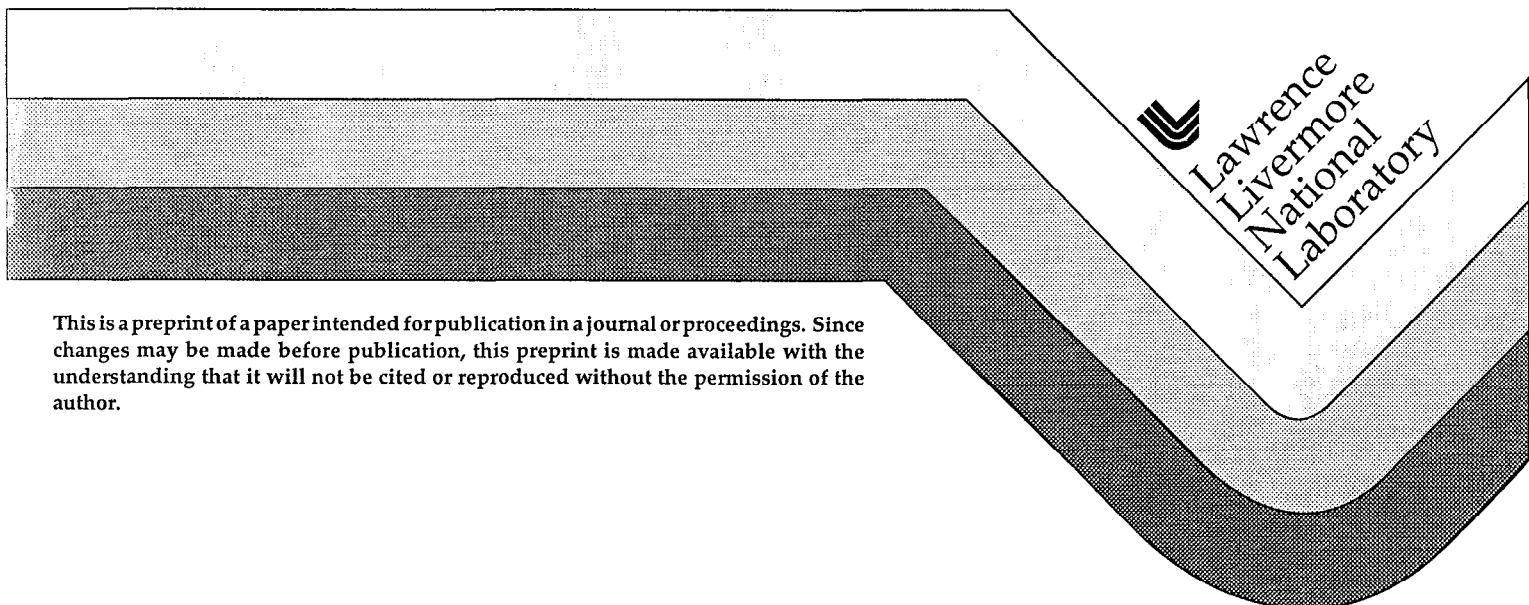


Wide Baseline Optical Interferometry with Laser Guide Stars

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Wide baseline optical interferometry with laser guide stars

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Abstract

Laser guide stars have been used successfully as a reference source for adaptive optics systems. We present a possible method for utilizing laser beacons as sources for interferometric phasing. The technique would extend the sky coverage for wide baseline interferometers and allow interferometric measurement and imaging of dim objects.

1. Introduction

Interferometry extends the bounds of high spatial resolution astronomy beyond that achievable with present day single aperture telescopes. The interferometric combination of light from two or more telescopes spaced apart from each other can form images with resolution increasing with baseline length, as opposed to primary mirror diameter. In the case of the Keck interferometer (currently under development) this will represent an eight-fold increase over the diffraction-limit of a single Keck aperture (considering only the two 10 meter telescopes, which are separated by 80 meters; planned outrigger telescopes will give even larger baselines).

The implications for astronomical science are astounding; certainly some of the greatest discoveries in astronomy will be due to optical interferometry in the coming century. Included in the list of interesting objects where extremely high resolution will greatly advance the state of knowledge are: the planetary systems around other stars, the close-in details of dusty disks around young forming stars, the details of active galaxies, and the regions around quasars.

It is important that we mention the dim distant astronomical objects as potential interferometry targets here, even though wide baseline interferometry has traditionally been limited to bright objects. This limitation is imposed by the use of the astronomical (or nearby star) light for fringe tracking to compensate for optical delays caused by turbulent atmosphere. With the advent of laser guide star technology for single aperture adaptive optics, we foresee that lasers might be useful for interferometry as well. The laser probe in adaptive optics removes the need for a bright natural reference star; it essentially creates an artificial guide star, and in so doing, opens high resolution imaging to (nearly) the whole sky. One might ask, is it physically possible to phase optical interferometric arrays with an artificial guide star, and thus open up interferometry to the whole sky.

The challenge is formidable, and more than simply a scaling up of current laser guide star techniques. The most important issue is that the interferometer requires a bright *diffraction-limited* source, that is, diffraction-limited to the interferometric baseline, not just to the individual apertures. This is in sharp contrast to the adaptive optics case, where information about the continuously connected wavefront can be obtained with a relatively large, many times diffraction-limited, guidestar.

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2. A proposed approach

The approach is to interfere laser beams in the atmosphere to form a pattern with diffraction-limited spatial structure as shown in Figure 1.

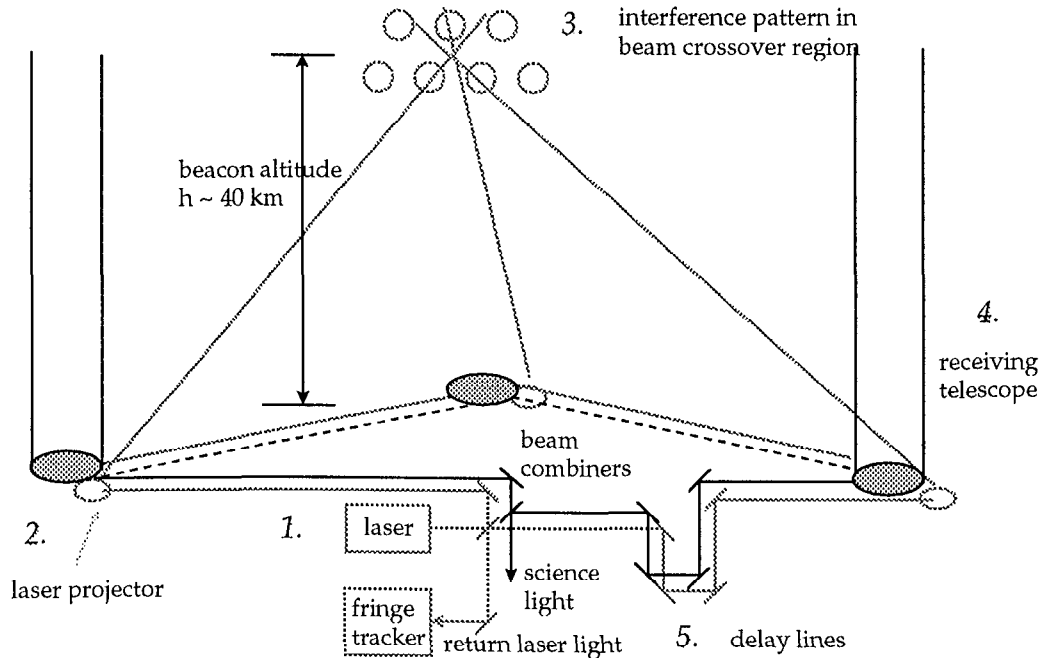


Figure 1. Scheme for producing a laser guide star with spatial structure that is diffraction-limited with respect to the interferometer

Referring to the labeled components in the figure: co-phased laser light, 1, is projected from apertures separated by the interferometer baseline, 2. An interference pattern will form in the region where the beams cross, 3. This interference pattern will have fringes spaced at the diffraction-limit of the interferometric baseline.

The receiving telescopes, 4, will collect light from both the science object and the laser beacon. By appropriately time-gating the laser return signal so that only light coming from the altitudes where the beams cross enters the detector, the fringe pattern will be detected. The observed fringe pattern will be the laser fringes in the sky convolved with the fringe pattern point-response of the interferometer. Because these two patterns are identical, the result will be a pattern of fringes on the detector.

Delay lines (labeled 5 in Figure 1) for the received laser light are adjusted to stabilize fringes on the detector[†]. The delay is measured and applied to a delay line in the path of the science light. This phases the science light, compensating for the optical path through the turbulent atmosphere.

A similar approach of interfering two or more projected laser beams was proposed by Ribak [1] in the context of producing multiple guidestars to reduce cone effect in adaptive optics systems.

3. Guide star geometry

The interference pattern geometry for the case of two apertures is shown in Figure 2. In the area of the beam overlap, the fringe spacing is

[†] For the moment, we assume that the laser-induced fringe pattern on the sky is fixed with respect to the celestial background. See section 5 for an important discussion of this topic.

$$\Delta x = z\lambda / b \quad (1)$$

where z is the altitude of the guidestar, λ is the laser wavelength, and b is the interferometer baseline. At Keck, $b = 80$ meters, so for the case of $\lambda = 500$ nm and $z = 40$ km, the spacing is $\Delta x = 0.25$ mm.

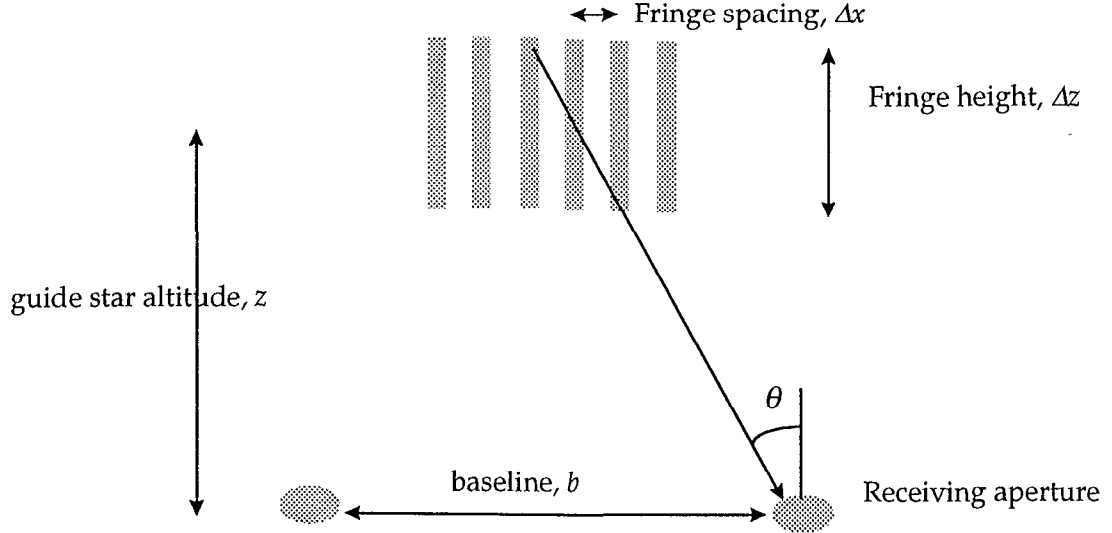


Figure 2. The fringe pattern geometry for the two aperture case. Fringes are formed in the portion of the atmosphere where the projected laser beams overlap.

As seen from the figure, the height of the pattern must be small enough that light from neighboring spots don't overlap as seen by either aperture. The beams cross in a region Δz_b meters high, where

$$\Delta z_b = 2 d_p z / b \quad (2)$$

and d_p is the projecting aperture diameter. For Keck, $b = 80$ m, and assuming $z = 40$ km and $d_p = 1$ m, the crossover region is $\Delta z_b = 1$ km, much too high to avoid the fringe overlap problem.

To avoid fringe overlap, the probed vertical height must satisfy:

$$\Delta z / \Delta x < z / (b/2) \quad \Rightarrow \quad \Delta z < 1/2 \lambda (z / b)^2 \quad (3)$$

For $\lambda = 500$ nm, $\Delta z < 62.5$ mm. This can be achieved by using a pulsed laser and a range-gated receiver as in lidar systems. The laser pulse must be less than 208 ps (=62.5 light-mm).

Although a receiver range gate of 208 ps, is feasible, a technique proposed by Beckers [2] can be used to track the laser pulse as it traverses through the overlap region. This has the benefit of multiplying the return signal by a factor of $\Delta z_b / \Delta z = 16,000$ over using a short range gate. The scanning technique involves steering mirrors at the receiving telescopes that move at a rate that tracks the moving pulse. The steering rate is $\theta' = c b / 2 z^2 = 7.5$ radians/sec, for an angle of $\theta = (\Delta z_b / z)(b/z) = 50 \mu\text{r}$, not an unusual requirement for current scanning systems.

Note that the 208 ps requirement eliminates the possibility of using induced fluorescence from the sodium layer as a guidestar. The sodium atomic resonance decay time is 16ns, thus a sodium fringe will glow for 16 light-ns (~5 meters) which will completely wash out neighboring fringes. We rely on the Rayleigh backscatter from air atoms.

4. Brightness and laser power requirements

The Rayleigh guidestar return flux, F , in photons / m² / pulse is given by

$$F = T_A^2 \sigma_R n_R \lambda E \Delta z / (4\pi z^2 h c) \quad (4)$$

where E is the pulse energy, σ_R is the Rayleigh backscatter cross section, n_R is the atmospheric density, and T_A is the atmospheric transmission. Measurements of $\sigma_R n_R$ were obtained by Gardner *et. al.* [3] (Figure 3).

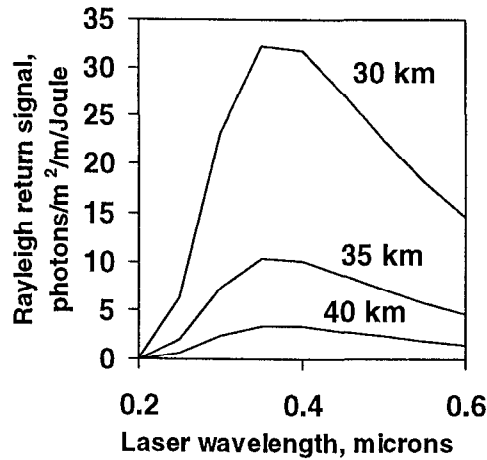


Figure 3. Rayleigh guidestar return signal as a function of laser wavelength and altitude of range gate. The graph shows optimum wavelengths are in the 350-400 nm region.

From this, the laser power requirements can be derived:

$$P = \frac{\overset{\substack{1000 \\ \text{photons}}}{n} \overset{\substack{\# \text{ fringes} \sim 80 \\ 100 \text{ Hz}}}{(b/d_p) \nu_l}}{(F/\Delta z E) \Delta z (\pi D^2/4)} \quad (5)$$

\uparrow Rayleigh return/pulse > 1 \uparrow 1000m \uparrow aperture area ~ 100 m²

A 100 Watt laser operating at $\lambda = 500$ nm, $z = 40$ km, $\nu_l = 100$ Hz projected from a $d_p = 1$ meter aperture will produce $n = 1,000$ photons per fringe per laser pulse per Keck aperture. (100 Hz is a nominal sample rate to track atmospheric fluctuations.) In equivalent stellar magnitude, the return flux of each fringe is a 17th magnitude star. The total flux from all 80 fringes is that of a 13th magnitude star.

5. Requirement for fringe stability against the celestial background

Since the laser traverses through the atmosphere on the way up, there has to be an independent means to stabilize the guidestar fringes against the sky. Without fringe stabilization, the optical path difference on the upgoing path will equal that of the downgoing path. The net result is that, at the receiver, the fringes would always appear fixed and the affect of the atmosphere would be unobservable.

The problem is analogous to the one of tip/tilt ambiguity in laser guide star adaptive optics. A solution to the tip/tilt problem has been proposed by Ragazzoni et. al. [4], who suggest the use of movable outrigger telescopes to line up the laser guide star, via parallax, against a bright reference star. The star is then used as a reference to stabilize the guide star position.

The same technique can be used to stabilize fringes, but the tilt accuracy requirement is more severe. Tilt accuracy must be to a fraction of a fringe's apparent separation angle:

$$\Delta \theta = \Delta x/h = 6 \text{ nr.} \quad (6)$$

which is much smaller than any one telescope's diffraction-limit, and smaller than can be achieved with photon statistics on the diffraction-limited image except for a very few bright stars in the sky. For this kind of accuracy we need an outrigger interferometer, which has a much smaller diffraction-limit. The concept is shown in Figure 4a. The fringe brightness requirement calculations from Section 4 now apply.

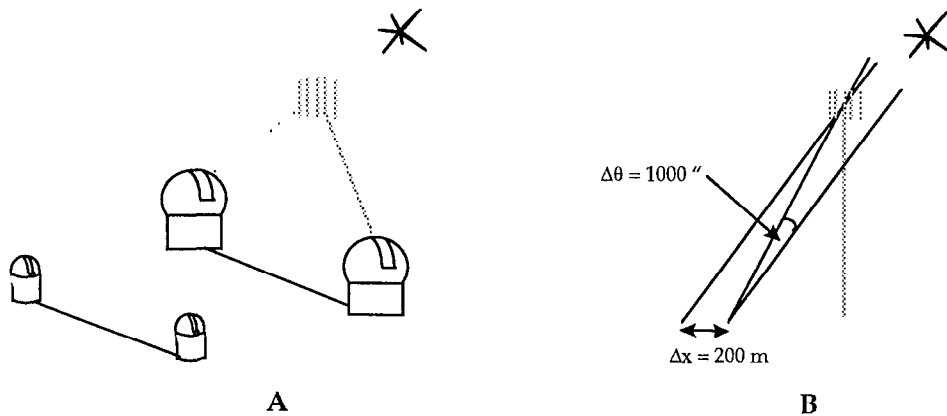


Figure 4 A technique of attaining fringe stability against the celestial background using outrigger telescopes. A) main telescopes and outriggers configured as interferometer pairs. B) mobility of the outriggers required to line up the fringes and a bright natural star.

Of course, with the smaller outrigger apertures, a brighter star is needed. For example, 2.5 meter outriggers need 16 times more light than a 10 meter, so the magnitude requirement goes from $m_v = 13$ to $m_v = 9.5$. The laser power requirement goes up by the same factor (since it too must be detected in the outrigger's sensors).

At least one natural star of $m_v = 9.5$ is available every ~ 1000 arcseconds solid angle on the sky. For a 40 km guidestar, the outriggers must be mobile in a 200 meter diameter circle to line up the natural star, as shown in Figure 4b.

6. Anisoplanatism

Anisoplanatism is the error caused by the guide star not probing the same part of the turbulent atmosphere as that traversed by the science light. In the interferometry scheme, the laser guide star fringe pattern is placed midway between the two apertures which minimizes the average anisoplanatism at each aperture. The offset angle is $\theta = b/2z = 400$ arcseconds for a guide star altitude of $z = 20$ km and 200 arcseconds for $z = 40$ km. At these angles, the guide star and science beam paths will be completely separated at altitudes above 5 km for the 20 km guide star and 10 km for the 40 km guide star. Clearly, the highest altitude guide star is desired to minimize anisoplanatism. Unfortunately, placing the guide star higher up results in a drastic loss of return signal because of the exponential fall off of atmospheric density. An increase in laser power can partly compensate for the loss as shown by the curves in Figure 5.

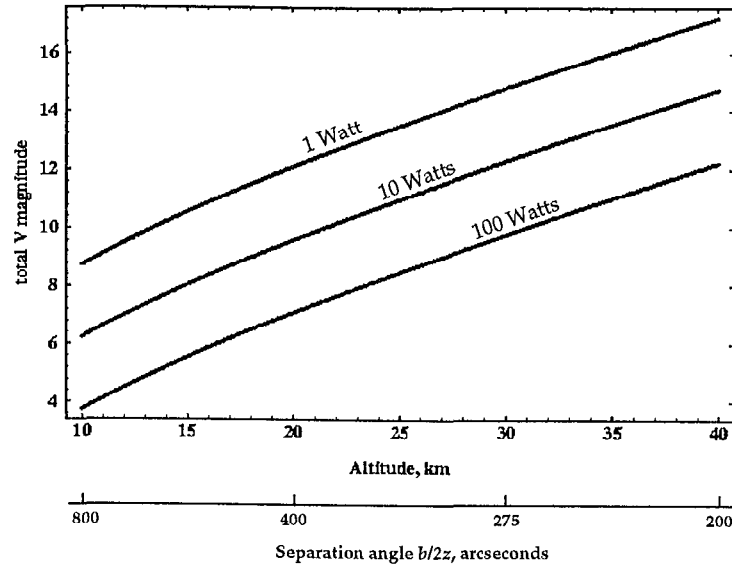


Figure 5 Relation of guidestar brightness and laser power requirement to guidestar altitude and separation angle between the laser and science beams, assuming $D = 10$ meter receivers. The higher altitude guidestar has smaller separation angle but requires more laser power.

7. Sky coverage

From Figure 5, we see that a 100 Watt laser will produce a 13th magnitude Rayleigh guide star at an angle of $\theta=200$ arcseconds away from the direction of science light. The probability of finding a natural 13th magnitude star in an arbitrary 200 arcsecond solid angle of sky is at most only 10%, and this is in dense star fields near the plane of the Galaxy. Thus a modestly bright laser will extend sky coverage of the interferometer by at least a factor of 10.

8. Discussion

Choice of wavelength —The Rayleigh cross-section curve peaks in the 350 to 400 nm region. The curves are rather broad however, and longer wavelengths can be used without catastrophic loss. The return is down by a factor of 2 at 600 nm.

Laser technology —There are several types of lasers currently available that can potentially produce 100 Watts at 100 to 1000 Hz repetition frequency with a 200 ps pulse. These include dye, Eximer, and Ti:Sapphire lasers. The technique of chirp compression allows long pulses to be amplified (reducing peak power in the laser optics), then compressed to short pulses just before launch. Ti:Sapphire seems the most promising; it is solid state, produces 800 nm light which can be frequency doubled to 400 nm which is near the return maximum. The second wavelength is also potentially useful in the 2λ approach to establishing true group delay (below).

Measuring group delay —Two color interferometry is an effective technique for removing systematic errors due to dispersion in the interferometer beam paths and avoiding 2π ambiguities in fringe tracking with narrow band light. A second color laser guide star can be used to measure true group delay.

9. Conclusion

We have introduced a technique for using a laser guide star to phase a wide baseline optical interferometer over atmospheric time scales. The altitude of the guidestar, by necessity limited to roughly the scale height of the atmosphere, will limit system performance particularly when there is significant air turbulence above a few kilometers, because of anisoplanatic effects.

The technical implementation is challenging but within today's capabilities. It requires a high power short pulse laser, fast scanning mirrors, and low-noise detectors for real time fringe tracking. The interferometer beam-combining optics must allow for a field of view wide enough to cover the entire fringe pattern in order to fully utilize all the available light. The stabilization of the laser fringe pattern on the sky is itself a formidable problem, possibly requiring the use of mobile outrigger telescopes.

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Acknowledgment

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