAR)** gpol:
reboot				Reboot the IOC	rebootC
init				Initialise system	initC
	a	mode	string	simulation mode	
datum				Datum all the mechanisms	datumC
park				Park all the mechanisms in a safe position	parkC
Test				Test all mechanisms so far as possible without moving them, reporting errors through statuses and alarms	testC
debug				Put into debug mode	debugC
	a	mode	string	debug mode	
plate[1|2]Sel				Select which waveplate to use	plate[1|2]C
	a	name	string	Name of waveplate as stored in LUT	
plate[1|2]Move				Move to a position and stop	plate[1|2]C
	a	angle	real	angle in degrees from datum	
plate[1|2]Stop				Stop any motion currently in progress	plate[1|2]C
plate[1|2]Rotate				Rotate continuously	plate[1|2]C
	a	period	real	Rotation period in seconds	
plate[1|2]Datum				Datum waveplate	plate[1|2]C
plate[1|2]Park				Park waveplate	plate[1|2]C
plate[1|2]Test				Test waveplate (without moving)	plate[1|2]C
calSel				Select calibrator	calC
	a	name	atring	Name of calibrator as stored in LUT	
calDatum				Datum calibrator	calC
calPark				Park calibrator	calC
calTest				Test calibrator (without moving)	calC

7.2.2 Status and Alarms

Record Name (SIR unless CAR is specified) gpol:	Type	Units	Description
name	string		Name of controller
health	string		Health of GPOL (GOOD, WARNING or BAD)
state	string		State of controller (BOOTING, INITIALIZING or RUNNING)
present	string	s	TAI time to be used as a heartbeat
inPosition	logical		Whether all mechanisms are in position
activeC	CAR		Overall status: IDLE, BUSY or ERROR
plate[1|2]Health	string		Waveplate health: GOOD, WARNING or BAD
plate[1|2]InPosition	logical		Whether waveplate is in position
plate[1|2]Name	string		Name of selected waveplate
plate[1|2]Angle	real	degrees	Waveplate angle from datum (-1 if rotating continuously or in motion between two positions)
plate[1|2]Period	real	s	Current continuous rotation period (-1 if not rotating continuously)
calHealth	string		Calibrator health: GOOD, WARNING or BAD
calInPosition	logical		Whether calibrator is in position
calName	string		Name of calibrator
offsetX	real	mm	Image offset in X direction (mm in focal plane)
offsetY	real	mm	Image offset in Y direction (mm in focal plane)

7.2.3 Implementation

Gpol control will be implemented in Gemini EPICS. Best practice to develop Gemini EPICS systems is still evolving but it is expected that code will be reused from the GMOS project. At the lowest level each motor will be controlled by a device Control record, which will read in and act on micro-switch values. Above this an assembly record will control all the motors associated with a mechanism, e.g. a single waveplate.

The current version of Gemini EPICS is 3.12gem5. It is hoped that by the time Gpol programming work commences, Gemini EPICS will have been updated to 3.13, which is more widely used in the EPICS community and has many technical advantages.

The TCS/Gpol ICD and the tables above define CAD and CAR records necessary to control Gpol from an operational point of view. In addition there will be engineering commands to assist testing and debugging.

7.3 Interaction with A&G

GPOL mechanisms and A&G mechanisms will be on close proximity and there is the possibility for interference between GPOL and the HRWFS probe, since when deployed they both share the same space.

In normal operation the A&G can check that GPOL is parked before deploying the HRWFS arm. Similarly GPOL can check that the HRWFS arm is not deployed before deploying its own mechanisms. Furthermore the TCS, which controls both the A&G and GPOL, should not request an impossible configuration from its subsystems.

Nevertheless it is important that malfunctioning software or control systems should not cause physical damage. The standard way to prevent this sort of thing is to use the Gemini Interlock System (GIS). The A&G and GPOL would send signals to the GIS to say there mechanism was occupying the contested space. Both GPOL and A&G would only be able to move a mechanism into this space if the signal from the GIS told them they could do this. This solution is rather messy (and therefore expensive) from the cabling and implementation points of view.

There are two other alternatives. First of all micro-switches could be cross-wired between the two systems, but this is probably just as bad or worse.

A better solution is to ensure that the mechanical design prevents damage occurring even if the control systems malfunction. It is believed this is possible and so no provision is made in the software or electronics to prevent collision, except the obvious checks mentioned above (GPOL checks A&G configuration before deploying and vice versa). It is possible that even these checks could be dispensed with, since the TCS can ensure that in operation conflicts do not occur.

7.4 Instrument Requirements

Instruments must be able to insert analysers and masks. Assuming these are installed in existing filter assemblies (HROS excepted), all that should be necessary is to make appropriate entries in Look Up Tables.

The Detector Controller of instruments must be able to define 4 windows on the CCD to be read out. It is believed the Science Detector Controller specification allows this, but it needs to be checked.

Instruments also need to be able to store Gpol parameters in FITS headers so that the data can be properly analysed, both on-line for quality assessment and off-line for final analysis. These FITS keywords will be defined.

7.5 TCS Requirements

The TCS needs to be modified to send out the commands listed above and to act on the status returns. It also needs to be able to interpret commands from the OCS that specify Gpol configurations.

The TCS needs to be able to modify telescope pointing to counteract any image shift that may be caused by waveplates and calibrators that are not perfectly flat. Gpol provides the necessary information through the offsetX and offsetY SIR records (names may need to be changed for consistency within the TCS). This will allow image shift to be corrected when waveplates are moved from one fixed position to another. It will not allow any correction to be applied when the waveplates are being rotated continuously.

7.6 OCS Requirements

The OCS controls the instrument, which controls data acquisition and the analyser, and the TCS, which controls the waveplates. The OCS will need to be developed to send appropriate configuration to both instruments and the TCS.

The OCS also controls the DHS. It may need to send commands or data to the DHS, although since the DHS should be data driven, these requirements on the DHS should be minimal or non-existent.

7.7 DHS Requirements

The DHS is responsible for storing data received from instruments. Gpol should not place any additional requirements on the DHS in this respect.

The DHS is also responsible for performing, or arranging to have performed, on-line data reduction to allow data quality to be assessed. It will be possible easily to display images (after flat fielding etc.) using the Quick Look Server, but this will reveal very little about the quality of polarimetry data. Procedures will need to be set up to allow automatic on-line reduction of the data.

Suitable algorithms and code exist, but integrating them into the Gemini system will take a significant amount of work. As with other Gemini instruments this is not the responsibility of the instrument team, but it is currently not clear who will perform this work or how.

7.8 Further Work

- ICDs need to be written and agreed with the responsible parties.
- FITS keywords need to be specified.
- Ensure Gemini Project understands implications for other systems
- Confirmation is required that the mechanical design prevents damage to hardware in the event of malfunctioning A&G and GPOL control systems.
- Confirmation is required that GPOL never needs to inhibit telescope motion damage to prevent internal damage to GPOL.
- Data reduction recipes, algorithms and code need to be provided to whoever in the Gemini Project is responsible for on-line data reduction.
- Confirmation is required that the Gemini Science CCD Controller supports four read-out windows.
- Mechanism control software needs to be implemented in EPICS.

7.9 Estimates

The following estimates for software effort are for a professional software engineer proficient in industry standard techniques, languages and tools. An allowance is made to gain familiarity with any proprietary software systems, in our case Gemini EPICS. If the software engineer selected is already competent in Gemini EPICS, this block of effort will not be required.

The work should be done by one individual, with the detailed design and implementation being done without interruption from other projects, to maximise efficiency. The longer this work can be delayed the less effort is likely to be required, since more code can be reused from existing projects.

Task		**Estimated Effort (weeks)**	**Comments**
1	System design participation	2	Part time
2	Gemini EPICS familiarisation		not required
3	TCS/Gpol interface definition	3	

4	Software design	2	
5	Linear slide control	1	
6	Waveplate rotation control	3	
7	Assembly control	1	
8	CAD/CAR/SIR interface	2	
9	Feedback to TCS of image shift	1	
10	Software User Manual	2	
11	Test procedures	2	
12	Integration and test	2	With proven mechanisms
13	Provision of data reduction recipes	?	Procedures and responsibilities need to be clarified
14	Liaison with Gemini regarding impact on other systems	2	
15	Set up of cpu,VME & Vxworks	1	
	Total	**24**	

8. ENGINEERING AND SCIENCE VERIFICATION TESTS

8.1 Introduction

The functional performance of Gpol will be tested, and the test extended to include a thermal environmental test. The operation of mechanisms, and alignment of optics will be tested at +/- 45 degrees orientation.

8.2 Engineering tests for Gpol

8.2.1 Checking of polarisation plates

The manufacturers make the waveplates to a set optical design and do not have the ability to check the plates over their full range of operation. Should the opportunity of a polarimitaty test with an infrared instrument arise, for example UIST, then advantage would be taken.

8.2.2 Mechanism reliability and repeatability

There are 6 mechanical mechanisms in the Gpol design: 3 wave plate blades for insertion into the telescope beam, and 3 waveplate carrier mechanisms for rotation. All must be tested to ensure that they reliably reach the state requested in software. Each of these tests must be carried out by visual inspection.

The waveplate carriers should have etched numbers to allow the polarisor identification, in addition to identification via software and sensor.

Reliability should be verified via a 'soak test' of several hours' duration, possibly overnight.

The position of the waveplates must be repeatable so that the displacement of the polarisor centre is less than +/- 0.5mm. This should be checked using an alignment telescope with a graduated crosswire. The polarisor wheel should be driven back & forth 20 times, then the position of the polarisor checked. It will not be necessary to have the polarisor in place; any target in the wheel will do.

Repeatability of rotation can be similarly checked to the required 0.2 degree.

8.2.3 Flexure tests

We intend to flexure test Gpol on the flexure rig at the ROE. Gpol can be mounted to an interface plate on the flexure rig which simulates its position in the ISS interface. With an alignment telescope and the target mounted in the central hole on the flexure rig any shifts of the polarisation plate due to flexure will be measured.

8.3 Acceptance tests

A half-day period of acceptance testing and training is included. It is assumed that this involves IGPO personnel. Realistically we believe that up to 3 days effort are required.

8.4 Status at the conclusion of the lab tests

At the conclusion of the lab tests identified above, the Gpol should have achieved the following:

1. Alignment of the optics to specification.
2. Reliable and repeatable deployment of the waveplate carriage and rotation of the wave plate carrier
3. Reliable operation of the status sensors

4. At the end of the laboratory-commissioning period, the following aspects of Gpol will remain untested:
5. Verification of the alignment of the Gpol to the telescope.

9. GPOL RELATED ICDS

Gpol Specific

1.12 Polarimetry Unit ICD

1.6/1.12 A&G System to Polarimetry Unit ICD

1.12/3.1 Polarimetry Unit to DHS ICD

1.1.11/1.12 Telescope Control System to Polarimetry Unit ICD

1.9/1.12 Science Instruments to Polarimetry Unit ICD

Software:

ICD-01a - The System Command Interface

ICD-01b - The Baseline Attribute/Value Interface

ICD-02 - System Status and Alarms Interface

ICD-04 - Logging Information

ICD-07a - ICS Subsystem Interfaces

ICD-12 - Interlock System

ICD-14 - Core Instrument Control System

ICD-16 - The Parameter Definition Format

General ICDs

ICD-G0013 - Gemini Environmental Requirements

ICD-G0014 - Gemini Observatory Optomechanical Coordinate System

ICD-G0015 - Gemini Facility Handling Equipment and Procedures

Science Instrument ICDs

1.1.1/1.9 Telescope Structure, Drives, and Brakes to Science Instruments ICD

1.1.11/1.9 Telescope Control to Science Instruments ICD

1.1.13/1.9 Interlock System to Science Instruments ICD

1.5.3/1.9 Instrument Support Structure to Science Instruments ICD

1.6/1.9 A&G System to Science Instruments ICD

1.7/1.9 Calibration Unit to Science Instruments ICD

1.9 Science Instruments ICD

1.9/2.7 Science Instruments to Facility Handling Equipment ICD

1.9/3.1 Science Instruments to Observatory Control ICD

1.9/3.2 Science Instruments to Data Handling ICD

1.9/3.6 Science Instruments to System Services ICD

1.9/3.7 Science Instruments to Thermal Enclosures ICD

1.9/3.21 Science Instruments to Environmental Monitoring System ICD

10. PROJECT PLAN AND SUMMARY

Gpol Project *8th May 00*

Summary

Project design work started in: February 1999

Major Milestones:

CoDR Meeting	1st October 99
PDR Meeting	15th January 00
CDR Meeting	18th May 00
Dtailing, manufacture & test	Jul 00/ Jan 01
Mauna Kea delivery	7 Feb 01
Cerro Pachon delivery	7 Feb 01

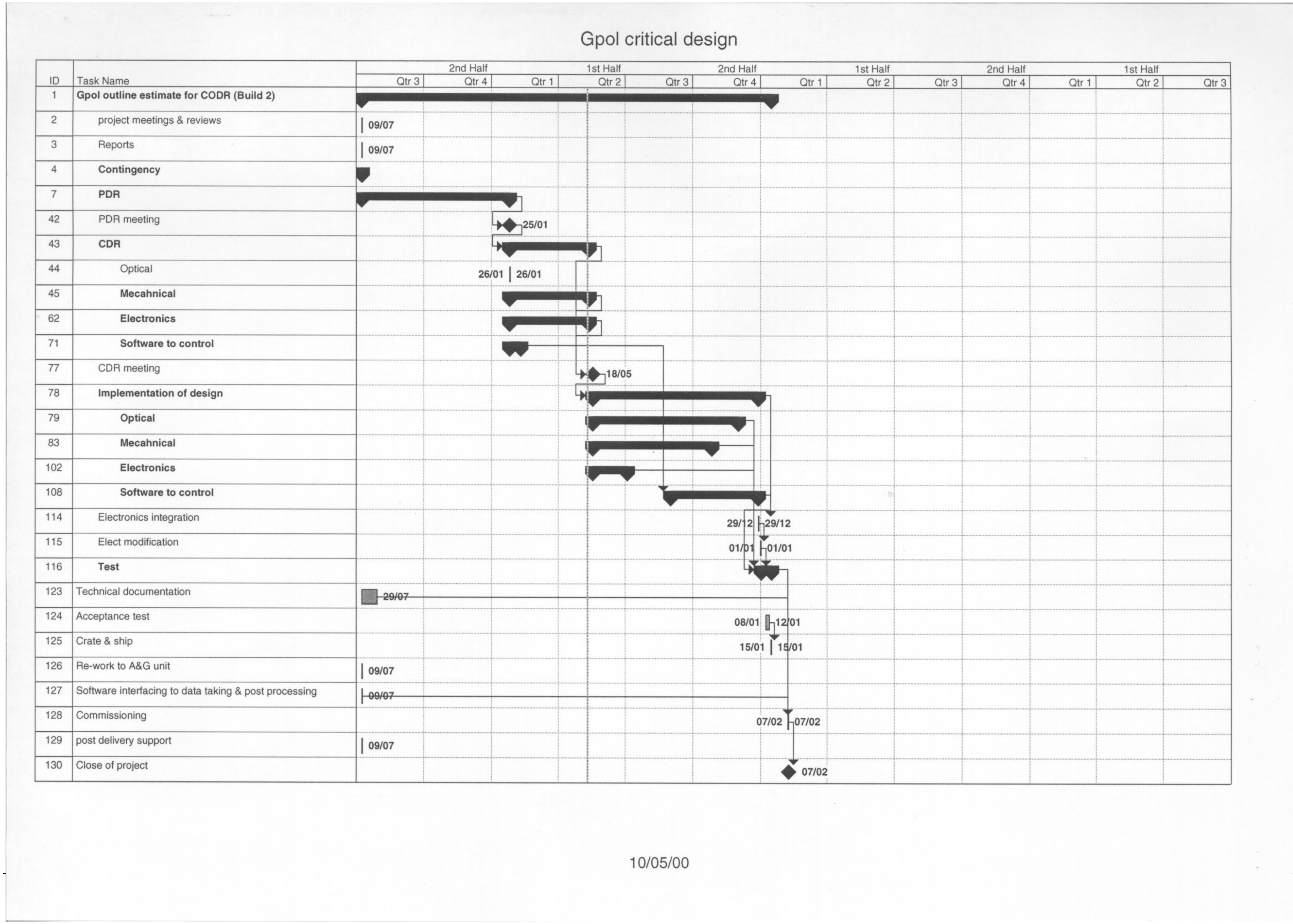
Resources:

		Yrs
Effort	1999/00	0.7
	2000/01	1.1
	2001/02	0.6
(assumes 208 days/year)		2.4

Note: 20% contingency 0.48 dsy not included,
ATC overhead 13% not included
(All inclusive **Total effort 3.3yrs)**

✓	Items cost of is for build and delivery of 2 Gpol instruments.	£123k
	(to which add 20% contingency)	£ 28k
✓	1set of 95mm waveplates + 2 calibrators + L band plate	£ 88k
✗	Re-work to A&G to accommodate Gpol not included	£0k
✗	Commissioning not included in estimate	£0k
✗	Post delivery support not included	£0k

Total £239k


Gpol critical design
ID
Task Name
2nd Half
1st Half
2nd Half
1st Half
2nd Half
1st Half
Qtr 3
Qtr 4
Qtr 1
Qtr 2
Qtr 3
Qtr 4
Qtr 1
Qtr 2
Qtr 3
Qtr 4
Qtr 1
Qtr 2
Qtr 3
1 Gpol outline estimate for CODR (Build 2)
2 project meetings & reviews
09/07
3 Reports
09/07
4 Contingency
7 PDR
42 PDR meeting
25/01
43 CDR
44 Optical
26/01
26/01
45 Mecahnical
62 Electronics
71 Software to control
77 CDR meeting
18/05
78 Implementation of design
79 Optical
83 Mecahnical
102 Electronics
108 Software to control
114 Electronics integration
29/12
29/12
115 Elect modification
01/01
01/01
116 Test
123 Technical documentation
29/07
124 Acceptance test
08/01
12/01
125 Crate & ship
15/01
15/01
126 Re-work to A&G unit
09/07
127 Software interfacing to data taking & post processing
09/07
128 Commissioning
07/02
07/02
129 post delivery support
09/07
130 Close of project
07/02
10/05/00

Gpol Items Estimate

ID	Task Name	Cost
1	**Gpol outline estimate for CODR (Build 2)**	**£238,400**
2	project meetings & reviews	£0
3	Reports	£0
4	**Contingency**	**£28,000**
7	CODR development	£0
8	CODR meeting	£0
9	**PDR**	**£0**
44	PDR meeting	£0
45	**CDR**	**£0**
79	CDR meeting	£0
80	**Implementation of design**	**£197,900**
81	**Optical**	**£87,500**
82	Calibration plates purchase	£6,000
83	Waveplate 1 purchase (2off)	£52,500
84	Waveplate 2 purchase (2off)	£0
85	Waveplate L&M purchase (2off)	£29,000
86	**Mecahnical**	**£91,400**
87	ICD documents	£0
88	Instrument frame	£10,000
89	DC motor drive in/out	£13,500
90	datum control	£2,800
91	interface panel	£2,800
92	wave plate carriage	£7,000
93	rotation mechanism design	£11,000
94	rotation datum control	£3,400
95	wind up cable design	£4,000
96	rotation mechanism drive	£15,000
97	electronics cabinet interface panel	£2,000
98	cabinet cable routing	£800
99	mounts for electronics	£4,000
100	DIN rail interface design	£5,600
101	housings for electronics	£4,500
102	Test rig manufacture	£5,000
103	Assembly	£0
104	Mech. Modification	£2,000
105	**Electronics**	**£17,000**

ID	Task Name	Cost
106	Manufacture cables	£4,500
107	DIN module manuf/purchase	£5,600
108	Wire instrument frame	£3,000
109	interface cabling	£1,500
110	connector panels	£2,400
111	**Software to control**	**£0**
112	system design	£0
113	code development	£0
114	fit with existing system	£0
115	test software	£0
116	technical documents	£0
117	Electronics integration	£0
118	Elect modification	£0
119	**Test**	**£2,500**
126	Technical documentation	£2,000
127	Acceptance test	£0
128	Crate & ship	£8,000
129	Re-work to A&G unit	£0
130	Software interfacing to data taking & post process	£0
131	Commissioning	£0
132	post delivery support	£0
133	Close of project	£0