D6.1 Astrophotonics Requirements

Development team: Roger Haynes (WP-lead), Theodoros Anagnos, Aurelien Benoit, Tim A. Birks, Ariadna Calcines, Mark Corrigan, John Davenport, Kerrianne Harrington, Robert J. Harris, Dionne Haynes, Philipp Hottinger, Hugh Jones, Tim J. Morris, Robert R. Thomson.

Institutions: Leibniz Institute for Astrophysics Potsdam (Lead), Heriot Watt University, University of Bath, University of Durham, Landessternwarte - Zentrum für Astronomie der Universität Heidelberg (ZAH), University of Hertfordshire.

Introduction

Astrophotonics is a rapidly developing field that aims to develop photonic technologies that can enhance the sensitivity and functionality of the next generation of ground-based optical/infrared instrumentation for European and Worldwide astronomical facilities, including the Extremely Large Telescope (ELT). Within this document we outline the top-level requirements of the astrophotonic technologies targeting precision spectroscopy for natural seeing and adaptive optics corrected applications. We chose to define this as those applications in which the required wavelength precision at the spectrograph detector is smaller than 1/50th of the projected dimension of the waveguide at the device input (i.e. the “on sky” end), i.e. the system requires a scrambling gain of ≥50. Examples of instruments with this precision are ELT- MOS and ELT-HIRES.

Science Case Examples

ELT-HIRES

- Exo-planetary atmospheres and the detection of signatures of life on rocky planets
- Chemical composition of planetary debris on the surface of white dwarfs
- Spectroscopic study of proto-planetary and proto-stellar disks
- Stellar physics and evolution over the full space of stellar parameters
- Extension of Galactic archaeology to the Local Group and beyond
- Evolution of galaxies without restriction strongly star-forming and/or very massive galaxies
- Unravelling stellar and AGN feedback, the supply and retention of baryonic matter in galaxies
- Chemical fingerprints from population III stars on the IGM during the epoch of re-ionization

ELT-MOS

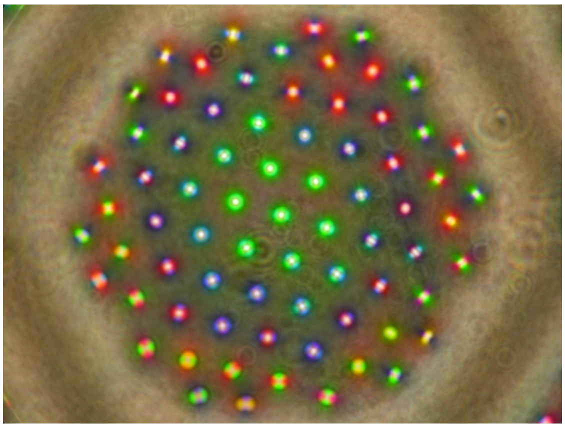
- Very first galaxies and epoch of re-ionisation
- Mapping the Inter-Galactic Medium (IGM)
- Outflows from AGNs and the co-evolution of Supermassive Black Holes and Galaxies
- Chemo-dynamical properties of dwarf galaxies at $1 < z < 3$
- Stellar lithium abundances and implication for Big Bang Nucleosynthesis
- Kinematics and metallicity of the Bulge, the past history of our Galaxy

Artist’s impression showing a view of the surface of the planet Proxima b orbiting the red dwarf star Proxima Centauri, the closest star to our Solar System.
Image credited to ESO/M. Kornmesser

Artist’s impression showing how ULAS J1120+0641, a very distant quasar powered by a black-hole with a mass two billion times that of the Sun, may have looked. This object is by far the brightest object yet discovered in the early Universe.
Image credited to ESO/M. Kornmesser

Development objectives

The objective is to develop revolutionary guided-wave photonic technologies that can efficiently couple seeing-limited (un-corrected) and partially AO-corrected focal surfaces to highly stable and precise optical/infrared spectrographic systems, whilst increasing stability by rendering their design insensitive to the telescope's focal plane parameters, using for example photonics reformatters, and suppressing modal noise in multimode relay fibres.



The technology developments will focus on four areas: 1) multicore optical fibres (MCF) and fibre–based photonic lanterns (PLs), 2) photonic reformatters and 3D waveguide structures, 3) light coupling into the devices by the optimisation of both the devices themselves and the Adaptive Optics (AO) systems that feed them 4) and photonic wavefront sensing devices.

Image of one of the 7 by 73 core section of the STELLA2 multi-core scrambling fibre illuminated with white light. The different colours and patterns indicate the different core diameters of the design.
Image credited to the CPPM, University of Bath

Different telescope image quality conditions

The suitability of scrambling fibres, reformatters and photonic wavefront sensors to different observing scenarios depends on the expected image quality/conditions and characteristics of the intended target or source.

Natural seeing conditions

Natural seeing describes the conditions at a typical ground-based telescope (i.e. the primary mirror aperture is significantly larger than the atmospheric coherence length) without AO correction, where the image quality is typically dominated by blurring produced by the atmospheric turbulence and the achievable spatial resolution is greatly reduced. The seeing also impacts the pupil, where it introduces high level aberrations. The parameters of primary significance for the technologies are the image size, the wavefront shape and the number of waveguide modes for optimal performance.

Partial AO correction

Partial AO correction describes the condition in which the seeing limited telescope performance is corrected to some extent, but not sufficiently to achieve the ultimate diffraction limit. It can provide significantly better image quality (or pupil wavefront uniformity) than natural seeing, but does not achieve the best possible image quality (or uniform pupil wavefront) possible with space-based application (i.e. without any atmospheric perturbation). The AO system redistributes the light within the image, usually with the goal of either concentrating as much light as possible into the central region of the image, or to maximize encircled energy within a given aperture. However, due to limitation in the wavefront correction, particularly these very high order wavefront terms, rapidly changing components, the systems cannot typically fully correct the light distribution in the wings of the point spread function (PSF). The resulting PSF can then have a well-defined/corrected central region, but significant energy in the extended wings, which can contribute considerable background/noise at the focal plane. In term of the pupil wavefront the AO system can correct much of the lower order wavefront aberrations, but not the very high order perturbations.

Diffraction limited conditions

Diffraction limited conditions can occur if: (1) the telescope is space based; (2) if the telescope aperture is close to or smaller than the local coherence scale of the atmosphere (as the coherence scales with wavelength, as you move to longer wavelengths it is easier to achieve the diffraction limit); (3) there is a highly effective AO system (such systems are often referred to as Extreme AO system on large telescopes).

Data management and control requirements

In order to facilitate simple and effective control of the devices/systems and effectively control the device/system and manage the data:

- The device/system shall operate behave and operate in a non-redundant and predictable manner.

Core Parameters for Photonic Lanterns, Reformatters and AO coupling optimisation

Key requirements/parameters that determine the design, complexity and performance of the devices are:

Number of waveguide modes

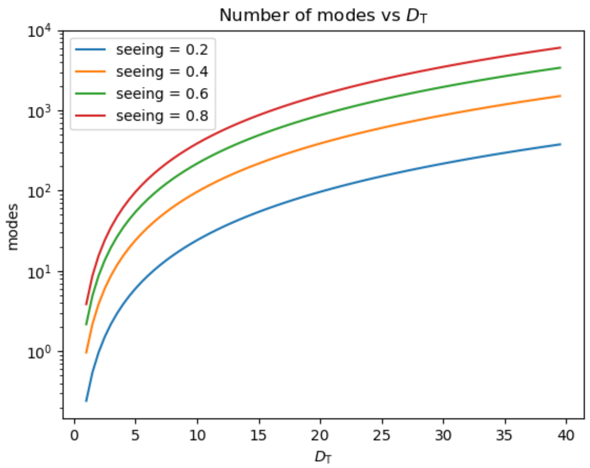
- The device/system should be mode matched to the respective input and output interface to maximise system efficiency.

The number of waveguide modes required for efficient coupling and propagation of light within photonic waveguide structures (such as optical fibres and photonics reformatters) can massively impact on the size, complexity and functionality of the device/system. Typically, the larger the number of modes, the larger and more complex the device/system, both in terms of fabrication and the final structure. The optimal number of modes for a given device/system depends strongly on the wavelengths of operation and the image quality being sampled at input.

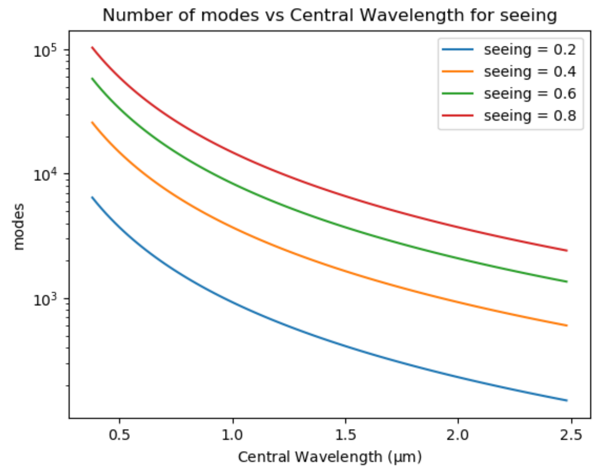
For large numbers of modes (N), a circular waveguide cross-section with a diameter (d) significantly larger than the wavelength (λ) of coupled light, this can be approximated as:

$$N \approx \left(\frac{\pi d NA}{2\lambda}\right)^2 = \left(\frac{\pi \chi D_\mathrm{T}}{4\lambda}\right)^2$$

where NA is the numerical aperture of the waveguide, where χ is the angular seeing and D_T is the telescope diameter.



Number of waveguide modes vs telescope primary mirror diameter shown on a y log axis, for different on sky waveguide angular apertures (circular) and a wavelength of λ=1550nm.



Number of waveguide modes vs wavelength of light for different on sky waveguide angular apertures (circular) shown on a y log axis and a telescope primary mirror diameter of 40m.

As can be seen the number of waveguide modes can vary between 1 (diffraction limited) to ~50,000 for natural seeing, AO corrected regimes. The wavelength range to be explored is from ~360nm up to 2500nm, which also has a large impact on the optimal number of modes. Three example applications are summarised below:

1. ELT-HiReS is a High-Resolution Spectrographic facility proposed for the Extremely Large Telescope in Chile. The concept proposes a wavelength coverage from 400 to 1800nm and operate in seeing limited mode, with a possible AO corrected mode. If the on-sky aperture of the photonics device/system was to be 0.8" in diameter and is required to operate at 400nm, the mode number for efficient coupling would be in excess of 90,000 modes.
2. STELLA2 Scrambling fibre: Developed as part of the OPTICON FP7.2 Astrophotonics development program, was developed to operate on the 1.2m diameter STELLA telescope in Tenerife in natural seeing condition and over a wavelength range of 380 to 860nm. For optimal coupling over the full wavelength range the device was designed to accommodate up to 2464 modes in a 511 core multi-core fibre, with some cores designed to accommodate more than one mode at the shorter wavelengths ("Multicore fibre photonic lanterns for precision radial velocity Science", Itandehui Gris-Sánchez Dionne M Haynes, et. al., MNRAS, Volume 475, Issue 3, 11 April 2018).
3. iLocater, to be deployed on the Large Binocular Telescope (LBT), is the world's first permanent high-resolution diffraction-limited Doppler spectrometer on a large telescope and is fed by a long optical fibre. Despite the LBT have primary mirror diameters of 8.4m, the combination of near-infrared operation and a highly effective adoptive optics system mean the optical fibre can, in principle, couple and propagate light highly effectively in the single-mode regime.

Wavelength range

- The device/system should be design to operate over the full wavelength range required for the intended application.

The wavelength range regime for this development program covers the visible and near-infrared wavelength regions, from 400nm to 1800nm. This limitation is partially set by the target application, but also the limitation of the materials typically employed in the manufacture of photonics devices/systems. A good example of a next generation instrument that is designed to work over this full wavelength region is ELT-HIRES, with the design optimised to operate from 400nm to 1800nm.

Note: The wavelength regime of an instrument, or instrument sub-units, is often limited by the deployed detector technology. For example, the “visible” regime instrument using CCD detector array technologies between ~380nm to 950nm, whereas the non-thermal infrared regime instruments typically use Mercury Cadmium Telluride based detector array technologies between ~1050nm to 1800nm.

Scrambling Gain

- The device/system should not be a significantly contribution in the overall instrument/system wavelength precision uncertainty budget.

Numerous factors contribute to the overall stability and precision of an instrument, however, for fibre/reformatter coupled instrument one contributory factor can be the “print-through” of image centroid motion from the input to the output of the device (often quality via the “scrambling gain”), the other can be output image centroid motion resulting from fibre/reformatter reacting to its environment, such a movement and/or thermal disturbance.

Scrambling Gain (SG) is defined as:

$$SG = \frac{\Delta d_{input}/D_{input}}{\Delta d_{output}/D_{Output}}$$

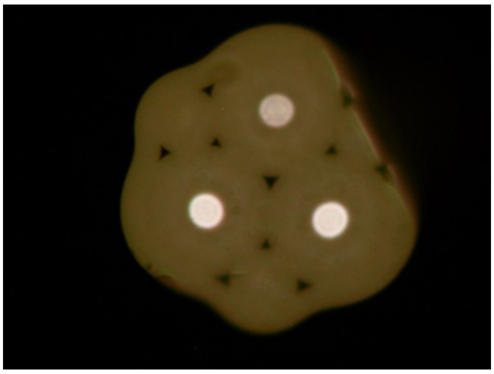
Where Δd is the shift of the image centroid on the waveguide entrance or exit and D is diameter of the waveguide.

The required Scrambling Gain of precision spectroscopic astronomical applications can be from ~50 to over 100,000. For example, the requirement for the 4MOST multi-object spectroscopic facility for the VISTA telescope with radial velocity precision requirement of 2km/s is a SG of greater than 50, whereas the ELT-HIRES instrument requires a redial velocity precision of better 1m/s and a SG >1000.

Wavefront cleaning and management

Previous experiments have shown wavefront control is very important for photonic devices using few modes (e.g. Harris & MacLachlan et al 2015). Unlike large multimode fibres, photonic devices act as a spatial filter, rejecting light that isn't in the modes that the device can support. This means the AO performance needs to be tailored for the specific device. Normally the AO performance would be quantified using existing AO metrics such as Strehl ratio and encircled energy, these may not be optimal for astrophotonic devices. Thus, the on-going development is striving to test and define new metrics/requirements for spatial filtering and AO optimisation.

Core Parameters for photonic wavefront sensing device



Photonics wavefront devices/systems show potential to improve the performance for low order wavefront sensing system for wavefront monitoring and/or wavefront correction applications. They also have the potential advantage that they can allow the wavefront sensing input to be mounted remotely from the detection/analysis parts. For example, instead of mounting a microlens array and 2D camera (typically several cm^3 in volume and includes its associated cabling and cooling units) at/near the focal surface of interest, a simple optical fibre of less than $1mm^2$ in area could transport the light to a remote and less environmentally control area many meters from the focal surface. This could be achieved with very little loss in system efficiency and with the benefits of remotely locating the detection/analysis functional unit.

Optical micrographs of the cross-sections of a prototype 3-core fibre-based wavefront sensor. *Image credited to the CPPM, University of Bath.*

Key requirements that drive the design, complexity and performance of the devices/systems are:

- The device/system shall sense at least the Tip, Tilt and Focus terms of the wavefront in unambiguous and predictable manner.
- The device/system shall be able to determine the wavefront error in Focus to better than 10 nm RMS for a focus error up to 100 nm RMS in magnitude.
- The device/system shall be able to determine the wavefront error when Tip and Tilt are within one diffraction limited Point Spread Function (PSF).
- The response of the device/system to changes in input wavefront shall be linear after calibration. (Note: this is required by both wavefront error requirements above).
- The device/system shall have a theoretical coupling efficiency into a single-mode fibre competitive with conventional systems. For example, a maximum of 65 % for the SCExAO system (Subaru telescope), or a

theoretical maximum of 72 % assuming a perfectly coupled single-mode fibre and a 10% beam-splitter to a Shack-Hartmann system.

Device/system environmental compatibility

- The devices/systems shall survive and operate in the environmental condition at the telescope of deployment.
- The devices/systems shall survive the environmental condition during transportation.

However, the environment conditions at each telescope site and with different transportation option (i.e. by air, sea and/or land) will potentially be very different and can vary significant on a daily and yearly cycle.

As an example, the some of the more critical that can impact the design of Astrophotonics devices are outlines below for the European Extremely Large Telescope. The full details are given in "E-ELT Environmental Conditions, ESO-191766, Version 6, Released 2015-03-25"

- *The extreme air temperature range is -15°C and +25°C (survival range)*
- *The air temperature will be between -5°C and +15°C (operational range)*
- *The operational range of air temperature gradient at night-time will be from -0.55°C/h to +0.5°C/h.*
- *38 The relative humidity (natural and induced) will be between 3% and 100% with condensation (survival range).*
- *25 The relative humidity (natural and induced) will be between 5% and 80% (functional and operational range) with a median value of 15%.*
- *The ozone concentration (natural and induced) will be less than 180 mg/m3.*
- *Dust and Sand: The natural cleanliness class of the telescope site at >7m above ground and inside the telescope dome is expected to be is better than ISO 7.2 (median) and ISO 8 (90% percentile).*

It should be noted that the transportation environmental requirements that the device shall comply with are typically much more severe and varied than the telescope environment in terms of survivability. For example, there is typically much more stringent vibration and mechanical shocks criteria and for sea transportation and coastal environments there is an added Salt Fog criterion.

Note: Many of the transportation risks can be mitigated using appropriate transportation containers for sensitive devices/systems.

Compatibility with interface requirements

The device/system shall comply with the relevant telescope/instrument interfaces. These can include:

- Optical Interfaces
- Mechanical interfaces
- Electrical Interfaces
- Cryogenic interfaces
- Cooling and Compressed air interfaces
- Safety system interfaces including: Alarm and Interlocks
- Control system interfaces
- Data Management interfaces

Note: The relevant telescope and/or interface requirements are highly dependent on the particular characteristics of the telescope/instrument on which the devices/system is to be deployed. Typically, the device/system interfaces require some customisation for the given application/deployment.

Product and Quality Assurance requirements

- The devices/systems should be dependable and comply with applicable RAMS (Reliability, Availability, Maintainability, Safety) protocols. Note: These will vary depending on the environment in which the device/system is developed and operated.
  - The devices/systems shall comply with the maintenance and repair requirements imposed by the telescope and instrument facilities on which they will be deployed.
  - The devices/systems should have an expected mean time between failure of greater than 10 years.
  - The devices/systems should follow line-replaceable-unit design protocols
  - The devices/systems should follow repair maintenance and repair friendly design protocols.
- The devices/systems should be readily manufacturable in a high quality and cost-effective manner.
- The devices/systems should be cost competitive with possible alternate technical solution
- The devices/systems should be competitive in terms of performance with possible alternate technical solution
- The devices/systems will be ready mass producible.
- The devices/system will be a simple as possible, avoiding complexity in the device/systems and associated interfaces.

Note: Generally, photonic-based devices are robust, reliable, maintenance free and fall naturally into the line-replaceable-unit category. However, this is not so commonly the case for the many telescope, adaptive optics and/or instrument systems.