Diffraction-limited high dynamic range imaging from the visible to the infrared

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abstract

We propose a novel technique to achieve high angular resolution imaging at high dynamic range that will be well adapted to some astrophysical cases such as imaging of planets very close to their central star and of structures in disks. The fundamental idea is to apply techniques developed for long baseline interferometry to the case of a single-aperture telescope. The pupil of the telescope is broken down into coherent sub-apertures each feeding a single-mode fiber. A remapping of the exit pupil allows interfering all sub-apertures non-redundantly. A diffraction-limited image with very high dynamic range is reconstructed from the fringe pattern analysis with aperture synthesis techniques, free of speckle noise. Raw dynamic ranges of a million can be obtained in only a few tens of seconds of integration time for bright objects and can be improved with off-line processing techniques. The technique can be applied to either visible or infrared wavelengths, the number of fibers matches the number of coherent patches over the pupil. The technique can also be applied to space coronography. First simulations show that contrasts of 10^{10} can be achieved within a distance of a fraction of λ/D on regular brightness candidates for planet search (for more detail about the application to space coronagraph, please visit the poster by Lacour et al).

Concept

The telescope pupil is divided into sub-apertures each feeding a single-mode fiber in order to filter out atmospheric turbulence. Output sub-apertures will be rearranged non-redundantly. The advantages of this technique are following: First, the use of single-mode fibers filter out atmospheric turbulence effects, as already demonstrated by a single-mode fiber long-baseline interferometry. Second, non-redundant pupil configuration eliminates redundant noise which affects wavefront measurement accuracy. Third, the full incident pupil of the telescope can be used thanks to the pupil remapping by fibers. The removal of atmospheric turbulence and redundant noise allows the calibration of degraded wavefront almost perfectly. Therefore this technique can take a full advantage of intrinsic high angular resolution of large ground-based telescopes and its large photon collecting capability.

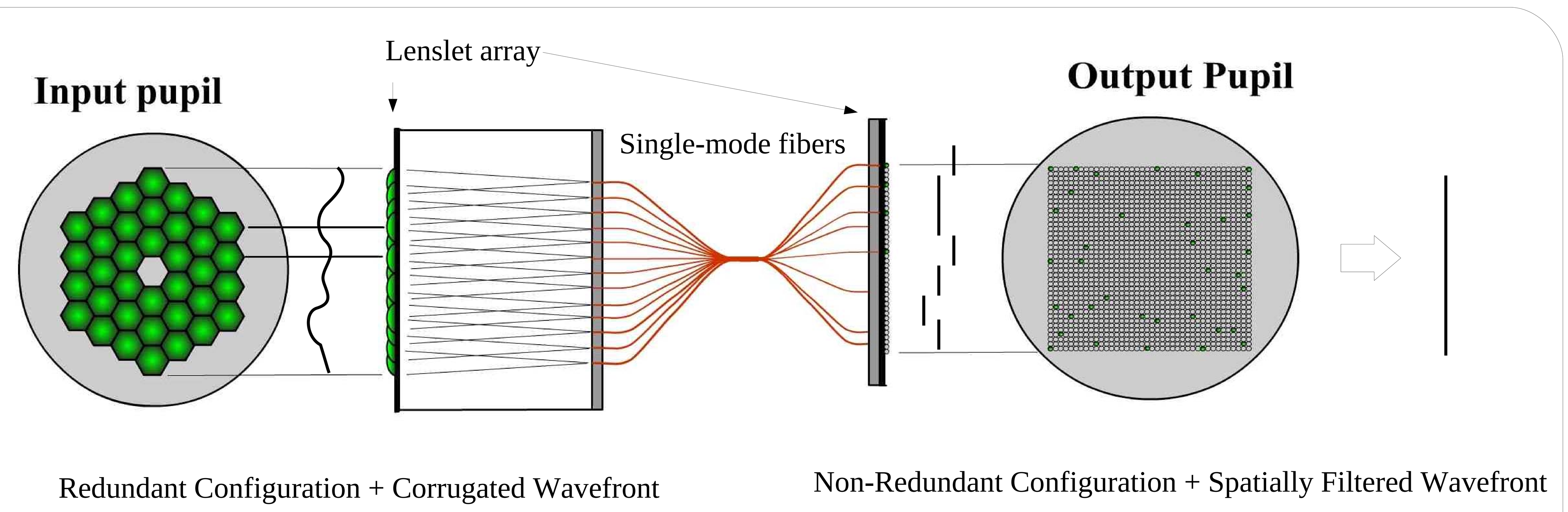


Fig. 1: Proposed instrumental setup.

Performance

The right panels show the simulations of reconstructed images with 36-element pupil remapping technique. They consist of 10000 snapshots of 4 ms each on an 8 meter telescope in the case of r_0 = 20 cm at the the visible wavelengths. The field of view of each image is 30 λ/D. The object is a central star with a circumstellar disk and two companions, of relative flux a 10^3 and 10^4. From left to right, the difference in the reconstructed images are due to the brightness of the object (magnitudes 10, 5 and 0). The reconstructions show dynamic range around or over 10^4 ~ 10^6. Further enhancement of a dynamic range may be possible: by increasing the number of exposures; increasing the number of sub-apertures; direct theoretical visibility fitting to observed visibilities to avoid image reconstruction noise.

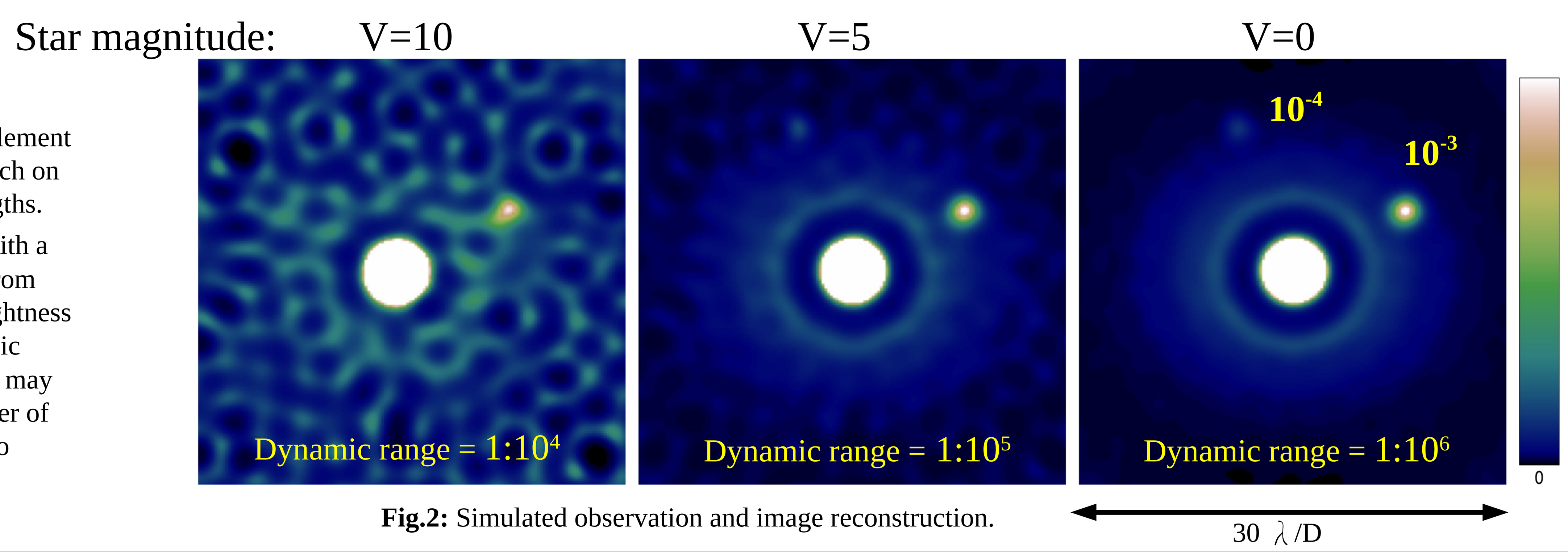
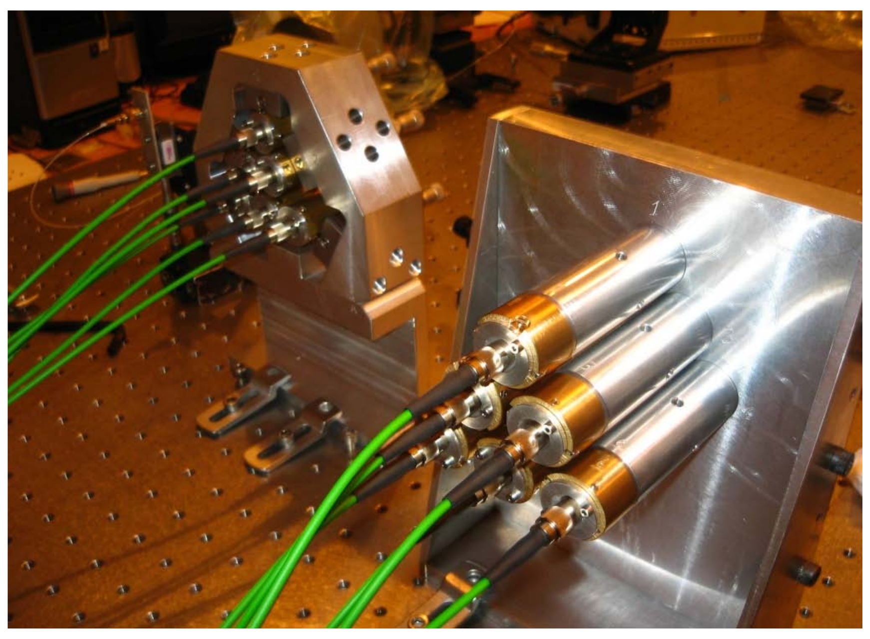


Fig.2: Simulated observation and image reconstruction.

6-element lab demonstrator

We have constructed the 6-element laboratory testbed in order to demonstrate our concept. The input telescope pupil is divided into the 6-redundant sub-pupils (Fig.3. Left) and the laser light is injected into the single-mode fibers. The output light from the fibers are collimated and remapped non-redundantly (Fig. 3. Right). The light is combined on the image plane to measure the interferometric fringes.

Fig. 4 shows the 6-beam interferometric fringes on the image plane. Thanks to the pupil remapping, all fringe peaks can be seen in the power spectrum of the PSF. It enables us to derive object complex visibilities (amplitude and phase) independently. We will investigate possible error sources with this system and quantify their impacts on the dynamic range.



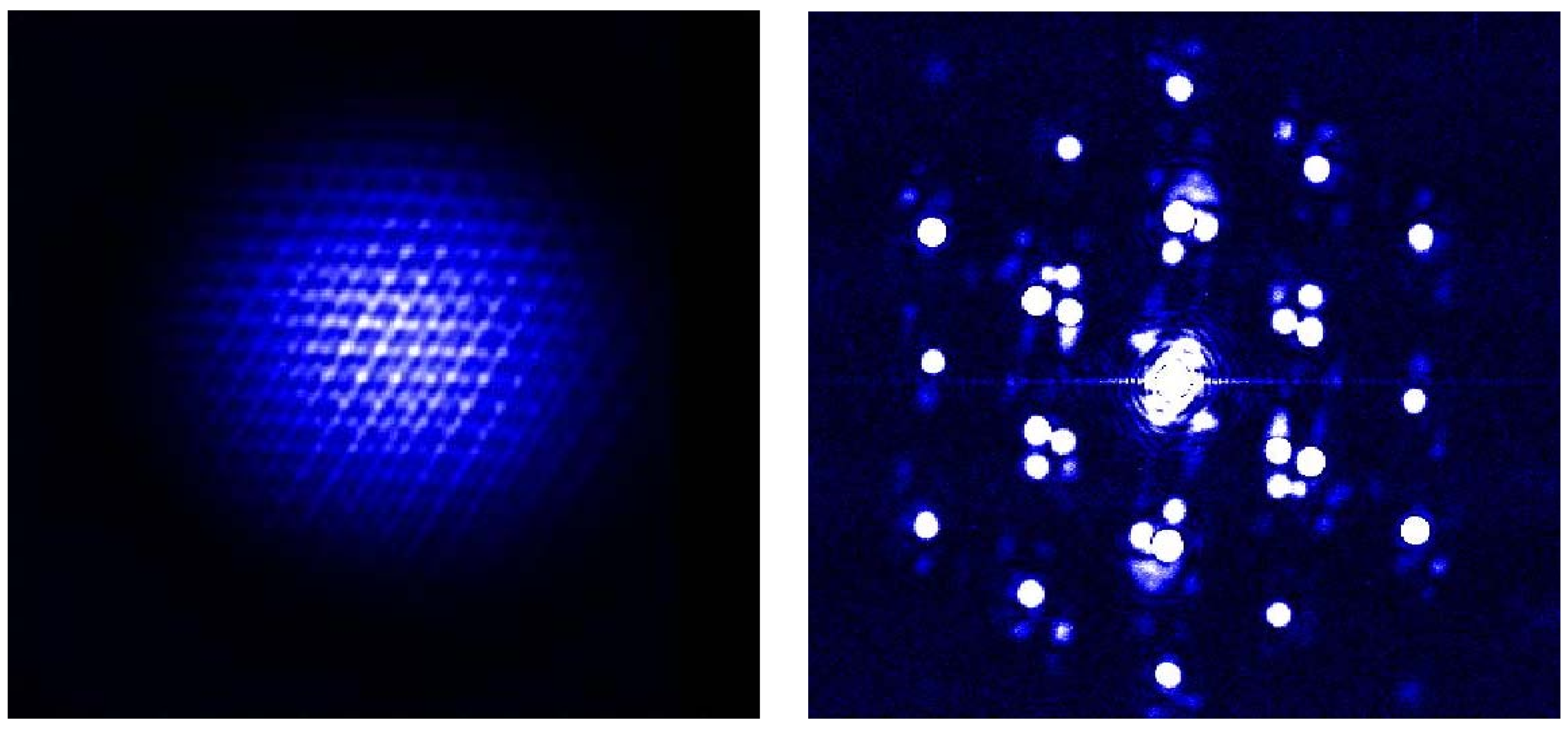


Fig. 4: Left: PSF with the remapped 6 pupil system. Right: Power spectrum of the PSF. The peaks correspond to 15 baselines are clearly seen.

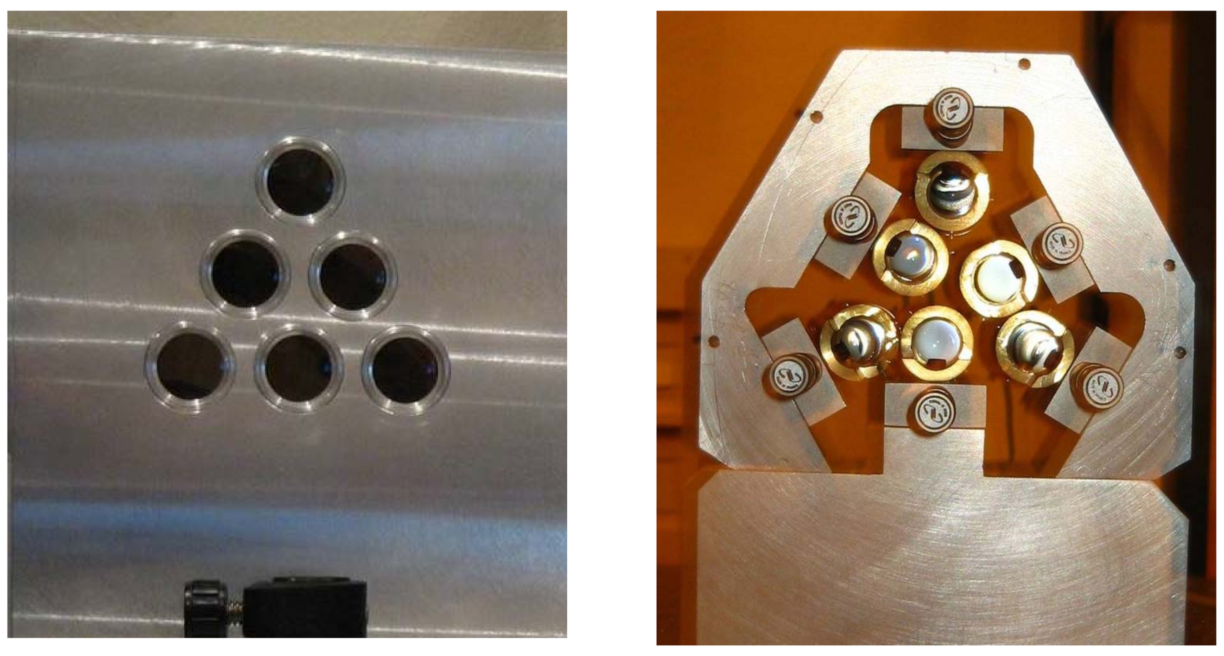


Fig. 3: Left: Input redundant pupil. Right: Remapped non-redundant pupil.

Perspective

The final goal of this project is to develop a prototype system with 36 fibers, which will be optimized for 8-m class ground based telescopes such as Keck, VLT, Subaru, etc. The most important task for achieving very high dynamic range with this system is to realize an extremely high-precision optical alignment of a coherent bundle of 36 single-mode fibers with respect to a microscopic lens array. We plan to use V-groove substrates to hold fibers, which can be positioned with sub-micron accuracy, or an active alignment system like a deformable mirror.

Although our technique can be applied to any astronomical source, it will be very suitable and unique method for detection and characterization of Jupiter-like planets around nearby stars at the visible wavelengths.

References

G. Perrin et al. 2006, MNRAS, 373, 7470
S. Lacour et al. 2007, MNRAS, 374, 832