Can laser self-focusing in air replace interferometer siderostats and delay lines?

Erez N. Ribak
Department of Physics, Technion – Israel Institute of Technology, Haifa 32000, Israel

ABSTRACT

Recent experiments in high-power lasers show that they modulate of the density of air at long ranges, up to filamentation in a restricted volume. There are two effects: light concentration and plasma filamentation, depending on the laser power. Two such laser-heated volumes can scatter stellar light into a central station, where they are made to interfere in speckled fringes. Usually the density modulations deflect the light only slightly, so the maximum baseline is not extended. However, if either the modulation of the density of air is strong, or its spatial frequency is high, then the stellar beam deflection is significant. In such a case, the scattering volumes can be further off to the sides, and baselines of hundreds of meters can be envisaged.

Keywords: Long-base-line interferometry, laser plasma, filamentation

1. A BIT OF BACKGROUND

1.1 Multi-telescope interferometers

The diameter of telescopes sets the resolution with which they can detect distant objects. For a wavelength λ and diameter *D*, details finer than λ/*D* are lost. In order to obtain better resolution, multi-aperture interferometers were introduced: if the distance between the apertures is *B* (*B*>*D*), the resolution is λ/*B* [1]. These interferometers are made of a number of siderostats or telescopes, and their light is combined at a central station into interference fringes (different arguments and methods apply at longer wave lengths, where heterodyne is possible). As the object of observation moves across the sky, delay lines are employed to compensate for the difference in path length between the paths from the object to the detector. This technology is now well established and well developed. At the same time, it is also complex, inefficient, and expensive.

1.2 Single-telescope interferometers

Aperture masking [2] is similar to multi-telescope interferometry, and is used to overcome path fluctuations caused by the turbulent atmosphere. Apart from these fluctuations, the paths are essentially equal, and no delay lines are required. Similarly, designs based on all siderostats moving together [3] allow equal paths even beyond the single-telescope aperture. Super-resolution (finer than λ/*D*) is also possible by using atmospheric turbulence [4], [5]: a distant screen scatters light into a smaller telescope pupil (Fig. 1), such that light reaches the detector from points $D + 2H\alpha$ apart (*H* is the distance of the screen, and α is the average scatter angle). Unfortunately, as the screen is higher up, the air density and the turbulence reduce, and so does α. The relative improvement in resolution is

$$\frac{\lambda/\left(D+2H\alpha\right)}{\lambda/D}=\frac{D}{D+2H\alpha}. \quad (1)$$

For example, let us assume $D = 0.1$ m, $H = 10$ km, $\alpha = 5\times10^{-6}$ (2.5"), in which case the resolved details will be half the size of those observed with the bare telescope. However, for a much larger telescope, $D = 10$ m, the resolution is only enhanced by a factor of 1/1.01.

1.3 Enhancing the turbulence

Is it possible to improve the resolution significantly beyond the single-dish limit? The usual turbulence is governed by the Komogorov spectrum and is known to saturate at the few arc-second level. This means that even very strong turbulence will not be able to shift the light beam by more than 10^{-5} or so. However, it is possible to produce artificially density perturbations in the atmosphere, which could be strong enough to divert the beams at higher angles. This is already happening today in high-power beam propagation through the atmosphere, where flaring occurs. This term means that the non-linear term of the refractive index is so enhanced by the beam power, that it creates a Kerr lens in air. This lens modifies the local refractive index so that the beam is concentrated and focused. At low to medium intensities the beam diverges after the focus and "blooms" into a flower shape.

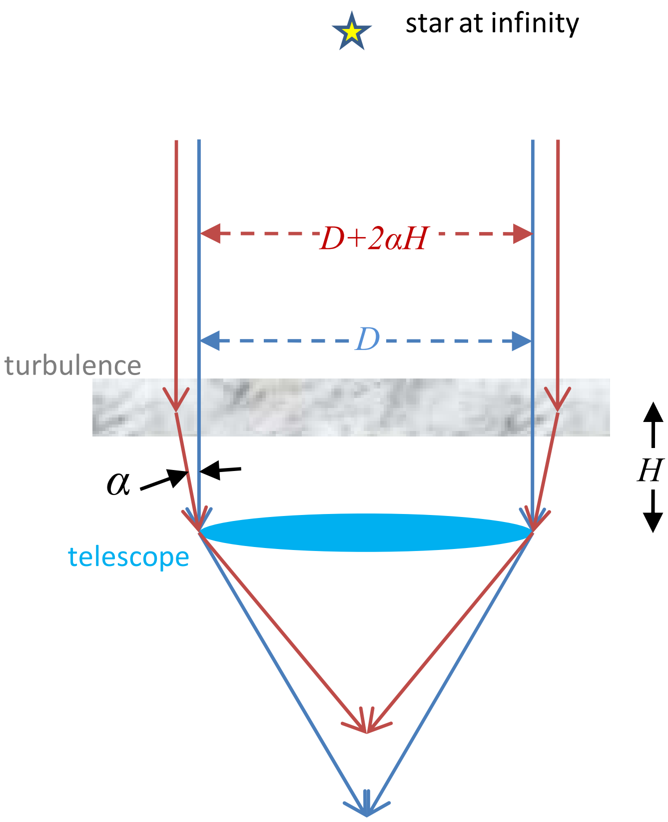

Fig. 1. Extension of the size of the telescope by using turbulence. If the angle of scatter by the turbulence is large and the turbulence is at distance, the effective radius of the telescope grows by their product. As a result the resolution improves by the same amount.

1.4 Formation of plasma in air

Let us quantify these processes. When a very strong laser is used, it evokes more non-linear effects in the medium it passes through. The refractive index is

$$n = n_0 + n_2\left(I\right) = n_0 + n_{Kerr} I \,, \qquad (2)$$

where $n_{Kerr} \approx 3 \cdot 10^{-15}$ $\mathrm{m^2/W}$ in air at sea level. Using femtosecond laser pulses in air, the Kerr lens forms rather fast, focusing a collimated beam into a tight spot. As the power density near the focus increases, the lensing effect increases even faster and the beam converges very fast, until it breaks down the air (Fig. 2), at power levels given by

$$P_{crit} = \frac{3.77\lambda^2}{8\pi n_0 n_2}. \quad (3)$$

For example, 800 nm pulses lasting 40-100 fs each, need to be at the critical power level of 3-5 GW to form filaments. Ionization of air, or the formation of plasma, also modifies the refractive index, and stops the focusing effect. Usually instabilities in the beam tend to concentrate it into local focal spots, from which the plasma filaments extend, and where light is trapped. Filaments of a few micron diameter form, with lengths extending to meters, all continuing in the original beam direction. If the power is too dispersed and filamentation stops, the energy density is still very high, self focusing resumes, and new filaments form. As they occur at occasional spots where the intensity happened to be high, their position and shape tend to be irregular [6]. The ionization process slowly bleeds the beam of its power until the process stops at large distances. Most of the power escapes the filamentation region in the form of radiation, mainly in lines of the prevalent atoms and molecules, namely nitrogen and oxygen. This radiation is not fully isotropic, and is funneled into a cone shape, with some power returning back in the direction of the source [6].

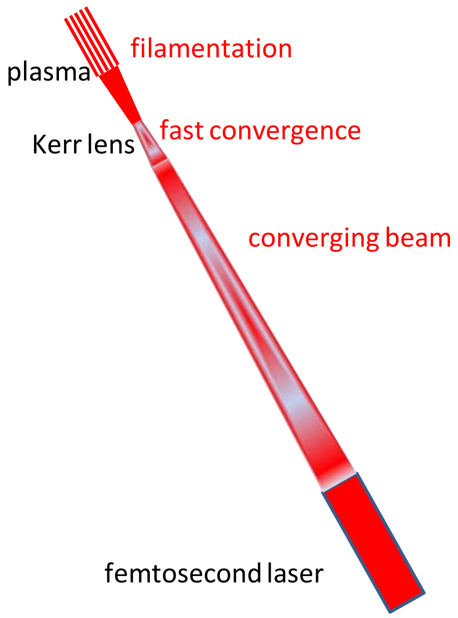

Fig. 2. Plasma formation by femtosecond lasers. As the beam converges, energy density increases and non-linear effects raise the local refractive index, which further converges the beam. At high enough density, the medium breaks down and plasma forms. The power is concentrated into thin long plasma filaments which also carry the laser beam along.

1.5 Breakdown distance and shape

Naturally, a collimated beam can made a very short path in air before it collapses into a focus and forms plasma. Recently there have been experiments which show that the distance at which this collapse occurs can be made hundreds of meters away, limited only by local topography, and lasting for kilometers [7], [8]. Furthermore, the filaments can be made stable and regular by shaping the wave front as it emerges from the laser [9], [10]. This means that the scattering volume will not be random and the scattering directions will be stable.

2. INTERFEROMETRY

2.1 Basic design

In order to utilize these ideas for interferometry, special attention must first be given to the desired process and its geometry. In Fig. 3 the concept is presented: using high-power, femtosecond lasers, the refractive index of the air at large distances from the central location are modulated. Stellar light encountering these perturbations is scattered at all directions, but in this context two preferred orientations exist: Bragg reflection and wave guiding. Both rely on the density of filaments, their orientation, and depth of modulation. Bragg diffraction is wavelength dependent, so either a limited spectrum is employed, or the baseline will increase with wavelength (which might be beneficial). Light guiding by the density modulation, similar to two-dimensional guiding by photonic crystals, is much less wavelength dependent. On the other hand the scattered light is in the direction of the forming laser which requires separation of the ascending and descending beams. In addition, there is a preference for the forming laser beam to be back-scattered, adding to the noise in the system.

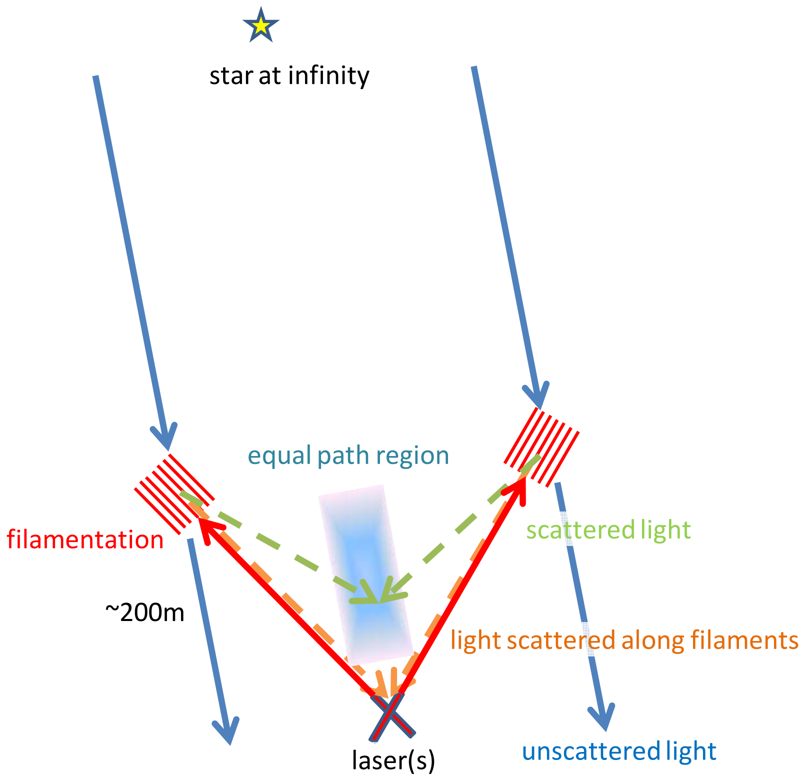

Fig. 3. By creating strong refractive index modulation, light is scattered in different directions. Some of it is captured by the periodic filaments which produce preferred directions. The lasers are adjusted to have the scattering volume at locations which will yield equal paths to the central collecting optics (not shown).

2.2 Geometry

The flexibility in forming the scatter centers has a great advantage: two such centers can be put at different heights, so that the beams take equal paths from the observed object to the final detector, where they are made to interfere. This interference takes place within the equal path region (Fig. 3), and for off-zenith objects, all that needs to be done is rotate the two lasers around their crossing point. To make the idea worth the investment, the baselines have to be on the scale of hundreds of meters. Assuming scattering at most at 45^0, this also means that the scattering centers need to be at a kilometer height or even more, something that has already been achieved [6].

If the main mechanism of scatter is by capture along the filaments, then the location of capture is not defined, which means that the baseline is not defined. In this case, the filaments need to be shorter, or else the capture would be Bragg-like diffraction.

2.3 Detection

Unlike solid optics interferometers, where the fringes are well defined and stable (mechanics and atmosphere permitting), here detection is essentially statistical: only a fraction of the light from the object will have equal paths through the different centers to the fringe-formation volume. The detected fringes can be distinguished through their modulation. The signal will be further contaminated by plasma-formed photons arriving from the same scatter center.

3. TECHNICALITIES

Before such experiments can take place, they must be modeled in the computer and the laboratory. There are many unresolved issues, some of which are listed here.

3.1 Power and duty cycle

Experiments today employ high-power femtosecond lasers at sea level. Plasma formation occurs quite low, usually below 1 km, but extending much higher [7],[8]. The design brought here requires that the filaments be rather ordered, which means that the Kerr lens height is well controlled [9], [10]. At higher elevations where astronomical observations usually take place, the air is more tenuous, and the Kerr lensing effect is weaker, so much so that it might not reach the gigawatt power required for breakdown. On the other hand, lower air density means a lower threshold for plasma formation, so the two effects might be balanced. In addition, the longer mean free path of ions will alter the filament diameter and period. Further modeling and experiments are required to identify the relevant parameters.

The short pulses of the femtosecond laser, and the long delay between these pulses mean rather low duty cycle. Typically, the pulses are shorter than 100 fs, and occur every 1-10 ms. However, since the plasma is formed where the air is thin and the mean free path is long, its life time is longer. Simulations, laboratory and field experiments will be needed to quantify these values.

One way to significantly reduce laser power is to support the initiation of plasma by radio beam(s) [12], even below the threshold of breakdown. Thus the radio power present in the vicinity of the scatter centers is not sufficient to create plasma, but the incremental laser power will already pass this threshold. In addition, since the volume heated by radio is much larger, many more filaments can be created and the scatter efficiency will increase. However, two radio transmitters (or phased arrays) are required for the two scatter centers, and the operation becomes complex.

3.2 Scatter efficiency

In solid optics, stellar light reflects from the folding mirrors within the interferometer, and as the number of reflections is large, light is lost. Here one has to worry how much light will the modulation of the refractive index of the air affect the stellar light. Estimates about the index modulation depth are from a fraction of a percent to few percent, but the interaction takes place over extremely long paths. It might also be possible to use the plasma modulation along the filaments [11] for enhanced lateral scatter. More modeling, simulations and measurements need to be taken to find the index modulation and the scatter efficiency as a function of off-axis angle.

3.3 Background light

Formation of plasma in thin air (by radio waves) was proposed for artificial beacons [12] and was proved experimentally [13]. Here, the effect is not beneficial, since we are not interested in the light formed within the filaments, but in the weak celestial light behind it. As the two arrive at the detector from the same location, they must be separated by other means. These include temporal, spectral and polarization controls. Since the laser operates in periodic pulses, the filaments and the scattered light are all modulated at this frequency but at a different phase delay between them. In addition, the light emitted by the plasma is usually in nitrogen and oxygen lines, which can be filtered away. Another way to reduce them is to increase third harmonic generation, which would take them out to energies above the visible spectrum.

Another effect is the supercontinuum modulation, the modulation of the wavelength of light to form essentially white lasers. In the presence of plasma, the refractive index is modified as a function of time since the femtosecond pulse started [6]

$$n(t) \approx n_0 + n_{Kerr} I(t) - \frac{2\pi e^2 N_e(t)}{m_e \omega_0^2}, \tag{4}$$

where e is the electron charge, m_e its mass, N_e its density in the plasma, and ω_0 the laser frequency. This coupling of frequency with temporal development leads to self phase modulation and variation of the light frequency [6]. Changing the relative time of different spectral components within the femtosecond pulse (chirping) enhances this effect, which is not beneficial here.

Finally, if the stellar light is scattered off a regular grid of filaments, it could have different polarization states than the plasma-formed light, which could also lead to their separation.

3.4 Safety issues

Of course it is rather dangerous to emit such a strong laser beam into the atmosphere, where it could hit air traffic. However, this issue was encountered before by observatories operating laser guide stars. Manual and automatic airplane detection systems and coordination with satellite operations are routine today. Further coordination is required in case of nearby telescopes which might be affected by the light pollution.

4. SUMMARY

Long baseline optical interferometers are large and complex systems. They can deliver information which is not available by other astronomical means. What is proposed here is an alternative way, namely to construct such a system from thin air. Not all the physics involved are understood, and not all the technology required is available now. However, the gap is not that large, and atmospheric and plasma scientists are closing it fast. The advantage of such a system is its flexibility to create weak siderostats anywhere in the atmosphere, and thus measure stellar components in a very flexible manner.

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