Instrumentation at the ESO VLT

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ABSTRACT

ESO's Very Large Telescope (VLT) on Paranal mountain in northern Chile comprises four 8.2m diameter 'Unit Telescopes' (also used for interferometry); four 1.8m movable outrigger telescopes dedicated to interferometry and two survey telescopes - the 2.6m VST to be used in the visible and the 4m class, infrared VISTA telescope. Here I will give an overview of the accompanying large instrument development programme which has so far delivered 11 operational facility instruments for the UT's (leaving one visitor Nasmyth focus) and 2 major instruments for the interferometric focus. In addition, a laser guide star facility has been added on UT4 to generate artificial (sodium) stars for the adaptive optics assisted instruments NACO and SINFONI; the optical and infrared cameras for the survey telescopes are almost ready; four major second generation instruments for the UTs (X-Shooter, KMOS, MUSE and SPHERE) are at various stages of development throughout Europe; a fifth (high resolution spectrograph capable of 10cm/s radial velocity stability at the incoherent combined focus of the four 8m telescopes) is the subject of a Call for Proposals; UT4 is being converted to a fully adaptive telescope and three second generation interferometric instruments (MATISSE, GRAVITY and VSI) have been approved following successful completion of their Phase A studies.

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Fig 1. The ESO VLT on mount Paranal in northern Chile with its four 8.2m diameter Unit Telescopes, four 1.8m movable outriggers and VST 2.6m and VISTA 4m survey telescopes.

1. INTRODUCTION

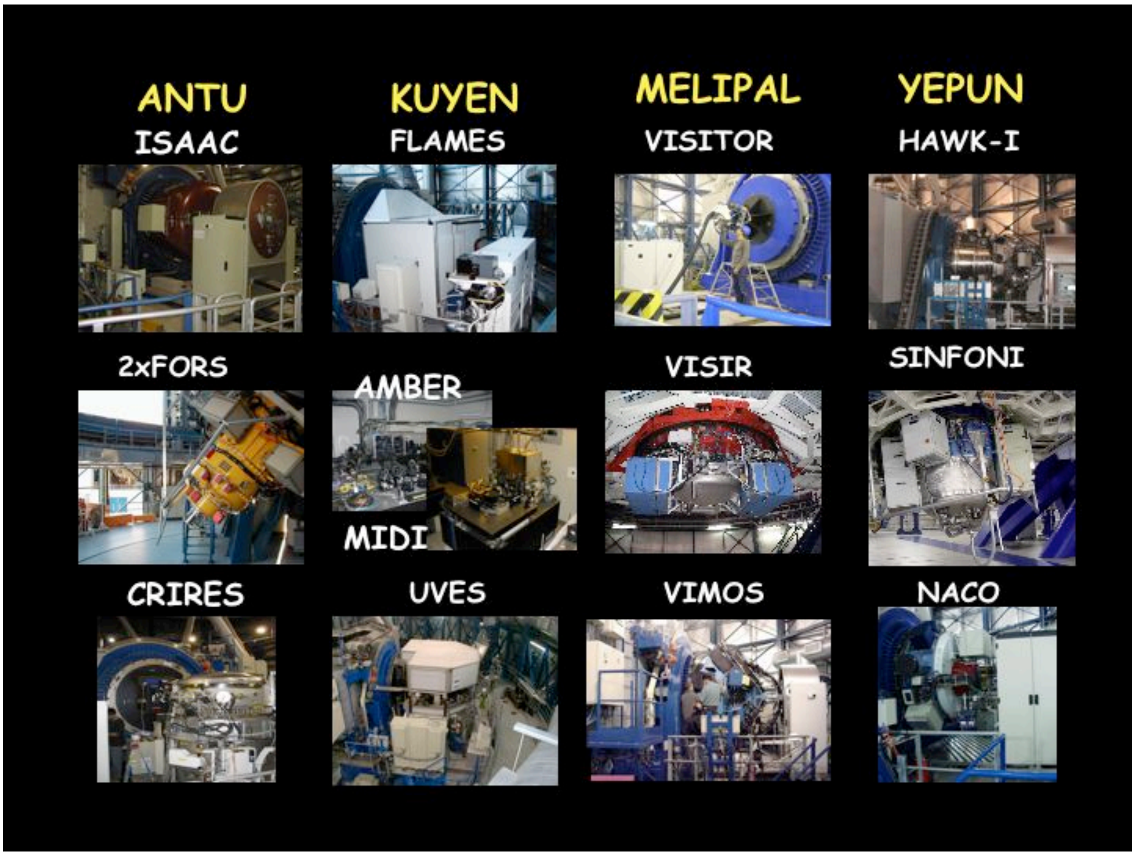
The development of large 8-10m class telescopes has also generated relatively large resources for their accompanying instrumentation. The VLT on Paranal, shown in Fig. 1, has posed a particular challenge given the 2 Nasmyth and 1 Cassegrain focus on each of its 4 8.2m Unit Telescopes (Antu, Kueyen, Melipal and Yepun) plus its interferometric focus, which receives light from any combination of the 4 Unit Telescopes and four 1.8m outrigger telescopes, plus its associated 2.6m optical VST (supplied by Italy) and 4m VISTA infrared survey (provided by the UK as a contribution in kind on joining ESO) telescopes. Evolving from an Instrumentation Plan drawn up around 1990, this effort has so far resulted in 13 first generation major VLT/VLTI instruments plus the laser guide star facility and survey cameras listed in table 1. Subsequently, as listed in table 2., four second generation instruments for the UTs are in development, and 3 second generation interferometric instruments have been approved and are listed in table 2. More detailed information about the complete instrumentation programme can be found under http://www.eso.org/instruments. In addition to this long list of instruments, the effort has had the beneficial spin-off in Europe of leading to the formation of several consortia of institutes capable of tackling such projects and willing to support the ESO VLT - in some cases at the expense of national programmes. In most cases the instruments have been required to conform to ESO defined standards in various areas e.g software, detector and instrument control systems, cryogenic systems etc. which have eased the problem of maintaining and operating so many complex systems at such a remote site as Paranal. Consortium manpower and, in the case of the second generation instruments also hardware costs borne by them, has been rewarded by allocations of Guaranteed Observing Time. Lessons learned from the first generation developments were reviewed in the overview given at the corresponding SPIE meeting in Glasgow in 2004 [1]. Looking further to the future, a Workshop on 'Science with the VLT in the ELT era' was organised in Oct 2007 as a forum for the community to discuss the expected evolution in usage of the VLT and its required instrumentation when the next generation of large telescopes come on line. At a meeting shortly afterwards, ESO's Scientific and Technical Committee recommended proceeding with the 3 second generation interferometric instruments studied to Phase A level and issuing a Call for Proposals for a high resolution spectrometer capable of 10cm/s radial velocity precision at the incoherent combined focus. Additional instruments and upgrades are currently being considered for inclusion in ESO's next Medium and Long Range Plans.

2. FIRST GENERATION VLT/VLTI INSTRUMENTS

Table 1. lists the first generation of operational VLT instruments together with a brief summary of their capabilities. The instruments, ISAAC, UVES, CRIRES and HAWK-I have been developed in-house at ESO while FORS1 and 2, FLAMES, NACO, VIMOS, MIDI, VISIR, OmegaCAM, SINFONI and AMBER have been developed largely by outside consortia with various contributions from ESO, usually the capital cost plus detectors and/or other systems. Pictures of the instruments are shown in Fig. 2

Table 1. First Generation VLT/VLTI instruments.

FORS1	Optical imager, MOS spectrograph and polarimeter
FORS2	Red sensitive optical imager and MOS spectrograph
ISAAC	Infrared, 1-5µm imager, polarimeter and long slit spectrometer (Rs ~ 3000)
UVES	UV-visible high resolution echelle spectrograph
FLAMES	Visible MOS facility - fibre positioner; GIRAFFE spectrograph; UVES link
NACO	1-5µm adaptive optics assisted imager, polarimeter and spectrometer
VIMOS	Wide field (14x14') optical imager, MOS and IFU spectrograph
MIDI	10µm interferometric imager and spectrometer
VISIR	10/20µm imager and spectrometer
SINFONI	1-2.5µm adaptive optics assisted, integral field spectrometer
AMBER	Near infrared interferometric imager and spectrometer
CRIRES	1-5µm, R = 100.000, echelle spectrograph
HAWK-I	0.9-2.5µm wide field (7.5x7.5') imager - to be used later with Adaptive Optics Facility
OmegaCam	Wide field (1x1 deg.) optical imager for the VST
LGSF	Laser guide star for use with NACO and SINFONI



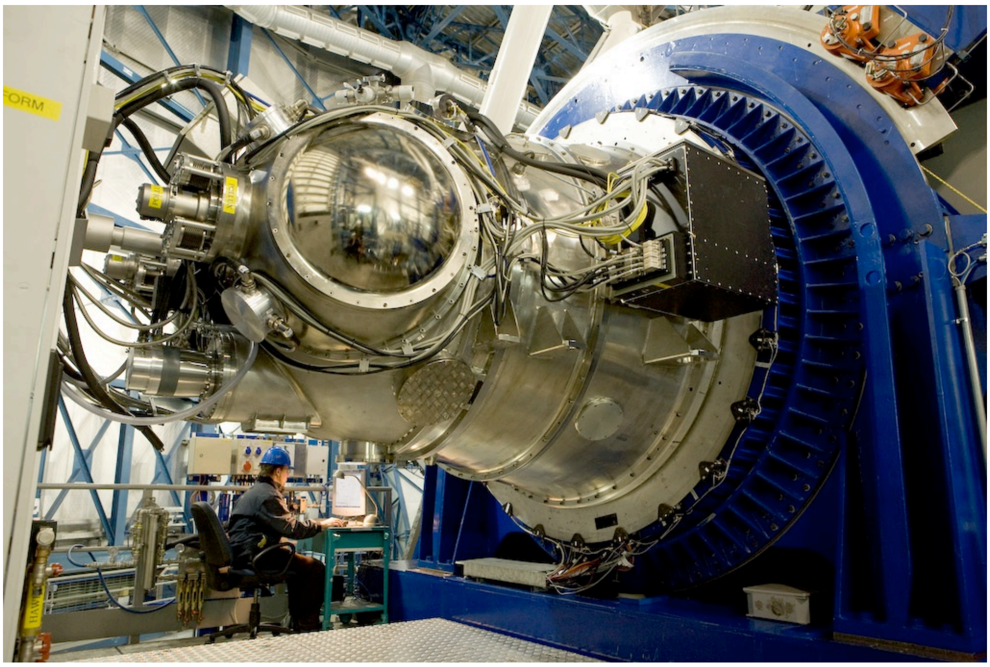


Fig. 2 Above. The 11 operational VLT instruments on the 4 Unit Telescopes plus the first visitor instrument (Ultracam) and the 2 interferometric instruments. Below, the HAWK-I infrared imager, built by ESO and the latest instrument to be commissioned and offered to the community.

2.1 Last of the major first generation instruments

The last first generation instruments for the unit telescopes, CRIRES and HAWK-I have both been developed by ESO.

CRIRES is a high resolution infrared cryogenic echelle spectrograph providing R ~ 100.000 from 1 to 5µm and fed by an adaptive optics system to maximize the light entering its ~ 0.2" slit and to improve spatial resolution. It has been offered since April 2007 although its polarimetric upgrade remains to be completed.

HAWK-I shown in Fig. 2, is a 'wide field' (7.5x7.5') 0.9-2.5µm imager which employs all reflecting optics and is equipped with a mosaic of four Rockwell Hawaii 2RG 2048x2048 pixel arrays to achieve a wide field but with high spatial resolution. Each pixel corresponds to ~ 0.1" to allow good sampling under the best seeing conditions of 0.2-0.3" which are expected to be achieved over the complete field for most of the time once HAWK-I can benefit from the ground layer adaptive optics correction to be provided by the adaptive optics facility being developed for UT4. It has been offered to community since April 2008 after a successful Science Verification phase which confirmed the excellent optical quality and throughput expected.

3. SECOND GENERATION VLT/VLTI INSTRUMENTS

Table 2 lists the already approved second generation VLT and VLTI instrument. For these instruments - X-Shooter is being developed by a consortium led by ESO while KMOS, MUSE, SPHERE and the three interferometric instruments have been largely contracted to external consortia with contributions of money, detector and other systems form ESO. Unlike the first generation however, all the consortia are also providing national funding in return for additional guaranteed 0bserving time. Also included is the Adaptive Optics Facility (AOF) being developed by ESO by equipping UT4 (Yepun) with a deformable secondary mirror and 4 sodium laser guide stars. Initially it will be used to deliver at least ground layer corrected images to the HAWK-I and MUSE instruments which are being designed to contain the appropriate wavefront sensors.

Table 2. Second Generation VLT/VLTI instruments

X-Shooter	UV-IR (2.5µm) wideband spectrograph
KMOS	0.82-2.5µm, deployable multiple IFU spectrograph
MUSE	Visible, AO assisted, large integral field (1') spectrograph
SPHERE	Visible/near IR, high contrast AO Planet Finder
AOF	Adaptive Optics Facility, deformable secondary, 4 LSGSs
MATISSE	Interferometric mid-IR imager/spectrometer
GRAVITY	Interferometric K band facility for high precision astrometry
VSI	Interferometric near IR imager/spectrometer
Ultra-stable spectro	Proposal phase

3.1 X-Shooter

Is a single target Cassegrain spectrograph being built by a Danish/Dutch/French/Italian consortium, led by ESO, and which covers an extremely wide spectral range from the UV to the K band in a single exposure. Figure 3. shows the instrument mounted on the telescope simulator at ESO in Garching. X-Shooter is designed for maximum sensitivity by splitting the light in three arms with optimized optics, coatings, dispersive elements and detectors. It operates at intermediate resolutions (R = 4000-14000, depending on wavelength and slit width) sufficient to address quantitatively a vast number of astrophysical applications while working in the background-limited S/N regime in the regions of the spectrum free from strong atmospheric emission and absorption lines. The layout and the small number of moving functions (and therefore instrument modes) make the instrument simple and easy to operate and permits a fast response. Its name is inspired by its capability for observing faint sources with an unknown flux distribution in a single shot at the sky limit. The instrument is now in its Preliminary Acceptance Europe phase and is expected to achieve first light on the VLT in the fourth quarter of 2008.

3.2 KMOS

Figure 4. provides an overview of the instrument and the UK/German consortium developing it under the leadership of Ray Sharples as PI. KMOS is a 0.82-2.5µm, near infrared, multi-object integral field spectrograph which employs 24 cryogenically cooled, deployable, pick-off arms to direct the light from the selected objects to 24 image slicers and 3

spectrographs each equipped with 2kx2k infrared arrays. One of the prime science drivers for this type of instrument is the possibility of measuring rotation curves and/or velocity dispersions and hence of estimating dynamical masses for a significantly large numbers of z~1-3 galaxies to study their mass assembly history. It will also provide the perfect complement to HAWK-I for finding and studying galaxies at z ~7.

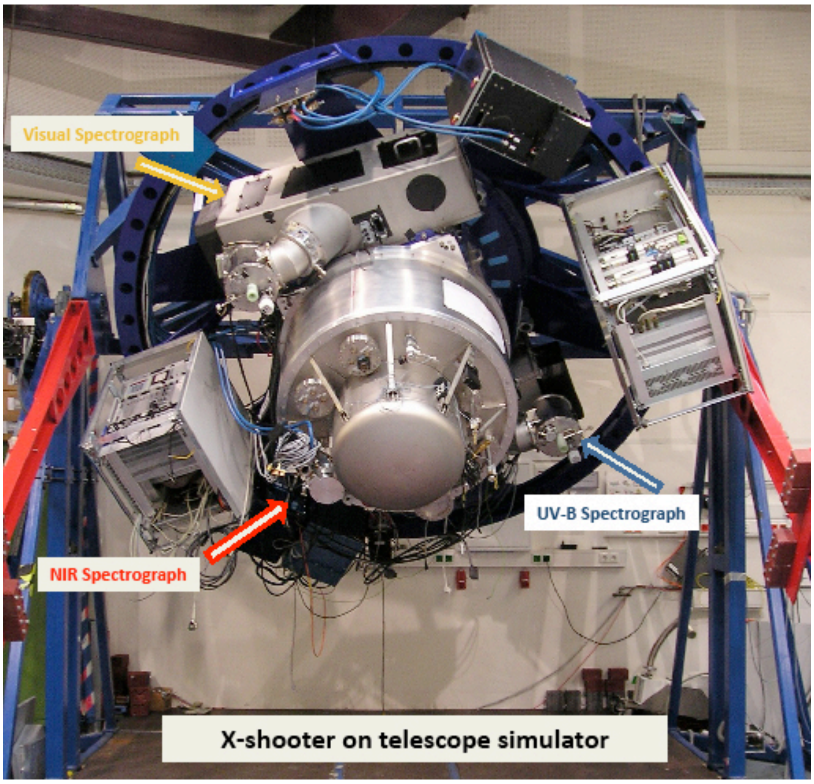


Fig. 3 X-Shooter on the telescope simulator at ESO in Garching.

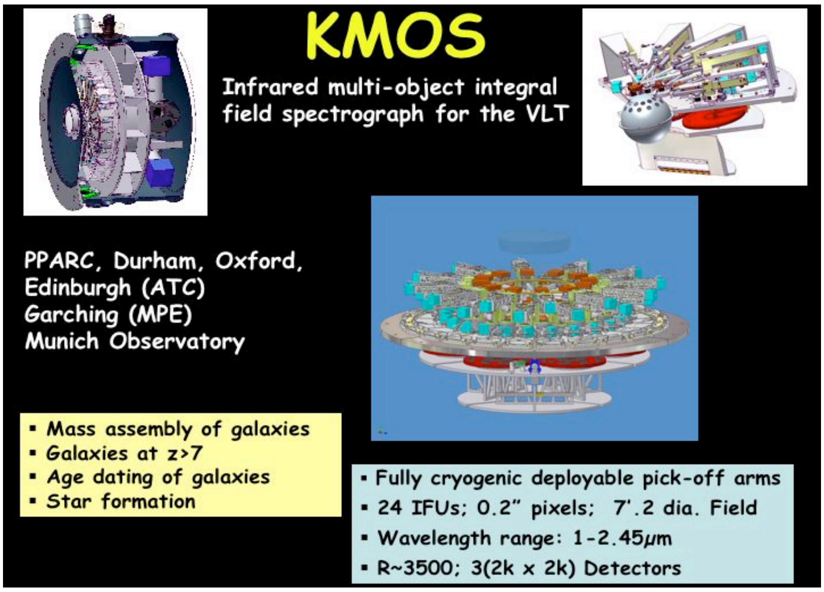


Fig. 4 The KMOS near infrared, deployable multi integral field spectrograph which employs 24 deployable, cryogenic, pick-off arms, 24 image slicers and 3 spectrographs for multi-object spectroscopy from 0.82-2.5μm.

KMOS passed its Final Design Review in May 2008 following successful tests of prototypes of key elements including a cryogenic pick - off arm and components of the image slicer optics.

3.3 MUSE

Fig. 5 provides an overview of the instrument which is being built by a consortium led by R. Bacon at CRAL, Lyon and containing Leiden, Göttingen, Potsdam, Toulouse, Zurich and ESO. MUSE employs an image slicer and 24 spectrographs to obtain optical spectra of ~ 100.000 points in a 1x1' field simultaneously. It is also proposed to be used with the AOF facility to obtain ground layer adaptive optics correction over its full field and higher order correction in a smaller (~ 7") narrow field mode. The instrument is currently in its Final Design Phase but with contracts already placed for the spectrographs and CCD detectors..

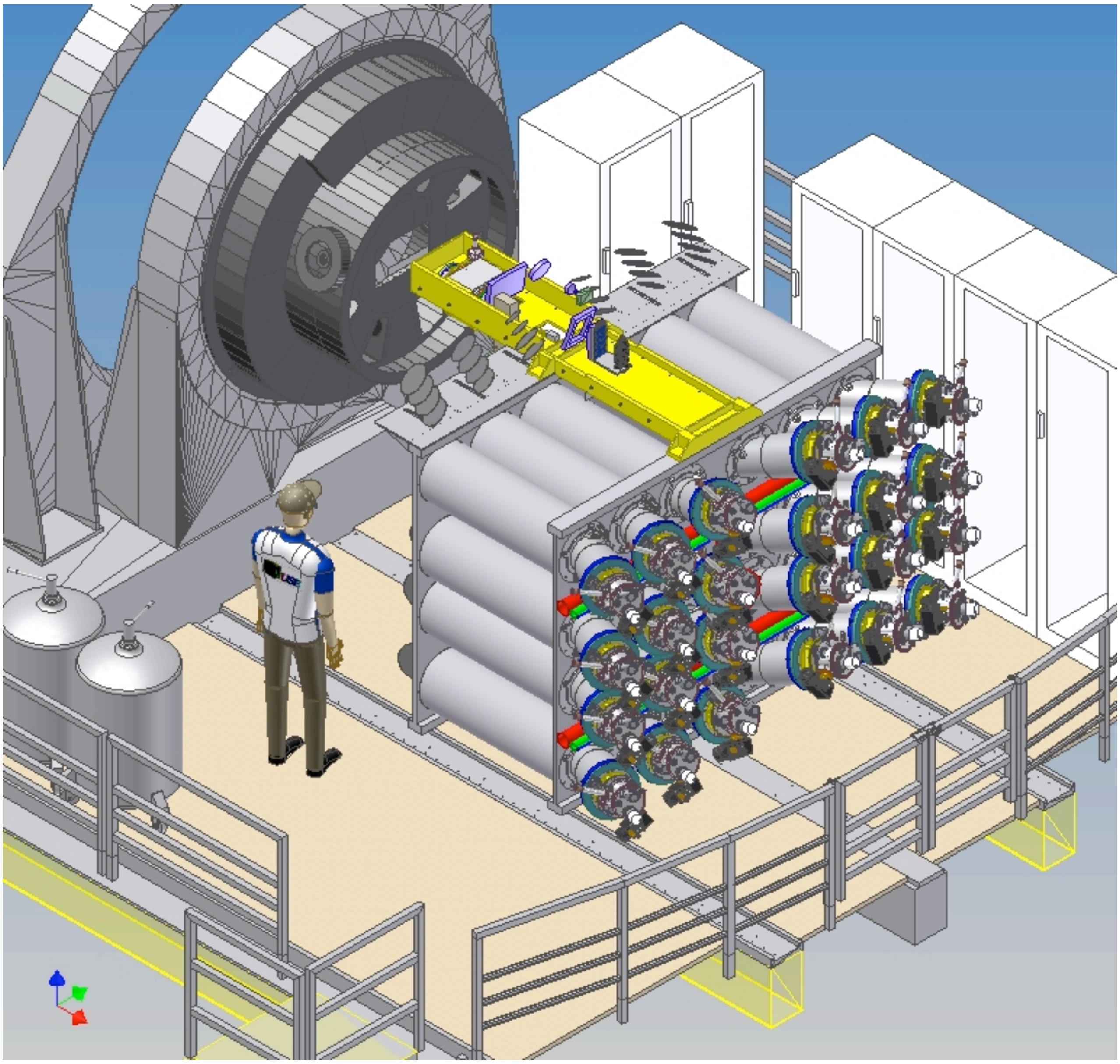


Fig. 5 The wide-field integral field spectrograph MUSE, assisted with adaptive optics and employing a large integral field unit and 24 spectrographs to simultaneously provide optical spectra at about 100.000 points in a 1x1'field.

3.4 SPHERE

Fig. 6 shows the preliminary design of the SPHERE Planet Finder instrument being developed by a consortium led by Jean-Luc Beuzit at LAOG, France and containing ASTRON, ESO, ETH, Geneva Observatory, LAM, LESIA, MPIA, ONERA, Padova, Amsterdam and Utrecht. This instrument is bench mounted at one of the Nasmyth foci and combines an extreme adaptive optics system with a variety of instruments designed to directly detect photons from extra-solar planets and to characterize their atmospheres. In order to achieve the large dynamic range required, most observations will use coronography and multiple differential techniques involving conventional or spectroscopic imaging at different wavelengths or polarimetry in the near infrared or visible.

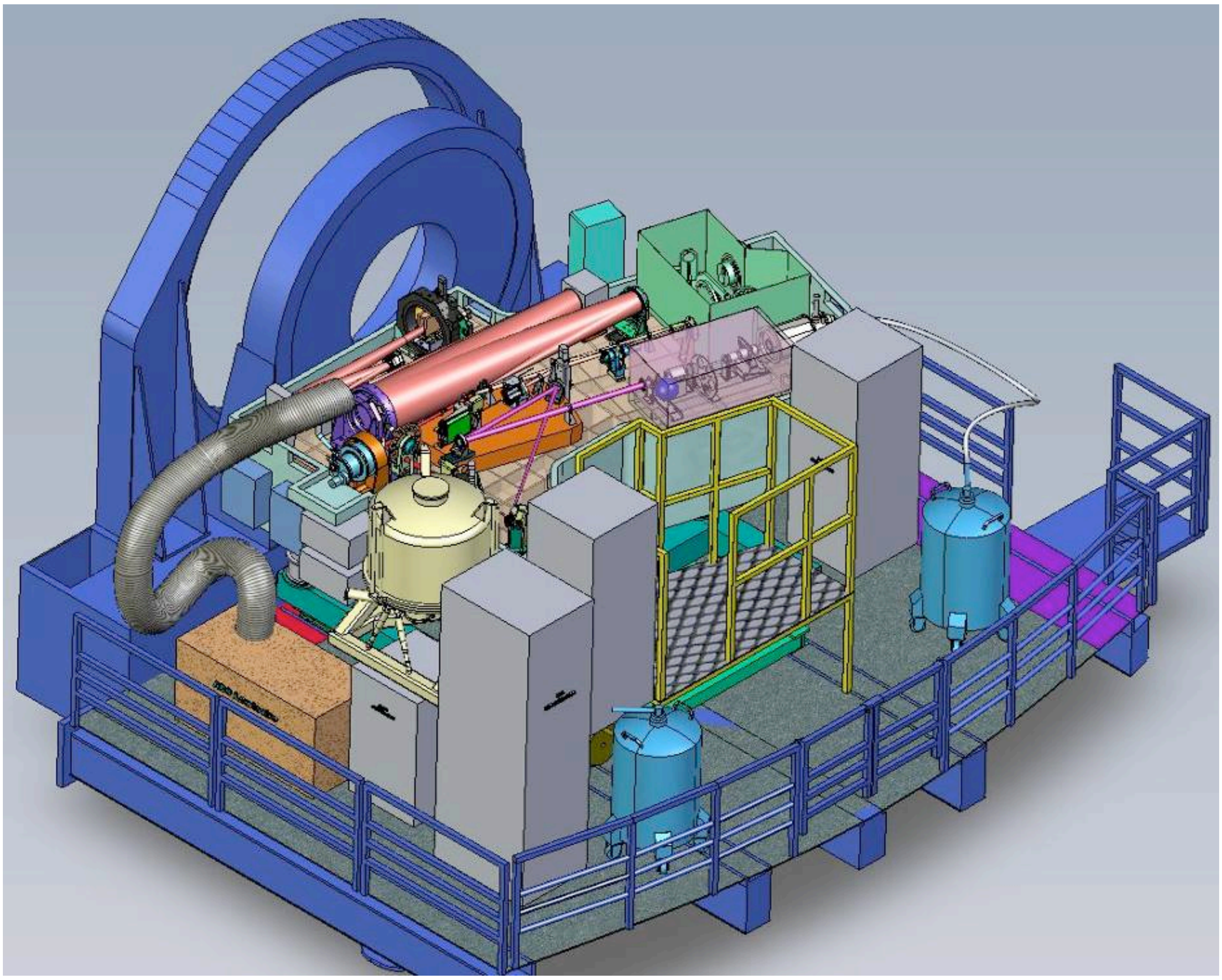


Fig. 6 The SPHERE instrument which employs extreme adaptive optics plus differential imaging and spectroscopy for the direct detection and characterization of extra-solar planets

3.5 AOF

The Adaptive Optics Facility is to be created by replacing the secondary mirror of UT4 with a deformable one, equipping the telescope with 4 sodium laser guide stars and providing wavefront sensors at the two Nasmyth foci to be occupied initially by the HAWK-I and MUSE instruments. The primary aim is to correct for the ground layer turbulence over the 7.5x7.5' field of HAWK-I in the infrared and over the 1x1' field of MUSE in the visible. It is also planned in the case of MUSE to provide a much higher Strehl ratio over a smaller 7" field.

3.6 VLTI

Following successful Phase A studies, ESO's Scientific and Technical committee has recommended that the two instruments MATISSE and GRAVITY proceed to the next design phase with high priority and VSI also be implemented on a longer timescale. Relative to the first generation MIDI and AMBER instruments improved performance is anticipated through the use of 4-6 rather than 2 beams, phase closure and fringe tracking - including on reference objects using the PRIMA facility currently being developed and which will allow the use of reference objects up to 1' from the target.

MATISSE - proposed by a consortium of French, Dutch, German and Polish institutes, led by Bruno Lopez as PI, for thermal infrared imaging and spectroscopy in the 3-10µm range. Compared with the current MIDI instrument it would offer an extended wavelength range plus the possibility combining 4 rather than 2 beams. Science topics include the circumstellar environment of young low and intermediate mass stars; massive star formation; young multiple stars; dust and winds from evolved stars; environments of hot stars; active galactic nuclei and direct exoplanet detections.

GRAVITY - proposed by a consortium of German and French institutes, led by Frank Eisenhauer at the MPE as PI, primarily for high precision astrometry in the K band using AO and phase referencing and fringe tracking on nearby objects. Science topics include the galactic centre (tests of general relativity); extragalactic nuclei; massive star clusters; stellar discs and jets; substellar objects; planets and microlensing.

VSI - proposed by a consortium of French, British, Austrian, Belgian, German, Italian and Portuguese institutes, under Fabien Malbet as PI, for near infrared imaging and spectroscopy. Compared to the current AMBER instrument it would offer the possibility of combining up to 6 rather than 3 beams. The science case is very broad and includes the formation of stars and planets; imaging of stellar surfaces; evolved stars; stellar remnants; stellar winds; active galactic nuclei and supermassive black holes. This instrument is considered particularly interesting if 2 more auxiliary telescopes could be procured to allow 6 telescope combination without mixing AT's and UT's.

One practical problem is accommodating all of these new instruments given that they are all larger than the 1st generation ones they are replacing while the interferometry laboratory has not increased in size. Fig 7 indicates it may be possible but further study is needed to ensure that the operational and maintenance requirements can still be met.

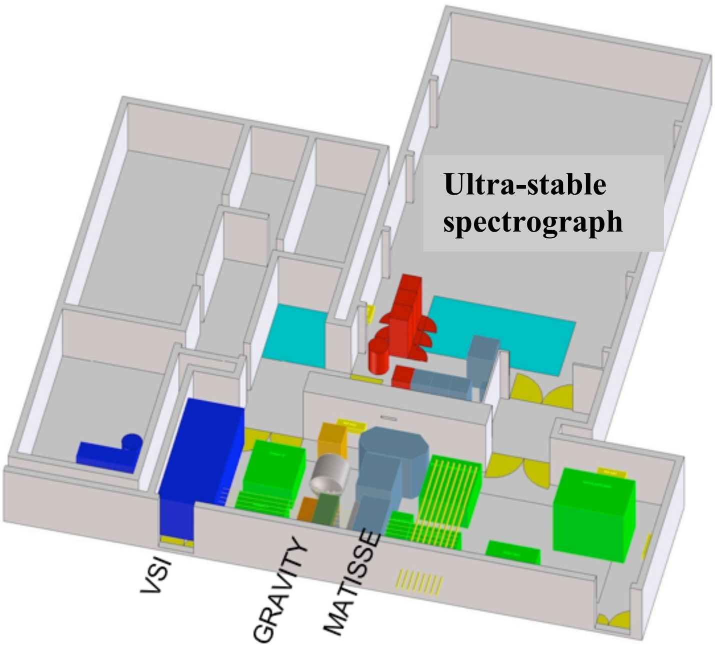


Fig 7. Possible accommodation of GRAVITY, MATISSE and VSI in the increasingly crowded interferometry laboratory at the ESO VLT together with an ultra-stable spectrograph at the incoherent combined focus.

3.7 Future Plans

ESO's long term perspectives foresee maintaining the VLT and VLTI as forefront research facilities beyond 2025 when even some of the currently planned second generation instruments will have exceeded their nominal 10 year lifetimes. In the meantime, new facilities including ALMA, JWST and, hopefully, at least one Extremely Large Telescope of the 30-40m class will also be operating. Against this background, ESO organized in Oct 2007 a Workshop 'Science with the VLT in the ELT era' as a forum for the community to discuss synergies between these facilities, possible changes in scientific usage of the VLT and specific needs for new instrumentation. One obvious conclusion was that some of the modes of the VLT will remain unique and of high scientific interest e.g the interferometric coupling of 4 8m telescopes and their, so far, unexploited incoherent combination. This feeling increased the support for approving MATISSE, GRAVITY and VSI and also for an ultra-stable, high resolution spectrograph at the incoherent combined focus for exoplanet searches and other programmes requiring high radial velocity stability down to around 10cm/s. One possible embodiment of the latter, ESPRESSO, was presented in considerable scientific and technical detail at the Workshop and has subsequently been the subject of a formal Call for Proposals which is still running. With this the current timeline for currently approved second generation instruments is as shown in Fig. 8.

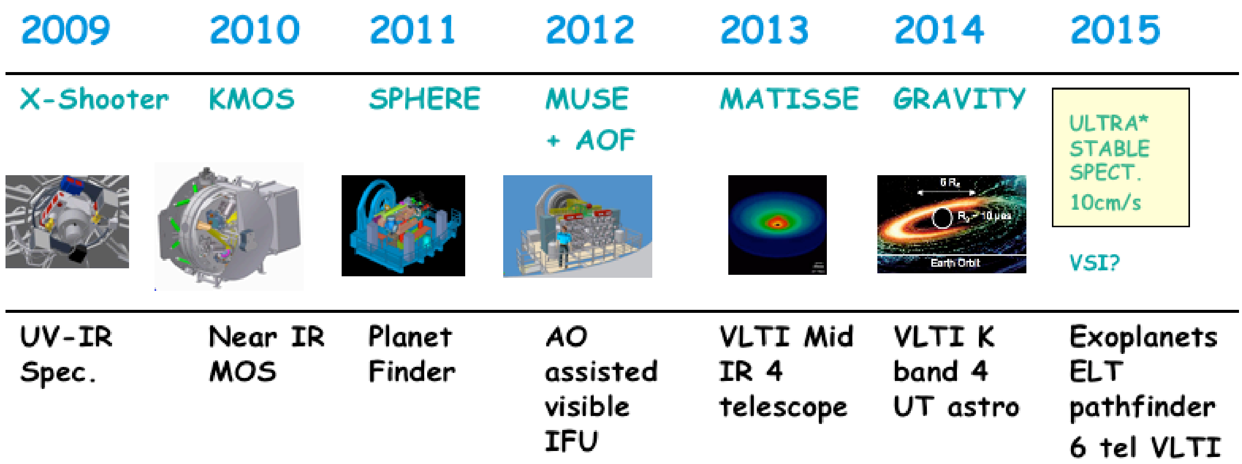


Fig 8. Currently approved VLT/I second generation instrument timeline.

Of course, the attendees also wanted everything else and, in particular, multi-object spectrographs with extremely high multiplex over fields of > 1.5 deg. which are not particularly easy on 8m class telescopes without prime focus! Nevertheless, we do still have resources available for additional upgrades and several new second generation instruments to be started in the next few years and are engaged in an on-going discussion of this and other possibilities with our Scientific and Technical advisory committee.

ACKNOWLEDGEMENTS

I am grateful to the many ESO staff in Garching and Chile as well as the external consortia who are contributing in one way or another to the instrumentation programme reviewed here. More detailed descriptions of most of these projects also appear in these Proceedings.

REFERENCES

1. A. Moorwood, *Instruments at the ESO VLT*, 2004, SPIE 5492, 13