A PROTOTYPE 11 METRE MODERN MICHELSON STELLAR INTERFEROMETER

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ABSTRACT

The Astronomy Department of the University of Sydney is currently exploring the feasibility of building a Micheson stellar interferometer using modern techniques and detectors to surmount the atmospheric and stability problems that limited the development of the original Michelson interferometers. The main part of this programme is the design and construction of an 11 m fixed baseline prototype instrument to establish whether fringe visibility can be measured with an accuracy better than ±2% over a range of atmospheric seeing conditions and instrumental parameters. The design of the prototype instrument, its status and prospects are discussed.

1. INTRODUCTION

In September 1974 the Australian Government announced that it had approved in principle a grant to the University of Sydney to construct a large stellar interferometer. It included in its Budget an initial grant for a detailed design study of the instrument. This announcement came in response to a proposal to design and build a very large stellar intensity interferometer but, because of the long interval between the submission of the proposal and its acceptance (3½ years), a detailed reappraisal of the proposal and of the likely contributions to be made by intensity and amplitude interferometry was carried out.

There is no doubt that the proposed large intensity interferometer could be built. As has been explained by Hanbury Brown[1] there are no unknown factors and it is simply a question of optimising the design. The proposed limiting magnitude V(limit) = +7.3 would allow a wide range of astronomical programmes to be tackled although additional sensitivity is desirable for stars at each end of the range of spectral types and also for measuring Cepheid variables[2]. Unfortunately it is extremely difficult and probably prohibitively expensive to increase the sensitivity beyond V(limit) = +7.3 and the reappraisal of our proposal, based on advances made in several related areas during the period that the proposal was being considered by the Government, led us to conclude that a 'modern' Michelson interferometer offers the possibility of greater sensitivity at lower cost. The work of Twiss and Tango with the Monteporzio two metre baseline amplitude interferometer[3] suggests that V(limit) = +8 or +9 could be achieved using their approach, although there are a number of questions, particularly concerning the accuracy that can be achieved in measuring fringe visibility through the atmosphere, which need answering.

On balance, a 'modern' Michelson interferometer appears to be an attractive alternative to the intensity interferometer *if* it will work through the atmosphere with the desired accuracy, but the answer to that question is not yet known. Faced with this situation it seemed prudent to put the design study of the large intensity interferometer "on ice" and to establish whether the 'modern' Michelson interferometer is a viable proposition. With Australian Government approval the design study grant is being used to investigate the feasibility of a 'modern' Michelson interferometer by building a small prototype instrument. The aim is to establish, by observations of both unresolved stars and stars measured with the Narrabri intensity interferometer, whether visibility can be measured with the desired accuracy of better than 2% through the atmosphere over a range of seeing and instrumental conditions.

2. THE PROTOTYPE 'MODERN' MICHELSON STELLAR INTERFEROMETER

The prototype instrument represents a logical step in the development of the work carried out by Twiss and Tango with the Monteporzio interferometer and the basic design features of the new instrument are similar to those described in the previous paper by Tango[3]. The most significant differences between the two designs result from the increase in baseline length from 2 m to 11 m. The two metre instrument is mounted on an azimuth platform and thus avoids the need for dynamic path compensation but this is not a feasible proposition for baselines exceeding a few metres in length. Since the ultimate aim of our programme is to build a high resolution interferometer employing baselines of the order of hundreds of metres, it was decided that the prototype would employ coelostats at fixed locations to direct starlight into the interferometer, that a dynamic optical delay line system would be used to maintain equality of the optical path lengths in the two sides of the interferometer, and that the optics would be designed so that they could be readily and directly incorporated in a future high resolution instrument.

It was also decided not to design the prototype interferometer with the aim of measuring new angular diameters but simply to use selected stars as test objects. The selected stars are ζ Pup and α CMa whose angular diameters were both measured with the Narrabri intensity interferometer. ζ Pup is a particularly suitable test object since it is essentially unresolved at the baselines under consideration and α CMa was chosen because of its brightness and the fact that it has an appropriate and well determined angular diameter (±2.7%)[4].

2.1 Design Parameters

The following parameters were fixed before the detailed design of the prototype interferometer was commenced:

(i) baseline length and orientation,
(ii) operating wavelength and spectral bandwidth,
(iii) primary aperture diameter,
(iv) secondary aperture diameter,
and (v) hour angle coverage

The selection of the values for these parameters will be discussed briefly before the layout of the instrument is described.

(i) Baseline length and orientation

In order to minimise the path length equalisation problem at this stage in the development of the technique it was decided to use a North-South orientation for the fixed horizontal baseline. The length was fixed at 11 m to give an *effective* baseline for α CMa corresponding to approximately 0.3 for the normalized correlation factor $\Gamma_\lambda^2(d)$ (equal to the square of the modulus of fringe visibility). Figure 1 shows the effective baselines for α CMa and ζ Pup at transit and the corresponding values of the correlation factor. For ζ Pup $\Gamma_\lambda^2(d)$ has a minimum value of 0.994 at transit.

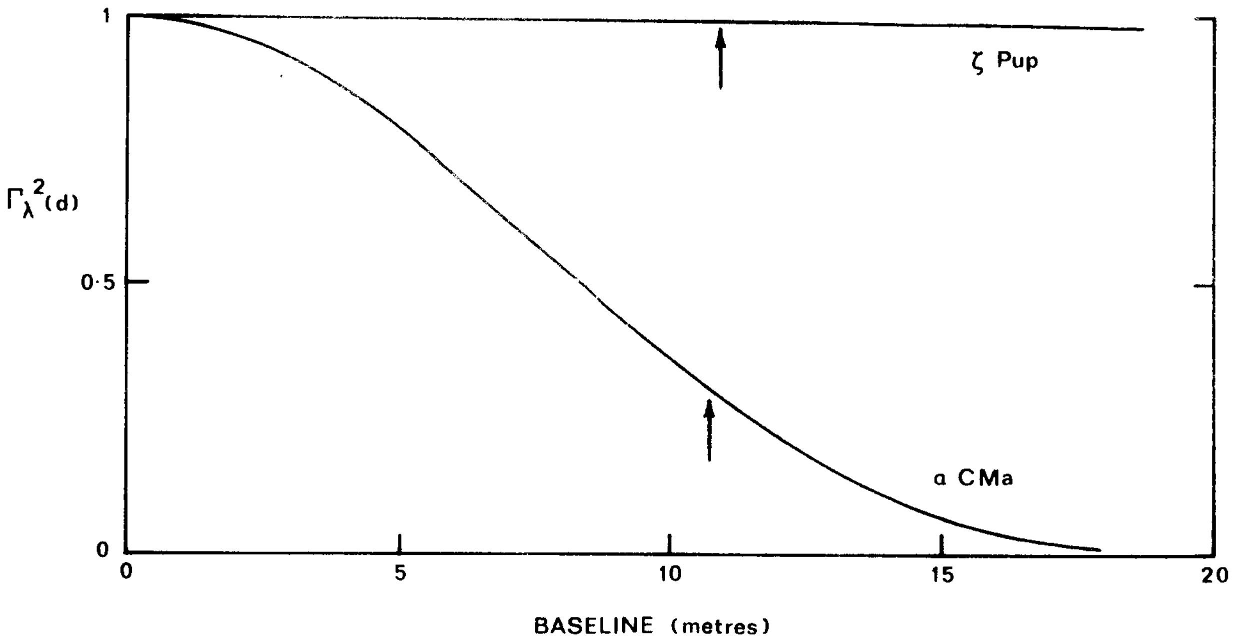

Figure 1. The normalized correlation factor as a function of baseline for α CMa and ζ Pup for a wavelength of 442 nm. The arrows indicate the points on the curves corresponding to the effective baselines of the 11 m prototype interferometer at transit for latitude 30°S.

Although the instrument is not designed to measure new angular diameters it turns out that the stars α Car, δ CMa, α CMi and α Aql, as well as α CMa, whose angular diameters were determined with the Narrabri intensity interferometer, could all be resolved with the 11 m baseline and, once the performance of the instrument is proven, the angular diameters of these stars could be independently redetermined.

(ii) Operating wavelength and spectral bandwidth

For ease of alignment of the spectral bandwidths in the two signal channels of the interferometer, the wavelength of the HeCd laser (441.8 nm) has been adopted as the mean operating wavelength for the prototype instrument. The spectral bandwidth will be a variable parameter and will generally be in the range 0.1 to 1 nm.

(iii) Primary aperture diameter

The primary aperture diameter has been set nominally at 10 cm to correspond to Fried's coherence diameter r_o for good conditions. An unobstructed aperture will be used and the aperture diameter can be readily stopped down to explore the effect of doing so and in order to optimise its value for given seeing conditions.

(iv) Secondary aperture diameter

It would be inconvenient and unnecessarily expensive to make all the optical components of the interferometer with 10 cm apertures. Thus, while it makes sense to reduce the diameter of the beams optically before they enter the interferometer proper, there is a limit to the reduction factor that can be used without serious loss in fringe visibility. This is because the optical path length equalising system introduces a path difference between the two light beams *within* the instrument, at the reduced beam diameter, and this results in differential diffraction effects at the point where the two beams are superposed. The resulting loss in fringe visibility which can, in principle, be calculated, depends on the difference in path length, which is proportional to the baseline, and also on the diameter of the light beams. It is clearly desirable to limit the visibility loss and corrections to a few percent. Based on the analysis by Tango and Twiss[5] and our hope of eventually using the prototype as the basis for a major high resolution instrument, the reduction ratio was set at 2.5, giving a secondary beam diameter of 4 cm for the full primary aperture of 10 cm.

(v) Hour angle coverage

The range of observable hour angles has been restricted to a nominal ±2 hours from transit to keep the length of the continuously tracking optical delay line short and to restrict the range of tracking speeds required. In practice, with the delay line currently under development, it will probably be possible to track to about ±3 hours from transit for α CMa and ζ Pup.

2.2 The Configuration of the Prototype Instrument

Figure 2 shows in diagrammatic form a cross-section of the prototype interferometer, the whole of which will be mounted on a monolithic mass of rock. The coelostats (C_s and C_n), which are mounted on 2 m high concrete plinths anchored to the rock, direct the light from the star via flat mirrors arranged as periscopes to the interferometer proper at X_s and X_n. For the major part of the optical path from the coelostats to X_s and X_n the light beams will pass through pipes sealed with optical windows at each end. The pipes will be thermally insulated and provision will be made to evacuate them should it prove to be necessary. The coelostats and periscope mirrors are all 15 cm diameter Zerodur flats and the 45° inclination of the periscope mirrors limits the primary beam diameter to 10.6 cm. As shown in Figure 2, the two coelostats face in the same direction and this has the advantage that they both require the same azimuth and elevation drive signals, they project beams of identical cross-section with no differential foreshortening as occurs with one 'looking over its back' in the more conventional arrangement, and also the polarization properties of the two beams are the same. The arrangement shown in Figure 2 is appropriate for stars transiting North of the zenith but it has the disadvantage that the coelostats should be moved and the top periscope mirrors rotated 180° in azimuth for observations of South transiting stars. In a major instrument this would be necessary but, for the proposed site of the prototype interferometer, ζ Pup transits sufficiently close to the zenith, although to the South, for the arrangement shown to be satisfactory. α CMa transits to the North of the zenith.

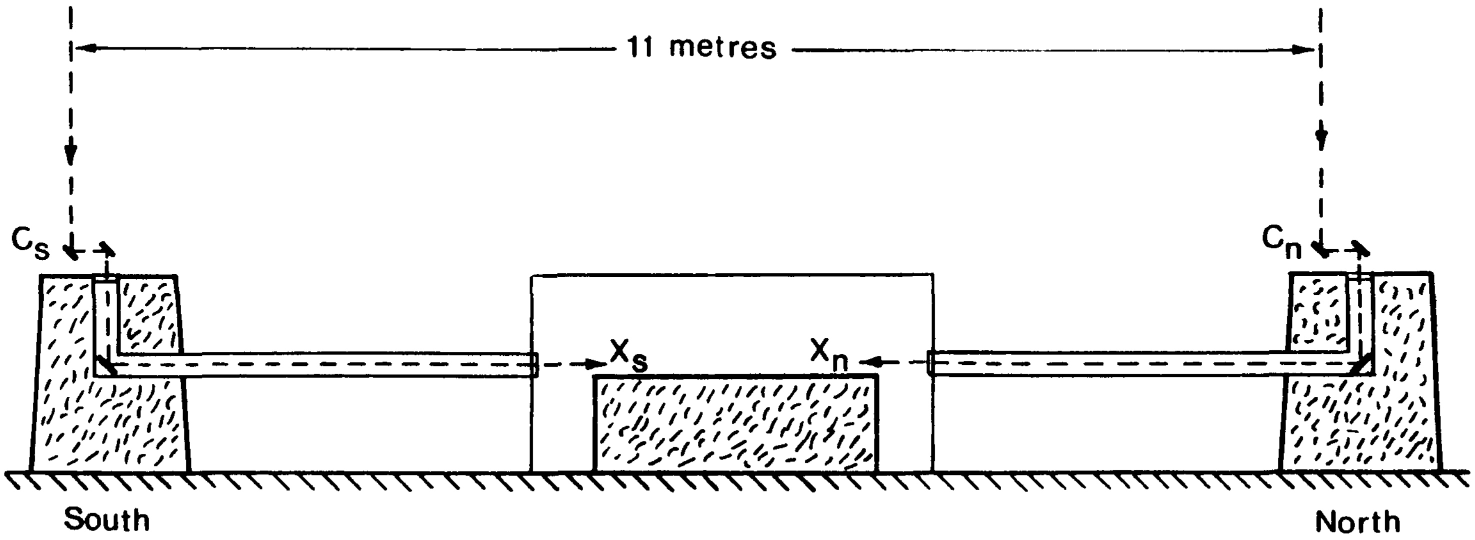

Figure 2. Diagrammatic cross-section of the prototype interferometer looking West. The coelostats C_s and C_n are mounted on concrete plinths and direct the light from the star via flat mirrors arranged as periscopes to the interferometer proper at X_s and X_n.

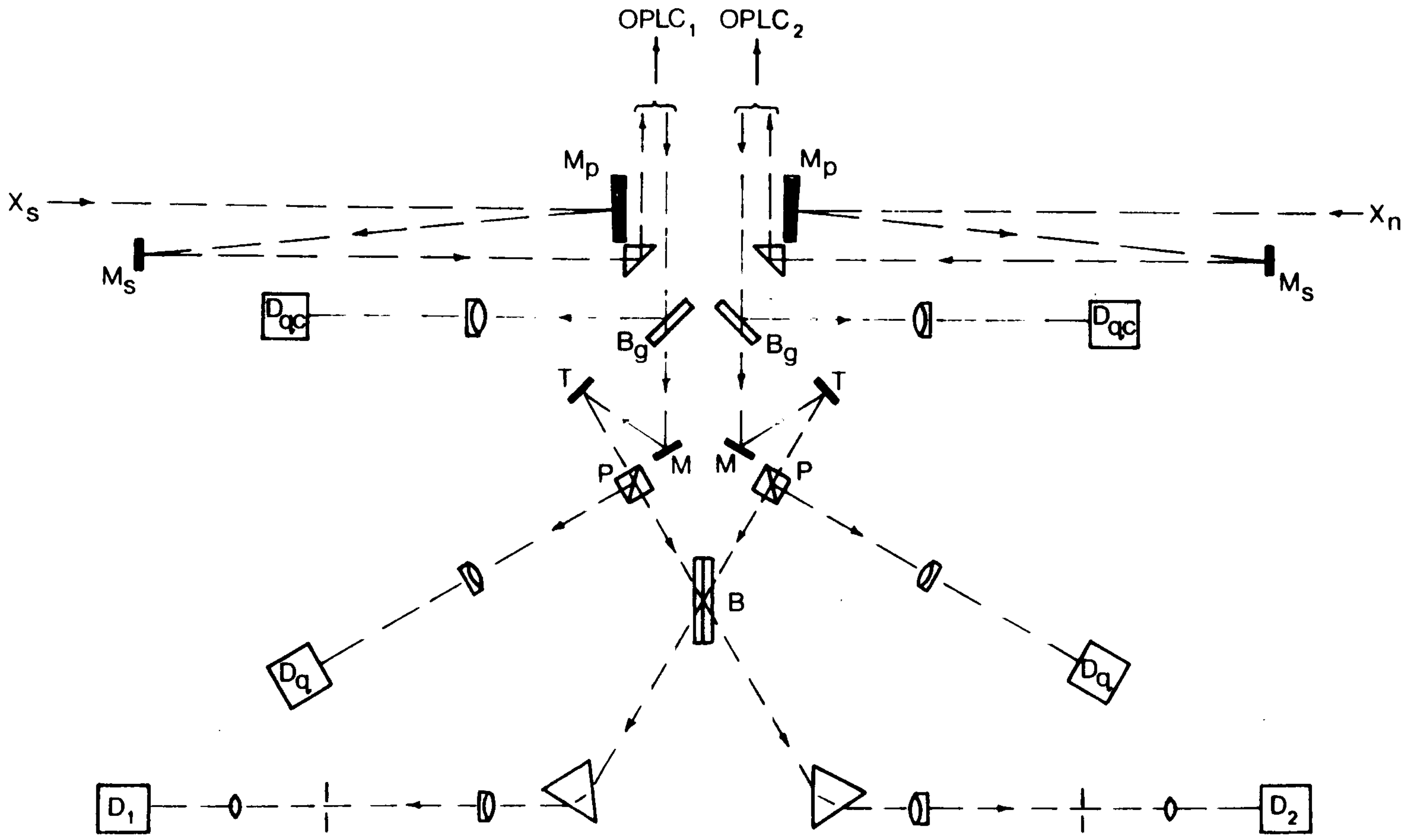

Figure 3. Diagrammatic layout of the prototype interferometer showing the main components. The components are identified and their functions are described in the text.

The interferometer proper is to be housed in a central laboratory and the optical layout is shown in Figure 3 with the starlight entering at X_s and X_n which correspond to X_s and X_n in Figure 2. The optical layout shown is not the final arrangement since it will be modified to fit on a standard Newport optical table top but, nevertheless, it shows the components and essential features of the instrument.

In an earlier paper Tango[6] described the principles and theory of a small aperture amplitude interferometer and these apply directly to the prototype instrument. The reader is therefore referred to Tango's paper for the underlying theory of operation of the interferometer and the discussion here will be limited to a brief description of the train of optical components shown in Figure 3.

Since the two sides of the interferometer are symmetrical it is only necessary to describe one side. The light enters at X_s or X_n and the beam diameter is reduced by a factor of 2.5 by mirrors M_p and M_s which are off-axis paraboloidal segments with focal lengths in the ratio of 2.5:1. The reduced diameter beam passes via the optical path length compensator ($OPLC_1$ or $OPLC_2$), which will be described later, the beamsplitter B_g, the mirrors M and T, and the polarizing beamsplitter P to the neutral beamsplitter B where the wavefronts from the two sides of the instrument interfere at nominally zero angle. Matched prism spectrometers, in which the light is incident at the Brewster angle on the prisms to minimise the insertion loss, are positioned in the output beams from B to select the mean wavelength and spectral bandwidth for observations. Photon counting detectors D_1 and D_2 measure the total flux in each beam within the sampling time which will be typically in the range 1 to 10 milliseconds. The correlation factor $\Gamma^2_\lambda(d)$ is computed from these observed photon counts[6].

A small fraction ($\sim$5%) of the light incident on the beamsplitter B_g is reflected to a long focal length lens which forms a diffraction limited image of the star on the quadrant detector D_{qc}. Error signals from D_{qc} are used to correct the pointing of the appropriate coelostat so that the beam transmitted by B_g is accurately aligned with the defined optical axis of the instrument except for the rapid variations in tilt due to seeing (of order 1-2 arcseconds r.m.s.). The polarized component of light reflected by the polarizing beamsplitter B is also focussed by a long focal length lens onto a quadrant detector (D_q). The error signals in this case are used to remove the seeing induced tilts via the piezo-electrically actuated tilting mirror T. The mirror M is mounted on a monolithic cylinder of piezo-electric material so that the mirror may be translated in a direction normal to its surface. This will enable a path difference of $\lambda/4$ to be introduced differentially between the two interfering beams in successive sample periods so that, providing the sample period is short compared with the timescale of changes in the relative phase ϕ of the interfering wavefronts, the analysis[6] gives the apparent correlation equal to $2\Gamma^2_\lambda(d)<\cos^2\phi + \sin^2\phi>$ instead of $2\Gamma^2_\lambda(d)<\cos^2\phi>$ and it no longer requires the assumption that the phase is a uniform random variable to obtain $\Gamma^2_\lambda(d)$.

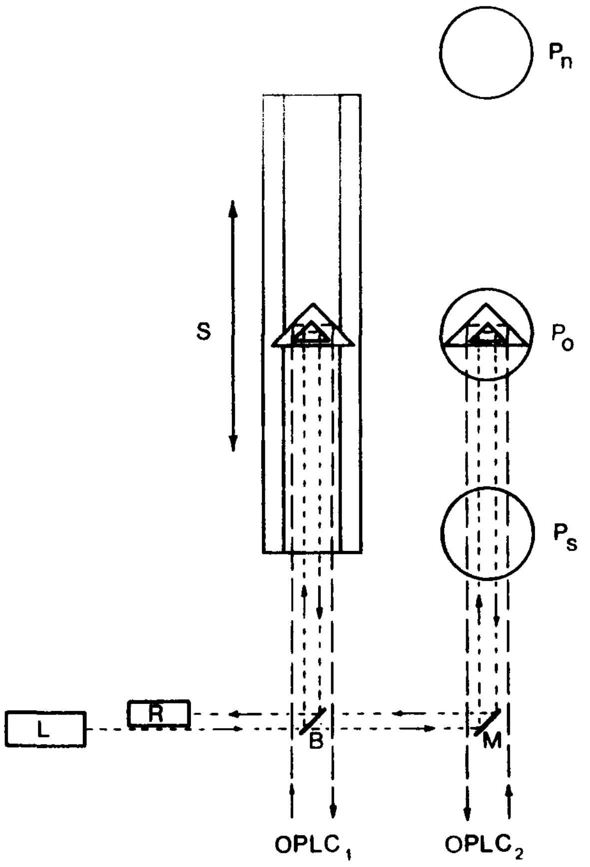

Figure 4. Diagrammatic layout of the optical path length compensation system. Light enters and leaves the system at $OPLC_1$ and $OPLC_2$ (see Figure 3). S represents a slide in the South arm of the interferometer on which the position of a retro-reflector can be continuously varied and P_s, P_o and P_n represent fixed positions for the retro-reflector in the North arm of the interferometer. The relative positions of the retro-reflectors are monitored by a Hewlett-Packard laser interferometer system represented in the diagram by L (laser), B (beamsplitter), M (beam bender) and R (receiver). Separate small retro-reflectors for the laser system are mounted above the main retro-reflectors as shown in the diagram. Further details are given in the text.

The layout of the optical path length compensation system is shown in Figure 4 with $OPLC_1$ and $OPLC_2$ representing the South and North arms respectively. Light enters and leaves the system at the positions labelled $OPLC_1$ and $OPLC_2$ which match those in Figure 3. The retro-reflector in $OPLC_1$ is mounted on a mechanical slide (S in Figure 4) and can be moved continuously over a distance of approximately 0.7 m. In contrast, the retro-reflector in $OPLC_2$ has a series of fixed kinematic locations which are represented by P_s, P_o and P_n in Figure 4. In operation the positions of the two retro-reflectors, relative to their positions for equality of the internal paths in the two arms of the interferometer, are monitored by a Hewlett-Packard laser interferometric system. The paths in the two arms of the interferometer will be equalised initially by introducing an artificial star as in the Monteporzio instrument[3], tilting the coelostats to an auto-collimating position to form a Twyman-Green interferometer, and then adjusting the position of the retro-reflector along the slide in $OPLC_1$ until the zero-order white light fringe is observed with the retro-reflector of $OPLC_2$ in position P_o (as shown in Figure 4). To observe a star the optical path difference at transit will be compensated by moving the retro-reflector in $OPLC_2$ to the appropriate kinematic location, such as P_s or P_n in Figure 4 depending on whether the star transits South or North of the zenith, with the laser system monitoring the actual distance moved. On either side of transit the continuously varying component of the optical path difference will be compensated by moving the retro-reflector in $OPLC_1$ along the slide S with its position and velocity controlled via the monitoring laser system.

The retro-reflectors in the optical path length compensation system are simple 45° prisms rather than corner cubes, partly to reduce the cost, but also to avoid difficulty with polarization. The parallelism of the incident and reflected beams is maintained in $OPLC_1$ by an automatic levelling system based on a Talyvel (a level sensor) mounted on the same moving platform as the retro-reflecting prism and, in $OPLC_2$, by individual alignment of each of the kinematic locations for the prism.

2.3 The Status of the Prototype Instrument

The prototype interferometer is currently under construction and a brief summary of its present status follows.

The optical components have been specified and ordered and some 50% have been delivered. Mechanical work on mountings for the optical components is well in hand and many have been completed and tested. The path length compensation system, tilt-correcting mirror mountings and coelostat mountings are all in an advanced stage of construction and the electronic control circuitry for these active elements is essentially complete. A Hewlett-Packard 9825A desk-top computer has been purchased and it will provide the azimuth, elevation and optical path length compensation positions and rates as well as being the overall system controller.

A site in the grounds of the new Australian National Measurement Laboratory on the outskirts of Sydney is under consideration for the prototype instrument. The site has a large monolithic mass of rock with a near horizontal surface on which the instrument would be mounted. The night sky is rather bright due to the proximity of the city but this is not a problem for the prototype. A final decision on this site is subject to more detailed examination and tests.

3. SUMMARY

The design of a prototype 11 m modern Michelson stellar interferometer is essentially complete and the component parts of the instrument are being manufactured and tested. The optical path length compensation, angular seeing compensation and guidance servo-systems are being constructed and tested in the laboratory and it is hoped to install the entire instrument at a field station during 1979. A site for the instrument is being investigated and, while it is dangerous to make predictions, it is hoped to have the prototype interferometer operating in 1980 and to carry out an observational programme with it to answer the questions posed in the introduction.

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DISCUSSION

C.O. Alley: Under optimistic projections of progress, to what length baseline are you prepared to go?

J. Davis: Unless fringe-tracking is used it may only be possible to go to 100-200 m using very narrow optical bandwidths to limit the loss in visibility due to errors in path equalisation. With fringe-tracking there is no limit in principle to the baseline and we would be looking to go to baselines in excess of 1 km.

M. Shao: When do you plan to build a fringe tracker?

J. Davis: We are considering the problems of fringe-tracking but have no immediate plans to incorporate it in our prototype instrument.

R. Wade: Do you have any measurements of r_o for your site? 10 cm is generally considered to be applicable to an observatory quality site. Have you chosen such a site?

J.Davis: We don't have measurements at the site we are considering. For the prototype instrument the selection of a site is a compromise between many conflicting requirements and we will have to accept less than the best seeing conditions. However, for a major instrument, you are quite right in drawing attention to the importance of selecting a site for which r_o is consistently large.