



EUROPEAN SOUTHERN OBSERVATORY

Organisation Européenne pour des Recherches Astronomiques dans l'Hémisphère Austral
Europäische Organisation für astronomische Forschung in der südlichen Hemisphäre

VLT PROGRAMME

2nd Generation Instrument MCAO Study
- FALCON -
Statement of Work

VLT-SOW-ESO-14680-2952

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Instrumentation
Division

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1 Scope

The scope of this document is to define the Statement of work of the 2nd Generation Instrument MCAO Study FALCON.

2 Background

The FALCON approach is to set up in the telescope focal plane a number of wavefront sensors (on reference stars) and science buttons (on astronomical targets), each equipped with its own low-order AO corrector. At the VLT, it could potentially use the FLAMES positioner to cover the full 25 arcmin field of UT2. Like for MUSE, the goal is to concentrate the light before feeding integral field spectrographs. In particular, the tomographic wavefront sensing using off-axis stars and the way the WFS signals are used to control the correctors is similar to what is done for the ESO MCAO demonstrator (MAD) downgraded to one deformable mirror. The present study will be an important contribution to the ESO MCAO plan as a whole and more specifically to the FALCON development plan.

The FALCON concept is for improving the AO correction for sources randomly distributed in the sky, including at large galactic latitudes. It aims at improving the light concentration entering in small apertures such as integral field units of spectrographs. An important FALCON specification is related to the light fraction of a star-like source which enters in an aperture of approximately 0".25 diameter. The gain is defined as the ratio of such a light fraction with and without correction. The goal of FALCON is to reach (on average for a random distribution of sources relatively to reference stars), a value of approximately 2 for the gain. (A second important specification is related to the required knowledge of the PSF at the location of the observed source).

This attractive concept is considered as potentially powerful for future ELT instrumentation (CELT, GSMT & OWL). Observatoire de Paris (OP) is conducting a full feasibility study in collaboration with ONERA and LAM, in particular to derive the novel algorithms needed for such a "pseudo closed-loop" multi-analysis approach.

The purpose of the present two-year study is to complement the system analysis and performance estimation, to evaluate the OKO deformable mirror performance in the context of FALCON and to investigate the pseudo-closed loop multi-analysis concept (ONERA contribution).

3 Project definition

The following objectives are part of the Contractor activities:

1. FALCON system analysis and performance
2. Propose a conceptual design of the 1st & 2nd generation of AO and Adaptive IFU buttons
3. Characterise the key parameters and performance of the OKO deformable mirror relevant for FALCON (performed on the LAM test bench)



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4. Develop an Adaptive IFU button with OKO mirror only
5. Develop a test bench to perform the testing of the Adaptive IFU developed above.
6. Perform all relevant testings of the OKO mirror in the IFU in static or quasi static only
7. Study the optimal MCAO command (ONERA)
8. Laboratory demonstration of the optimal MCAO command on BOA (ONERA)
9. As a goal dynamic testing of the Adaptive IFU

3.1 FALCON system analysis and performance

A FALCON system analysis and performance shall be performed based on the simulation tool developed by Observatoire de Paris. This analysis shall evaluate the gain in S/N for a stellar source in I, Z, J, H Bands (within a diameter of 0.25") under median Paranal atmospheric conditions compared to seeing limited observation. Taking into account the sky coverage and the average FOV in which the required number of reference stars can be found, the key AO characteristics shall be deduced (number of actuators, subapertures,...)

In addition an evaluation of the pourcentage of Cosmological sources observable with FALCON taking into account the Adaptive Optics constrains (Limiting magnitude of the reference stars used by the FALCON AO buttons) shall be performed.

Paranal atmospheric conditions are provided in Annex A. Typical wavefront decomposition in Zernike modes from reference stars for the three following conditions: The system performance estimate shall be performed taking into account the FALCON expected exposure time of several hours (and probably integration time of about one hour) and therefore atmospheric conditions might very significantly during the single exposure. The survey nature of FALCON will also play a role in the atmospheric percentile selected for the performance estimate. Atmospheric conditions should be corrected from Zenith angle effect at 30°.

3.2 Conceptual design of the 1st & 2nd generation of AO & Adaptive IFU buttons

Conceptual designs of FALCON buttons (stars / AO and object / IFU), which aim at including a movable motorized lens (large motions, correction of tip-tilt and defocus: 1st generation) and an OKO mirror (small motions, correction of higher order: 2nd generation) will be developed.

3.3 Characterization of the OKO-37 deformable mirror

OKO mirrors are potentially good candidates for the FALCON project. In that frame the characterisation of the OKO 37 actuator is crucial. The Contractor shall perform the following measurements on their test facility at LAM:

- **Surface quality**
 - Roughness



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- Figure error
- Local defects
- **Actuators**
 - Inter-actuator spacing
 - Maximal deflection
 - Actuation precision
 - Actuation repeatability
 - Actuation stability
 - Cross talk
 - Edge effects
 - Hysteresis
 - As a goal: measurement of the DM transfer function

A parametric model of the OKO 37 deformable mirror simulating the static & dynamic (goal) behavior of this component will be developed or procured. This model will be tuned based on experimental results obtained in the frame of this contract.

3.4 Development of a 2nd generation Adaptive IFU button

In order to test the OKO mirror in a configuration close to FALCON expected design, a 2nd generation adaptive IFU will be developed based on an OKO mirror and on the conceptual design proposed in section 3.2. To keep the system simple and the planned testing well focused on the OKO mirror characterisation no first stage correction will be implemented (no tip-tilt and focus correction).

3.5 Test bench development

To perform the required testing of the Adaptive IFU button, a test bench consisting of a turbulence generator, “medium order” wavefront sensors, a control system driving the 2 OKO mirrors and relevant analysis tools will be developed.

3.6 Testing of the Adaptive IFU in static or quasi-static

The so-called static or quasi-static tests will be performed:

- a) Energy distribution (coupling) will be evaluated at the micro-pupil entrance of the IFU before and after correction
- b) The Adaptive IFU button (microlens array removed) will be installed on the test bench and will be driven to create different static aberrations. The wavefront distortions created by the OKO mirror will be measured with a wavefront sensor and the actual amplitude, resolution, accuracy, stability and repeatability will be evaluated.



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- c) The turbulence generator will be used to create a slowly varying wavefront perturbation representative of the Kolmogorov turbulence (without tip-tilt and de-focus terms). The loop will be closed using the on-bench WFS and the Adaptive IFU button (without lenslet array). The performance will be evaluated from the wavefront sensor signal.
- d) A second Adaptive IFU using also an OKO mirror will be implemented on the test bench as well as a second wavefront sensor. The relative performances of the 2 adaptive IFUs using a single wavefront will be evaluated. Each individual performance of the 2 adaptive IFUs will be measured by one WFS.
- e) The two adaptive IFUs are operated in quasi-static closed loop using the same WFS and the same turbulence. The first adaptive IFU is in closed loop the second is in quasi-closed loop. The shape of the second Adaptive IFU is monitored with the second WFS to record the actual surface shape produced by the OKO mirror operating in quasi-closed loop (FALCON operation scheme).

3.7 Study of the optimal command (ONERA)

The following activities will be sub-contracted by the Contractor to ONERA under its own responsibility.

3.7.1 Study of the optimal (pseudo) close-loop command: off-axis case

FALCON, although specific because of its architecture spread over several mirrors, shares however strong similarities with "classical" multi-analysis AO systems. Among these similarities, a particular problem is to have a loop closed (or pseudo-closed, the terminology here remains to be invented) using several off-axis wave-front sensors analysing the effects of a particular on-axis compensation.

A first step to tackle this problem is to study the way to close a loop on axis, with a single mirror in the pupil plane and a single off-axis WFS. ONERA will study this problem, based on ONERA internal activities. in particular he will:

- a) Determine the accuracy required from the DM model and calibrations
- b) Determine the accuracy required from the WFS model and calibrations
- c) Evaluate the impact of these errors on the final control performance of the loop and how the error propagates
- d) use the apriori knowledge for the spatial and temporal information of the turbulence to optimize the on-axis command.

The algorithms of this (pseudo?) closed-loop command, the hypothesis, assumptions, the temporal filtering will be communicated to the Contractor (O.P.).

The FALCON concept is not interested in accuracy requirements and error propagation in the case of several deformable mirrors (actual so-called MCAO case), and such considerations are not part of this study. It is not expected for this ONERA study to specifically include the very particular case of OKO mirrors. However, it is expected that the

ONERA results are general enough, so that they can be extrapolated by OP to other DM types or micro-DM types, including OKO technology.

3.7.2 Study of the multi-analysis case

The multi-analysis case consists in controlling a single DM in the pupil plane using the measurements of *several* off-axis WFSs. The goal of this study is to

- extrapolate the results given in items a/ to d/ of paragraph 3.7.1 to the multi-analysis case
- evaluate the impact of the error on the final close-loop control performance, when using an optimized command similar to 3.7.1 (Kalman-type or equivalent, etc).

This activity is submitted to the relevance of the results produced from the first step, described in 3.7.1. The amount of work to be done on the multi-analysis case depends on the results from the single off-axis case; hence it could be redefined at T0+18m. In any case this work will be provided on a best effort basis.

3.8 Laboratory experiment of the optimal command on BOA (ONERA)

The following activities will be sub-contracted by the Contractor to ONERA under its own responsibility.

A laboratory experiment will be developed to demonstrate the performance of the optimal command described in section 3.7.1. This laboratory experiment will be based on the existing BOA bench.

The following measurements will be performed:

- Calibration of the wavefront sensor and deformable mirror in static and prediction of the off-axis correction according to the study results obtained in section 3.7.1
- Using an off-axis reference star (few arcmins away from the on-axis object) for wavefront sensing and one DM conjugated in the pupil plane, the closed loop correction will be optimised for the on-axis object. This optimisation will make use of the calibration data and modelisation obtained above and of the a priori spatio-temporal knowledge of the turbulence

An upgrade of the BOA Real Time Computer is needed to perform the command required above. This upgrade is funded by the present contract.

3.9 FALCON adaptive IFU testing in dynamic

As a goal, the Contractor should propose a test plan to pursue the dynamic closed-loop analysis of the adaptive IFU buttons using the OKO mirrors. Ultimately these tests should be pursued on the SESAME bench on a best effort basis.



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4 Project Management

4.1 ESO Contribution

The financial contribution of ESO to the FALCON study consists in an inclusive amount of 111615 € (106,300 € + 5315 € (5%) for Observatoire de Paris overhead cost). No manpower contribution from ESO is foreseen, except for a small contribution about optics (less than one man-month) which could be envisaged.

4.2 Project schedule and key milestones

The study phase undertaken by the Consortium extends over a period of 24 months from kick-off to delivery of final report:

Milestones	Date	Payment
Kick-off (To)	To	60,000 €
Progress Meeting & Report 1	To + 8 months	0
Progress Meeting & Report 2	To + 16 months	40,000 €
Progress Meeting & Report 3	To + 20 months	0
Final Meeting & Report	To + 24 months	11,615 €

4.3 Deliverables

The 4 Progress reports in English are the deliverables. However some technical reports, with the agreement of ESO, could be written in French, under the condition that they display an executive summary in English.

- Progress report 1: This progress report shall contain the results of activities defined in Sections 3.1, 3.2
- Progress report 2: This progress report shall contain the results of the activities defined in Sections 3.3, 3.4, 3.5
- Progress report 3: This progress report shall contain the results of the activities defined in Sections 3.6 a, b, c, 3.7.1, 3.8.
- Final report 4: This progress report shall contain the results of the activities defined in Sections 3.6 d, e, 3.7.2 and 3.9.

No hardware is to be delivered in the frame of this contract.



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4.4 Progress meetings

Four-progress meetings will be organised at the Contractor premises to review the work progress at each Milestone and to discuss the progress reports delivered one week in advance. Progress meeting agenda will be agreed upon before the meeting.

Additional meetings either at ESO or at Contractor premises can be decided in the course of this study to review problems and major scope of work changes due to unforeseeable showstoppers or to assist to a key laboratory testings (OP, LAM, ONERA).

4.5 Result dissemination and Publications

All results obtained and simulation codes developed in the frame of the study described in this SOW shall be made available to ESO. Article 17 of the “Conditions Governing Calls for Proposals and Contracts for the VLT Instrumentation, Munich, January 1997” shall apply, but in the frame of this Contract:

- The list of Authors (but not the Author list order) of any publication describing the study and results obtained by O.P., LAM & ONERA in the frame of this contract, shall be agreed upon with the ESO contact point.
- Prior to publication, no results could be disseminated and communicated by ESO, outside ESO or O.P., without mutual agreement between O.P. and ESO.

4.6 Contact points

ESO contact points for this contract are:

- For technical and scientific matters: N. Hubin, (nhubin@eso.org)
- For contractual matters: G. Wieland (gwieland@eso.org)

Observatoire de Paris contact points for this contract are:

- For scientific matters: F. Hammer, (francois.hammer@obspm.fr), tel: +33 1 45 07 74 08
- For technical matters: F. Sayède, (frederic.sayede@obspm.fr), tel: +33 1 45 07 75 60
- For contractual matters: J. Pluet, (Jacqueline.pluet@obspm.fr), tel: +33 1 45 07 78 47



ANNEX A: Paranal atmospheric conditions to be used for FALCON performance estimates and PARANAL seeing, coherence time and isoplanatic angle statistics (values were computed for years between 1999 and 2002).

Seeing (at 0.5 mm, zenith)

Percentile (%)	Seeing (")
10	0.51
20	0.60
30	0.67
40	0.74
50	0.81
60	0.90
70	1.00
80	1.14
90	1.40

Correlation time (at 0.5 mm, zenith)

Percentile (%)	Tau0 (ms)
10	6.54
20	4.96
30	4.14
40	3.54
50	3.04
60	2.59
70	2.19
80	1.81
90	1.42

Note that here Tau0 is computed as $\tau_0 = 0.31 r_0 / v_0$ where r_0 is the Fried parameter given by the DIMM and v_0 is the wind at 200 mbar. This is a rough estimate, but seems to be in agreement with NAOS measurements.

Note also that τ_0 is very much season dependant, unlike the other two parameters. The following table summarizes the probability to get a correlation time larger than 3 ms (NAOS specification), as a function of month in the year (Data taken from: <http://www.eso.org/gen-fac/pubs/astclim/paranal/seeing/adaptive-optics/stattau0.html>):



**Seasonal variations of the correlation
time**

Photometric Nighttime (23h- 10hUT)	median (ms)	tau0 > 3ms (%)
January	4.6	78
February	4.8	83
March	4.1	76
April	3.5	61
May	2.6	41
June	2.2	27
July	2.4	37
August	2.9	47
September	2.4	35
October	3.2	55
November	3.0	50
December	3.5	64
Year	3.1	53

Isoplanatic angle (at 0.5 um, zenith)

Percentile (%)	Theta0 (')
10	3.69
20	3.20
30	2.89
40	2.64
50	2.42
60	2.22
70	2.01
80	1.78
90	1.51

The methods used to measure these quantities can be obtained from:

<http://www.eso.org/gen-fac/pubs/astclim/paranal/seeing/adaptive-optics/stattau0.html>