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A Measurement of the Size of the Isoplanatic
Patch Using a Phase-Correcting Telescope

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In the presence of several-arc-second seeing at Mt. Wilson Observatory, a flexible-mirror image-sharpening telescope produced diffraction-limited (0.5 arc second) images of the primary stars in the double star systems of Castor (α Gem), Algieba (γ Leo) and Almach (γ And). The images of both the primary and the companion star were simultaneously sharpened for Castor (separation 2 arc seconds) and Algieba (4 arc sec) but not for Almach (10 arc sec). Thus the size of the isoplanatic patch lay between 4 and 10 arc seconds. Using a single layer model, we conclude that the bulk of the turbulent air responsible for the seeing lay between 1.1 and 1.7 km above the ground.

INTRODUCTION

Atmospheric turbulence limits the resolution of large telescopes to about one arc second. Various techniques such as interferometry¹, intensity interferometry², speckle interferometry³⁻⁷, and active phase correction⁸⁻¹⁴ have all achieved success in attaining diffraction-limited resolution under certain conditions. All of these image improving techniques require that the optical transfer function be the same for all parts of the object being observed. The small solid angle of the sky over which the transfer function is constant is called an isoplanatic patch. Fried¹⁵ has given a clear quantitative treatment of this subject.

A characteristic size of the isoplanatic patch depends inversely on the height of the turbulent layers responsible for atmospheric phase distortion, as one can see from the following example. Suppose that the distortion comes from a single layer at height h as shown in Figure 1. The light rays arriving at any point on the telescope aperture from two stars separated by an angle θ cross the phase-distorting layer at two points separated horizontally by $d = h\theta \sec^2 \alpha$, where α is the zenith angle. If d is large enough, the rays undergo different phase shifts and the images of the two stars cannot be simultaneously corrected. A characteristic transverse distance for which the phase difference is appreciable is called the transverse coherence distance r_0 . Then a characteristic size of the isoplanatic patch is given by $d \cos \alpha = r_0$, or $\theta = r_0/h \sec \alpha$.

In the context of the Kolmagorov model, Fried¹⁶ defines r_0 as

$$\langle (\phi(\vec{x}+\vec{r}) - \phi(\vec{r}))^2 \rangle = 6.88 (x/r_0)^{5/3}$$

where ϕ is the atmospherically induced phase distortion at the telescope aperture, $\vec{x}$ and $\vec{r}$ are vectors in the aperture plane and $\langle \rangle$ denotes the time average. In order that this definition of r_0 via a measurement at the telescope aperture agree with the definition of r_0 given in the previous paragraph (which implied a measurement made at the perturbing layer) it is sufficient that the wavelength λ satisfy the condition $\lambda h \sec \alpha < r_0^2$. This condition appears to be satisfied for our measurements. As shown in the Appendix, Fried's definition implies that the full-width at half-maximum (FWHM) of the angular distribution of light intensity in one dimension for a single star is approximately λ/r_0 , provided that that value sufficiently exceeds the diffraction limit of the telescope. That is how we measure and define r_0 in this paper.

A quantitative measure of the phase-distorting turbulence is given by the index-of-refraction structure constant C_n^2 , which is defined by the formula

$$\langle (n(\vec{x}+\vec{r}) - n(\vec{r}))^2 \rangle = C_n^2 x^{2/3}$$

where n is the index of refraction.¹⁷

Many experiments¹⁸⁻²⁹ have measured the height distribution of C_n^2 . They show numerous discrete layers of turbulence, with the largest contributions generally coming from the lowest few kilometers^{18,29-31}. Hufnagel³² proposed a model which well describes the average of these measurements.

Indirectly, a given model of $C_n^2(h)$ determines a characteristic size of the isoplanatic patch for a specific resolution-improving technique. Unfortunately, very few direct isoplanatic measurements have been made. Stachnik et al.⁷ simultaneously sharpened an 8 arc-second

square patch of the sun, using speckle imaging.

Schneiderman and Karo³³ analyzed speckle-interferometry data taken atop Mt. Haleakala in Hawaii, and found that speckle correlation dropped sharply at several arc seconds. Nisenson and Stachnik³⁴ performed a similar experiment in speckle interferometry with a 60 inch telescope. They found that at the angular frequency of 3 cycles/arc second (one fifth of their angular frequency cutoff), the speckle correlation dropped by 50% for a binary star spacing of 4.7 arc seconds. In this paper we present a new measurement of the isoplanatic patch using a real-time phase-correcting telescope⁹ at Mt. Wilson Observatory.

APPARATUS

The measurement used a flexible-mirror telescope⁹ that corrects the phase perturbations induced by the atmosphere, restoring the image to the diffraction limit of the 30 x 5 cm aperture. For simplicity, the apparatus was designed to correct along one dimension only, as this is adequate for binary stars and for atmospheric studies. The active optical element is placed three quarters of the way from the primary mirror to the focus. This element is a flat mirror divided into six 1.3 cm squares, each mounted on a separate piezoelectric crystal. A slit whose width corresponds to the calculated diffraction limit of the telescope is placed at the focus. A phototube mounted behind the slit measures the image "sharpness", with the sharpness defined as the maximum intensity of the stellar image. Any atmospheric degradation spreads the image, reducing the intensity at the slit. The six mirrors then move by trial and error, with a feedback loop closed in such a way as to maximize the image sharpness. With three passes through the six

mirror elements, the system attains the configuration necessary to correct the phase perturbations, thus producing a diffraction-limited peak. This correction cycle must be repeated within five to ten milliseconds, the characteristic speckle-change time. A gate on the image-recording device selects the better Portions of the images produced by the telescope and rejects those for which the telescope was unable to keep up with the atmospheric phase changes. A typical run lasts 20 minutes. Figure 2 shows a schematic diagram of the apparatus with its feedback circuitry.

RESULTS

We obtained real-time corrected images of Castor (α Gem)¹¹, Algieba (γ Leo) and Almach (γ And) at Mt. Wilson Observatory from October 3 to November 18, 1977. These double stars were chosen because they are bright, the relative-magnitude difference of each pair is small, and they could be observed near the zenith.

We recorded many images of these three double stars. Most of these images are not useful for isoplanatic patch studies because the seeing was "too good" for our telescope. Two inoperative mirror elements at one end had reduced the effective aperture to 20 cm, for which the diffraction limit is 0.5 arc sec. At Mt. Wilson the seeing (which in this paper denotes the FWHM of the image with the phase correction turned off) frequently approached that limit, so that little or no phase correction was needed to achieve the diffraction limit of our small aperture. When the seeing was as bad as 1.5 arc sec we could easily detect the effect of phase correction in improving the image of the bright star, but noise in the image-acquisition system would have

demanded excessively long runs to determine the extent to which the dim companion was similarly sharpened. Therefore we restrict ourselves to the results obtained when the seeing was worse than two arc sec.

Figures 3, 4, and 5 present images of the three double stars taken when the seeing was worse than two arc seconds. For these images the brighter star in each pair provided the light for the sharpness defining slit in front of photomultiplier PM1. When the feedback loop was closed, the mirror elements maximized the amount of light through the slit and corrected the atmospheric phase distortion for the bright star.

Table I compares the measured separations and intensity ratios taken from Figures 3, 4, and 5 with the values predicted from the literature. The measurements agree with the expected values within the stated errors.

In Figures 3 and 4 it is apparent that the telescope sharpened the image of the dim star nearly as much as that of the bright star. Therefore light from both stars must have undergone approximately the same distortion, and we conclude that the dim companion lay within the isoplanatic patch of the brighter star. In Figure 5, the bright star's image was sharpened when the feedback was turned on but the dim star's image was not. Thus the dim star of Almach lay outside of the isoplanatic patch of its brighter companion.

If we assume that the isoplanatic patch size was similar on these three nights of poor seeing, then as the stellar separations in Figures 3, 4, and 5 are 2, 4, and 10 arc seconds respectively, the isoplanatic patch size must have been between 4 and 10 arc seconds, for spatial frequency components less than our cutoff of 2 cycles/arc sec.

DISCUSSION

The results of our isoplanatic-patch-size measurements constrain the height dependence of C_n^2 . Since only three measurements were made, each on a different night, we can not map a height distribution of C_n^2 at Mt. Wilson. However, one can estimate an average height by considering a simple model with a single turbulent layer at height h , as in Figure 1. If both stars lie within the isoplanatic patch, then $d = h \theta \sec \alpha < r_o \sec \alpha$ or $h < r_o \cos \alpha / \theta$. If the dim companion lies outside the isoplanatic patch of the brighter star, then $h > r_o \cos \alpha / \theta$. Table II lists several parameters and $r_o \cos \alpha / \theta$ for each binary image. Since, according to Figures 3, 4, and 5, both stars were simultaneously sharpened in the cases of Castor ($r_o \cos \alpha / \theta = 2.8$ km) and Algieba (1.7 km) but not for Almach (1.1 km), we conclude for this simple model that h lay between 1.1 and 1.7 km above the ground (2.8 and 3.4 km above sea level).

This estimate of the average turbulence height assumes that the height distributions were similar on all three nights. However, on these nights the seeing varied by 30% and the characteristic speckle-change times varied over a factor of 2.4. More measurements are needed to see whether or not the assumption of similar $C_n^2(h)$ values is justified.

The measurements of C_n^2 by Barletti et al.²⁹ suggest that conditions above about 4 km above sea level are similar everywhere, and that seeing differences at different places and different times depend on additional local turbulence generated by the ground and nearby geographical structures. In Hufnagel's 1974 model³², the integrated value of C_n^2 above 3 km is

$$\int_{3 \text{ km}}^{24 \text{ km}} C_n^2(h) dh = 2.8 \times 10^{-13} \text{ m}^{1/3}.$$

This value produces 0.6 arc second seeing on the ground (Appendix, eq. (4)). As we have roughly 3 arc second seeing, corresponding to $\int C_n^2(h) dh = 4 \times 10^{-12} \text{ m}^{1/3}$, the main contribution to the integral should come from turbulence closer than 3 km to be consistent with Barletti's measurements and Hufnagel's model. Our estimate of the turbulence height agrees with this.

Isoplanatic patch measurements are important to astronomers because the size of the patch determines how much of an extended object can be simultaneously sharpened.³⁵ There is a controversy about the size of the isoplanatic patch: whether it is about one arc second or several arc seconds. The results presented here suggest that when the seeing is two or three arc seconds, the bulk of the turbulence is within 2 km of the ground and the isoplanatic patch is roughly 6 arc seconds. We calculate that if C_n^2 is zero below 3 km and follows the Hufnagel model above 3 km, then the isoplanatic patch size is 3 to 4 arc seconds.

It is important to determine whether or not our results can be extended to larger telescopes. Suppose that our small image-sharpening telescope has sharpened both images of a double star to the diffraction limit, and that both stars lie within the isoplanatic patch. Now suppose our image sharpening telescope is replaced by a much larger one and we sharpen the primary star to its (much smaller) diffraction limit. The secondary star will presumably be sharpened to an image narrower than the diffraction limit of the small telescope, but will it be sharpened all the way to the diffraction limit of the large tele-

scope? Putting it differently, can we predict the size of the isoplanatic patch for a large telescope from measurements made on a small telescope?

Consider the residual phase error ϕ of the wavefront at a given point in the aperture from the dim star after phase correction is applied to the brighter star. In a one-layer model with a Kolmogorov spectrum, this phase error has a variance of

$$\langle \phi^2 \rangle = 6.88 (h\theta/r_0)^{5/3}$$

and a characteristic transverse correlation distance of $h\theta$. If the telescope aperture size D is much less than $h\theta$, then the phase error ϕ is essentially constant over the aperture and the dim star appears diffraction limited. If $D \gg h\theta$, then the variation of ϕ across the aperture is independent of the aperture size and is just $\langle \phi^2 \rangle^{1/2}$. The size of the image is then roughly independent of telescope size. In our three isoplanatic-patch-size measurements, $D/h\theta$ is about 16, 7, and 3 for figures 3, 4, and 5 respectively. Since our small telescope is in this asymptotic region, we expect that under the same atmospheric conditions the 200 inch telescope would also measure the isoplanatic patch to be about 6 arc seconds.

We emphasize that our measurements were taken in one place and one season with different speckle-change times. More measurements are needed, especially with larger apertures so that the isoplanatic patch size can be measured on nights when the seeing is closer to the 0.6 arc-second limit predicted from the Hufnagel model and the measurements of Barletti et al.²⁹. It will be interesting to determine whether, on

such nights, the isoplanatic patch turns out to be smaller because h is larger, or to be larger because r_0 is larger. Double stars are obviously useful in these measurements. We suggest the Galilean moons of Jupiter for such measurements, the main advantage being that the moons provide a continuous set of angular spacings.³⁶

SUMMARY

Atmospheric turbulence limits the resolution of ground-based telescopes to about one arc second. Current techniques that seek to improve the resolution beyond the atmospheric-seeing limit have their correctable field of view limited by the size of the isoplanatic patch. Using a flexible-mirror telescope that corrects atmospheric-phase errors in real time, we have measured the size of the isoplanatic patch near the zenith using the double stars Castor, Algieba, and Almach. We found that when the seeing at Mt. Wilson was about 3 arc seconds, the size of the isoplanatic patch was between 4 and 10 arc seconds. In a single-turbulent-layer model, the turbulence lay 1.1 to 1.7 km above the ground.

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APPENDIX

We define the following variables:

- x Transverse separation between two points in the entrance aperture.
- D Diameter of telescope aperture
- $D_\phi(x)$ Phase structure function = $\langle (\phi(x+x') - \phi(x'))^2 \rangle$
- $I(\beta)$ Intensity of image
- k wave number (= $2\pi/\lambda$)
- s path-length variable (= $h \sec \alpha$)
- β image-plane variable (rad)

Other variables are defined in the text or in Figure 1.

Tatarski³⁷ derived a formula relating $D_\phi(x)$ to $C_n^2(s)$. With the substitution $s = h \sec \alpha$, his result becomes

$$(1) \quad D_\phi(x) = 2.91 k^2 \sec \alpha x^{5/3} \int C_n^2(h) dh$$

Fried¹⁶ incorporated the $x^{5/3}$ dependence to define r_o by

$$(2) \quad D_\phi(x) = 6.88(x/r_o)^{5/3}.$$

For a one-dimensional telescope such as ours, the uncorrected point spread function is (within a proportionality constant)

$$(3) \quad I(\beta) = \int_0^D dx \cos(\beta x) (1 - x/D) \exp\left\{-\frac{1}{2} D_\phi(x)\right\}.$$

For $r_o \gg D$, D_ϕ is essentially zero and we obtain the usual diffraction-limited shape. For $D \gg r_o$, $D_\phi(x)$ wipes out the contributions from x larger than r_o and the resultant seeing [FWHM of $I(\beta)$] turns out to be $1.0 \lambda/r_o$. We combine this result with equations (1) and (2) to obtain (in arc sec)

$$(4) \quad \text{Seeing} = 2.04 \times 10^7 (\lambda/0.5\mu)^{-1/5} (\sec \alpha)^{3/5} \left(\int dh C_n^2(h) \right)^{3/5}$$

FOOTNOTES

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- 36 The orbital inclinations are all less than a tenth of a degree, so when the Earth passes through the plane of their orbit, the moons pass each other at a spacing less than one arc second. When two satellites are in conjunction, their relative motion is 5 to 20 arc seconds per hour when moving in opposite directions and less than 5 arc seconds per hour when moving in the same direction. If we discard conjunctions that occur within 30 arc seconds of Jupiter or occur at zenith angles greater than 45° , there is roughly one useable conjunction every three days when Jupiter is overhead.

This occurs every six years as the Earth moves through the plane of their orbit. The Galilean satellites are of 5th and 6th magnitudes, so they are bright enough to sharpen with an active optical system.

37 Reference 17, p. 170.

FIGURE CAPTIONS

Figure 1. Atmosphere with one turbulent layer. The rays of light from the binary star system cross the layer at two points separated by $d = h\theta \sec^2 \alpha$. When $d \cos \alpha$ is greater than the transverse coherence distance r_0 , these rays undergo different phase shifts.

Figure 2. Schematic diagram of rubber mirror telescope. The second diagonal mirror corrects the phase of the incoming wavefront while photomultiplier PM1 senses the resulting sharpness of the stellar image. Digital electronic circuitry completes the feedback loop. PM2 reads the image. PM3 and PM4 are used to steer the telescope on the star. Details are given in Refs. 9 and 11.

Figure 3. Images of the binary star Castor (α Gem). In (a) the two stars were unresolved when no phase correction was applied. In (c) two diffraction limited peaks appear above an uncorrected background. Although the feedback loop involved the bright star only, the telescope sharpened the images of both stars. In (c), the uncorrected background beneath the corrected peaks has contributions from phase variations within a single mirror element and from incomplete phase correction due to seeing changes more rapid than the telescope could follow.

Figure 4. Images of Algieba (γ Leo). Both stars appear equally sharpened, showing that the isoplanatic patch size at this time was at least 4 arc seconds.

Figure 5. Images of Almach (γ And). Although the telescope sharpened the bright star, the image of the dim companion was not improved. Therefore the size of the isoplanatic patch was less than ten arc seconds.

XBL 785-880

Fig. 1

Fig. 2

XBL 762-2245B

XBL 783-362

Fig. 3

XBL 783-363

Fig. 4

Fig. 5

XBL 783-361

TABLE I.

Comparison of observed separation and intensity ratios
with predicted values

Star Name	Castor (α Gem)	Algieba (γ Leo)	Almach (γ And)
ADS Number ^a	6175	7724	1630
Predicted Separation (arc seconds)	2.13 ± 0.04^b	4.36 ± 0.06^b	9.5 ± 0.2^c
Observed Separation	2.0 ± 0.1	4.3 ± 0.1	9.3 ± 0.2
Predicted I_1/I_2^d	2.4 ± 0.1	3.2 ± 0.1	6.9 ± 1
Observed I_1/I_2	2.6 ± 0.2^e	2.9 ± 0.2^e	7.8 ± 0.8^f

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^c Smithsonian Astrophysical Observatory Star Catalog, (Smithsonian Institute, Washington D.C. 1966). Ephemerides calculated for 1977.8.

^d Predicted intensity ratios were obtained from visual-magnitude differences, taking into account photomultiplier response at different wavelengths.

^e Measured with feedback on.

^f Measured with feedback off.

TABLE II.

Parameters of interest for the three figures

Fig. #	Star Name	Date (1977)	Time (PST)	τ^a (ms)	$\langle \lambda \rangle^b$ (nm)	Zenith Angle	Seeing	r_o^c (CM)	$r_o \cos \alpha / \theta$ (km)
							FWHM (")		
3	Castor	Nov 4	4:00	4.5	450	7°	3.4 ± 0.2	2.8 ± 0.2	2.8 ± 0.2
4	Algieba	Nov 16	5:00	11	540	25°	3.2 ± 0.3	3.9 ± 0.3	1.7 ± 0.2
5	Almach	Nov 2	22:00	4.5	540	14°	2.3 ± 0.2	5.3 ± 0.4	1.1 ± 0.1

^a Characteristic speckle-change time, defined in ref. 10.

^b Average wavelength, obtained from frequency response of phototube and spectral class of bright star.

^c Transverse coherence distance, corrected to remove zenith-angle dependence (Appendix eq. (4)) and corrected for size of telescope aperture (Appendix eq. (3)). We neglect here the effect due to the removal of a portion of the seeing by our steering system.

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