E-ELT phase-A instrument studies: a system engineering view

J.C. González*, S. D'Odorico, S. Ramsay
European Southern Observatory, Karl-Schwarzschild str. 2, 85748 Garching, Germany

ABSTRACT

During the last two and half years ten phase-A instrument studies for the E-ELT have been launched by ESO and carried out by consortia of institutes in the ESO member states and Chile. These studies have been undertaken in parallel with the phase B of the E-ELT telescope. This effort has pursued two main goals: to prove the feasibility and performance of a set of instruments to meet the project science goals and to identify and incorporate in the telescope design those features that satisfy best the needs of the future hosts, i.e., the science instruments. To succeed on this goal it is crucial to identify such needs as early as possible in the design process.

This concurrent approach definitively benefits both the instruments concept design and the telescope development, but implies as well a number of difficult tasks. This paper compiles, from a system-engineering point of view, the benefits and difficulties as well as the lesson learned during this concurrent process. In addition, the main outcomes of the process, in terms of telescope-instruments interfaces definition and requirements from the instruments to the telescope and vice-versa, are reported.

Keywords: interfaces, requirements, system engineering

1. INTRODUCTION

The European Extremely Large Telescope (E-ELT) program is undertaking the preparation of a construction proposal for a 42m-telescope and observatory (hereinafter, the telescope) plus a suite of science instruments, some of them will be available for first light and the rest later on as part of the first generation instruments. The E-ELT construction proposal will be submitted to the ESO governing body by the end of 2010.

The E-ELT telescope project entered into phase B early in 2007. The scope of this phase is to produce a design of the telescope leading to prepare the construction proposal. Almost in parallel to this telescope phase B, ten phase-A instrument studies were launched starting in September 2007 and lasting until March 2010. They were carried out by consortia of institutes (including ESO itself) in the ESO member states and Chile[1]. Two of these studies were devoted to post-focal AO modules while the rest were for instruments that covered the parameter space required to deliver the E-ELT science case.

This effort pursued several goals, both from the managerial and system engineering point of views:

- Managerial:
    - To prove the feasibility and performance of a set of instruments to meet the project science goals.
    - To be in a solid position to prepare the instrumentation part of the E-ELT construction proposal.
    - To contribute in preparing the European science instruments community for the construction of the E-ELT instrumentation.
- System engineering:
    - To identify and incorporate in the telescope design those features satisfying best the needs of the instruments.

*jcgonzal@eso.org; phone +49 89 32006641; fax +49 89 32006530; www.eso.org

- To define the telescope-instruments interfaces.
- To define general requirements on the instrument side as derived from the top-level E-ELT observatory requirements.

At this stage in the E-ELT program one can state that these goals have been met. A number of benefits and lessons learned have been derived from this concurrent approach, which has suffered also from some difficulties both for ESO and for the consortia in charge of the instrument studies. The next sections discuss these topics and also provide evidence for the success of the process in terms of telescope-instruments interfaces definition and requirements from the instruments to the telescope and vice-versa, i.e., the system engineering goals of phase-A instrumentation studies (see Figure 1).

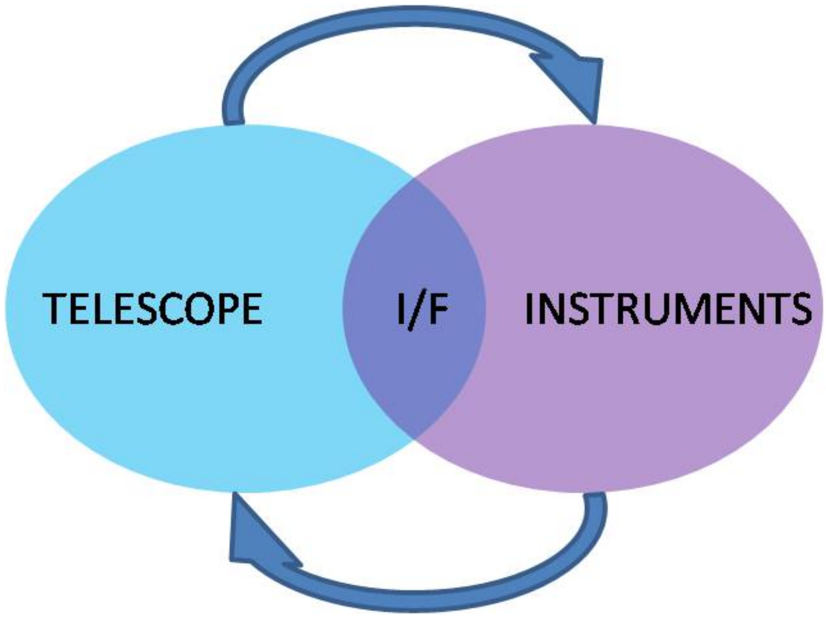

Figure 1. The system engineering view of the adopted approach. Instruments needs have influenced the telescope design and vice-versa. Also, telescope-instruments interface definition has largely benefitted from this process.

2. BENEFITS AND DIFFICULTIES OF THE CONCURRENT APPROACH

As already said, instrument consortia started to work in the phase-A studies when the telescope had just started its phase B, i.e., a concurrent approach was adopted early. On the one hand, this means that in the beginning ESO was not in a position to provide the instrument developers with much detail on the telescope characteristics driving instrument design and, in particular, on the interfaces which the instruments had to be compliant with. On the other hand, the instrument developers had the possibility to influence the telescope design in such a way as to better satisfy their needs.

Aiming to minimize the impact of the first point, a telescope-instruments interface document was released by the beginning of the instrument studies (October 2007). This document compiled the already known characteristics of the telescope relevant to the instruments, many of them still to be confirmed, and also contained a number of open points to be defined. As the telescope design progressed and new information became available, this document was updated, leading to a new issue in June 2008 and to a final one in June 2009. The latter was frozen until the end of the instrument studies.

As a matter of fact, instrument consortia had therefore to cope with uncertainties and unknowns in the beginning and also with new information and changes during the studies, at least until some point in time. This required a frequent interaction between them and ESO in order to discuss and clarify aspects still not well defined in the interface documentation. Such interaction was extremely useful in helping the consortia to better understand the telescope characteristics as they were being defined, in improving the interface documentation and also in letting ESO to better understand which were the critical points for the instruments.

In this sense, ESO got many questions from consortia on the telescope that could not be replied in full or even at all at the moment they were raised, simply because they concerned a telescope characteristic that was not yet defined or analyzed. However, if this telescope-instruments concurrent development approach had not been adopted, ESO had not asked itself some of those questions relevant for the telescope. On the other side, instrument developers were early made aware of important issues related to interfaces and other telescope characteristics that must be considered in the instruments design.

In some cases, aspects not well enough defined from the telescope side lead to making extra provisions on the instrument side. These provisions will have to be revisited in next phases once the interface information and the telescope characteristics are well defined.

As mentioned before, the adopted approach gave the consortia the opportunity to influence the telescope design to some extent aiming to satisfy their needs. To succeed on this goal, identifying such needs as early as possible in the design process was considered crucial. In practice, this was conducted by means of a number of questionnaires sent to the consortia asking for feedback on subjects such as:

- Optical and mechanical interfaces
- Telescope performances (pupil stability, telescope transmission and uniformity, offsetting, etc.)
- Common AO calibration facilities (for instruments with in-built AO capabilities)
- Laser guide stars
- Control system (performance, preferences on hardware and software standards, real-time computers, etc.)
- Requirements on observatory infrastructure (power supply, cooling fluid, cryogenics services, instruments integration and testing facilities, handling equipment, etc.)
- Detectors requirements

The replies to these questionnaires, issued along the phase-A time period, were discussed within the E-ELT program offices at ESO and the conclusions used to feed the telescope design. It must be said that it was not always possible incorporating the instruments demands, mostly because of telescope performance constrains or managerial reasons.

As the major results of this process from the system engineering point of view, the telescope development has been tuned according to the instruments demands, the telescope-instruments interfaces have been defined at a level sufficient for the next phase of the instrument development and, finally, a compilation of the general requirements for the E-ELT instruments was produced. From now to the beginning of instruments next phase, the outcomes of this process, both in terms of interface specification and instruments general requirements, will be used to produce consolidated issues of the concerned documents.

3. OUTCOMES OF THE PROCESS

This section summarizes the outcomes of the process described above. To better understand what follows, a short description of the telescope focal stations is given first.

3.1 Summary of telescope focal stations

The E-ELT telescope will have a number of focal stations available for instrumentation. Each Nasmyth platform will be equipped with three focal stations: one straight-through (A1, B1 in Figure 2) and two lateral bent (A2, A3, B2, B3) focal stations, also called ports. Below each Nasmyth platform a gravity invariant focal station will be located (see Figure 3). The gravity invariant focal stations will be reserved for instruments that can benefit from compensating the field rotation by rotating around a vertical axis (i.e., large and heavy instruments). Finally, one coudé focal station with provisions for two laboratories will be placed within the telescope foundations beneath the telescope azimuth tracks. It will be specialized to host instruments requiring a very high long-term thermal and mechanical stability.

The active focal station will be selected by sending the optical beam towards one of the two Nasmyth platforms, then by switching the M6 mirror (see Figure 2) in order to let the beam pass to the straight-through port or re-direct it towards any of the lateral ports, the gravity invariant focus or the coudé focus.

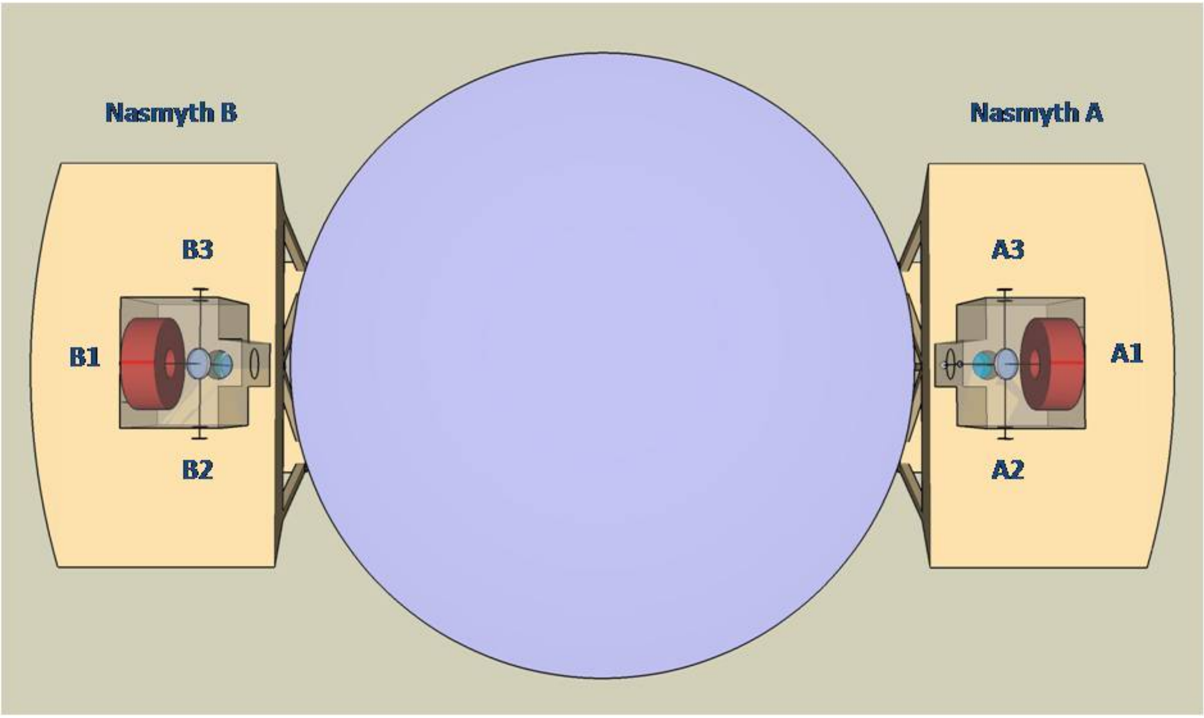

Figure 2. The focal ports at the Nasmyth platforms. The removable/rotating M6 mirror located in the pre-focal station (the transparent box in the figure, which also contains the wavefront sensors and cameras for telescope control) can direct the science beam to three different locations on each Nasmyth Platform as shown in the figure. By directing the beam below the platform the M6 mirror feeds the gravity invariant focal station or the coudé train.

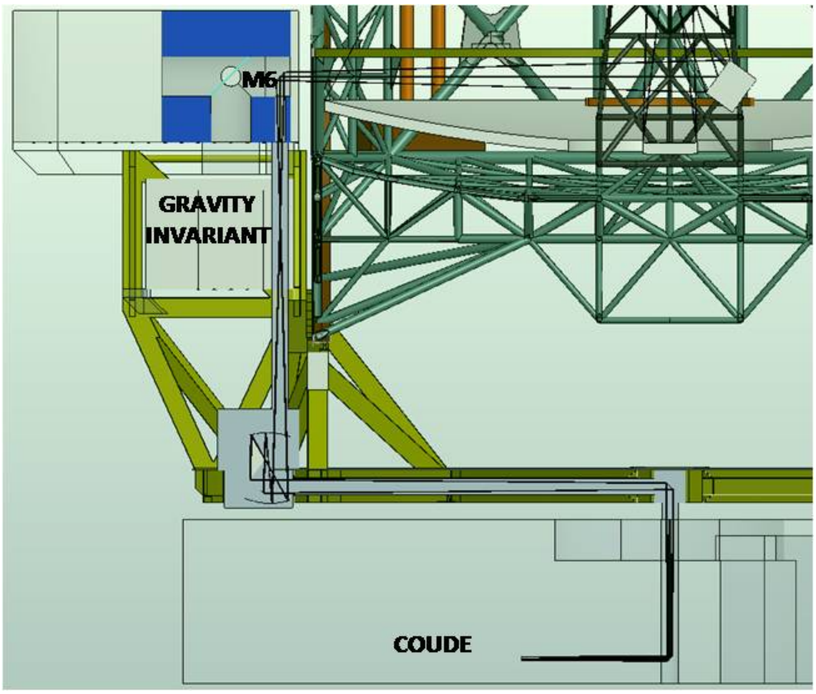

Figure 3. The gravity invariant and coudé focal stations.

3.2 Requirements on the telescope

A number of requirements were set on the telescope side coming from instruments needs. The most representative cases are:

- The size of the Nasmyth platforms, which was derived from the estimated dimensions of the instruments, taking into account the required space for accessing and maintenance as well as the safety constrains (escape routes). This size is approximately 28m x15m.
- The height of the optical axis with respect to the Nasmyth floor, which was defined as 4m. This was driven by allowing for enough room to cope with the foreseen dimensions of the larger instruments. Phase-A studies have found this approach very useful; some instrument concepts took benefit by designing in a two-floors arrangement (see Figure 4). This leads to saving very valuable Nasmyth floor area and allows for more compact instruments. Also, this height makes possible for small and medium-size instruments to implement gravity-invariant field de-rotation on the Nasmyth platforms. This has been the adopted solution by some consortia. On the other hand, it implies more effort for smaller instruments to comply with their stability requirements and to be earthquake proof.

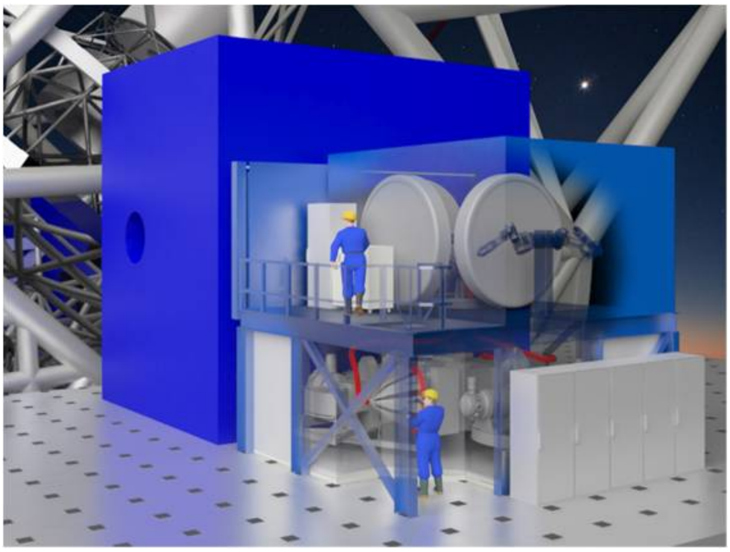

Figure 4. Two-floors concept of the OPTIMOS-EVE instrument standing on the straight-through port of the Nasmyh platform. The big box behind the instrument represents the pre-focal station of the telescope. (Courtesy of the OPTIMOS-EVE consortium).

- Some telescope performance parameters were defined from the instruments demands. This was the case of the exit pupil stability and the motion of the adaptive mirror M4 as seen from the focal plane, which is relevant for the AO in-built instruments.
- Requirements on the common AO calibration facilities and the laser guide stars, which are subsystems to be incorporated in the telescope, were established after compiling and analyzing the feedback given by the consortia on these topics.
- As a significant outcome of the phase-A studies, it became clear that almost all the explored instrument concepts did not foresee making use of the field de-rotators to be provided by the telescope. Instead, they were relying in their own rotators, either optical (in the case of small field instruments) or mechanical. This fact obviously forced ESO to reconsider the number of telescope field de-rotators, which was initially set as six (one at each Nasmyth port).
- Power supply, coolant fluid and cryogenics fluid budgets for instrumentation were built from the information provided by the consortia and derived requirements set on the telescope. Also, the concept for implementing the cryogenics infrastructure was based on the demands defined by the consortia[2].

- Other requirements on the observatory infrastructure, such as instrument integration hall, handling equipment (lifting platform to reach the Nasmyth areas, dome cranes, etc.), meteorological station or astronomical site monitoring, have been confirmed or even defined looking at the instruments demands.

3.3 Telescope-instruments interfaces

A first definition of the main interface requirements was given to the consortia at the beginning of the studies in the first release of the telescope- instruments interfaces document. According to the design progress of the telescope and taking into consideration feedback from the consortia, this definition was updated in the next issues of the document. Currently, the major interface specifications are as given below:

Optical interfaces:

Table 1. First order characteristics of the focal stations.

	Nasmyh	Gravity Invariant	Coudé
Angular FOV (ø arcmin)	10 (straight-through) 5 (lateral ports)	10	0.33
Linear FOV (ø mm)	2162.7	2302.1	209.3
Focal Ratio	17.71	18.85	51.4
Plate Scale (mm/arcsec)	3.605	3.838	10.46
Field Curvature (mm)	43800	49694	1100
Exit Pupil Position (mm before focus)	43263	46283	31200
Central obscuration (% in area)	9.2	9.2	9.2

Mechanical interfaces:

Table 2. Mass and dimensions interface requirements for instruments at the focal stations. According to mass and volume, two types of instruments are considered to populate the Nasmyth platforms, namely, light and heavy instruments.

	Nasmyh	Gravity Invariant	Coudé
Mass (tons)	Light instruments: 6.5 Heavy instruments: 25	20	Distributed load: $10kN/m^2$ Concentrated load: 20kN on 95x40 mm^2
Volume	Light instruments: 4m x 4m plant, 6m high Heavy instruments: 6m x 6m plant, 7m high	Gravity Invariant A: a cylinder 4m ø, 6.04m high Gravity Invariant B: a cylinder 5m ø, 6.04m high	To be defined in a case-by-case basis
Back-focal Distance (mm)	750 ± 50	1200 ± 50	1000 ± 150
Optical Axis Height (m)	4	N/A	1.5

Control system interfaces:

Instruments can work in telescope-control modes (seeing-limited and ground-layer AO) or in instrument-driven modes (e.g., in-built AO instruments).

The Telescope Control System (TCS) can be understood as a “black box” isolating the instrument from the telescope. It will provide services for pointing, guiding and offseting, for configuring guide stars, for monitoring and delivering performance data, etc. The TCS will also be able to receive offset requests from the instruments concerning some functions delivered by the telescope (e.g., guiding, focus).

In telescope-control modes the TCS will also be responsible for fully performing the wavefront control. However, in instrument-driven modes, instruments need to participate in the wavefront control and therefore need to penetrate the "black box" quoted above. They will operate isochronously with the wavefront control telescope devices and will not be allowed to command M4 (adaptive mirror) nor M5 (fast tip-tilt mirror). Instead, they will publish requests to the TCS, which will be in charge of performing other M4/M5 related tasks, as for instance, pupil positioning control. The TCS will remain the sole responsible for the integrity of the system, will monitor the wavefront quality and will take control back if it degrades.

Concerning control and data communication, the E-ELT network infrastructure will provide communication channels for:

- The control and data flow between the various subsystems. This will be used for sending commands from instruments to TCS and to receive status information. In this sense, the data distribution system of the TCS is designed so as to enable instruments accessing any telescope data publicly available.
- Deterministic data flow between various subsystems, essentially for real-time applications.

Services interfaces:

A number of interfaces between the observatory and the instruments (including the control and data network interfaces) will be materialized by means of Service Connection Points (SCPs) available at the focal stations, namely:

- Power supply
- Earthing and bonding
- Control and data flow
- Deterministic data flow
- Time distribution
- Fail-safe interlock distribution
- Connections for locally installed safety devices and emergency stops
- Cooling fluid
- Compressed air
- Cryogenic fluid (to be confirmed)
- Vacuum (to be confirmed)

3.4 General requirements to the instruments

Like in the case of the telescope-to-instruments interfaces, a first definition of the instruments general requirements was made available to the consortia at the beginning of the studies. By general requirements it is meant requirements that any E-ELT instrument, irrespective of the science targets it addresses, must be compliant with. This refers essentially to operation and calibration aspects, design standards and guidelines, installation at the telescope and RAMS (Reliability, Availability, Maintainability and Safety).

A second release was distributed some months before the end of the studies, taking into consideration not only the evolution of the general observatory requirements but also some feedback from the consortia until that moment.

4. CONCLUSIONS AND LESSONS LEARNED

Carrying out the E-ELT phase-A instruments studies in parallel with the telescope design has definitively yielded important benefits concerning both managerial and system engineering aspects. By adopting this concurrent approach from the very beginning in the E-ELT program, a very useful interaction between instruments and telescope design has been possible. Focusing on system engineering, the observatory design has largely benefitted from the feedback coming from the consortia in charge of the phase-A instrument studies, while a set of requirements on the instruments, derived from the observatory concept has been put very early on the instruments development side. At the same time, this interaction has leaded also to complete and consolidate the telescope-instruments interfaces specification which was drafted in the very beginning of the process.

A number of lessons learned from this process are reported below; many of them can be even applied to the next instrument design phases:

- Define from the very beginning the objectives of the process and the milestones as well, and make both public to all the stakeholders (observatory developers, instrument developers). The objectives should be the interface specification, the instruments general requirements and the inputs from the instruments design to the observatory. By doing so, instrument developers can plan from the beginning the effort and the deliverables related to the process.
- Draft and distribute very early in the process an interface specification document, an instruments general requirements document and a number of questionnaires on the requested feedback for the observatory design. These drafts should evolve according to the milestones of the process, which obviously poses constrains on the instruments schedules.
- Explicitly encourage a system-engineering approach to instrument development. The goal is preventing that system level aspects, such as system budgets or RAMS analysis, are poorly addressed or even neglected. This can be done in practice by:
    - Drafting a System Engineering Documentation Plan (SEDP); this specifies the technical documents to be delivered as an outcome of the process as well as the relationships between them.
    - Defining deliverable documents in terms of Data Item Description (DID). DIDs define, among other things, the purpose and the contents of these documents.
- In relation to the previous point, explicitly request a life-cycle cost analysis. This is to avoid that only requirements derived from the instrument (scientific) function are taken into consideration when making design trade-offs. Requirements derived from the instrument support needs along the lifetime should be considered very early in the design process and the related cost in cash and manpower minimized. In this sense, an Integrated Logistic Support (ILS) approach should be encouraged.
- Make an effort to define some basic characteristics of the control interfaces and standards as soon as possible. Usually, control system definition is made late since it needs inputs from other subsystems. Therefore, the control interfaces and standards are also defined late. This has been a recurrent issue in the case of the E-ELT studies.

REFERENCES

[1] Ramsay, S., D'Odorico, S., Casali, M., Gonzalez, J.C., Hubin, N., Kasper, M., Kaeufl, H.U., Kissler-Patig, M., Marchetti, E., Paufique, J., Pasquini, L., Siebenmorgen, R., Richichi, A., Vernet, J., Zerbi, F.M., "An overview of the E-ELT instrumentation programme," Proc. SPIE 7735, (2010).

[2] Lizon, J. L., Gonzalez, J. C., Monroe, C., Bryson, I. and Montgomery, D., "First concept for the E-ELT cryogenic infrastructure," Proc. SPIE 7739, (2010).