12. Instrumentation

12.1 Technical instrumentation

According to plan. one focal station (No 6) is reserved for permanently mounted technical instrumentation. Its purpose will be to provide extensive on-sky diagnostics. It will be OWL's first instrument but its operation will in principle not be limited to the integration phase of the system.

No conceptual design of the instrument(s) has been initiated yet. The following list provides a set of preliminary requirements:

1. It shall allow for simultaneous imaging of the pupil. of the seeing-limited Point Spread Function and of the adaptively corrected Point Spread Function (correction with M6 only or with M5 and M6).
2. It shall allow simultaneous imaging of the primary and secondary mirrors.
3. The wavelength range and field of view shall be defined in the design phase.
4. It shall allow simultaneous operation of
    - 4.1. At least 7 active optics wavefront sensors;
    - 4.2. At least 6 adaptive optics wavefront sensors;
    - 4.3. At least 3 phasing cameras;
    - 4.4. At least 3 guiding probes.
5. At least 1 active optics and 1 adaptive sensors and 1 phasing camera shall be able to simultaneously use an on-axis reference (with a magnitude v=8).
6. At least 3 active optics sensors shall be able to access field positions with a field radius of 3 to 5 arc minutes.
7. Filed de-rotation shall be provided by the adapter-rotator.
8. The adapter-rotator is not required to provide on-sky metrology.

It is expected that the instrument requirements and concept will be defined after laboratory and on-sky tests with the Active Phasing Experiment (APE. see appendix A-1.2).

12.2 Science instrumentation

12.2.1 Scope of the instrument concept studies

In the iterative process to establish OWL feasibility. it is essential to develop valid concepts for a set of instruments that addresses its main scientific drivers. ESO launched in 2004 8 instrument concept studies in collaboration with several European institutes (Table 12-1). In this phase of the OWL project. the studies had the following goals:

- to support the main OWL science cases with feasible and affordable instrument concepts
- to verify and optimize the interfaces and operation scheme of the telescope
- to evaluate the scientific impact of potential sites for the Observatory
- to identify the enabling technologies and the R&D required to develop them

In the selection of the initial instrument concepts. we have been guided by the science cases identified in the OPTICON study of the science case for a generic 50-100 m ELT and by preliminary studies on the OWL scientific goals. The selected instruments offer various imaging and spectroscopic modes of observing and address different wavelength bands from the blue to sub millimeters. They are well representative of the different possible modes of operation of OWL and probe the telescope ultimate capability. The sample is however by no mean exhaustive of all possible. potentially unique observations to be done with an ELT of the OWL class. High resolution spectroscopy in the near infrared. astrometry at the diffraction limit are examples of two interesting modes not explored in this phase.

Instrument	**Wavelength range**	**Main Capability**	**Primary Science Goals**	**Institutes**
CODEX	0.4-0.7 µm	High velocity accuracy. visual spectrograph	To measure the dynamics of the Universe	ESO. INAF-Ts. Geneve Obs. IoA Cambridge
QuantEYE	0.4-0.8 µm	Photometry at 10^{-3} - 10^{-9} second resolution	Astrophysical phenomena varying at sub-msecond time scale	Padova Univ. & Lund University
HyTNIC	1.1-1.6 µm	High-contrast diffraction-limited imaging	Imaging of massive planets. bright galactic and extra-gal. sources	LISE- Collège de France
EPICS	0.6- 1.9µm	Camera-Spectrograph at diffraction limit	Imaging and spectroscopy of earth-like planets	ESO + ext. experts
MOMFIS	0.8-2.5 µm	Near IR spectroscopy using many deployable IFUs	Masses of high z galaxies. regions of star formation. GC stars	CRAL. LAM. OPM
ONIRICA	0.8-2.5 µm	NIR Imaging Camera on a field up to 3 x 3 arcmin	Faint stellar and galaxy population	INAF Arcetri & Heidelberg MPIfA
T-OWL	2.5-20 µm	Thermal. Mid Infrared Imager and Spectrograph	Search. study of planets. high redshift Hα galaxies	MPIfA Heid.. Leiden. ASTRON. ESO
SCOWL	250-450-850 µm	Imaging at sub-millimeter wavelengths	Surveys of dusty regions. of extrag. fields for star-forming galaxies	ATC

Table 12-1. Instrument Concept Studies.

These studies were not started in vacuo. CODEX owes much to the results of QSO absorption spectra studies from high quality VLT-UVES observations and to the development of the spectrograph dedicated to radial velocity studies of planets .HARPS. EPICS to the two competing feasibility studies for the VLT Planet Finder project. MOMFIS to the current development of KMOS at the VLT. Also. technological developments pertinent to e.g. EPICS & MOMFIS are currently pursued within the OPTICON FP6 program.

The scope and the content of various concept studies were defined in ad hoc Statements of Work. The study teams were asked to specify the science cases which were driving the instrument definition. to produce a first concept of the opto-mechanical layout of the instrument and to estimate its performance. They were also asked to identify whenever possible interface problems with the telescope or special requirements. to investigate the dependence on the telescope aperture and to compare the expected performance with those of the JWST and when applicable other planned space-born facilities. To support the work on the instruments ESO prepared a telescope interface document and made available on the web an Exposure Time Calculator.

The short time frame available for the completion of the OWL report (less than 1 year after the instrumentation activities were started) has constrained the choice of the groups to carry out the studies to the ones which had both the necessary expertise and the manpower to be assigned to this task in this time frame. Six of the instrument concept studies have been carried out under the responsibility of external P.I.. two were led by ESO.

The eight study reports are available as reference documents. In the next section the results of the various concept studies are presented in a synthetic form. Since the final version of the Concept Studies reports were delivered very close of after the closure of this version of the OWL study. it is possible that the information provided in the next section does not matched exactly the final content of the reports.

12.2.2 Instrument Concept Studies

12.2.3 CODEX: high resolution. ultra-stable VIS-R spectrograph

The concept study of **CODEX (COsmic Dynamics EXperiment)** summarized here was carried out jointly by scientists at ESO. the Institute of Astronomy in Cambridge. the Observatoire de Genève and the INAF-Osservatorio di Trieste. The Concept Study report is provided in RD52 and its content is summarized here.

The primary science objective- CODEX will provide the first direct dynamical measurement of the change of the global expansion rate of the Universe with time. This will allow to test whether the dark energy inferred from other (non-dynamical) cosmological measurements has the dynamical effect predicted by General Relativity.

Essential for this measurement is a significant improvement in the stability and wavelength calibration compared to current instruments and the collecting power of a 100m-class telescope. Capitalizing on the expertise of scientists and engineers at ESO and the other institutes with regard to high spectral resolution spectrographs and in particular to High Accuracy Radial velocity measurements for planetary searches (HARPS). we propose to build an array of ultra-stable high resolution spectrographs. capable of obtaining a radial velocity precision about two order of magnitudes more accurate than is achieved with the best current instruments.

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CODEX will measure the time derivative of the redshift of objects at fixed cosmological (coordinate) distance using the Ly α forest. which is related in a simple manner to the evolution of the Hubble parameter.

$$\dot{z} = (1+z)H_0 - H(t_e)\ .$$

CODEX will thus measure the change of the global expansion rate with time and will be sensitive to the accelerating effect of the postulated dark energy. CODEX will use QSO absorption spectra taken at two different epochs separated by 10 years or more along many lines of sight towards z ~1 to z ~ 4 quasars to measure the wavelength shift in the intervening Ly α forest and metallic lines due to the cosmic expansion as illustrated in Figure 12-1.

Measuring the time derivative of the redshift is challenging. Figure 12-2 shows the expected wavelength shift for a variety of cosmological parameters in cm/sec/yr. For the parameters of the concordance model the wavelength shift corresponds to ~6 cm/sec/10yrs at z = 4. It is thus necessary to achieve a velocity accuracy of around 1 cm/sec over a time span of 10 years or more. This is almost 2 orders of magnitudes better than achieved by the best current instruments. Our extensive simulations indicate that such an accuracy can be achieved for spectra with a sufficient S/N ratio. and that such S/N can be obtained with a reasonable amount of observing time on OWL. Figure 12-3 illustrates that the brightest QSO from existing catalogues will provide a sufficient number of photons to ensure the required 1 cm/sec accuracy.

Eq. 12-1

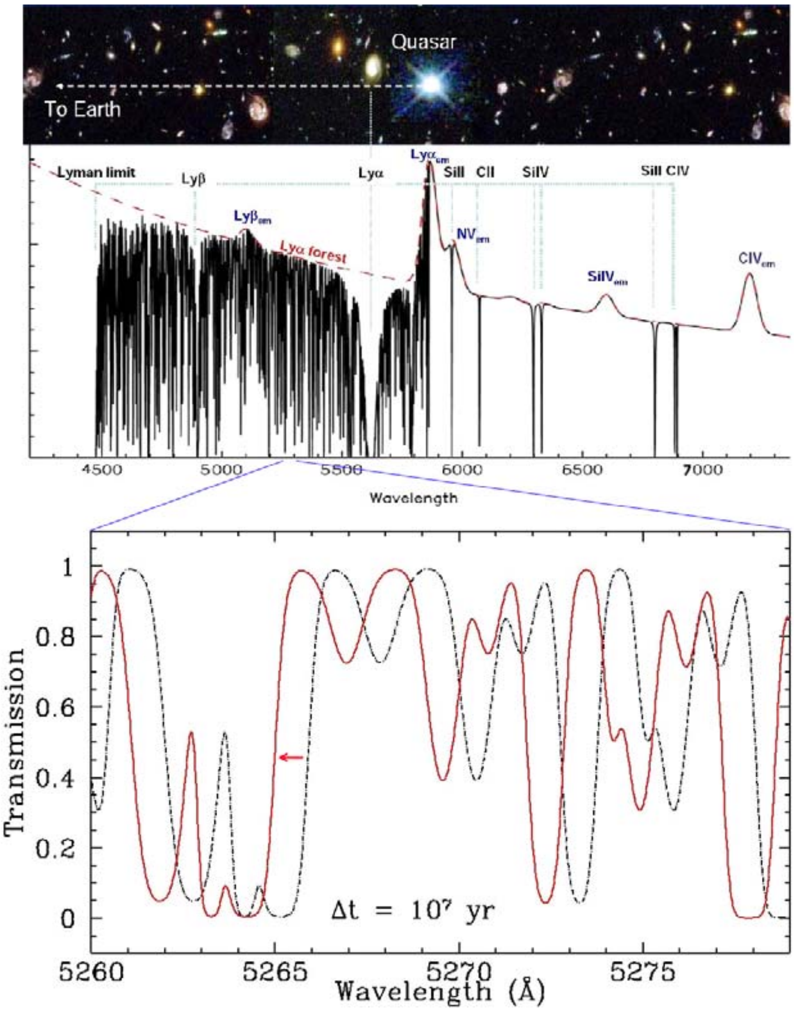

Figure 12-1. The CODEX concept. The simulation represents two observations of the Ly α forest of the same QSO taken at time T_0 (dotted line) and at time T_0+10^7 years (continuous). CODEX/OWL will measure this effect for a separation of the two epochs as short as 10 years by comparing a large sample of high S/N QSO absorption spectra obtained with OWL.

Large number of experiments are planned to further improve measurements of the cosmological parameters and in particular the contribution of the infamous dark energy to the total energy density (Ω_m. λ). These experiments are. however. predominatly geometrical in nature and assume that the Robertson-Walker-Friedman Universe based on General Relativity in 4 dimensions is the correct paradigm. CODEX does not aim (nor indeed will it initially be able) to compete with these measurements in terms of overall accuracy. CODEX will. however. be the only experiment probing the evolution of the dark energy in the red shift range z =1.5-4. which corresponds to the epoch when the largest fraction of the star formation occurred.

More importantly. CODEX will be the only experiment aiming at directly measuring the dynamical evolution of the Universe. In this way CODEX will allow us to check if the dark energy actually has the dynamical effect predicted by General Relativity.

The CODEX measurement should be considered as a fundamental physics experiment which does not make any assumption regarding the dynamical evolution of the Universe. The measurement accuracy of an experiment like CODEX will improve linearly with time. The CODEX measurement will thus be an important legacy to future generations of astronomers who will be able to use the sample of extremely well calibrated high resolution spectra of bright QSOs obtained with CODEX/OWL as a 'first epoch' measurement .

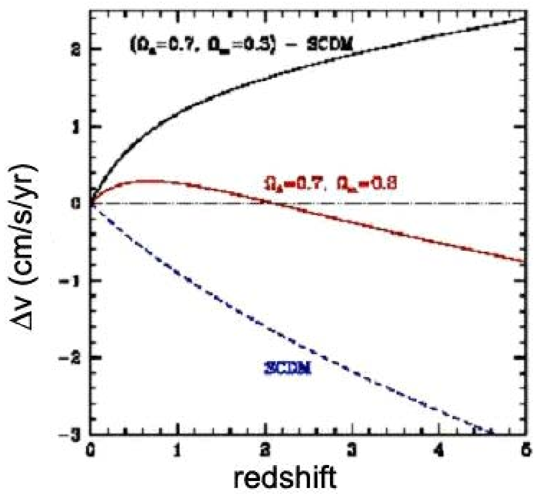

Figure 12-2. Expected wavelength shift for different cosmological models: Standard Cold Dark Matter (lower line. no cosmological constant) and Λ Cold Dark Matter (middle line) with cosmological constant = 0.7. The upper line gives the difference of the two. The signature of the non-zero cosmological constant is the change in sign of the wavelength shift.

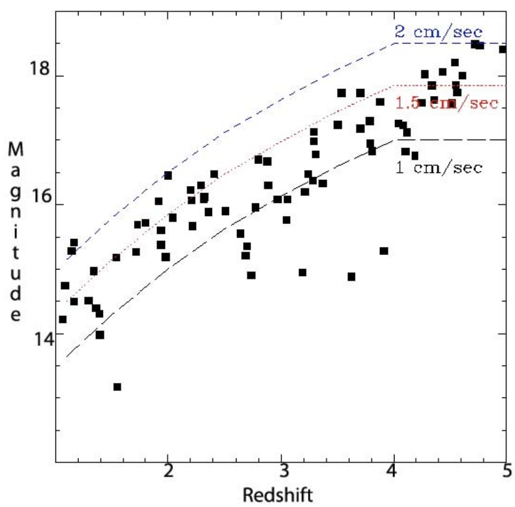

Figure 12-3. Magnitude distribution of known brightest QSO's vs. redshift. From photon statistics and simulations of measurements in the Ly α forest at different redshift one derives the "iso-accuracy" curves plotted in the diagram. The required 1 cm/s/ accuracy is obtained with all the QSO below the 'iso-accuracy' curve in 2000 hours integration (80m telescope. total efficiency 14%. S/N= 13600). In reality the required statistics will be obtained by observing with shorter integrations different QSOs (~40) distributed over the whole sky and at different redshifts.

Serendipity science and other science goals – A very high resolution spectrograph combining the large collecting power of OWL with the highest stability ever achieved by an astronomical spectrograph will have a tremendous impact on many astrophysical programs. many of which we cannot anticipate. The study report discusses three specific examples of great astrophysical relevance.

To achieve its main scientific goal. CODEX will produce a set of unprecedented high resolution (R~150000). high S/N (S/N~2000) QSO spectra. These data could be used in serendipity mode to determine the variations of the fine structure constant to a relative accuracy of 10^{-8}. comparable or better than what can be obtained in the OKLO natural reactor. at least 2 orders of magnitude more accurate than present astronomical measurements. CODEX will also be able to confirm. characterize and eventually discover earth masses planets in habitable zones around other stars. The radial velocity signal of terrestrial planets will have an amplitude of a few cm/sec/yr. but the most difficult (and time consuming) task will be to eliminate the stellar 'noise' mixed to it. CODEX will also be able to determine with exquisite accuracy the abundance of primordial elements (and their isotopes). providing the possibility of relating the physics of the first 20 minutes after Big Bang to that of ~$4x10^5$ years later: CODEX will produce Li^7 and Li^6 /Li^7 abundances for very metal poor stars in our Galaxy and our nearest companions.

The instrument concept and requirements on OWL - CODEX will be realized by building an array of super stable high resolution spectrographs (R=150000). fibre fed. and working in the 440-680 nm spectral range. The proposed concept uses five spectrographs to deliver a 0.65 arcsec entrance aperture for a 100m telescope (or a 1" aperture for a 60m telescope). The spectrographs are hosted in a stabilized laboratory outside the main telescope structure. The concept is modular and can be adapted to a variety of telescope diameters and sky apertures just by changing the number of spectrograph units (for example. a field of view of 1" on a 100m would need 11 spectrographs). In order to keep the grating size acceptable (160 x 20 cm) some novel approach (pupil slicing. anamorphic collimator and VPH) has been adopted. as shown in the optical scheme given in Figure 12-4 and detailed in the report.

CODEX requires seeing correcting active optics only. Its main requirement on the telescope is the need to be located in a thermally and gravity-stable laboratory. This most likely will have to be located outside the telescope structure. The instrument will have to be fed by fiber optics or. preferably. by a coude-type optical train which given the restricted spectral range can be very efficient.

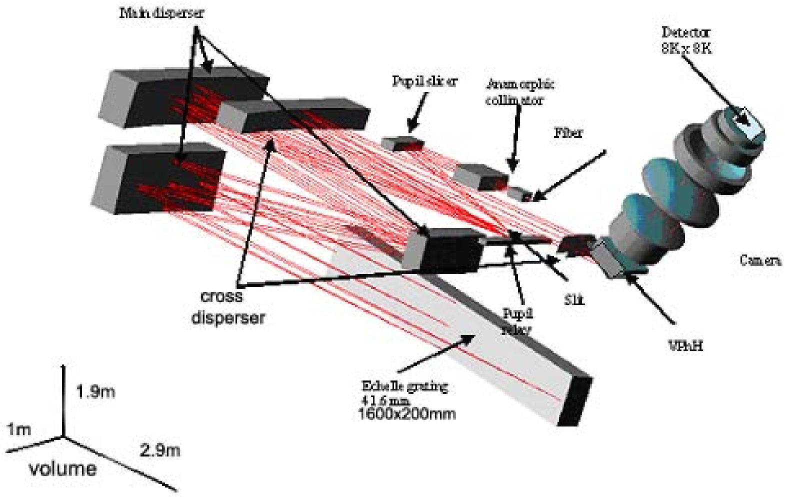

Figure 12-4. Optical Layout of one of the CODEX units. Each spectrograph is contained in a volume of ~3x2x1 meter. The 5 Units will be identical.

To achieve its outstanding long term accuracy CODEX proposes to develop a novel calibration scheme. based on laser frequency combs. which shall achieve the wavelength stability. reproducibility and accuracy typical of an atomic clock over the time scale of the experiment Some of the corrections (e.g. earth rotation. residual systematic trends) will be known only while the experiment is running for some time. and re-processing of the whole data set could be performed several times with improved data extraction and correction techniques and increasing accuracy.

The concept study shows that CODEX although demanding. is technically feasible with present technology or low-risk developments. Research and development is required in several areas (fibre feeding. detectors. calibration system). and the project will require extensive prototyping and will benefit from targeted scientific programs. such as preparatory analysis of high resolution. high S/N ratio QSO spectra and surveys increasing the number of bright QSO known.

Cost and schedule - The estimated HW cost of the whole project is in 20-30 ME depending on the telescope size and spectyrograph numbers. in addition to ~100 FTEs; a development plan within 12 years is foreseen. which includes the development of a prototype and 3 years of its operations at the VLT.

12.2.3.1 QuantEYE

The QuantEYE study was carried out at the Department of Astronomy of the University of Padova and at the Lund Observatory. P.I. of the study report were C.Barbieri and D. Dravins. The Concept Study report is provided in RD52 and its content is summarized here.

QuantEYE is conceived to be the highest time-resolution instrument in optical astronomy. It is designed to explore astrophysical variability on microsecond and nanosecond scales. reaching down to the quantum-optical limit. Expected observable phenomena include instabilities of photon-gas bubbles in accretion flows. p-mode oscillations in neutron stars and quantum-optical photon bunching in time. The precise timescales of such phenomena are variable and unknown. and studies must be made of photon-stream statistics. e.g.. power spectra or autocorrelations. Such functions increase with the square of the intensity. implying an enormously increased sensitivity at the largest telescopes. QuantEYE covers the optical spectrum and its design utilises an array of photon-counting avalanche diode detectors. each viewing one segment of the OWL entrance pupil. QuantEYE can begin operation while the OWL pupil is only partially filled and it will not require [full] adaptive optics.

The concept study starts with a review of quantum optical phenomena in general and then focuses on those of potential interest in astrophysics. After examining the current state of high-speed astrophysics. it examines the instrumental requirements for extension to higher time resolution and then presents a conceptual design for an instrument that exploits the huge advantage offered by the OWL aperture.

High-Speed Astrophysics and Quantum Optics - Numerous discoveries have been made with resolutions of milliseconds and slower: optical and X-ray pulsars; planetary-ring occultations; rotation of cometary nuclei; cataclysmic variable stars; pulsating white dwarfs; flickering high-luminosity stars; X-ray binaries; gamma-ray burst afterglows. and many others. A limit to such optical studies has been that CCD-like detectors do not readily permit frame-rates faster than 1–10 ms. while photon-counting detectors either have low efficiency or else photon-count rates limited to no more than some hundreds of kHz. Such instrumental limitations have been compounded with the lack of adequate telescope light-collecting power. For reasonable sensitivity. the required photon flux must match the time resolution: microseconds require megahertz count rates.

QuantEYE on OWL is designed for sub-nanosecond resolutions with GHz photon count-rates to match. This will enable detailed searches for phenomena such as: millisecond pulsars; variability close to black holes; surface convection on white dwarfs; acoustic spectra of non-radial oscillations in neutron stars; fine structure across neutron-star surfaces; photon-gas bubbles in accretion flows; and possible free-electron lasers in the magnetic fields around magnetars. Nanosecond-resolution photon-correlation spectroscopy will enable spectral resolutions exceeding R = 100 million (as is probably required to resolve narrow laser-line emission around sources such as Eta Carinae); and QuantEYE will have the power to examine quantum statistics of photon arrival times (Figure 12-5)

QuantEYE Conceptual Design - With QuantEYE aiming at timescales down to nanoseconds. there is the corresponding need to count photons at sustained rates up to some GHz. The requirement of a high quantum efficiency leads to single-photon counting avalanche diodes (SPAD) as the detectors of choice. although — at least at present — there appears not to exist any *single* detector that can handle such count rates. This leads us towards the concept of a multi-element — although not necessarily contiguous — detector array over which the light from the source is distributed. A further technical limit is set. at least at present. by the small physical size (of order 100 μm) of the detector elements which complicates the optical interface to large telescopes. Existing silicon-based SPAD cover the optical from 400–1000 nm. while for the near infrared (1–1.8 μm). SPAD based on germanium and similar materials are being developed in industry. Although such infrared SPAD already exist. their dark-count rates are still too high for our applications.

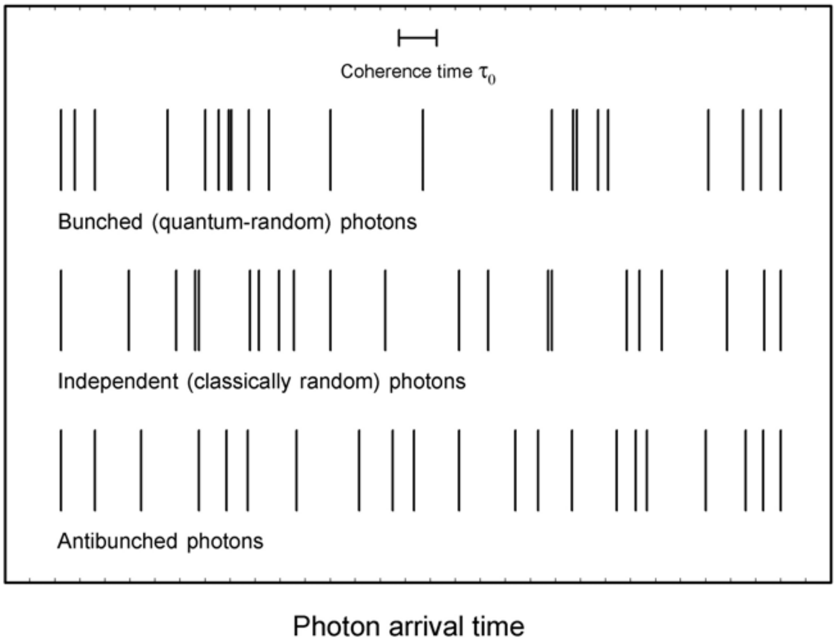

Figure 12-5. Statistics of photon arrival times in light beams with different entropies. Light may carry more information than that revealed by imaging and spectroscopy: Photons from given directions with given wavelengths give the same astronomical images and spectra. though the light may differ in statistics of photon arrival times. These can be "random". as in maximum-entropy black-body radiation (Bose-Einstein distribution with a certain "bunching" in time). or may be quite different if the radiation deviates from thermodynamic equilibrium. (Loudon: The Quantum Theory of Light. 2000).

For the first conceptual design. a "conservative" approach has been taken. shaping the system within existing detector technologies. Besides demonstrating the feasibility of concept. this means that a prototype instrument could be constructed along these lines and using commercially available components.

The optical design is for point source observations and uses pupil-slicing by optically subdividing the OWL 100m entrance pupil into one hundred 10m segments. Light from these 100 pupil segments is then focused onto an array of 100 fast (f/1) lenslets to feed an array of 100 SPAD through optical-fibers. Each detector can sustain photon-count rates of up to some 10 MHz. enabling a combined output of 1 GHz. Although. after photon detection. each detector has a deadtime of around 50 ns. the timing of each photon can be recorded with subnanosecond precision. as can the correlation between photon arrivals in different detectors. An exact differential timetag is assigned by a hydrogen maser clock (or future optical clock). and a GPS (or future *Galileo*) satellite receiver system provides an absolute time reference. thus enabling coordinated observations with other instruments on the ground or in space. A second detector unit. independently positionable over a 3 arcminute field of view. will allow calibration and reference measurements on a second source. Besides enabling GHz count rates. the segmented-pupil design has advantages in that (a) The detector redundancy enables the confirmation of possibly doubtful signals through their expected simultaneous occurrence in different channels; (b) Some events imply an illumination sweeping across the entrance pupil (e.g. occultations by Kuiper-belt asteroids). which can be both spatially and temporally resolved; and (c) By suitable cross-correlations of the detected signal. a digital intensity interferometer of the Hanbury-Brown & Twiss type can be realized between a large number of different sub-apertures. Raw data rates of 100–1000 Mb/s will be highly compressed in real time by on-line digital signal processors outputting only the appropriate statistical functions. Thanks to the pupil-slicing concept. *QuantEYE* will be able to work already with a partially filled OWL pupil. and (assuming the source is kept within the 1 arcsec aperture) will function well also without [full] adaptive optics. The present optical solution is outlined in RD53 This present design has limitations. in particular only permitting observations of one point source per detector head at a time (field-of-view is one arcsecond). Developments in avalanche-diode array technology are in progress in industry and. when their performance reaches satisfactory levels. these should enable a fully *imaging* system with nanosecond resolution. For example. such an imaging device could observe a globular cluster containing an active X-ray source of unknown location. and then search for an optically rapidly variable object over a field of perhaps a megapixel.

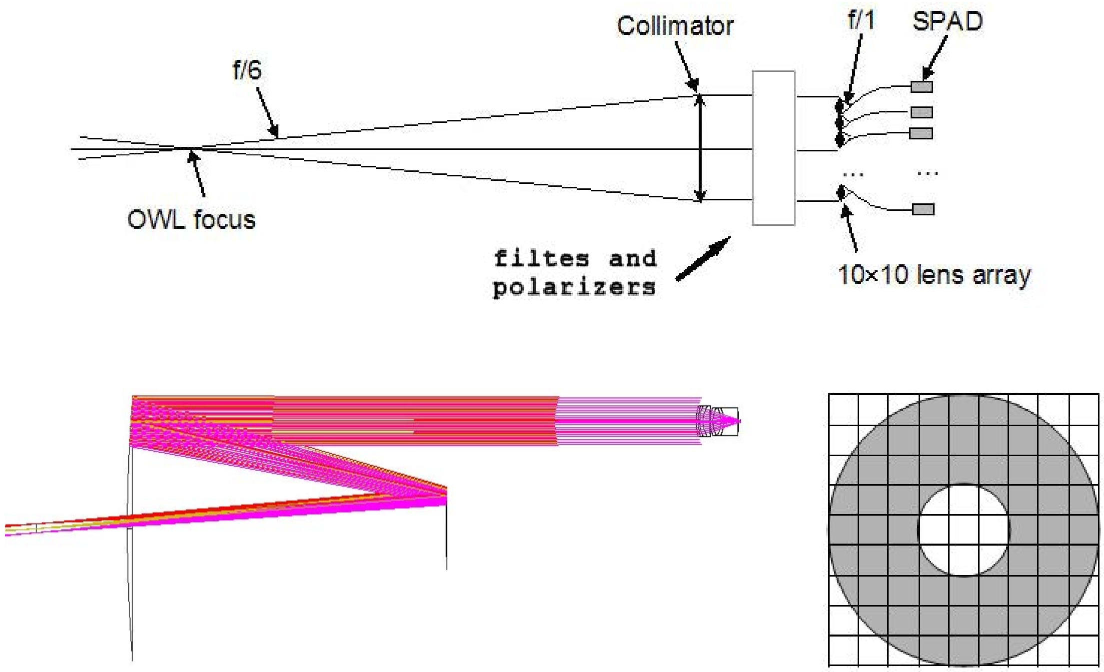

Figure 12-6 Current optical concept for a QuantEYE detector head: a distributed detector array and a segmented aperture. The collimator-lens system magnifies 1/60 times (collimator focal length = 600 mm. lens focal length = 10 mm). giving a nominal spot size of 50 μm for a 1arcsec source.

Telescope diameter	Intensity <I>	Second-order $\langle I^2 \rangle$	Fourth-order photon statistics $\langle I^4 \rangle$
3.6 m	1	1	1
8.2 m	5	27	720
4 x 8.2 m	21	430	185.000
50 m	193	37.000	1.385.000.000
100 m	770	595.000	355.000.000.000

Table 12-2. Gain in photon statistics with telescope size

The need for extremely large telescopes - The largest optical telescopes offer new opportunities for studying astrophysical variability on timescales of milli-. micro-. and nanoseconds. Since the astrophysical phenomena are normally not periodic. and their exact timescales are both unknown and variable. studies must be of photon-stream statistics. e.g.. power spectra or autocorrelations.

Table 12-2.compares the observed signal (I). its square and fourth powers. for telescopes of different size. The signal for classical quantities increases with the intensity I; the signal in power-spectra as I^2; and that of four-photon correlations as I^4. This very steep dependence makes the largest telescopes enormously more sensitive for high-speed astrophysics and quantum optics.

12.2.3.2 Hyper-telescope NIR camera

This Section outlines the results of a 4-month study by O. Lardière. V. Borkowski & Antoine Labeyrie at LISE-Collège de France Laboratory at Observatoire de Haute-Provence. The study report is a reference document (RD58).

Giving the long lead time in the fabrication and installation of the M1 mirror segments. it is tempting to optimize the filling geometry of the 100-m aperture to achieve the best high resolution imaging capability during these first years of operation with reduced collecting area. A densified-pupil mode can improve OWL sensitivity during this phase. The report discusses initially various filling configurations and their intensification gain. It advocates the use of an adaptive fringe sensor unit to co-phase all segments in the case of a non-contiguous configuration. It finally mentions a speckle interferometry mode. suitable for observing faint objects in the absence of adaptive optics or of a suitable guide star. an adaptive imaging mode with a densified array. and a coronagraphic mode for imaging extra-solar planets .

A hypertelescope (Labeyrie et al. 1996. RD58) is a multi-element imaging interferometric array having a densified pupil. It allows direct imaging with high resolution. Indeed. densifying a pupil increases the ratio of the sub-aperture diameters to their spacing. It can be done by bringing closer optically the entrance sub-apertures or by increasing their diameter. It does not degrade the image properties if the geometrical pattern formed by the centre of each mirror is preserved. In an image given by a Fizeau interferometer. the light energy is spread across secondary peaks. unlike in an image given by a hypertelescope where almost all the energy is concentrated in the central peak surrounding by very few secondary dispersed peaks.

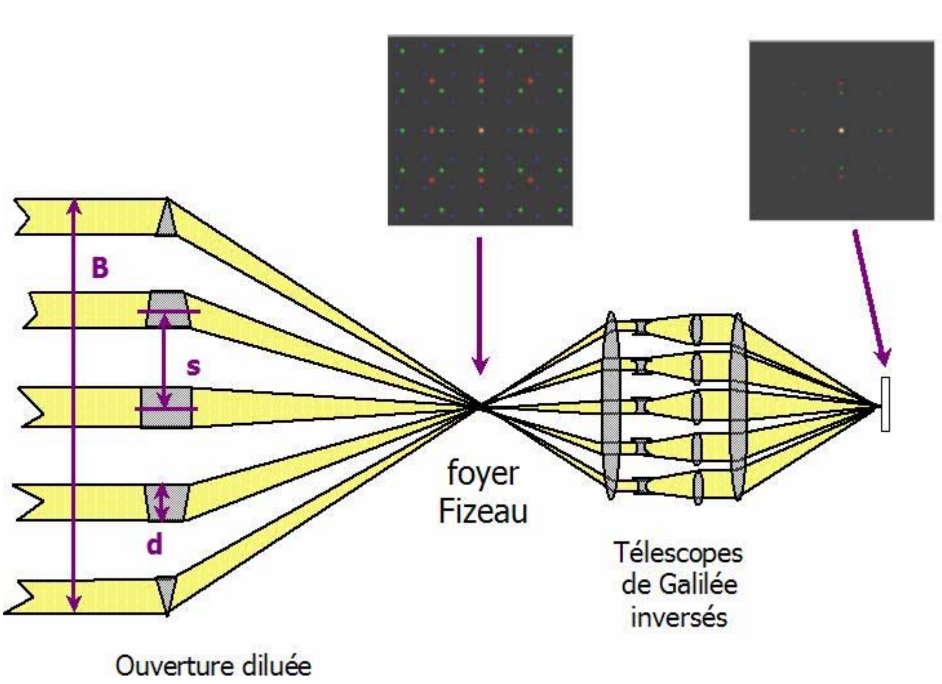

Figure 12-7 The concept of the Hypertelescope

12.2.3.3 ONIRICA: OWL NIR Imaging Camera

The study of ONIRICA was carried out by INAF Arcetri and MPIfA Heidelberg. P.I.of the study was R. Ragazzoni. The ONIRICA Concept Study report is provided in RD54 and its content is summarized here.

The large collecting area of a ground based ELT. together with its high resolving power. can provide unique observations of extremely faint objects. However. in order to reach this goal it is mandatory that the telescope be able to deliver nearly diffraction limit images. It is only under this condition that an ELT can gain significantly with respect to smaller aperture ground-based or space-born telescopes due to the increased contrast of sources with respect to the underlying background dominated by the sky emission.

This consideration led to a concept of a AO-aided NIR imaging camera that is working at (or very close to) the diffraction limit condition over a field where MCAO (Multi Coniugate Adaptive Optics) can achieve a competive concentration of light in the diffraction-limited central peak. This will be possible with AO with optimal seeing during 10 -30 percentile of the night time only. depending on the choice of the site. and with limitations on the sky coverage.

Science cases

Science cases based on deep imaging of faint point-like and extended objects with a 50-100 m telescope have been discussed extensively in the “Science Book”. Within the ONIRICA concept study. a few specific cases have been explored in more detail taking into account the proposed characteristics of the instrument and the results of simulations.

As an example. we recall here the study of the stellar population of massive elliptical galaxies performed through the analysis of color-magnitude diagrams (CMDs). These galaxies are noticeable absent in the Galaxy neibourhood but their old stellar population hold the key to understand galaxy formation in the early phases of the Universe. By the simple counting of stars of different ages in the CMD the rate at which stars where formed can be directly obtained. While the classical studies carried out so far were centered mainly in the B. V . I bands. more recent investigations are focussed on the NIR bands. where ONIRICA will operate. Theoretical isocrones from the Padova database for stars of solar metallicity are showm in the C-M diagram in Figure 12-8. The boxes superimposed on the CMD have been chosen so as to sample different age ranges. Specifically: the bright cyan box samples the youngest stars. in the core Helium burning phase; the blue box is populated with older core Helium burners; the orange box samples bright. intermediate age AGB (asymptotic giant branch) stars; and the red box targets the upper two magnitudes on the Red Giant Branch (RGB). populated with stars with ages from 2 Gyr up to the oldest ages. The detection limits for a star of m_K = 30 in Coma (m-M= 35.3). Fornax (m-M= 31.6) and Virgo (m-M= 30.9) are also marked

Using the stellar counts in the various regions one can sketch the average star formation (SF) history in a galaxy. or a portion of it. More sophisticated computations of synthetic CMDs can be used to test the SF modalities like bursting or costant SF rates. the initial mass function (IMF) slope and the effect of metallicity.

With the current instrumentation and telescopes these studies are feasible in galaxies up to a distance of 4-5 Mpc (distance modulus ~ 28). With a 100m class telescope it would make them feasible for objects up to 100 Mpc. thus allowing us to reach the members of the nearest rich clusters of galaxies and to derive the SF history of galaxies of all morphological types. including giant ellipticals. which are noticeably absent in the very nearby volume of the Universe.

At 100 Mpc. a field of view of 30” across corresponds to a diameter of ~15 kpc. comparable to a significant section of a massive galaxy. It would then be possible to derive the CMD of a substantial portion of one galaxy with two deep frames (one per photometric band) taken at time of best seeing.

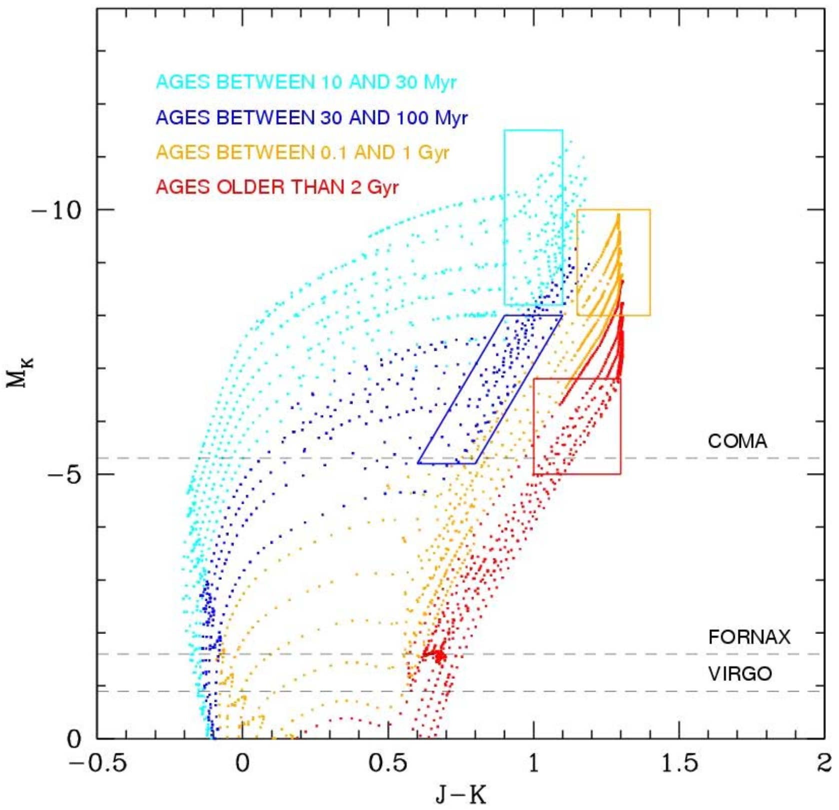

Figure 12-8: NIR C-M diagram from therotical isocrones by Girardi wt al. (2002. A&A 391.195)

Instrument Requirement and Limiting Magnitude

To surpass the performance of smaller ground-based or space-born telescopes. a camera is required which operates at diffraction limit over a relatively large (for AO–aided systems) field. The two cases of MCAO and GLAO are discussed at length in the report RD54 . The goal of the diffraction limited PSF over a field of 30" could be achieved with MCAO operating with two deformable mirrors and in conditions of optimal seeing. The predicted PSF is shown in Figure 12-9. Assuming this PSF and standard instrument properties the performance in limiting magnitude of ONIRICA has been studied for different telescope diameters (TMT = 30m. SMT = 60m and OWL = 100m) and compared also to JWST performance (Figure 12-10 and Figure 12-11. Table 12-3 and Table 12-4). There is a clear advantage with respect to JWST for imaging of point sources. These predictions have been supported by photometric measurements on simulated images based on a stellar population set at the distance of the Coma cluster with the predicted PSF of OWL.

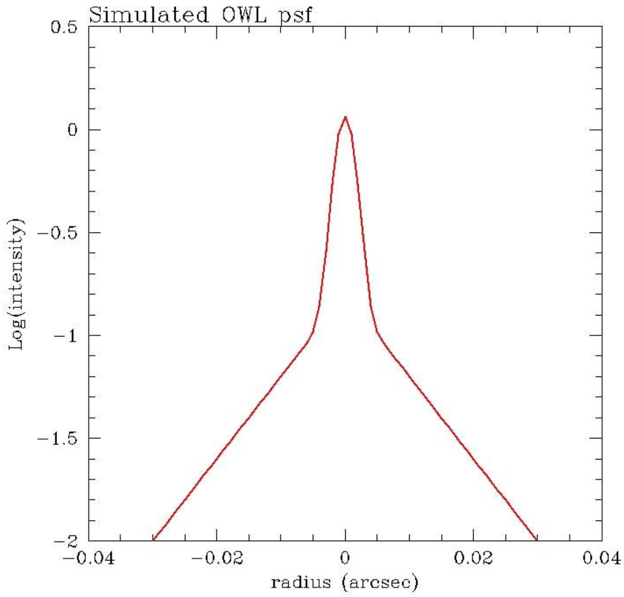

Figure 12-9 The PSF radial intensity distribution as derived from MCAO assessment for the central field of ONIRICA at OWL and used in the simulation of photometry in crowded stellar fields

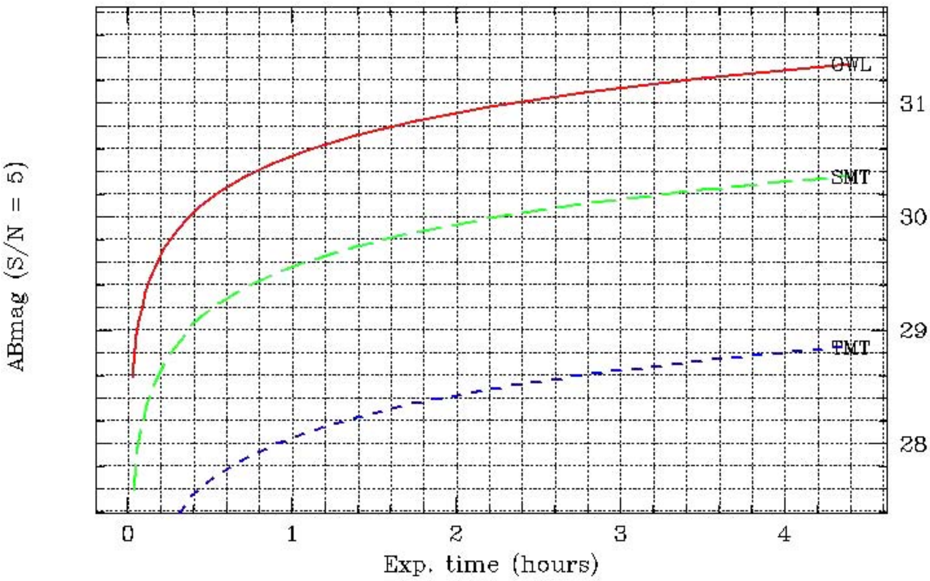

Figure 12-10 The limiting (S/N=5) magnitude $K_{(AB)}$ for point sources as a function of the exposure time

The same efficiencies are assumed for the three telescope diameters.

Telescope	**Diameter M1 (m)**	**Mag lim (1 hour. S/N=5)**
OWL	100	30.5
SMT	60	29.5
TMT	30	28.0

Table 12-3 Magnitude limits for point sources at 100m. 60m and 30m

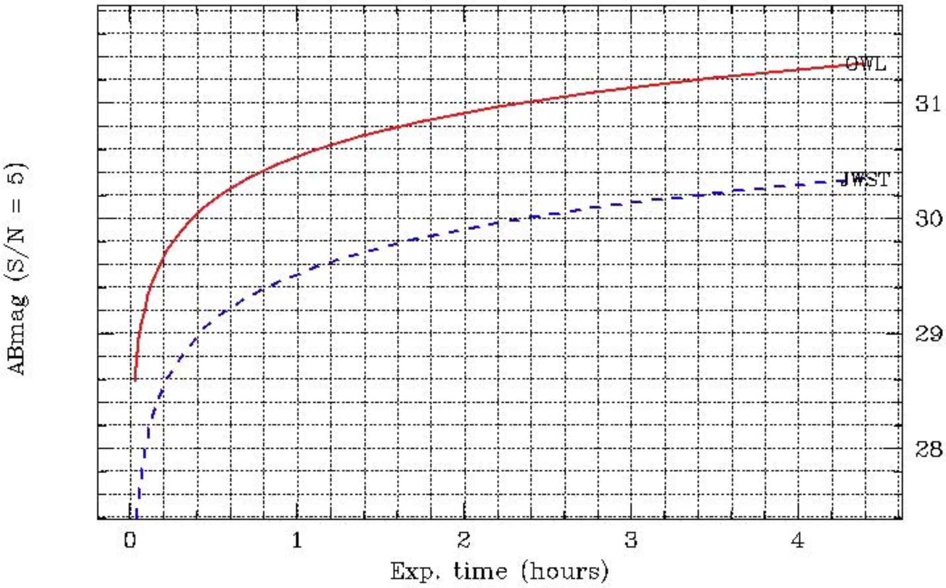

Figure 12-11 The limiting (S/N=5) magnitude K(AB) for point sources as a function of the exposure time for OWL and the JWST (assuming same instrument and detector performance)

Telescope	**Diameter M1 (m)**	**Mag lim (1 hour. S/N=5)**
OWL	100	30.5
JWST	6	29.5

Table 12-4 Magnitude limits (S/N=5) for 1 hour integration time for OWL and JWST

Optical design

The proposed ONIRICA optical concept. shown in Figure 12-12. couples a center field camera of 30”-60” diameter capable of delivering diffraction limited images with possibly a piggy-back one where preference is given to a larger field at a 10-20 times lower resolution. With this larger pixel scale in the sky the camera is less performing than the JWST. but it remains interesting e.g. for the observations of high z galaxies which have typical half intensity radii of 0.1 arcsec. with substructures at 1/10 this size.

Narrow field channel

The narrow field channel has a maximum 1 arcmin diameter centered on the optical axis This channel enlarges the diffraction limited images provided by a MCAO correcting system to obtain a correct sampling of the diffraction-limited PSF and splits the field over several subchannels in order to keep optics and detector array size small. Figure 12-13 shows the concept of two level splitting feeding 16 large IR detectors. The OWL focal plane (F/6) is doubled in size by an optical relay optimized for wavelengths between 1.0µm and 2.35µm and then split by a pyramidal mirror. The optical relay has an intermediate pupil image for placing a cold stop to reduce telescope emissivity. For each arm a second optical relay doubles (downsized copy of the previous one) again the FoV size and a second pyramidal mirror splits again the portions of the FoV which are then imaged on independent IR detectors with the proper sampling (at F/24 is 11.635mm/arcsec).

In the case of a 30” FoV and three level splitting (16 arms) each arm images 7.5 × 7.5 arcsec and requires a mosaic of 2 × 2 IR detectors of 4k×4k pixels of 18µm size for Nyquist sampling of the diffraction limited PSF in the J band.

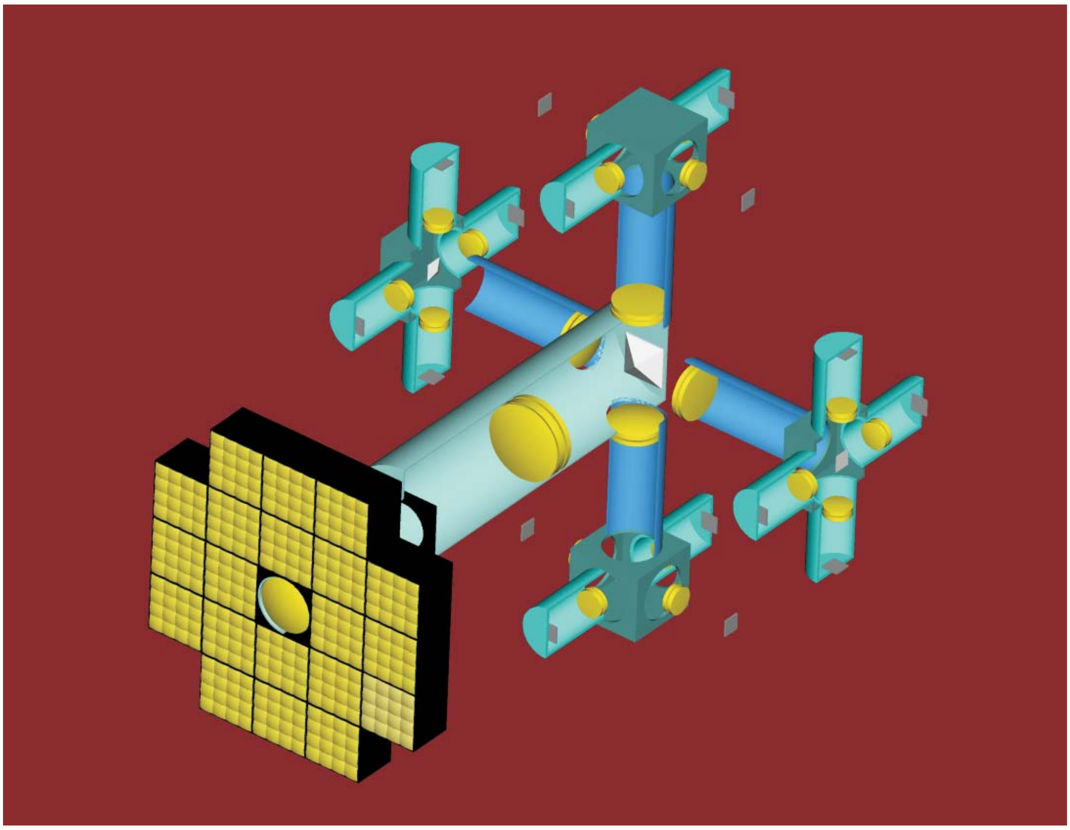

Figure 12-12 Optical layout of ONIRICA (central field)

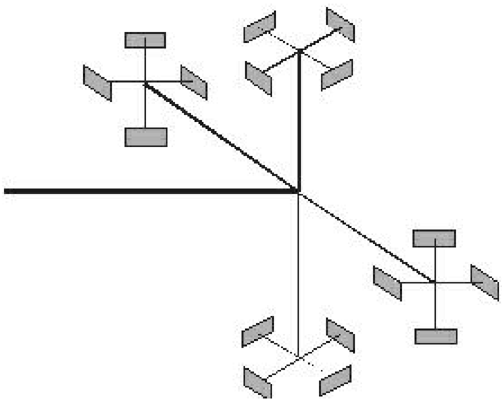

Figure 12-13: Concept of the channel splitting in ONIRICA. The FoV splitting is provided by a pyramidal mirror located at the intermediate focal planes.

Wide field channel

The wide field channel is surrounding the narrow field one and has a FoV of 3-6 arcmin (Figure 12-12).More extended simulations of the performance of this wide FoV channel with GLAO correction and of its scientific justification will be needed to fully define its scope and in particulat to optimize its pixel scale.

The channel refocuses partially GLAO corrected images with a coarser spatial sampling and it is based on a concept known as a Smart Fast Camera (SFC). It is essentially a focal reducer with a relatively large plate scale. with the FoV split in smaller portions. each imaged by a lenslet array on a dedicated detector.

The array of lenslets of the dimension of about 15arcsec to 1 arcmin. In the pupil plane an array of aberration correctors is placed in order to correct the approximately constant aberrations in the FoV of each lenslet system. At the end an array of camera lenses produces an array of images detected by the scientific arrays. with the requested plate scale (Figure 12-14 and Figure 12-15). Different focal ratios can be considered depending on the sampling needed: for example a sampling of 15mas/pixel is obtained with F/2.5 lenslet and a FoV patch of 1×1 arcmin is covered by 1 IR detector of 4k×4k pixels of 18µm size.

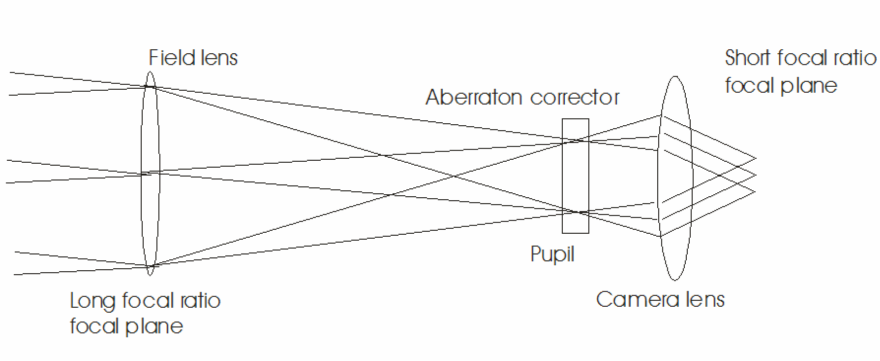

Figure 12-14: Sketch of a single unit of a Smart Fast Camera

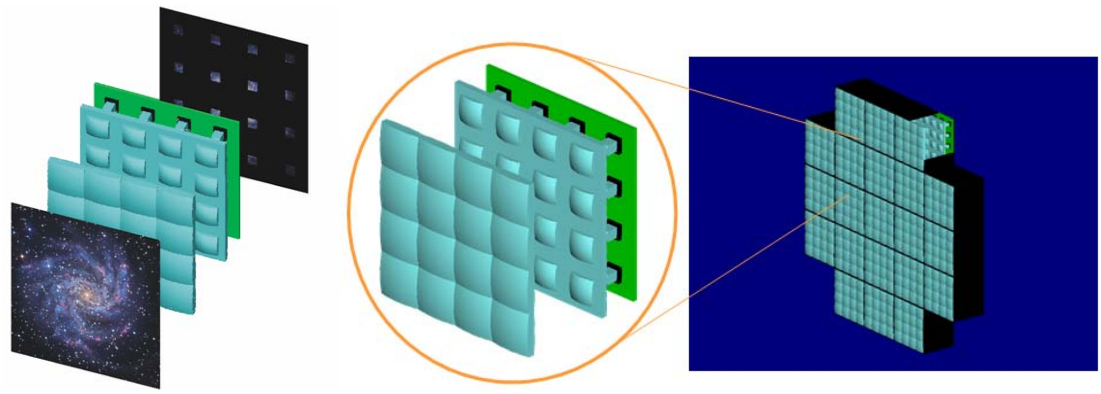

Figure 12-15: The picture on the left illustrates the SFC concept in which the light of a wide FoV is divided by a lenslet array.

Mechanical design

In Figure 12-16 is shown the opto-mechanical concept of ONIRICA. The whole instrument has a small size with respect to the typical size of other 100m class instruments. The SFC incorporates on its entrance side the flange for the rotator adapter. A system of tubular trusses is designed to give stiffness to the optical tubes. Figure 12-17 shows the accommodation of ONIRICA within the allowed volume for the OWL instrumentation.

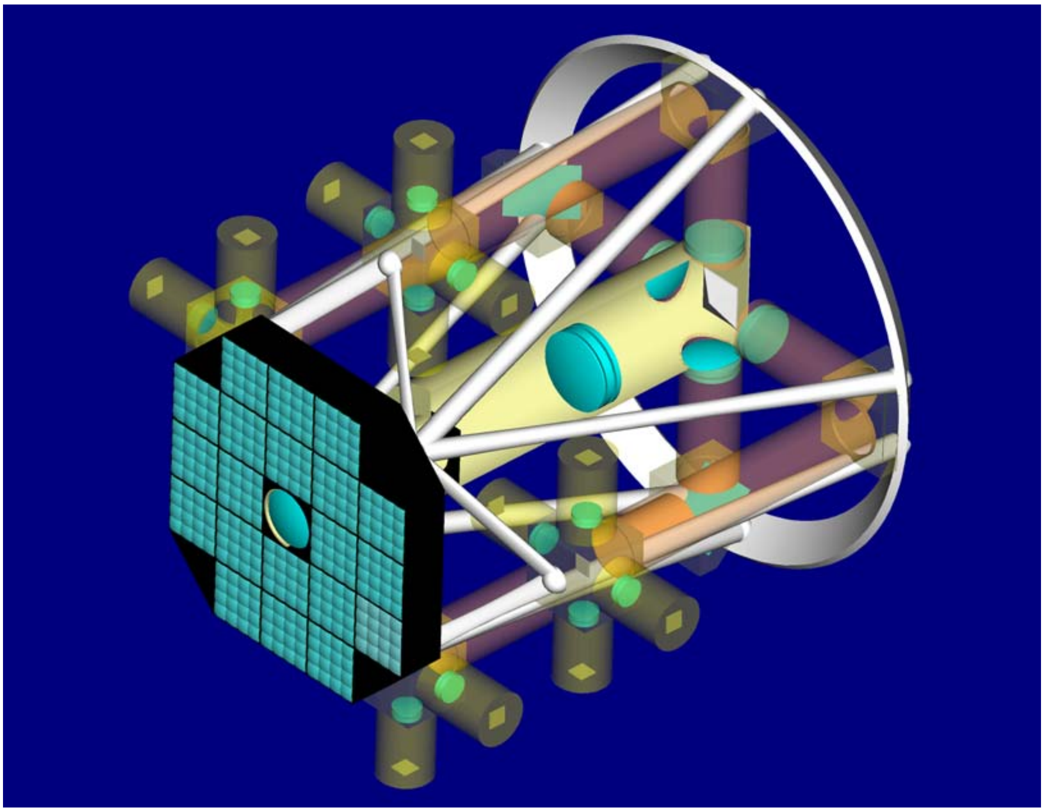

Figure 12-16: Opto-mechanical layout of ONIRICA including the two. wide and narrow. channels. The tubular trusses have the function to stiff the cryogenic tubes.

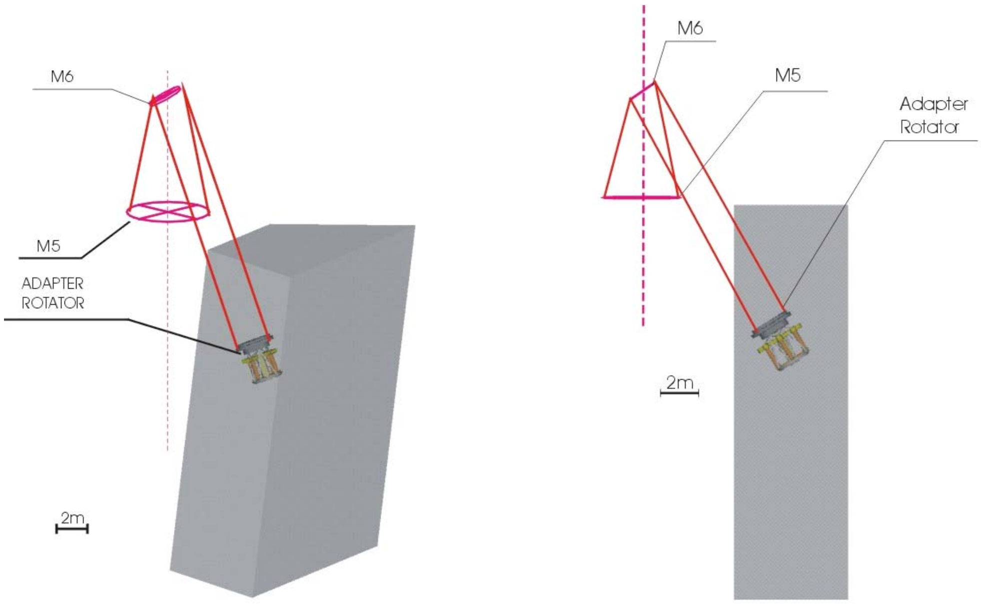

Figure 12-17 Two views of the instrument envelope in the instrument bay .

12.2.3.4 MOMFIS: Multi Object. Multi Field Near –IR Spectrograph

The study of MOMFIS was carried out by a consortium of LAM. CNRS/CRA Lyon. CNRS/GEPI . CNRS/LESIA and ONERA in France. J.G. Cuby was the P.I. The Concept Study report is provided in RD55 and its content is summarized here.

Scientific objective - A highlight science case of all the future large telescope projects is entitled: 'The End of the Dark Ages: First Light and Reionization'. After the recombination epoch. space was filled with dark matter. energy and neutral gas. As it continued to expand. regions of higher density stopped following the expansion. turned around and collapsed into the sites where the first objects formed. Primordial objects are thought to be primordial galaxies powered by young massive stars and early quasars accreting matter around growing black holes. As they lit up. they modified the gas between them. ionizing the hydrogen and making it transparent to ultraviolet light. In effect. the Universe underwent another phase transition. from a neutral to an ionized state. MOMFIS is designed for this highlight science case. it aims at pushing back as early as possible into the Dark Ages to observe and characterize these sources that once re-ionized the Universe.

Requirement specifications - The high-level science requirement specifications for MOMFIS on OWL were set as follows:

- Simultaneous observation of several targets over the OWL science field of view
- Spatially resolved spectroscopy of individual targets (integral field)
- Image quality: 50 milliarcseconds or better. This requires local adaptive optics correction
- A spectral resolution in the range 4000-8000 for OH suppression

The MOMFIS acronym is derived from these high level specifications: Multi-Object Multi-Field Infrared Spectrograph.

Sub-systems

MOMFIS provides for 30 independent channels. each channel consisting of the following sub-systems:

- A target selection system consisting of pick-off and beam steering mirrors which direct the science beams from the telescope focal plane to the deformable mirrors
- A deformable mirror correcting the atmospheric perturbations in the direction of the target
- An image slicer dividing individual fields of view into 40 slices 20 milliarcsecond wide
- A spectrograph providing one spectral band (Y. J. H or K) at once at a spectral resolution of ~ 4000.
- A 2k x 2k IR array.

In addition. the instrument is equipped with wavefront sensors which sample the atmosphere over the whole instrument field of view.

Conceptual design and performance - In total. the instrument features 30 fully identical beams and 10 cryostats with 3 spectrographs per cryostat. The instrument is modular. highly redundant. and designed for easy preventive or corrective maintenance. The principle of operation and overall design is shown in Figure 12-18. Figure 12-19. and Figure 12-20. As shown on the left side of Figure 12-18. pick-off mirrors are positioned and oriented in the telescope focal plane prior to the exposure to collect and rely the light of the distributed targets. They send the light to movable steering mirrors which in turn send the light to the fixed deformable mirrors and instrument (image slicers and spectrographs). On the right side of Figure 12-18 is the conceptual optical implementation showing the beam steering mirrors (BSM). the deformable mirrors (DM). the wavefront sensors (square boxes at top) and for each channel at the bottom the atmospheric dispersion compensators. the filter wheels. the slicer and spectrograph optics. The overall height of the instrument as shown is 3.5 m.

MOMFIS allows to observe 30 targets in integral field mode at once in the 5' (diameter) OWL scientific field of view down to IR AB magnitudes of ~ 28. This ideally meets the science high level specifications.

Interface with telescope - MOMFIS is big. As designed. it fits in the OWL instrument focal station. however exceeding the allowed mass budget within limits which are considered acceptable at this level of conceptual design. The main interface issue is with the telescope adapter / rotator which has a limited weight limit. To overcome this MOMFIS provides its own adapter / rotator replacing the telescope one. as well as wavefront sensors that can (and need to) be used by the telescope in place of the original ones.

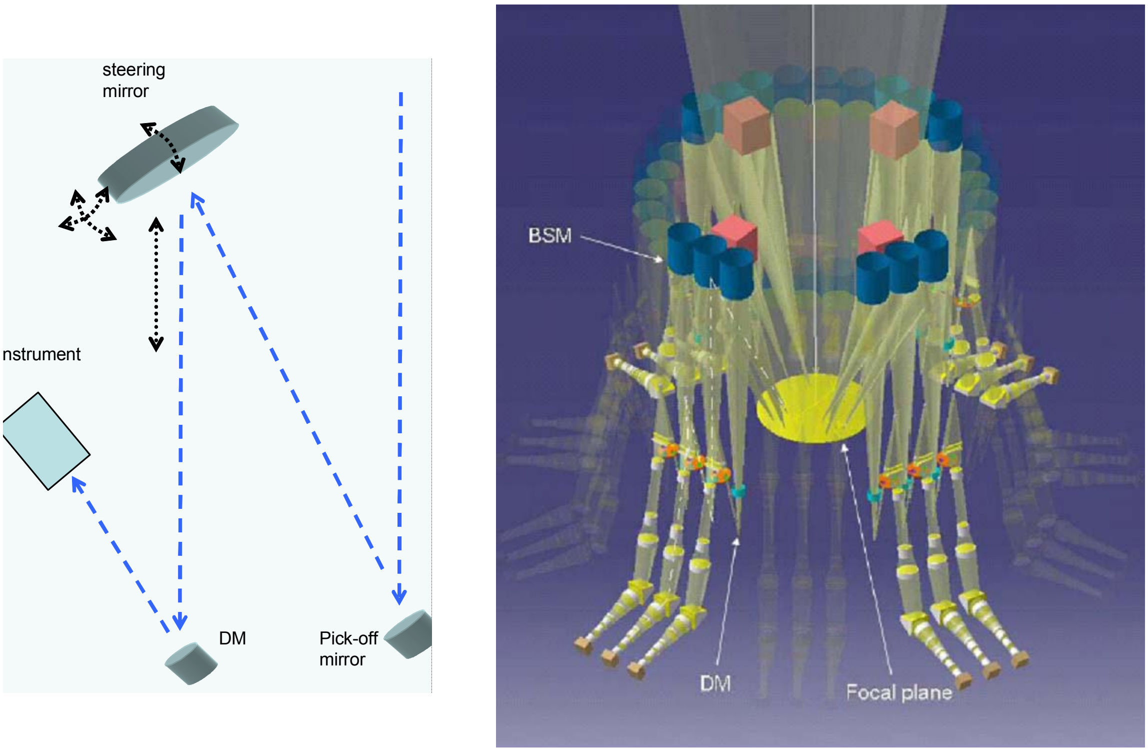

Figure 12-18 MOMFIS conceptual optical layout (see text).

Technological developments and roadmap - The entire instrument concept relies on existing and well demonstrated technologies. but for 2 items which will require specific developments and roadmaps:

- multi-object adaptive optics (MOAO). MOAO is at the core of the MOMFIS operation. it requires several wavefront sensors sampling the atmospheric wavefront over the telescope and one deformable mirror per channel (assuming telescope provides ground layer correction). The MOAO concept has never been implemented and needs further studies and laboratory and / or on-sky prototyping to be demonstrated and validated. Laser guide stars are a must for full sky coverage.
- Internal metrology. Internal metrology and control of the main optical elements is required in the instrument to compensate for flexures (the focal station is not gravity stable) that cannot all be absorbed by the stiffness of the structure. This internal metrology will also be used for alignment. calibration and operation purposes.

Options - At this stage. several options to the baseline instrument described above can be contemplated:

- 1st phase and / or fallback solution without adaptive optics. In a first implementation phase. MOMFIS could be deployed without the deformable mirrors which can be replaced by flat mirrors. or low order deformable mirrors. Wavefront sensors would still be required for telescope control. Exquisite image quality could still be obtained in the central field of view (1 to 2 arcmin multi-conjugated adaptive optics field). gently degrading towards the outer edge of the OWL field of view (ground layer correction only). More than just a 1st light option. this option is actually also a fallback option in case MOAO developments fail or prove to be more difficult than expected to implement

- A second option is to resort to partial cryogenic cooling combined with moderate cooling (-40°C or so) of the whole instrument. This option allows to simplify the cryogenics and mechanics of the instrument. albeit at the expense of the performance in the K band.
- Other possible options are: smaller individual fields of view allowing to pack 2 target beams in one spectrograph. hence allowing to reduce by a factor 2 the number of spectographs and cryostats. An alternative option would be to use 1k x 1k detectors with twice as small (in area) individual fields of view and to combine with spectral dithering. A third to reduce the multiplex gain. All these options would give large savings in size. weight and cost at the expense of reduced scientific efficiency (but without affecting its limiting magnitude).

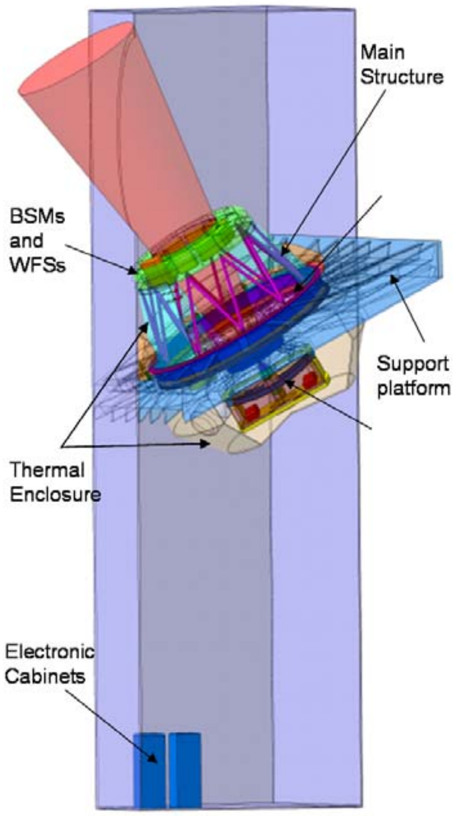

Figure 12-19. Overall MOMFIS implementation in the focal station.

Alternative designs - Alternative designs to MOMFIS have been considered. They could take the form of traditional multi-slit spectrographs (MOS). or fiber-fed spectrographs still requiring the pick-off and adaptive optics stages. Designs for these alternative designs are presented in the report. The MOS instrument could serve as an OWL first light instrument that could be used for commissioning and initial science.

Operation with a “growing” telescope - Both the MOMFIS baseline concept and the alternative multi-slit (MOS) concept could be used in the ‘growing telescope’ phase. under the condition that the telescope pupil is grown in an annular shape.

Development effort - MOMFIS is a complex instrument. Its development and integration will require a broad range of expertise and facilities across Europe. The hardware cost is estimated to be in the range 20-40 M€. depending on the selected options. and the required manpower (at institutes) in the range 150-250 person-years. The instrument development requires 10 years. including a few years of continuing R&D activities.

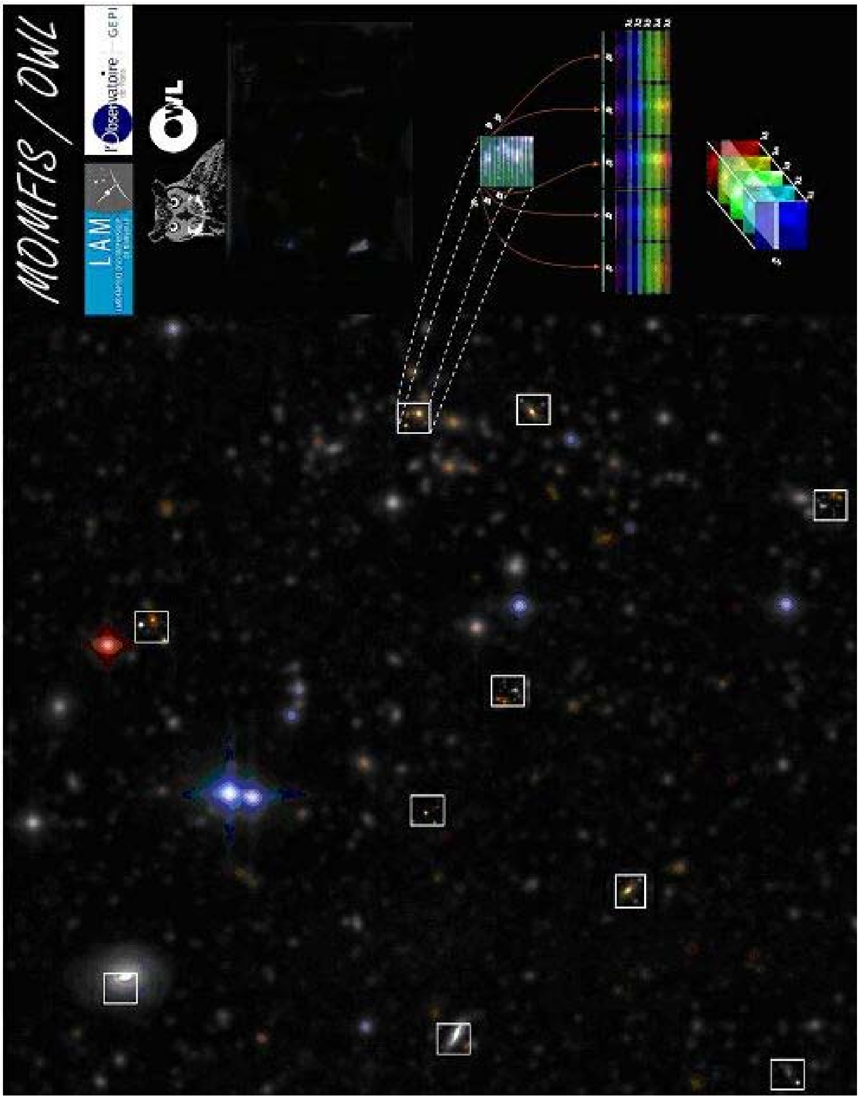

Figure 12-20. Illustration of the MOMFIS operation. Image Correction is performed locally along the line of sight of the target before image slicing and wavelength dispersion.

12.2.3.5 EPICS: Exo- Planet Imaging Camera Spectrograph

The study of **EPICS** was carried out at ESO with the support of scientists and engineers from different European Institutes. It was started significantly later than the other instrument conceptual studies. after the completion of the VLT Planet Finder phase A studies in late 2004. The EPICS concept has been naturally biased but also inspired by the VLT Planet Finder feasibility studies made by the two external European Consortia: the VLT PF led by LAOG and the CHEOPS instrument led by MPIA. Those studies have demonstrated that it is necessary to combine an “extreme” adaptive optics system (hereafter XAO) with other methods (coronagraphy and differential detection) to reach the contrast permitting exoplanets detection. The science case and the instrument are summarized here. the XAO in 8.3.2.2. The full Concept Study report is provided in RD51. XAO. the coronographs and the instrument modules are discussed together in the report. The need to understand the interaction and to control the error sources from the different sub-systems calls for a global system approach in the definition and in the evaluation of the performance of EPICS.

12.2.3.5.1 Science drivers

- Primary science goal: the detection of Earth-like planets

One of the most ambitious science objectives of OWL is the detection and characterization of extra-solar systems in an advanced evolutionary stage. for a statistically meaningful sample of stars. Rocky planets with possibly Earth-like features is the ultimate and most challenging goal of EPICS. The direct detection of exo-planets is made very difficult by the very high relative flux ratio from the star and planets orbiting it and their small angular separation. Figure 12-21 illustrates the requirements in contrast for different types of planets as a function of angular separation. Ultimately the primary science goal of EPICS requires the detection of faint point sources in proximity of a bright star with an object-star contrast down to about 2.10^{-10} at 0.05 arcsec from the star. Moreover. to observe a planet and to characterize its atmosphere. EPICS must be sensitive at the wavelengths of H_2O. CO_2 . CH_4 and O_2 molecular absorption lines.

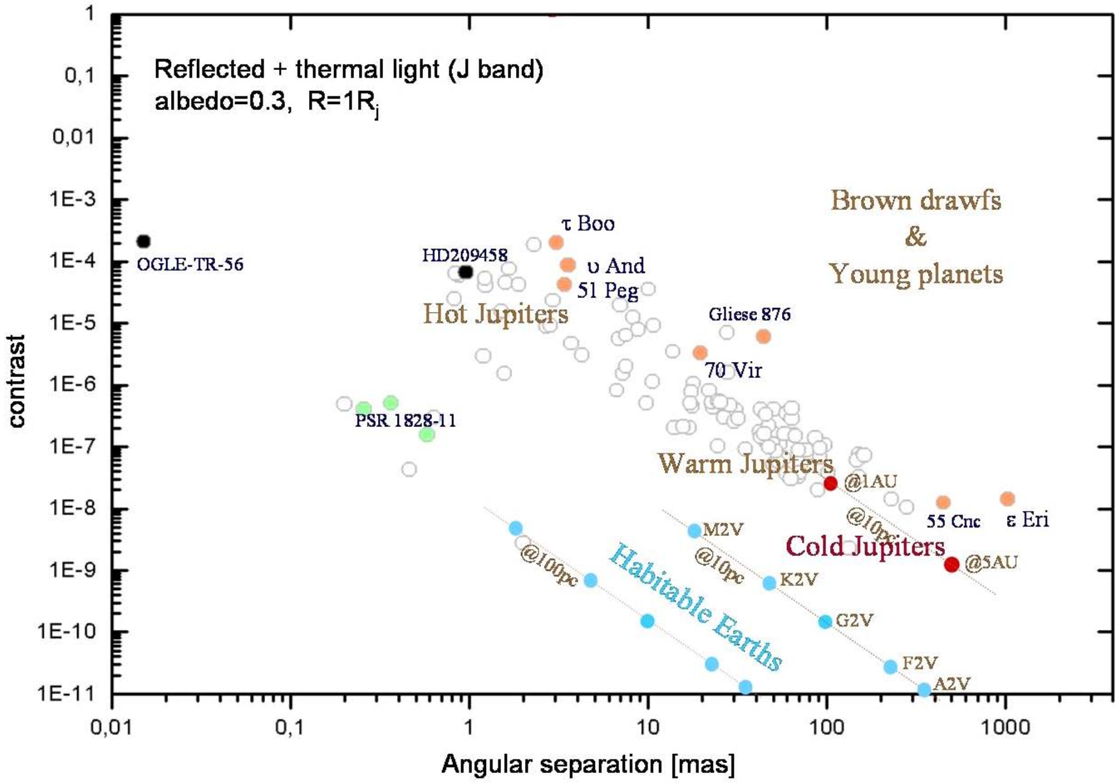

Figure 12-21. Contrast vs. angular separation for different types of planets. (Courtesy O. Lardiere).

- Gas giant planets in a late evolutionary stage

EPICS will also permit a significant breakthrough in the detection and characterisation of cold gas giant planets. The better contrast (the contrast of Jupiter at 5 AU is 10^{-9}) and larger separation. permits an easier detection. and opens the door to high resolution spectroscopy. In particular. radial velocity measurements and the analysis of atmospheric composition and dynamics of close-in giant planets will be possible. The contrast between a Jupiter mass planet at 0.5 AU and its star is around 10^{-7}. so roughly corresponding to the stellar AO residuals. For 10 pc distance from Earth. assuming a G2 star. its magnitude would be around 22.5 and the photon flux at resolution 50.000 would be about 0.5 photons per second and spectral bin (16% overall quantum efficiency). Therefore. a reasonably high SNR for the high resolution spectroscopy appears feasible in observing times of a couple of hours.

12.2.3.5.2 Targets

Performing the required XAO correction usually requires very bright NGSs (m_V <8-10). The number of possible targets has been investigated.

Figure 12-22 shows the number of stars as a function of distance from Earth listed in the NSTAR database (http://nstars.arc.nasa.gov) as visible from a low latitude site (e.g. Paranal) and the zenith angle is restricted to <30 degrees. In order to have access to about 100 stars of the spectral types G. K and M. one has to observe out to

- 25 pc for G-stars ($m_V \approx 7$)
- 20 pc for K-stars ($m_V \approx 8.5$)
- 15 pc for M-stars ($m_V \approx 9 – 16$ for M0 to M5). There are about 50 M-stars with $m_V < 10$ and 100 M-stars with $m_I < 10$ observable at low latitudes.

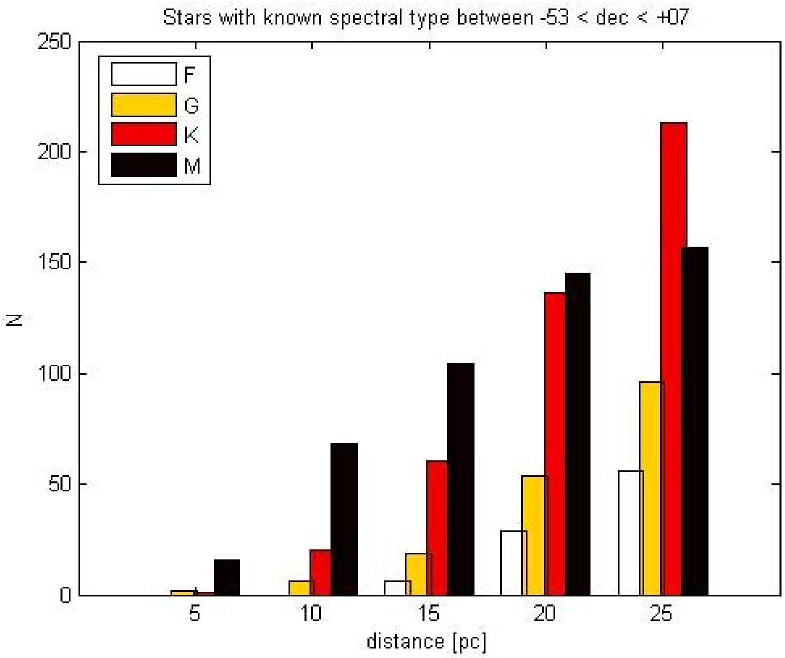

Figure 12-22: Number of stars versus distance from Earth for different spectral types

An acceptable sample of bright stars is available within a distance of 25pc for the purpose of a survey with OWL. This distance. and the resulting angular and magnitude scales. directly sets the instrument top-level requirements as described in paragraph 12.2.3.5.3.

12.2.3.5.3 Top level requirements

The top-level equirements to the instrument. the telescope+ AO and the site are summarized in the following sections.

12.2.3.5.3.1 Instrument. general

- The instrument shall cover the wavelength range 0.6 – 1.7 micron

  For the detection of terrestrial planets the wavelength range 600 nm – 800 nm (R band) is interesting because of the high degree of polarization of rocky planets at shorter wave-length. The very interesting O_2 band is also included in this wave-length range. In J- and H-band. one is sensitive to both Gas giants and Rocky planets. Gas giant planets spectra are dominated by the CH_4 features. and CO_2 and H_2O are part of the telluric planets' features detectable in J and H band.

- The total field of view in all observing modes shall be at least 2″ in diameter at visible wavelengths and 4″ in diameter in the NIR.

  A field of view of 2″ in diameter is large enough to cover terrestrial planets at 1AU. The bigger field in the NIR accounts for the larger separation at which giant planets are searched. The 4″ field covers the solar system (apart from Neptune and Pluto) at distances larger than 10 pc.

- The inner working angle in all observing modes working at visible wavelengths shall be smaller than 30 mas (goal 15 mas).

This inner working angle corresponds to 0.3 AU at 10 pc. small enough to cover the solar system at 10 pc or to resolve Earth-like planets out to 25 pc. The atmospheres of close-in and therefore bright giant planets could be studied at smaller angular separations down to 15 mas.

- The spatial sampling will at least fulfill the Nyquist criterion at all working wavelengths. Over-sampling may be required to deal with interpolation issues in differential imaging.

12.2.3.5.3.2 Instrument main observing modes and performance requirements

- There shall be a low resolution differential spectroscopic mode covering at least the following lines
  - O_2 at 760nm. R = 150. see Figure 12-23
  - CH_4 in J- and H-band. R > 15
  - H_2O between J- and H- bands. R > 15
  - CO_2 in H band. R> 15
- There will be a broad band (~200 nm. TDB) differential polarimetric mode
- The relative astrometric precision shall be better than ~100 µarcsec (goal 10 µarcsec)
- The photometric (absolute/relative) precision shall be better than 1% (tbc)
- Earth-like planet up to 20 pc shall be detectable in polarimetric and spectroscopic modes at SNR > 5 in one night of observation at a phase angle of 90°

Properties of Earth at 20 pc: Contrast 2e-10. m_V = 30.6. angular separation 50 mas.

- Jupiter up to 20 pc is detected in spectroscopic mode at SNR > 50 in less than 4 hours exposure time at a phase angle of 90°

Properties of Jupiter at 20 pc: Contrast 1e-9. m_V = 28.8. angular separation 250 mas.

- The AO control radius will be larger than 0.4″ at 800 nm

This control radius corresponds to about 1 AU at 2.5 pc. and ensures that – besides for the Alpha Centauri system – the prime targets are inside the control radius. Note that the control radius is given by the $\lambda/(2d)$. where λ is the observation wavelength and d is the actuator pitch of the deformable mirror. This Top Level Requirement corresponds to an actuator pitch of ~0.2 m.

- AO limiting magnitude for achievement of Top Level Requirements: compatible with a sample larger than 100 stars for each spectral types G. K and M (Figure 12-22).
- The operational efficiency of all modes. including acquisition and observation of the target and any required calibrations is better than 50%

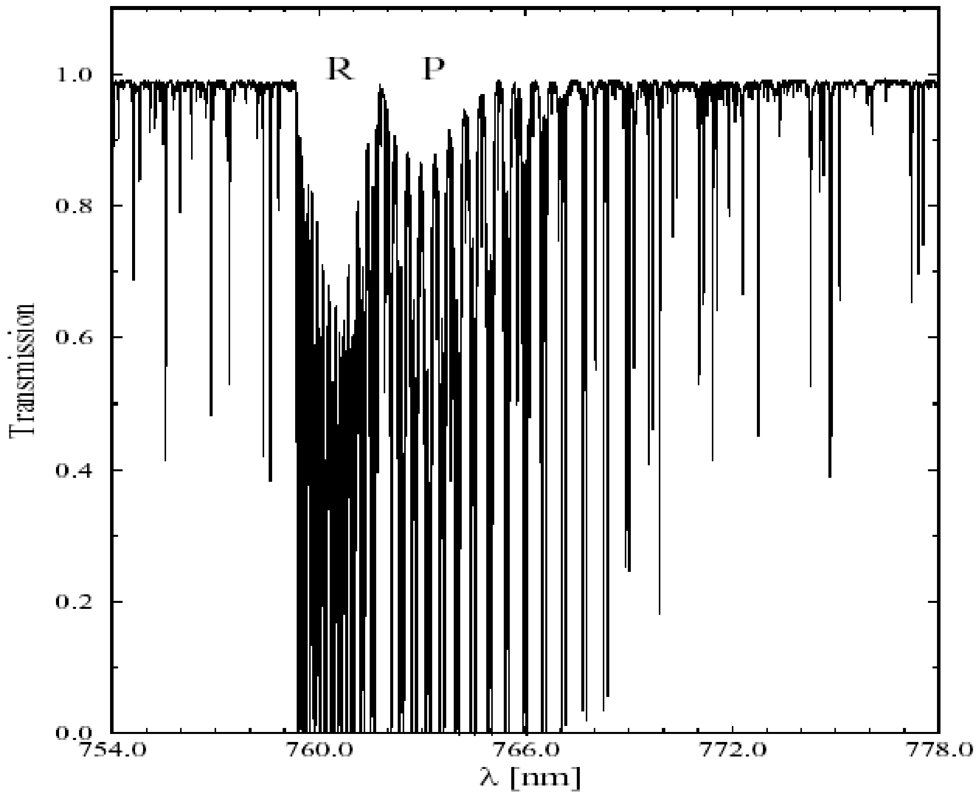

Figure 12-23: O_2 A-band at high spectral resolution.

12.2.3.5.3.3 Requirements to the site . the telescope and observing time

The properties of the site and the requirements to the telescope will be defined at a more advanced stage of the project.The following issues have been preliminarily identified:

- A dry site in terms of precipitable water vapor is required
- Sky accessibility: large enough to cover significant number of targets (~> ½ of sky)
- Polarimetric stability better than 1% over 4 hours
- Diffraction pattern. required SNR shall be reached for at least two/thirds of FoV. Coronagraphic performance should be close to ideal (variation < 20% (TBC)) for this fraction of the FoV
- A very significant fraction of telescope time will be required over several years. E.g. a survey of 300 objects. with 1 night for each target and follow-up observations would lead to 400-500 nights.

12.2.3.5.4 InstrumentConcept

The EPICS concept should be compatible with the detection of both gas giants and rocky planets. Due to different locations of the spectral and polarimetric features of these two groups of planets. different channels over the spectral domain are needed. Each scientific channel will be equipped with its own coronagraph.

The three main instruments will be:

- a wavelength splitting Differential Imager
- an Integral Field Spectrograph
- a Differential Polarimeter.

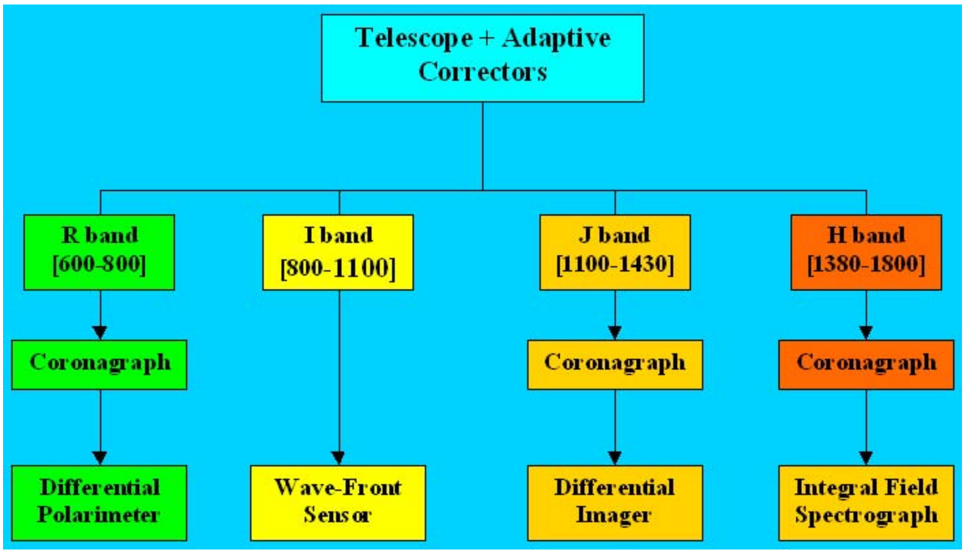

Figure 12-24: EPICS will be composed of three spectral channels for the scientific instruments and one for wave-front sensing.

- The **R band** is dedicated to the Polarimetric Differential Imager for detecting rocky planets and to the follow-up observations for the detection of O_2.
- The **J band** will be equipped with a differential imager using pairs of filters that will be sensitive to both CH_4 and H_2O absorption bands.
- The **H band** will be equipped with an Integral Field Spectrograph. The main features that can be detected in this band are CH_4 and CO_2.
- The **I band** is reserved for wave-front sensing. This band has been chosen because of the lesser scientific interest for planet detection. Moreover its location. spectrally speaking. between the visible and NIR instruments. is optimal with respect to important atmospheric chromatic limitations for XAO on ELTs.

The EPICS concept is summarised in Figure 12-24.

12.2.3.5.5 Adaptive optics

The EPICS ultimate contrast requirement is 4-5 orders of magnitude higher than the VLT-Planet Finder science goal of about 10^{-5} – 10^{-6} contrast at 0.1 arcsec. When scaling from a 10-m to a 100-m class telescope. the contrast naturally improves by a factor of 100 for a given rms value of the wave-front error. This means that the XAO system for EPICS should provide a 2 or 3 orders of magnitude better starlight halo rejection than a simply scaled version of the VLT Planet Finder system. This matter of fact calls for system specifications that are tremendously more stringent.

- a significantly higher AO system frame rate (up to 3-4 KHz) to reach high rejection in the central part of the field-of-view (for separations less than 0.1 arcsec for the Earth-like planets detection goal).
- the systematic errors must be kept at a very low level on the low and mid spatial frequencies (f < 2.5 cycles/m in the entrance pupil frame). For VLT Planet finder. on these spatial frequency range. the static errors contributes by about 40-50 nm. A gain of at least an order of magnitude is needed (requirements: less than 5 nm rms).
- the wave-front sensing measurements error propagation on low and mid-spatial frequencies must be very low: the use of phase-type sensor instead of a slope sensor is needed at least for the correction of the halo at separations less than 0.1 arcsec.

The likely characteristics of the XAO system coupled with the instrument are described in 8.3.2.2. The integrated EPICS concept is given in RD51.

12.2.3.5.6 Coronagraphy

The coronagraphs are very critical components of EPICS. Since the science instruments cover a very broad band of wave-lengths. it has been chosen to equip each individual channel with its own coronagraph. This choice permits to optimise the coronagraph parameters with more flexibility. Whereas a sufficiently achromatic coronagraph dedicated for the visible range is probably the most challenging one. the ones for J and H band could eventually. if an acceptable concept is found. be combined in one single coronagraph. But no definite concept has now been chosen. Coronagraphy is a very fast evolving field with a lot of very new ideas that appeared recently (see RD22 for a review). For EPICS two concepts have been considered and some preliminary results have been obtained. The first concept. the double stage reticulated Lyot coronagraph is described in section RD22 and permits to deal with diffraction residuals induced by gaps between the segments. This concept is quite complex to simulate and has been studied only in the diffraction limited case for the moment. The second concept. a prolate apodized double stage Lyot coronagraph is less complex but doesn't reach a contrast as high as the reticulated double stage coronagraph.

12.2.3.5.7 Instruments

12.2.3.5.7.1 Differential Imager

A differential Imager (IRDIS) based on filters has been studied for the VLT Planet Finder. The advantage of this kind of instrument is the less complexity but has the disadvantage of being less flexible and with a loss of 50 % of the light. For EPICS. we chose to study a dichroic based differential imager which main advantage is the high throughput and the possibility to implement more than two wave-lengths at the same time. A preliminary optical design has been studied (Figure 12-25). The most critical issue of this concept is the optical quality of the dichoics that should permit less than one nanometer differential aberration for the primary science goal requirements.

The proposed filter set presented in table Table 12-5 can be used either for CH_4 or for H_2O spectral differential imaging in J-band using multiple wavelengths.

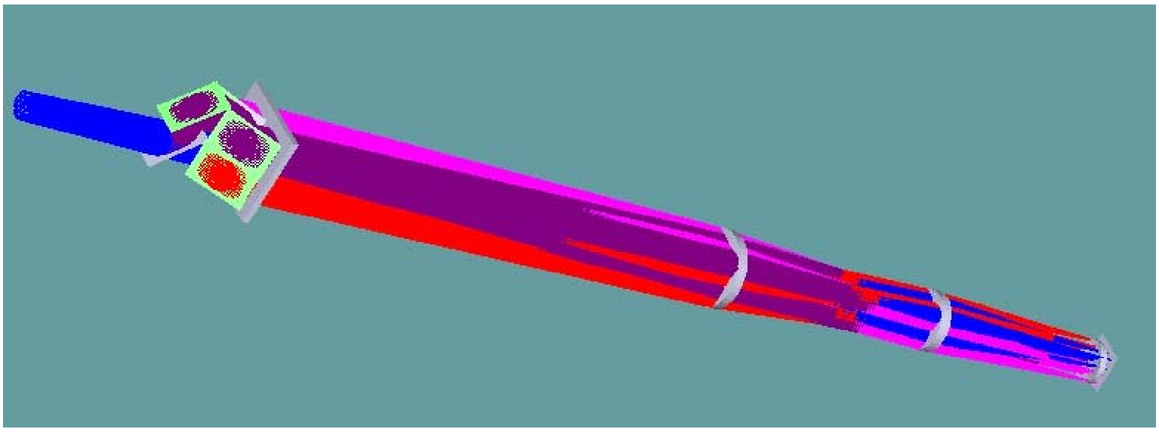

Figure 12-25: Differential Imager based on dichoics splitting the beam in 4 wavelengths.

Filter	Central wavelength	FWHM	$\lambda/\Delta\lambda$
1 ('on-line')	1140 nm	75 nm	~ 15
2	1220 nm	80 nm	~ 15
3	1300 nm	85 nm	~ 15
4 ('on-line')	1385 nm	90 nm	~ 15

Table 12-5 Proposed wave-lengths set for the differential imager

Filters 1 and 4 would be ‘on-line’. i.e.. a planet with either CH_4 or H_20 would be significantly dimmed by them. while it would appear bright in the other filters 2 and 3. Three-wavelength imaging to further reduce chromatic speckle residuals would also be possible. The spectral resolution is kept nearly identical to avoid relative speckle elongation.

12.2.3.5.7.2 *Integral Field Spectrograph*

An Integral Field Spectrograph has been the proposed for the CHEOPS VLT planet finder project by the MPIA et al. consortium. In the frame of EPICS a Tiger-type IFS in the H band is being studied in collaboration between the two consortia. An IFS has an enormous advantage in terms of the multiplexing capability and allows to deal with unexpected spectral features. Another important adavantage is that. in principle. an IFS could be free of differential aberrations. However during the VLT Planet Finder Phase A study. the LAOG et al. consortium identified a serious problem regarding differential aberrations due to cross-coupling when using an IFS in the diffraction limited regime. In depth investigations of the problem are being pursued for the VLT Planet Finder and will naturally benefit to EPICS.

The EPICS IFS will operate in H band with a 2x2 arcsec field and with spectral resolutions per pixel from 15 to 30. Square and hexagonal shapes are studied in order to find a compromise between cross-coupling and size of the detector.

A Fourier Transform Spectrograph is also being studied. This concept could have a better performance in terms of differential aberrations but has some other complications due to time dependent effects. One important advantage is that the spectral resolution can be adjusted from low resolution to very high resolution. The FTS is a very good candidate for a follow-up instrument for the O_2 detection in R band.

12.2.3.5.7.3 *Differential Polarimeter*

The Differential Polarimeter for EPICS is directly based on the ZIMPOL concept proposed for the VLT Planet Finder. The main requirement is that the telescope polarisation remains low and relatively stable so that a suitable place can be found for the polarisation switch. Different possibilities are still under investigations. The implementation of the differential polarimeter in OWL and within EPICS is shown in Figure 12-26 .

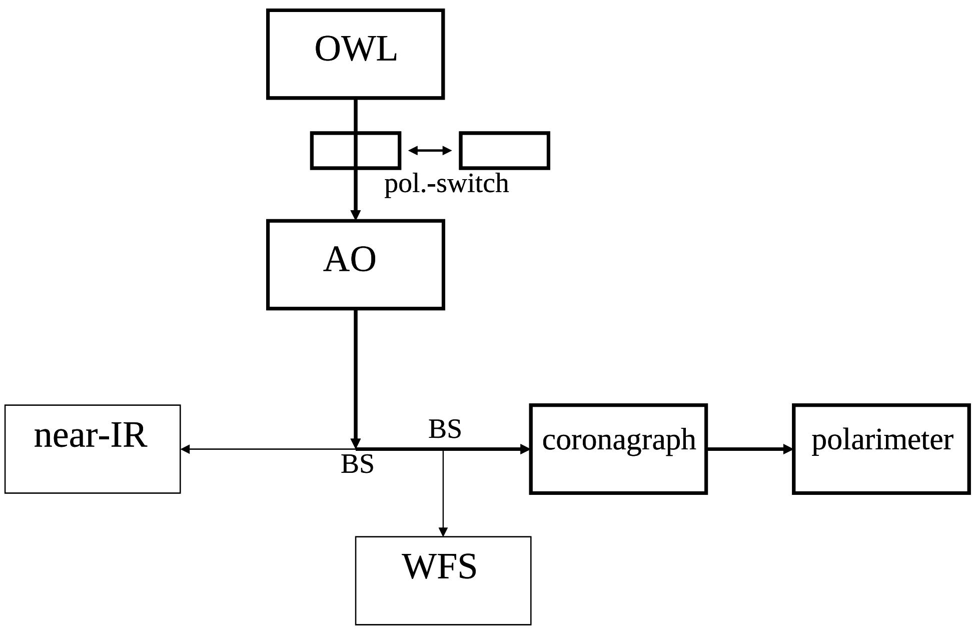

Figure 12-26: Block diagram for the EPICS polarimetric mode concept.

The concept of the polarimeter itself is described in Figure 12-27 .It is assumed that the beam comes from the coronagraphic focal plane and passes first through a collimating lens and a coronagraphic (Lyot) pupil mask before it enters the high precision polarimeter.

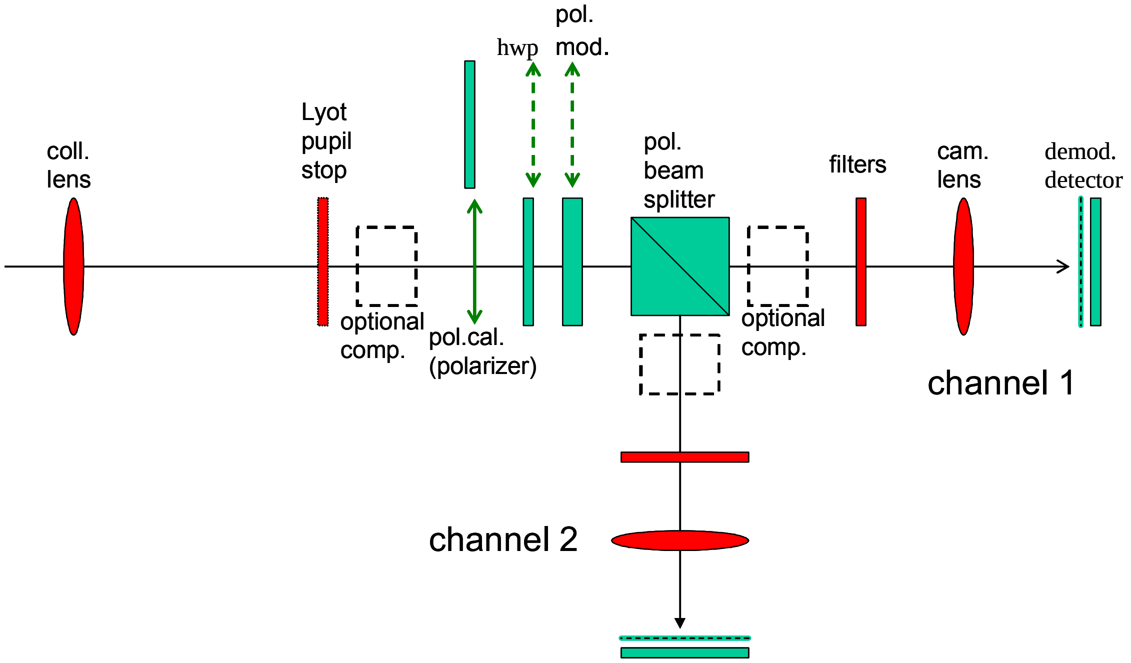

Figure 12-27: Optical scheme for the high precision polarimetric mode in EPICS

In the high precision polarimeter the beam passes first through a rotatable half wave plate which selects between a Stokes Q or U measurement. Then follows the polarization modulator package. including a modulator and a polarization beam splitter producing two beams (see Figure 12-27). Both beams will be recorded with their own detector systems in order to collect all light from the telescope. In both beams the same polarization signal is encoded as intensity modulation. Thus. double beam mode observations provide two full polarimetric observations which can be reduced and analysed independently of each other. The result from both beams can then be combined at the end in order to achieve maximum efficiency. This is the basic concept of all polarimeters based on fast polarization modulation.

12.2.3.5.8 Integration times for a 5 σ detection in case of background limited observation

Wavelength splitting differential detection (IFS and Differential Imager).

As a first step to compute the expected performance for planet detection with EPICS. an analytical model has been used to compute AO corrected PSFs after a perfect coronagraph. The detailed AO error budget taken onto account the most important error sources is described in the EPICS study report (RD51). An example of residual halo for a G2 star at 25 pc (V=7.0) is shown in Figure 12-28. One can notice the two AO control radii at 0.2 and 0.7 arcsec corresponding to the two stages of the currently envisaged XAO system.

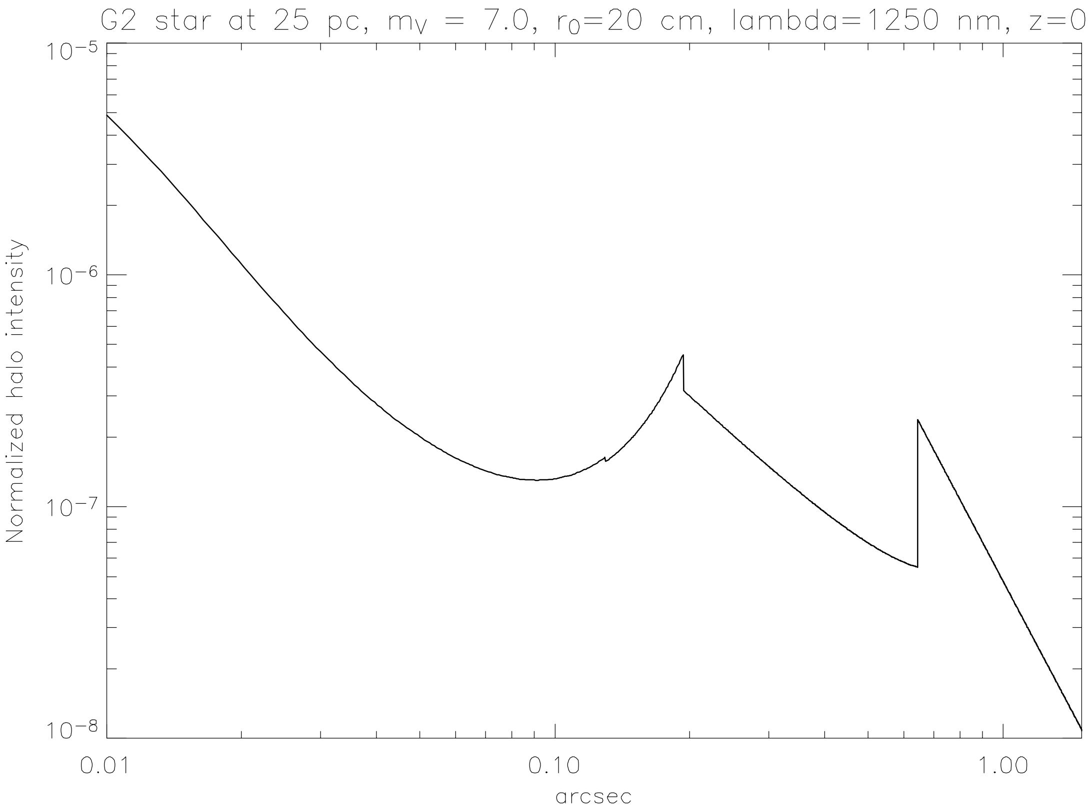

Figure 12-28: Example of halo intensity with perfect coronagraph after adaptive optics correction . Error sources: servo-lag. photon noise (30 % transmission + L3CCD noise excess in WFS). chromatic seeing. aliasing. fitting. static aberration (5 nm rms).

Different AO haloes have been computed considering the targets of EPICS. for three representative spectral types G2. K2 and M2 stars at distances ranging from 10 to 25 pc. Apparent star magnitudes range from V=5.0 for a G2 star at 10 pc to V=12 for a M2 star at 25 pc. For each spectral type. an Earth-like planet and a Jupiter-like planet are placed at separations depending on the star temperature so that the planets are in a thermodynamical equilibruium at similar temperature as in the solar system. For Earth-like planets. this ensures that the orbits are in the habitable zone. Contrast and angular separation for a 90 deg. Phase angle are then derived (see Table 12-6 and Table 12-7).

Spectral type	**Star-planet distance (AU)**	**Star-planet contrast in NIR**	**Angular separation at 20 pc 90 deg phase**
G2	1.00	2.21×10^{-10}	50 mas
K2	0.51	8.07×10^{-10}	25 mas
M2	0.16	8.30×10^{-9}	8 mas

Table 12-6: Characteristics of Earth-like planets used in the simulation.

Spectral type	**Star-planet distance (AU)**	**Star-planet contrast in NIR**	**Angular separation at 20 pc 90 deg phase**
G2	5.10	1.40×10^{-9}	250 mas
K2	1.67	5.32×10^{-9}	80 mas
M2	0.83	5.50×10^{-8}	40 mas

Table 12-7: Characteristics of Jupiter-like planets used in the simulation.

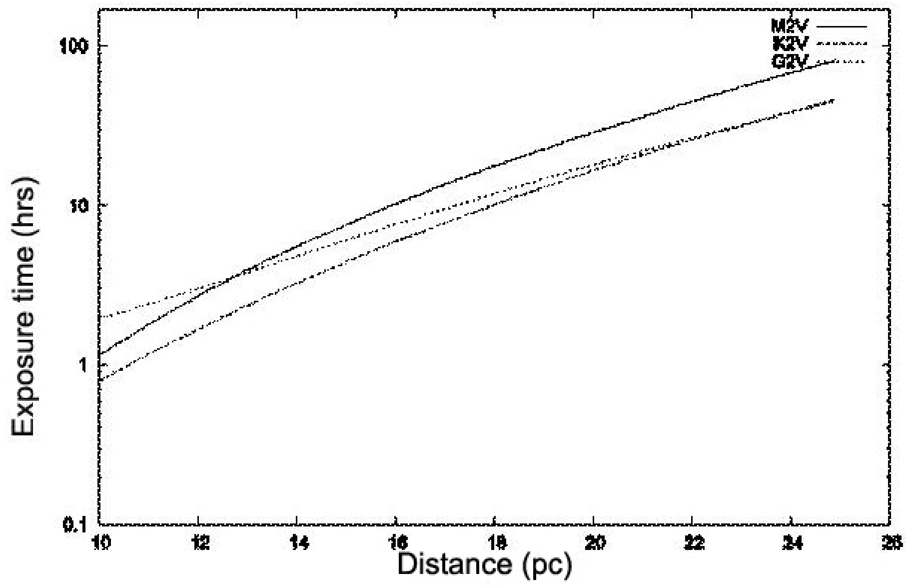

Figure 12-29: Minimum exposure time as a function of distance to detect at 5 σ an Earth-like planet in the H20 band (1.25μm. r_0=12.1cm. τ_0=10mn. Simple Differential Imaging. 0.08μm bandwidth. 0.44 atmospheric transmission)

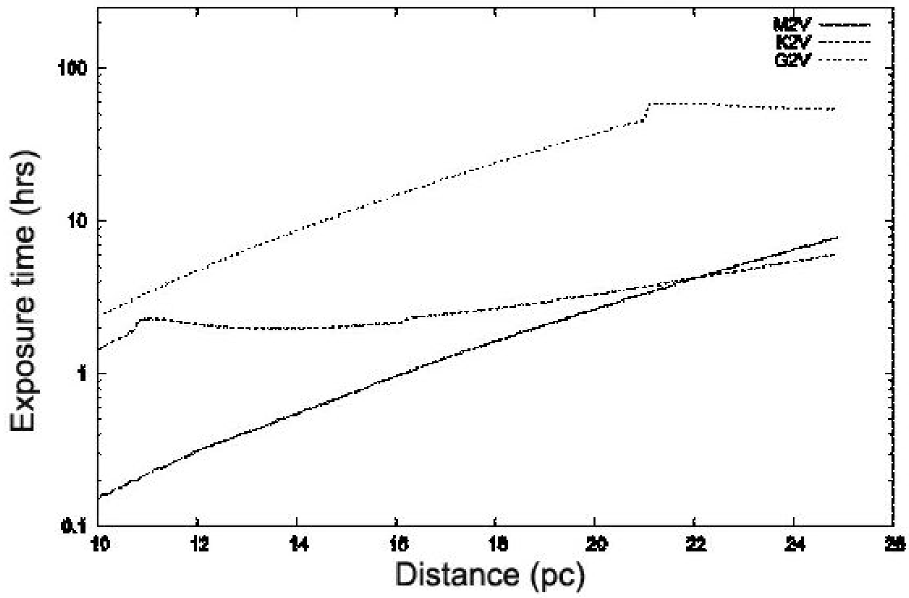

Figure 12-30: Minimum exposure time as a function of distance to detect at 50 σ a Jupiter-like planet in the CH4 band (1.60μ. r_0= 12.1cm. τ_0= 10ms. Simple Differential Imaging. 0.055μm bandwidth)

Exposure times have been computed for differential imaging (either with the Differential Imager or the IFS) to detect the planets around the 3 types of stars.

- The case of H_2O detection in J band for an Earth-like planet is shown in Figure 12-29. Planets around G2 and K2 stars are detected in one night up to 20 pc. and aound M2 stars up to about 15 pc. One can notice that from 10 pc to 20 pc the needed integration times are roughly multiplied by 10 which comes from the less planet photons detected and the brighter halo in the direction of the centre. Transmission of our Earth atmosphere for a location at 4000-m has been taken into account. Note that this estimation doesn't take into account possible oceans and clouds cover which may decrease significantly the contrast of the features.

- Similar results can be obtained for detection of CO_2 in H band if abundant (see RD51).

- For O_2. the needed spectral bandwidth is of 5 nm (R=150) and is in the R band (760 nm). The combination of a low number of planet photons in the O_2 band and the significantly brighter halo in the visible. leads to integration times larger than 100 hrs for detection at 5 σ in an Earth at 10 pc (> 1000 hrs at 20 pc). For this reason. using the O2 line for detection will not be very efficient. Only follow-up observations for detection of O2 in near exo-Earths can be foreseen.
- Jupiter-like planets are very easily detected with very high SNR in the CH_4 absorption line in the H band (Figure 12-30).
- Performance with differential polarimetry: a preliminary estimation of the performance on detection of Earth-like planet with the Differential Polarimeter on the range [600n-800 nm] has been made. Assuming a 20% polarization. a 5 σdetection would require about 3hrs at 10 pc and 30hrs at 20 pc under medium turbulence conditions.

12.2.3.5.9 Need for 100m

The integration time to reach a given SNR scales as D^{-4} where D is the telescope diameter. in case of photon noise background limited observation as in our case. One can easily evaluate the performance that would be obtained with a 60-m telescope: the needed integration times presented in section 12.2.3.5.8 would be multiplied by about 8. To get the same performances the AO should deliver an 8 times better halo rejection. which would be basically impossible to obtain since the needed frame rate (~ 8-9 KHz) wouldn't leave much photons for the wave-front sensing. Moreoever all the requirements on systematic errors (static and differential) have also to be scaled down by about a factor 3 with the diameter since the contrast for a given error figure is proportional to D^{-2}.

Basically. for the primary science goal. only close Earth-like planets at distances less than 10 pc would be detectable with a 60-m telescope equipped with an instrument based on the current EPICS concept. The sample of targets stars would be rather limited. A more detailed discussion of the effect of the diameter is given in RD51. In particular new techniques favouring the use of broader bands. yielding thus more planet photons for the detection. may have a significant impact on the observation strategy and change the conclusions on the diameter dependence.

12.2.3.5.10 Systematic Errors

The study report (RD51) discusses how to correct two potential show-stoppers for planet findind at ELTs: cophasing errors and differential aberrations.

12.2.3.5.11 Technological requirements for EPICS

EPICS will require significant technological developments of hardware to achieve its goals:

- CCDs: 1KxK (goal 3Kx3K) detectors with fast read-out (3 KHz) and low noise (read-out noise less than one electron) are required. Developments of L3CCD are already part of the OPTICON Joint Reasearch Activity 1.
- Micro Deformable Mirrors): EPICS requires a micro deformable mirror with about 2.10^5 actuators. Actually only 1K micro DM2 with about 1 micron mechanical stroke are available (Boston Micro-Machine). A 2K micro DM with larger stroke will be developed in the frame of OPTICON.
- More powerful real-time-computers
- High precision coronagraphic masks (in phase and in amplitude) .

- High quality optical polishing for a number of optical surfaces (less than 1 nm rms error). The effect of coating on super-polished surface is an other important issue to be thoroughly investigated.

12.2.3.6 T-OWL: Mid-Infrared Imager

The study of T-OWL was carried out at the MPIfA. at Leiden University and at ASTRON. P.I. of the study was R. Lenzen with B. Brandl as Co P.I.. The Concept Study report is provided in RD56 and its content is summarized here.

Study Scope and Science Drivers - Scope of the study was first to review the science for an instrument to operate in the thermal infrared. that is the wavelength regime λ ≥ 3μm where the thermal emission of sky and telescope dominate all other noise contributions up to approximately λ = 24μm. where the atmospheric interferences become prohibitive for sensible astronomical research. Secondly. an instrument concept had to be developed with the capability to carry out the primary science cases.

In the study the science case and the instrument definition were developed in parallel. always keeping an eye on competing instrumentation on future air-borne and space-borne observatories to avoid costly duplication of observing facilities.

The study team could enlist a fair fraction of the scientific community interested in thermal IR astronomy in Europe. The science cases presented in the report cover most areas of present astronomical research from the inner Solar System to the nuclei of galaxies and on to observations of GRB in the early universe. They were used to set the initial set of requirements to the instrument. In this summary we point out as an example one of the most exciting science cases. the precise mass determinations of massive black holes. Figure 12-31 shows the rotation curve obtained close to the center of the Seyfert 2 galaxy NGC 7582 (M. Wold. 2005) with a spatial resolution of 0.4” (40pc). Various models for different black hole masses are compared with the observations. It can clearly be seen. that the increase of spatial resolution in long-slit spectroscopy by a factor of 12 to ~4pc linear scale (OWL vs. VLT) would be highly advantageous for a precise determination of the dust obscured central black hole.

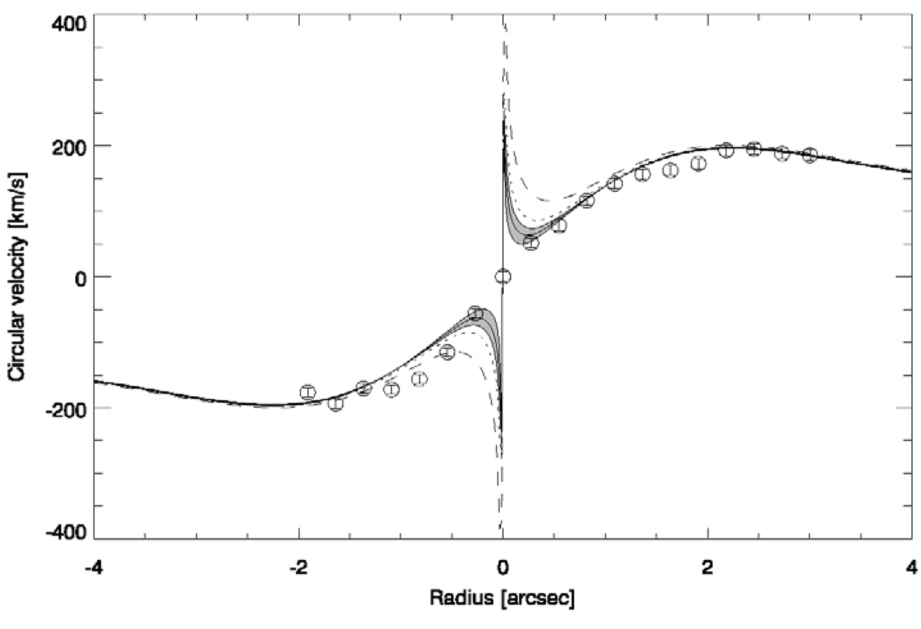

Figure 12-31. Rotation curve of the nucleus Seyfert 2 galaxy NGC 7582 (M. Wold. 2005). Circles: VLT-VISIR measurements using the [NeII] line at 12.8μm with a spatial resolution of 0.4” (40pc). Lines: models with different masses of the central blac hole..

In synthesis – keeping a balance in complexity and cost - the T-OWL requirements were set as follows:

- Wavelength range: 3µm - 20µm →LMNQ bands (goal : 3µm – 27µm) using two types of dedicated detectors (HgCdTe or InSb in the "blue" arm and As:Si in the "red" arm)
- Diffraction limited imaging using an all reflective system and typical pixel scales of 3.5mas for the "blue" and 7mas for the "red" part and a minimum field of view of the order of 50 arcsec^2 ; for the "blue" arm a tunable Atmospheric Dispersion Compensator (ADC) was found to be necessary and has been designed. albeit an experimental verification of the atmospheric dispersion formulae used is pending. As T-OWL works in the back-ground-noise limited regime. sensitivity will not be compromised by the too fine sampling in case the AO can not deliver diffraction limited images.
- spectroscopy should ideally encompass both low (R=300). medium (R=3000) and high resolution (up to $\lambda/\Delta\lambda \approx 50000$) and potentially an integral field- unit with ~10 arcsec^2

To select an optimum instrument configuration the design concepts of various 8m-class telescope IR instruments were compared: VLT-VISIR. VLT-ISAAC. VLT-NAOS-CONICA or Subaru COMICS. The mechanical and cryogenic designs adopted in these instruments provide for a repository of well-tested solutions. which can be re-cycled for T-OWL.

Figure 12-32 shows the T-OWL elementary instrument block in the imaging and low-resolution spectroscopic configuration: behind the cryostat entrance window (top left) a slit is positioned. A three mirror anastigmat (TMA). the building block of many ESO-VLT instruments. creates a collimated beam at the instrument pupil. To minimize the thermal background from the OWL central obscuration and the mechanical structure. a cold pupil stop is foreseen which can be combined with other enabling devices for high contrast imaging. such as apodizing masks. At this location filters and grisms for low resolution spectroscopy can be inserted. Behind this pupil stop a second TMA forms an image in the detector plane. "Blue" and "Red" ranges within the 3-24 µm would be selected by a detector exchange mechanism. The T-OWL imager in this relatively simple configuration could consist of 2-4 such elements. each covering e.g. 4 x 4 arcsec at the required pixel scale with a 2K x 2K array.

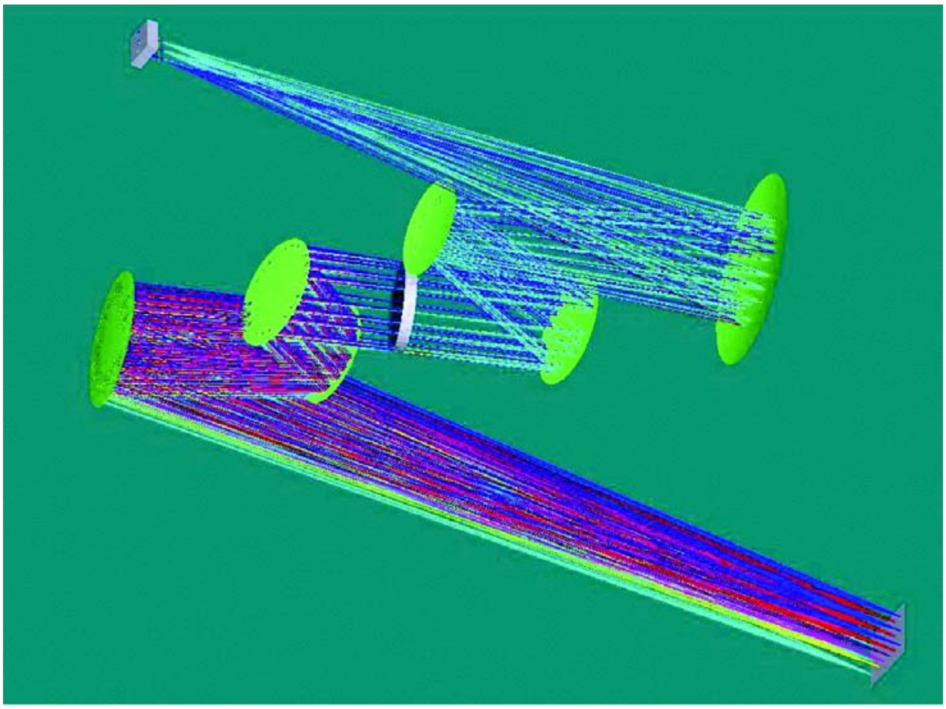

Figure 12-32: Optical concept of one of the imaging-low resolution spectroscopy of T-OWL.

Sensitivity and Context – The T-OWL imager will work in the background noise limited regime; this implies for diffraction limited performance of the telescope that the sensitivity scales with D^2. In that sense T-OWL would be a factor of 150 (or 5.5mag) more sensitive than the present instruments on 8m class telescopes. A careful analysis of the emissivity of OWL has been done. under the assumption. that the central obscuration and the spiders can be masked by a adapted and motorized cold pupil stop. Detailed atmospheric transmission and emissivity calculations were done. as precise as possible without knowing the exact telescope site. The calculations were cross checked with values reported for ESO's VLT.

The T-OWL sensitivities have then been compared to the following contemporaries: JWST (6.5m diameter. MIRI and NIRCam instruments). SAFIR. a NASA FIR-space telescope (10m diameter) under study right now and to the Spitzer Space Telescope (0.85m diameter). The result is condensed in Figure 12-33. It should be noted. that in many cases the spatial resolution will be required to lift the confusion limit set by the brightness fluctuation of “empty” sky in the infrared.

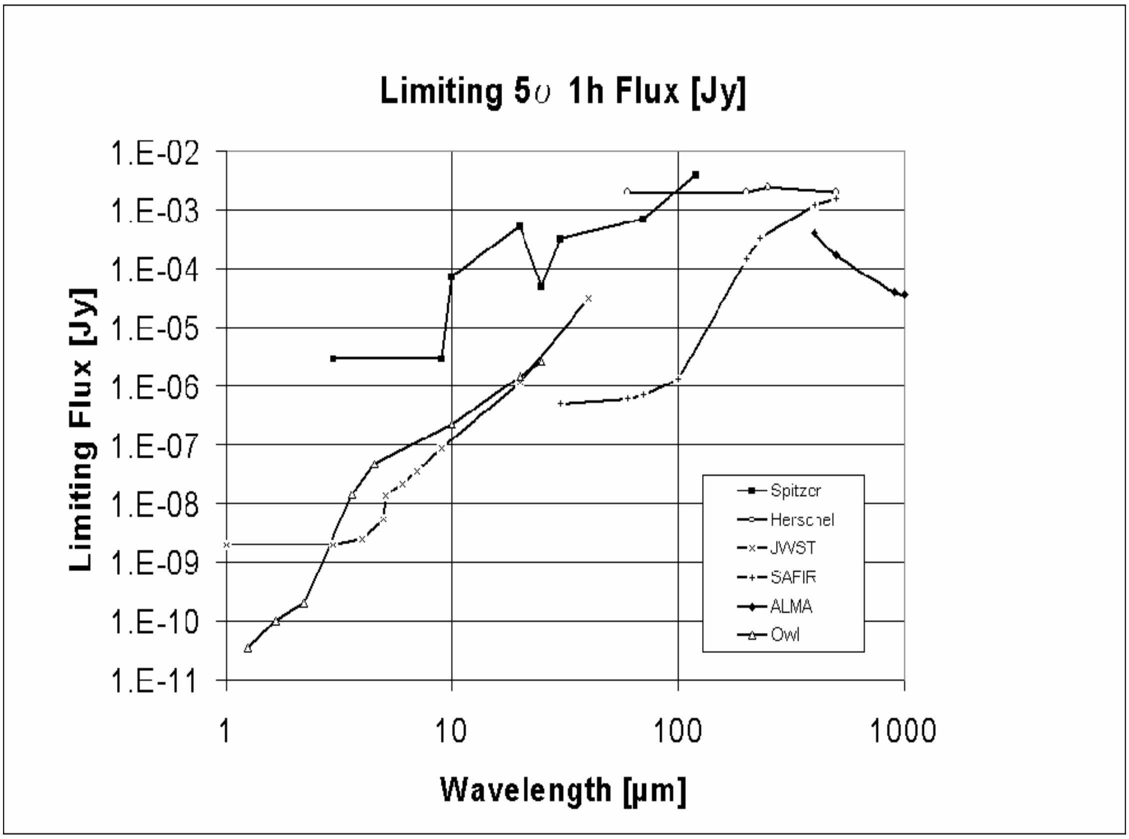

Figure 12-33. Sensitivity of T-OWL as compared to other thermal infrared facilities for imaging of stellar-like sources.

The concept study does also explore in a preliminary way the feasibility and performance of the R= 3000 and R = 50000 spectroscopic. with the following conclusions:

* The predicted line sensitivity in the N band provided by T-OWL at R=3000 is basically the same as for JWST/MIRI. The 15 times better spatial resolution makes its performance unique.
* The high resolution (R=50000) mode will provide unsurpassed sensitivity to measure unresolved lines and hence be a much more powerful tool to study very narrow spectral features than JWST+MIRI in the atmospheric windows.

T-OWL Interfaces and Compatibility with the Telescope

Optomechanical Interfaces - The T-OWL imaging module fits without problem into the design space provided for instruments at OWL. The situation for the spectrograph is more critical and needs further study. The problem of field de-rotation has been studied in great detail. For f/6 an optical derotator can be excluded. A stationary instrument with derotation in software is possible. but leads to a variety of unpleasant constraints and a substantial amount of additional cryogenic mechanisms and much more demanding data handling. Thus the instrument should be interfaced to a VLT-type mechanical de-rotator. and the weight/torque limits might require to use a VLT-VIMOS-type support “leg” (or better a set of arms) supporting T-OWL with an additional rotational bearing from the instrument cabin structure.

Flexure in the instrument is not considered to be a problem as Piezo-driven active optics would be employed.

Adaptive Optics Interfaces - T-OWL spans a very wide wavelength range where the requirements for AO are quite diverse. The performance of any AO-system at λ>16μm can be considered just perfect. The most demanding requirements for T-OWL stem from 2 different roots: at λ~10μm T-OWL shall be used to do extremely high contrast imaging for the direct detection of extra solar planets. albeit in a small field and with rather bright reference stars right on-axis. while at 3-5 μm a moderately large field is necessary. generally no bright guide star will be in the field. and good control/understanding of the PSF over the field is necessary for further photometric processing of the data. For λ>8μm the isoplanatic patch is much larger than the OWL field of view. but even for the shorter wavelengths un-isoplanatism is not considered to be a major problem.

In all cases it can be assumed. that the best point for the wave-front reference star pick-off(s) is the entrance window to the T-OWL Dewar. the second best point would be a dichroic mirror at the cold pupil stop. In any case the AO wavefront sensor should work as far in the infrared as possible. e.g. at λ~2.2μm. just to keep all differential effects as small as possible.

The starting point for AO should be a natural-guide-star system using typically a 100x100 grid of sub-apertures and consequently approximately 10^4 actuators. A multi-conjugate plane AO system or a ground layer AO system might be of high interest for the “blue” region of T-OWL and further optimisation of the T-OWL AO-concept in this region on the basis of selected science cases is still needed.

Special Requirements - The operation of an instrument in the thermal infrared sets a strong requirement on the choice of the site for OWL. A very dry site is required to minimize the effect of the atmosphere and enhance the performance of the instrument.

The only non-standard requirement for T-OWL resulting from the study is the availability of liquid Nitrogen (500-1000 l tank) in the instrument compartments. Chopping by means of M6 as offered in the OWL documentation may be an asset to detect the faintest isolated point-like sources but generally new ways for modulation and noise filtering have to be found.

T-OWL Operations with a “Growing Telescope” - Various schemes of filling up the OWL M1 during the construction phase have been investigated at 10 μm (see Figure 12-34). A zero-order ranking of the possibilities would put a ring-like structure starting from the outer circumference of M1 at position #1. a cross shaped filling of the primary at position(#) and a filling up from the centre at #3. Both the outer-ring and the cross filling concept provide for the full spatial resolution from year 1. A detailed trade-off of the two strategies has to be based on the science cases.

Preliminary conclusions of the study - A T-OWL instrument would be highly desirable at OWL. While there is a solid broad general science case for such an instrument. there are at least the following truly unique opportunities:

- possibility for high contrast imaging for planet detection and characterisation involving coronagraphy and spectroscopy
- detection of signatures of planets in young circumstellar disks
- the study of massive black holes in galactic centers

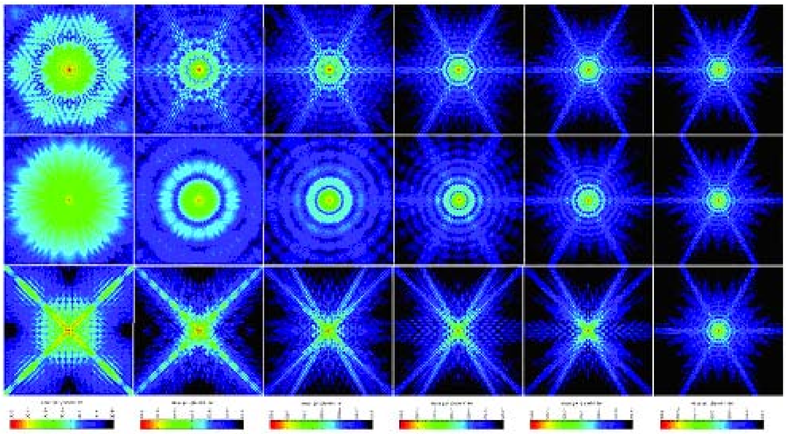

Figure 12-34. The effect of a "growing" telescope primary on the PSF . Each frame is a $2x2arcsec^2$ field with the resulting PSF. The columns from left to right correspond to year after year until completion of the OWL-. The rows are for three filling strategies: the top row is by starting with a 100m x 100m cross. the middle row is a ring-like geometry starting from the outside and the lower row is a ring-like geometry starting from the inside.

At shorter wavelengths T-OWL has a meaningful sensitivity. exceeding or fully competitive with the next generation space telescope. the JWST; at longer wavelengths JWST is only in imaging moderately more sensitive. but lacks in any case at least an order of magnitude spatial resolution. An high resolution spectroscopic mode appears also potentially unique for the observations of narrow lines.

A T-OWL imager would be feasible with a modest extrapolation of state-of-the-art instrumentation at 8m-class telescopes. The hardware cost for a T-OWL would of course depend on the exact configuration. but a basic imager instrument could be built for 5M€ and <100 manyrs. A full implementation of high resolution spectroscopy. however. leads in the preliminary estimates to a very substantial growth of these numbers (hardware cost 18M€. manpower 240 person-years).

Important aspects which require future research –

- Properties of atmospheric dispersion beyond 5 μm. dependence on humidity
- Chopping needs for MIR observations with ELTs and possible solutions at 100m telescope
- Feasibility of high resolution mode in Q band
- Pixel size for detectors in the Q band (present 25 μm pitch makes the optical design of the camera very complicated)

12.2.3.7 SCOWL : Imager at Submillimeter Camera at OWL

The study of SCOWL was carried out at the Advanced Technology Center in Edinburgh with B. Dent as P.I.. The Concept Study report is provided in RD57 and its content is summarized here.

SCOWL is an initial concept for a large-format sub-millimetre camera to be used on the OWL Telescope. Such an imager would be unique. more sensitive than any other facility in the same spectral band. and be able to map large areas of sky a million times faster than ALMA. The results would impact a wide range of research. It could answer some of the most fundamental questions about the *origins* of dust. planets. stars and galaxies. and would significantly increase the scientific return from the OWL telescope. It requires a high altitude. dry site to operate efficiently.

Primary science objectives

Astrophysics at sub millimetre wavelengths (300μm to 1mm) is most sensitive to cold gas and dust. with for example the blackbody emission of a 10K source (or a 40K source at z=3) peaking at around 300μm. Such very cold material is associated with objects in formation. that is. the mysterious earliest evolutionary stages of galaxies. stars and planets. To understand the origins of these most fundamental astronomical structures. the sub millimetre is the waveband of choice. An additional important feature of the sub millimetre is that the continuum emission from nearly all objects is optically thin. This means that observations probe right to the heart of the most crucial processes. and trace dust masses over a wide dynamic range. Some of the key science questions that would be addressed by SCOWL are illustrated here.

554 **Why is the Solar System so free of dust: do we live in an unusual planetary system?** Debris discs are the result of collisions and the grinding down of asteroids around main-sequence stars. Most images of them have been obtained in the submillimetre. but so far we have only been able to study the very dustiest examples. For the first time. *SCOWL will enable us to detect debris systems with dust masses similar to our Solar System*. This will not be possible with proposed far-infrared mission over the next ~20 years because of the large beams and subsequent confusion by the bright stellar photospheric emission. It will allow SCOWL to investigate the planetary systems with the least dust confusion. influencing the target selection for deep searches for thermal emission from Terrestrial Planets. The Planet Finder capability of other OWL instruments combined with SCOWL will allow us to investigate the complete range of objects around nearby stars. from giant planets down to dust grains.

How do the lowest and highest mass stars form? Existing surveys suggest that the stellar IMF may be controlled by the pre-stellar clump mass spectrum; however. even in the closest regions. they are incomplete below 0.1 Solar mass. The mass sensitivity limit of SCOWL can be translated to a 10σ detection of a 0.1 Jupiter mass clump in a 1 degree survey of Orion. It would therefore be able to study the formation of the lowest mass stars or even “free-floating” planets.

The early stages of *high*-mass star formation are also very poorly understood. partly because there are fewer high-mass stars. but also because the formation process is so fast and consequently rare. This is important to understand. because of the significant affect they have on the large-scale ISM. SCOWL would allow a full census of *all* high-mass star formation throughout the Galaxy. showing the rarest of phases. and allow us to understand what defines the highest-mass end of the stellar IMF.

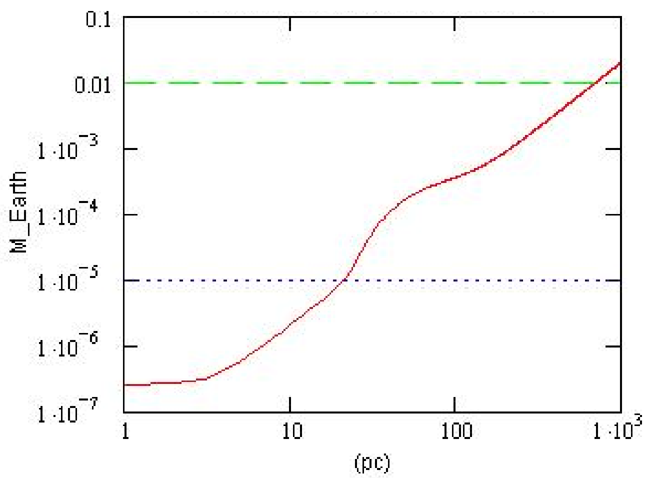

Figure 12-35: Dust mass detectable (10σ) by SCOWL at 450μm around nearby stars as a function of distance. The upper green line represents the mass of the dusty system ε Eri. and the lower line the dust mass of our own Solar System.

Where is the bulk of dust in Galaxies? Is there an additional “cold. dark” massive component? The only reliable way to trace the bulk of dust in galaxies is through submillimetre imaging. Dust in spirals is detected in extreme cold (<15K). low-surface brightness disks often extended far from the nucleus. Such cold dust radiates strongly in the submillimetre and is faint already in the far infrared. *This component dominates the total dust mass*. How far such dust extends beyond the disc is unclear: does it enter the intergalactic medium? Is it distributed in galaxy clusters or present in cooling flows? How much does it contribute to the rotation curve and is there a relation to cold dark matter in Galaxies? High-sensitivity submillimetre mapping is the only way to answer these questions.

The origin of dust. It is unclear whether dust forms mostly in supernovae remnants or in evolved stars. Most SNR are too large and have too low surface brightness to be studied with current facilities. Other dust production factories may. Their episodic violent ejection produce rings of enhanced emission. High resolution imaging of arcmin large fields. as provided by SCOWL. is required to trace their inter-ring spacing. This will allow us to verify ejection time scales. production rates and also clumping.

What is the star formation history of the Universe? Detecting "normal" Galaxies to the edge of the Universe. The existence of submillimetre (or "SCUBA") galaxies has changed our view of Galaxy evolution. But currently we can only detect the very brightest "monsters" at high redshifts. with extreme star formation rates of ~10^3 Solar masses per year. 1000 times that of the Milky Way. SCOWL could map the field of view and detect objects ~1000x fainter at 850μm in ~50 hours. reaching well below the confusion limitations of the next decade of deep far-infrared or submillimetre surveys. Such a survey would resolve almost all the submillimetre background flux. The negative K-correction for dust emission in the submillimetre means that a galaxy like the Milky Way would have an 850μm flux of ~10μJy if observed at *any* redshift between 1 and 10. *SCOWL would therefore be able to detect normal Galaxies like the Milky Way throughout the Universe*.

Instrument capabilities

The basic design goal of SCOWL is to pave the full field of view with Nyquist-sampled pixels with sky-limited sensitivity at all three primary submillimetre wavebands. The huge OWL collecting area (effectively larger than ALMA) and high detector sensitivity means it will be possible to image objects at the 10μJy level at 850μm. more than two orders of magnitude better than existing instruments. The beam is sufficiently small that confusion from high-redshift galaxies and local galactic cirrus over most of the sky is at the level of a few μJy. At the shorter wavelengths. assuming a precipitable water vapour (pwv) content above the OWL site of 0.5-1 mm. a point-source sensitivity of 100-200μJy (10σ/1hr) at 450μm will be reached. This will deteriorate to ~1mJy (10σ/1hr) if the pwv is 2mm. and indicates that a high dry site such as Mauna Kea or Chajnantor would maximise the potential for short-wavelength observing. At 850μm the effect is significantly less pronounced.

As well as three-band imaging. SCOWL will also have a polarimetry capability. The basic specifications are given in Table 12-8

Parameter	**Requirement**	**Notes**
Wavelength	850μm. 450μm. 350μm (simultaneously)	Set by atmospheric transmission windows.
Sensitivity	50μJy at 850μm (100μJy at 450μm)	10σ. 1hr. per pixel
Resolution	1-2 arcsec	Diffraction limited
No of pixels	≥10000-20000 per wavelength	May be larger. depending on detector technology used
Field of view	2.5x2.5 arcmin	Set by telescope design
Mapping capability	2-10mJy per square degree per hour	10σ. 1hr. 1 square degree

Table 12-8 Main characteristics of SCOWL

SCOWL and ALMA complementarity

SCOWL and ALMA will both operate in the submillimetre. but their capabilities are clearly different. ALMA will be the facility of choice for the high resolution studies. But SCOWL is the only instrument capable of widefield mapping. For example. at 850μm SCOWL will map 1 square degree down to 1σ=40μJy within 10 observing nights. while ALMA even if it were possible would need 10Myr! Observing large sky areas in the submillimetre to high depth become feasible *only* with SCOWL. As such. SCOWL would also act as a pathfinder. searching for new objects for high-resolution followup with ALMA. However. even for sheer point-source sensitivity. on a similar site SCOWL beats ALMA by a factor of 20 at 450μm. and more at 350μm.

Instrument concept design

The baseline design of SCOWL uses the same basic system as SCUBA-2. currently the cutting edge of submillimetre continuum cameras. This is the lowest risk approach. and uses 48 of the existing TES detector arrays with a total of ~20000 pixels at each wavelength. The instrument layout is shown below. The cryostat volume is ~24m^3. with a total weight of 6t.

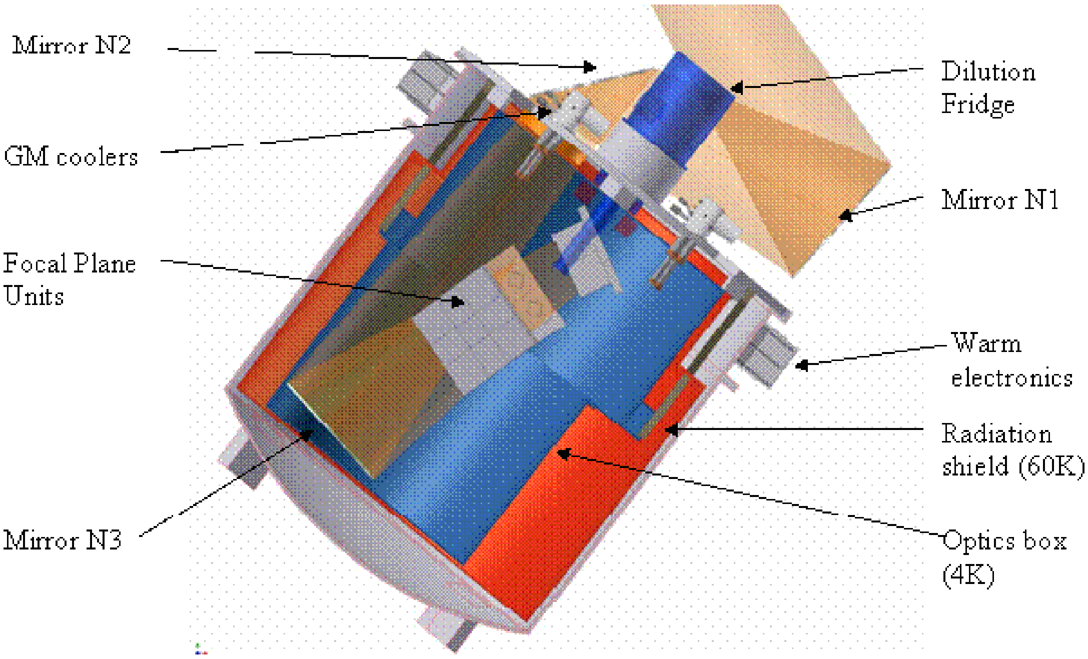

Figure 12-36: SCOWL cryostat cross section.

Advanced designs and risk items

The baseline design uses three wavebands (850. 450μm and 350μm). and partly paves the field of view with detectors. However. the goal is to fully cover the field of view.. The existing and projected TES detector technology is limited. both in the size of detector array. and in the cooling requirements it places on SCOWL. An alternative - Kinetic Induction Detectors - may prove in the next few years to be more capable. and significantly relax the cooling requirements as well as increasing the fraction of field of view covered by pixels. and reduce the cost. However. it will require a technology development programme. For the baseline design there are several areas where manufacturing capabilities must be developed. Cooling is a key risk area because the current generation of coolers required for the final stages of cooling at milliKelvin level are gravity dependent and therefore limit the operation of an instrument that moves with the telescope. In addition. manufacturing capabilities will need to be developed to allow filters. waveplates for polarimetry and the cryostat window to be produced as current sizes of these items are below what is required for SCOWL.

Cost and schedule

Based on SCUBA-2 technology alone the total cost is provisionally estimated to be of the order of €36M. with a construction time of ~5 years. These estimates are dependent upon the availability of the key components described above. Ideally development programmes would be in place before a commitment to build SCOWL were made so that manufacturing techniques were established prior to the start of design activities.

12.2.4 Versatile Instruments and Dedicated Experiments or Surveys

The ESO Very Large Telescope (VLT) is by far the most important facility for optical and infrared astronomy completed in the last 20 yrs by the European (and probably worldwide) astronomical community. The VLT consists of four 8m telescope. each with the possibility to host permanently up to three instruments. The instrumentation plan for the VLT in its original conception before the telescopes were build and through the subsequent adjustments foresaw 11 instruments covering different wavelength ranges and. within a given range. different observing modes in imaging and spectroscopy. The science objectives and the actual programs being carried out with each instrument are much diversified. Most of the instruments have been actually used for discoveries ranging from nearby stars to the most distant universe. This versatility in the discovery space has been one of the main strength of the VLT observatory.

The OWL instrumentation Plan. and hence the selection of the first priority instruments. will take shape during the subsequent phase of the project. It is important to note however that it will not be possible to apply in full the VLT paradigm to OWL instrumentation. To reach the challenging goals of some of the OWL science. some of the instrument will have to be optimized to achieve an optimal performance in a specific mode of observations only. These OWL instruments could then be more conceived as experiments which will occupy a focal station at the telescope for the time required collecting a specific set of observations and then be dismantled leaving space for new dedicated projects. Other instruments like SCOWL are likely to express a large fraction of their scientific potential in an extended survey to be carried out at the beginning of their operational life. *The OWL Instrumentation Plan is likely to contain a balanced mixture of general capability instruments to be used for a large variety of science programs and experiment-type instruments mainly used by dedicated teams to pursue a specific scientific goal or to carry out a survey for the community.*

12.2.5 Telescope Interface and Deployment Considerations

As a cautionary note to this section. it is important to stress that the instrument concept studies have become available toward the end of the telescope study only and the OWL team had therefore very little time to incorporate the feedback from the studies in the design. This will happen at the beginning of the next phase of the project.

Telescope Properties

Non-optimal features for most of the instruments are the fast beam (F/6) and the short back focal distance (separation from the adapter flange and the focal plane. away from the telescope) and to a lesser degree the angle at which the beam from M6 enters the focal station room. A much slower beam would however not be free from technical drawbacks. One of these would be the very large physical dimension of the adapter-rotator. Ideally a F/8-F/10 beam would be a good compromise but it is not compatible with the present optical design of the telescope.

A scientific field of 3’ x 3’ is required by the distributed multi-object spectroscopy (MOMSI) and the wide field module of the ONIRICA imager. Both would operate with pixel size of ~10-30 mas.

Diffraction limited images at NIR and thermal infrared wavelengths are required over a field of at most 1 arcmin diameter.

Diffraction limit images at visual-red wavelengths are required by one observing mode of EPICS only and over a field < 5 arcsec.

Focal Stations

The present OWL design foresees 6 large focal stations which move with the telescope structure. Access is secured via lifts in the central body of the telescope structure. Working at these focal stations for integration and maintenance will be more cumbersome than at Nasmyth or Cassegrain foci of the VLT or other telescopes of the same class.

Of the instrument studied so far QuantEYE and the HyTNIC could be easily attached to the adapters. QuantEYE call for an atomic clock mounted in a stable environment in the telescope building.

CODEX requires a volume in excess of the present allocation and an ultra-stable environment. The instrument has been located in a laboratory outside of the telescope structure and could be fed by a long fiber. An optical feed via a coude train with a very small field would be however much preferable for reason of efficiency. It will be evaluated in the design phase.

EPICS call also for very high opto-mechanical stability. It will have to be mounted on a gravity-invariant optical bench in a protected enclosure. This solution has not been studied in any detail.

T-OWL would also require special arrangements within the focal stations if the spectroscopic module is fully implemented.

The very preliminary mechanical concept of ONIRICA appears in line with the available volume.

SCOWL would be attached to the adapter and does presently exceed the allocated volume by a small amount only.

MOMFIS will need to be mounted on a bench structure inclusive of a derotator. The present design exceeds the allocated volume by a relatively large amount. The design will have to be optimized or possibly partly descoped to fit in the focal station volume.

Most of the instruments include large cryostats. An overview of the cooling requirements has not been prepared yet. Effects of the changes in the orientation with respect to gravity for the large cryostats- cryo-tanks has also to be investigated.

Observatory Site

Both the thermal and sub-millimetre instruments (T-OWL and SCOWL) call for a site with a very low content of precipitable H_2O. For SCOWL a dry. high altitude site is a must to achieve a competitive performance.

Optimal results (in particular values close to the theoretical diffraction limit) with some of the foreseen AO systems will be achieved in nights of optimal seeing only. Atmospheric properties of the site must be carefully considered together with a likely instrument package to optimize the efficiency of the observatory.

Instrument / Requirement	CODEX	QuantEYE	HyTNIC	ONIRICA	EPICS	MOMFIS	T-OWL	SCOWL
Field diameter	Center (2”)	Center (2”) + pick-up arm over 3’	Center (1”)	Diffr.limited ≤ 1’; 3’ x 3’ at ~10 times lower resol.	Center (2”)	5’	≤ 30”	2.5’ x 2.5
Wav. Range µm	0.4-0.7	0.4 – 0.8	1.1- 1.6	0.8- 2.5	0.6- 1.9	0.8- 2.5	2.5-20	250-450-850
AO system type	Not required*	Not required*	SCAO	MCAO. GLAO	XAO	MOAO	SCAO GLAO	Not req.+

Table 12-9 AO Requirements from Instruments

: seeing-reduced image quality desirable

+: high frequency monitoring of water content of atmosphere desirable

12.2.6 Adaptive Optics Requirement Overview

The development of AO system for OWL and the various configurations are described in detail in chapter 8 where references to the various instruments are also given. Table 12-9 gives an overview of the requirements from the instruments.

12.2.7 Detector Requirement Overview

The instruments for OWL which have been studied in this phase of the project do require special development of array detectors. The appear as possible extrapolation of current state of art but they will undoubtedly represent a major (in same cases dominant) fraction of the costs of the instruments. even taking into account the substantial cost/pixel reductions envisaged by potential suppliers.

Instrument	Wavelength-Range (μm)	Main Operating Modes	Pixel size (mas)	Instrument Detector needs
CODEX	0.4- 0.7	High velocity accuracy. visual spectrograph	n.a.	40-80 (4K x2K) CCDs or equivalent devices
QUANTEYE	0.4- 0.8	Photometry at 10^{-3} -10^{-9} second resolution	n.a.	2 (10 x 10) sparse SPAD arrays
HyTNIC	1.1- 1.6	High-contrast diffraction limited imaging	tbd	1 4K x 4K HgCdTe array (tbc)
EPICS	0.6- 1.9	Imaging and spectroscopy of earth-like planets (three observing modes)	1-2	2 (8K x 8K) HgCdTe mosaics; 8K x 4K frame transfer CCD; 8K x 8K HgCdTe mosaics
MOMFIS	0.9-2.5	Distributed multi IFU spectroscopy over 5 ' x 5' field	20-30	~ 50 (2K x 2K) HgCdTe
ONIRICA	0.9-2.5	Imaging at diffraction limit over extended field	1-2(DL). 10-20 (wide field)	~ 60 (4K x 4K) HgCdTe arrays for 30" DL field.
T-OWL	2.5-27	Imaging. low. medium and high resolution spectroscopy	3.5- 7	2 (2K x 2K) InSb; 12 (1K x 1K) SiAs (tbc)
SCOWL	250-450-850	Imaging in three sub-mm bands	~1000	Mosaic of 16 (41 x 32) Transition Edge Sensors (SCUBA-2 detectors) or equivalent KIDs

Table 12-10 Detector Array Requirement

Table 12-10 presents an overview of the detector needs as derived from the possible focal plane configurations of the 8 instrument studied in this phase. It is obviously a very preliminary estimate.The suite of instruments which have been conceptually investigated in this phase of the OWL project does not represent the final complement of instruments to be built for the future European ELT. They can however be effectively used for a preliminary assessment of the likely needs in detector area and they give the following results:

- CODEX is the only instrument which requires a large number of CCDs or equivalent devices. The number of devices (~ 40 4K x 2K for the five spectrograph configuration) is of the same order of magnitude of what is used in wide field cameras of the last generation. Operating properties are also very close to those of existing devices. Given this. they should not represent a major procurement issue. The polarimetric mode of EPICS requires low noise. large size CCDs or equivalent devices to be read at relatively high speed. While devices of that size and characteristics do not exist at present. they are conceivable as a development of current devices.

- OWL will deploy its unique diffraction-limited capability with the help of AO systems which for the first years of operation will be effective at IR wavelength only. Key OWL instruments like MOMFIS and ONIRICA operating at NIR wavelengths do require a very large number of NIR arrays to sample a field of reasonable size at or close to diffraction limit. At the current market value. the cost of these detectors will exceed the likely instrumentation budget for OWL by a factor ~10. NIR array manufacturers (specifically Rockwell Scientific. see RD528) have however signalled that substantial cost reduction could be achieved if the number of 4k x 4k arrays on order exceeds is significant (>100 units).
- Detectors for the thermal infrared (2 – 17 µm) do require a factor of ~4 increase in area with respect to today's arrays. Around 15 devices would be required by a T-OWL type instrument. This appears a manageable development.
- Instruments like QuantEYE and SCOWL do require very special detectors. which do represent significant upgrades of state-of-the art devices of the same type. Their development will have to be properly supported by dedicated funding.

In addition to the science arrays. it is necessary to account for the detectors needed for the telescope tracking. for the active controls of the mirror and for wavefront sensing. The preliminary concept of the adaptors (6 units) and its active optics sensing probes calls for ~ 30 (2K x 2K) visual-red CCDs to be read at ~1 Hz frequency. The requirement for the detectors for the wavefront sensing are more variate as they are strictly related to the type of AO system to be implemented and the wavelength region where the images have to be corrected. A preliminary view can be extracted from chapter 8.