PARALLAXES AND DETECTION OF DARK COMPANIONS: THE CASE OF INTERFEROMETRY VERSUS IMAGING.

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ABSTRACT

One tries to define an optimal method for the measurement of small apparent stellar motions. The available or proposed techniques and atmospheric disturbances are studied first. A special purpose interferometer is then devised; it is found far more complex and not in any way better than a previously described direct imaging system.

INTRODUCTION

We consider here the problem of measuring stellar parallaxes, and of the detection of dark companions, a highly traditional field in which there has been only minor change for close to a century. While there are already proposals for doing some of the work in space, it cannot yet be justified, since so far no overall study of the sources of errors, particularly atmospheric ones, was available. The questions we try to answer here are: what is the best technique for detecting small apparent stellar motions, and how much should still be done from the ground? As shown by the list of papers in the Colloquium, this question has attracted far less attention than one of resolving power; however we believe the potential scientific windfall to be no less if a good solution is found.

1. AVAILABLE OR POSSIBLE TECHNIQUES.

Small apparent stellar motions are traditionally measured by long focus photography relative to a frame of reference consisting of at least 3 "background" stars within a field of the order of 1^{o} (the case of close visual binaries is not considered here). We have discussed elsewhere the accuracy obtainable in this way[5]: there is a large difference between the errors for "run of the mill" stars (10 to 40 x 10^{-3} arc sec probable parallax errors in catalogs) and those achieved in a few selected cases. For the best documented one[6] a standard deviation from the mean of 1.7 x 10^{-3} arc sec is obtained for 4 totally independent parallax determinations for the same star.

An altogether different possibility is offered by the Astrometric Satellite proposal, or Hipparchus Project[7]. In this case one compares, by means of a reflecting prism in front of a small telescope, the positions of stars within two different fields at large angular distances (of the order of 90^{o}). A coherent system of stellar positions is built over the whole sky, and the number of stars studied (of the order of 10^{5}) cannot be matched in any other way. However if one is interested in highly accurate (1 x 10^{-3} arc sec or better) parallaxes for a moderate number of stars preselected for their astrophysical interest, Hipparchos is not the best nor cheapest tool[5]. It is also unsuitable for the detection of dark companions because the lifetime (2.5 y) is too short.

Then we shall have the Space Telescope. Astrometry is not considered an important subject: a proposal for a dedicated focal plane astrometric device has unfortunately been rejected. However the fine guidance system has some astrometric capabilities[8]. A full system description and an estimate of available observing time will be needed to predict how much may eventually be done.

Lastly we have made a proposal for developing a new ground based, narrow field photoelectric technique. The scientific goals are very accurate parallaxes for selected stars and a systematic search for dark companions, possibly down to planetary sizes, around more or less solar type stars. The proposal contains four parts: A) The description of a special purpose astrometric telescope that eliminates coma, atmospheric dispersion and - hopefully - all instrumental instabilities[2]. B) A photoelectric detection technique making use of special masks but common photomultipliers[3]. It is specific of the proposed program in the sense it does not measure stellar positions but detects directly the motions. Basic improvements compared to photography are increased quantum efficiency, perfect linearity and elimination of emulsion shifts. Also the (heavy) off-sky labour involved in reduction of a large plate set, each with many stars and exposures, is replaced by the much lighter one of mask fabrication. C) An analysis of atmosphere induced errors[4] using all available data; it is briefly discussed here in § 2. D) An attempt to devise an interferometer adapted to the same problems. The conclusion is negative in the sense that technique A + B is found to be much simpler and of comparable accuracy.

Considering the theme of this colloquium and the fact points (A), (B) and (C) have been or are being described elsewhere, this unsuccessful attempt shall be the main subject here. Since we do not propose implementation of A + B, it is necessary to show an altogether different technique would not be any better

2. ATMOSPHERIC LIMITATIONS.

The central problem is the one of the atmosphere; we have discussed it in Refs. (1) and (4). Only the main conclusions need to be given here. As seen by a telescope, atmospheric perturbations may be classified under four headings: Seeing, Normal refraction, Dispersion and Anormalous refraction.

2.1. Seeing.

We define here seeing as a time varying image spread, not affecting the image photocenter position (this will be dealt with as refraction). The fine instantaneous speckle structure of the turbulence patch is irrelevant in our case precisely because it does not contain any information on image photocenter position, and image shape is sufficiently well approximated by a Gaussian distribution of half width α, of the order of 1 arc sec under usual circumstances.

The consequences for setting accuracy on photocenter may be computed. For a given number of photoelectrons, N, the RMS error is $\varepsilon = \alpha/\sqrt{N}$ (neglecting factors of the order of unity). Hence for usual telescope diameters $\emptyset$, the error is proportional to α, to $\emptyset^{-1}$ and to $T^{-1/2}$ where T is the observing time. We have given curves of ε versus stellar magnitude using reasonable assumptions for $\emptyset$, T and instrumental efficiency[1,3]. For instance if $\emptyset = 1$ m, $\alpha = 2$ arc sec, $T = 10^3$ s (and bandpass as in 2.3 below) we find $\varepsilon = 0.5$ m arc sec at $m_V = 15$. Consequences for a parallax program have been discussed[1,5], if there were no other limitations parallax accuracies in the

0.05×10^{-3} to 1×10^{-3} arc sec range depending on magnitude would be achievable from the ground.

2.2. Normal refraction

This appears as a large slowly varying deflection of image photocenter. Since it is computable from atmospheric models, and moreover varies linearly across a small field it poses no problem. It is fully taken into account either by classical plate reduction techniques or by our mask system[1,3]. The same would apply to an interferometer.

2.3. Dispersion.

Only normal dispersion need be considered, i.e. the small $\Delta Z = \Delta n \tan Z$ spread of the stellar image in the Z direction. It is again fully computable (we can predict exact photo-center position) and poses no serious problem. However in photographic astrometry one prefers to restrict the bandpass (at a severe loss in number of photons) because of photographic non-linearity) and uncertainty on actual spectral range. With any photoelectric system the deleterious effects should be much less. Furthermore with our astrometric telescope dispersion is compensated and a spectral bandpass of 3500 to 9000 Å (i.e. the one of a Ga-As photocathode) is allowed. No basic difficulty is expected either with an interferometer.

2.4. Anomalous refraction.

Anomalous refraction induces a random, non-predictable fluctuation of photocenter in both zenith angle and azimuth; its amplitude is greatest at high frequencies (10 to 100 Hz) but the spectrom does extend to very low frequencies. It is best studied by photographic zenith tubes, Danjon's astrolabes and meridian circles; results have been reviewed[9]. The absolute random fluctuations of stellar positions are found to be in the 300 to 50 $\times 10^{-3}$ arc sec range even when long integration times (minutes to hours) are considered. They do limit the accuracy in all measurements of large angles, hence the accuracy of reference star positions in catalogues. Nothing much can be done about it and going to space is fully warranted in this case.

The mere fact that we already have some stellar parallaxes accurate to a few milli arc seconds shows the differential effects must be much smaller. Nevertheless, the limitation was unclear; our papers[1,4] give a first attempt at a (rather crude) treatment. One considers the atmosphere as a sum of thin superposed anomalously refracting layers, moving with different horizontal velocities. Very little is known about actual vertical structure, but the overall image photocenter fluctation must be no greater than the one measured by absolute astrometry[9].

The first conclusion is that a non-negligible fluctuation must be expected in the angular distance between two nearby stars even at very low frequencies (10^{-1} to 10^{-3} Hz). There is indeed some indication that solar diameter estimates are perturbed in this way (10). This is a first order, or scale, effect; it is fully eliminated either by classical plate reduction techniques or by our mask system[1].

The next - and essential - conclusion is that any second or higher order effect (i.e. distortions within the field) is fully compensated for if the following conditions are met: A) integration times of the order of minutes at least, B) a large number of reference stars, distributed in a more or less uniform fashion over the field, C) all angular measurements have to be simultaneous.

These conclusions are independent of the instrument aperture or even of its nature. Whether we use a telescope, and set on the stellar image photocenters (i.e. locate the average wavefronts) or sample these wavefronts at two places a few meters or tens of meters apart is irrelevant (VLBI is a somewhat different case). They come at no great surprise: the procedure is precisely the one traditional long focus astrometrists, in their wisdom, had been approximating: however their number of reference stars is too small. Moreover, due to non-linearity the integration capability of photography is a poor quality one. On the other hand, our proposed mask technique fully meets all these points A B C. By contrast, they would not be satisfied by a transit instrument (even a photoelectric, fully automated one) jumping from star to star. Any interferometer attempting to do the same would fare no better.

Some comments are needed. The problem has nothing to do with the better known one of the so called isoplanatic patch size (i.e. a few arc sec at most). We are not interested here in the instantaneous atmospheric structure (or photocenter position, or wavefront distortion, but in the averaged ones (over minutes at least). These have attracted far less attention, because they do not bear on the problem of resolving power. Hence the potentially important conclusion that it is possible to improve considerably from the ground the measurements of small stellar apparent motions by proper techniques has remained hidden from view.

3. IS INTERFEROMETRY APPLICABLE?

Interferometry under different forms (e.g. two beams, or speckle) is widely used for measuring stellar angular diameters or the separation of close doubles, i.e. angles of the order of 1 arc sec or less. The problem here differs on three counts: A) the angles are much greater (several minutes at least) B) one has to use white light or very little filtering; otherwise the system unavoidably becomes inferior to the direct imaging competitor from the photon noise viewpoint. C) as discussed above, one must work on many stars simultaneously.

To show interferometry is a possible solution one has to answer two questions: first: is it even possible to design an interferometer satisfying points A, B, C? Second: does one expect a basic increase in accuracy compared to direct imaging?

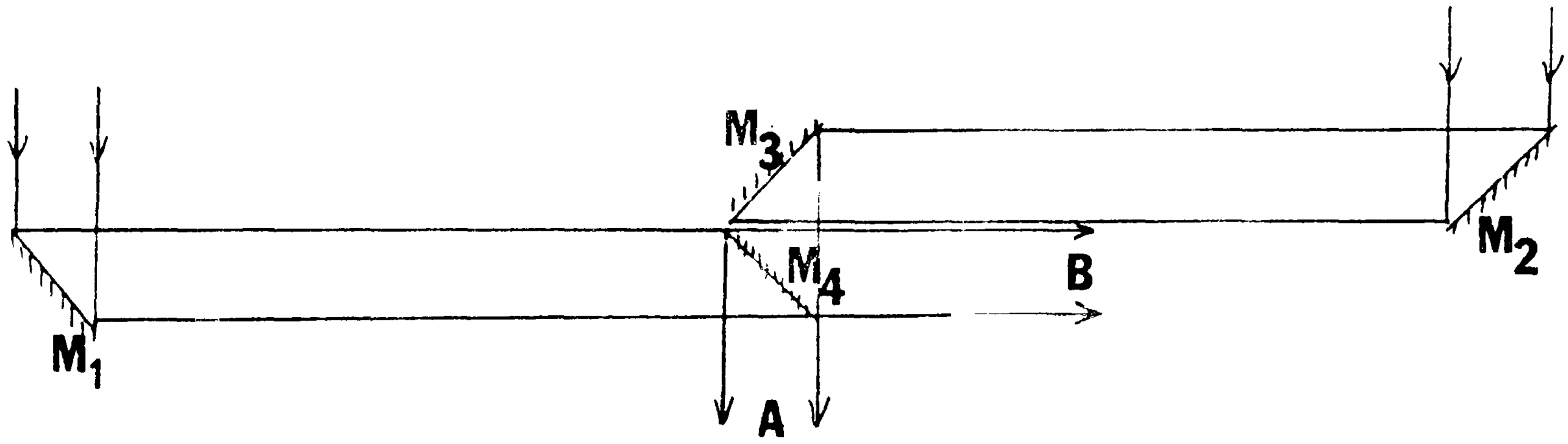

Figure 1. Spatial interferometer.

M_1M_2 may be servocontroled in tilt; M_4 is a semi transparent beam mixer. There are two outputs A and B.

3.1 A possible interferometer.

Let us consider an equatorially mounted two beam interferometer of the general type of Figure 1. The path difference for any incident ray making angle β with the system plane of symmetry is $\Delta = L \sin \beta$. If the sky was illuminated by monochromatic light, the system would produce rectilinear equidistant fringes with angular spacing λ/L; the plane of symmetry coincides with the zero order fringe. If light is non-monochromatic with band width $\Delta\lambda$, a limited number of fringes (approximately $\lambda/\Delta\lambda$) is seen, with vanishing contrast for increasing β. The interferometer is usable for angular measures only if $\beta < \lambda^2/L\Delta\lambda$. If $L = 1$ m, $\lambda = 5000$ Å, we have $\beta < 8$ arc min. A field suitable for parallax or proper motion work is only realized with a bandpass which might possibly be achieved with a narrow band filter but is not admissable because of energy considerations.

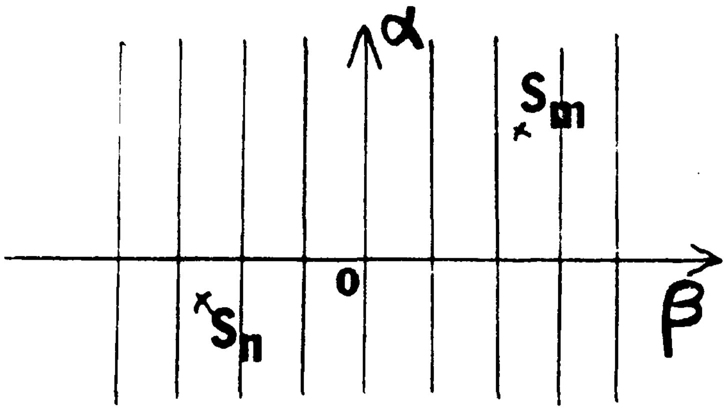

Figure 2. Grid of equal path difference lines projected onto the sky irrespective of wavelength. S_M S_n are two stars randomly located in the field.

In white light only a few fringes are visible; the flux from randomly located stars in the field is unmodulated and no interferometric signal recorded. However let us forget about fringes altogether; we may understand the interferometer as a device projecting onto the sky a grid of <u>equal path difference</u> lines (Figure 2). Each star S_n has a well-defined path difference $\Delta_n = L \sin \beta_n$ attached to it. Any kind of telescope is a machine which transforms angles into linear distances (in the focal plane). The interferometer transforms angles into path differences, i.e. lengths susceptible of very accurate measurements, and this is done with no aberrations of any order, no optical axis and a field limited by vignetting only.

In principle the path difference is measurable in several ways. The spectrum of stellar light (Figure 3) after passage through the interferometer is a channeled spectrum with characteristic spacing $\sigma_n = 1/\Delta_n$. Thus any spectroscope will do the trick. If L = 1 m, $\beta = 1/100$ rad, we get $\Delta = 1$ cm, $1/\Delta = 1\ \text{cm}^{-1}$; a modest-sized grating spectrometer has adequate resolution. However quite obviously all the field and aberration problems are transferred into the spectrometer.

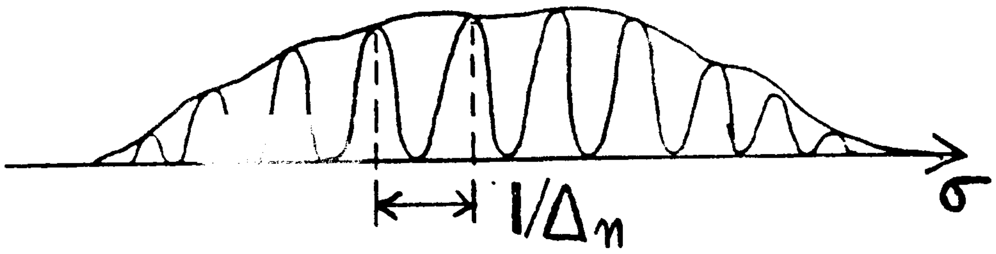

Figure 3. Channeled spectrum in the light of star S_N after passage through spatial interferometer.

Interferometric FOURIER spectroscopy may look like the answer. Suppose we feed the light from the "primary" astronomical interferometer into a "secondary" interferometer of the type commonly used for Fourier spectroscopy and record an interferogram in the usual way be increasing the path difference Δ from 0 to $\Delta\text{max} > \Delta_n$. Each star S_n will produce a pulse in the interferogram when Δ equals Δ_n. However the measurements for the different stars are not truly simultaneous, which is inadmissable since we must eliminate guiding and atmospheric errors.

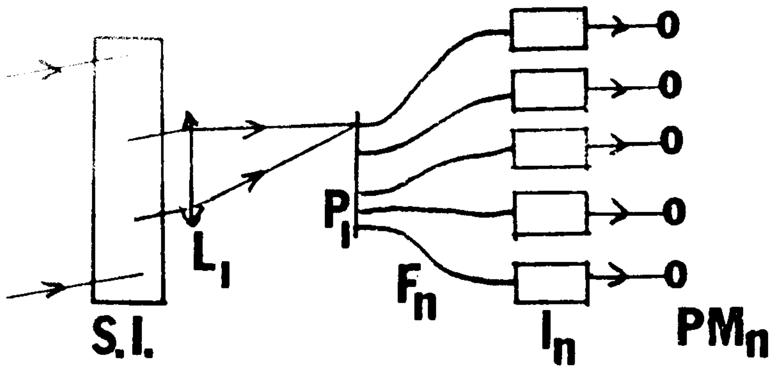

Figure 4. First detection system. At the output of spatial interferometer S.I. lens L_1 images the field; in the focal plane P_1 optical fibers F_n take the light to small Michelson interferometers I_n. Each is used on axis; aberrations of lens and fibers are irrelevant since coherence does not have to be preserved. One PM per star is needed (two if both outputs are used).

The only possible solution implies a set of secondary interferometers I_n (Figure 4) i.e. one per star. Each I_n is continuously servo-adjusted at $\Delta = \Delta_n$ from the light output. The operation may be understood in various ways; for instance we can speak of low order BREWSTER's fringes produced in white light after passage through two equal path difference two beam interferometers. The entire spectral range is used. The path difference, inside each I_n becomes a fluctuating quantity which is simultaneously measured with laser beams.

The difficulties are quite severe. Secondary interferometers may be small (1 cm^2 cross section) and simple devices; it is reasonable to consider having perhaps 10 of them, definitely not 100. So the averaging of anomalous refraction will not be as good as with the imaging device (1, 3). Then the servoing operation itself is difficult; in principle a very low bandpass is adequate since only the average of Δ over minutes or hours is required. However the approximately linear range of the error signal produced is extremely small (of the order of $\pm 24 \times 10^{-3}$ arc sec with $\lambda = 0.5\ \mu$, $L = 1$ m). This is small compared to fast image motions or guiding errors; hence a slow servo will easily run out of lock. A fast one (= 100 Hz bandpass) solves the problem, but this is not feasible on faint stars because of photon noise.

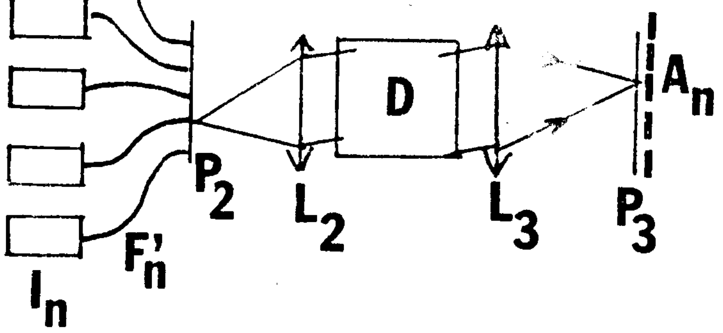

Figure 5. Second detection system. At the output of each I_n light from the star is picked up by a second fiber F'. The outputs are evenly spaced in the entrance focal plane P_2 of a low resolution spectrometer Disperser D produces dispersion perpendicular to the figure plane. In the final output focal plane P_3 a set of one dimensional photodiode arrays A_n continually measures the spectra.

The difficulty may be obviated in a hybrid system. The secondary interferometers are now locked at <u>fixed</u> (non-fluctuating) path differences Δ'_n. These are precomputed from known stellar positions; integer multiples of the reference laser wavelength may be selected. The difference $\Delta'_n - \Delta_n$ would not exceed a few wavelengths. The channeled spectrum at the output of each I_n now contains only a few fringes and may be analysed by a very low resolution spectrometer Figure 5 presents the final system. The outputs of all secondary interferometers go to a single spectrometer; in the output focal plane an image detector is used. The most appropriate one would probably be a single image intensifier followed by a set of one-dimensional photo-diode arrays (one per stellar spectrum), each with perhaps 128 elements. The records are sampled, Fourier transformed in real time and the results time averaged. The aberrations, field distortions, instabilities etc. of the spectrometer-image detector system no longer matter because it is not measuring the large angles between stars but only the very small ones between actual and precomputed stellar positions. These last may be refined after a first trial and the Δ'_n corrected to minimize $\Delta'_n - \Delta_n$ normal refraction and dispersion are also precomputed and taken into account.

Only one stellar coordinate is measured, for instance the declination if the baseline is N-S; a second run with the interferometer rotated 90^o around the central star direction is needed to record R.A. From the background stars one derives enough information to either control the base length or take into account any variation. Small differential wavefront tilts (either flexure or atmosphere induced) also disappear from the final results. One thing to be said in favour of this dreadful system is that it might prove remarkably free of systematic errors. However we have shown the same would be true of our astrometric telescope[2].

3.2. Basic limitations and discussion.

Any interferometer delivers a fringe signal in which phase and amplitude are available. We sup he stars to be fully unresolved; only the phase is of inte

T e is to reduce fringe visibility; it is
discus (11). We can perhaps add fast guiding
capabil Figure 1) (clearly flexible active mirrors
are too seriously here); then visibility is
reduced ture at the two entrances. Curves have
been plot function of D/R where D is the beam
diameter a ius characteristic of turbulence.[11] Unlike
cases where e unknown, one can tolerate substantial
loss; the a signal amplitude. Nevertheless we
cannot incre ince we are interested in orders of
magnitude onl ly want a simple comparison with the telescope case
in 2.1, we take $R = \lambda/\alpha$ and $D = R$ (i.e. beam diameter matched to actual turbulence). The angular RMS setting error on the fringe system for a given photon flux is again proportional to α, to L^{-1} and to $T^{-1/2}$. Hence the base length L plays the same role as $\emptyset$ for the telescope. Taking L = 1 m (and using the same figures for all other parameters as in the telescope case in

2.1, particularly $\alpha = 2$ arc sec) and $D = 5$ cm, one finds $\varepsilon = 0.3\ 10^{-3}$ arc sec at $m_V = 15$, slightly better than the telescope result. The interferometer's superior sensitivity comes mostly because it is technically and economically feasible to increase L: the 15 m equatorially mounted interferometer of Hale and Pease is still available in Mount Wilson. For telescopes we are stuck at $\emptyset = 6$ m and any dedicated instrument might only be much smaller.

However the mere consideration of seeing as we have defined it is misleading. While, as noted, normal refraction and dispersion pose no real problems, anomalous refraction induces random phase fluctuation, hence another limit to accuracy. Classical turbulence theory merely says we should have $\varepsilon' = 0.4\ \lambda L^{-1/6}\ R^{-5/6}$ where ε' is a new RMS angular fluctuation. Unlike ε it is independent of photon statistics, and covers all frequencies present in turbulence. If $\lambda = 0.5\ \mu$ $R = 5$ cm and $L = 1$m, then $\varepsilon' = 500 \times 10^{-3}$ arc sec, or 340×10^{-3} arc sec at $L = 10$ m.

Apart from this very slow predicted improvement with increasing L, the result is not very useful. We do not know how large the residual fluctuation will be for long integration times; the absolute fringe phases have so far not been measured in a direct manner within the visible part of the spectrum down to very low frequencies. The problem is a difficult one because extreme instrumental stability is required: all equatorially mounted interferometers measure solely the high frequency terms, since these are the only ones which bear on resolving power. There has been comparatively little interest at the low frequency end.

However we have results at cm wavelnegths[12], and in the 10μ window[13] down to 10^{-3} Hz. Translated into angular fluctuations, the points fit reasonably well on the curve giving results from optical astrometry[9] which shows two things. First there is no large excess fluctuation due to water vapour - a point of little interest here. Second, we can indeed predict slow fringe phase fluctuations from image photocenter motions measured with highly stable telescopes. No great surprise or improvement is to be expected from interferometers, even with very long baselines.

Differential fringe phase fluctuation between two stars a few arc minutes apart has not been measured; this could only be done with an interferometer more or less like the ones proposed above, in which guiding or stability problems disappear. Again little surprise is to be expected, and there is no reason to believe such a system would compensate for the effects of anomalous refraction any better than a telescope observing both stars simultaneously.

4. CONCLUSION.

By designing into an interferometer system all the safeguards needed to make it at least as good as a direct imaging one for parallax or small proper motion work, we have made it absurdly complex and of purely academic interest. Simpler interferometers (1) might be tried but we are confident they could not compete with our even simpler, non-interferometric proposal.

While only the negative part of our study has been developed here, the very positive conclusion is that atmospheric errors are not presently a limitation. The potential improvement, for instance in parallax work, if one replaces the photographic plate by a suitable photoelectric system, seems as large as the increase in resolving power realized by going from direct photography to speckle interferometry with a given telescope. Actual demonstration may be harder, because while speckle interferometry works with any telescope, improved accuracy here might well require the special one we propose[2]. In any case, the project is very small scale compared to any space undertaking with similar aims.

Note 1

In space the situation is somewhat different. With the fast atmospheric perturbations gone, the interferometer becomes simpler and more efficient. It is at least permissable to consider a shuttle launched interferometer with $L = 10$ m, $D = 50$ cm; the system is continually rotated around the direction of the central star, that is kept close to zero path difference.

The number of reference stars may be reduced to 3, the number of secondary interferometers to 4. They are continually servoed as in Figure 4 and the path difference recorded. After one revolution all the information needed to deduce central star position with respect to reference configuration is available, and even to correct for instrumental errors (e.g. variation of L induced by solar heating). A somewhat different interferometer (operating on only two stars) has been proposed by Labeyrie[14]. More speculation seems idle now; however the sensitivity of the system is very great (about 0.01 x 10^{-3} arc sec RMS error in the distance between two $m_V = 20$ stars in 1000 s). Something along those lines might be considered by NASA some time in the next century.

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DISCUSSION

J.A. Hughes: I would like to point out that the projected plan for Hipparchus, as I understand it, involves an observing phase of one or two years, followed by a single global solution for the positions, parallaxes and proper motions for all objects. This is quite a statistical undertaking.

G. Westerhout: To set the record straight, ESA expects to make a decision on whether to fund the next stage of Hipparchus in early 1980. If that is positive, the earliest launch year is 1983-84, but 1985 seems more realistic.