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LASER GUIDE STARS FOR HYPERTELESCOPES

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Abstract. Optical interferometry has achieved milli-arc-second resolution in an increasing number of science cases as well as some image reconstruction with incoherent aperture synthesis using a limited number of apertures. "Hypertelescopes", i.e. many-aperture arrays exploiting pupil-densification for efficiently producing direct images, have been proposed for improving the imaging performance. Provided that phasing is possible, such an instrument may in principle provide higher resolution than achievable within the 40m size limit currently considered for "Extremely Large Telescopes". Hypertelescopes will require adaptive phasing to cope with atmospheric turbulence. In order to achieve adaptive phasing in the abscence of a natural guide star a modified laser guide star method, suitable for large diluted apertures, has been proposed in order to extend the limiting magnitude. We report on our initial laboratory and numerical simulations, providing evidence for the feasibility of such a method.

1 Introduction

Optical interferometers are a diluted version of an extremely large telescope. The versions using several fixed telescopes, built in the recent decades, cannot be globally pointed and have thus required the use of optical delay lines. These costly elements have so far limited the number of optical beams that are coherently combined. On simple science targets, images have been reconstructed with incoherent forms of aperture synthesis, achieved by combining exposures recorded as intensity patterns at different times. The imaging performance is however greatly improvable in principle, also on complex sources, if the number of sub-apertures is increased (as achieved in radio-astronomy) to tens or hundreds and their beams combined directly and coherently. Numerical simulations, confirmed by laboratory bench top exposures [2], have indeed shown that a given collecting area thus exploited coherently can provide direct images with information content growing with the number of sub-apertures. Current projects in radio-astronomy, which will combine more than 10,000 small antennas, benefit from the same effect [9].

A simple way of directly combining many sub-apertures, the Fizeau design, is increasingly affected by diffraction effects as the pupil becomes more diluted. The light concentration can be improved by densifying the exit pupil, a design known as the "hypertelescope". It was already used by Michelson, in embryonic form, in his 20 feet interferometer at Mt. Wilson. Among the various hypertelescope design architectures considered, the spherical version called Carlina may be considered as a dilute form of the Arecibo radio-telescope, where the spherical geometry of the primary array removes the need for optical delay lines, and therefore favors using many tiny mirrors rather than few large ones, greatly enhancing the imaging performance.

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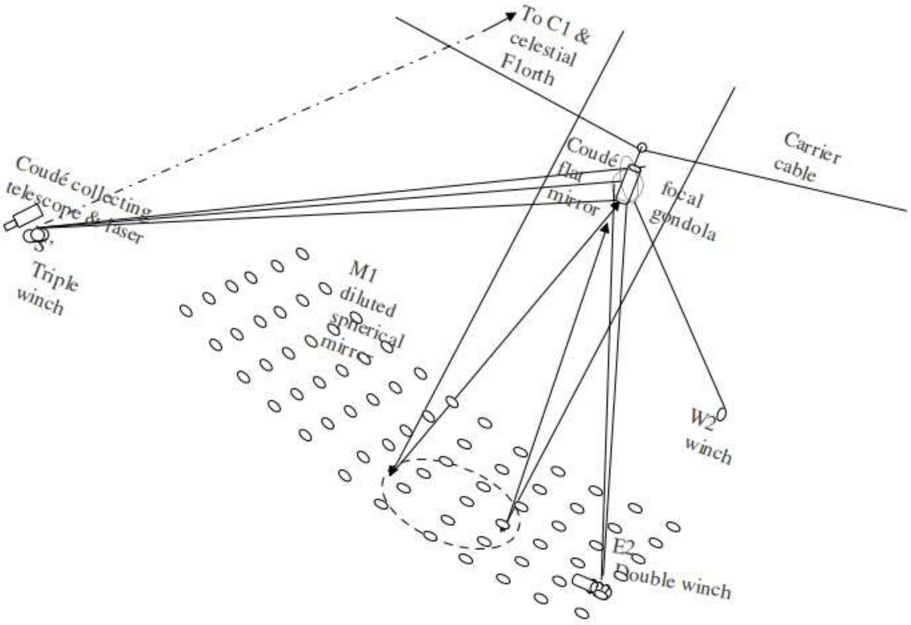

Fig. 1. The Ubaye Hypertelescope under construction: An array of ground mirrors focuses light on a gondola which is suspended from two sides of a deep east-west valley. A coude beam is sent to the southern slope of the valley.

Possible science applications of terrestrial hypertelescopes range from stellar astrophysics by directly imaging the surfaces of stars, to exoplanet science by imaging transits, to deep field galaxies and cosmology. Like conventional telescopes, however, hypertelescopes have much to gain if equipped with adaptive optics for removing the wavefront distortions caused by the atmospheric turbulence. Such co-phasing is similarly achievable with a small deformable mirror installed near the science camera. A fast wavefront sensor is also similarly needed for mapping the phase errors, at millisecond intervals in the visible range. This similarly requires that a rather bright guide star be present near the observed source, within the narrow isoplanatic patch typically spanning $\sim$ 15 arc-seconds. In the absence of such guide star, a laser guide star is usable, according to techniques [1] which became successfully developed in the recent years.

The existing forms of Laser Guide Star, developed for conventional telescopes, however appear unsuitable for dilute apertures, but a modified form has been proposed for such apertures [4]. We have explored through laboratory and numerical simulations the feasibility and possible designs for such "Hypertelescope Laser Guide Stars" (H-LGS) . We consider testing H-LGS designs on the "Ubaye Hypertelescope " prototype currently built in the southern French Alps, and briefly described below . Combined hypertelescope and H-LGS systems may indeed have the potential for greatly expanding the applicability of stellar interferometry, well beyond stellar targets and toward much fainter extra-galactic sources including the faintest cosmological objects currently known.

The prototype hypertelescope at la Moutiere valley in the French Southern Alps is sketched in Figure 1. There are currently two 15 cm mirrors with a north-south baseline of 16 m and a gondola suspended at 100 m that serves as the beam combiner. The gondola has an equatorial motion and allows a Coudé focus to be projected on a collecting telescope on the south slope. We will gradually install more ground mirrors every few meters which will have to be adaptively

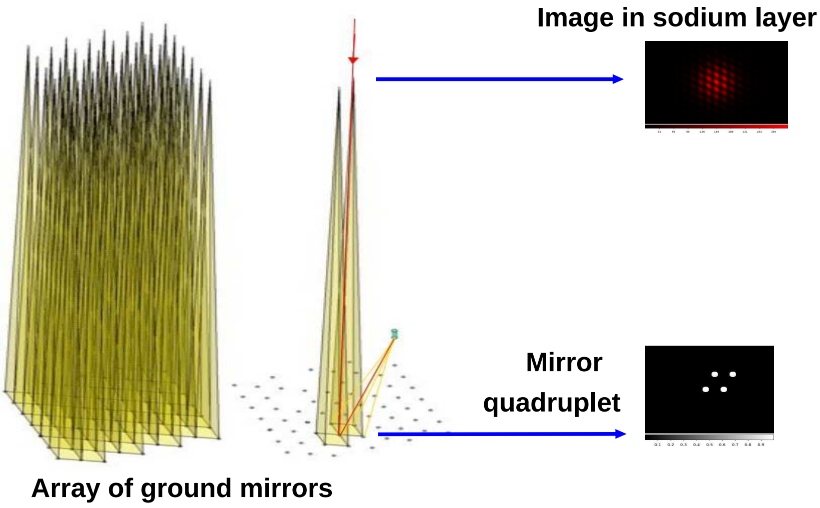

Fig. 2. Quadruplets of adjacent mirrors can be used to form an array of spots in the sky. Each spot is an interference pattern, whose image in the focal plane of the hypertelescope is sensitive to wavefront errors.

phased to compensate for atmospheric turbulence. Larger valleys in the Himalayas and Andes are being considered for kilometric-sized apertures [7].

2 The Hypertelescope Laser Guide Star

Conventional laser-guide star techniques cannot be used with a large ($\sim 100\,\mathrm{m}$) aperture for two main reasons:

1. A typical artificial star would be resolved with the smallest baselines of a large hypertelescope
2. Light rays from the star would sample a different atmospheric column as those from the artificial star, i.e. the *Cone effect*

Therefore, our approach is to use sub-sets of adjacent mirrors as the laser emitting optics, thus creating an array of artificial stars in the sodium layer. Each spot on the sodium layer is in fact an interference pattern (see Figure 2), and the same sub-set of mirrors can be used to re-image the interference pattern, near the science camera. Laser-light passes twice through the same optics, once to form an image in the sodium layer, and a second time to create the "double-pass" image which can be shown to be sensitive to piston errors between adjacent mirrors. The double-pass interference pattern is still contrasted, which resolves the first item mentioned above. The cone effect is reduced by using adjacent mirrors spaced by a few meters as the laser emitting optics.

3 Sensing piston errors

In the following discussion we concentrate on a single mirror quadruplet which is used as the laser-emmiting optics. The interference pattern formed in the sodium layer is the convolution of a point source and the PSF of the mirror quadruplet, i.e. the Fourier transform of the complex

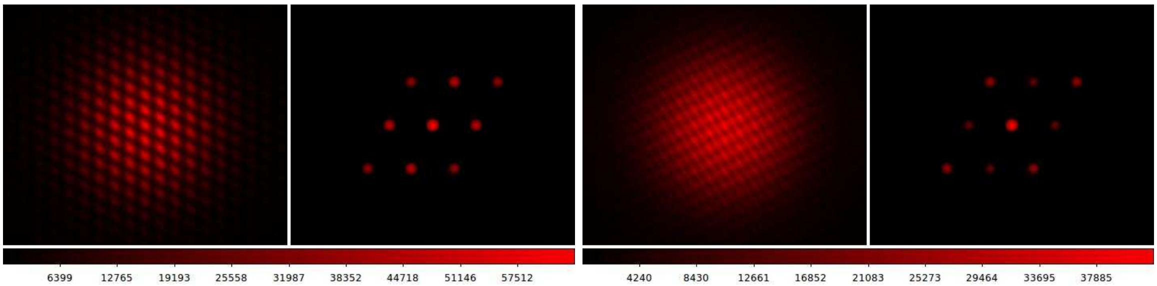

Fig. 3. Left: Focal image corresponding to no piston errors between mirrors and its Fourier transform (in log-scale). Right: Piston error of $\pi/2$ between two of the mirrors.

pupil. The image formed at the focal plane of the Hypertelescope is the convolution of the image in the sodium layer and the PSF of the reversed pupil. In Fourier space, this is the product of the autocorrelation of the quadruplet and an inverted copy of it. If there are redundant baselines, such as with the rhombus pattern used in our analysis, some autocorrelation peaks will contain contributions from two redundant baselines. Therefore, in the case of the rhombus-type pupil, the squared modulus of the complex pupil's autocorrelation retains some phase information [8].

The phase information can therefore be extracted by taking the Fourier transform of the laser-guide-star image and measuring the relative height of two (squared) autocorrelation peaks. If we compute the squared autocorrelation of rhombus-type pupil containing phase errors ϕ_i at each aperture, it can be shown that [8]

$$\phi_1 - \phi_2 + \phi_3 - \phi_4 = \pm \cos^{-1}\left(\frac{8I_1}{I_0} - 1\right), \tag{1}$$

where the sub-pupils are ordered clock-wise in the quadruplet, I_0 is the height of the central peak (corresponding to the zero baseline), and I_1 is one of the peaks containing contributions from two redundant baselines. The sign ambiguity can be resolved by using a phase diversity method [3], i.e. by simultaneously taking a separate image with a known *additional* phase error. Equation 1 is the "building block" for an array of mirrors consisting of several overlapping quadruplets and can be used to find the pistons across a large array of mirrors. Figure 3 shows some numerical simulations of hypertelescope laser-guide-star images and their Fourier transform (in logarithmic scale). From the Figure it can be seen that the peaks of the Fourier transform of the interference pattern change in intensity when a piston error is introduced.

Sources of uncertainty in the piston determination include photon/readout noise, Rayleigh back-scattering of laser light and sampling of the focal images. The relative importance of each of these sources of error is currently being investigated [8].

4 Experimental efforts

For an initial experimental simulation, we use an arrangement such as the one shown in Figure 4. Light incident on a mask (which simulates a mirror quadruplet) is focused with a lens on a rotating diffuser (which simulates the sodium layer). The hypertelescope focal image is recorded by the camera (below left). An adjustable phase shifter is introduced in one of the apertures.

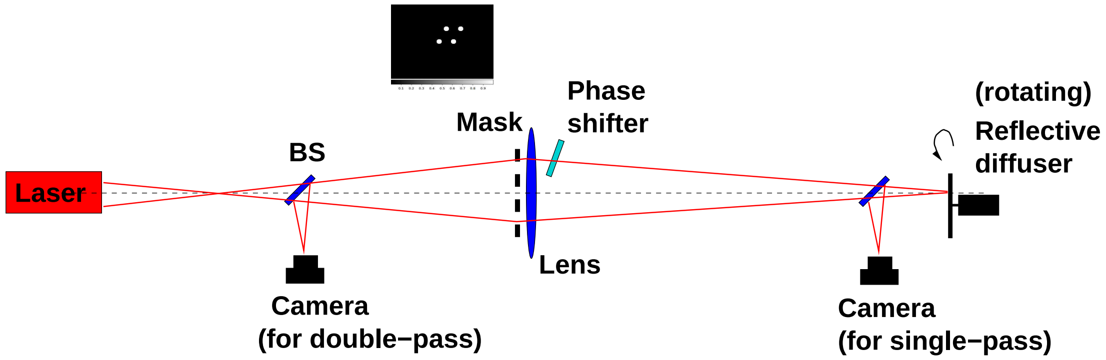

Fig. 4. Initial laboratory set-up. To simulate the laser spot on the sodium layer we use a mask followed by a lens, which creates an interference pattern on a rotating reflective diffuser. The image formed on the sodium layer (single-pass image) can be detected with the camera shown on the right. The light returning from the rotating reflective difusser (double-pass image) is detected in the focal plane of the hypertelescope with the camera shown on the left. An adjustable (tiltable) phase delay plate after one of the sub-apertures simulates the effect of the atmosphere.

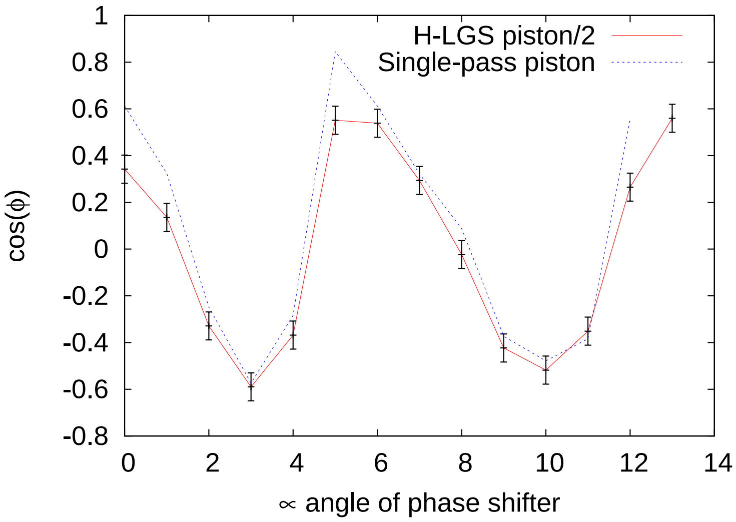

Fig. 5. Measured cosine of the (wrapped) phase for different angles of the phase delay plate. The “single-pass” phase can be accessed directly by recording the image on the simulated sodiium layer. The “double-pass” phase can be measured with the method of Section 3. The error-bars in Figure 5 were estimated for a single piston error by finding the standard deviation of an ensemble of 100 measurements.

In order to test the analysis of the Hypertelescope focal image, the introduced piston can be independently measured by Fourier analyzing the (complex) image formed in the simulated sodium layer. Preliminary results shown in Figure 5 provide evidence that piston errors can be measured down to a fraction of the wavelength. The curve labeled “single-pass piston” was obtained by measuring the phase of the single-pass interference pattern, while the curve labeled “H-LGS” was obtained by measuring the relative height of peaks in the Fourier transform of the double-pass interference pattern.

5 Conclusions

A technique for sensing wavefront piston errors with a dilute aperture has been developed. Preliminary laboratory and numerical simulations show that piston errors can be sensed to within a fraction of a wavelength ($< \lambda/10$). The simulations presented here are limited to 4 apertures arranged as a rhombus, which yield a single piston error. For an array of several overlapping quadruplets, the method described above yields local wavefront slope information, which can be used to find a global map of the phase [8]. This method does not solve the global tip/tilt problem so each co-phased image should be re-centered in real time. The method described here may also be directly applicable to extremely large telescopes with a segmented pupil as long as it can be sub-divided into overlapping quadruplets, each with two redundant baselines (i.e. rhombi).

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