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| ***Authors*** | PARIANI, Giorgio, Aliverti, Matteo, Moschetti, Manuele, LANDONI, Marco, RIVA, Marco, ZERBI, Filippo Maria, Mégevand, Denis, CRISTIANI, Stefano, Pepe, Francesco |
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# Integration, alignment, and verification of the ESPRESSO Front-End

G. Pariani[a*], M. Aliverti[a], M. Moschetti[a], M. Landoni[a], M. Riva[a], F. M. Zerbi[a], D. Mégevand[b], S. Cristiani[c], F. Pepe[b]
[a]Osservatorio Astronomico di Brera, INAF, via E. Bianchi 46, 23807 Merate (Italy);
[b]Observatoire Astronomique de l'Université de Genève Sauverny, Chemin des Maillettes, 51 CH-1290 Versoix (Switzerland); [c]Osservatorio Astronomico di Trieste, Basovizza, 302, 34149 Trieste (Italy)

## ABSTRACT

ESPRESSO, Echelle SPectrograph for Rocky Exoplanets and Stable Spectroscopic Observations, is now under the assembly, integration and verification phase and will be installed beginning next year at Paranal Observatory on ESO's Very Large Telescopes. The Front End is the modular system in the Combined Coudé Laboratory receiving the light from the four VLT Units, providing the needed connection between the input signal, i.e., object light, sky light, and calibration light, to feed the spectrograph through optical fibers. The modular concept of the FE Units drove the system design and the alignment workflow. We will show the integration method of the single FE modules adopted to guarantee the necessary repeatability between the different Units. The performances of the system in terms of image quality and encircled energy in the observed point spread function are reported. Finally, the strategy followed in the Paranal Combined Coudè Laboratory to define the convergence point of the four UTs is described, along with the procedure used to align the ground plates, the main structure, and the mode selector.

**Keywords:** High Resolution Spectroscopy, ESPRESSO, Front End, Integration

## 1. INTRODUCTION

The Front End (FE) Unit will be installed in the Combined Coudé Laboratory (CCL) of the Very Large Telescopes (VLTs) as interface between the four Coudé Trains (CT)[1] and the ESPRESSO spectrograph[2–4]. The FE exploits a modular concept[5,6]. It is made by four identical units-module (FE Unit), receiving the beam from the relative telescope CT and the calibration light from the calibration unit. On the other side, the FE Unit feeds the fibers that carry the light to the spectrograph, corresponding in number and size to the scientific observing modes conceived for ESPRESSO.

Each FE Unit will provide field and pupil stabilization via piezoelectric tip/tilt mirrors driven by a reimaging system, before injecting the beam into the spectrograph fiber through the Fiber Link (FL). A toggling system, called mode selector, is provided to switch between the different observation modes, using single or multiple VLT Units (UTs), according to the desired observation mode.

The FE shall perform the above task maximizing the throughput, i.e. the amount of light injected in the fiber link, to maximize the spectrograph efficiency in any observation mode and benefit from the large collecting areas of the VLT, either single UT (about 50 m$^2$ of collecting area for a single 8.2 m telescope) or multiple UTs (corresponding to a collecting area of a 16.4 m equivalent telescope). Image and pupil stabilities on the FL have direct consequences on the radial velocity measurement accuracy. Therefore, the stabilization is done through tip/tilt mirrors placed in intermediate pupil plane and focal plane, respectively. The stabilization loop is closed through Technical CCDs conjugated with the image and pupil, respectively, collecting the light form the halo of the star out of the injection hole at the FL.

## 2. OPTOMECHANICAL DESIGN OF THE FRONT END

### 2.1 Optical layout

Figure 1 shows a sketch of the optical design for the single FE Unit mode. The FE Unit interface is the focal plane at F/22.8, which is located into the CCL at 554 mm from the convergence point in direction of the correspondent UT. The

*giorgio.pariani@brera.inaf.it

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main path collects the light from the Coudé train, applies pupil and field stabilization, and inject the light into the Fiber Link (FL). The FEU, like the Coudé train, will provide a corrected FoV of 17 asec. The two reflective elements of the main path are located near the focal plane (Pupil Mirror PM) and near the pupil plane (Field Mirror FM) providing pupil and field stabilization, respectively. A refocusing system provides the overall focusing adjustments for the correct injection of the light into the FL. The FL is a holed mirror (2 holes of 0.5 mm in diameter, spaced 3.5 mm) reflecting the light to the guiding system, consisting in a refocusing camera (F/8) and a dichroic mirror to reflect the visible light into the field technical CCD; a wheel provided with neutral density filters will properly dump the light as a function of the star brightness. The NIR light passing through the dichroic mirror is used to reimage the telescope pupil onto the pupil CCD.

The injection of the calibration light into the FL is obtained with a mirror (GM) that can slide into the main path to fold the light of the calibration arm toward the FL. The shape of the GM was optimized to fold all the calibration light without vignetting field and pupil for the guiding arm.

The calibration arm is a telecentric F/12.7 beam, as for the FE main path, bringing the light of two fibers to the holes of the FL. The projected spot of the fiber is 1 mm onto the FL plane, large enough to completely cover the FL holes. The GM can slide into the main path in different positions, allowing the operation of the spectrograph in four different modes: sky/object, calibration/object, sky/calibration, and calibration/calibration.

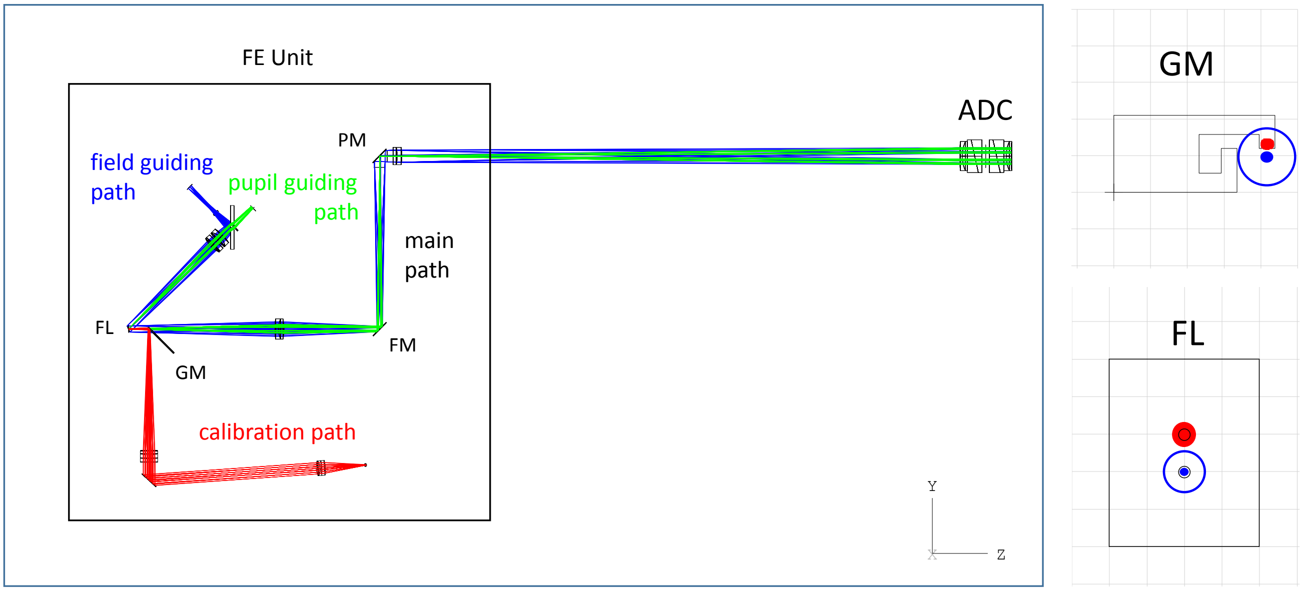

Figure 1: optical layout of the FE unit (left); particular of GM (blue: sky light, red: calibration light) and FL (right);

### 2.2 Mechanical design

An overall view of the FE mechanics is shown in Figure 2. The steel structure in red (main structure) is used to support the mode selector (in light blue), the four FE units and, at the end of each arm, the Atmospheric Dispersion Correctors (ADCs). The overall alignment of the structure and the mode selector is presented in chapter 5. The alignment of the six FL injections is not presented here but follows a similar concept as the rest of the optomechanical elements of the FE units.

Concerning the FE Units (Figure 2, center), they show the same optical and mechanical design, to simplify construction and guarantee the performance repeatability. The position of every element in the unit is defined by three screws and three pins. On the main path, the field and pupil stabilization are performed with 2 PImicos piezo tip/tilt S330 with an extended range of 13 mrad while the refocusing system is made with a 26 mm stroke PImicos linear stage LS65. A similar stage with a stroke of 52 mm is used for the injection of the calibration light (where the G mirror is mounted). The guiding system is composed by 2 AVT Bigeye g132b CCD cameras as feedback and one filter wheel PImicos AFW65 to avoid saturation on the field camera in case of bright source observation.

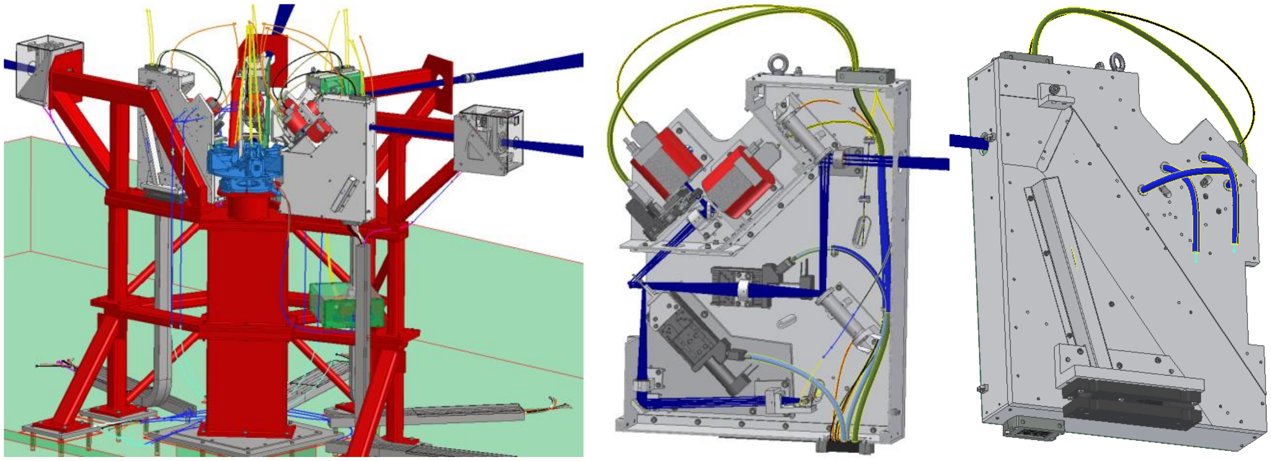

Figure 2: From left to right, overall view of the FE, front view of each FE Unit with its optomechanical components, and back view of each FE Unit with the kinematic mounts.

The kinematic mount system is used to align the FE units over the structure without overconstraining it. The system is composed by a sphere to constrain three degrees of freedom, one cylinder to constrain two of them and a screw to fix the last one. The sphere and cylinder support is a single piece designed to easily perform rotation of the bench around the fibre link injection.

## 3. FRONT END ALIGNMENT STRATEGY

The FE is a modular system, where any FE Unit is interchangeable with the others. Therefore, the absolute alignment of the FE modules has quite loose tolerances, to be adjusted during mounting in Paranal CCL. Instead, a stringent repeatability must be guaranteed between the different FE Units, at the level of the FE Bench. Concerning the mechanics, they idea is the production with standard tolerances, followed by an accurate metrology, to reference the mechanical structure vs optical axis/planes. The mechanical bench as well as all the mountings are milled to obtain mechanical reference for translations and rotations (i.e., kinematic mounts on the FE bench and on the main structure, or reference points on small mountings). The mechanical metrology is performed through an anthropomorphic arm (FARO Arm EDGE ) with a MPE of 41 microns for the integration of the single elements, and a dedicated CMM (COORD3 Universal) with a MPE of 1.8+L/333 for the metrology of the single mountings.

The alignment strategy consists of two main steps:

- in laboratory, the alignment and integration of the different FE Units on a common optical and mechanical reference. A Telescope Simulator (TS) is constructed to act as optical reference. Kinematic mounts are used as mechanical references for the FE Unit. In this way, the kinematic mounts are all positioned univocally as respect to the TS optical axis for any FE Unit.
- at Paranal CCL, the alignment of the main structure, mode selector and FE mechanical references as respect to the four telescopes convergence point.

## 4. ALIGNMENT OF THE SINGLE FE UNITS

### 4.1 Telescope Simulator

To create the optical axis acting as global reference for the alignment of the different FE Units, we designed and constructed a Telescope Simultator (TS). The TS generates pupil and field planes at the correct position into the FE main path, allowing the verification of the FE performances in terms of optical quality and guiding capabilities.

The TS design is optimized at a single wavelength to reduce costs and procurement time, employing two commercial doublets (EO32935 - 40mm diameter/250mm EFL, named TS L1, and EO45270 – 40mm diameter/500mm EFL, named TS L2). The TS produces a telecentric beam at the FE FL, with unitary magnification between the TS Field and the FL

plane. Accordingly, the field size is 8.4 mm, corresponding to 17 arcsec on sky, and the pupil size is 20.2 mm (the double of the FE pupil). Field and pupil masks are custom designed to reproduce an array of pinholes and the actual telescope pupil, respectively, and were produced with Laser Cutting on steel foils of 0.2 mm thickness (we kindly acknowledge Valentina Furlan of the Department of Mechanical Engineering of Politecnico di Milano).
The designed image quality at the fiber link of the FE is comparable to the one obtained at the telescope, and was practically verified after the TS alignment. The optical scheme of the TS and some pictures are reported in Figure 3. The TS alignment was performed with the anthropomorphic arm.

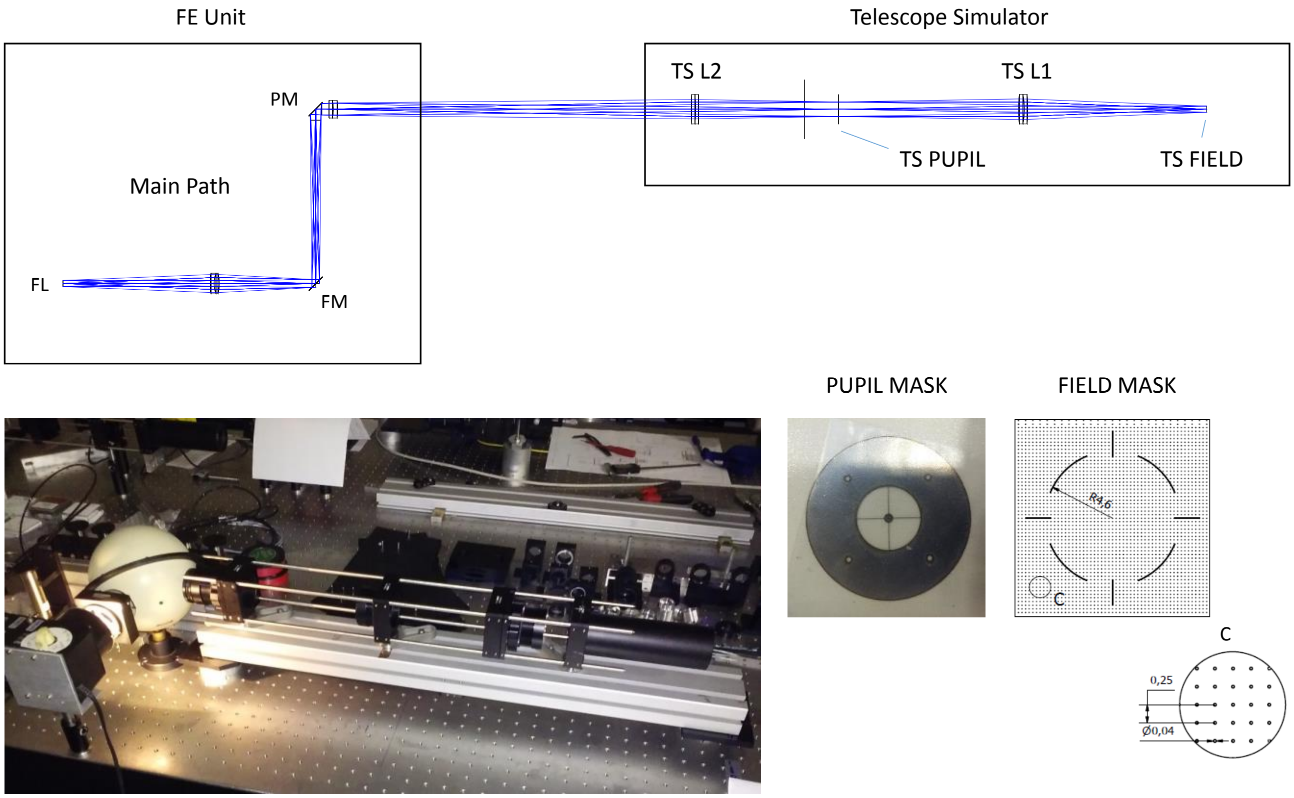

Figure 3: Optical scheme of the TS (top) along with the FE main path; the TS aligned on the optical bench (bottom left); pupil and field masks (bottom right).

## 4.2 Integration procedure

The detailed integration procedure of the single FE Unit is described hereafter.

**Definition of a working optical and mechanical reference**
On the optical bench we defined a working optical axis and a mechanical interface, to use as global reference for the alignment of the any FE Unit. This point is essential to guarantee the alignment repeatability between the different modules, since any FE Unit is mounted on the same mechanical interface for integration. After integration, the FE Unit is removed, to proceed with the following one. Mounting repeatability was verified to be in the precision of the measuring system.
In particular, the steps followed are:

- definition of the optical axis of the entrance beam, with the TS, to reproduce the telescope optical axis, field and pupil planes in the desired position and size
- alignment of a Field Camera/Fiber Link dummy mirror in the nominal position, to use as control system of the alignment of the FE module on the bench
- definition of the mechanical reference for the FE Unit, with a kinematic mount, similar to the one mounted on the FE Structure.

**Definition of the mechanical references of the single elements**

Any optical mount (lens holders or mirror mounts) is characterized with the CMM, and six coordinates on the holder are referenced to the mechanical barrel. These coordinates block the six degrees of freedom of the single element, taking care of their accessibility with the FARO Arm for the subsequent positioning of the mounting in the FE Unit.

**Integration of the single elements**

On any FE Unit, the single elements are integrated in the correct position with proper shimming, by using the six coordinates identified on the mountings (Figure 4). Fine tuning of the alignment, if requested, is then performed with the Field Camera for the main path, and with the Guiding CCDs for the guiding path (Figure 5).

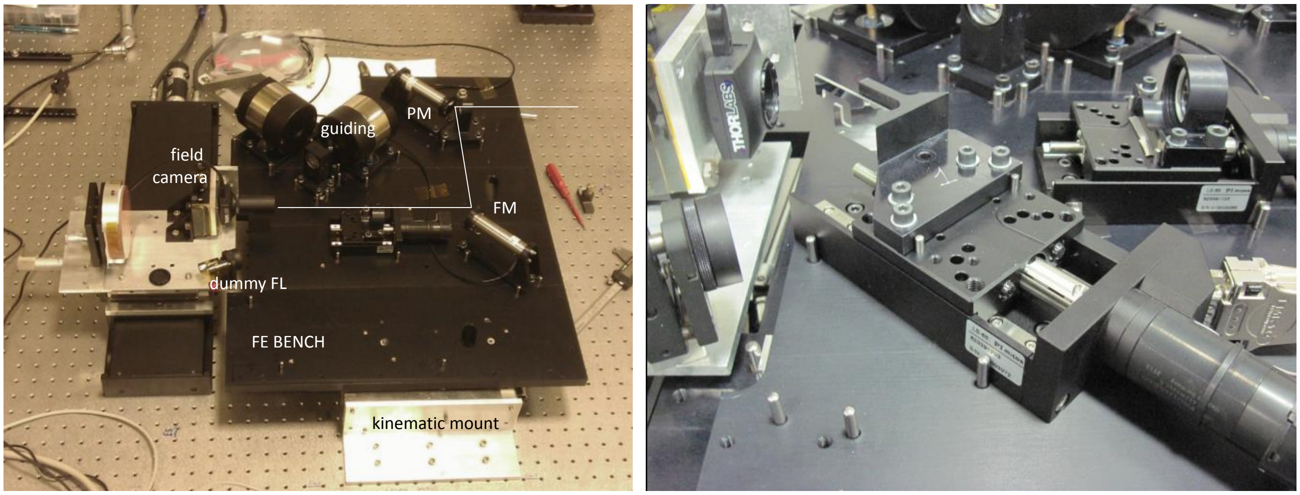

Figure 4: the FE Unit main path aligned on the optical bench (left); the calibration path with the GM during integration (right).

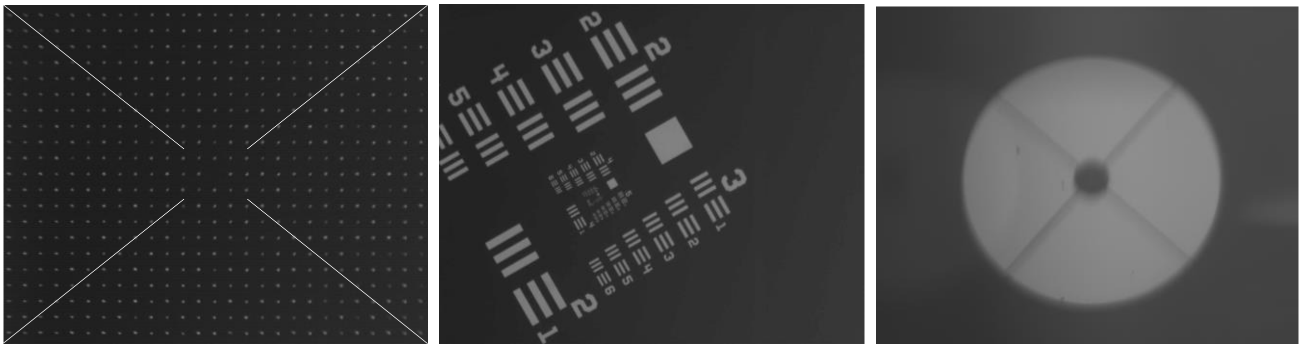

Figure 5: Field CCD image at the FL plane (left), image quality of the Field Guiding CCD (center), and pupil at the Pupil Guiding CCD (right)

## 4.3 Verification of the performances of the FE modules

We evaluated the image quality at the level of the focal plane of the FL by measuring the Point Spread Function (PSF). In particular, we used a mask with a pinhole matrix (25 um diameter) to simulate point like sources at the level of the focal plane. The mask has been mounted at the focal plane of the TS and illuminated with quasi monochromatic 530 nm light.

Each dot can be safely treatable as a point source since its dimension on the fiber link focal plane span few pixels (the pixel size is about 5 um). Moreover, since we are interested in probing the quality of the optical system in terms of Encircled Energy (EE), a slight contamination from the extended object could only cause an underestimation of the whole performances of the system, enabling us to accept the system even with this caveat.

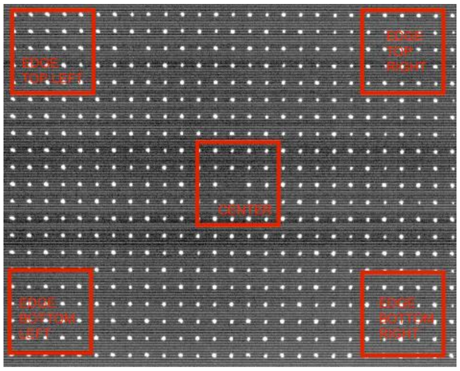

Figure 6: pinhole mask on the Fiber Injection focal plane and areas where PSFs has been measured

We collected images for each Front End unit by adoption of a small off-the-shelf CCD camera (Thorlabs DCC1545M). The PSF has been measured through analysis of some spots on the four corners and at the center of the field, as illustrated in Figure 6 (namely Edge Top Left, Edge Bottom Left, Center, Edge Top Right and Edge Bottom Right), by the adoption of a 2D Gaussian function. A sample results is shown in Figure 7. The first panel shows the measured data on the CCD (background subtracted), the central panel the Gaussian best fit to the data. The RMS error on the whole fit is of the order of 2-3% (right panel). Then, on the obtained best-fit model, we evaluated the encircle energy in a radius of 0.09 arcsec on sky (the subsystem requirement is EE = 80% in 0.09''). In case of slight asymmetry of the fitted PSF, we assume for the standard deviation of the Gaussian spot the quadrature sum of the two (for x and y axis). The EE is then evaluated on this PSF.

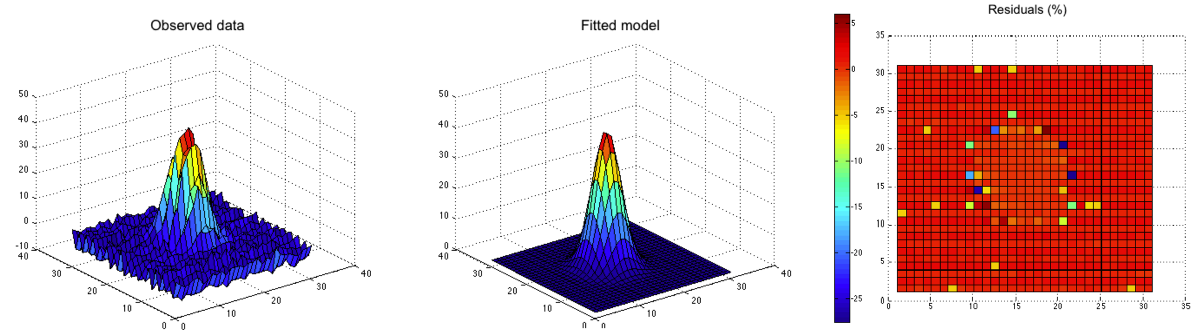

Figure 7: PSF evaluation on a spot taken at the Fiber link focal plane. Left panel: raw data (background subtracted only). Central panel: Gaussian 2D best fit. Right panel: fit residuals.

Results for each FE are reported in the table below. As can be easily seen, the requirement is fulfilled for each subsystem in each portion of the image.

| *UT* | *Edge Top Left* | *Edge Top Right* | *Edge Bottom Left* | *Edge Bottom Right* | *Center* |
|---|---|---|---|---|---|
| *1* | 91% | 93% | 92% | 91% | 94% |
| *2* | 93% | 93% | 94% | 90% | 97% |
| *3* | 96% | 94% | 95% | 92% | 95% |
| *4* | 90% | 96% | 90% | 95% | 95% |

An analog procedure has been applied to evaluate the delivered image quality at guiding focal plane. In this case we measured similar performances (about 80% EE in the PSF at 0.1''), although there is no a specific requirement.

## 5. ALIGNMENT OF THE FE STRUCTURE AT PARANAL

The strategy followed at Paranal to define the FE reference system is described hereafter, along with the procedure used to align the ground plates, the main structure, the mode selector, the kinematic mounts, and the alignment laser.

### 5.1 Definition of the convergence point and service reference system

The first step of the FE alignment in the CCL consisted in the definition of the service reference system for the alignment of the mode selector. Since the mode selector has to switch the FE operation between the different observation modes (single UT in Ultra-High, High or Normal Resolution Mode/multiple UTs in Normal Resolution Mode), the four CTs optical axes shall be aligned on a common plane, corresponding to the mode selector rotation plane, and shall converge to a common point, corresponding to the intersection of the optical plane with the mode selector rotation axis. Accordingly, the center of each circular flange at the entrance of the Coudé tunnel (on the Coudé room side) were measured with the laser tracker, and the best fit of the four points provided the optical plane. The convergence point was identified as the projection of the central pin in the CCL basement onto the optical plane.

### 5.2 Main structure and mode selector alignment

Once the service reference system was defined, the basement of the main structure, consisting of seven flanges, was aligned and glued as follows. The position of the flange holes was determined projecting the laser tracker on the floor in their nominal positions. A balancer, holding the flanges to be glued in the proper position, was aligned using the laser tracker in real time, and the flanges grouted to the ground. After the grouting, the balancer was removed. A residual alignment error between the optical plane and the basement planes of 34.6 asec was obtained.

The main structure, which was machined with very tight planarity tolerances between the basement and the mode selector interface, was fixed to the plates. The fine mechanical alignment of the mode selector on the top of the main structure (x-y centering on the convergence point and tip/tilt on the optical axis) was performed with shimming. A residual tip/tilt of 2.85 asec and 0.61 asec between the optical plane and the mode selector plane was measured with the laser tracker.

Figure 8: (top left) the central pin at the convergence point was the first hardware piece of ESPRESSO installed at Paranal, on July 3rd, 2014; (bottom left) the laser tracker pointed in the Coudé Room of UT2; (center) balancer and plates during alignment before gluing; (right) FE structure mounted in the CCL.

### 5.3 Definition of the reference system and integration of the alignment laser

At this point, the mode selector is considered as reference for the alignment of the CTs and the FE Units. Its rotation axis is parallel to the optical plane vector, and defines the convergence point in the x-y directions. The optical plane is offset in the z direction of 560 mm. The kinematic mounts position for any FE Unit were then determined in the new reference system.

In order to project the optical axis in the four Coudé rooms, we mounted and aligned a laser beam to the mode selector rotation axis, and a pentaprism folding the light horizontally into the Coudé tunnels. For the laser alignment as respect to the mode selector axis, we placed a CCD camera on the ceiling of the CCL, and recorded the laser beam position for two opposite angles of the mode selector. Decentering was determined from the relative positions of the two collimated spots, while tip/tilt from the relative positions of two focalized spots after placing a lens in front of the camera. The overall procedure consisted in:

- alignment of the clock between the laser x-y movements and the camera
- tip/tilt laser alignment, with an accuracy below ±5 asec. This corresponds to less than 1.5 mm accuracy at 60 m (Coudé tunnel entrance), well below the final success criteria.
- x-y laser alignment, with an accuracy of 100 µm. This corresponds to the same misalignment at the entrance of the Coudé room.
- alignment of the pentaprism in the vertical direction, to position the optical plane at the correct level for the CTs.

The procedure provided the pointing at the entrance of the Coudé tunnel with an accuracy of 2 mm, well below the required accuracy for the CT alignment of 10 mm.

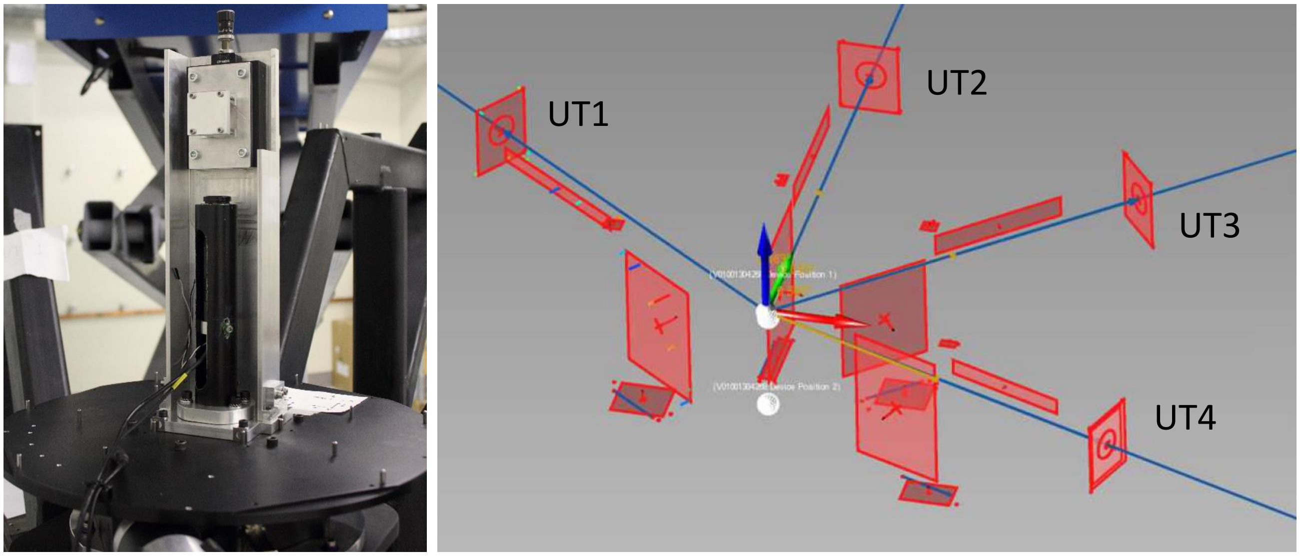

Figure 9: (left) detail of the Front End structure with the mode selector, the laser, and the pentaprism defining the optical axis; (left) FE structure interfaces acquired as respect to the optical axis of the 4 UTs; the convergence point can also be noticed.

## 6. CONCLUSIONS

Alignment and integration methods followed during the construction of the ESPRESSO FE have been described. A modular approach was adopted at the single FE Unit level to guarantee the repeatability between the different Units.

The strategy followed in the Paranal CCL to define the convergence point of the four UTs was described, along with the procedure used to align the ground plates, the main structure, and the mode selector. The CCL is now ready for the integration of the FE Units. After the preliminary acceptance of the FE at INAF Merate at the end of May, the FE is now under shipment to the Observatory of Gèneve for the re-integration and verification phase, before the installation at Paranal Observatory on ESO's Very Large Telescopes foreseen for the beginning of next year.

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