VSI: the VLTI spectro-imager

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ABSTRACT

The VLTI Spectro Imager (VSI) was proposed as a second-generation instrument of the *Very Large Telescope Interferometer* providing the ESO community with spectrally-resolved, near-infrared images at angular resolutions down to 1.1 milliarcsecond and spectral resolutions up to $R = 12000$. Targets as faint as $K = 13$ will be imaged without requiring a brighter nearby reference object; fainter targets can be accessed if a suitable reference is available. The unique combination of high-dynamic-range imaging at high angular resolution and high spectral resolution enables a scientific program which serves a broad user community and at the same time provides the opportunity for breakthroughs in many areas of astrophysics. The high level specifications of the instrument are derived from a detailed science case based on the capability to obtain, for the first time, milliarcsecond-resolution images of a wide range of targets including: probing the initial conditions for planet formation in the AU-scale environments of young stars; imaging convective cells and other phenomena on the surfaces of stars; mapping the chemical and physical environments of evolved stars, stellar remnants, and stellar winds; and disentangling

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the central regions of active galactic nuclei and supermassive black holes. VSI will provide these new capabilities using technologies which have been extensively tested in the past and VSI requires little in terms of new infrastructure on the VLTI. At the same time, VSI will be able to make maximum use of new infrastructure as it becomes available; for example, by combining 4, 6 and eventually 8 telescopes, enabling rapid imaging through the measurement of up to 28 visibilities in every wavelength channel within a few minutes. The current studies are focused on a 4-telescope version with an upgrade to a 6-telescope one. The instrument contains its own fringe tracker and tip-tilt control in order to reduce the constraints on the VLTI infrastructure and maximize the scientific return.

Keywords: astrophysics, instrumentation, compact astrophysical objects, infrared, interferometry, interferometer, high angular resolution

1. INTRODUCTION

At the beginning of the 21st century, infrared observations performed at the milli-arcsecond scale are essential for many astrophysical investigations either to compare the same physical phenomena at different wavelengths (like sources already observed with the VLBI or soon to be observed by ALMA) or to get finer details on observations carried out with the *Hubble Space Telescope* (HST) or 10-m class telescopes equipped with adaptive optics. The astrophysical science cases at milli-arcsecond scales which range from planetary physics to extragalactic studies can only be studied using interferometric aperture synthesis imaging with several optical telescopes. In this respect, the *Very Large Telescope* (VLT) observatory of the *European Southern Observatory* (ESO) is a unique site world-wide with $4 \times$ 8-m unit telescopes (UTs), $4 \times$ 1.8-m auxiliary telescopes (ATs) and all the required infrastructure, in particular delay lines (DLs), to combine up to 6 telescopes. The *VLT Interferometer* (VLTI) infrastructure can be directly compared to the *Plateau de Bure Interferometer* (PdBI) which combines $6 \times$ 15-m antenna over 500-m in the millimeter-wave domain. The quality of the foreseen images can be directly compared to the images provided by the PdBI. However, the angular resolution of the VLTI is a few hundred times higher due to the observation at shorter wavelengths. The large apertures of the VLTI telescopes and the availability of fringe tracking allow sensitivity and spectral resolution to be added to the imaging capability of the VLTI.

In April 2005, at the ESO workshop on *"The power of optical/infrared interferometry: recent scientific results and second generation VLTI instrumentation"*, two independent teams have proposed two different concepts for an imaging near-infrared instrument for the VLTI: BOBCAT[1] and VITRUV.[2] In October 2005, the science cases of these instruments were approved by the ESO *Science and Technical Committee.* In January 2006, the two projects merged in order to propose the *VLTI spectro-imager* (VSI) as a response to the ESO call for phase A proposals for second generation VLTI instruments. The phase A study ended in September 2007 after an ESO board review. The VSI instrument has been recommended by the ESO *Science and Technical Committee* in October 2007 and ESO is currently proposing to proceed with the construction in 2009-2010 for an installation of the 4/6 telescope version at the VLT in 2015. In this volume, we present the result of the VSI phase A study.

2. VSI OVERVIEW

The VLTI Spectro Imager will provide the astronomical community with spectrally-resolved near-infrared images at angular resolutions down to 1.1 milliarcsecond and spectral resolutions up to $R = 12000$. Targets as faint as $K = 13$ will be imaged without requiring a brighter nearby reference object; fainter targets can be accessed if a suitable off-axis reference is available. This unique combination of high-dynamic-range imaging at high angular resolution and high spectral resolution for a wide range of targets enables a scientific program which will serve a broad user community and at the same time provide the opportunity for breakthroughs in many areas at the forefront of astrophysics.

A great advantage of VSI is that it will provide these new capabilities while using techniques which have extensively been experimented in the past. VSI will be capable of making maximum use of the new VLTI infrastructure as it becomes available. Operations with less than 8 telescopes are the scope of the first phases of VSI. Three development phases are foreseen: VSI4 combining 4 telescopes (UTs or ATs), VSI6 combining 6 telescopes (4UTS+2ATs or 4ATs+2UTS and eventually 6ATs), and perhaps in the long-run, VSI8 combining 8 telescopes (4UTs+4ATs or eventually 8ATs). The current study is focused on a 4-telescope version with an

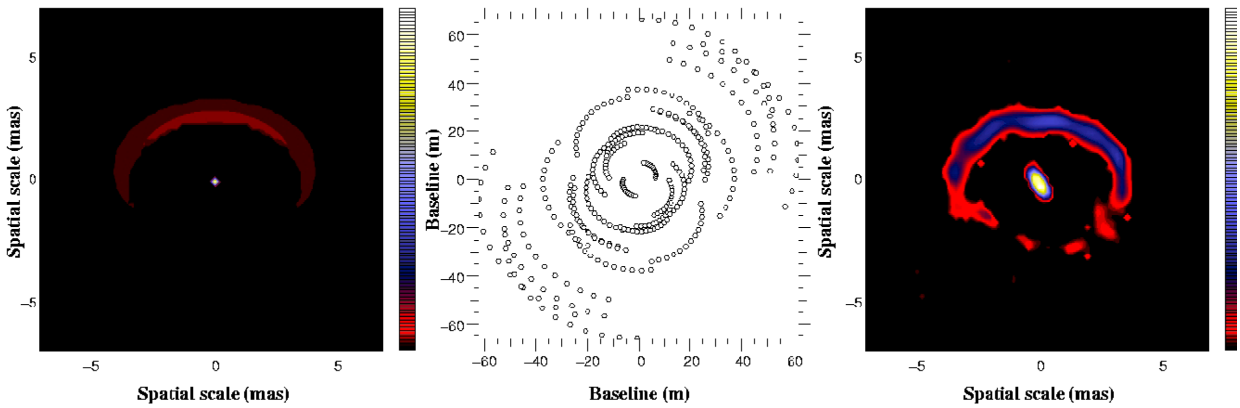

Figure 1. Image reconstruction performed with 6 ATs on a model disk around an Herbig Ae star. Left: model image; middle: coverage of the spatial frequencies; right: reconstructed image. The dust structure, the inner dust radius and the asymmetry (vertical structure) are well retrieved. Relative photometry is reliable (17% vs 19% of flux in the central star).

upgrade to a 6-telescope one. The instrument contains its own fringe tracker and tip-tilt control in order to reduce the constraints on the VLTI infrastructure and maximize the scientific return.

3. SCIENCE CASES FOR VSI

The high level specifications of the instrument are derived from science cases based on the capability to reconstruct milli-arcsecond-resolution images of a wide range of targets. These science cases are detailed by Garcia et al.[3] in this volume, but we list here the 4 main scientific cases:

- **Formation of stars and planets**. The early evolution of stars and the initial conditions for planet formation are determined by the interplay between accretion and outflow processes. Due to the small spatial scales where these processes take place, very little is known about the actual physical and chemical mechanisms at work. Interferometric imaging at 1 milli-arcsecond spatial resolution will directly probe the regions responsible for the bulk of excess continuum emission from these objects, therefore constraining the currently highly degenerate models for the spectral energy distribution (see Fig. 1). In the emission lines a variety of processes will be probed, in particular outflow and accretion magnetospheres. The inner few AUs of planetary systems will also be studied, providing additional information on their formation and evolution processes, as well as on the physics of extrasolar planets. Renard et al.[4] in this volume detail the case of the detection of extrasolar planets with VSI.

- **Imaging stellar surfaces**. Optical and near-infrared imaging instruments provide a powerful means to resolve stellar features of the generally patchy surfaces of stars throughout the Hertzsprung-Russell diagram. Optical/infrared interferometry has already proved its ability to derive surface structure parameters such as limb darkening or other atmospheric parameters. VSI, as an imaging device, is of strong interest to study various specific features such as vertical and horizontal temperature profiles and abundance inhomogeneities, and to detect their variability as the star rotates. This will provide important keys to address stellar activity processes, mass-loss events, magneto-hydrodynamic mechanisms, pulsation and stellar evolution.

- **Evolved stars, stellar remnants & stellar winds**. HST and ground-based observations revealed that the geometry of young and evolved planetary nebulae and related objects (e.g., nebulae around symbiotic stars) show an incredible variety of elliptical, bi-polar, multi-polar, point-symmetrical, and highly collimated (including jets) structures. The proposed mechanisms explaining the observed geometries (disks, magnetohydrodynamics collimation and binarity) are within the grasp of interferometric imaging at 1 mas resolution. Extreme cases of evolved stars are stellar black holes. In microquasars, the stellar black-hole

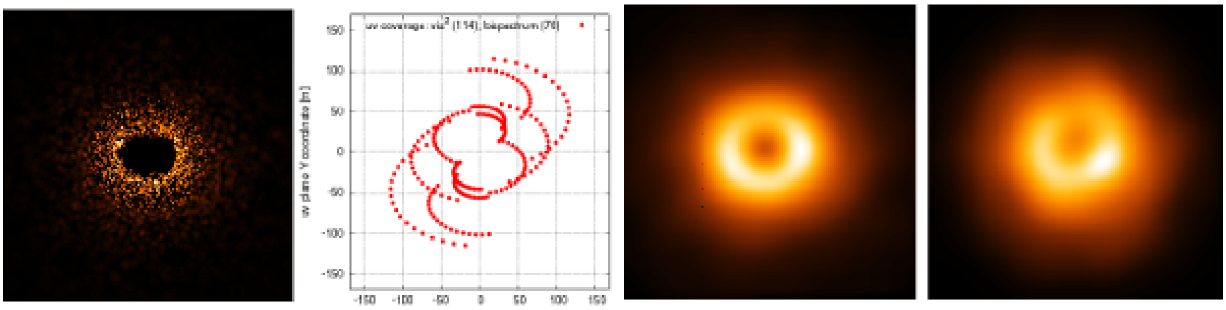

Figure 2. VLTI/VSI image reconstruction simulation performed with 4 UTs on a model of a clumpy torus at the center of an AGN. Left: model torus image; middle left: simulated coverage of the spatial frequencies corresponding to the southern AGN NGC 1365 at declination of $-36°$; middle right: model image convolved with a perfect beam corresponding to the maximum spatial resolution; right: image reconstructed from simulated VSI data using the Building Block method.

accretes mass from a donor. The interest of these systems lies in the small spatial scales and high multi-wavelength variability. Milliarcsecond imaging in the near-infrared will allow disentangling between dust and jet synchrotron emission, comparison of the observed morphology with radio maps and correlation of the morphology with the variable X-ray spectral states.

- **Active Galactic Nuclei & Supermassive Black Holes**. AGN consist of complex systems composed of different interacting parts powered by accretion onto the central supermassive black hole. The imaging capability will permit the study of the geometry and dust composition of the obscuring torus and the testing of radiative transfer models (see Fig. 2). Milli-arcsecond resolution imaging will allow us to probe the collimation at the base of the jet and the energy distribution of the emitted radiation. Supermassive black hole masses in nearby (active) galaxies can be measured and it will be possible to detect general relativistic effects for the stellar orbits closer to the galactic center black hole. The wavelength-dependent differential-phase variation of broad emission lines will provide strong constraints on the size and geometry of the Broad Line Region (BLR). It will then be possible to establish a secure size-luminosity relation for the BLR, a fundamental ingredient to measure supermassive black hole masses at high redshift.

We have shown that this astrophysical program could provide the premises for a legacy program at the VLTI. For this goal, the number of telescopes to be combined should be at least 4, or better 6 to 8 at the VLTI at the time when the *James Webb Space Telescope* will hammer faint infrared science ($\sim$ 2013), when HAWK-I, KMOS, will have hopefully delivered most of their science, and ALMA will be fully operational. The competitiveness and uniqueness of the VLT will remain on the high angular (AO/VLTI) and the high spectral resolution domains. In a context where the European *Extremely Large Telescope* (ELT) will start being constructed, then have first light, and, where Paranal science operations will probably be simplified with less VLT instruments and an emphasis on survey programs, VSI will take all its meaning by bringing the VLTI to a legacy mode.

4. ASTROPHYSICAL SPECIFICATIONS

The astrophysical and technical specifications of VSI are listed in Table 1. The three first lines of this table are the ones that makes VSI unique.

As a matter of fact in the VSI science case, which is the study at high spatial and spectral resolutions of compact astrophysical sources, the variation of the morphology of the objects can be quite rapid. For example the RS Ophiuci[5] novae expansion was measured 5 days after outburst by AMBER and 14 days after outburst in radio. The sizes doubled from about 5 mas to about 10 mas in less than 10 days. As another example, at Taurus distance, Keplerian period at 1 mas from the star is 20 days. When magnifying at higher angular resolution, it is expected that the phenomena at stake vary more rapidly. Our understanding is that VSI should be able to image within a night and therefore avoid any changes of array configurations.

Therefore, it is important to understand how many telescopes are required to obtain an image within a night. Figure 3 illustrates this argument in the case of a disk around a young star. One sees that 6 telescopes are

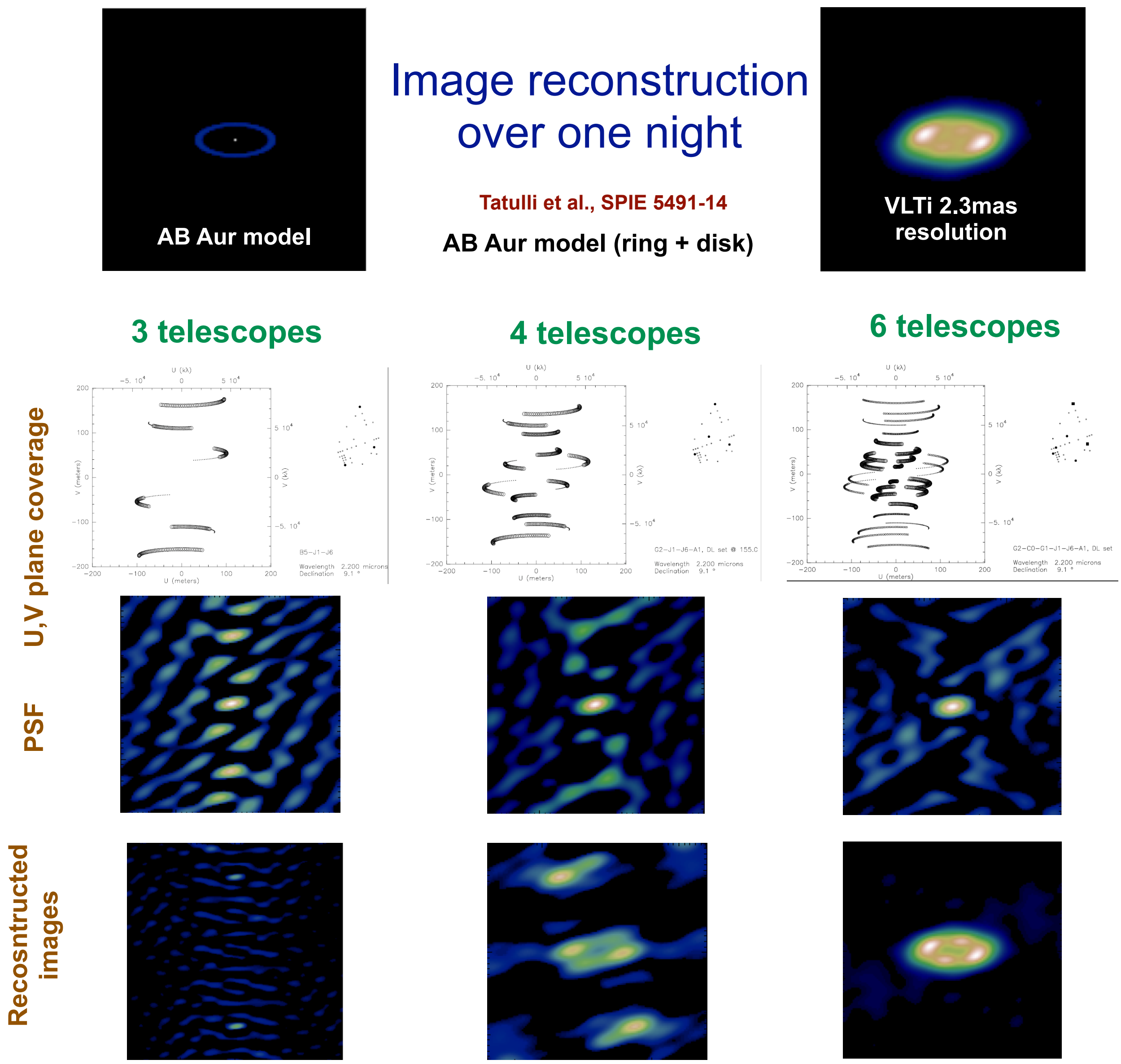

Figure 3. Simulated image for the young star AB Aurigae reconstructed with 3 different VLTI configuration in one night: left with 3 telescopes, middel with 4 telescopes and right with 6 telescopes. Top left is the original model and top right is the model has would be seen by a single telescope of the size of the VLTI. From Tatulli[6] et al. 2004.

Table 1. VSI specifications

Criteria	Specifications
Time resolution	Minimum: 1 night
Data set interval	30 min
Spectral coverage	J, H, K
Exposure time	10 ms - 100s
Spectral resolution	100, 2000, (5000), 12000
Polarization	No scientific requirements
Faintest objects	J: 12, H: 12, K: 15
Science data product	Raw data with OI-fits files
Dynamic range	1/100 (Standard), 1/1000 (High dynamic), 1/10000 (Parametric)
Environmental data	Turbulence parameters, AO/Tip-Tilt and Fringe Tracker performance
Image complexity	10×10 pixels
Image reconstruction	Image reconstruction software available
Field of View	J-UT: 30 mas to K-AT: 250 mas
Instrument life expectancy	10 years

required to get an sensible image within a night.[6] In fact to obtain the same quality would require 3 nights with different configuration of the VLTI with 4 telescopes and 7 nights with 3 telescopes, like in the case of AMBER.

Another important specification of VSI is the spectral resolution. With spectral resolution, one is able to identify tracers of different species like for the gas atomic lines (Brγ, carbon, oxygen) or molecules (H_2, CO, ...) or for dust the continuum or silicate lines. Spectral resolution allows also the observed regions to be probe kinematically: for example distinguish between solid and differential rotation for stars, identify Keplerian motion in disks, detect the wind kine-morphology or measure expansion (novae, SN,...). Finally spectral coverage over several astronomical bands enables to probe the physical conditions of the environments by measuring color temperature. It allows also (u, v) planes to be extended by wavelength super-synthesis.

Other important but more classical specifications are the limiting magnitudes required to detect the faintest objects of the different categories, the dynamic range expected in the image and the complexity of these images (see Table 1). Several studies on image reconstruction can be found elsewhere in this volume.[7,8]

5. INSTRUMENT CONCEPT

The phase A study has led to an instrument concept which is presented elsewhere in this volume[9] consisting of:

- Integrated optics multi-way beam combiners[10] providing high-stability visibility and closure-phase measurements on multiple baselines;
- A cooled spectrograph[11] providing resolutions between $R = 100$ and $R = 12000$ over the J, H, or K bands;
- An integrated high-sensitivity switchable H/K fringe tracker capable of real-time cophasing or coherencing of the beams from faint or resolved sources;
- Hardware and software to enable the instrument to be aligned, calibrated and operated with minimum staff overhead.

These features act in synergy to provide a scientific capability which is a step beyond existing instruments. Compared to the single closure phase measured by AMBER, the 3 independent closure phases available by VSI4, the 10 independent closure phases measured by VSI6 and the 21 independent closure phases measured by VSI8 will make true interferometric imaging, a routine process at the VLTI. The capability to cophase on targets up to $K = 10$ will allow long integrations at high spectral resolutions for large classes of previously inaccessible targets, and the capability to do self-referenced coherencing on objects as faint as $K = 13$. It will allow imaging of targets for which no bright reference is sufficiently close by. VSI will be able to provide spectrally and spatially-resolved "image cubes" for an unprecedented number of targets at unprecedented resolutions.

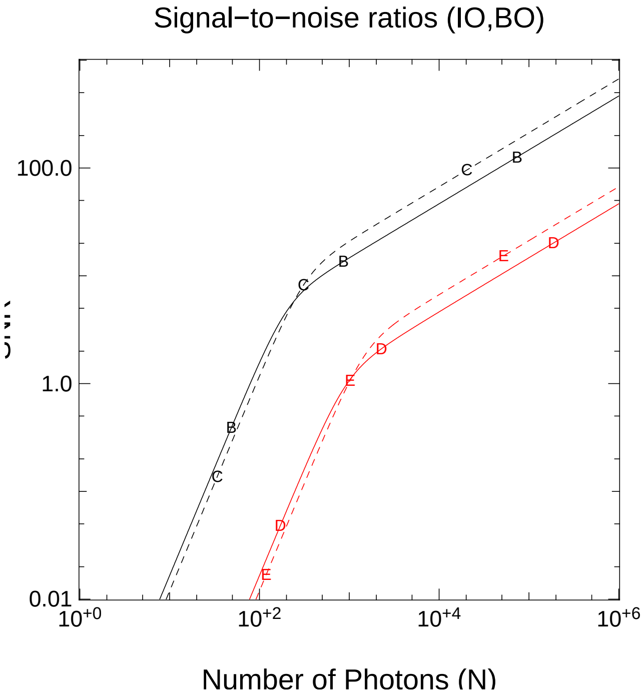

Figure 4. Signal-to-noise ratios computed in H-band for the IO combiner (solid lines) and the BO combiner (dashed lines) with a respective transmission of 65% and 90%. The black lines corresponds to a visibility of 1 and the red lines to a visibility of 0.1. The background noise is ignored.

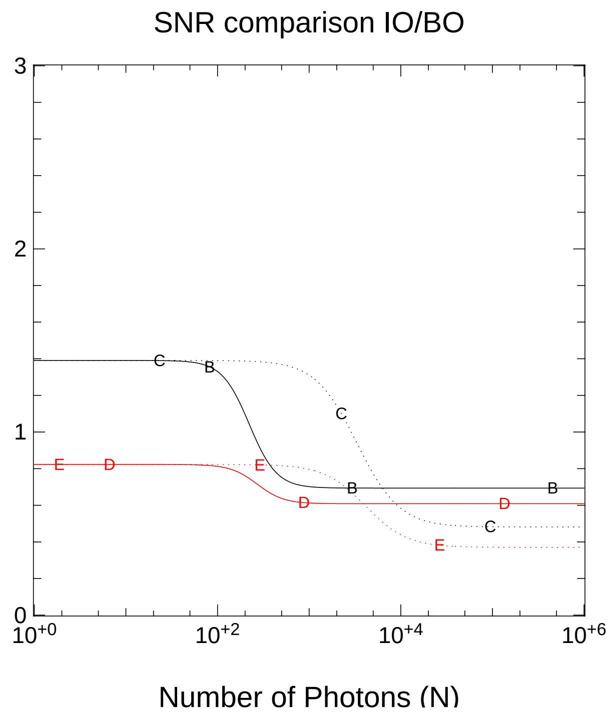

Figure 5. Relative comparison between the signal-to-noise ratio in H-band (black) and K-band (red) for the IO combiner and the BO combiner with a visibility of 1 (solid line) in same conditions as in Fig. 4. The dashed line corresponds to the limit where the visibility tends toward zero.

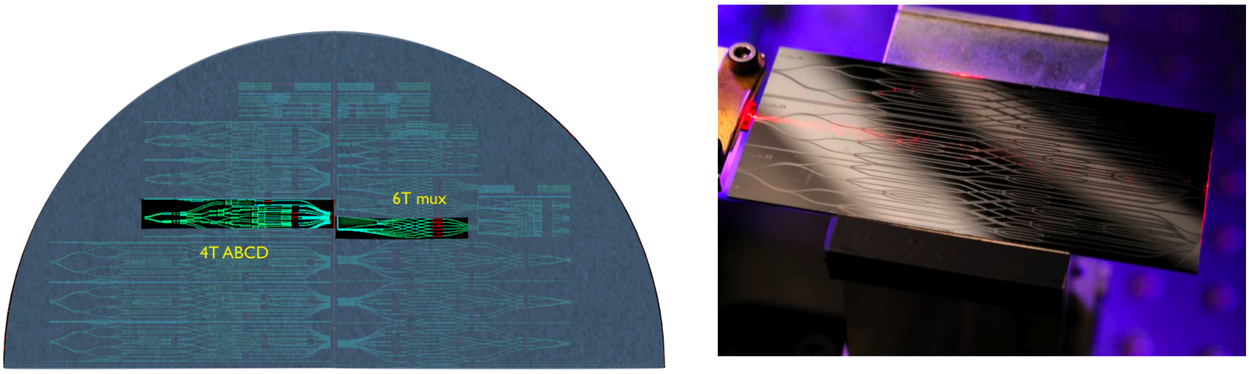

Figure 6. Science beam combiners[10] of the VSI instrument: left the wafer with the 4T and 6T combiners enlighted and right the 4T component.

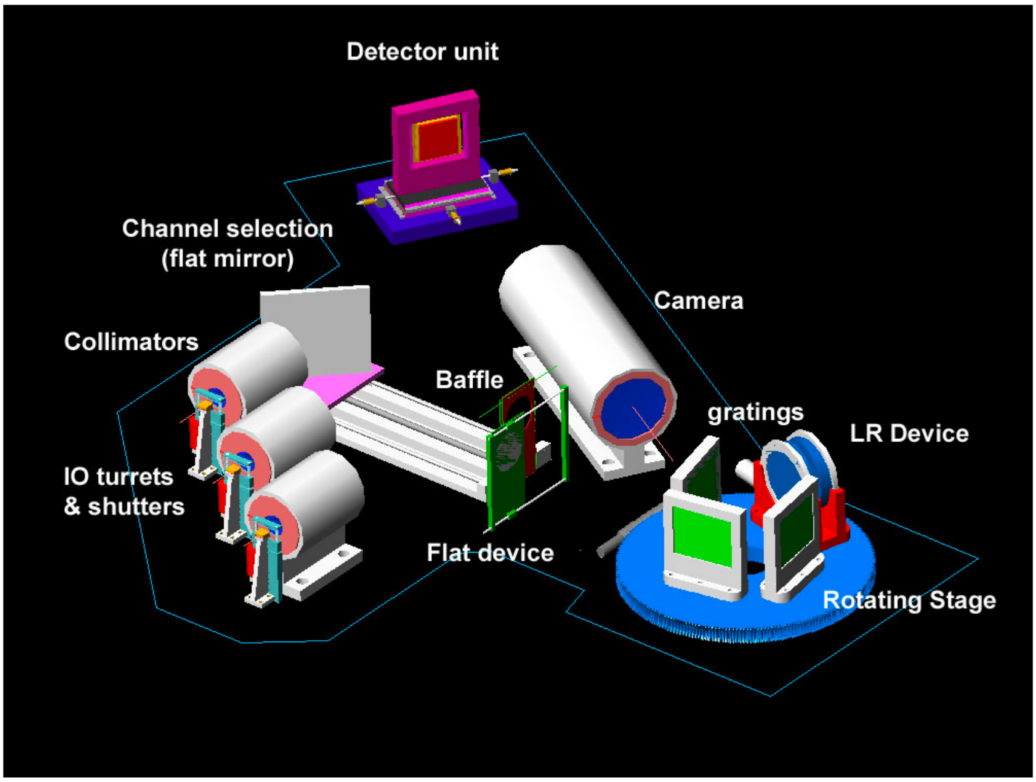

Figure 7. Implementation of the science instrument[11] within the cryostat of the VSI instrument

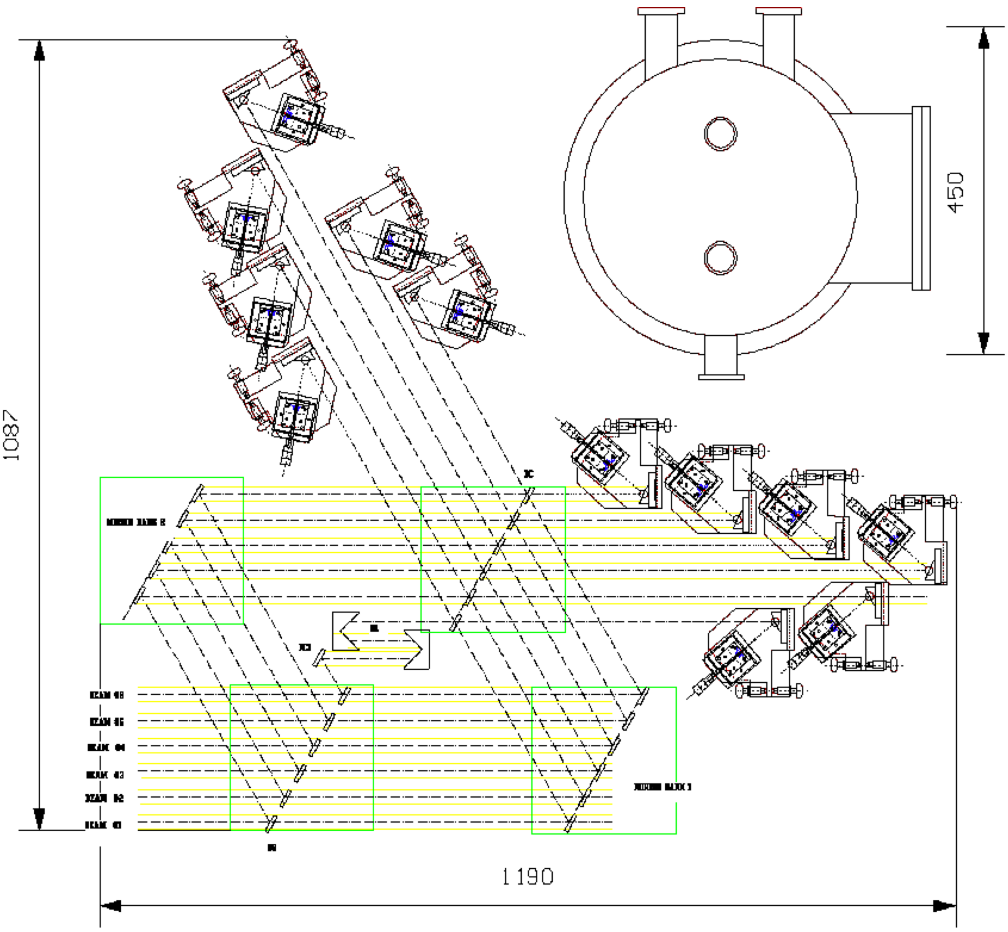

Figure 8. Fringe tracker concept[12] of the VSI instrument

A system analysis of VSI has allowed the high level specifications of the system to be defined, the external constraints to be clarified and the functional analysis to be performed. The system design[9] features 4 main assemblies: the science instrument[11] (SI, see Fig. 7), the fringe tracker[12] (FT, see Fig. 8), the common path (CP) and the calibration and alignment tools (CAT). The global implementation is presented in Fig. 9.

The optics design of the science instrument features beam combination using single mode fibers, an integrated optics chip[10] and 4 spectral resolutions through a cooled spectrograph described by Lorenzetti et al.[11] in this volume. We showed that beam combiners in integrated optics or in bulk optics are comparable in terms of SNR performances by comparing the beam combiners of BOBCAT and VITRUV. Figures 4 and 5 show that IO is better in the photon-starved regime whereas the BO is better in the photon-rich regime, but the gain is all cases limited to 30%. The integrated optics solution has been chosen for additional reasons like maintainability, easiness of operation and availability of manpower. The common path includes low-order adaptive optics (with the current knowledge reduced to only tip-tilt corrections). VSI also features an internal fringe tracker (see 8) which an integral part of the instrument. Indeed it is critical to have a full system analysis with the fringe tracker. These servo-loop systems relax the constraints on the VLTI interfaces by allowing for servo optical path length differences and optimize the fiber injection of the input beams to the required level. An internal optical switchyard allows the operator to choose the best configuration of the VLTI co-phasing scheme in order to perform phase bootstrapping for the longest baseline on over-resolved objects. Three infrared science detectors are implemented in the instrument, one for the Science Instrument, one for the fringe tracker, and one for the tip-tilt sensor. The instrument features 3 cryogenic vessels.

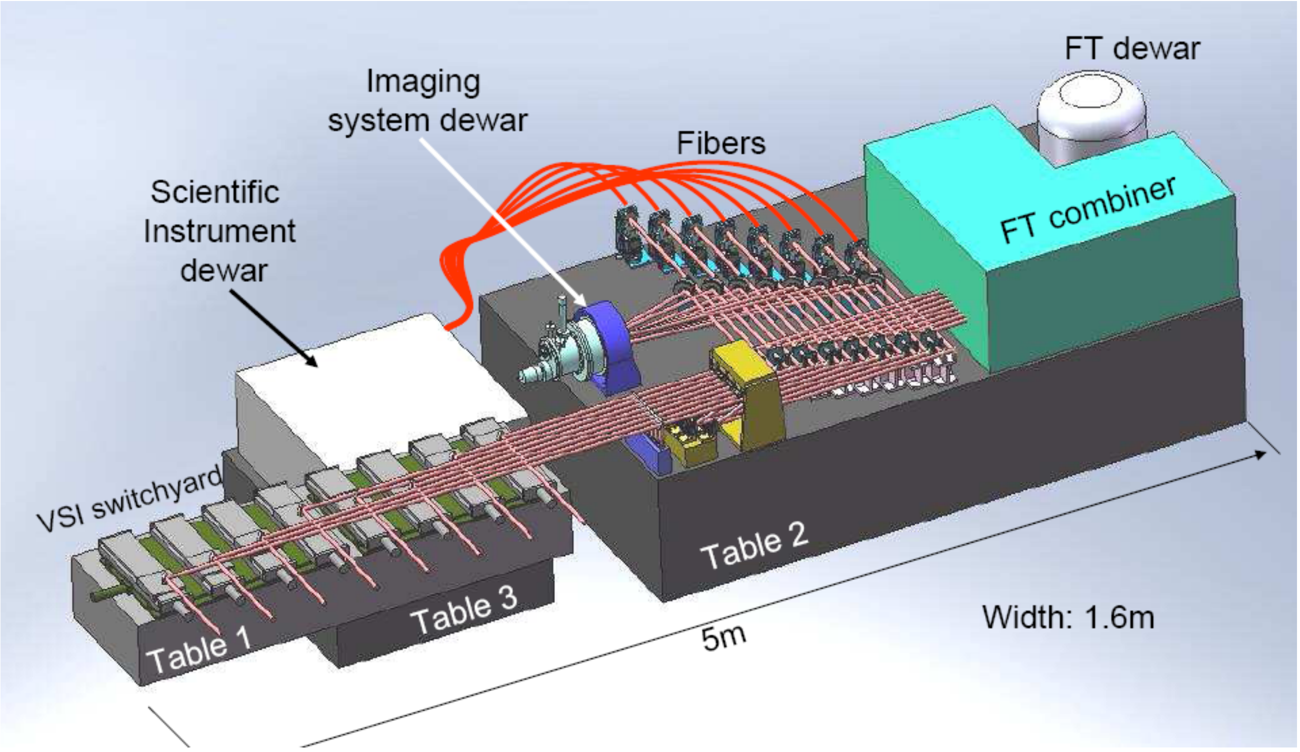

Figure 9. General implementation of the VSI instrument

An important part of the instrument is the control system which includes several servo-loop controls and management of the observing software. The science software manages both data processing and image reconstruction since one of the products of VSI will be a reconstructed image like for the millimeter-wave interferometers. The instrument development includes a plan for assembly, integration and tests in Europe and in Paranal.

An instrument preliminary analysis report discusses several important issues such as the comparison between the integrated optics and bulk optics solutions, the standard 4- and 6-telescope VLTI array for imaging, the proposed implementation of M12 mirrors to achieve these configurations with VSI4 and VSI6, implication of using an heterogeneous array and analysis of the thermal background.

The needs for future VLTI infrastructure can be summarized in an increasing order of completeness as:

- Interferometry Supervisor Software (ISS) upgrade: upgrade from 4-telescope version to a 6-telescope version allows VSI to use 6 telescopes of the existing infrastructure for science cases which require imaging on a short timescale.
- AT5 and AT6: 2 additional ATs allow the VLTI to use VSI in an efficient way without fast reconfiguration of the array.

On a longer term, 8T combination at the VLTI could be foreseen but this is not a VSI priority. In any case, it would require:

- DL7 and DL8: 2 additional delay lines allow even without AT5 and AT6 to use all telescopes on the VLTI (4ATs+4UTs) and would be useful for complex imaging of rapidly changing sources.
- AT7 and AT8: could be implemented if DL7 and DL8 are procured. Then, the 8T VLTI capability could be exploited only with the ATs.

The total cost of VSI for its 4-telescope version has been estimated to about 4000 kEuros for hardware and a manpower of about 90 FTEs over 4 years before the commissioning begins.The VSI6 version would cost only 400 kEuros and 6 FTEs in addition to the VSI4 version.

6. CONCLUSION

The VLTI Spectro-Imager is an instrument whose science objectives is to image astrophysical sources at the milli-arcsecond scale with both high angular and high spectral resolutions in the near-infrared. The image fidelity requirements drive a 6-beam design which makes use of the full potential of the VLTI site (including the use of 4 or 6 telescopes, use of PRIMA,...). VSI will deliver spectro-images as final data product like in the ALMA scheme.

The design of the instrument is relatively simple and self-consistent with its own fringe tracker in addition to other service modules like tip-tilt, ADC,... The main science instrument is based on integrated optics technology which has been shown to be as performant as a solution bulk optics and has been sky validated. The fringe tracking is an integral part of the imaging strategy.

In conclusion, the design of VSI is the simplest one that maximizes science return for a large number of astrophysical domains interested to phenomena at the milli-arcsecond scale.

ACKNOWLEDGMENTS

The VSI phase A study has benefited from a contract by ESO, and support from JRA4 of OPTICON and from CNRS/INSU. Amorim, Cabral, Garcia, Lima, Rebordão, was supported in part by the Funda cão para a Ciência e a Tecnologia through project PTDC/CTE-AST/68915/2006 from POCI, with funds from the European programme FEDER.

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