In Laboratory Assessment of Hypertelescope Prototype

1. Origin of the Proposal:

Historically, optical astronomy, also called visible light astronomy, is one of the oldest forms of natural sciences. The technology deployed for its study has evolved over centuries. Reflecting telescope was introduced on seventeenth century to overcome the difficulties of its refractive counterpart. On the other hand, Fizeau's proposal to install a mask with two holes or sub-apertures on top of a telescope allowed Michelson to resolve the satellites of Jupiter on 1868.

At present the largest telescope being planned is known as the Thirty Meter Telescope (TMT), which is proposed to be constructed at Mauna Kea, Hawaii with India being one of its official R&D partner. This is essentially a monolithic reflecting telescope with thirty meter diameter primary mirror. Due to its monolithic nature, it occupies a large area at a stretch, and also technically difficult to expand. These difficulties can readily be overcome with an array structure of primary mirror segments, which is the fundamental concept of astronomical interferometer, with Hypertelescope being its extreme possibility.

Hypertelescope can be defined as a dilute multi-aperture imaging interferometer that uses a densified pupil. Densification improves the image luminosity with respect to Fizeau interferometers, and they can be equipped with coronagraphic optics for reaching a high dynamic range, typically needed for observing extra-solar planets. Since its initial formulation (1996, Labeyrie), the theory of pupil-densification has been verified in the laboratory and on the sky with multi-aperture miniature versions ((2000, Pedretti), (2003, Gillet), (2008, Patru), (2011, Allouche)). Recent theoretical work ((2007, Lardiere),(2007; 2008, Labeyrie)) has quantified the expected performance gain with respect to first-generation interferometers using a few large apertures, rather than many small ones. With adaptive phasing and a modified version of a laser guide star, it appears feasible to obtain direct images of faint galaxies at the limit of the known universe.

The current project proposal combines the pupil densifier system along with the spherical primary array of mirrors to generate a laboratory prototype of total hypertelescope scheme. We also propose to make a complete housing for the pupil-densifier and collecting optics part which can be hanged vertically to acquire the light from the primary mirror pointing upward. In future, we also plan to incorporate the air turbulence simulation using Spatial Light Modulator (SLM) and adaptive phasing using Wave-Front Sensor (WFS) to nullify that turbulence effect.

2. Risk elements and Rewards

The idea of hypertelescope was first introduced by Prof. A. Labeyrie in 1996. Since then, as stated earlier, many authors have worked on this topic and proved the robustness of the theory. The problem faced at the time of implementation was primarily regarding the vertical hanging of the focal optics, which all the working groups wanted to keep low cost. Different methods were tried for this purpose, such as hanging the optics from hydrogen balloon, using long cable with winches and lately hanging it from drone.

Here we would like to check first the opto-mechanical tolerance level of the system if it is hanged from a steady heavy-bottom support. This measurement will help us to decide if we can use a large column structure for this purpose at the actual site in our next project.

Apart from the challenges of retrieving high-resolution images from the experimental set-up and the following image processing software, there are certain risk factors attached to the project, which may nullify the future implementation plans with currently available technology. On the other hand, if we get success, this will open a new door for future astronomical telescopic systems. The risks and rewards attached to this work are tabulated below.

Risk Factors

- The experimental tolerance limit for optics can be lower than the mechanical sensitivity.
- Air turbulence and other vibrations may become the limiting factors for fringe acquisition
- The total system can be destroyed falling from a height when hanging vertically.

Rewards

- Sensitivity of the final system will be more than any other existing telescope
- The base-line can be increased without destroying the total system
- No relay line compensation
- The primary mirror components can be installed even within township area without any hazard.

From this study we can see the Rewards points look really lucrative in comparison to the Risk factors. This encourages us to submit the current proposal.

3. Review of status of Research and Development in the subject

3.1 International Status:

The concept of Hypertelescope was first discussed by Antoine Labeyrie in 1996. Since then many theoretical and experimental works have been done towards capturing the star image with hypertelescope construction. Below we present a brief description of the important works in this field.

- In 1996 Antoine Labeyrie[1] developed the basic theory of hypertelescope by analyzing the image formation in an extended version of Michelson's Stellar Interferometer. It showed it is possible to acquire high resolution image of extra-solar planets in the recombined focal plane of large number of telescopes.
- In the year of 2000, Predretti *et. Al*[2]. reported capturing First Image with hypertelescope scheme, i.e. with a miniature ``densified pupil imaging interferometer'', based on observations performed at the Observatoire de Haute Provence. They experimentally obtained an intensity gain of (24± 3 times) when a densified-pupil interferometer is compared to an equivalent Fizeau-type interferometer and show images of the double star α Gem. The initial results presented confirm the possibility of directly obtaining high resolution and high dynamic range images in the recombined focal plane of a large interferometer if enough elements are used.
- In 2003, Gillet *et. al.*[3] tested experimentally a new scheme for pupil densification, with a pair of micro-lens arrays, where each pair of facing lenses behaves like a tiny demagnifying telescope. They tested the direct snapshot performance with laboratory-simulated multiple stars and observed the binary star Castor (α Gem).
- Martinache and Borkowski *et. al.*[4-5] along with Labeyrie worked extensively on determination of piston error for such diluted aperture system from multi-spectral images. They studied the limiting magnitude of the method in the case of non-redundant apertures using analytical derivations and numerical simulations, which demonstrated the method's sensitivity is comparable to that of the Shack-Hartmann and other methods used for monolithic apertures.
- Lardiere and Patru *et. al.*[6-7] studied the limitation of the system in terms of field of view and the beam combination scheme. It was shown that the choice of the configuration of the array is a trade-off between the resolution, the halo level and the field of view. A regular pattern of the array of telescopes optimizes the image quality (low halo level and maximum encircled energy in the central peak), but decreases the useful field of view. Moreover, a non-redundant array is less sensitive to the space aliasing effect than a redundant array.
- Residori and Bortolozzo[8] along with Labeyrie worked on the design of Laser trapped mirror flotillas on space for the formation of the primary collecting mirror array. They suggested to use 3-10cm diameter mirrors to be trapped in space axially in interference pattern of standing waves formed by a pair of counter-propagating laser beams.

- Le Coroller, Dejonghe *et. al.*[9-10] worked on 1 km “multi-aperture densified-pupil imaging interferometer” for space named Luciola. They also set-up hypertelescope prototype at Haute-Provence Observatory and successfully gathered the interference fringes. In their configuration they suspended the focal collecting optics from a helium balloon, 5-10 m over the ground with accuracy of a few microns.
- Chakraborty and Allouche[11-13] along with Labeyrie and Rondi studied the concept of extremely large hypertelescope using a detailed ray-tracing, which is getting built in the site of southern Alps.

Nunez *et. al.*[14] investigated the feasibility of using a modified laser-guide-star technique that is suitable for large diluted apertures. The method consists of using subsets of apertures to create an array of artificial stars in the sodium layer and collecting back-scattered light with the same subapertures. They presented numerical and laboratory simulations that quantify the requirements and sensitivity of the technique.

3.2 National Status:

In India work on hypertelescope related field has mainly been carried out in the Indian Institute of Astronomy & Astrophysics. Here are some of its important aspect.

- Saha *et. al.*[15-18] studied stellar interferometry with emphasis on aperture synthesis using an array of telescopes particularly at optical/IR wavelengths. He discussed the basic principle of intensity interferometry corroborating with basic mathematical steps and its requirements, its limitations and the technical challenges it poses.
- Surya[19] and Saha discussed the speckle imaging with hypertelescope, which demonstrates the possibility of retrieving high resolution images from a large number of short-exposure primary images acquired with random phase errors such as caused by turbulent “seeing”. They simulated such observations using an aperture which changes through the night, as naturally happens on Earth with fixed grounded mirror elements, and find that reconstructed images of star clusters and extended objects are of high quality. They also estimated the required photon levels for achieving a good signal to noise ratio using such a technique.

3.3 Importance of the proposed project in the context of current status

Hypertelescope is such a scheme, which in principle is able to render extremely high resolution image of astronomical objects, without occupying much space at a stretch on ground owing to its array structure. Due to this property, the sub-apertures of the primary mirrors can even be installed within a township area at high altitude, where light and environmental pollution is low.

On the other hand, for a ground based long-baseline telescopic system, ideal locations should be at high-altitude mountain valley, such as Himalayan valley. But in India, land acquisition is always a problem wherever it is due to its high population density.

In that scenario, Hypertelescope should be the ideal astronomical project for India, since neither a large land acquisition is required for it, nor has it any environmental impact. In contrast, such an array telescope should eventually become the future of all the telescopes due to its high resolution.

3.4 If the project is location specific, basis for selection of location be highlighted:

The project in its current state is not location specific. But upon successful completion of this project, we plan to start the actual installation of Ground Based Hypertelescope in collaboration with Prof. A. Labeyrie on behalf of Hypertelescope LISE, France. For that purpose, our first choice is Spiti Valley, Himachal.

4. Work Plan:

4.1 Methodology:

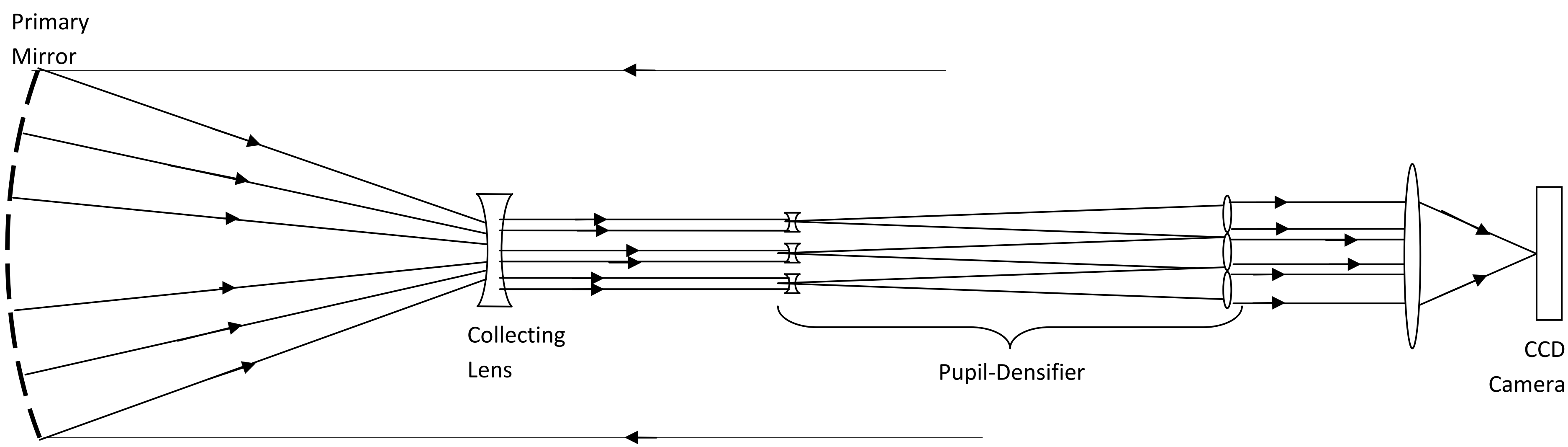


Figure 1: The schematic set-up of Hypertelescope Laboratory Version

1. **Laser Guide Star:** A He-Ne laser of wavelength 632.8nm followed by a beam-expander and collimator combination is to be used as the source. It replicates the light coming from distant star.
2. **Spherical primary array of mirrors:** The collimated light will be used to illuminate an array (at least 3x3) of small mirrors arranged over a spherical surface of radius *R* creates the primary aperture. The spherical, as opposed to paraboloidal, shape of the primary mirror is of interest for very large apertures which cannot be pointed. The rays reflected from the sub-aperture mirrors are to be collected near the focal plane of the spherical structure.
3. **Collecting and Collimating Optics:** The original Hypertelescope scheme employs a pair of clam-shell type mirrors to collect and collimate the incoming beam for further processing. This pair of mirrors also corrects the inherent spherical aberration of full-size system. Here we propose a suitable negative lens along with a suitable adaptive phase corrector to serve this purpose. This kind of collecting optics will incur no obscuration in the light path and can also provide in-situ phase correction.
4. **Pupil Densifier:** The scheme of pupil densification provides a Densified copy of entrance pupil at the exit pupil by increasing the size of the sub-aperture with respect to their relative distance. This can be achieved either by zooming the sub-apertures (1996, Labeyrie) or by using inverted Gallilean telescopes. This homothetic transformation keeps the overall pattern of the entrance pupil unchanged at the exit pupil and known as conformal Michelson scheme. This method densifies the energy into a strong interference peak, which was initially dispersed in a wide PSF of Fizeau mode. For an off-axis star the angular shift of the fringe pattern is more than the angular shift of the envelope; in the other words the peak moves faster than the Airy envelope when a star crosses the field. The basic structure of this scheme, made-up of mini-lenses, is described in Figure 1. Here we propose to build it using a SLM, since often the mini-lenses suffer from various optical aberrations and it becomes a big task to separate out the usable lenses and place them properly on optical bench (F. Allouche, 2011)[20]. The use of SLM will reduce the wastage of time and money for this purpose.
5. **Recording Optics:** An imaging lens along with a CCD camera is to be used for this purpose. A dedicated PC/Laptop must be there to acquire the CCD images.

Theory

The fundamental theory was proposed by A. Labeyrie in his seminal paper in 1996, which was eventually reviewed by many authors. Here I would like to discuss the basic imaging theory of Hypertelescope in brief, adhering to the notations used by Labeyrie in his original paper.

Since hypertelescope is basically an imaging interferometer having diluted array of sub-apertures, the final image is actually a recombined image produced by the individual ones.

In case of monochromatic point source, this image $B_P(x, y)$ can be represented as

$$B_P(x, y, \alpha, \beta) = I(x + \gamma_d \alpha, y + \gamma_d \beta) A(x + \alpha, y + \beta)$$

where, $I(x + \gamma_d \alpha, y + \gamma_d \beta)$ is the complete interference pattern generated by the array structure and

$A(x, y)$ is the Airy pattern of a single sub-aperture. α, β are the angles made by the source to the axis.

γ_d is the densification parameter defined as $\gamma_d = \dfrac{d_o / D_o}{d_i / D_i}$, where Ds and ds are the diameters of the complete arrays and of the individual sub-apertures respectively in entrance pupil plane (denoted by i) and exit pupil plane (denoted by o).

Therefore, in case of a distributed object $O(\alpha, \beta)$, the final image can be written as

$$B(x, y, \alpha, \beta) = O(\alpha, \beta) * B_P(x, y, \alpha, \beta)$$

where $*$ denotes convolution operation.

Now, for highly diluted array and very small angular dimension of the object, following Labeyrie's approximation, i.e. the array is highly diluted ($\gamma_d >> 1$) and the field angles are very small ($\alpha, \beta << 1$), we can write

$$B(x, y) \approx \gamma_d^{-2} A(x, y) \left[O\left(\frac{x}{\gamma_d}, \frac{y}{\gamma_d} \right) * I(x, y) \right]$$

This result shows:

- The image is formed in the focal plane as a convolution with the interference function and it can be seen through a fixed Airy window.
- The image size can be controlled by changing the factor γ_d.
- Only the coordinates of the object-term is affected by the densification factor. Therefore, increasing γ_d, does not affect the window size. But, since the array function itself is affected by the alteration of γ_d, the interference term is affected. And in the limiting case, for a completely filled exit-pupil, we get a clear image of the object.

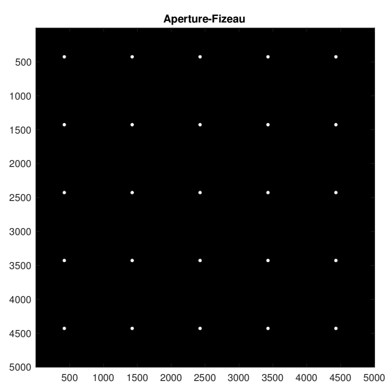
- Now, with a large γ_d, the image is magnified; but the total number of photons entering the system remains unchanged. Therefore, an amplification of the image intensity by a factor of γ_d^2 can be observed if we de-magnify the object-term to its initial size. Mathematically it means

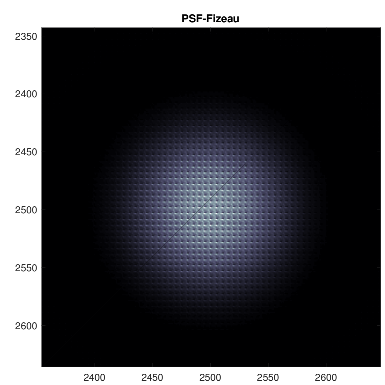
$$B(\gamma_d x, \gamma_d y) \approx \gamma_d^2 A(\gamma_d x, \gamma_d y)[O(x, y) * I(\gamma_d x, \gamma_d y)]$$

- Also, this kind of pupil densification indicates translation of some spatial-frequency regions to lower frequency regions, central frequency of which are related by a factor of γ_d. That is, the grid in frequency plane responsible for producing the interference pattern has been squeezed by a factor γ_d, which results in an expansion in the image plane pattern by same factor. It makes the speed of interference peak different from the speed of Airy envelope when the source moves.

Simulation Results:

Below are some selected simulated results:





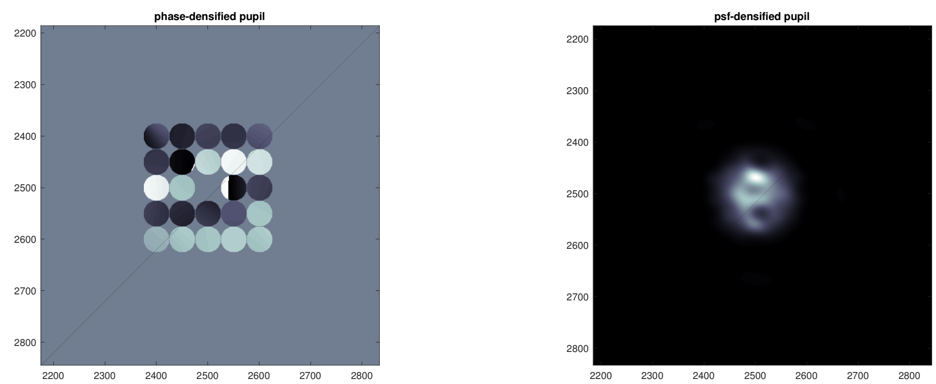
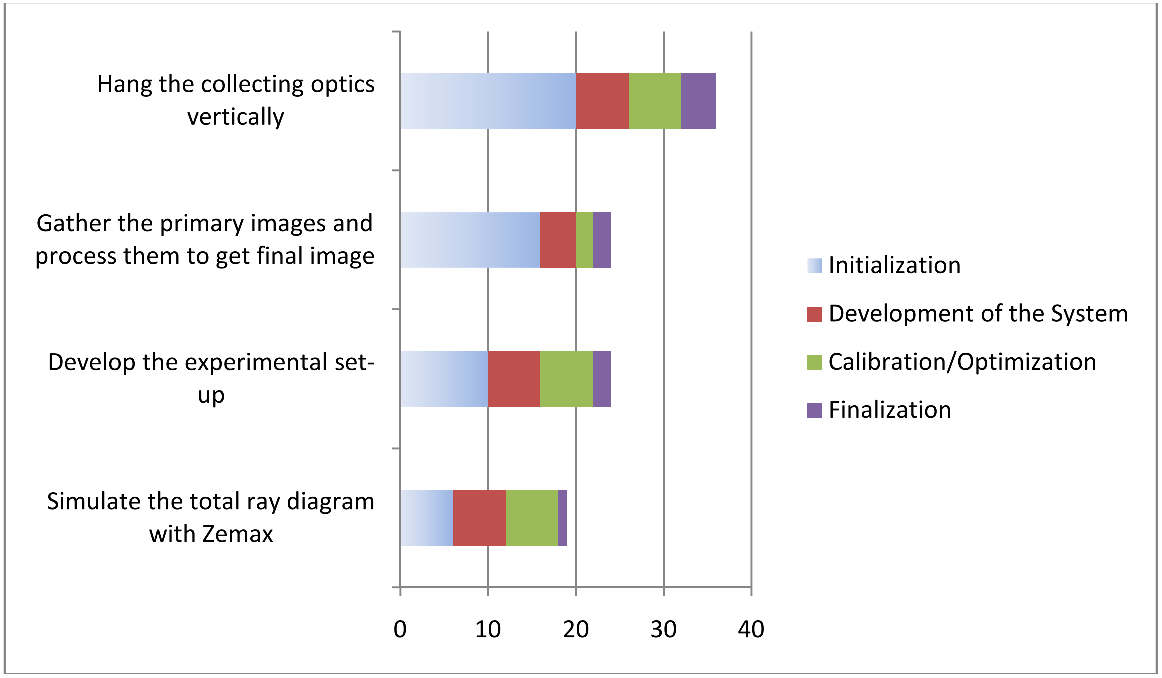


Figure 2: Comparison between Fizeau and Hypertelescope mode: Pupil structures and Images

The upper two figures of Figure 2 present the structure of the pupil and its corresponding direct image in Fizeau mode, i.e. when the pupil is not densified. The lower two figures shows the phase structure in the densified pupil and its direct image. For source, a high contrast image of Jupiter was taken.

4.2 Time Schedule of activities giving milestones through BAR diagram.

The following BAR diagram shows the tentative time-schedule for starting, developing, calibrating, optimizing and finalizing the system.



4.3 Suggested Plan of action for utilization of research outcome expected from the project.

The research outcome can be used extensively in astronomical imaging purpose. The results are expected to help the original hypertelescope project running in southern Alps. Moreover, on its successful completion, we are to suggest a bigger collaborative project in Himalaya with Hypertelescope, LISE, France as partner. Our first choice for that purpose is Spiti Valley in Himachal Pradesh.

4.4 Environmental impact assessment and risk analysis.

There is no Environmental risk associated with this project-proposal. This will be a complete indoor project with enough Laser safety measure. This project does not deal with any biological or chemical substance, and nothing used in this project will have any negative impact on environment.

5. Expertise:

5.1 Expertise available with the investigators in executing the project:

The PI of the proposed project has a long history of working with optical systems since her B.Tech. She did her Ph.D in Generation of Quasi Propagation-Invariant beam with Diffractive-Optical Elements, which resulted in numerous journal publications and awards. These special kinds of beams were generated keeping in mind the necessities of the Optical Tweezers needs particularly.

The professional expertise for this work was gained by the PI of the project working in Observatoire de la Cote d'Azur, France during her post-doctoral studies under Prof. A. Labeyrie in Hypertelescope project. She studied the system behavior extensively using Zemax.

Later she worked in LIGO, Caltech, USA which enhanced her research capabilities and earned her Breakthrough Prize awarded by Breakthrough Prize Foundation, USA, which she shares with LIGO team.

Besides, in this project, a provision for having consultation from other experts has been kept in the proposal, in case it is needed.

5.2 Summary of roles/responsibilities for all Investigators:

S.No.	Name of the Investigators	Roles/Responsibilities
1.	Rijuparna Chakraborty	Full Responsibility

5.3 Key publications published by the Investigators pertaining to the theme of the proposal during the last 5 years

1. A. Labeyrie, F. Allouche, D. Mourard, F. Bolgar, **R. Chakraborty**, J. Maillot, N. Palitzyne, J. R. Poletti, J.-P. Rochaix, R. Prud'homme, A. Rondi, M. Roussel, and A. Surya. Construction of a 57m hypertelescope in the Southern Alps. In society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, vol. 8445, July 2012.

2. A. Labeyrie, D. Mourard, F. Allouche, **R. Chakraborthy**, J. Dejonghe, A. Surya, Y. Bresson, C. Aime, D. Mary, and A. Carlotti. Concept study of an Extremely Large Hyper Telescope (ELHyT) with 1200m sparse aperture for direct imaging at 100 micro-arcsecond resolution. In Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, vol. 8445, July 2012.

5.4 Bibliography

1. A. Labeyrie. Resolved imaging of extra-solar planets with future 10-100km optical interferometric arrays. A&A, vol. 118:517–524, September 1996.

2. E. Pedretti, A. Labeyrie, L. Arnold, N. Thureau, O. Lardiere, A. Boccaletti, and P. Riaud. First images on the sky from a hyper telescope. A&A, vol. 147:285–290, December 2000.

3. S. Gillet, P. Riaud, O. Lardiere, J. Dejonghe, J. Schmitt, L. Arnold, A. Boccaletti, D. Horville, and A. Labeyrie. Imaging capabilities of hypertelescopes with a pair of micro-lens arrays. A&A, vol. 400:393–396, March 2003.

4. F. Martinache. Global wavefront sensing for interferometers and mosaic telescopes : the dispersed speckles principle.Journal of Optics A : Pure and Applied Optics, vol. 6:216–220, February 2004.

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6. O. Lardiere, F. Martinache, and F. Patru. Direct imaging with highly diluted apertures - I. Field-of-view limitations.MNRAS, vol. 375:977–988, March 2007.

7. F. Patru, N. Tarmoul, D. Mourard, and O. Lardiere. Direct imaging with highly diluted apertures - II. Properties of the point spread function of a hypertelescope. MNRAS, vol. 395:2363–2372, June 2009.

8. A. Labeyrie, H. Le Coroller, S. Residori, U. Bortolozzo, J. Huignard, and P. Riaud. Resolved Imaging of Extra-Solar Photosynthesis Patches with a "Laser Driven Hypertelescope Flotilla". In Pathways Towards Habitable Planets,Astronomical Society of the Pacific Conference Series [V. Coude Du Foresto, D. M. Gelino, and I. Ribas, editors], vol. 430 : 239, October 2010.

9. A. Labeyrie, H. Le Coroller, J. Dejonghe, O. Lardière, C. Aime, K. Dohlen, D. Mourard, R. Lyon, and K. G. Carpenter.Luciola hypertelescope space observatory : versatile, upgradable high-resolution imaging, from stars to deep-field cosmology. Experimental Astronomy, vol. 23:463–490, March 2009.

10. H. Le Coroller, J. Dejonghe, et al. Tests with a Carlina-type diluted telescope. Primary coherencing. Astronomy & Astrophysics, vol. 539, March 2012.

11. A. Labeyrie, F. Allouche, D. Mourard, F. Bolgar, R. Chakraborty, J. Maillot, N. Palitzyne, J. R. Poletti, J.-P. Rochaix, R. Prud'homme, A. Rondi, M. Roussel, and A. Surya. Construction of a 57m hypertelescope in the Southern Alps. In society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, vol. 8445, July 2012.

12. A. Labeyrie, D. Mourard, F. Allouche, R. Chakraborthy, J. Dejonghe, A. Surya, Y. Bresson, C. Aime, D. Mary, and A. Carlotti. Concept study of an Extremely Large Hyper Telescope (ELHyT) with 1200m sparse aperture for direct imaging at 100 micro-arcsecond resolution. In Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, vol. 8445, July 2012.

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17. S. K. Saha. Aperture Synthesis. Methods and Applications to Optical Astronomy. Springer-Verlag New York, 466 p, 2011.

18. S. K. Saha. Diffraction-Limited Imaging with Large and Moderate Telescopes. World Scientific, 636 p, 2007.

19. A. Surya, S. K. Saha and A. Labeyrie. Speckle Imaging with Hypertelescopes. Monthly Notices of the Royal Astronomical Society, vol. 443 : 852-859, September 2014.

20. "Étude de concepts coronographiques pour la détection directe d'exoplanètes", F. Allouche, Ph.D. Thesis, Nice Observatory France(2011)

6.1 Details of Projects submitted to various funding agencies:

S. No	Title	Cost in Lakh	Month of submission	Role as PI/Co-PI	Agency	Status
1.	Restraining the motion of cantilever fiber tip with an adaptive optical tweezer	1,26,98,600	9.12.2016	PI	DST-SERB	Accepted for Evaluation

6.2 N/A

6.3 N/A

7. List of facilities being extended by parent institution(s) for the project implementation.

7.1 Infrastructural Facilities

Sr. No.	Infrastructural Facility	Yes/No/ Not required Full or sharing basis
1	Workshop Facility	Yes
2	Water & Electricity	Yes
3	Laboratory Space/ Furniture	Yes
4	Power Generator	Yes
5	AC Room or AC	Yes
6	Telecommunication including e-mail & fax	Yes
7	Transportation	Yes
8	Administrative/ Secretarial support	Yes
9	Information facilities like Internet/Library	Yes
10	Computational facilities	Yes
11	Animal/Glass House	Not Required
12	Any other special facility being provided	Not Required

8. Name and address of experts/ institution interested in the subject / outcome of the Project:

Prof. A. Labeyrie
HYPERTELESCOPE LISE
Laboratoire d'Interférométrie Stellaire et Exoplanétaire, France
Association Loi de 1901
Web site http://hypertelescope.org/

Prof. D. Mourard
Observatoire de la Cote d'Azur, Nice, France