TUnable LIquid Crystal Polarimeter

(TULIP)

for

MAST

Version 1.2

A proposal for MAST polarimeter
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Abstract

A Tunable Liquid Crystal Polarimeter (TULIP) for the upcoming MAST telescope is proposed. The design is based on tunable retarders called Liquid Crystal Variable Retarders. In the first phase instrument is designed for operation in the optical range (600 to 900 nm). The specifications are decided with the goal of achieving polarimetric sensitivity of $1x10^{-3}$ within few seconds. For higher sensitivity one can make longer integrations. The polarization analysis of the modulated beams can be done in single beam mode (large FOV, less sensitivity) as well as dual beam mode (reduced FOV, more sensitive). The FOV constraint in dual beam mode is due to single CCD camera in proposed MAST filtergraph (IforMast) and spectrograph (RES). However, future upgradation to two identical CCD cameras will allow sensitive polarimetry over a large FOV. The sensitivity in case of dual beam is larger as all the photons are utilized as compared to single beam mode where only 50% are used. Also, the seeing induced spurious signals are minimized in dual beam design. The accuracy of polarimeter is determined by quality of calibration. A dedicated unit with calibration optics is proposed for routine calibration leading to polarimetric accuracy of about $1x\ 10^{-3}$. The estimated budget for the proposed design is given together with scheme for execution of the project and time schedule.

1. Introduction

The proposed 50cm solar telescope is scheduled to be operational in 2009. The design of the telescope is described in detail elsewhere (MAST Document). The important features of the telescope are:

- (i) large field-of-view (6 arc-minutes), suitable for the study of sun on the spatial scales of typical solar active region,
- (ii) high optical performance (lambda/10 rms wavefront over entire FOV with diffraction limited resolution of 0.2 arc-sec),
- (iii) large photon flux to allow sensitive polarimetry and spectroscopy.
- (iv) thermally and mechanically stable design with state-of-the-art telescope-control systems.
- (v) Off-axis design with no obscuration and minimal instrumental polarization.

2. Science Goals

The large aperture of MAST telescope is suited to perform observational studies at a higher spatial resolution and utilize the large number of photons available to perform sensitive measurements.

A brief list of MAST science goals are as follows:

- (i) to study the structure and evolution of small scale magnetic features.
- (ii) to study the role of small scale magnetic features in energetic events like flares.
- (iii) structure of sunspot
- (iv) structure and evolution of polar magnetic fields
- (v) fine structure of prominences and filaments

These scientific goals require a large-aperture telescope equipped with adaptive optics. These goals also constrain the design of the polarization modulator- analyzer-detector system.

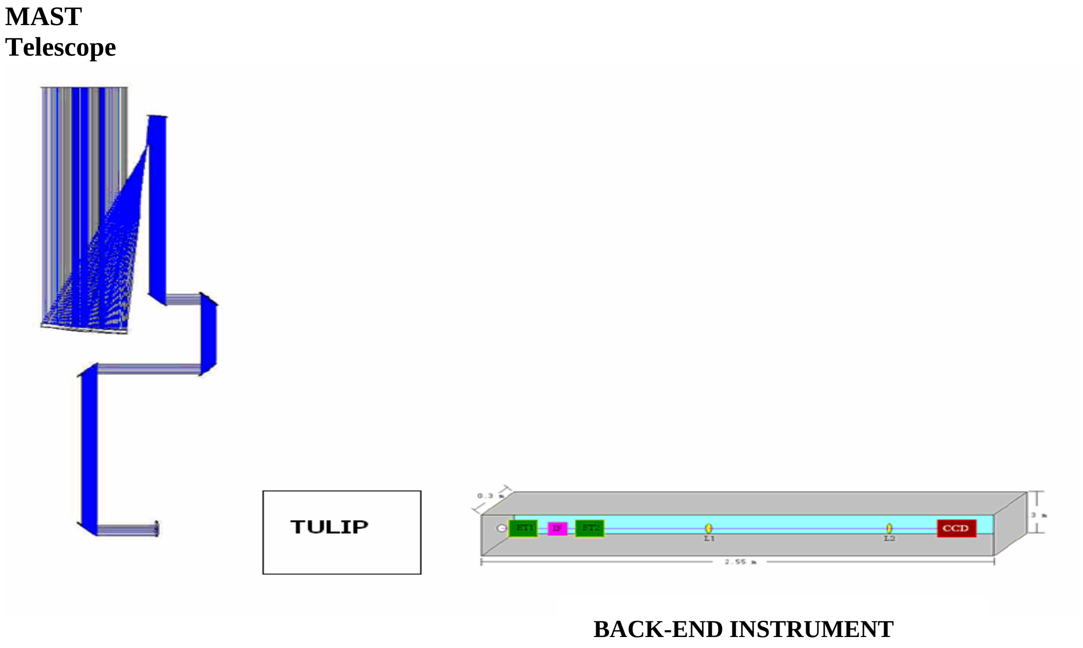
3. Polarimeter: Design Considerations

In order to study the magnetic structure and dynamics of the small-scale elements one needs a sensitive spectro-polarimeter. Since observations at higher angular and spectral resolution are severely limited by the number of photons available. Also to study the dynamics, good signal-to-noise ratio (SNR) should be achievable in relatively short timescales. Using Unno-Rachkovsky inversion technique one can distinguish weak fields (with typical errors in the inferred field strength of ±25 G and in the inclination of ±6° for fields as weak as 100 G), provided the filling fraction of such fields is not very much smaller than unity (Skumaich et al 1997). This requires good S/N ratio, typically > 1000. The large aperture of MAST will allow large photon flux to permit such studies. The flux budget for MAST telescope and the required exposure time to achieve SNR of 1000 is given in IforMast proposal document (Mathew, 2007). Also, the study of the solar magnetic structures at different heights of the solar atmosphere needs observations at different spectral lines. The design of MAST back-end instruments IforMAST and RES is optimized at two wavelengths 617.3 nm (photospheric line) and 854.2 nm (chromosphereic line). However, the instruments shall still operate at other wavelengths, that is, over the entire visible range with somewhat reduced efficiency. Thus the design of the polarimeter should be such that it works at diverse wavelengths (see Table 1.1).

The main components of typical polarimeter setup are (i) Polarization modulator and analyzer, which we call as the polarimeter unit, and (ii) calibration optics, or calibration unit. In the following sections the relevant parameters of these components crucial for the design are discussed and a design for all three components is proposed with estimated time and financial budget.

Table 1.1 Design Goals for TULIP

Polarimetric Sensitivity	~$1\text{x}10^{-3}$ of Ic (within few seconds)
Polarimetrc accuracy	< $1\text{x}10^{-3}$ of Ic
Wavelength Range	400 to 900 nm (tunable to any one wavelength at a time)



Schematic layout of TULIP location with respect to MASTtelescope

3.1 Polarization Modulator

Choice of Modulator:

This component modulates different states of polarization like linear and circular by introducing a known amount of phase retardation. The parameters of importance while choosing a modulator are as follows:

4. operating wavelength range,
5. modulation frequency,
6. response time,
7. transmission,
8. max. flux,
9. temperature response,
10. field-of-view response (acceptance angle),
11. retardation variation over aperture,
12. maximum aperture size available,
13. retardance accuracy.

The choice of modulator is crucial in the performance of a polarimeter.

There are two types of retarders that are commonly used in solar polarimeters: (a) fixed waveplates (made up of single or multiple birefringent materials like quartz or quartz-MgF2 etc.), (b) electro-optic crystals, which have variable birefringence which can be tuned. The examples are KD*P, nematic liquid crystals etc. First we shall discuss the fixed wave-plates. The modulation of polarized light using these fixed retarders is done by rotating the waveplate about the direction of beam propagation. Thus the synchronized detection of the modulated signal at the modulation frequency yields the information on the polarization state of light.

In the present TULIP design we avoid using these type of fixed retarders due to following reasons:

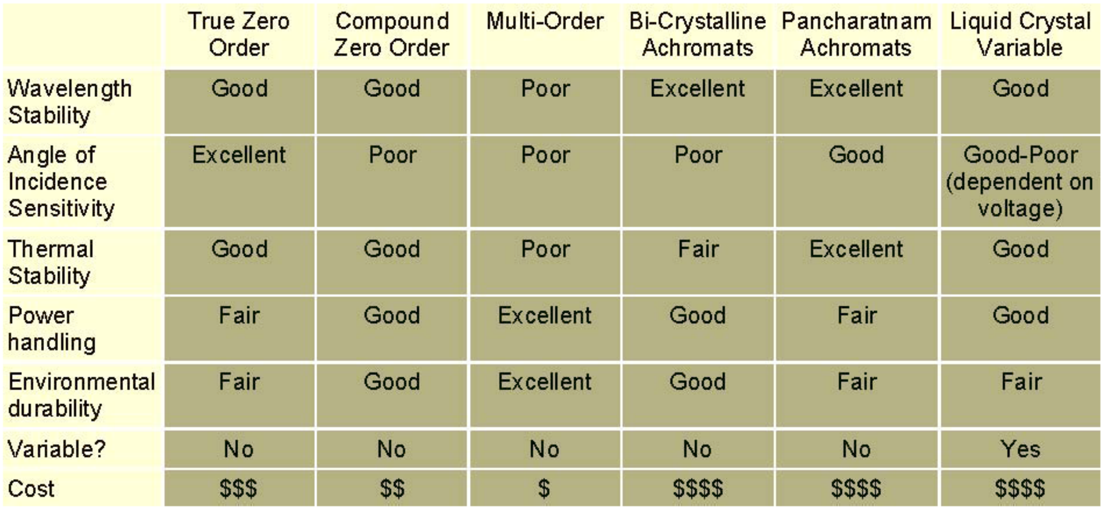
> (i) These retarders are usually designed for a given wavelength and work efficiently over a narrow range of wavelengths. Although, achromatic waveplates can be made out of bi-crystalline designs, they have associated problems of polarized interference fringes (Clarke, A. D. 2005) which hamper the imaging polarimetry.
> (ii) The rotating waveplate modulators have problems of beam wobble associated with them and require additional constraints on image stabilization system.
> (iii) The availability of large aperture achromatic retarders.
>
> (iv) The cost of servo-electronics and opto-mechanics for fast and accurate rotation of waveplates is large compared to the cost of voltage tunable retarders.

A design based on nematic liquid crystal variable retarders (LCVR) has some advantages, and this is proposed in the present design of polarimeter for MAST. The choice is made due to the following facts:

(i) Large operating wavelength range (UV, visible, IR options available)
(ii) Off-the-shelf availability of LCVRs, associated waveform drivers and software, hence less development time.
(iii) Voltage tunable, no mechanical motions and no beam wobble.
(iv) The variable retardance allows operation with good modulation efficiency over a large wavelength range.
(v) other optical properties comparable with other retarders (see Table 1.2).
(vi) proven design, already in use at TIP, LPSP instruments at La Palma, IMAX onboard SUNRISE.

A detailed account of the properties of LCVRs is given in Appendix-A.

Table 1.2 Comparison of various retarders



	True Zero Order	Compound Zero Order	Multi-Order	Bi-Crystalline Achromats	Pancharatnam Achromats	Liquid Crystal Variable
Wavelength Stability	Good	Good	Poor	Excellent	Excellent	Good
Angle of Incidence Sensitivity	Excellent	Poor	Poor	Poor	Good	Good-Poor (dependent on voltage)
Thermal Stability	Good	Good	Poor	Fair	Excellent	Good
Power handling	Fair	Good	Excellent	Good	Fair	Good
Environmental durability	Fair	Good	Excellent	Good	Fair	Fair
Variable?	No	No	No	No	No	Yes
Cost	$$$	$$	$	$$$$	$$$$	$$$$

(Source= Meadowlark Optics, USA)

The Modulation scheme:

The setup of the Polarimeter Box (PB) is schematically shown in figure 1 below. The light entering the PB first crosses an interference filter, which is kept to reduce the light level outside the observed bandpass falling on the optical elements. This will be followed by calibration optics. The calibration optics will consist of a linear polarizer and an achromatic zero-order quarter wave retarder. These two units shall be mounted on rotary stages and can be moved in and out of the beam together or individually by a linear translation stage. Following this there are two electro-optic modulators

(LCVR 1 and LCVR 2). The fast axis of the LCVR1 is rotated by 22.5 degrees and for LCVR2 by 45 degrees with respect to the reference axis.

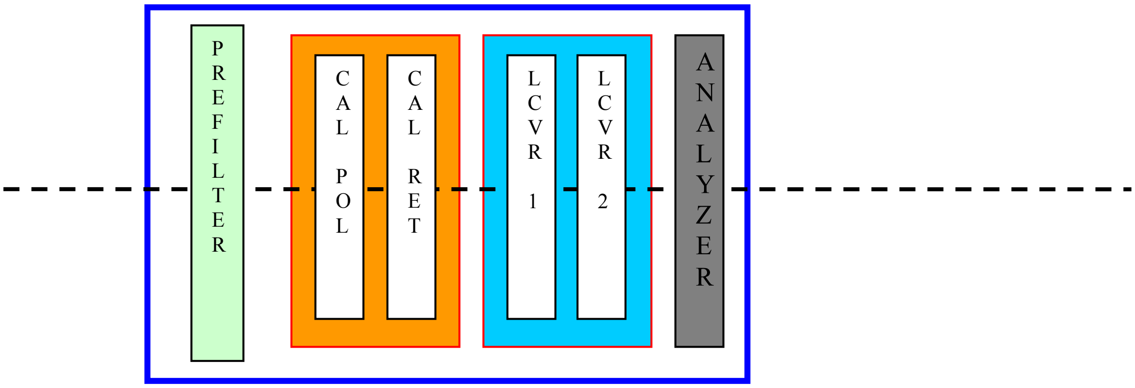


Figure 1. *Schematic of Polarimeter Box (PB).*

The retardation of electro-optic modulator are varied to 0, λ/4 and λ/2 by applying voltages. This transforms the various states of polarization into linear polarization passing through analyzer. A description of modulation scheme and the efficiency is given in next section. The sequence of modulation states to measure orthogonal states of polarization is given in figure 2 below. This scheme is adopted from Collados, M. (2002).

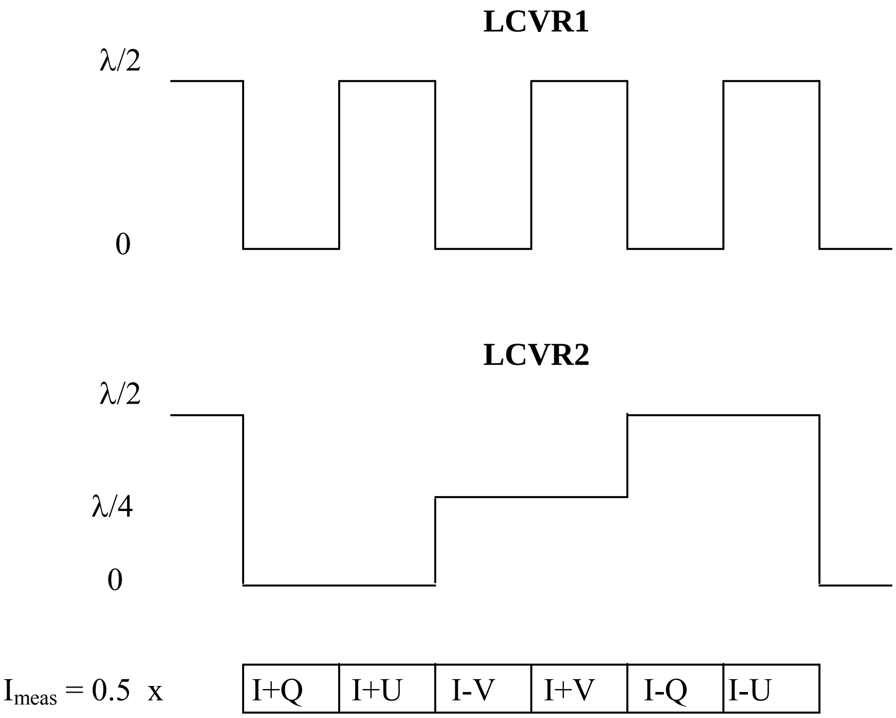


Figure 2. Proposed modulation scheme using the two LCVRs

Modulation Efficiency:

In general there are six intensities that are measured given by I^i

Modulation Matrix of the proposed modulation scheme is given by

$$M = \begin{pmatrix} 1 & 1 & 0 & 0 \\ 1 & -1 & 0 & 0 \\ 1 & 0 & 1 & 0 \\ 1 & 0 & -1 & 0 \\ 1 & 0 & 0 & 1 \\ 1 & 0 & 0 & -1 \end{pmatrix}$$

Stokes parameters are then obtained from the demodulation matrix $D=M^{-1}$ by

$$S_j = \Sigma_{i=1 \text{ to } 6}\ d_{ji}\, I^i$$

There are four parameters to be determined and number of measurements is larger than four, that is the system is overdetermined and several solutions can be found for D. We shall select solution

$$D = \begin{pmatrix} 1/6 & 1/6 & 1/6 & 1/6 & 1/6 & 1/6 \\ 1/2 & -1/2 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1/2 & -1/2 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1/2 & -1/2 \end{pmatrix}$$

The **efficiency** of the polarimeter is defined by a four-element vector E whose components are

$$E_j = (n\ \Sigma_{i=1 \text{ to } n}\ dji^2\ )^{-1/2}$$

It characterizes the ability of the modulation scheme to recover the input Stokes vector. Using the elements of D we obtain efficiency of $E= [1,1/\surd 3,\ 1/\surd 3,\ 1/\surd 3)$ which is that with the largest efficiency for Stokes I. Other solutions of D lead to same efficiencies for Stokes QUV but smaller ones for Stokes I (Collados, M 2002 SPIE). The efficiency for the analysis of the polarizations (so called total polarization efficiency) calculated by $\sqrt{E_Q^2 + E_U^2 + E_V^2}$ which amounts to 1.0 that is maximum for this scheme.

The Analyser:

The analyzer has two options (i) a single beam mode and (ii) dual beam mode. For single beam mode a linear polarizer is inserted after LCVR2. This analyzer is mounted on manual rotation stage for adjustments. In dual beam mode the linear polarizer after LCVR2 is removed from the beam and the dual beam analyzer (polarizing beam splitter cube or Savart Plate) is placed just in front of CCD camera of either Filtergraph (IforMast) or spectrograph (RES). The dual beam analyzer is placed just in front of CCD camera because it minimizes the distortions due to differential aberrations, transmission and seeing effects inside the instrument.

Calibration strategy :

The input Stokes vector Sin=[IQUV] and the measured Stokes vector Smeas=[I`,Q`,U`,V`] are related by the relation Smeas= [X]. [T]. Sin. Where T is the telescope Mueller matrix and X is the polarimeter Response matrix. In order to deduce Sin from Smeas we need to know T and X matrices accurately. The determination of these matrices requires a calibration unit with polarizing optics of known characteristics. Using the CU one can then generate known Stokes vectors and by measuring them with the polarimeter one can determine the response matrix of the polarimeter. Ideally one would want the CU to be placed before the entrance aperture of the telescope. Due to unavailability of polarizing optics of large apertures this is often not feasible. However, mosaic of polarizers and retarders to calibrate large aperture optics has been used to calibrate German VTT Coelostat mirror. Another method for calibration of large aperture optics is by beam expansion technique and small aperture method suggested by Socas Navaro (2007).

Finally, as T is time dependent it is not practical to measure the T matrix everytime. So, we need to construct a theoretical model for T matrix and use it for offline corrections. The realistic modeling of T matrix needs to be done by considering measured refractive index of the optical coatings (Sankarasubramanian et al 2001). The measurement of T frequently (using a mosaic of calibration optics or by method suggested by Socas Navarro (2007)) will help in checking theoretical model of the T.

Placing the polarimeter calibration unit after the prime focus (final output from tip-tilt and AO system) decouples the calibration of telescope Mueller matrix from that of polarimeter package.

THE CALIBRATION SCHEME:

The calibration scheme that we propose to adopt is the POLIS scheme (Beck et al 2005). In this scheme the calibration unit CU consists of a polarizer and a zero order quarter wave retarder. These optics are mounted on a motorized stage and are moved in the beam together. The retarder and the polarizer can be rotated independently around the optic axis.

The CU is used to generate different known polarization states to retrieve the response matrix of the instrument X. High precision of the calibration requires good knowledge of the polarizing properties of the elements of the calibration unit like retardance and fast axis of retarder and the orientation of the transmission axis of the polarizer.

The orientation of the polarizer axis and the retarder axis should first be determined in the laboratory using standard techniques with best possible accuracies. Also the retardance of the waveplate for wavelengths of interest must be determined in the laboratory as accurately as possible. The description of procedures for doing this calibration in laboratory will be given in separate technical reports generated during laboratory characterization of calibration optics. With these accuracies one can start procedure for finding polarimeter response matrix as well as constraining retardance value of CU retarder simultaneously as described in POLIS paper by Beck et al 2005.

For sake of completeness I shall give a brief account of the method followed.

Derivation of Polarimeter Response Function in MAST polarimeter for single beam mode:

The relation between measured Stokes vector S_{out} and true solar polarization state before entering the telescope S_{true} can be related as

$$S_{out} = X. T. S_{true}$$

Where X is polarimeter response matrix and T is the effect of telescope (MAST primary and secondary mirrors) on Stokes vector. The calibration unit CU, generates different known polarization states to retrieve X. Good knowledge of polarizing properties of elements of CU leads to good precision of polarimetric calibration. Since the MAST telescope does not produce serious instrumental polarization as the reflections take place at near normal incidence (even though it is an off-axis design) . The use of disk-center quiet sun continuum intensity as a unpolarized light source is valid. Thus the input intensity level after CU polarizer (Stokes-I) during calibration, will not vary much. The estimated time for carrying out calibration run is less than 2 to 3 minutes. Only intensity variations will be due to sky transparency variations, which is negligible in 2-3 minutes.

The general equation between solar input $[I_0\ 0\ 0\ 0]^T$ and measured output during calibration is given by

$$S_{out} = X.\cdot M_r(\theta_r) \cdot M_p(\theta_p) \cdot T \cdot [I_0\ 0\ 0\ 0]^T$$
$$= I_0 \cdot X.\cdot M_r(\theta_r) \cdot M_p(\theta_p) \cdot [1\ \ T_{2,1}\ \ T_{3,1}\ \ T_{4,1}]^T \qquad \ldots\ldots.. \quad \text{Eq (1)}$$

Where θ_p and θ_r are defined as the angles between reference plane (in MAST the plane in which the M1 and M2 lie) and the transmission axis of the polarizer and fast axis of the retarder. $M_i(\theta_i)$ are th Mueller matrices of the rotated optical elements. The total transmission of the telescope $T_{1,1}$ has been set to 1. If the linear polarizer is kept fixed e.g., at θ_p=0° the equation 1. reduces to

$$S_{out} = I_0 \cdot ½ (1 + T_{2,1}) \cdot X \cdot M_r(\theta_r) \cdot [1\ 1\ 0\ 0]^T$$

The variation of $T_{2,1}$ during the time needed for calibration is expected to be negligible. Keeping the polarizer fixed isolates the polarimeter calibration from telescope polarization as a fixed polarization state with almost constant light level is generated after the polarizer.

Standard procedure for calibration will then be to measure Stokes vector for fixed polarizer at θ_p=0°, and various orientations of the retarder varying from θ_r=0° to 180°, in steps of say 5°. The calibration input then is

$$S_{inC} = M_r\,(0°, 5°, 10°, 15°\ldots180°) \cdot [1\ 1\ 0\ 0]^T$$

To derive the observed Stokes vector S_{outC} the individual images are first corrected for dark current and flat field. Then the polarimeter response function X is derived from measurements after arranging the Stokes vectors into 37 x 4 matrices by a solution of the linear problem

$$S_{outC} = S_{inC} \cdot X^T$$

Writing as

$$Y = A \cdot X^T$$

$$A^T \cdot Y = A^T \cdot A \cdot X^T = D \cdot X^T$$

With $X^T = D^{-1} \cdot A^T \cdot Y$

X is the 4 x 4 matrix of polarimeter response to polarized input, the individual columns give response to a pure input state I, Q, U or V. The error is estimated from $B = D^{-1} \cdot A^T$ in the following way:

$$\sigma^2_{Xi} = \Sigma_j B_{ij}^2\, \sigma^2_{Yj} = \langle\sigma\rangle^2\, \Sigma_j B_{ij}^2$$

where $\langle\sigma\rangle^2 = 1/N\ \Sigma_{cal} (Y - A \cdot X^T)^2$

The errors of the single measurements σ_{Yj} are approximated by the total deviation of the fit $\langle\sigma\rangle$.

In addition to 16 elements of X other free parameters that are fitted are

1. linear dichroism, b of the retarder (Skumanich et al 1997)
2. an offset angle θ_{off} between CU polarizer and retarder to account for misalignment.

The free parameters are computed by minimizing the χ^2 value

$$\chi^2 (b, \theta_{off}) = \Sigma_{i=0, ..3} (S_{outC} - S_{inC}(b, \theta_{off}) X^T)_i^2$$

These two free parameters will only change S_{inC}.

The retarder of CU is modeled as

$$Mr = \begin{pmatrix} 1 & b/2 & 0 & 0 \\ b/2 & 1 & 0 & 0 \\ 0 & 0 & \alpha.C\delta & -\alpha.S\delta \\ 0 & 0 & \alpha.S\delta & \alpha.C\delta \end{pmatrix}$$

with the retardance of the waveplate δ, the linear dichroism b, and $\alpha = \sqrt{1 - b^2/4}$. α is close to unity even for large b.

Further, the accuracy of polarization calibration can be further improved if the retardance of CU retarder is known to accuracy better than 1 degree. Beck et al (2005) show that using indirect method one can determine retardance to 0.1 degree accuracy. The idea is that the polarimeter response matrix, X, is independent of the input known polarization states used for calibration purpose. Thus repeating measurements of X by the method described above, and changing CU polarizer angle by 10 degrees each time we can constrain the retardance to about 0.1 degrees accuracy. This leads to polarimetric accuracy of $\sim 1.4 \times 10^{-3}$ of continuum intensity. It is to be noted that this is the error in determination of the relative crosstalk, not the absolute accuracy of the measurements. The absolute accuracy will depend on other factors like accuracy in determination of M1, M2 Mueller matrix (Telescope Mueller matrix) and seeing induced effects.

TIME ESTIMATE

The time schedule of the polarimeter development is as follows:

Procurement of optomechanical hardware : ***6-8 months***
(Estimated Time for 1-4 below)

1. Preparing list of items to be procured
2. Making specifications and placing indents with vendors list
3. Placing orders
4. receipt of items

Mechanics of various components : ***3 months***

Software of various components : ***2 months***

Laboratory testing of Modulator / Analyser ***:*** ***1 months***

Laboratory testing of Calibration unit ***:*** ***1 months***

Integration of Polarimeter/Calibrator with Filtergraph: ***2 months***

Total Estimated time : 15 to 17 Months

MONEY ESTIMATE

The list of opto-mechanical and electronic components required for TULIP are given below in Table 1.2 along with estimated price.

Component	Cost
MODULATION UNIT Three Liquid Crystal Variable Retarders in visible wavelength range (400 to 700 nm) (custom made for 65 mm aperture) Meadowlark optics	USD 15,000
Three Liquid Crystal Variable Retarders in Infra-red wavelength range (650 to 950 nm) (custom made for 65 mm aperture) Meadowlark optics	USD 15,000
Three Quad Cell Digital Interface with Temperture sensing and control option .	USD 7000
CALIBRATION UNIT	
5 units of Custom made/off the shelf Glass Polarizer (Polymer based) > 60 mm aperture	USD 4000
5 Units of Custom made / off the shelf Quarter wave retarder (polymer based) > 60 mm aperture	USD 4000
MECHANICAL STAGES & CONTROL Two Newport Translation stages (Newport IMS300V) **USD 16,654 @ 8,327** Two Newport Rotary Stages (Newport RV240CC) **USD 16,654 @ 8,327** TCPIP based Control interface (Newport XPS-C4) **USD 6,259** Four Manual rotation/linear translation stages (with micrometer) for laboratory tests Posts and post holders Base plates/mounting plates Pin holes/ adjustable slits/ lenses / light sources/ collimators/ Spatial filters/ heat filters / optical quality glass windows/	USD 40,000 USD 4000
ANAYSER	
Single beam analyzer :: 70 mm aperture good quality sheet polarizer Dual beam analyzer :: Polarizing beam splitting cube/ Savart plate (aperture = twice the final image size of FOV on CCD chip).	USD 500 USD 10000
CONTROL SOFTWARE Outsourcing to Labview developers of Polarimeter Calibration/ Modulation/synchronous Camera Readout software	USD 4000
Fabrication of polarimeter box Outsourcing of Polarimeter Box fabrication	USD 2000
TOTAL	USD 105,500 (Rs 44 lakhs)

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APPENDIX - A

Properties of Nematic Liquid Crystal Variable Retarders

Typical nematic Liquid Crystal Variable Retarders (LCVRs) are constructed using optically flat fused silica windows coated with transparent conductive indium tin oxide (ITO). A thin dielectric layer is applied over the ITO and gently rubbed, creating parallel micro-grooves for liquid crystal molecular alignment. Two windows are then carefully aligned and spaced a few microns apart. The cavity is filled with birefringent nematic liquid crystal material. Electrical contacts are attached and the device is environmentally sealed. Anisotropic nematic liquid crystal molecules form uniaxial birefringent layers in the liquid crystal cell. An essential feature of nematic material is that, on average, molecules are aligned with their long axes parallel, but with their centers randomly distributed, as shown in Figure 1. With no voltage applied, the liquid crystal molecules lie parallel to the glass substrates and maximum retardation is achieved.

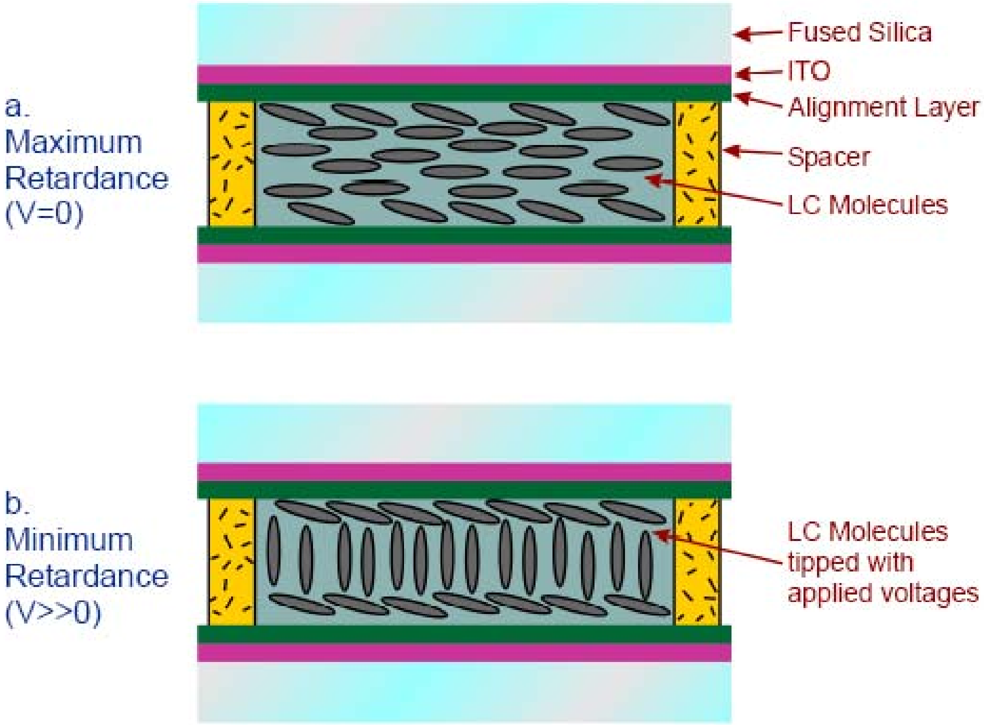
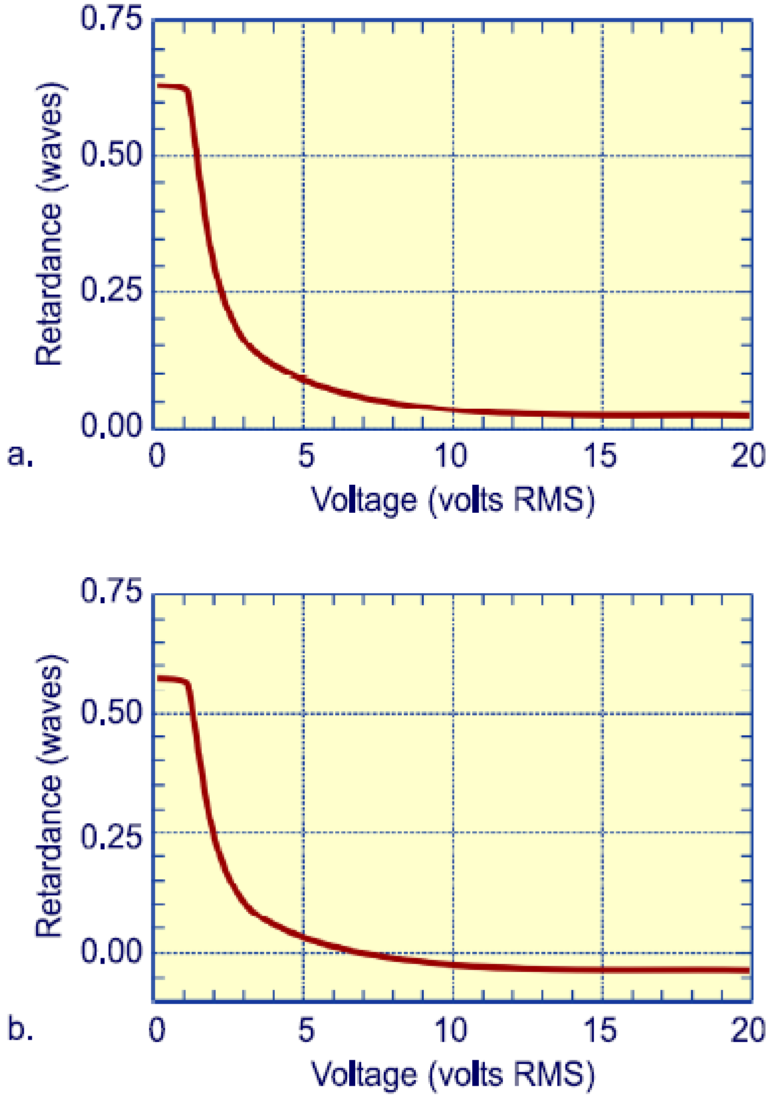


Figure 1 Liquid Crystal Variable Retarder construction showing molecular alignment (a) without and (b) with applied voltage

When voltage is applied, liquid crystal molecules begin to tip perpendicular to the fused silica windows. As voltage increases, molecules tip further causing a reduction in the effective birefringence and hence, retardance. Molecules at the surface, however, are unable to rotate freely because they are pinned at the alignment layer. This surface pinning causes a residual retardance of ~30 nm even at voltage ~ 20 volts. However, zero or any fixed retardance can be achieved with a subtractive fixed polymer retarder, called a compensator, attached to the liquid crystal cell. Negative retardance values are sometimes preferred for example, when converting between right- and left-circularly polarized states. Figure 2 illustrates retardance as a function of voltage for a typical LCVR with and without an attached compensator.



(Source= Meadowlark Optics, USA)

Fig.2 Liquid Crystal Variable Retarder performance versus applied voltage at 632.8 nm, 21° C. (a) without compensator, and (b) with compensator

As with any birefringent material, retardance is dependent upon thickness and birefringence. Liquid crystal material birefringence depends on operating wavelength, drive voltage, and temperature. The overall retardance of a liquid crystal cell decreases with increasing temperature (approximately -0.4% per °C).

Nematic LCVR response time

LCVR response time depends on several parameters, including layer thickness, viscosity, temperature, variations in drive voltage, and surface treatment. Liquid crystal response time is proportional to the square of the layer thickness and therefore, the square of the maximum cell retardance. Response time also depends upon direction of the retardance change. Nematic molecules can be forced into a tilted orientation faster than the intermolecular forces (from the alignment layers) can realign the molecular directions back to the zero-voltage state. Typical response time for a standard visible LCVR is shown in Figure 3. It takes about 5 ms to switch from one-half to zero waves (low to high voltage) and about 20 ms to switch from zero to one-half wave (high to low voltage). Another technique involves the Transient Nematic Effect (TNE) to improve response times. With this drive method, a high voltage spike is applied to accelerate the molecular alignment parallel to the applied field. Voltage is then reduced to achieve the desired retardance. When switching from low to high retardance, all voltage is momentarily removed allowing the liquid crystal molecules to undergo natural relaxation. Response time achieved with the transient nematic effect is also shown in Figure 3. Liquid crystal devices should be electrically driven with an AC waveform with no DC components to prevent ionic buildup which can damage the liquid crystal layer.

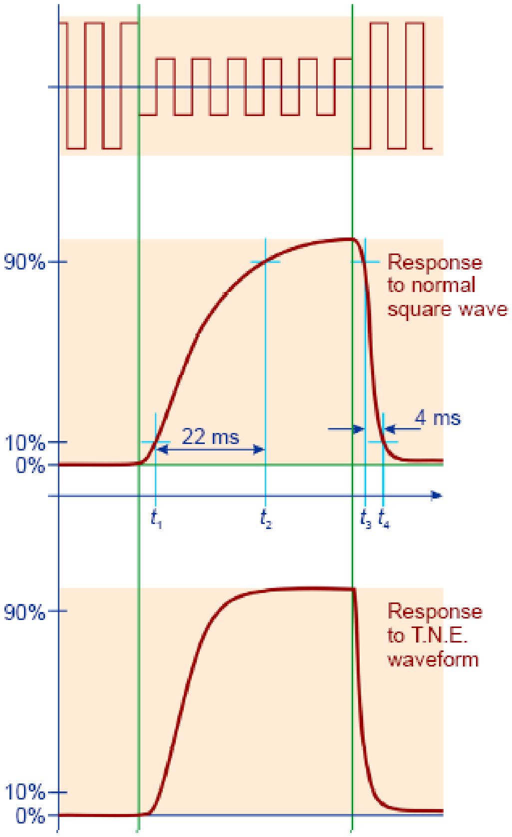


Fig 3. Temporal response of LC Variable Retarder

Comments by Dr. K.Sankarasubramanian

I could go through the proposal and well written covering most of the aspects of the polarimeter. Sorry for the delay but I hope these suggestions will be of some help. In keeping the view of moderate seeing conditions at USO and the non-availability of high-order AO system (atleast during the initial period of MAST), I have the following suggestions.

(i) Go for the balanced modulation scheme where all the Stokes parameters are weighted equally in all the measurements. This will allow you to reduce the number of measurements to four and also reduce the seeing induced errors in your Stokes parameters. There is a paper by Sanchez on the optimization of the polarization modulation and also a very nice book by del Toro Iniesta on the Spectro-polarimetry. This does not deviate much from the design point of view, with the same LCVRs you can achieve this but with some funny voltages and angles will be involved in it.

(ii) If there is a provision and place to put the calibration unit after the prime focus, then that will be the best choice. This is not a must for the accuracy intended to achieve, but I see observers wanting to go better atleast an order (look at the potential of doing a Hanle-Zeeman transition studies which may be interesting during the formation of sunspots) once they realise the potential of the instrument. The calibration closer to the image plane will also work, as is done with ASP or DLSP or at Kodaikanal now. Make sure that you get a uniform and good optical quality calibration as this may be placed close to the image plane and also will limit your final accuracies.

(iii) Please do look for a fast camera and do the summing of several images to achieve the desired SNR (a typical speed of few tens of Hz will be required). This will reduce the seeing induced systematics as well as produce a true average sum of the instrumental effects (as the instrumental polarization is going to be time dependent).

(iv) You must place an UV cut of filter (like Hoya-420) in order to avoid any UV damage to the LCVRs. This ofcourse will limit the wavelegth in the blue region.

About the analyser part...

If it is going to be a single beam system, even with few 10ths of frames per second, read-out getting an accuracy better than 1% is very tricky. So, it will be very difficult to achieve 0.1% (may be under very good seeing conditions only).

What I said in my earlier email is for dual-beam mode? Now, looking at the placement of the beam-splitter, which has to be closer to the CCD or need to have your spectrograph/IforMast able to take in two beams. If they can take two beam into it, then you donot have many issues. In case of you putting the beam-splitter infront of CCD, then you must look into the following:

(1) Effect of partially analysed beam getting into the IforMast, especially with Lithium Niobate which is sensitive to polarization and how that changes your polarization while tuning. You may be able to simulate it, atleast theoretically, and convince yourself that the effect is atleast less than 10% in the intensity of the two beams (if it is going to be more than that then you will end up with one beam brighter than the other and hence SNR difference and all sorts of issues).

(2) For spectrograph, then you must go for less no. of lines per mm grating and so the polarization sensitivity of the grating is minimized.

(3) If you find that you are not able to get the best use of the system by keeping the beam-splitter close to the CCD, then you can try to add a circular analyser (or a 2/3waveplate as David Elmore always likes this) after the LCVRs and it will reduce the instrumental effects for IforMast and Spectrograph as most of the system likes circularly polarized light. Again, you need to do a full theoretical study to understand the effects.

Given that sending two beam into the system complicates both IforMast and Spectrograph (in terms of sizes and FOV), first look in to the details of putting it closer to the CCD.

As an observer, I will not be very keen on single-beam system due to several limitations and especially for spectrograph based system when you already loosing so much of light throwing another 50% is not a good idea.

Hope this helps. If you need any help in simulating (either experimentally or theoretically), donot hesitate to contact me. I can help you wherever I can. I guess already with your experience, you must be able to simulate most of the system performance.

Liquid Crystal Variable Retarder (LCVR), with compensator 3 No.

Specifications:

Retarder Material : Nematic liquid crystal
Compensator Material : Birefringent Polymer
Substrate Material : Optical-quality synthetic fused silica
Custom Wavelength Range : 400 – 700 nm
Retardance Range : 0 to $3\lambda/4$ at 700 nm
Transmitted Wavefront Distortion : $\leq \lambda/4$ (at 632.8 nm)
Surface Quality : 40 – 20 scratch and dig
Beam Deviation : $\leq$ 2 arc min
Outside Diameter : 80 mm, nominal
Clear Aperture : Central 65 mm diameter
Operating temperature range : 10 to 50 deg C
Temperature Sensing and Control : within +/- 1 deg C of operating temperature set point
Antireflection coating : R $\leq$ 0.5% , at normal incidence over 400 – 700 nm

Liquid Crystal Variable Retarder (LCVR), with compensator 3 No.

Specifications:

Retarder Material : Nematic liquid crystal
Compensator Material : Birefringent Polymer
Substrate Material : Optical-quality synthetic fused silica
Custom Wavelength Range : 650 – 950 nm
Retardance Range : 0 to $3\lambda/4$ at 950 nm
Transmitted Wavefront Distortion : $\leq \lambda/4$ (at 632.8 nm)
Surface Quality : 40 – 20 scratch and dig
Beam Deviation : $\leq$ 2 arc min
Outside Diameter : 80 mm, nominal
Clear Aperture : Central 65 mm diameter
Operating temperature range : 10 to 50 deg C
Temperature Sensing and Control : within +/- 1 deg C of operating temperature set point
Antireflection coating : R $\leq$ 0.5% , at normal incidence over 650 – 950 nm

Digital Interface for controlling upto four LCVRs 2 No.

Specifications:

Fundamental Drive Waveform : 2 kHz ac square wave
Number of output channels : 04, four
Modulation Amplitude : 0 – 10 V rms

Modulation Resolution : 1 mV
DC Offset : < 5 mV
PC Controller Interface : USB or RS232
LC Cell to Controller : SMA to SMB connectors 2 meter cable length
Power Requirements : 100-240 Vac, 47-63 Hz, 500 mA
Modulation Waveforms : external modulation input (0-5 V) sinusoidal, triangle Square, sawtooth, transient nematic effect

Temperature Control : Active heating/passive cooling to within ± 1° C of nominal set point for controlling **upto four (04) LCVRs simultaneously (extra controllers may be included)**

Sync Output : TTL, 1 μs pulse, user specified phase

To be supplied with calibration certificate, documents,operating manuals, maintenance guides, cables & connectors, power supply, SDK libraries, drivers for Windows Vista/XP/2000/NT and Red Hat Linux in C, C++, Labview, Visual Basic, ActiveX drivers etc. with example, sample programs.

Liquid Crystal Variable Retarder (LCVR), with compensator

Compliance Sheet

Specification Compliance(Yes/No)

Retarder Material	: Nematic liquid crystal	
Compensator Material	: Birefringent Polymer	
Substrate Material	: Optical-quality synthetic fused silica	
Custom Wavelength Range	: 400 – 700 nm	
Retardance Range	: 0 to $3\lambda/4$ at 700 nm	
Transmitted Wavefront Distortion	: $\leq \lambda/4$ (at 632.8 nm)	
Surface Quality	: 40 – 20 scratch and dig	
Beam Deviation	: $\leq$ 2 arc min	
Outside Diameter	: 80 mm, nominal	
Clear Aperture	: Central 65 mm diameter	
Operating temperature range	: 10 to 50 deg C	
Temperature Sensing and Control	: within +/- 1 deg C of operating temperature set point	
Antireflection coating	: R $\leq$ 0.5% , at normal incidence over 400 – 700 nm	

Liquid Crystal Variable Retarder (LCVR), with compensator

Compliance Sheet

Specification Compliance(Yes/No)

Retarder Material	: Nematic liquid crystal	
Compensator Material	: Birefringent Polymer	
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Antireflection coating	: R $\leq$ 0.5% , at normal incidence over 400 – 700 nm	

Digital Interface for controlling upto four LCVRs

Compliance Sheet

Specifications **Compliance (Yes/No)**

Fundamental Drive Waveform	: 2 kHz ac square wave	
Number of output channels	: 04, four	
Modulation Amplitude	: 0 – 10 V rms	
Modulation Resolution	: 1 mV	
DC Offset	: < 5 mV	
PC Controller Interface	: USB or RS232	
LC Cell to Controller	: SMA to SMB connectors 2 meter cable length	
Power Requirements	: 100-240 Vac, 47-63 Hz, 500 mA	
Modulation Waveforms :	external modulation input (0-5 V) sinusoidal, triangle, Square, sawtooth, transient nematic effect	
Temperature Control	: Active heating/passive cooling to within ± 1° C of nominal set point for controlling **upto four (04) LCVRs simultaneously (extra controllers may be included)**	
Sync Output	: TTL, 1 μs pulse, user specified phase	

1. Narrow Band Interference filter :

Specifications:

CWL : 617.3 nm
FWHM : 0.5 nm +/- 0.05
Tmax : > 40 %
Width at 1% of Tmax : 1.5 nm +/-0.1 nm
size : 50 mm diameter
thickness : < 6 mm
angle of incidence : 0 deg
operating temp : 45 deg C
polarization : random
Surface quality : 80-50 (Per MIL-O-13830)
Out-of-band blocking **:** 1 x 10-4 from X-ray to FIR

2. Narrow Band Interference filter :

Specifications:

CWL : 854.2 nm
FWHM : 0.5 nm +/- 0.05
Tmax : > 40 %
Width at 1% of Tmax : 1.5 nm +/-0.1 nm
size : 50 mm diameter
thickness : < 6 mm
angle of incidence : 0 deg
operating temp : 45 deg C
polarization : random
Surface quality : 80-50 (Per MIL-O-13830)
Out-of-band blocking **:** 1 x 10-4 from X-ray to FIR

1. Motorized Linear Translation Stage 3 No.s

Specifications:

Load Capacity (Vertical) : 5 kg
Travel : 100 mm
Resolution : 5 micrometer
Accuracy : 1 micrometer
Speed : ~ 10 mm/sec
Weight : < 2.5 kg
Limit switches : on both ends
Homing switch : on one end
Homing accuracy : 1 micrometer
Construction : Aluminum
Servo Control, shaft Encoders : Required

Manual adjustment via knob required

2. Motorized (360 deg. Continuous) Rotary Stage 3 No.s

Specifications:

Resolution : <1 arc-second
Rotation : 360 degrees
Load capacity : 50 kg
Weight : < 1.5 Kg
Drive Mechanism : worm drive
Limit Switches : Reference Signal Every 360°
Wobble : 0.5 arcmin
Eccentricity : 10 µm
Torque : 1Nm
Clear aperture : 2 inch diameter
Construction : Aluminum
Rotation speed : ~ 10 deg per sec
Servo Control, shaft encoders : Required

Manual adjustment via knob required

3. Multi- Axis motion control system 2 No.s

Specifications:

A Multi-axis motion controller system fully compatible with the rotary and linear translation stages mentioned above. If more than one options are available please quote separately all otions.

To be supplied with full set of connection cables, power supplies, rack cabinet adapters, mounting kit, manuals, maintenance guides etc.

Software: Software libraries in C, C++, ActiveX DLLs for development on Visual Studio, Drivers for Labview, Linux drivers support, sample programs
Quote separately for third party solutions or custom software development options.

NOTE:

Quote separately for extra long cables (20 metre length, with possibility of custom fabrication) between controller and rotary and/or linear stages.

Quote for the accessories that are compatible/recommended with these products.

Motorized Linear Translation Stage

Compliance Sheet

Specifications		**Compliance(Yes/No)**
Load Capacity (Vertical)	: 5 kg	
Travel	: 100 mm	
Resolution	: 5 micrometer	
Accuracy	: 1 micrometer	
Speed	: ~ 10 mm/sec	
Weight	: < 2.5 kg	
Limit switches	: on both ends	
Homing switch	: on one end	
Homing accuracy	: 1 micrometer	
Construction	: Aluminum	
Servo Control, shaft Encoders	: Required	
Manual adjustment via knob	required	

Motorized (360 deg. Continuous) Rotary

Compliance Sheet

Specifications		Compliance(Yes/No)
Resolution	: <1 arc-second	
Rotation	: 360 degrees	
Load capacity (horizontal)	: 50 kg	
Weight	: < 1.5 Kg	
Drive Mechanism	: worm drive	
Limit Switches	: Reference Signal Every 360°	
Wobble	: 0.5 arcmin	
Eccentricity	: 10 μm	
Torque	: 1Nm	
Clear aperture	2 to 2.5 inch diameter	
Construction	: Aluminum	
Rotation speed	: ~ 10 deg per sec	
Servo Control, shaft encoders	: Required	
Manual adjustment via knob	required	

Multi- Axis motion control system

Compliance Sheet

Specifications	**Compliance (Yes/No)**
A Multi-axis motion controller system fully compatible with the rotary and linear translation stages mentioned above. If more than one options are available please quote separately all otions.	
To be supplied with full set of connection cables, power supplies, rack cabinet adapters, mounting kit, manuals, maintenance guides etc.	
Software: Software libraries in C, C++, ActiveX DLLs for development on Visual Studio, Drivers for Labview, Linux drivers support, sample programs Quote separately for third party solutions or custom software development options.	
Quote separately for extra long cables (20 metre length, with possibility of custom fabrication) between controller and rotary and/or linear stages.	
Quote for the accessories that are compatible/recommended with these products.	