ADAPTIVE OPTICS

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ABSTRACT

Adaptive optics is a technique for correcting atmospheric wavefront disturbances to yield diffraction limited imaging. It is a technique whose advantages are most apparent in the 2-5μ spectral region, where wavefront corrections are derived from study of visible objects. Graphs are presented to show performance needs of adaptive optics systems.

INTRODUCTION

The idea of correcting the wavefront arriving at a ground telescope to get perfect images has been around for some time e.g., Babcock (1953). Of the various ways of getting high angular resolution images, this adaptive optics has the greatest potential for studying faint objects, it has the greatest difficulties of implementation and the greatest cost. There is also a lesser task, which is that of correcting the optical figure of a telescope so as to get seeing limited performance. This latter goal is called active optics. The figure of telescope optics, focus, misalignment, etc., changes on a slow timescale, and can be corrected at frequencies below 0.1 Hz. In constrast, atmospheric fluctuations of wavefront occur at higher frequencies, and adaptive optics may, for some observations, need to operate at frequencies above 1000 Hz. Whereas active optics is usually unable to compensate for any significant fraction of atmospheric disturbances, adaptive optics will readily correct for optical imperfections of the telescope provided only that wavefront errors do not have too high an amplitude or spatial frequency. In general, active optics is likely to be able to work by modifying support forces and positions of existing optical components, whereas adaptive optics will require new optical components capable of high frequency articulation to be inserted into the optical train. Detailed discussions of adaptive optics have been given by Hardy (1978, 1982). Woolf and Angel (1980) have discussed some IR aspects of adaptive optics.

Adaptive optics theory is based on the assumption that atmospheric disturbances obey a Kolmogorov spectrum. The evidence that this is indeed the case has been presented by the author (Woolf 1982). There is a deviation from this spectrum expected at small scales where turbulence turns into heat. This

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has no major effects on seeing. In addition there are deviations at large scales where turbulence is injected. One indication of this is shown in Woolf, McCarthy, and Angel (1983). This may also show itself by images from extremely large telescopes showing less motion in proportion to their size than would otherwise be expected.

Deviations from a Kolmogorov spectrum would be expected to have repercussions on the design of adaptive optics, and therefore require consideration before using the theory. There are two kinds of images which might suggest deviations from a Kolmogorov spectrum. These are, large images with very little motion, and small images with very large amounts of motion. If there is little moton, then the outer scale of turbulence (for the dominant turbulence), must be smaller than the telescope primary. This will occur when the primary mirror temperature is severely out of equilibrium with ambient air. Benard convection cells, or roll convection on the primary will be responsible, depending on the tilt of the mirror. There will be a need to correct high spatial frequencies, at a low temporal rate. In general such problems should be seen as indicators against the use of adaptive optics, and rather for a rigorous program of facility seeing improvement.

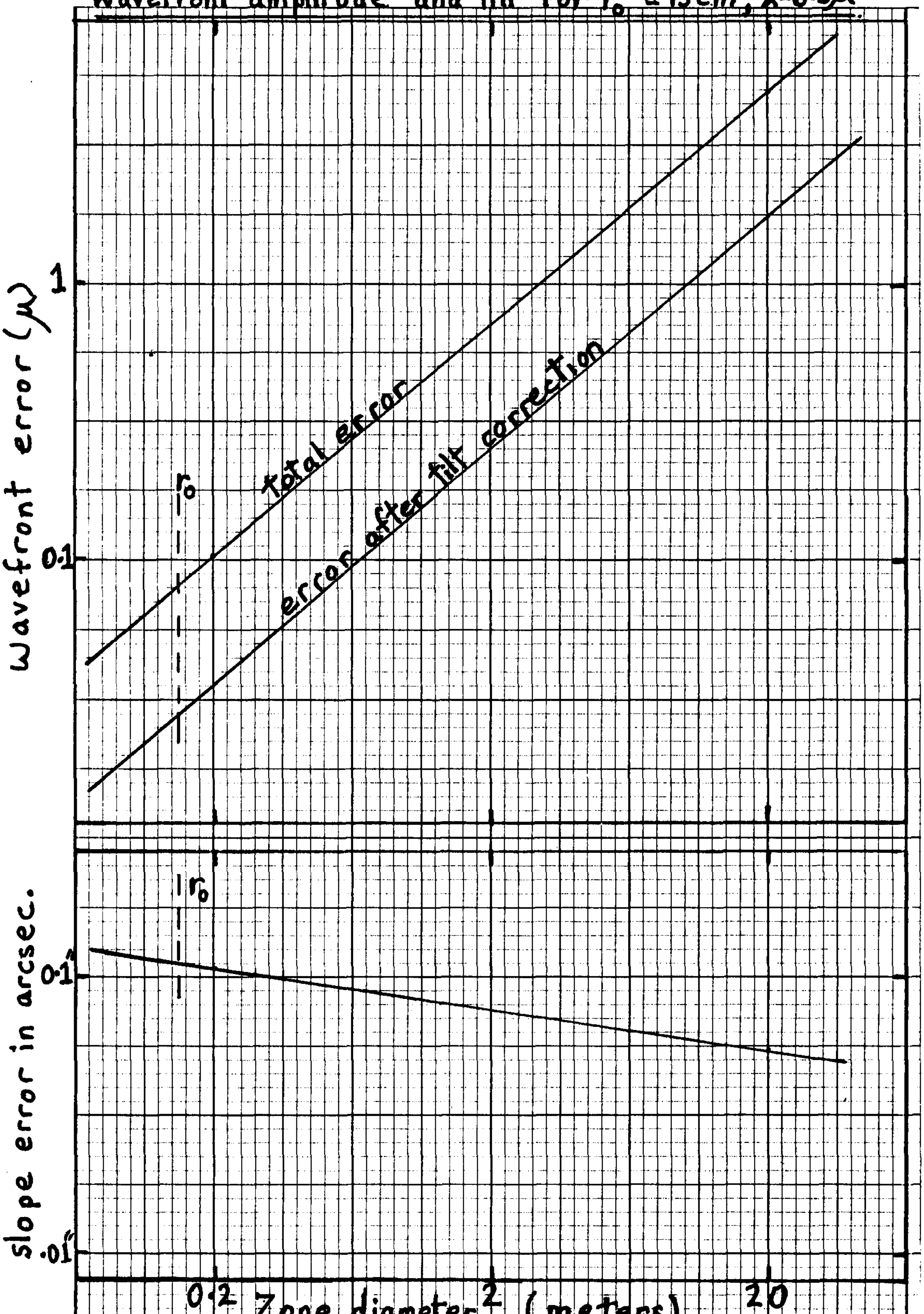
Exquisite images, dancing around at high speed have on occasion been reported from large telescopes. If the motions were indeed implying that large scale disturbances had been injected into the atmosphere, there is no known way of preventing these eddys decaying and producing enlarged images. Therefore it seems that these image motions must instead be produced by vibration of the telescope or some optical component ("sailing", rather than "seeing", Woolf and Ulich 1984). In general, sailing is correctible by adaptive optics, but may place a severe load on the amplitude of wavefront correction required. Thus e.g. a 10m telescope showing 1" peak-to-peak image motion requires 50μ peak-to-peak wavefront correction, whereas a typical seeing motion will be ~ 5 times smaller. The comments about mirror seeing correction are also applicable here. Adaptive optics should be considered as a way of making good images better. It is a most expensive way of correcting for poor telescope design or implementation.

BEHAVIOR OF THE ATMOSPHERE

The seeing disturbance of the atmosphere produces a peak-to-peak wavefront error increasing to large distances as $d^{5/6}$, see Figure 1. Correspondingly, the rms slope of the wavefront is proportional to $d^{-1/6}$. In the geometric optics condition this sets the image size. However, the steepest wavefront slopes occur with the least wavefront amplitude. Below ~ $\lambda/6$, wavefront errors are

Figure 1

Wavefront amplitude and tilt for $r_0 = 15$ cm, $\lambda = 0{\cdot}5\mu$



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such that they depress the central diffraction core, but do not affect the image core FWHM. Thus apertures over which wavefront errors are less than ~ $\lambda/6$ are diffraction limited, and larger apertures are seeing limited. The transition dimension r_o is a wavelength dependent length. Thus $\lambda \propto r_o^{5/6}$ or $r_o \propto \lambda^{1.2}$. Since the diffraction limited resolution θ, is proportional to λ/r_o, it is proportional to $\lambda^{-0.2}$.

Adaptive optics deforms a surface in the optical train to correct for wavefront errors in the incoming beam. If the corrections could be inserted at an image plane of the region of the atmosphere which inserts the errors, then a perfect optical system would have been restored. In practice, wavefront errors are inserted from the upper stratosphere down to the focus, and while perfect correction can be applied to one image point, the corrections cease to be adequate beyond a so-called "isoplanatic patch". This area of sky increases to long wavelengths, where less perfect correction of the atmosphere is adequate, and also can be larger if less perfect image correction is acceptable.

It is in principle possible to have correction applied to a number of planes conjugate to those where errors are inserted. In practice it is hard enough to get information adequate to correct one plane and in consequence this isoplanatic patch is set by the ratio of r_o to a characteristic height range of the atmosphere over which wavefront errors are inserted. If this height is 10 km, and r_o = 10 cm, then the isoplanatic angle is 10^{-5} radian or 2". Correspondingly, if r_o is 8 meters at 20μ, the isoplanatic patch is ~ 3'. If one stellar object is used for sensing errors, and another one is to be observed, it is essential for the two objects to be in the same isoplanatic patch.

It is not essential for the two objects to be observed in the same wavelength band. The refractive index of air at visible and IR wavelengths is very similar, further, differential refraction is usually much smaller than the IR isoplanatic patch, thus it is possible to observe an optical object and apply corrections for an IR observation (Woolf and Angel 1980).

THE SIZE OF WAVEFRONT ERRORS

Hardy (1983) has given the size of wavefront errors across an aperture of diameter d:

Total wavefront error $\approx 0.16\ (d/r_o)^{5/6}$ waves rms.

After tilt removal, residual error $\approx 0.06\ (d/r_o)^{5/6}$ waves rms.

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There is a wavefront error that the active optics will produce if the reference source is faint, producing N photoelectrons/second from the mirror area

Photon noise errors $\approx 0.06\ (7.5/N)^{1/2}$ waves rms.

There is a time delay error if corrections are made at a time Δr later than they are measured. This error increases with the speed $\bar{v}$ at which the disturbed wavefront crosses the telescope, increasing as

$$\Delta r \bar{v} / r_o$$

Finally, there is an isoplanatism error if the reference source is separated from the imaged object by an angle $\Delta\theta$, with the error increasing with $\Delta\theta h / r_o \cos^{8/5} z$, where z is the zenith angle.

The effects of these terms are shown in a series of graphs. Figure 2 shows how it is necessary to control smaller and smaller patches of the entrance pupil to obtain diffraction limited images as the wavelength gets shorter, or the seeing worse. The seeing conditions assumed are r_o = 15 cm at 5000Å for good seeing. Poor seeing is r_o = 6.5 cm, excellent seeing r_o = 34 cm.

The wavefront error effect can be related to the energy concentration in the core of a diffraction pattern.

$$\frac{I}{I_o} \approx 1 - 4\pi^2 \left(\frac{\varepsilon}{\lambda}\right)^2$$ where ε is the rms wavefront error.

Thus for a 0.1 wave total budget, there is about 60% of maximum energy within the core, and for 0.05 wave budget about 90%. The error budgets assume that three equal terms contribute, being typically residual curvature over the corrected patches, correction applied later than the measurement made, and the third being an assumed equal contribution from photon noise and lack of isoplanicity.

Figure 3 shows the total response time for observation and control corresponding to Figure 3. One of the less expensive control options is to use a television camera as sensor, with an overall response time of at least 0.015 second, probably twice as much. Lines corresponding to these response rates are also marked on the figures.

Figure 4 shows the angular field of view corresponding to the isoplanatic patch for these same conditions. Figure 5 asks under what conditions one can expect to find a bright enough star to make corrections within the isoplanatic

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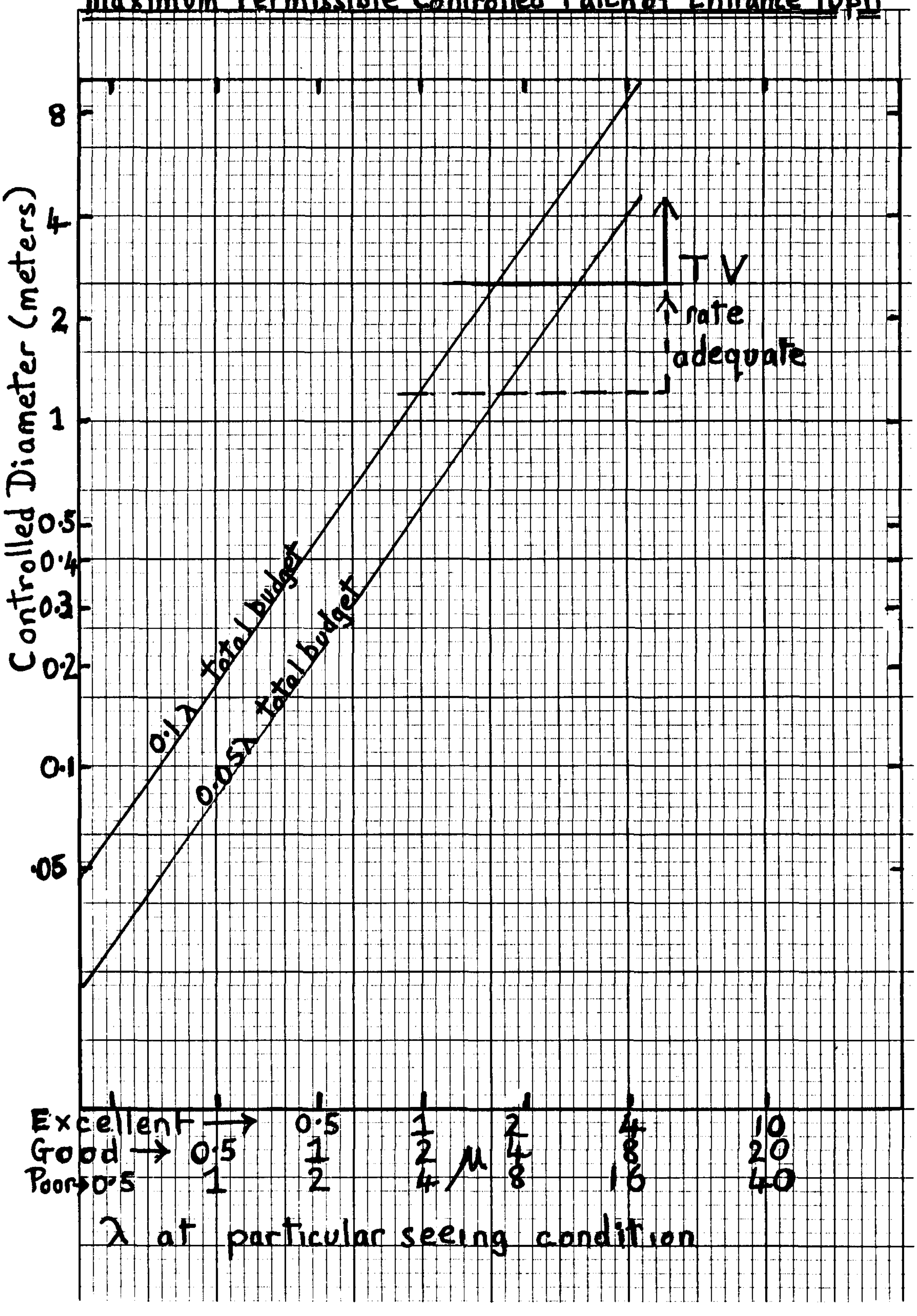
Figure 2

Maximum Permissible Controlled Patch of Entrance Pupil



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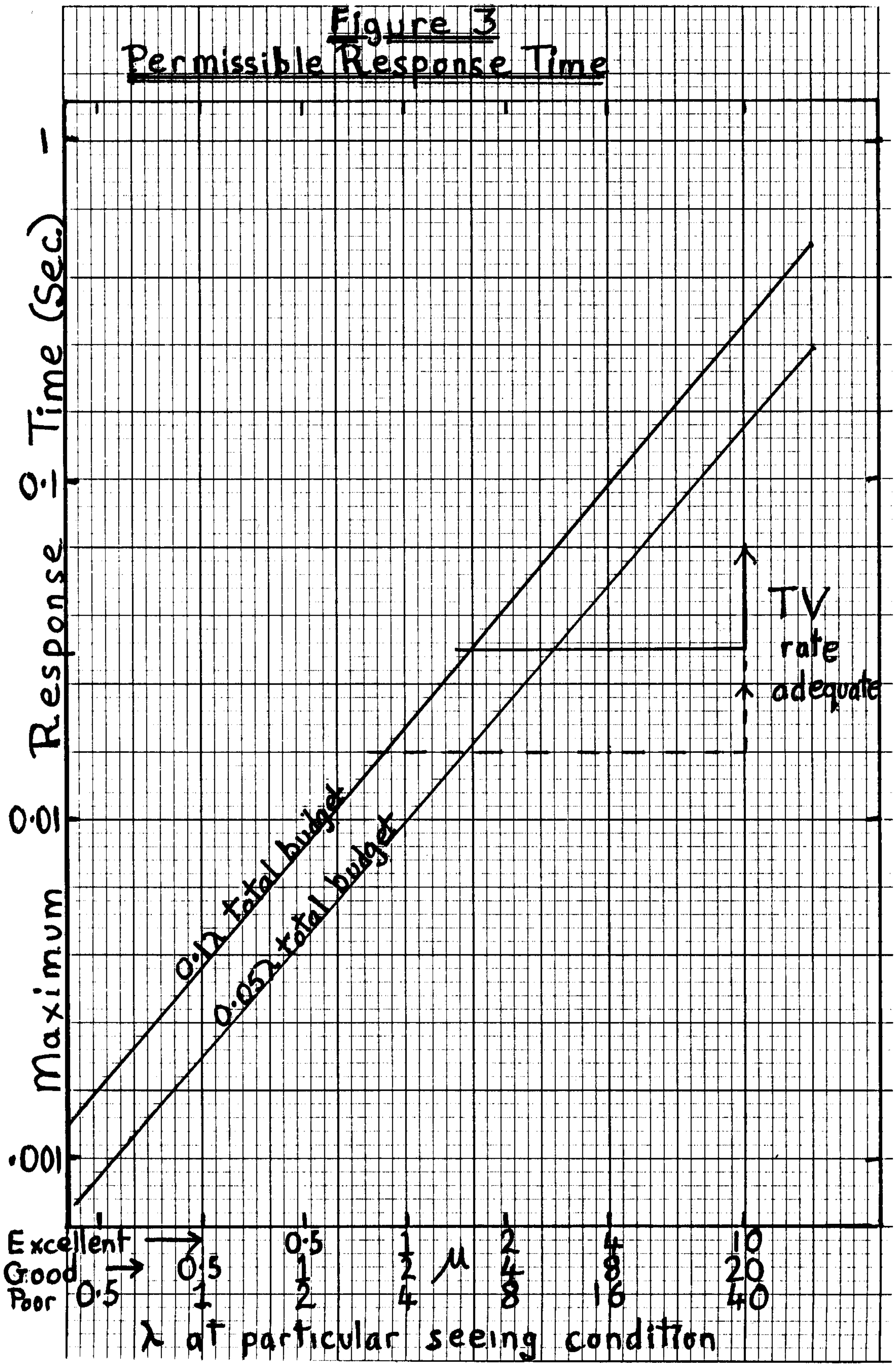

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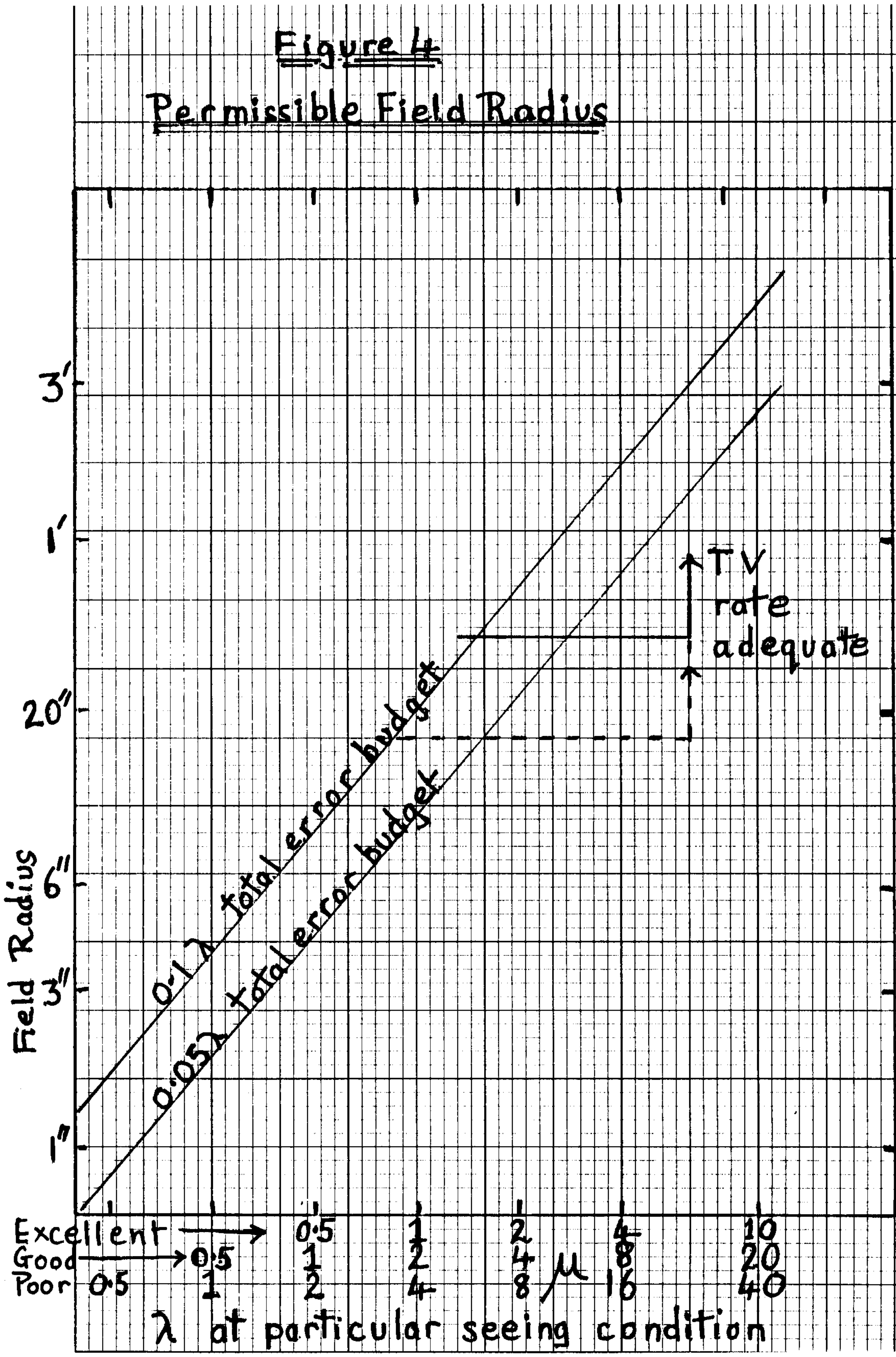

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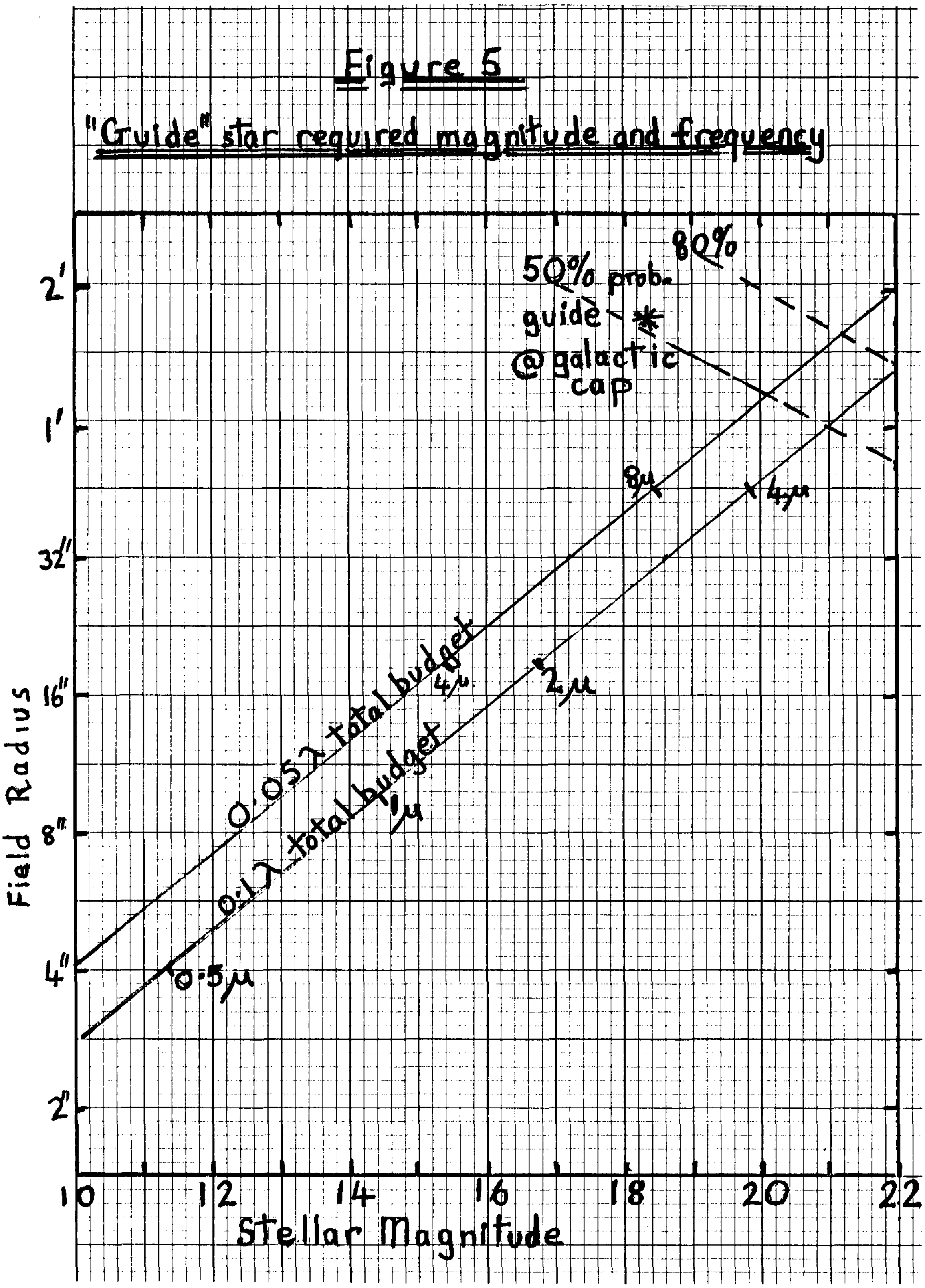

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patch near the galactic poles. Here it is assumed that the correction is obtained from the visual light of the object, but that adaptive optics is used to correct an IR image.

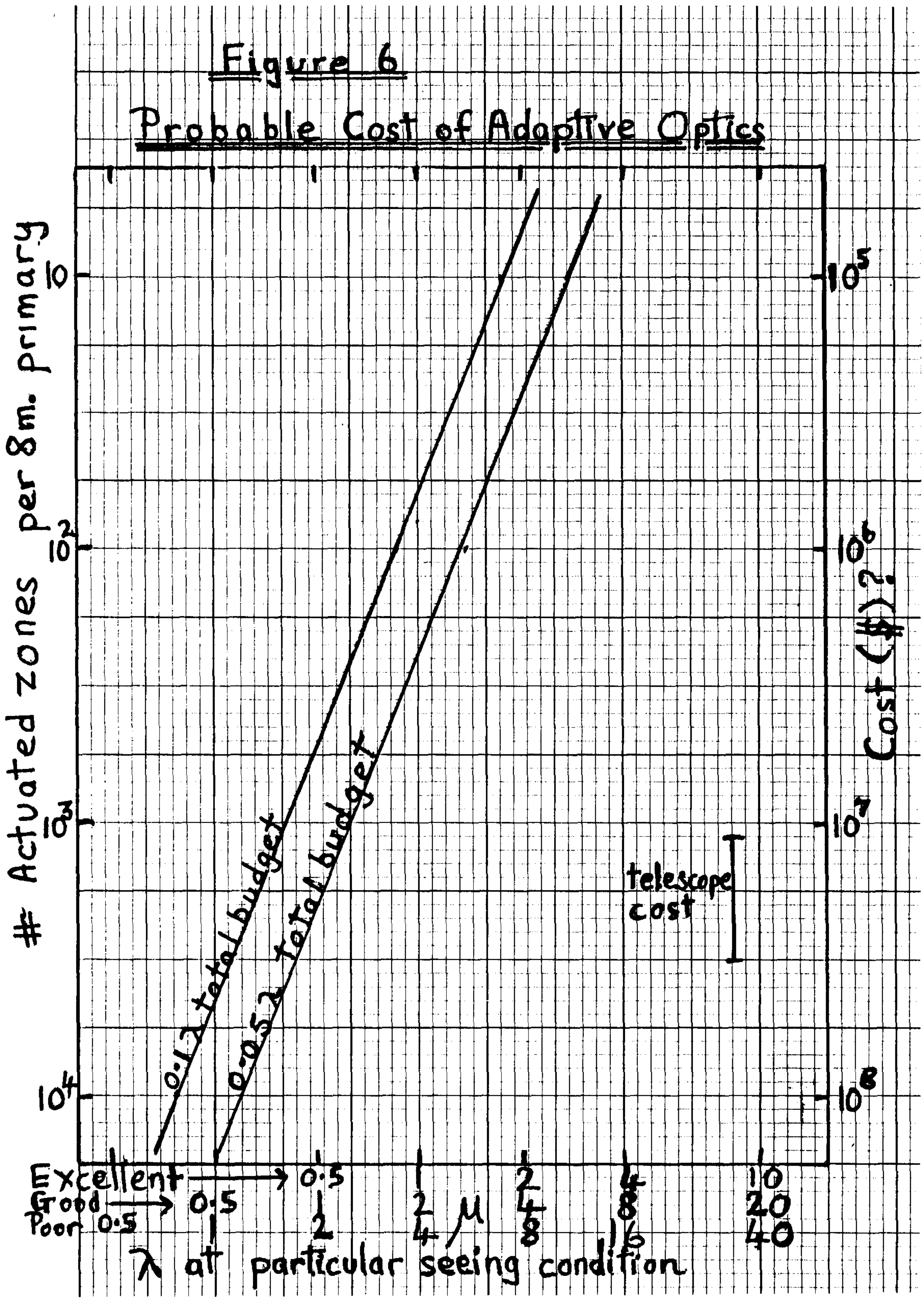
It can be seen that random reference stars will only be suitable for use at long IR wavelengths, or under exceptionally good conditions. In general it seems likely that adaptive optics will need to operate with the visual light of the object. Fortunately even quite faint objects will provide enough light to operate adaptive optics in the IR.

Finally in Figure 6, we have attempted to estimate the cost of fitting an 8m telescope with adaptive optics. The assumption is that each corrected element of surface will cost a total of $\$10^4$. If one corrects many elements, then the correction will need to be at high temporal frequency. The extension to higher and higher frequency is likely to wipe out the mass-production advantages of more channels. This is a very crude reconnaisance of the problem, but does indicate that adaptive optics for visible or near visible wavelengths is likely to be very expensive. In addition, the tiny isoplanatic patch may well also be limiting. In contrast, adaptive optics that can operate down to 2-3μ under the best seeing conditions seems likely to be both useful and to have a reasonable cost.

ADAPTIVE OPTICS AND ALTERNATE TECHNIQUES

Adaptive optics at O-IR wavelengths differs from adaptive optics at radio wavelengths because at O-IR wavelengths, individual telescope apertures tend to be greater than r_o. In consequence, real time correction of the wavefront increases the peak brightness in an image and shrinks its size, so giving greater contrast with thermal or airglow background radiation. This means that greater sensitivity to faint objects is available from adaptive optics than with other techniques. Another way of seeing this is to consider that with adaptive optics, a total observation of 10^4 seconds is coherent for addition of signals. In contrast, speckle techiques operate with coherence times of 10^{-2} to 1 second. In consequence, Fourier components in the image can be determined ~ 10^2 to 10^3 times more precisely by adaptive optics for a given observing time.

In contrast however, when real time wavefront correction produces a corrected isoplanatic patch, nothing outside that patch is correctible. When speckle produces a similar sized isoplanatic patch, that merely sets the size of the patch that can be corected in a single analysis process, and does not limit the patch of sky that can be mapped.



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Another question about adaptive optics concerns the correction of images for the thermal infrared. In general, the part of the atmosphere creating seeing disturbances will not be the same as those contributing emissivity fluctuations. Therefore there will be an interaction between seeing correction and sky noise. Even more disturbing is the possibility that the seeing corrections will produce modulation of the telescope's thermal emission, which often exceeds image flux by $\sim 10^6$. It does not seem profitable to ponder these questions without an empirical test. Adaptive optics of reasonable cost seems likely to permit interesting observations in the 2-5μ region. Tests of such a system in the 10μ window will reveal whether there are background noise problems, and how serious they are.

A further question that is often asked is whether some reduced level of adaptive optics, such as correction of image motion alone should offer major advantages. Here the question revolves around the causes of image degradation. If aberrations or mirror thermal problems dominate, there will be little benefit from correcting for image motion. If telescope shake is dominant, then correcting for image motion may result in results as good as if a stable telescope had been built. However if the dominant image degradation is by atmospheric turbulence, then there is a rather abrupt transition between slight improvement of the image, and seeing the diffraction core. It would seem a waste of effort not to go all the way and fully correct the diffraction pattern at some interesting wavelength.

Adaptive optics also seems interesting for correcting the individual apertures of a Michelson interferometer.

CONCLUSIONS

Adaptive optics is a promising technique for use with Very Large Telescopes. It warrants practical tests. It is expensive, but should pay off by providing higher sensitivity than other techniques for getting high angular resolution. Support is acknowledged under NASA grant NAGW-121. Thanks are also due to Dr. R. N. Wilson for asking questions that permitted substantial improvement of this paper.

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DISCUSSION

G. Burbidge: I would like to ask again about the costs of making corrections. If I understand you correctly you believe, and I agree, that the cost of correction should only be a fraction ($\lesssim$ 25%) of the total cost. What is the total cost for a 7-8 meter single dish telescope?

N. Woolf: This is a vital question. It is answered at some length in the written version of the paper jointly authored with Angel and Williams. Depending on how the primary is aluminized, what primary focal ratio is chosen, and whether this is the first to a given design, the cost is likely to range between $12 and 30 million for a telescope, housed, but without instrumentation or on-site facilities.

R. Bingham: Has the pattern of turbulence enough duration as it sweeps across the aperture to give some improvement in signal-to-noise ratio if we translate an observed pattern?

N. Woolf: In principle, if a single layer of turbulence were responsible, and one had separated the telescope aberrations by time averaging, one could take advantage of the slow decay of large scale turbulence. It seems likely that in practice the multiplicity of turbulent layers, and the deviation of their wind vectors would make the problem intractable.

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