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THE LARGE BINOCULAR TELESCOPE:
A UNIQUE SCIENTIFIC AND TECHNOLOGY PRECURSOR TO PLANET FINDER

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The Large Binocular Telescope: a unique scientific and technology precursor to Planet Finder

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Abstract. Before a space mission such as Planet Finder to image other solar systems can be well defined, key precursor observations and technology studies are needed. It is necessary to measure the strength of thermal emission from zodiacal dust in these other systems. If it is found to be much stronger than in our own solar system, then its photon noise will prevent the detection of planet signals, without very long integrations with large apertures. It is also necessary to explore the technology of starlight suppression by nulling interferometry.

The Large Binocular Telescope (LBT), now under construction in Arizona, is ideally suited to both tasks. Realistically achievable nulling and low thermal background will allow 11μm zodiacal cloud fluxes to be measured from the ground, despite their being both extremely faint and unresolved by any single telescope. The LBT is especially favorable for the nulling method in that its two 8.4 m mirrors are to be mounted on a beam held perpendicular to the line of sight, just as is planned for Planet Finder's mirrors. Interferometric cancellation of the starlight to a part in 10,000 is needed to sense dust at near the solar system level. The cryogenic, nulling beam combiner to achieve this will be built first on a test bed with small telescopes attached, allowing many of the common techniques of phase and amplitude stabilization for Planet Finder as well as LBT to be developed early on.

The dust emission will be measured in the highly transparent 11μm atmospheric window, so thermal background will be dominated by telescope emission. The direct path for interferometric beam combination provided by the co-mounted elements of the LBT will be especially helpful in minimizing this background. Correction of atmospheric turbulence will be made with deformable secondary mirrors, without the emissivity penalty of conventional adaptive optics. Through the use also of a cold beam combiner in a central dewar, the number of thermally emissive surfaces is reduced to three (primary, secondary, tertiary). The 8.4 m apertures of the LBT result in an 11μm beam width well matched to the $\sim$0.25 arcsec zodiacal cloud diameter of candidate stars, further minimizing unnecessary background flux. Allowing time for background subtraction, and assuming a system emissivity of 5%, detection of a 200μJy cloud at 3σ will take an hour. For a system at 10 pc, this represents zodiacal emission only 3 times brighter than in the solar system, a level that would begin to compromise Planet Finder's operation.

1. Introduction

Advances in space technology have opened the possibility of a mission, called Terrestrial Planet Finder, to study nearby extra solar planetary systems. It would have the sensitivity to detect terrestrial planets in images obtained in the thermal infrared, and to undertake spectroscopic study of their atmospheres. Spectra are our best guide to finding habitable exoplanets and the presence of primitive life. The presence of atmosphere-transforming microorganisms could be signaled by an atmospheric spectrum showing oxygen in the form of ozone, as does Earth's infrared spectrum. (Angel et al. 1986).

The currently favored design for Planet Finder is a linear interferometer with four to eight elements extending over a baseline of 50 - 100 m, following the concepts we advanced (Angel & Woolf 1996, 1997, Woolf & Angel 1997). An artist's concept (figure 1) shows a linear interferometer being assembled in Earth orbit. Interference of the radiation received by several elements accomplishes two purposes: first, to obtain a reconstructed image, in the manner of an interferometric radio telescope array, that will show the different planets orbiting the star; second, to interfere destructively the emission from the star, so its radiation is not seen by the detector. This must be accomplished successfully, for unless suppressed by several orders of magnitude, the photon noise associated with the starlight would prevent detection of the far weaker planet signals.

But even with the starlight canceled to a very low level, and mirrors cooled to eliminate their therml emission there are other potential sources of photon noise. One of these is the diffuse background emission from zodiacal dust particles in our solar system. This background would be severe for an interferometer in Earth orbit, but following a proposal (Leger et al. 1996), Planet Finder's background will be reduced to negligible level by placing it in a heliocentric orbit, several AU from the sun.

The third source of photon noise, potentially the most troublesome, comes from thermal emission of zodiacal dust in the system being studied. Because this takes the form of a diffuse halo about the star, larger than the interferometric resolution required to resolve planets, it cannot be suppressed by the nulling method. Photon noise in the signal from this cloud is predicted to be the limiting factor that sets the time needed to map and obtain spectra of planets. Thus for a cloud of the same strength as in the solar system, this noise leads to integrations times of a day for imaging and 3 months for spectroscopy in the 6-17 μm band. (Angel & Woolf, 1997). If the clouds in other systems are brighter, these times will increase in direct proportion to cloud brightness, for a given interferometer configuration. Zodiacal clouds brighter than the sun's are a possibility - we know of stars such as β Pictoris whose clouds are detectable with current instrumentation because they are several orders of magnitude brighter. If stronger emission by even one order of magnitude above solar is found to be typical, a Planet Finder configuration with large elements in Earth orbit would be preferred. (Angel 1990).

In this paper we examine the proposal (Woolf & Angel 1995) of measuring the strength of extra-solar zodiacal clouds from the ground. It is a very challenging task. The zodiacal cloud in another planetary system like our own will have total emission only 3 x $10^{-}5$ as bright as the star at 11 μm wavelength. In order to include a few dozen good candidates, single stars like the sun, it

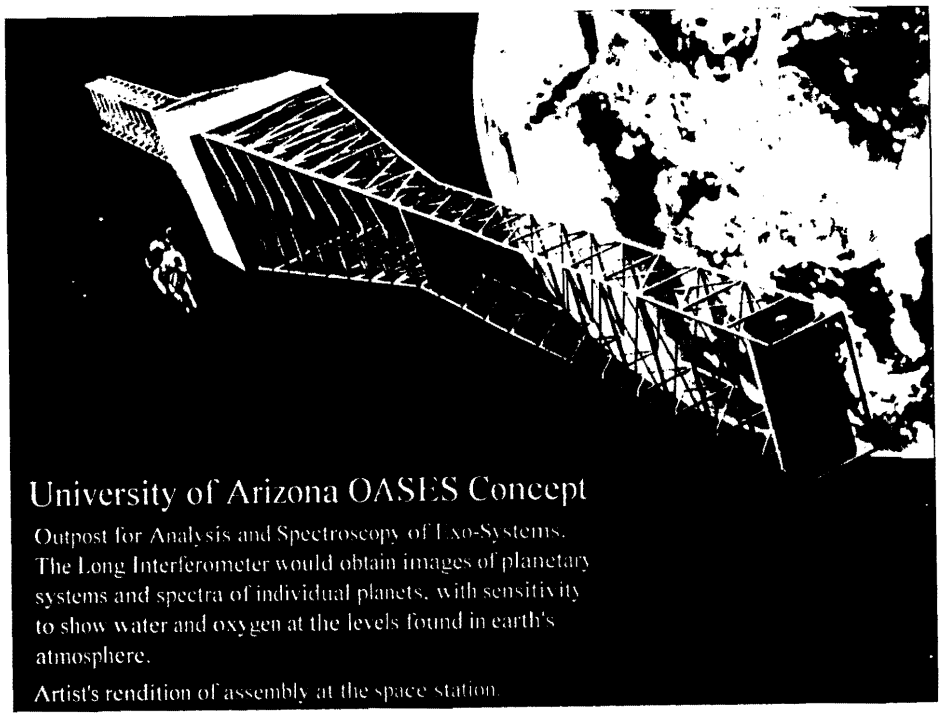

Figure 1. Artist's concept (drawn by Luke Morgan) of the OASES imaging, nulling interferometer concept. Four telescopes are rigidly mounted to a long beam, and their light is interfered at the center to cancel the stellar emission.

will be necessary to extend the survey to stars at 10 - 14 pc distance, including several stars now known to have planetary companions with masses comparable to Jupiter. The emission at 1 AU radius around a star at 10 pc will appear as a disc or ellipse 0.2 arcsec across. At solar system level, its surface brightness will be $\sim 10^{-7}$ of a 300 degree black body. Seen with a state-of-the-art ground based telescope with mirrors emitting a few percent of a 270 degree black body, the cloud will cause only a few parts per million increase in the diffuse thermal background, extending over a patch of sky much less than an arcsecond.

Even the largest ground based telescopes will be unable to resolve such a small cloud at 10μm. Being so faint relative and underlying the star, the zodiacal flux will not be discernable by image deconvolution or as a perceptible infrared excess. For these reasons, detection must rely on interferometry to suppress the stellar emission. In fact, we need a nulling interferometer for dust detection from the ground, just as in space we need it for detection of the even fainter planets.

2. Nulling interferometry for Planet Finder and the LBT

The key requirements in an interferometer for zodiacal dust cloud detection from the ground are 1) element separations of order 10 - 20 m, chosen so that at 11 μm wavelength there can be full constructive interference of cloud radiation while the star is strongly suppressed by destructive interference. 2) very large primary mirrors, whose beam width is matched to the small angular size of the cloud, to reject the very high thermal background from warm, ground-based mirrors.

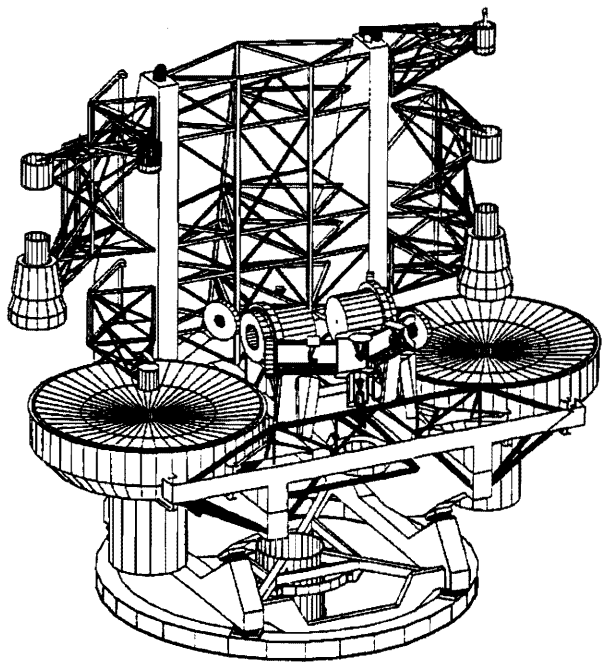

Figure 2. Drawing showing the Large Binocular Telescope (LBT). Two 8.4 m telescopes are rigidly mounted to a 23 m long beam, with 14 m center-to center spacing. Their light will be interfered at a cooled beam combiner in the center, above the mirror plane.

While the principles of nulling interferometry are well understood, they have never been tested in a working telescope array. An ideal array to make such a test and with the power to measure zodiacal cloud strengths is the Large Binocular Telescope, being built in Arizona by an international consortium including Italy, Germany, Arizona's Universities, Ohio State University and the Research Corporation. It is unique among ground based interferometers in having two mirrors rigidly mounted side by side in the same telescope structure and held perpendicular to the line of sight (figure 2), similar to the configuration of Planet Finder. We show below that the favorable geometry, including the large size of the mirrors, 8.4 m diameter, will yield a sensitivity in nulling mode high enough to detect zodiacal clouds of nearby stars. On-site construction of the LBT was started in 1996, when the 1300 ton telescope pier foundation was completed (figure 3). The first 8.4 m mirror blank was cast in January 1997, and first light is projected for 2002, with full interferometric operation with both mirrors in 2004.

The principle of nulling interferometry (Bracewell & Mc Phie 1979) is shown in figure 4. Light from two mirrors, held in fixed relation to each other and perpendicular to the star, is passed through a semitransparent mirror. Each of the two foci is thus formed with light in equal parts from both mirrors. By adjusting the path lengths, we can arrange for the stellar wavefronts to be exactly out of phase at one focus, so destructive interference results in no photons from the star at that detector. At the same time, light waves from dust or a planet very close by (angular separation λ /2d) will arrive at the same detector exactly in phase, so all the photons from both mirrors appears at the detector. In Bracewell's concept, the interferometer assembly is rotated the line of sight to

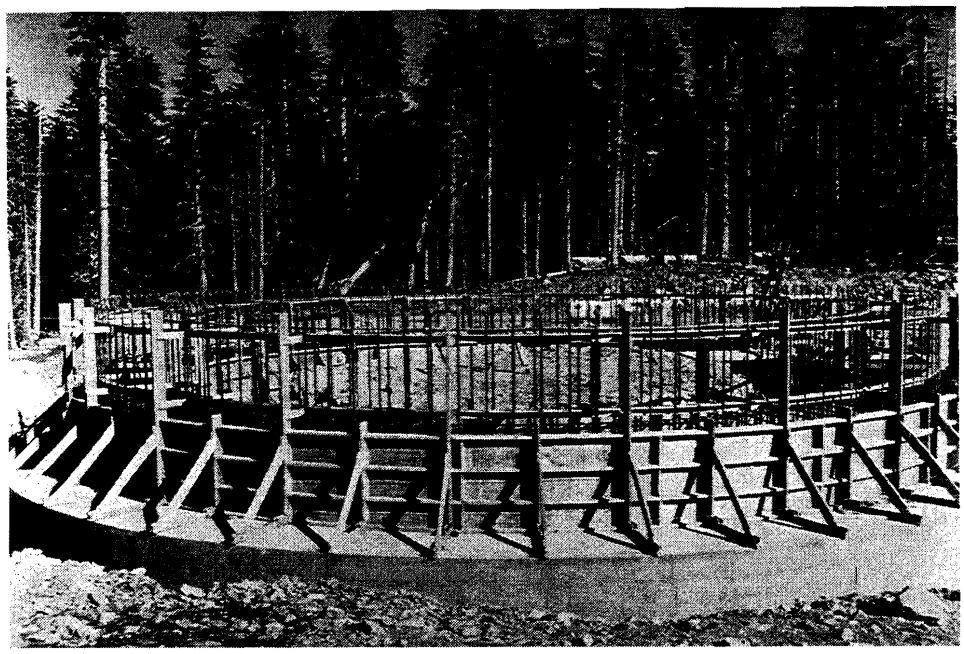

Figure 3. Foundations for the LBT on Mt Graham, Arizona.

the star, and the signal is modulated as a planet as moves in and out of the interference fringes.

For the detection of terrestrial planets with Planet Finder, suppression of the starlight to a part in a million is required, requiring the use of more complex arrays to ensure the interferometric null covers the extended disc of the star. These are based on multiple Bracewell pairs, with 4 or more elements, and they allow full imaging of the planetary system (Woolf & Angel 1997). To search for dust clouds from the ground, however, the single, two-element Bracewell configuration is satisfactory, provided stability and cancellation to a part in 10,000 can be achieved, with the residual "leak" maintained stably at this level. The detection can not rely on modulation with rotation, since a cloud may be quite round. Instead, a precise measurement of the flux remaining after nulling will be needed, with comparison to stars of similar brightness with no dust cloud. If there is an excess flux at the 10^{-4} level of the candidate over the reference star, then this would indicate a dust cloud three times brighter than in the solar system.

The spacing of the two elements should be such that the highest sensitivity to dust will be at the angular radius expected for terrestrial planets. For a twin of the sun at 14 pc, the distance needed to survey a few dozen solar type stars, the angle is thus 0.07 arcsec. Setting this equal to $\lambda/2d$, where $\lambda = 11\mu$m, we obtain d =16 m. Thus the 14 m spacing of the LBT elements is ideal. If large separately mounted telescopes were to be operated as a nulling interferometer, the array elements have considerably larger spacing, resulting in unwanted sensitivity to brighter dust close in to the star that would not be seen by a Planet Finder.

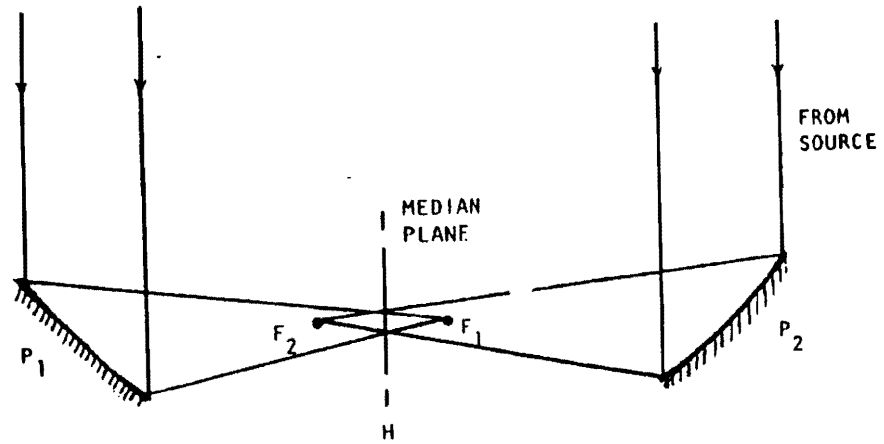

Figure 4. Conceptual design of the nulling interferometer. The two wavefront are superposed with 180 degree phase shift, for complete cancellation of the starlight. From Bracewell and McPhie.

The key issues in determining the sensitivity of an 11μm nulling interferometer are its ability to reject stellar emission, and to minimize thermal background noise. In the following sections, we show how these goals will be met with the LBT, and determine its sensitivity

3. Implementation at the LBT

A key aspect for nulling is to ensure an exact half wave difference between the combined beams, independent of wavelength over the waveband used. In analyzing the LBT problem, we have realized an important general property of beam combination by amplitude division, which will affect the combining optics for both LBT and Planet Finder. The phase relationships on passage through a symmetrical semitransparent mirror can be determined by the following thought experiment. Consider the case of an ideal Bracewell interferometer (figure 4) in which the optical layout is mirrored exactly in the beam combiner, and the star is exactly on axis, so the waves arrive in phase at the combining mirror. It follows from symmetry that the two interferometer outputs must be equal in intensity, for any wavelength, and for any type of beamsplitter coating. Thus signals arriving exactly in phase at a 50/50 beamsplitter must emerge with $\lambda/4$ phase difference, independent of wavelength. This is in contrast to the situation for Young's fringes (division of wavefront), for which the achromatic fringe, again from symmetry, must be bright, i.e. no phase difference. For a nulling interferometer we require the beams to emerge with $\lambda/2$ phase difference from one of the outputs (they will be in phase from the other). This must be accomplished by introducing a quarter wave achromatic retardation differentially between the two beams, before they arrive at the beam combiner. This requirement has not been recognized in earlier discussions of nulling beam combination (Bracewell & McPhie 1979, Angel 1990, Shao & Colavita1992, Angel et al. 1996). To obtain

such retardation, suitably chosen transmissive materials of different dispersion will be introduced in the two incoming beams, analogous to an achromatic lens, or by other means to be discussed elsewhere (Burge & Angel 1997).

An implementation of a nulling interferometer with the LBT that respects these considerations is shown schematically in figure 5. The individual telescopes are being built with adaptive f/15 Gregorian secondaries (Hill 1996) for wavefront correction to the diffraction limit in the infrared. Tertiary mirrors direct the converging beams to the windows of a large central dewar, extended out by vacuum pipes. Inside the vacuum there are cold field stops at the bent Gregorian foci, followed by ellipsoidal relay mirrors that re-image the star to the combined interferometric foci. At the pupils formed by these mirrors are located cold pupil stops. Before the 50/50 beam combining mirror are the refractive elements for achromatic $\lambda/4$ phase difference at 11 microns. The two 11 micron output channels from the beam combiner would be focussed onto array detectors to record the complementary nulled and bright star images.

To ensure strong destructive interference of starlight, the two optical paths to the nulled focus, averaged over each of the telescopes must be held to half wave difference, with an accuracy of a small fraction of a wavelength. For cancellation to a part in 10,000 targeted for dust cloud detection, the phase error must be no more than 1/100 radian, i.e. a path difference error of $\lambda/2\pi/100 = 17$ nm rms. Such accuracy in the face of atmospheric turbulence demands adaptive control of pathlength. Cancellation to better than a part in a million for Planet Finder requires a tolerance is about 1 nm, when again active stabilization will be required.

The most striking features of the LBT nulling configuration are its symmetry, simplicity and its minimal number of warm reflecting surfaces. The beams enter the dewar after only three reflections (primary, secondary and tertiary). The telescope primaries will be sometimes coated with silver, and both secondary and tertiary will have silver coatings, for a total system emissivity of less than 5%. We will find that such low emissivity is essential if zodiacal clouds similar in strength to the sun's are to be detected.

4. Wavefront and pathlength control

The key control elements in the LBT interferometer will be its adaptive Gregorian secondary mirrors. Though 910 mm in diameter, these will be made of glass only 2 mm thick, supported at 500 actuation points (Salinari, Del Veccio and Biliotti 1993). Wavefront errors in shape, tilt and phase difference will all be corrected by control of these actuators, with no need for any additional control elements. Because the secondaries are large and very close to the telescope exit pupils, wavefront control actuation will cause the smallest possible modulation of the strong 11μm thermal background. In making the correction at the secondary, we are respecting the well proven principle for field chopping at the secondary (Low and Rieke 1974).

4.1. Individual wavefront measurements

For the measurement of wavefront and phase errors, we envisage a multipronged approach, involvoving sensors for the individual and combined telescope wave-

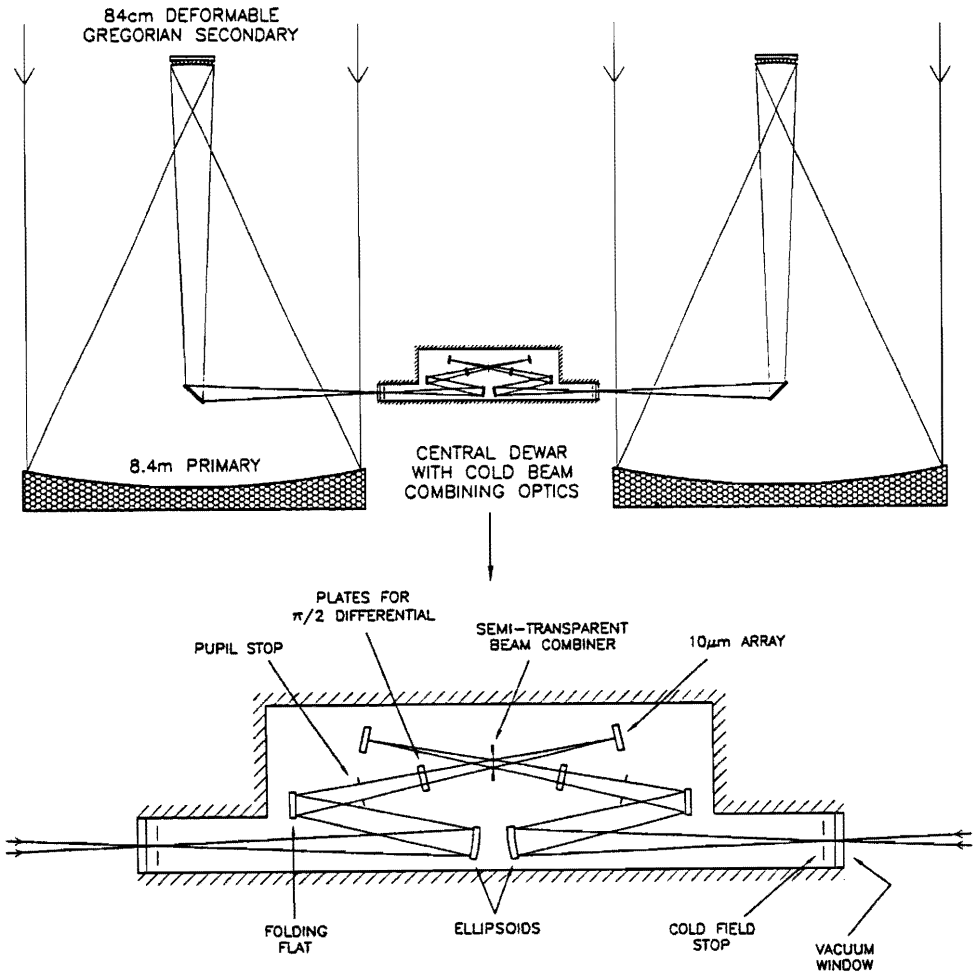

Figure 5. Implementation of a Bracewell nulling interferometer for the LBT. The optical elements and their placements are shown to scale, and the end to end dimension is 23 m. Atmospheric aberrations and phase difference are corrected at the Gregorian secondaries, which are in the form of a thin glass membrane with deformation controlled by many fast-acting actuators. The beam combining optics following the bent Gregorian foci are located inside a dewar, where they are cooled to avoid any additional thermal background. See text for details.

fronts, and multiple wavebands. Atmospheric distortion and tilt of the individual wavefronts will be measured by sensors in the central dewar, operating at optical or 1.6 μm wavelengths (H band). The folding flats of figure 5 will be made as dichroics, transmitting wavelengths$\leq 2\mu$m for this purpose. The sensors will measure phase errors using the Zernike self referencing method (Colucci 1994, Angel 1995). Control of the wavefront by the deformable, tiltable secondary will then follow by the well established servo control method of adaptive optics (Sandler et al. 1994). Because the stellar signal is relatively bright, the accuracy of correction will be limited primarily by the accuracy of fitting the wavefront with the 500 actuator parameters (fitting error). Under typical conditions, this error will be about 75 nm rms (Salinari et al 1993). It follows from the Marechal approximation that the Strehl ratio at 11μm wavelength will be about 99.8%.

4.2. Measuring phase difference

The average optical path difference between the two telescopes must be corrected by piston motion of the secondaries to an accuracy of 17 nm rms. Obviously some form of servo control is needed to correct rapid phase fluctuations caused by large scale atmospheric turbulence, or irregularities in the azimuth tracking of the 23 m long LBT. At first sight it might seem that precise laser metrology would be essential. However, light from a stellar disc of a only few milliarcsec diameter is coherent at shorter infrared wavelengths, making it the perfect tool for measurement and control of both the ground and space interferometers.

This is illustrated by an experiment conducted at the MMT a few years ago, to actively remove phase errors measured by starlight. The optical configuration of the MMT in its present array configuration is similar to that of LBT and Planet Finder, in having separate telescopes rigidly mounted to a common, pointed structure. In the experiment interference fringes were obtained between light from two of the MMT's 1.8 m telescopes having 4.4 m center-to-center separation. In this case, Young's fringes were formed in the focal plane by division of wavefront at a central beam combiner, rather than division of amplitude, but the angular sensitivity is not altered. Measured at 2.2μm wavelength with an infrared array reading at 80 Hz frame rate, the fringes with 0.1 arcsec spacing were easily visible, but jitter about. The motion corresponded typically to 1.2μm rms fluctuation in path length.

A servo loop based on real time measurement of the fringe position was used to stabilize the motion by path correction with a piezo-driven mirror. An example of a long exposure of Young's fringes stabilized in this way is shown if figure 6. During this exposure of the bright star β Cyg, atmospheric path length variations of 1.2μm that correspond to an angular jitter of 40 milliarcsec were reduced to about 200 nm rms ($\sim$4 mas rms jitter). This fluctuation is still about 10 times larger than is needed for the LBT system, but an improvement of this magnitude is quite realistic. Most of the residual error in the MMT experiment is accounted for by the relatively long time delay before correction; there was an 18 millisec delay from signal arrival to piezo correction. Much higher accuracy could have been realized with a control cycle time of 1 msec.

For nulling interferometry at 11μm with the LBT, phase stabilization by direct measurement of fringes at that wavelength is not practical. The signal to noise ratio obtained with candidate G stars of 5th magnitude will not be high

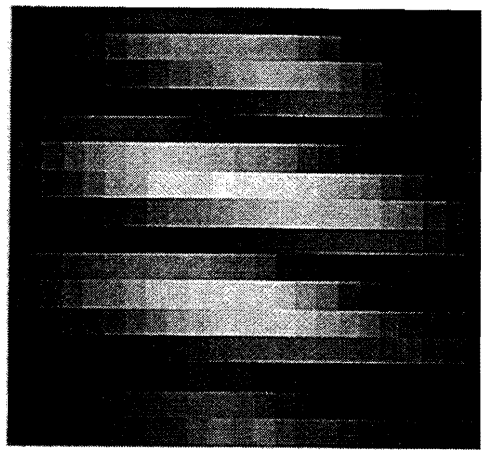

Figure 6. Long exposure of Young's fringes obtained by interfering 2.2 μm radiation from two of the six component telescopes of the MMT. The outer circular envelope is the Airy disc of the individual telescope apertures, and the fringes are spaced at 0.1 arcsec, corresponding to the 4.4 m baseline. A servo based on fringe phase measurements at 80 Hz rate and a piezo driven mirror was used to largely remove phase errors from atmospheric turbulence.

enough to measure phase at the required accuracy and speed. Noise from thermal background is too high. Thus the stabilization will be made at 2.2μm, where the stellar fluxes will be enormous, typically 1,000,000 photons/ millisecond in the K band, and there is negligible sky background. Wavefront stabilization at the shorter wavelength is valid because atmospheric dispersion between 2.2 and 11 μm is small, $\Delta n/(n-1) = 0.001$. The atmospheric path length over the 14m LBT spacing will be $\sim$5μm rms. Thus the residual error from dispersion will be $\sim$5nm rms, an acceptibly small fraction of our 17nm total phase error.

In a specific concept for the LBT, we plan to superpose the 2.2μm wavefronts from the two telescopes with $\lambda/4$ phase difference, so both outputs from the beamsplitter are gray. This gives maximum sensitivity to phase differences. The interference would be measured in the pupil plane, by imaging the output pupils onto imaging arrays. In this way, we would determine not only the overall phase difference between the two wavefronts, used to control piston motion of the secondary mirrors, but local differences in phase across the overlapped pupils. These would be caused by residual errors in the individual wavefront correction loops. A region in which one wavefront was ahead of the other would show as a lighter patch in one pupil, darker in the other. A path length error of 17 nm, for example, will result in an intensity difference of 5%, readily detectable even in a small subaperture. An additional term to the adaptive secondary shape correction would be added to minimize these local differences, to further reduce scattered light in the 11μm nulled image.

4.3. Combining different phase requirements for control at 2.2μm and nulling at 11μm

The phase difference needed at the detectors are $\pm\ \lambda/4$ for the 2.2μm control band, and $\lambda/2$ for the 11 μm nulled image. These two may be achievable with a single semitransparent mirror. Remembering that the mirror alone will introduce an achromatic $\lambda/4$ difference, we need a further $\lambda/4$ for the 11 micron

band, and could accept a full wave of difference in the 2.2 micron band. Since these additional path difference requirements are in inverse proportion to wavelength, and both correspond to about 2.5 microns path difference, they may be realizable in practice with carefully chosen refractive plates located before the beam combiner. We plan to explore this possibility and use it if practical. An alternate solution with separate beam combiners for the two wavebands could always be made to work, but using the single mirror would ensure an exact correspondence between the measured wavefront difference and the interferometric null at 11μm.

The exploration in practice of the different approaches should be extremely useful in determining just how to implement phase controls for the still more critical nulling for the Planet Finder mission.

5. Detection and estimated sensitivity

Detection at 11μm in a 1μm bandwidth will be made with an imaging array such as the MIRAC infrared array detector (Hoffmann et al 1993) . This reads out at about 1 kHz frame rate, to avoid well saturation, and provides the observer with a real-time display as well as long integrations. The stellar image will be focussed on the array, with a scale chosen so the Airy pattern is well sampled.

What will we see? The ratio of star signal to thermal background noise for a candidate 5th magnitude G star is large, so the star will be easily visible in real time. With no adaptive controls, the two overlapping star images will each be well formed Airy patterns of width $11/8.4\ \mu$mR $= 0.27$ arcsec, but moving largely independently with amplitude $\sim$0.1 arcsec rms. With the independent telescope AO servos on, the Strehl ratios will become high (99.5%) and the motion will be stabilized, but the single combined image brightness will vary wildly as the two wavefronts are brought in and out of phase by the turbulence. (Note there are no fringes in the image plane, as there were in the MMT experiment. The fringes for amplitide division are in the plane of the sky). When the phase servo is switched on, the entire Airy pattern for a candidate star will double in brightness in one of the real time displays and will be lost in the thermal background noise in the other. Only after a long integration, with sky chopping will we see a residual star signal at the core of the Airy pattern. If there is a dust cloud, then we will see an additional signal, which if strong enough may appear slightly resolved.

Note that because the wavefront of the individual beams is corrected locally only to $\sim$75 nm rms, the total starlight energy will not be cancelled to a part in 10^{-4} The corresponding local phase errors in each of the nominally cancelling phase vectors are 0.043 radians rms at 11μm and will lead to local intensities (and to a total transmitted energy) of 10^{-3} of the in phase peak value. However, since we expect the phase errors in the two beams to be on a small scale and uncorrelated across the pupil, this energy will be spread into out in a uniform halo much larger than the Airy disc. Within the suppressed Airy disc, where the dust cloud flux is concentrated, the star intensity will be not be raised above the 10^{-4} level by the halo. It has been suggested that single mode fibers or spatial filters to "clean up" local wavefront errors before the detector. However,

detection made in the Airy core of the focal plane has the same effect, allows for diagnostic information when the phase is detuned, and is simple.

The null to 10^{-4} accuracy requires good matching of amplitude as well as phase, with average intensities from the two telescopes equal to 1%. With care, the very high reflectance coatings of the optical system should result in balance close to this level. In any case, the signal strengths at the 11μm detector will be checked, by blanking each telescope input sequentially with a cold baffle in the dewar. Observations of a bright star and will allow accurate comparison, obtained over a resolved image of the pupil if desired. Imbalances would be corrected by cooled, custom-made pupil masks.

Let us suppose that the required balance in phase and amplitude has been accomplished, and we now need to measure the strength of the residual flux at a level of the 10^{-4} level. The strength of the 11 μm thermal background, even with only 5% telescope emissivity, is still very high. A sun-like star at 10pc, imaged through an 8.4 m telescope in the diffraction limited beam width of 1/4 arcsec, is still fainter than the sky emission in the same beam. The thermal emission is the equivalent of a 33 Jy source, while the star is 1.5 Jy. The photon noise from the sky flux, again taking the diffraction limited beam width, is 2 mJy per root Hz.

When the telescope outputs are combined, the thermal background fluxes remain unchanged. A dust cloud will appear more strongly in the constructive than destructive output, because it is centrally concentrated. We will assume the output ratio is 2:1. Allowing for a 50% loss in integration time for time spent nodding or chopping to the sky for background suppression, we find that a 200 μJy cloud (10^{-4} of the candidate star) will appear at 3σ above the thermal photon noise background in an hour of integration. A solar system twin at 10 pc would show a zodiacal cloud at 70 μJy, thus the LBT will clearly see in an hour clouds at only three times this level. These absolute calculations have been confirmed by comparison with the observed performance of the MIRAC mid infrared camera on the IRTF telescope. With several weeks of integration spent on the candidate list, a clear picture of zodiacal cloud strengths would be obtained, the information needed to design the Planet Finder mission.

6. Test Bed for Cryogenic Nulling Interferometry

While the LBT is needed for the sensitivity to detect such faint zodiacal clouds of other stars, much of value to LBT and Planet Finder can be learned now with a test bed aimed at developing the special requirements of nulling interferometry. These requirements are sufficiently exacting, it is likely that an extended experimental effort will be needed to reach even the 10^{-4} extinction goal needed for zodiacal dust detection with the LBT. For this purpose we propose to build early on the central dewar of the LBT system, and to use it as a test bed for nulling performance. This cryogenic nulling test bed will play the same relation to Planet Finder as the Palomar test bed does to SIM.

The tests will be initially conducted with artificial laboratory sources to yield coherent 10μm laser or white "light" beams at the two inputs. Then nulling will be tested with starlight, by mounting the dewar on an azimuth bearing, and equipping the two ends with small telescopes on elevation drives (figure 7). In

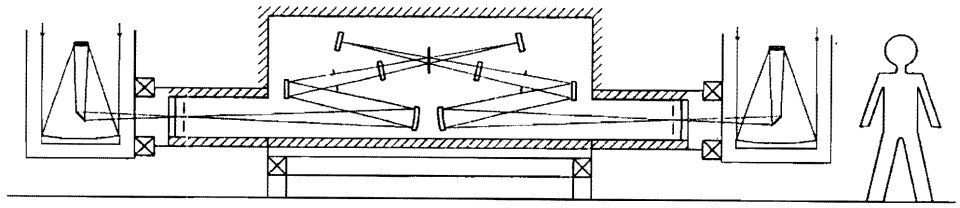

Figure 7. Test bed for cryogenic nulling interferometry. The dewar is the same will be installed in the LBT, but is shown here fitted with small feed telescopes for early development and testing. The test bed rotates in azimuth with the dewar in fixed orientation to gravity. The two telescopes are cantilevered from independedent elevation bearings.

the drawing we show apertures of 1/10 the LBT mirror size (84 cm). These small telescopes will be fitted with adaptive secondary mirrors, whose corrective motion will be largely in tip, tilt and piston. Low order adaptive control of the differential (nulled) wavefront will be used as needed to match the wavefront quality of the LBT system. This test bed will yield the same accuracy of phase stabilization and the same thermal background and 11μm signal/noise ratio as the LBT for stars 5 magnitudes brighter. There are sufficient bright stars for testing to this limit at any time. For access to fainter stars, we are considering the use of two of the 1.8 m telescopes surplussed from the MMT array.

Many of the most challenging technology problems for Planet Finder will be explored by the nulling test bed and LBT systems. Thus measurement and control to high accuracy of wavefront, phase and amplitude errors are common requirements. Cryogenic beamcombiners and dichroics with very well controlled properties are needed in both cases, with real world measurements of phase differences and amplitude balance. The rapid fluctuations of the atmosphere may seem like a complicating problem on the ground, but in fact residual vibrations in space could easily set up rapid motions of a few microns over $\sim$50 m length, needing similar stabilization techniques. Thermal noise on the ground is far larger than in space, but not so much in proportion to the signals, which for planets will be several hundred times smaller. Long integrations to overcome photon noise will be needed in both cases, and the long term stability to make these valid.

While planet signals have the advantage of being modulated by Planet Finder's rotation, the dust cloud signal we seek is static and therefore apparently more elusive. We note, though, that strong, stable nulls are needed for both systems. The LBT needs a null stable to better than 10^{-4}, to reveal the diffuse dust underlying the star. Planet Finder must at the very least null the star

to an absolute level fainter than its zodiacal cloud, or stellar photon noise will dominate. As a further requirement, noise modulation of the residual star flux must not have a component that mimics any planet modulation pattern, at the level of 10^{-7} of the star. Valuable, hands-on experience in dealing with such stringent nulling requirements can be gained with the test bed and LBT experiments.

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