



**N G - C F H T**

The Next Generation

Canada-France-Hawaii Telescope

*Replacement study, phase 1 report*

*November 2000*

**T C F H - P G**

Le Télescope Canada-France-Hawaii

de la Prochaine Génération

*Etude de remplacement, rapport de phase 1*

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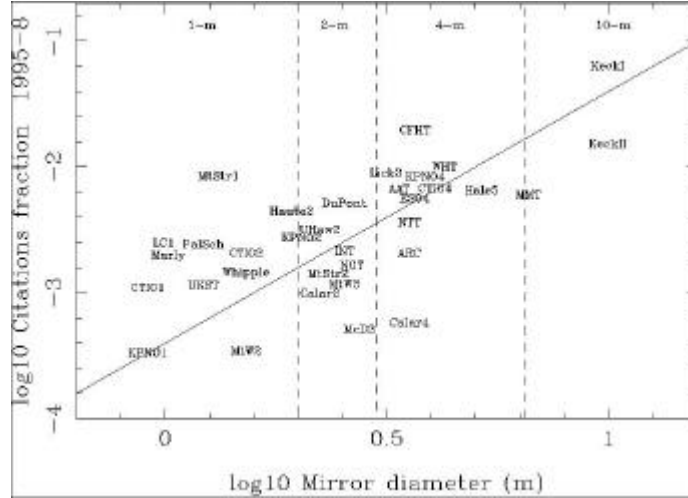
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# 1. Introduction

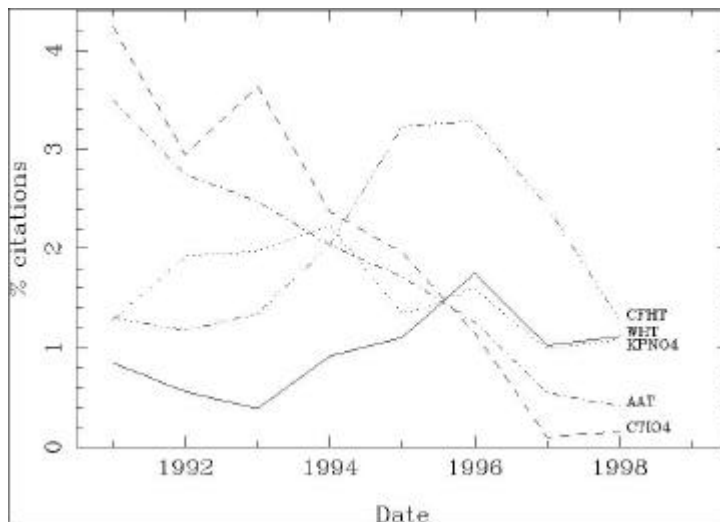
The Canada-France-Hawaii Telescope (CFHT) saw its first light in mid 1979. It is now more than 21-year old. Thanks to the very best conditions on top of the Mauna Kea and to the evolution of the instrumentation in phase with the evolving science requirements CFHT was during these 21 years, one of the best (if not *The Best*) telescopes in the world (Fig.1). However, with its 3.6 m diameter, it has recently been bypassed by larger telescopes. Indeed, the competition with the 10-m class telescopes is now tough and the decrease of the CFHT citation fraction (Fig.2) seems to be correlated with the advent of Keck and VLT. Being aware of those potential problems, the CFHT Science Advisory Council (SAC) solicited proposals from the CFH community groups to replace the present CFHT by a world-class research facility before the end of the decade.



**Figure 1:** Citation fraction for the period 1995-1998 vs. telescope diameter of a large number of ground-based telescope. Note that CFHT is the leading 4-m telescope with respect to this criterion during this 4-yr period. Figure extracted from Benn & Sanchez (2000).

When a community is building a new telescope, this operation is often motivated by the need to observe fainter and fainter sources. We therefore try to increase the size of the primary mirror to reach farther in the universe but also fainter in the luminosity functions. But, beyond the need to collect photons, the way we are using them is more important. The development of new technologies (e.g. Wavefront Control, Adaptive Optics = AO, Micro Opto Electro Mechanical Systems = MOEMS) will certainly provide a state-of-the-art telescope coupled with state-of-the-art instruments and we believe that scientific goals in the first decade of the coming century will be more focused on physical analyses. New telescopes must be very competitive to the present-generation of 8-m telescopes. Our goal for NG-CFHT is to provide a large field of view ( 1 sq. degree), combined with an image quality by at least two times better than image quality currently obtained at present-day 8-m telescopes. The facility proposed here would be by several order of magnitude superior to present day 8 meter telescopes, allowing for example the study of a  $z > 1$  galaxy as if it was a nearby galaxy observed with the present day CFHT.

Another parameter that we believe to be crucial is the scientific efficiency of a telescope. Beyond the increase in collecting surface, the success of a telescope is linked to the way it is used. The larger the number of astronomers who gain access to the telescope, the larger the chance to see breakthrough results coming out from this telescope. HST showed that parallel observations is scientifically rewarding. We must develop NG-CFHT to make it possible to handle this way of observing with several instruments.



**Figure 2:** Citation fraction with a 3-yr running mean vs. time for a sample of five 4-m telescopes. In this figure is presented the fractions of all observational papers. Note again the leading position of CFHT in the 1994-1998 period. The decrease in the late-90s might be due to the progressive use of VLT : the commission date for first VLT instruments (ISAAC and FORS) on VLT-1 are about at the same date. Figure extracted from Benn & Sanchez (2000).

In the present report, we will present our project to build a Next Generation 16-m Canada France Hawaii Telescope (NG-CFHT). This facility would replace the present CFHT by the end of this decade.

## 2. Science Goals

The science objectives of most of the projects due by the end of the decade are often similar and linked in some way to NASA's Origins program. This large and ambitious program summarizes all the efforts of astronomers since the first human looked at the sky. Of course, it will benefit from a world-wide effort but no one telescope will be able to fully address the two questions raised ([origins.jpl.nasa.gov/whatis/whatis.html](http://origins.jpl.nasa.gov/whatis/whatis.html)) :

- **Where do we come from ?**
- **Are we alone ?**

Translated into an astronomical wording, the questions posed are those of the origin of galaxies - and stars within them - and the origin of planets - and life onto them. A success will only be possible through a collaborative work of all telescopes observing throughout the whole electromagnetic spectrum in space or on the ground. For this very reason and to be scientifically efficient, we must define and finely tune the characteristics of NG-CFHT in order not to overlap too much with other facilities working in the same wavelength range (for instance NGST, ground-based 10-m telescopes and other larger telescopes still to be built, very wide field-of-view telescopes such as VISTA, etc.). We have therefore started this study by trying to find the best niche(s) in the context of a telescope usable by the Canada-France-Hawaii communities. In the remainder of this section, we centre our analysis on two main themes which will be key-programs for the NG-CFHT : (1) formation and evolution of galaxies and (2) formation of planetary systems. Of course, a large number of other topics not detailed here will certainly take advantage of a 16-m telescope onto Mauna Kea.

## 2.1. Formation and Evolution of Galaxies

### 2.1.1. Galaxies

It is no surprise that understanding the formation of galaxies and their evolution up to the present day universe is within the core of most extragalactic programs. The HST and large ground-based telescope have pushed the limits of the observations to very faint objects and high spatial resolutions. The NG-CFHT Study Group defined the origin and evolution of galaxies as one of the central topics. By the end of the decade NGST and ALMA will should be able to image the first galaxies and the high-redshift universe is among the highest priority program.

*CFHT* (mainly from the CFRS project and follow-up programs), *HST* (essentially through the Hubble Deep Fields) and the 10-m class ground-based telescopes have allowed tremendous progresses in the last five years and we have now a rather good idea of the global star formation history over most of the universe lifetime. However, we must develop now facilities able to carry out physical studies of galaxies numerous enough to get representative samples within sub-classes (luminosity, morphological types, redshift, etc.). Indeed, a number of open questions are still waiting observational constraints :

- **Did all galaxies form through a hierarchical process (e.g. Cold Dark Matter model) where sub-clumps/disky systems formed in dark matter halos and later merged to form large galaxies, or did some of them form through a monolithic collapse?**
- **What is the evolution with time of the Hubble sequence?**
- **At which epochs was most of the stellar and metal content of galaxies formed?**

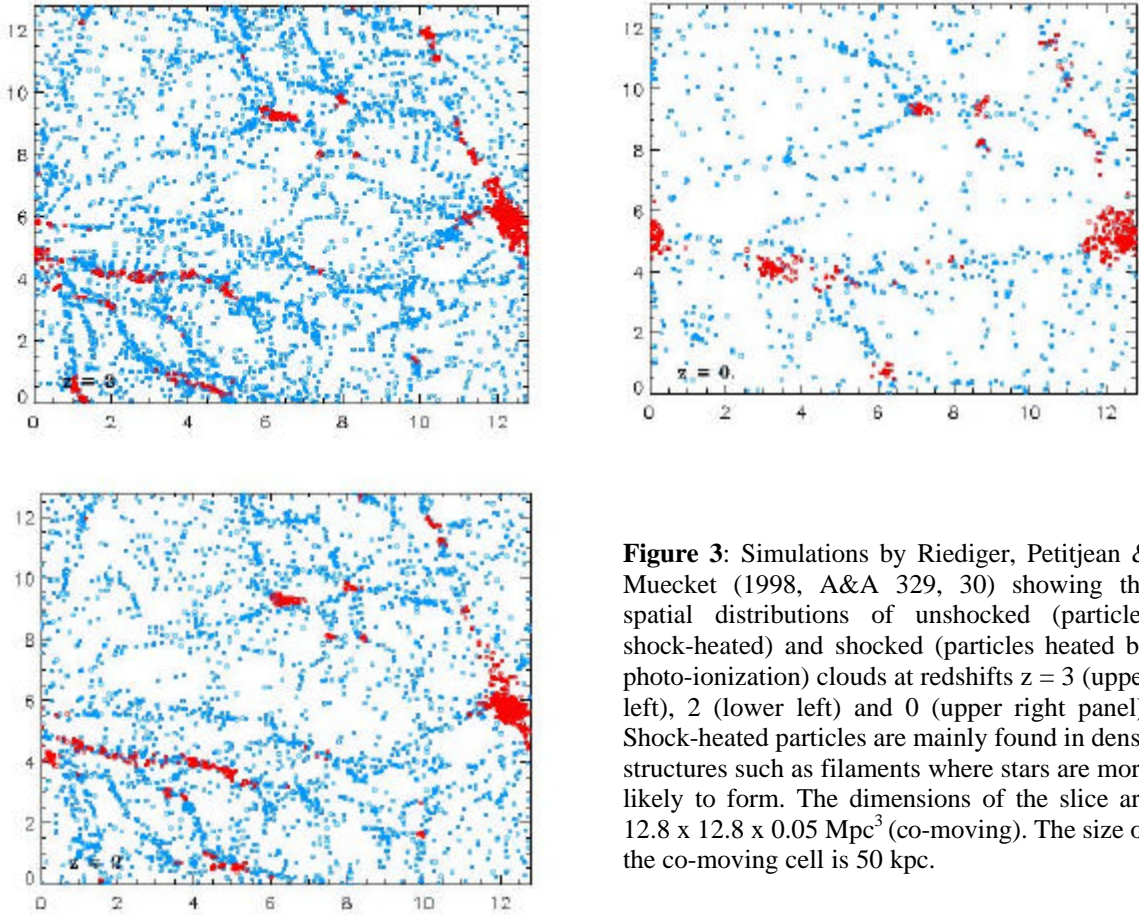
#### 2.1.1.1. *Quasars and Active Galactic Nuclei: Reconstruction of the density field of the intergalactic medium using absorption lines in quasars*

A large number of absorption lines are observed in the spectrum of quasars. Through this so-called Ly $\alpha$  forest, we are able to get some information on neutral hydrogen in intergalactic clouds. At high redshifts ( $z > 2$ ), the Ly $\alpha$  forest contains an amount of baryons very close to the predictions from the primordial nucleo-synthesis theory. Improving our knowledge of the Ly $\alpha$  forest is therefore a priority to understand the first phases in the formation of galaxies since it constitutes the gas reservoir out of which stars and galaxies formed.

Recently, a coherent model for the spatial distribution of intergalactic gas emerged from a confrontation of the absorption line observations and the results of N-body numerical simulations. It appeared that the spatial distribution of the clouds forming the Ly $\alpha$  forest follows the filamentary structure of dark matter. Nodes are likely to be the preferential galaxy formation sites (Fig.3). Studying the spatial distribution of the absorbing gas at high redshift is therefore a unique and powerful way of probing the structure of the universe, of following their cosmological evolution and to get crucial information on the formation of galaxies.

On the one side, by observing independent lines of sight, we can only have access to the 1D-structuration which mixes the local spatial and kinematical (clouds within a given halo) structures of the object (Hubble flow) and it is very difficult to disentangle these two effects. On the other side, the observations of several adjacent lines of sight allows to study the correlation of absorptions along different lines of sight. And, if the number of lines of sight is sufficient, we can characterize the 3D-structuration. Besides, inversion methods can be used to reconstruct the whole 3D-density field.





**Figure 3:** Simulations by Riediger, Petitjean & Muecket (1998, A&A 329, 30) showing the spatial distributions of unshocked (particles shock-heated) and shocked (particles heated by photo-ionization) clouds at redshifts  $z = 3$  (upper left), 2 (lower left) and 0 (upper right panel). Shock-heated particles are mainly found in dense structures such as filaments where stars are more likely to form. The dimensions of the slice are  $12.8 \times 12.8 \times 0.05 \text{ Mpc}^3$  (co-moving). The size of the co-moving cell is 50 kpc.

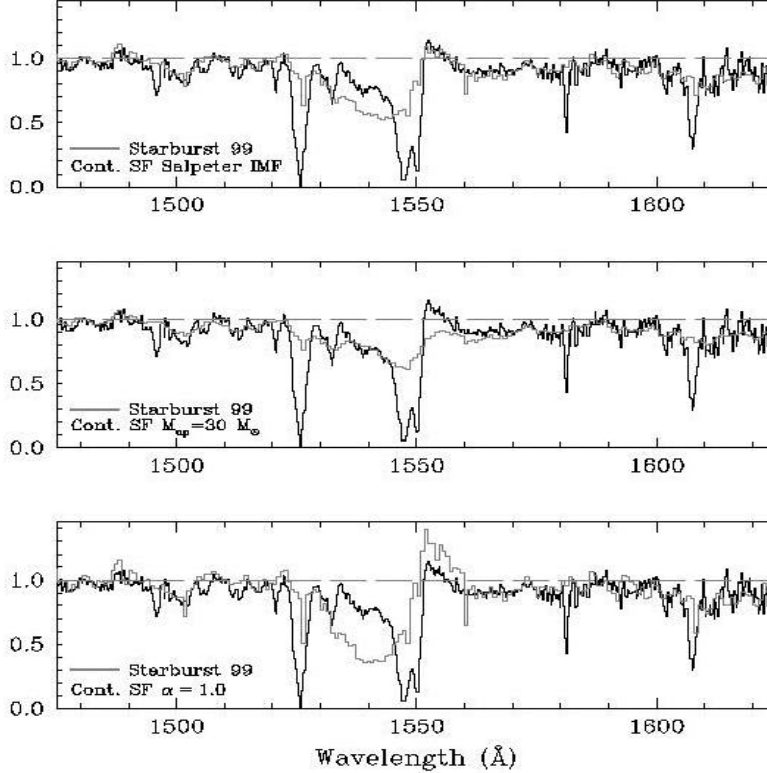
This reconstruction can only be performed if a large number of lines of sight are observed within the same field of view, with a spectral resolution of  $R \sim 5000$ . Assuming a magnitude for the faintest accessible objects of the order of  $V \sim 23$ , we would need exposure times of 20h or more for a 16 -m telescope. A minimum multiplexing of 10 within a field of view of 20 arcmin is necessary. We must also observe in the blue around  $3500 \text{ \AA}$  for the Ly $\alpha$  forest but the study of C IV around  $5000 \text{ \AA}$  could be carried out as well.

#### 2.1.1.2. *Star Formation History*

The star formation activity is mainly traced by spectral features like the hydrogen Balmer lines and the ultraviolet continuum shortward of  $2500 \text{ \AA}$ . For instance, the H $\alpha$  recombination line is commonly used (e.g. Kennicutt 1983) to study the Star Formation Rate (SFR) of star-forming objects at low and moderate redshift ( $z \sim 0.4$  in the visible and  $z \sim 1.5$  in the J -band). The number of photons emitted by the ionized gas of an HII region is directly proportional to the number of young stars and to the SFR over timescales of the order of  $10^6$  years. This is the lifetime of massive ( $M > 10 M_{\odot}$ ) stars emitting the Lyman continuum photons. The integrated ultraviolet light of a star forming population decreases after a single burst or reaches a plateau for a constant SFR. Under the latter assumption (reasonable to the scale of a large galaxy), the rest frame ultraviolet (shortward  $2500 \text{ \AA}$ ) directly traces the SFR in galaxies over timescales over 100 Myrs. This is the lifetime of Intermediate-mass stars ( $2 < M(M_{\odot}) < 10$ ). Multi-Object spectroscopy with  $R \sim 1000$  of a large sample of galaxies will provide the emission line diagnostics for SFR while low spectral resolution spectroscopy or imaging ( $R \sim 20 - 50$ ) will provide information on the rest-frame UV.

### 2.1.1.3. Initial Mass Function

The far UV absorption lines like Ly $\beta$ , CII or OVI (1030 -1040 Å) as well as CIV (1550Å) and SiIV (1400Å) are also very sensitive to the star formation history and Initial mass function of massive stars (Fig.4 and Leitherer et al. 1995). The Balmer lines and the rest-frame UV emission provide two independent estimates of the previous star formation events. Hence, a small variation of the current star formation rate will produce a very large effect in the ultraviolet while hardly detectable in visible rest-frame (for instance Fig.1 of Leitherer et al 1999, [www.stsci.edu/science/starburst99](http://www.stsci.edu/science/starburst99)). An interesting way to constrain the upper IMF is to compare the H $\alpha$  flux related to very massive short-lived stars ( $M > 10 M_{\odot}$ ) with the ultraviolet continuum dominated by intermediate stars ( $2 < M(M_{\odot}) < 10$ ) (Buat et al. 1987; Glazebrook et al.1999).

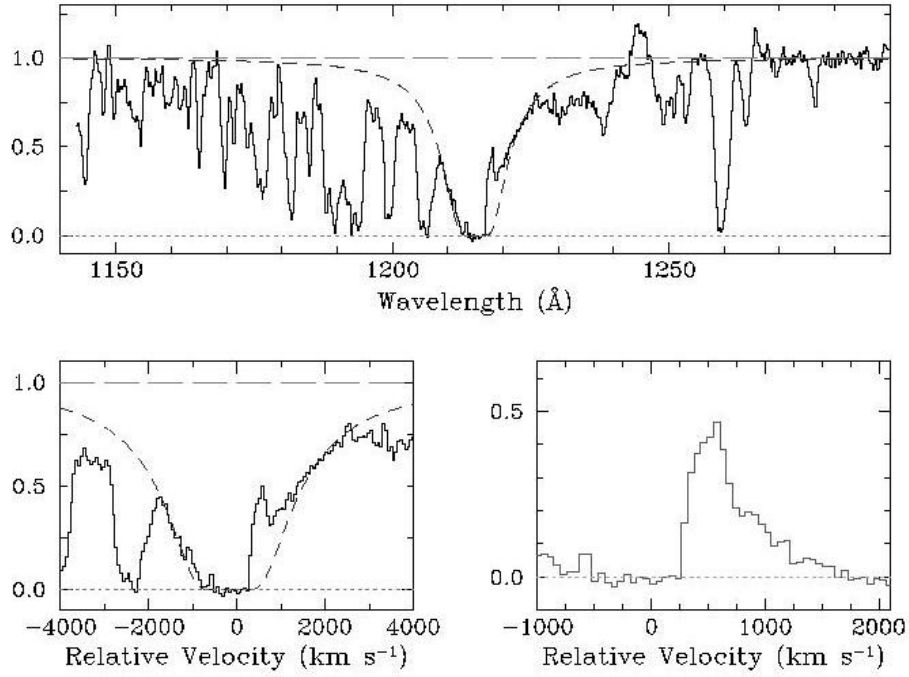


**Figure 4:** Comparison of the observed spectrum of the lensed galaxy at  $z = 2.72$  MS1512-cB58 observed (black spectrum) by Pettini et al. (2000) with different spectral synthesis models (grey spectrum) from Leitherer et al. (1999). The profile of the CIV line can be decomposed into several features in absorption and emission which provide indication on the Star Formation Rate but also on the Initial Mass Function in this galaxy. It must be noted that this spectrum is the best UV-rest frame spectrum of a starburst galaxy observed thanks to the magnification (by a factor of 30 compared to a normal  $z \sim 3$  galaxy).

### 2.1.1.4. Lyman $\alpha$ emission line and Lyman break

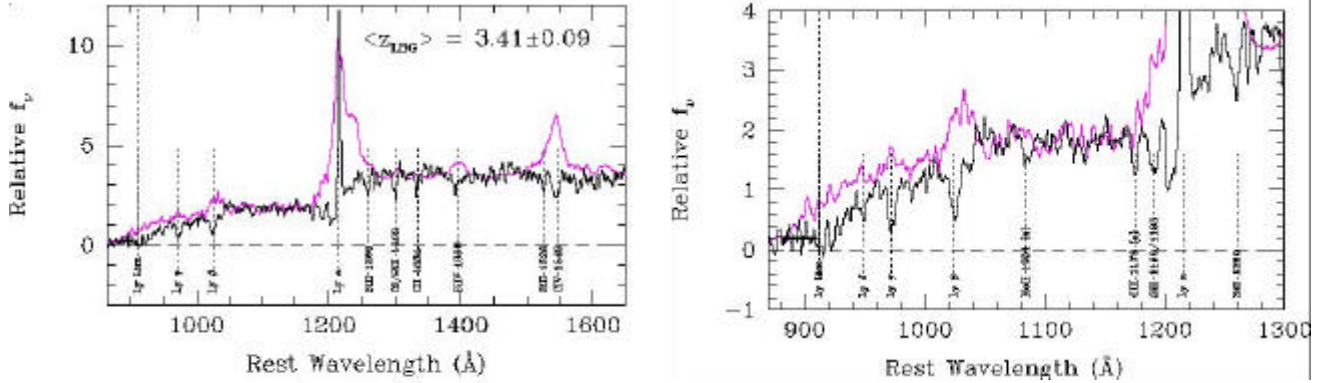
The Ly $\alpha$  emission line is expected to be in principle very intense in starburst galaxies. Nevertheless, this emission has been found to be weak or absent in star-forming galaxies at low and high redshift (e.g. Hartmann et al. 1998). Very complex processes are probably at the origin of this depletion of the Ly $\alpha$  photons like the resonant scattering and geometrical and velocity effects in the HII regions and the HI surrounding gas (e.g. Kunth et al. 1998, Tenorio Tagle et al 1999). This might lead to asymmetric line profiles (Fig. 5). Moreover, timescale effects might also intervene, and very young starbursts (less than 10 Myr) can be found with a very large Lyman  $\alpha$  equivalent width i.e. a very strong line and almost no underlying continuum (Stern et al. 2000). The observation of the Lyman  $\alpha$  line in a large number of high-redshift galaxies and with a high spectral resolution will allow to test the various scenarii proposed for this line.





**Figure. 5** :Decomposition of the Lyman  $\alpha$  profile of the  $z = 2.72$  galaxy MS1512-cB58 observed by Pettini et al. (2000). In the top panel, the black spectrum is the observed one and the dashed one is the theoretical absorption profile for  $N(\text{HI}) = 7.5 \times 10^{20} \text{ cm}^{-2}$ . In the bottom left panels is presented the same line on a velocity scale. In the bottom right panel, the residual Lyman  $\alpha$  in emission after subtraction of the absorption component. This spectrum is observed with a spectral resolution  $R = 5000$ .

The Lyman break provide a powerful way of estimating the redshift, it might be used up to  $z = 7$  in the visible and up to  $z = 12$  in the J -band. With the NG-CFHT we can also hope to measure the escape fraction of the ionizing photons shortward  $912\text{\AA}$  which is an important clue to understand the ionization of the early universe (Steidel et al. 2000).



**Figure. 6** : This figure presents a composite spectrum of 29 Lyman Break Galaxies at  $\langle z \rangle = 3.40$  (in black) observed by Steidel et al. (2000) along with a composite spectrum of 12 QSOs (in violet) in the redshift range  $2.5 < z < 3.5$ . A significative emission over the rest -frame wavelength range  $880\text{--}910\text{\AA}$  seems to be present in the LBG spectrum indicating that the LBGs provide more hydrogen ionising photons than QSOs at the same redshift. Carrying out these studies for galaxies at  $z < 4$  implies very good performances of NG-CFHT below  $4000\text{\AA}$ .

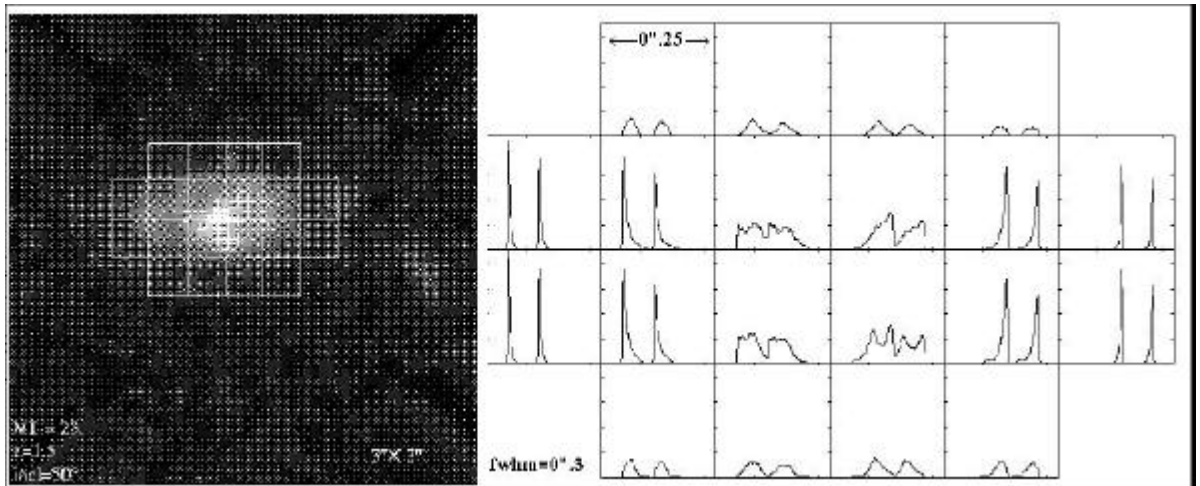
#### 2.1.1.5. Extinction in galaxies

A major limitation in using the UV emission of galaxies and the emission lines is the effects of the dust extinction which can be dramatic. The observation of several Balmer lines and in particular the Balmer decrement  $H\alpha / H\beta$  will allow to estimate the extinction in the lines. In starburst galaxies, the extinction in the UV continuum can be measured from the shape of the continuum (Calzetti et al. 1994). However, this relationship does not seem to hold for massive starbursts, as those detected firstly by IRAS in the nearby Universe, then those detected by ISO or SCUBA in the distant Universe. The knowledge of the star formation history of the galaxies needs data over a large range of wavelength, from the far UV to the near-infrared (rest-frame). At high redshift it corresponds to observation from visible to infra-red. The NGST will essentially observe in the near infrared, the rest-frame ultraviolet continuum ( $1000 < \lambda < 2500\text{\AA}$ ) will be redshifted in the visible for most of the observed high redshift galaxies will be observed from large ground based telescopes such as NG-CFHT if NGST has no or little visible capabilities. To estimate the extinction from the Balmer lines implies that high spectral resolution ( $R \sim 2000$ ) are needed to resolve the blend of the absorption + emission features.

#### 2.1.1.6. Kinematics

Key questions in astrophysics are to understand the physical mechanisms which drive the galaxy and star formations. Results from the recent deep surveys (CFRS, HDF, DEEP) show that galaxies beyond  $z=0.5$  were smaller, more irregular and showing higher star formation than present-day galaxies. IRAS, COBE and more recently ISO, have shown that nearly half of the light emitted during star formation is reprocessed by dust to IR wavelengths. The corresponding galaxies (from  $z=0$  to  $z=1.5$ ) show evidences for interactions and merging (Flores et al, 1999; Hammer et al, 2000).

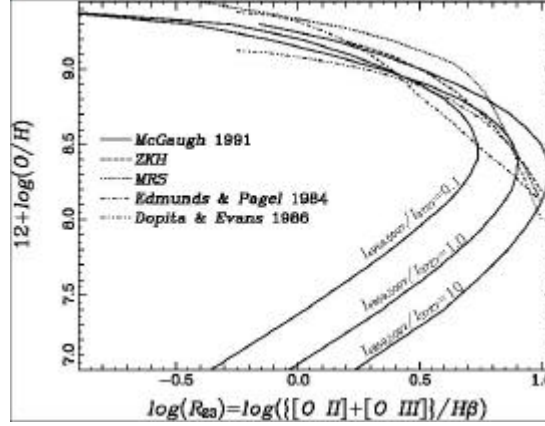
The way galaxies are assembling, and how they are re-distributing their masses, velocities and angular momentum, are largely unknown. Kinematics and chemistry of galaxies should be studied at different redshifts, to determine how important the merging phenomenon is, to know the distribution of disks and spheroids at various times, and to firmly establish the evolution of the Hubble sequence. Distant galaxies are very irregular on scales smaller than  $0''.5$ . Their dynamical "sizes" are generally not larger than 50 km/s. Only 3D spectroscopy, with resolving power of a few 10 km/s and high spatial resolution, can detail their velocity fields (Fig. 6). NG-CFHT with its large field of view would allow detailed and simultaneous study of a large number of galaxies.



**Figure. 7 :** This Figure presents the simulated observation of a galaxy at a redshift  $z = 1.5$  as it would be observed by NG-CFHT. The right panel shows the 3D-spectroscopy carried out on this galaxy. Such high spectral resolution data, providing an exceptional insight into the physics of the galaxy, is impossible today. These observations are carried out with a spectral resolution  $R \sim 10000$ .

### 2.1.1.7. Metal Abundance

NG-CFHT will also be a key-facility to measure the abundance of intermediate redshift galaxies. One of the best tool to determine the oxygen abundance for instance will be to use the Edmunds & Pagel (1984, MNRAS 211, 507)  $R_{23}$  index defined by:



**Figure. 8 :** This figure from Kobulnicky et al. (1999) presents the relationship between the index  $R_{23}$  and the oxygen abundance  $O/H$  from several authors. However, the relationship is degenerated and may require some a priori knowledge of the galaxy metallicity. Indeed, at low metallicities ( $\log Z/Z_0 = -0.5$  corresponds to  $12 + \log(O/H) \approx 8.4$ ) expected at high redshift, the degeneracy is raised.

$$R_{23} = ([OII]\lambda 3727, 3729 + [OIII]\lambda 4959, 5007) / H\beta$$

For metal abundance larger than  $0.2 Z_0$ , the oxygen abundance is monotonically related to  $R_{23}$ . This technique has already been applied to high-redshift galaxies. To carry out these studies, we will also need a good sensitivity down to ground-based UV wavelengths for low-redshift galaxies.

### 2.1.1.8. Morphology

We cannot explain so far the origin of the Hubble sequence. Moreover, the distribution of galaxies in the Hubble sequence is apparently strongly evolving with the redshift: the frequency of spiral galaxies is decreasing at high redshift while the frequency of irregular galaxies is increasing (van den Bergh et al. 1996; Driver et al. 1998). Brinchmann et al. (1998) performed simulations and observed an apparent migration of galaxies towards later Hubble types which can be interpreted as a misclassification of galaxies by about 24 % at  $z \approx 1$ . Bunker et al. (2000) analyze the redshift evolution of high-redshift galaxies directly from multi-wavelength data. They compare the appearance of galaxies at the same rest-frame wavelengths and find that morphological K-corrections are generally not very important. However, in the specific case of spiral galaxies, the effect is more important and when the rest-frame wavelength moves to the UV, the morphology does become more irregular. By using rest-frame ultraviolet images Burgarella et al. (2000) and Kuchinski et al. (2000) confirms this phenomenon.

As already noted before (e.g. Bohlin et al. 1991; Kuchinski et al. 2000), it seems necessary that this irregular-shifting of spiral galaxies be taken into account in morphology-sensitive works. For instance, works have been using the morphology classification of HDF galaxies to compute morphological-dependent number-counts (Abraham et al. 1996; Driver et al. 1998). The misclassification of spiral galaxies due to band-shifting is a strong bias that needs to be quantified before going on in the comparison of observations with models as underlined by Abraham et al. (1996). The effect might be negligible at redshifts below  $z \approx 1$  but it becomes crucial when moving at redshifts of the order of  $z \approx 2$ . Observing UV rest-frame galaxies with high S/N ratio will play a key-role in the interpretation of future observations and in the understanding of the formation and evolution of galaxies.

### 2.1.1.9. *Science Requirements for Galaxies*

We conclude that the best niche will be to perform a physical analysis (chemistry, kinematics, morphology, stellar formation) of galaxies on a large number of objects. The field of view is a first constraint. As the limiting magnitude for point sources will be around  $m_{\text{lim}} = 30$  for 8h-exposures. We can use the HDF to compute the total density of sources:  $600 \text{ arcmin}^{-2}$ . The number of high-redshift objects ( $z > 2$ ) is lower and around  $100 \text{ arcmin}^{-2}$  in imaging. In spectroscopy, the limiting magnitude will be around  $m_{\text{lim}} = 24$ , providing about  $15 \text{ galaxies arcmin}^{-2}$  for high resolution spectroscopy ( $3000 < R < 20000$ ). A wide field of view is necessary (0.5 to 1 degree) along with spectral resolutions unreachable with NGST over the whole visible / near-infrared wavelength bands are therefore needed. A number of themes also call for ground-based ultraviolet (below  $4000\text{\AA}$ ) capabilities. On the other hand, we need lower spectral resolution observations to study spectral energy distributions: multi-band filters with  $R \sim 20-50$  can be used in addition to more wide-band filters in imaging. In order to match the size of high-redshift, the spatial resolution must be of the order of  $\sim 0.2 \text{ arcsec}$ .

## 2.1.2. Stellar populations in resolved galaxies

### 2.1.2.1. *Individual stars*

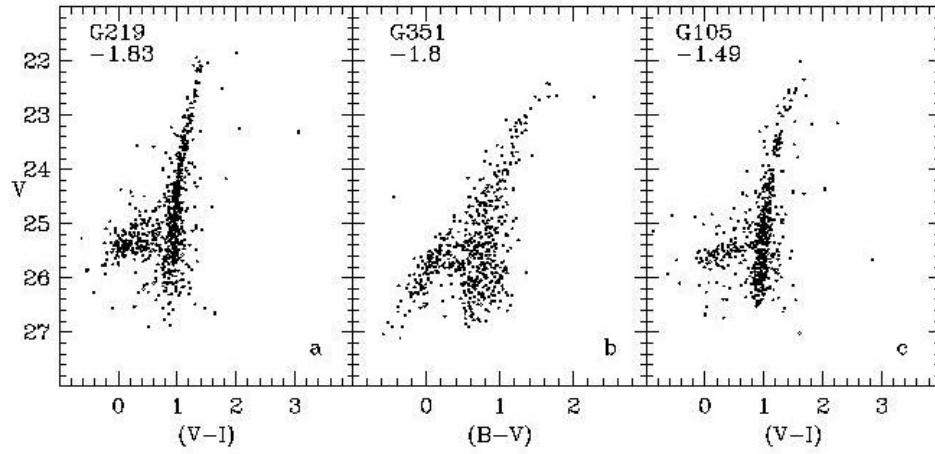
Colour-magnitude diagrams remain the most secure way of analysing the nature of a composite stellar population. Individual stellar light curves (e.g. RR Lyrae, with  $M_V = 1$ , or Cepheids, brighter) give relatively direct access to distance. Red giant branch positions and slopes indicate metallicity. The main sequence turn-off and the extent of the Asymptotic Giant Branch in luminosity are measures of age. All this precious information about the stellar population is invaluable help in the understanding of the nature and evolutionary status of the target galaxy.

Determination of age and metallicity distributions are also a preliminary requirement in studies of some of the remaining most fundamental problems of stellar evolution models. One example is the "second parameter effect": the physical parameter(s) responsible for very significant changes in the morphology of horizontal branches, in old populations with similar metallicities and apparently similar ages, is (are) unknown (e.g. Sandage & Wiley 1967, van den Bergh 1967; Sweigart & Catelan 1998; Sarajedini et al. 2000).

A sensitive telescope allows to reach intrinsically fainter stars. But fainter stars are more numerous, and the confusion limit will be reached in the central regions of dense galaxies even with the highest spatial resolutions. A wide field will allow exploration of large outer regions of galaxies, where the stellar density is sufficiently low.

In practice, with a spatial resolution of  $0.2''$ , the confusion limit for  $V=30$  stars will be reached if more than  $\sim 10$  stars brighter than  $V=30$  are present within  $1''$ . Population synthesis models show that, at distances smaller than about 100 Mpc, main sequence stars with  $V < 30$  are responsible for more than 90 % of the integrated light produced by all the main sequence stars present (assuming constant star formation), and that giants contribute similar amounts of optical light in addition. The limit of 10 detectable stars per square arcmin thus roughly corresponds to a surface brightness of  $26.5-27 \text{ mag.arcsec}^{-2}$  (exact values depend on the precise star formation history). In brighter regions, the depth to which photometry of individual stars will remain possible will be limited by confusion instead of the telescope's sensitivity.

At higher spatial resolution (40 mas), the confusion limit of, say,  $100 \text{ stars arcsec}^{-2}$  is reached for  $V=30$  stars when the optical surface brightness is brighter than about  $24 \text{ mag arcsec}^{-2}$  with the same assumptions as above.

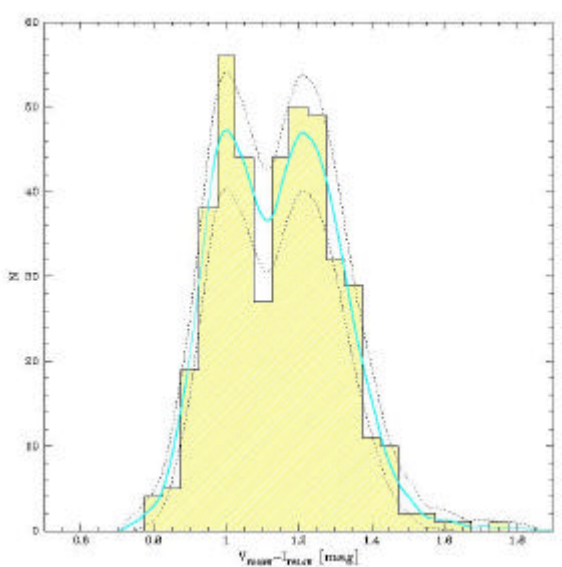


**Figure 9 :** The Color Magnitude Diagrams built by Fusi Pecci et al. (1996, AJ 112, 1461) on three globular clusters of M31 are examples of performances that NG-CFHT will be able to perform up to distances larger than 50 Mpc.

Stars with apparent  $V=30$  have  $M_V = 1$  at 60 Mpc (about 4 solar masses on the main sequence, or typical horizontal-branch stars in globular clusters),  $M_V = 3.5$  at 6 Mpc (about 1.5 solar masses on the main sequence). Thus, horizontal branch stars can be counted out to 60 Mpc (Fig. 9) in objects with surface brightnesses fainter than 27.5 ( $0.2''$  resolution) or than about 25 (higher resolution).

#### 2.1.2.2. *Stellar clusters in external galaxies*

With a 16-m telescope the determination of cluster ages, metallicity and masses will be extended to a large number of nearby galaxies. Here we will address some specific topics related to this field. The globular clusters are considered as fossils of the galaxy formation. At present only the globular clusters around giant ellipticals have been studied with a good statistics and multiple sub-populations are frequently found which suggests that these galaxies have experienced more than one major star formation episode (Fig. 10). Nevertheless, such studies are restricted to very nearby giant ellipticals (up to the Virgo cluster) and little is known about low-luminosity field ellipticals as well as about the globular cluster systems around spiral galaxies outside the local group. Imaging capabilities down to  $V = 30$  mag and a spectroscopic mode down to  $V = 25$  will lead to considerable progress in this field.



**Figure 10 :** Color distributions of the globular clusters around the elliptical galaxy NGC 4472 from Puzia et al. (1999, AJ 118, 777). A bimodal distribution clearly appears at the 99.99 % confidence level indicating that two globular cluster populations are present and consequently that there has been more than one stellar formation episode in this galaxy. Such studies can be carried out up to 20-30 Mpc today and may be extended up to 100 Mpc with NG-CFHT.



A typical globular cluster ( $M_v = -7.4$ ) will be seen up to a distance of 300 Mpc. Nevertheless, a good sampling of the gaussian luminosity function of globular clusters needs to reach at least 1 or 2 sigma above the peak. With a peak at  $M_v = -7.4$  and  $\sigma=1.3$  (typical values for spiral and elliptical galaxies), the luminosity function will be properly traced up to 100 Mpc. In the same way color distributions will also be obtained for such a distance.

For stellar clusters, spectroscopy is the only way to disentangle the effects of age and metallicity. Indeed, colours are affected by a degeneracy since both parameters have similar effects on them. A moderate resolution ( $R$  of some thousands) is sufficient to measure the spectral indices. It is mandatory to have a good statistics, i.e a large number of spectra of globular clusters around each galaxy (more than 100), with a limiting magnitude of 25 in the spectroscopic mode and spectral resolutions in the range 500  $R$  2000 and if we want to reach the peak of the luminosity function, we can observe globular cluster systems up to 30 Mpc, that is to say twice the Virgo distance.

The determination of cluster masses, once their age and metallicity are determined, gives access to the mass/light ratio and thus provides constraints on the lower part of the stellar mass function (with standard mass functions, low mass stars contribute to the mass, but insignificantly to the light). Mass determinations can be derived from velocity dispersion measurements and dynamical models. The obtention of a light profile as a constraint on the adequate dynamical model improves the precision of the estimates. Colour gradients are useful complements, as they may indicate the importance of mass segregation. A well resolved profile can be obtained for a 10pc diameter cluster with a spatial resolution of 0.2" at a distance of 1 Mpc (10 Mpc at 0.02" resolution).

#### 2.1.2.3. *Galactic structure in terms of stellar ages and abundance (in gas and stars)*

The chemical and stellar evolution of galaxies is responsible for global trends such as the correlation between metallicity and luminosity, that many of the competing galaxy evolution models succeed in reproducing. Model prediction differ in more subtle points, such as the spatial variations of the abundances in gas and in stars (primary/secondary elements, products of massive/intermediate mass stars). These gradients also reflect the intimate link between the structural and the chemical evolution of a galaxy. Their study is necessary to understand the respective roles of initial collapse, of gradual gas infall, of outflows induced by massive star formation, of dynamical perturbations and of many other mixing processes. Comparison with maps of the interstellar medium, produced for instance with sub-mm or radio arrays, will help us understand the conditions under which star formation occurs, and how the processed materials are redistributed.

Colour magnitude diagram studies will remain limited to an extended Local Group. Imaging spectroscopy / spectrophotometry will remain the main tool for the systematic exploration of the structure of external galaxies.

A large telescope pushes the surface brightness limits for spectroscopic/ spectrophotometric studies of the chemistry of galaxies and their stellar populations out to larger galactic radii. Searches for the limits of stellar populations in the dark halos of galaxies can be undertaken (large fields are useful here). High sensitivity also allows us to combine spectral and spatial information in objects of low intrinsic surface brightness: known low surface brightness galaxies have typical effective surface brightnesses of 25-26 mag / sq. arcsec and 3D spectroscopy becomes possible. In irregular galaxies, clearly separated studies of the background populations underlying the patchy brighter areas become possible, allowing us to distinguish purely from spatial changes in age, extinction and chemistry.

For a typical large spiral, the I band surface brightness in the central region is around 21.6 mag per square arcsec. It decreases by about one magnitude over one disk scale length, and thus reaches about 25.5 at about 5 scale lengths of the centre. For the Milky Way (with a scale length of 3.5 kpc), this limit would be reached at a radius of 17.5 kpc.

For large galaxies, light for spectroscopy may be integrated over about one square arcsec without too much loss in spatial information. A galaxy as large as the Milky Way could be observed spectroscopically out to its outer limbs with an interesting spatial resolution at a good 100 Mpc distance.

For smaller or more distant galaxies, the telescope's spatial resolution should not be degraded. Then, the 25.5 magnitudes required for spectroscopy must be received in, typically, a 10th of a square arcsecond; limiting surface brightnesses are of the order of 23 mag/sq. arcsec. For a twin of the Milky Way, this is reached at about 5 kpc from the center.

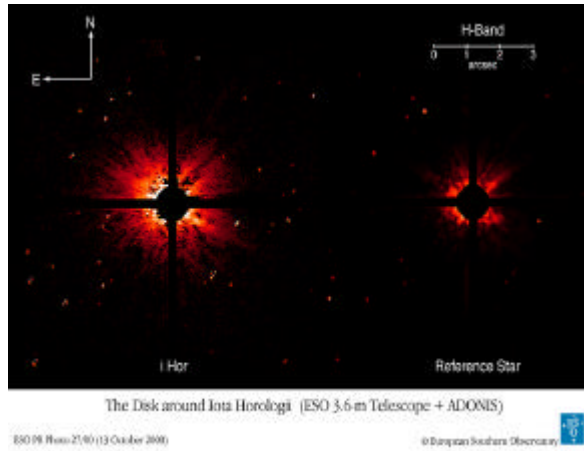
#### **2.1.2.4. *Science Requirements for Stellar Populations in Galaxies***

Stellar populations in galaxies require a high spatial resolution at 0.2 arcsec or less. The field of view must be large when we are dealing with the Milky Way or local galaxies but a few tens of arcmins is sufficient at larger distances. For very specific fields that the core of globular clusters and very dense fields, an even better spatial resolution (say 40 milliarcsecs or whatever the AO can provide) is mandatory. Spectral analysis call for high multiplexing (at least a few hundreds) and intermediate spectral resolutions (500 R 2000).

## **2.2. Formation of stars and planetary systems**

### **2.2.1.1. *Solar system***

The discovery of a faint object ( $R = 22.8$ ) in 1992 by Jewitt (1992, IAU Circular No. 5611) exhibiting a slow ( $3 \text{ arcsecs.hr}^{-1}$ ) motion led to the awareness of a large population of small bodies beyond Neptune at 30 - 50 AU from the sun and orbiting it. Further observations suggest that more than 100 000 (maybe millions if very small are taken into account) of such small bodies are located in a ring, which was later baptised the Kuiper Belt. The exploration of the outer Solar System has been largely driven by the desire to characterize the population of this region. The scientific interest for the Kuiper belt objects (KBO) is driven by the fact that they formed at the very beginning of the Solar system lifetime. The internal regions of the belt probably condensed very quickly to form the planets while the external regions only formed smaller objects. Consequently, the studies of small bodies in the Kuiper Belt will tell us about the accretional environment of the early Solar System. Studying their orbital distribution (which requires a field of the order of  $0.5 - 1$  degree in order to find them and track them) tells us about the dynamic processes which shaped our forming giant planets. Recent studies (e.g. Lynne Allen et al. 2000, astro-ph/0011037) suggest that the mean volume density of large ( $D > 160\text{km}$  KBOs is decreasing beyond  $\sim 50$  AU, implying that some process or event in the history of the Solar System has truncated the distribution of 160-km planetesimals at  $\sim 50$  AU. It is interesting to note that ring structures are observed around young systems where planets are still forming from circumstellar material (Fig. 11). It is probable that these ring structures are young structures analog to the Kuiper Belt in our solar system and that the central region has been partially cleared by the formation of grains into planetesimals. (Greaves et al. 1998, ApJ 506,133) Besides, it is thought that the Kuiper belt is a potential source for short-period comets. It can therefore play a role similar to the Oort cloud for long-period comets.



**Figure 11 :** Example of a dust disk detected around the star iota horologii at ESO with ADONIS. A planetary companion about twice as heavy as Jupiter was detected around this same star in an almost Earth-like orbit (ESO PR 12/99).

The discovery of the Kuiper belt, with its huge ramifications for the study of the formation of the outer Solar System, is due to the development of wide-field imaging: large areas of sky need to be imaged. CFHT led the way with the sequential deployment of several increasingly powerful large-field CCD cameras, which will finish with the implementation of MEGACAM for several years. The current extreme over-subscription of CFH12k proves that not just solar system science benefits from wide-field imaging. Although one might argue that large-field imaging will be exhausted by 2010, it is unlikely that the entire sky will be surveyed to 25th magnitude in all filters. This is especially important in Solar System science, where the sky is continually changing due to the dynamic nature of the problem. When the CFHT closes at the end of the decade, it will leave the French community without ANY wide-field imaging capability on anything larger than a 2-meter class telescope. This seems strange given the immense effort that has been put into the development of world-class wide-field imaging capability over the last decade.

But another parameter is the faintness of the Kuiper belt objects : a deep study is necessary to assess the composition of the surface materials and to compare them with other Solar system objects. The absolute magnitude of the KBOs is directly related to their diameter. Only about 200 of them have been identified to date (Tegler & Romanishin 1999, DPS 31,2301) but to extend our quest and get a statistical view of the Kuiper Belt, we need to perform deeper observations: Gladman et al. (1998, AJ 116, 2042) deep survey found about 90 trans-Neptunian objects  $\text{deg}^2$  brighter than 25.9.

#### 2.2.1.2. *Exo-Solar Systems*

Compared with the capacity of future space-based facilities like TPF and DARWIN, the limited angular resolution of a 16 m telescope diffraction limited at  $1 \mu\text{m}$  (about 16 mas) gives a reduced sample of accessible stars. Detection of planets with 1 AU orbit will only be possible for stars closer than 65 pc. The collecting power of a 16 m aperture is larger than the planned space facilities, however, and will permit extensive studies of trajectory, albedo variations, and spectroscopy upwards of  $R = 100$ . This resolving power is sufficient for detection of life signature gases like methane and  $\text{CO}_2$ . [This section will be expanded in phase II].

#### 2.2.1.3. *Science Requirements for Formation of Stars and Planetary Systems*

In the first place, the search for Kuiper Belt Objects requires a field of view larger than about 0.5 degree because the density is low and these objects are moving quickly. On the other hand, reaching smaller KBOs means that NG-CFHT must detect very faint objects. To study their composition, colors might be used but low-spectral resolution spectroscopy with a moderate multiplexing (about 100) would bring better data.. Exo-Solar Systems are much more demanding : the detection of planets requires both a high spatial resolution and a high dynamics while a small field of view is sufficient. Low spectral resolution spectroscopy would also be useful to analyse the composition of the planets and their atmospheres.

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### **3. NG-CFHT compared to existing and planned telescopes**

[To be Completed in Phase 2]



## 4. Technical proposal

### 4.1. System study

#### 4.1.1. Basic concept and mission profile

The NG-CFHT is a 16 m class telescope to replace the existing 3.6 m telescope on the same site. The telescope concept is based on a high level of multiplexing, i.e., ability to observe numerous objects simultaneously with different instrument types. Its principal characteristics are:

- Large bandwidth, 390 nm to 2500 nm
- Large collecting area
- Large FOV ( $1^\circ$  diameter goal)
- High angular resolution and provision for MCAO in the central part of the FOV
- Simultaneous operation of 6-8 instruments
- Optimal reuse of existing buildings

Optimal overlap between construction of the new telescope and operation of the old facility is searched in order to minimize the dead time. Its operational period is foreseen to bridge the gap between today's 10 m class telescopes and future 50-100 m telescopes, planned for 2020 or later.

#### 4.1.2. Principal constituents

The NG-CFHT may be decomposed into the following sub systems:

- Optical system based on a four-reflection (3-4 mirrors) design and actively controlled segmented primary
- Adaptive telescope structure
- Dual-axis (alt-az) telescope pointing and tracking system
- Instrument suite
- Adaptive optics systems
- Building and its thermal control system
- Dome and its control system
- Scientific data handling, processing and storage
- Maintenance and infrastructure

#### 4.1.3. Interfaces

Telescope interfaces to consider include:

- Building and foundations
- Remote control systems
- Data transfer and pipeline facilities
- The sky and the observational objects
- The astronomer

#### 4.1.4. Telescope specifications

##### 4.1.4.1. Functional specifications

|     |  |   |
|-----|--|---|
| FS1 | Accessible FOV                         | 1°  |
| FS2 | Telescope transmission, spectral range | 350-500nm: >60%<br>500-1100nm: >80%<br>1100-2300nm: >80%  |
| FS3 | Time for mode changes                  | TBD   |
| FS4 | Pointing time                          | TBD   |
| FS5 | Zenithal distance                      | 1° - 60°  |
| FS6 | Spatial resolution                     | <ul style="list-style-type: none"> <li>For a seeing of 0.6" and using a mag 17 (TBC) guide star separated by less than 50" (TBC) from a mag 24 object, a TBD low-order AO system shall provide 80% energy within 0.2".</li> <li>The central 2' shall be diffraction limited at 1 <math>\mu</math>m to allow full MCAO correction</li> </ul> |
| FS7 | Observation multiplexing               | > 6 (TBC) instruments working in parallel   |

##### 4.1.4.2. Operational specifications

|     |                                |   |
|-----|--------------------------------|---|
| OS1 | Temperature range              | Operational in range: -10 to +20°C (TBC)<br>Functional in range: -15 to +25°C (TBC)<br>Survival in range: TBD |
| OS2 | Temperature gradients          | Range of gradients: -0.7 to +0.4°C/h (TBC)  |
| OS3 | Disponibility of old telescope | Until 2005  |
| OS4 | Disponibility of new telescope | First scientific light before 2010  |
| OS5 | Reliability                    | TBD   |
| OS6 | Maintenance                    | Maintenance shall be assured by the current CFHT staff level.   |
| OS7 | Lifetime                       | 20 years  |
| OS8 | Functional duration            | 330 nights/year (TBC), 10 h/night (TBC), in total 66 000 hours.   |
| OS9 | Safety                         | TBD   |

##### 4.1.4.3. Interface specifications

|     |                                      |  |
|-----|--------------------------------------|--|
| IS1 | Re-use of old facility               | Shall be optimised for minimal cost  |
| IS2 | Ground footprint                     | No greater than present  |
| IS3 | Mass of telescope on existing pillar | < TBD kg   |
| IS4 | Eigenfrequencies                     | The ensemble telescope+pillar shall have eigenfrequencies within range TBD to TBD Hz |
| IS5 | Electrical power                     | < TBD Watts  |
| IS6 | Absolute pointing accuracy           | 1" RMS (TBC)   |
| IS7 | Tracking accuracy                    | 0..05" RMS by the aid of guide star  |
| IS8 | Mass of dome on existing building    | < TBD kg   |
| IS9 | Data pipeline capacity               | TBD  |

#### *4.1.4.4. Conception and realisation requirements*

To be completed.

#### *4.1.4.5. Logistics requirements*

To be completed.

#### *4.1.4.6. Verification requirements*

To be completed.

### **4.1.5. Development plan**

The development of the telescope facility is divided into five phases:

- Phase A: Preliminary studies and R&D activities
- Phase B: Pre-design and R&D activities
- Phase C: Design
- Phase D: Fabrication
- Phase E: Assemblage, integration, and testing (AIT)

A tentative planning for these activities is given in the management section (sec. 5.1.3). In the present section we discuss the implementation of the phases, in particular phases A, B, and E.

Preparational conception and definition activities foreseen for phases A and B include:

- Implementation of the concept of adaptive structure in the context of a large astronomical telescope
- Conception of a 16 m segmented primary mirror with active control of segment shape and inter-segment phasing
- Fabrication procedure for large concave secondary
- Thermal studies of structure and dome

#### *4.1.5.1. Adaptive structures*

Apart from the obvious difficulties involved in the fabrication of the optical surfaces for a versatile 16 m telescope, a major component of the proposed concept is the use of an adaptive structure. Adaptive structures consist of dimensional sensors and actuators operating in closed loops. Acting upon the structure carrying the optical surfaces, perfect alignment of the telescope is continuously ensured. The use of such structures optimizes the ratio mass/performance by including structural sensors and actuators which, when operated in closed loop, assures constant dimensions of the structure in the presence of varying external perturbations (gravity vector, thermal variations, wind loading (TBC), etc), see Sec. 4.3.2 and 4.4.2. System level analysis in phase A/B must be performed in order to identify and evaluate the external factors involved and to establish operational frequencies, adjustment ranges, and required precisions, both for the actuation and for the measurements. On the basis of such studies, optimal structural parameters (stiffness, mass, etc) can be established and the gain with respect to a passive structure can be evaluated.

#### 4.1.5.2. *Assembly, integration and test*

This concerns assembly and testing of telescope sub systems as well as final integration and testing of the entire telescope. Typically, the following structural tests should be applied:

- Static tests under load to determine residual deformations
- Thermo elastic tests to characterize thermal deformations
- Vibration tests to determine vibrational modes and their propagation in the structure
- Functional tests
- Optical performance

The large dimensions and high precisions involved render these tasks heavy and delicate. The use of adaptive structures can relax the assembly tolerances by at least an order of magnitude as long as these requirements are taken into account in the design of these systems so that the added adjustment range is provided.

Optical performance measurements must be based upon the analysis of astronomical objects by the aid of wavefront sensors (WFS). Its use during the integration permits the definition of an absolute zero for the adaptive structure. The strategy for the use of WFS during telescope operation must be defined. Permanent monitoring of the telescope optical quality as in VLT is surely necessary, at least for the primary mirror shape control.

## 4.2. *Optical design*

### 4.2.1. Telescope

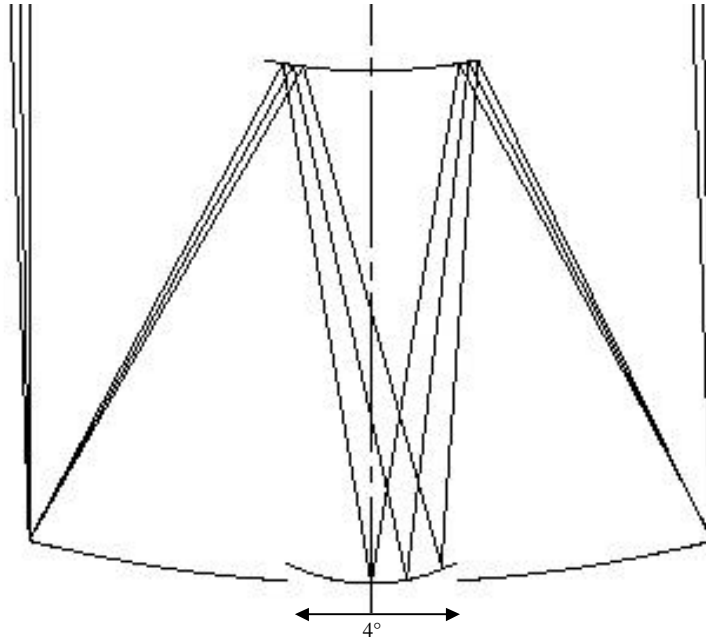
Our original proposal consisted of a fast 16 m Ritchey-Chretien telescope with a primary at F/1 and a Cassegrain focus at F/3 provided by a 5 m secondary (Fig.12). The circular primary consisted of four or six 6-8 m segments. With a focal length of 48 m, the 4 deg FOV covered 3 m, fitting within the secondary obstruction. The focal surface was curved and poorly corrected beyond some fraction of a degree, but with local active corrector optics, aberrations could be eliminated within instrument sub-fields, offering diffraction limited operation at any point in the FOV.

The focal surface was divided into four concentric zones:

- Zone 1: In the inner disc of diameter 2', diffraction limited at 1 micron.
- Zone 2: Out to a diameter of 11', seeing limited with geometrical spots smaller than 0.3"
- Zone 3: Out to a diameter of 30', astigmatism only considerable aberration
- Zone 4: Out to a diameter of 4°, complex combination of aberrations.

The focal ratio of F/3 provided a plate scale of 0.23mm/arcsec. For NGST-type NIR detectors with 27 $\mu$ m pitch paving the Zone 2 in a Megacam manner, this provided a sampling of 0.12" per pixel, requiring a 5.7K square array.

Although the concept of local correction has been proven by optical modelling, it has only been found possible for very small sub-fields (few arcseconds). Correction over arcminute-sized sub-fields would require exceedingly large and complex optics. The outer focal plane zones are therefore limited to the study of compact objects, either with a seeing limited single pixel approach (Giraffe), seeing limited or low-order AO corrected multi-pixel approach (Giraffe, Falcon), or using classical, single-conjugate AO.



**Figure 12.** Preliminary optical design of the large FOV versatile NG-CFHT concept.

#### 4.2.1.1. *Revised specifications*

As seen in the scientific discussion above, the merit of a  $4^\circ$  FOV under these conditions are not obvious, and it has been decided to search for more complex optical designs providing better performance over FOV diameter greater than  $0.5^\circ$  with a goal of  $1^\circ$ . A set of baseline zones within this FOV have been defined:

- Zone 1, diameter  $2'$ : Diffraction limited at 1 micron.
- Zone 2, diameter  $10'$ : Sub-seeing limited, better than  $0.2''$
- Zone 3, diameter  $30'$  -  $1^\circ$ : Median-seeing limited, better than  $0.6''$

Also, a focal ratio in the range F/5-10 would be preferable in order to facilitate design of instruments. This eliminates the possibility to pave the focal plane directly, but it was felt that such Megacam approach should be reserved for dedicated telescopes, and that the NG-CFHT should favour a more analytical, multi-instrument approach. Large FOV imaging would therefore require focal reduction as in VIRMOS-style instruments, providing very fast camera optics with F/1 - F/3. A telescope focal ratio of F/7.5 has been taken as a good compromise (see table below).

*Baseline telescope parameters and platescale.*

|                         |   |
|-------------------------|---|
| Entrance pupil diameter | 16 m  |
| Focal ratio             | F/7.5   |
| Focal length            | 120 m   |
| Plate scale             | 2.1 m/deg<br>35 mm/arcmin<br>0.6 mm/arcsec<br>1.7 arcsec/mm |

The telescope should have a fast (F/1) primary, M1 and M3 should lie in the same plane to benefit from the same support structure, and the focal plane should be located 2 m below the primary for accessibility.



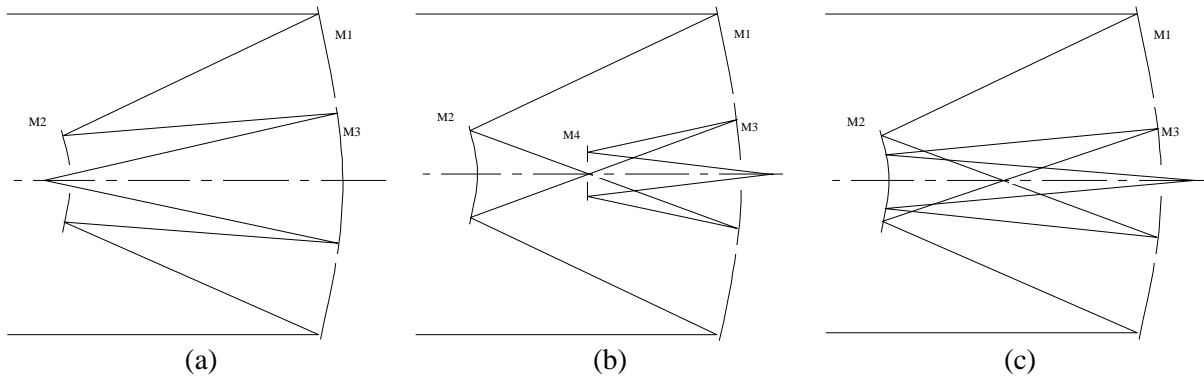
#### 4.2.1.2. Alternative designs

The revised telescope specifications eliminate classical two-mirror (Richey-Chretien) telescope designs which only correct spherical aberration and coma, leaving astigmatism uncorrected. According to the Schwarzschild principle (Wilson, 1996), three aspheric mirrors are necessary in order to correct all three third-order aberrations. Wilson provides a thorough review of telescope designs with three or more mirrors, in both single axis (Cassegrain) and double axis (Nasmyth) configurations. We consider the advantages of the single-axis configuration to be prevailing (compactness of opto-mechanical design, accessibility of focal plane, limited variability of gravity vector) and have therefore concentrated on this class of designs.

The simplest three-mirror design, as proposed by Rumsey (1969), see Fig. 13(a), has the tertiary in the plane of the primary and the final focal plane behind the secondary mirror. This design is impractical for many reasons in the context of a multi-purpose telescope (focal plane accessibility, instrument seeing, etc), and we have not investigated it further.

The more classical Cassegrain position behind the primary may be obtained by adding a fourth mirror between the primary and the secondary, Fig 13(b). When the primary is aspheric, this mirror may be spherical or even flat, reducing constraints on alignment and difficulty of fabrication. However, it is close to an image of the telescope pupil and may therefore be used to correct the spherical aberration of a spherical primary mirror (Robb 1979). Wilson & Delabre (1995) claim excellent image quality over a  $1.5^\circ$  FOV in a similar design for a 4m telescope with a spherical primary. The trade-off between fabrication of an aspheric primary versus a smaller but highly aspheric quarternary is not obvious however, see the Reosc report.

A third design option, due to Korsch (Wilson 1996) consists of using the secondary mirror as quarternary, eliminating the need for a fourth mirror, see Fig 13(c). This very elegant solution has the obvious advantage of reduced mechanical complexity and limited number of alignment parameters. Since M1 and M3 are in the same plane, they may be mounted in a common structure, reducing, if not eliminating, their relative displacements. The positioning of the secondary remains the only critical item; one may indeed imagine that its alignment sensitivity doubles because it is used twice. An opto-mechanical trade-off is required.

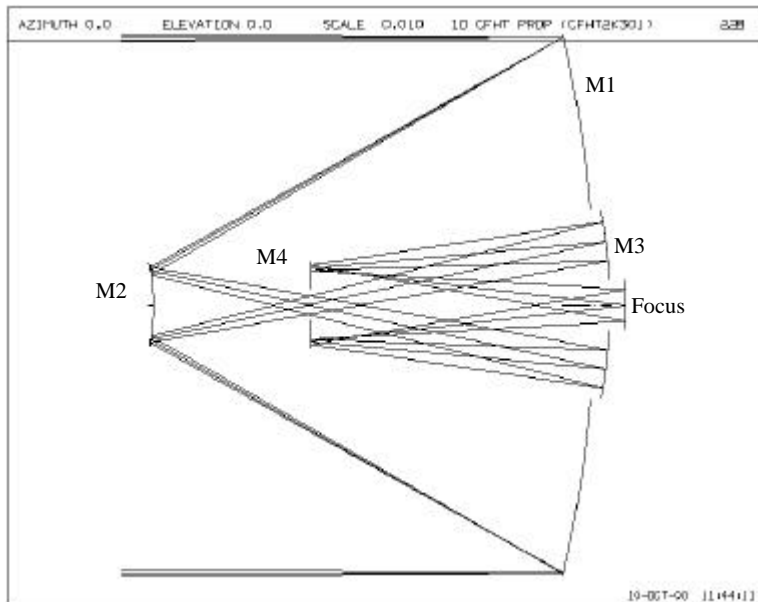


**Figure 13.** Basic options for single-axis telescope designs using three aspherics: Rumsey (a), Robb (b), Korsch (c).

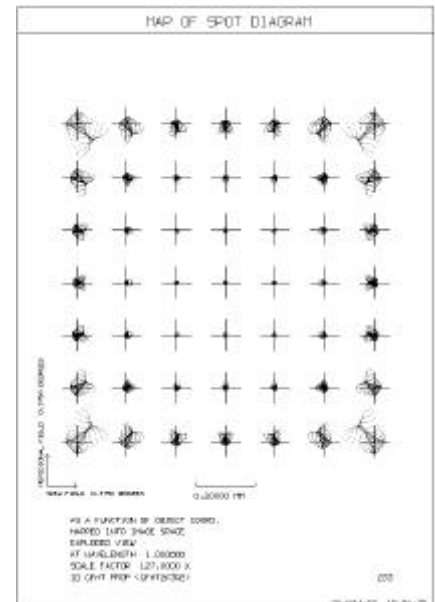
#### 4.2.1.3. The four mirror option

A design based on the four-mirror Robb concept has been created for a final focal ratio F/5, see Figure 14. Further investigations are required in order to transform it into F/7.5. The design has an aspheric primary and a flat quarternary, but since M4 is very close to the pupil, it should be possible to obtain similar field characteristics with a spherical primary and an aspherical, Schmidt-plate M4.

Image quality is illustrated in Fig. 15. The design is diffraction limited at 1  $\mu\text{m}$  out to a diameter of about 15', and the geometrical spots are smaller than 0.2" out to a diameter of about 50'. Exceeding 1°, image quality degrades rapidly and the size of M3 and the central obscuration become prohibitive.



**Figure 14.** Beam diagram showing rim rays for an axial object and objects at  $\pm 22'$  (FOV = 0.75°).



**Figure 15.** Spot diagrams for the four-mirror, F/5 design. The FOV shown has a 1° diagonal, crosses are 100  $\mu\text{m}$  (0.27") wide.

Linear central obscuration for an axial object is about 30%, corresponding to 9% of the pupil area. This increases towards the edge of the field, mainly due to beam "walk" on M4, and at 30' from the axis, the areal obscuration reaches 19%.

M1: 16 m diameter with a central hole of about 5.5 m. With a 32m radius of curvature, the primary focal ratio is 1. Its aspheric shape is nearly parabolic.

M2: 2.5 m convex hyperboloid. From a fabrication point of view, this is a great improvement with respect to the original R-C proposal, for which the secondary was a 5m convex.

M3: 5.5 m prolate ellipsoid with a 500 mm central hole to access the focal plane.

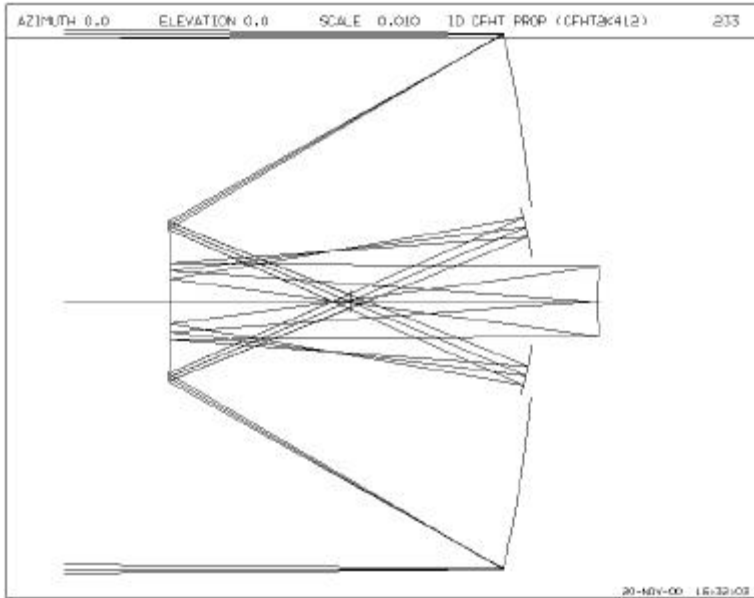
M4: 2.6 m flat asphere (Schmidt plate) with a 800 mm central hole.

The focal plane has a curvature of 16m, curved towards M2. With a final focal ratio of F/5, the defocus at the edge of a 3' sub-field is 40 $\mu\text{m}$ , corresponding to a geometrical defocus spot diameter less than 10 $\mu\text{m}$  (0.025"). Such a field curvature therefore appears acceptable.

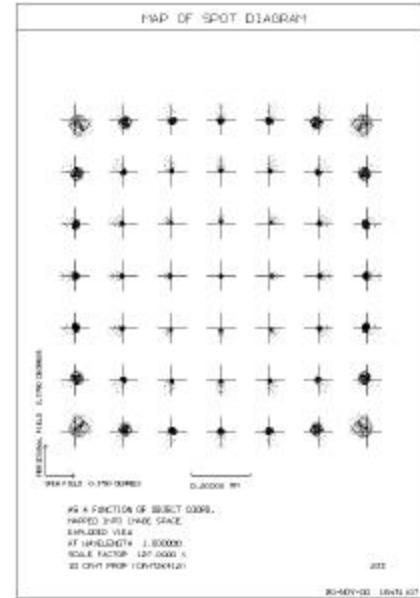
#### 4.2.1.4. The three mirror option

A three-mirror Korsch design has been created for a final focal ratio  $F/7.5$ , see Figure 16. Due to its double use of M2, this design is highly constrained and offers little room for geometrical variations. An important result of this is a large (4.9 m) secondary mirror and a fairly curved focal plane. This situation may be improved at the price of an increased M1-M2 separation and larger M3 diameter. The optimal design must be determined by a thorough opto-mechanical trade-off study.

Image quality is illustrated in Fig. 17. The design is diffraction limited at  $1\ \mu\text{m}$  out to a diameter of about  $30''$ , and the geometrical spots are smaller than  $0.2''$  over the entire  $1^\circ$  FOV. Exceeding  $1$  degree, image quality degrades rapidly and the size of M3 and the central obscuration become prohibitive.



**Figure 16.** Beam diagram showing rim rays for an axial object and objects at  $\pm 22'$  ( $\text{FOV} = 0.75^\circ$ ).



**Figure 17.** Spot diagrams for the three-mirror,  $F/7.5$  design. The FOV shown has a  $1^\circ$  diagonal, crosses are  $100\ \mu\text{m}$  ( $0.18''$ ) wide.

Linear central obscuration for an axial object is about 50%, corresponding to 25% of the pupil area. Further optimization may reduce this somewhat at the price of a larger tertiary mirror.

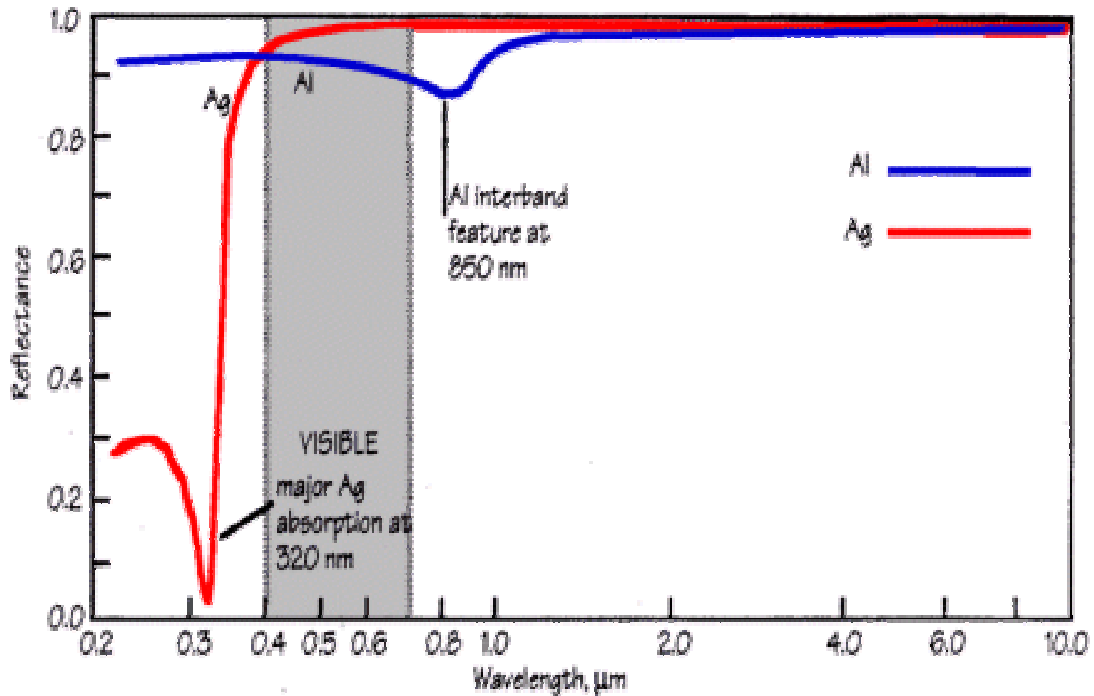
M1: 16 m diameter with a central hole of about 5.5 m. Primary focal ratio is 1. Its aspheric shape is ellipsoidal with a conic constant of -0.8.

M2: 4.9 m convex hyperboloid.

M3: 5.2 m diameter prolate ellipsoid ( $cc = -0.5$ ) with a 2.3 m central hole to access the focal plane. The focal plane has a curvature of 5.8 m, curved away from M2. The defocus at the edge of a  $3'$  sub-field is 1 mm, corresponding to a geometrical defocus spot diameter less than  $130\ \mu\text{m}$  ( $0.23''$ ). It should be possible to absorb this amount of field curvature in the instrument optics.

#### 4.2.1.5. Mirror coating

Investigations made for the Gemini project identifies protected silver as the most promising coating for 8m telescopes (Wilson 1999, p. 434). As seen in Figure 18, silver is substantially better than aluminium over the entire visible band and well into the infrared. Below 390nm, the reflectivity of standard protective silver quickly drops, however. Enhanced silver coatings pushing this edge down to below 300 nm exists, but it is not clear whether such coatings are equally performant at longer wavelengths and sufficiently resistant. The table gives telescope efficiency assuming four reflections off protected silver mirrors.



**Figure 18.** Comparison of silver and aluminium mirror coatings.

*Telescope efficiency with protected silver coating.*

| Wavelength           | 390 | 500 | 1000 | 2500 |
|----------------------|-----|-----|------|------|
| Surface reflectivity | 90% | 98% | 99%  | 99%  |
| Telescope efficiency | 65% | 92% | 96%  | 96%  |

#### 4.2.1.6. References

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 R. N. Wilson, Reflecting telescope optics II, Springer Verlag, Heidelberg (1999).  
 Wilson, Delabre, "New optical solutions for very large telescopes using a spherical primary," Astron. Astrophys. 294, 322-338 (1995).

## Focal plane a

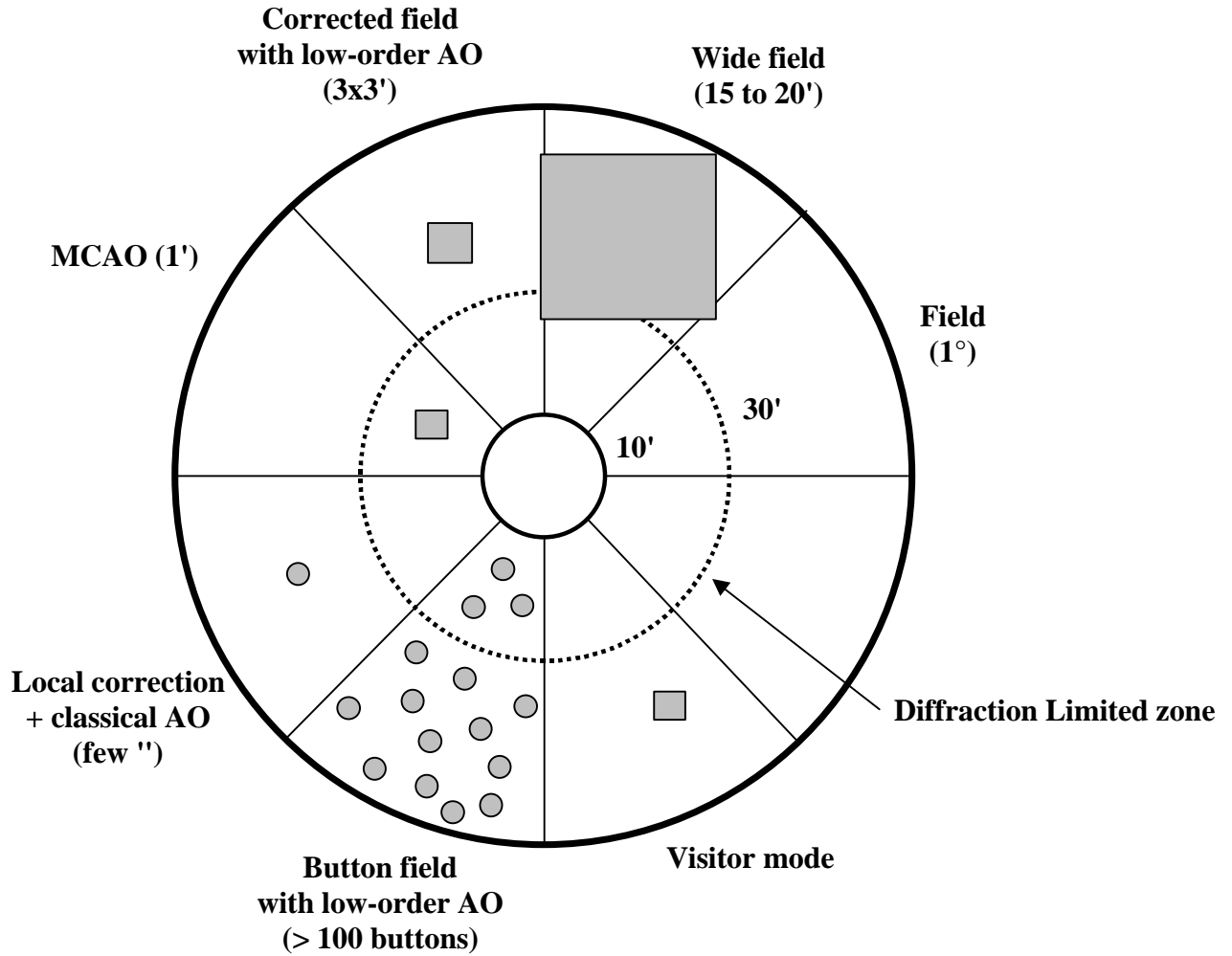
In the case of the three-mirror telescope, the  $1^\circ$  field of view may be divided into two areas, a central  $30'$  zone, diffraction limited at  $1\ \mu\text{m}$  wavelength, and the surrounding ring with a maximal  $0.18''$  residual optical aberration.

We allocate nine instrumental zones in the focal plane.

- A  $10'$  central zone will be reserved for high spatial resolution instruments with advanced Adaptive Optics (AO) systems. Two types of AO systems are foreseen, a low-order correction AO on contiguous  $3'\times 3'$  fields for a  $0.2''$  spatial resolution and/or an MCAO on contiguous  $1.5'\times 1.5'$  for diffraction limited operation.
- Eight sectors are located around the central zone allowing simultaneous observations using separate instruments. We have identified six observational modes, each corresponding to an “instrument class” (Fig. 19):
  - Wide Field mode ( $15$  to  $20'$  squares) for seeing limited observations, imaging, low-medium resolution spectroscopy (Megacam, Virmos)
  - Medium field mode ( $3'\times 3'$ ) with low-order AO correction for a  $0.2''$  spatial resolution, imaging, low-medium resolution spectroscopy.
  - MCAO mode,  $1'$  field in the diffraction limited area of the focal plane.
  - Classical AO mode for diffraction limited operation over a few arcsec field of view.
  - Fiber-coupled multi-object mode for high-resolution spectroscopy and integral field spectroscopy,  $>100$  buttons in a field of view of  $20'\times 20'$ .
    - Seeing limited, single or multiple fibers
    - $\sim 0.2''$  spatial resolution with integrated low-order AO correction
  - Visitor mode (coronagraphy, AO,...).

These modes are replicable and could be implemented in one or more sectors, permitting a high degree of flexibility and versatility.





**Figure 19.** Focal plane allocation scheme.

#### 4.2.3. Instrumentation

Following the scientific goals of the telescope and the instrumental classes defined in Sec. 4.2.2, the following tentative instrument specifications can be defined;

##### 4.2.3.1. Wide-field mode

|     |                     |   |
|-----|---------------------|---|
| WF1 | Wavelength Range    | U-band to K-band (TBC)                                      |
| WF2 | Angular Resolution  | Seeing limited, 0.6 arcsec (TBC)                            |
| WF3 | Spectral Resolution | Imaging, R = 1-10 (TBC)<br>Spectroscopy, R = 100-5000 (TBC) |
| WF4 | Field of View       | 15-20'  |
|     |                     |   |
|     |                     |   |

#### 4.2.3.2.

|  |     |     |
|--|-----|-----|
|  | TBD | TBD |
|  |     |     |
|  |     |     |
|  |     |     |
|  |     |     |
|  |     |     |

#### 4.2.3.3. *MCAO mode*

|     |     |     |
|-----|-----|-----|
| MC1 | TBD | TBD |
|     |     |     |
|     |     |     |
|     |     |     |
|     |     |     |
|     |     |     |

#### 4.2.3.4. *Classical AO mode*

|     |     |     |
|-----|-----|-----|
| AO1 | TBD | TBD |
|     |     |     |
|     |     |     |
|     |     |     |
|     |     |     |
|     |     |     |

#### 4.2.3.5. *Fiber-coupled MOS mode*

|     |     |     |
|-----|-----|-----|
| FC1 | TBD | TBD |
|     |     |     |
|     |     |     |
|     |     |     |
|     |     |     |
|     |     |     |

#### 4.2.3.6. *Visitor mode*

|    |     |     |
|----|-----|-----|
| V1 | TBD | TBD |
|    |     |     |
|    |     |     |
|    |     |     |

### **4.3. Opto-mechanical design**

#### **4.3.1. Telescope:**

##### **4.3.1.1. Primary mirror segmentation:**

The proposed design includes the two major concepts proven during the last decade, segmentation and active optics, in a way that allows to combine advantages and minimize drawbacks of each approach.

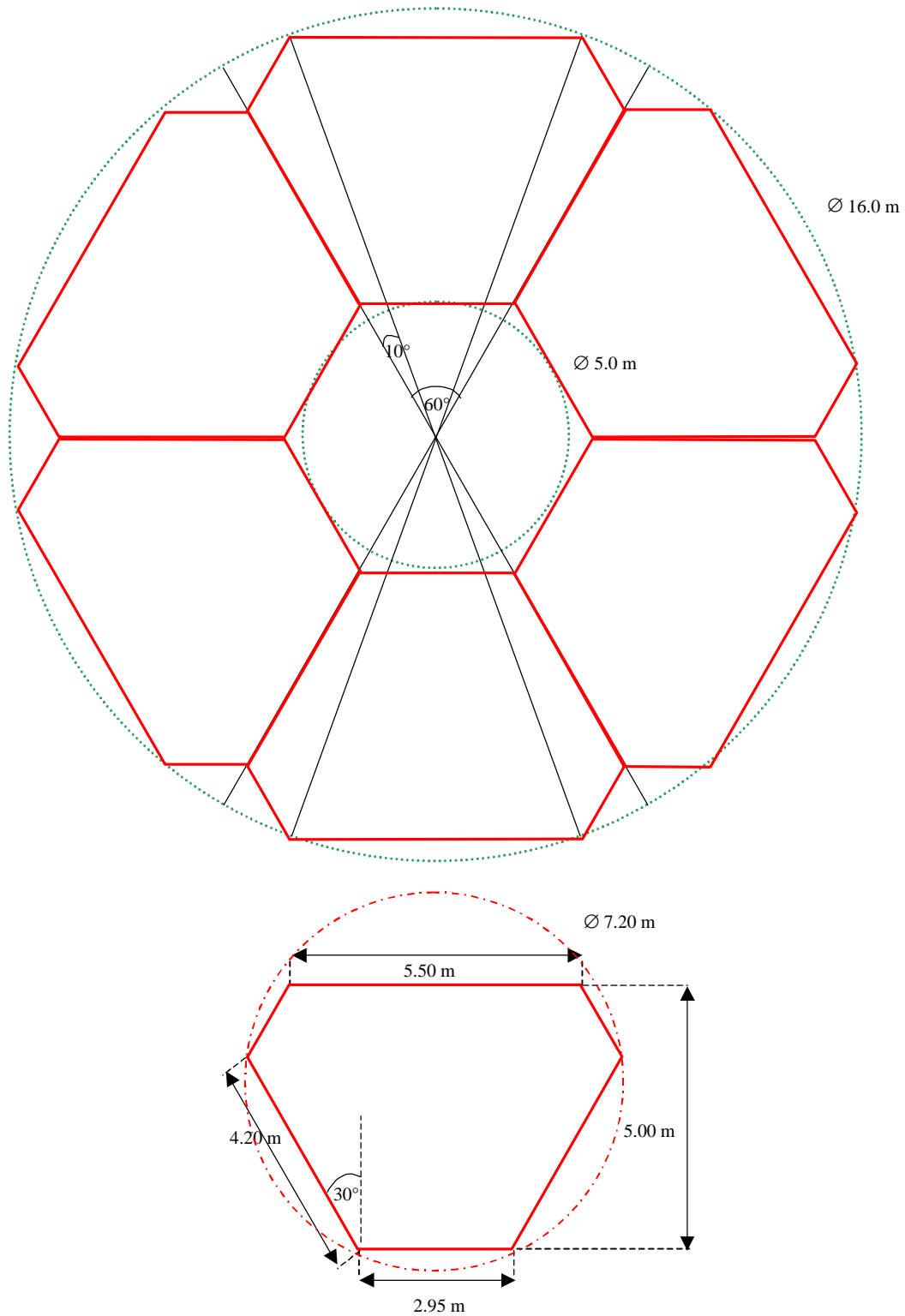
Active optics on large segments will permit 1) to use computer controlled thin meniscus mirrors (VLT/Gemini type) and reduce overall primary mass, 2) to relax fabrication tolerances and thus reduce cost. Large-segment segmentation as we propose will allow an important step forward in collecting power with use of existing 8-m class manufacturing tools. Also, the use of identical segments permits cost savings.

In the proposed designs, the primary mirror is composed of off-axis aspheric 7-m class mirrors (Fig. 20). Compared with the use of a large number of 2-m passive segments, the use of six active segments has some advantages:

- For 2-m size passive segments tight tolerances are imposed on the surface figure, and this leads to severe material selection and polishing tolerances. For the 6 to 8-m class active segments, figure errors can be corrected by the support system, and these tolerances can be relaxed.
- With a limited number of segments the problem of surface discontinuities between segments and scattered light is reduced. The phasing algorithm, using position sensors and other techniques, is also less complex.

A preliminary alignment and phasing procedure has been established. This procedure is tentative and a complete evaluation has to be done in the next system phase.

- The secondary mirror is taken as the optical axis reference.
- The six petals/segments are centred and aligned relatively to the secondary axis by using adaptive telescope structure and tip-tilt control of individual segments. This procedure is automatic and referenced to the optimal alignment defined during the telescope integration and test phase.
- The shape of individual segments is controlled using a Shack-Hartmann (SH) sensor.
- Finally, co-phasing of the segments is achieved by piston correction of individual segments and a TBD phasing sensor.



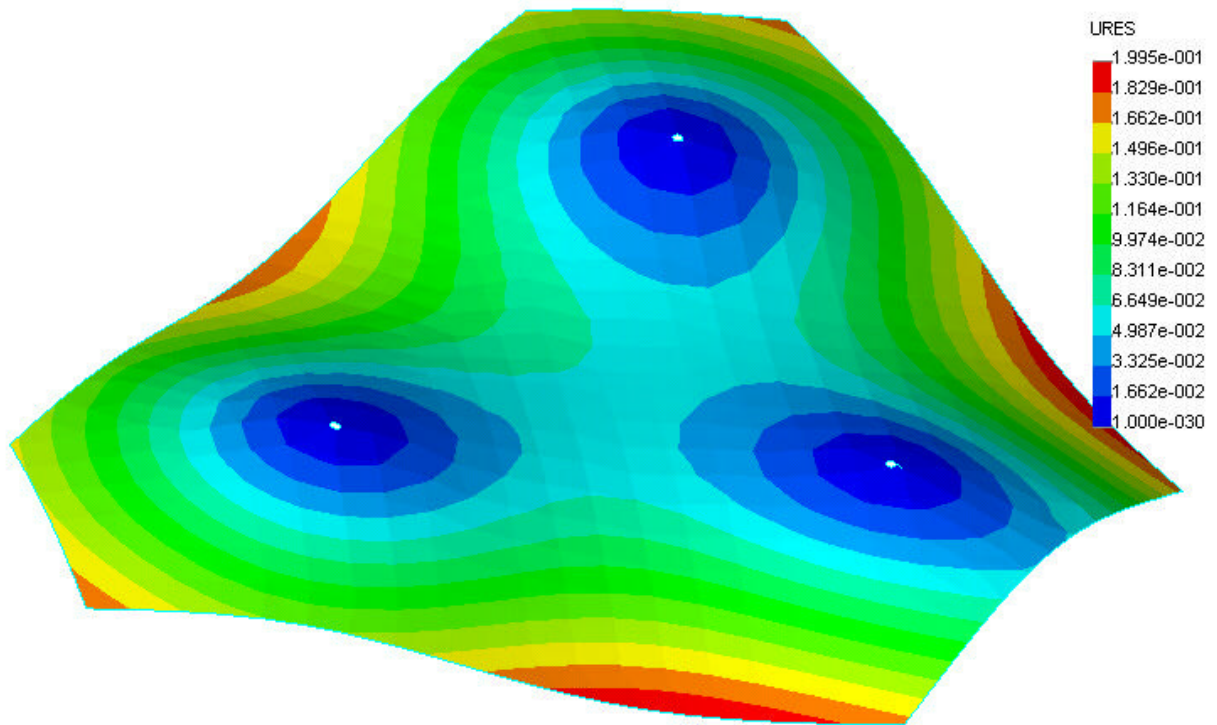
**Figure 20:** Proposed primary mirror segmentation- This design provides a 5-m diameter central hole for the tertiary mirror (3M and 4M concepts). The 6 petals are identical off-axis aspheric segments and can be generated in a 7.5-m blank.

#### 4.3.1.2. Support of individual segments

The surface of each individual segment will be computer controlled using a SH sensor and a large number of actuators (100-200) as it is done in current 8-m class telescopes. The system complexity at operational and maintenance levels of such active systems and the sensibility to frequencies higher than the control-loop, are well identified and managed in present-generation large telescopes. The number of segments used in NG-CFHT will increase this system complexity but by less than one order of magnitude. As the six segments are identical, their support systems will also be identical, a single S-H sensor will measure the entire pupil simultaneously.

Concerning tip-tilt control of individual segments, a support concept using three position controlled actuators in addition to the active figuring system has been studied. An alternative solution would be to correct tip-tilt of individual segments by moving the associated cell, but the mass to displace is then important and can generate other flexions and mis-alignments of the structure. Further evaluation and trade-offs will be done in the next phase. Preliminary finite-element analysis has been done to optimize the position of the three support points for minimal deflection (Fig. 21).

Petale2-Gravite-vertical :: Déplacement Statique  
Unités: mm



**Figure 21:** Simulated deflection under gravity for an individual segment supported on three fixed points before adding the active figuring system.

#### 4.3.2. Mechanical structure

Assuring the dimensional stability of such a construction by a passive structure would be excessively massive. In order to re-use the existing building and foundations, it is therefore necessary to consider the implementation of an adaptive structure. Such structures have recently been extensively studied in the context of military applications, and its implementation in astronomical instruments is a logical step forward.

The dimensional sensors are implemented such as to measure as directly as possible the parameters acting upon the image quality of the telescope. For example, the axial position of the secondary directly relates to image defocus. The sensor to be implemented should therefore be design so as to measure this distance with a minimum of intervening mechanical structure.

The telescope can be divided into blocks consisting of one or several optical components and associated structure. This partitioning must be done in consideration of all the etapes in the life of the telescope, fabrication, assembly, test, and operation. An optical sensitivity study is the backbone of this analysis, and it should allow important simplifications in terms of assembly and test compared to classical procedures. Dimensioning elements for the adaptive structure system are:

- Measurement precision and amplitude
- Actuator resolution and amplitude
- Closed-loop control bandwidth

Control bandwidth influences upon the residual alignment errors of the optical system. For example, a 1 Hz bandwidth will handle perfectly any thermal variations (Long Term instability), but will be without action on 10 Hz perturbations (Short Term instabilities).

#### 4.3.2.1. *Structural concept*

Based on the three-mirror Korsch-type optical design, a preliminary structural concept has been made (Fig. 22). The design shown assumes an earlier four-petal design, but the current six-petal design has a similar mechanical implementation. The structure is adaptive, with the following block division (Fig. 23):

- Block 1: Secondary mirror, acts as reference for the structure
- Block 2: Segmented primary and tertiary mirrors
- Block 3: Focal plane and relay optics
- Block 4: Instrument table

A rigorous study leading to a definite block division will be made in phase A/B, based on the following type of considerations:

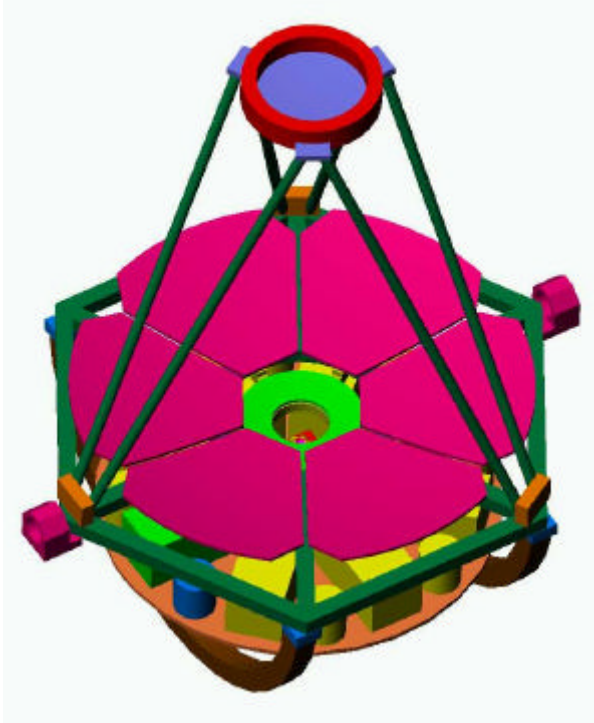
- Optimal choice of reference block
- Possibility of supporting M1 and M3 in the same structural frame
- Implementation of the instrumentation, use of relay optics, etc
- Field derotation mechanism

An important point in the definition of the adaptive structure is its interface in terms of mechanisms and control frequencies with the active control of the primary mirror.

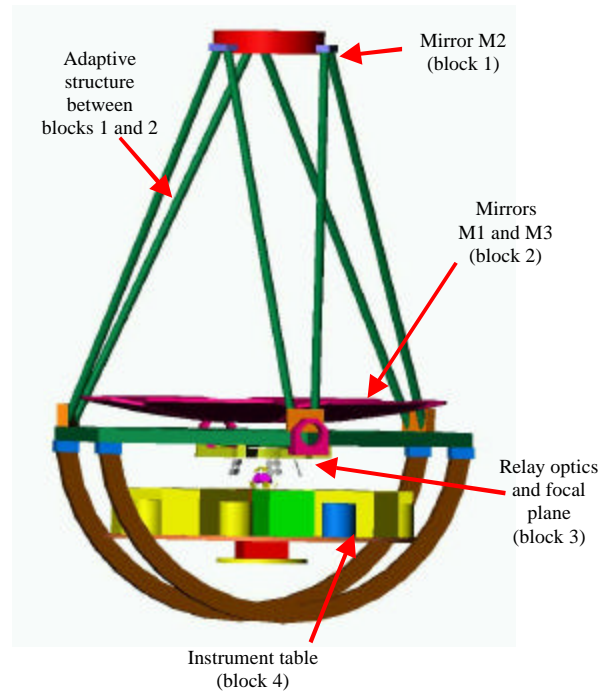
In the proposed concept, the adaptive actuation is implemented between blocks 1 and 2 by controlling the length of each bar in the secondary mirror strut structure, while the position sensing is performed between blocks 1 and 3.

#### 4.3.3. *Dome/building*

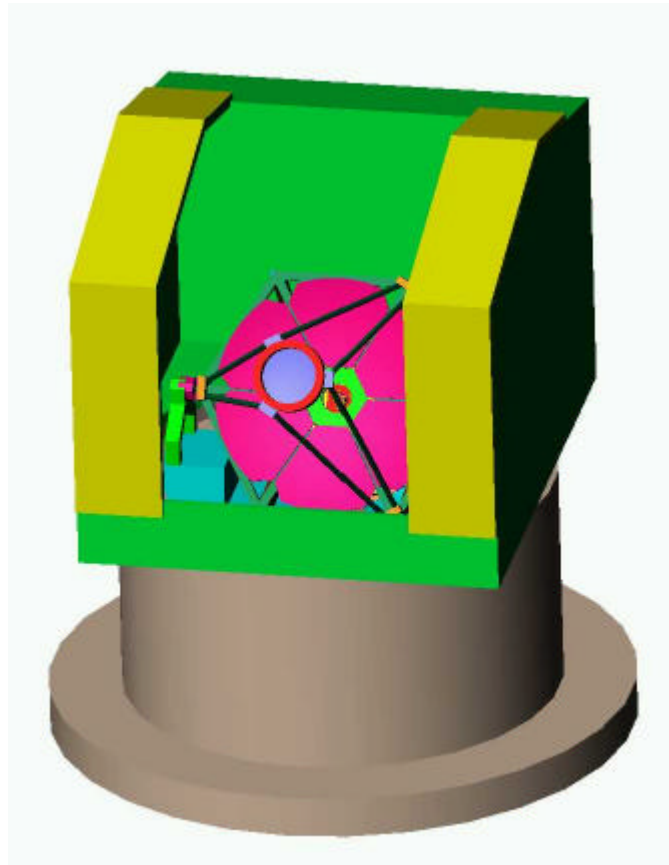
The preliminary concept is based on a VLT-type dome mounted on the existing pillar (Fig. 24). During phase 2 we will investigate more thoroughly the dome/pillar/foundation configuration concept with respect to mass, thermal effects, air flow and wind loading. General infrastructure questions should also be considered, including coating plant, and other auxiliary activities.



**Figure 22:** General view of the telescope in its four-petal version.



**Figure 23:** Tentative block allocation.



**Figure 24.** Conceptual dome design conserving the existing pillar.

## **4.4. Key technologies**

### **4.4.1. Mirror manufacturing**

The realization of the current 8 and 10-m telescopes has been possible with only substantial developments and industrial efforts made during the last decade, including the two major fundamental concepts: segmentation and active optics. In theory, segmentation allows any size extrapolation without scaling fabrication processes and active optics relaxes fabrication tolerances and allows automated control of optical quality.

These two technologies not only drive telescope optical design but also optics fabrication, and the planned next generation telescopes, as the concept proposed for CFHT replacement, thoroughly include both concepts.

As demonstrated within the VLT project, active optics systems allow increasing and maintaining mirror performance in real time. Active optics, due to the relaxation of surface tolerances and the possible use of less classical material, has also advantage in cost reduction and feasibility. The induced drawbacks, like the added system complexity (at operational and maintenance levels) and the sensibility to frequencies higher than the control-loop, are well identified and controlled in the present generation of large telescopes.

The main advantages of segmentation are scalability and cost reduction. This latter is even more efficient in the case of identical segments, for spherical primary mirrors or with a limited number of large aspheric ones.

With passive segments in the 1- to 2-m range, the solution using a spherical primary mirror is certainly the most effective as it allows for segments mass-production. However, as the segments are passive, a tight tolerance has to be imposed on the curvature of the different segments, leading to a severe material selection (homogeneity of thermo-mechanical properties). For the 6- to 8-m class segments, as those considered in the NG-CFHT proposal, this tight tolerance can be reduced, as the surface figure will be actively controlled, and thus leading to a cost reduction.

The realization and testing of off-axis aspheric surfaces is obviously more difficult than generation of spherical ones, however this problem has already been solved during the last decade, by using computer-controlled polishing and testing. The manufacturing of a limited number of large and identical off-axis aspheric segments does not seem to be critical point. With a limited number of segments the problem of surface discontinuities is also reduced and the phasing by using position sensors is less complex. This drawback (discontinuities and phasing) may completely disappear with the development of new piston sensor techniques.

In the NG-CFHT proposal three optical configurations are considered: a Ritchey-Chretien (RC), a four mirrors (4M) and a three mirrors (3M) designs. A preliminary trade-off between the proposed solutions, relatively to the mirror manufacturing difficulties, is mandatory. This phase has been realized in close collaboration with an optics manufacturer (REOSC-SAGEM) and a copy of his report and conclusion can be found in Annex.



#### 4.4.1.1. *Mirror M1*

In the proposed designs, the primary mirror is constituted of 6 off-axis aspheric 7-m class mirrors (Fig. 20). If spherical segments are certainly easier to manufacture such design require a highly aspheric corrector and its testing is still difficult. According to the optics manufacturer REOSC-SAGEM, the off-axis aspheric segments are also feasible but with a cost increase. This increase can be negligible once the realization and the test of the highly aspheric corrector are included. A careful trade-off is necessary.

The irregular hexagon form of the segments implies to use larger mirror blanks (7.2 m) and to carefully pay attention to stress and strain releases during the cutting process.

#### 4.4.1.2. *Mirror M2*

The major difference between the various designs is the secondary mirror size. In the RC and the 3M configurations this mirror has a 5-m diameter while is only 2.5-m in the 4M solution.

The manufacturing and testing of a 5-m convex aspheric mirror is certainly the most complex point. Testing the complete surface in one shot is not feasible and a surface reconstruction technique, from partial interferograms will be necessary. Taking into account a 1-m secondary central obscuration, a 2-m null lens can be used to control the mirror on its radius and the final surface figure reconstructed from multiple tests with overlaps. The 2-m null lens is a critical point as a good material homogeneity in such a large piece of refractive optic is difficult to obtain. Lens with a reduced diameter (1.3-m) would be easier to manufacture but the testing will then require using two different null-lenses for the inner and outer parts of the mirror. This will lead to a larger number of sub-tests and a more complex algorithm to reconstruct the entire secondary surface. The use of a computer-generated hologram could be a solution to test this large convex asphere. This possible test set-up has still to be investigated and if no practical solution is found, a design with a smaller secondary mirror will have to be considered.

The 2.5-m mirror in the 4M configuration is a more classic optic and its realization does not generate any particular problem. The manufacturing could be done by ion-beam figuring for a size slightly lower than 2.5-m as this is the actual limit size of the mirror manufacturer ion-beam tools.

#### 4.4.1.3. *Mirror M3*

This mirror, in the 3M and 4M configuration, is a 6-m aspheric surface with no particular difficulty. If a test set-up can be found the manufacturing won't be a major problem.

#### 4.4.1.4. *Mirror M4*

In the 4M design, this mirror is flat or slightly aspheric with a 2.6-m diameter. The ion-beam figuring and polishing could also be used for this mirror for a size lower than 2.5-m. A flat mirror or a concave radius of curvature shorter than 40-m would be easier to test within the existing test tower of the mirror manufacturer.

#### 4.4.1.5. *Conclusion*

The realization of the different mirrors, for the various optical designs considered, does not raise any fundamental impossibility. Some modification of the designs could facilitate the manufacturing of mirrors and a complete trade-off, in term of cost and time demanding process, has to be pursued during the next design phase. The mirror manufacturer (REOSC-SAGEM) is confident that if a test set-up is possible, any surface can be generated.

#### 4.4.2. Adaptive structure systems

The novelty of the adaptive structure concept proposed is its integration within the telescope structure. Developments of metrology systems will be required within the fields of mirror positioning, primary phasing, and segment shaping. This follows naturally from the R&D activities carried out in our laboratories. Mechanical actuation concepts will also require further studies: low-resolution, large-range actuation systems, and high-resolution, medium-range actuation systems. Technological evaluation and validation will require construction of functional demonstrators. In phase two we will make a technological roadmap for the required developments.

#### 4.4.3. Adaptive optics systems

In order to obtain images with diffraction limited spatial resolution, Adaptive Optics (AO) systems must be implemented to correct atmospheric perturbations. For our telescope proposal, we consider three different AO concepts:

- Classical AO, diffraction limited over a field of view of a few arcsec.
- Multi-Conjugate Adaptive Optics (MCAO) using multiple deformable mirror and complex wavefront sensors to recover tomographically the atmospheric turbulence over a 1' field of view.
- Low-order AO to provide angular resolution of about 0.2" over a field of view of up to 3' using tomographic wavefront sensing.

Although low-order perturbation correction can be achieved with conventional technology (for example, stacked piezoelectric actuators with thin flexible mirrors), high order correction for a 16m telescope would require a prohibitive number of actuators for this technology. Development of new devices based on MOEMS (Sec. 4.4.5) is therefore of great interest for our project. Due to their compactness and replicability, these micro-optical components are also perfect candidates for numerous low-order AO buttons.

#### 4.4.4. Micro-optics

MOEMS are designed for a wide range of applications like sensors, switches, micro-shutters, beam deflectors, and micro-deformable mirrors. The main advantages of micro-optical components are their compactness, scalability, and specific task customization using elementary building blocks. As these systems are easily replicable, the price of the components is decreasing dramatically when their number is increasing. They will be widely integrated in next-generation astronomical instruments, especially for space missions, as they allow remote control. The two major applications of MOEMS in astronomy are Multi-Object Spectroscopy (MOS) masks and deformable mirrors for Adaptive Optics (AO) systems.

##### 4.4.4.1. Principle

MOEMS technology is closely linked to the micro-electronics fabrication process. Various materials are deposited on the surface of a substrate, and, using masks, their localization on the substrate is precisely defined in order to ensure their specific tasks. In micro-systems, there are two kinds of layers: structural layers and sacrificial layers. The structural layer materials are polysilicon or metal, and the sacrificial layers are silicon oxides or organic materials. The sacrificial layers are chemically dissolved at the end of the fabrication process in order to create air gaps between the remaining structural layers. A great level of sophistication in the micro-electronics technology ensures excellent tolerances on layer thickness and patterning precision.

Micro-mechanical actuation is obtained using electrostatic, magnetic or thermal effects, but the most advanced actuation is achieved by the electrostatic effect. The electrostatic actuator consists of two electrodes of metal or polysilicon heavily doped with phosphorous, isolated from each other by a gap of thickness  $g$  filled with dielectric medium, usually air.

When a voltage  $V$  is applied between the electrodes, an attractive force  $F$  is generated, and if one of the electrodes is mobile, it moves toward the other. By neglecting edge effects and bending of the electrodes, i. e. assuming good stiffness of the electrodes, the instantaneous, nonlinear electrostatic force  $F$  is defined by the following relationship of key parameters:

$$F = \frac{A\epsilon V^2}{2g^2}$$

where  $A$  is the overlapping electrode area and  $\epsilon$  is the dielectric constant in the inter-electrode spacing. Assuming  $h$  the initial inter-electrode gap (without voltage), and  $x$  the deflection of the upper electrode, the value of  $g$  is decreasing from  $h$  to  $(h - x)$  when the upper electrode is moving. The accessible motion is generally limited to  $x < h/3$ . At this limit, the nonlinear electrostatic force increases more rapidly than a linear restoring force, applied for example by springs attached to the upper electrode. The electrostatic effect then becomes unstable and the mobile electrode drops toward the fixed electrode and sticks to it.

In the design of MOEMS components, various parameters have to be tuned. These parameters differ according to the functionality of the component. We will consider two different devices, a Micro-Mirror Array (MMA) for MOS and a Micro-Deformable Mirror (MDM) for AO systems.

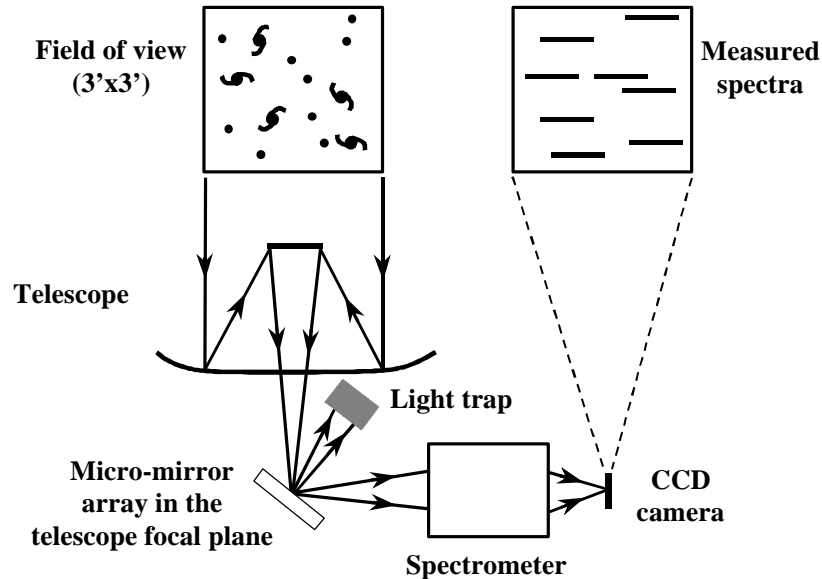
An MMA is an array of electrostatically driven bistable mirrors, with a size of a few tens of micrometers, which can occupy two discrete positions, ON and OFF, with switching times of a few microseconds. The two positions are obtained when the mirror hits physically the substrate, using the electrostatically induced motion until its unstable portion. Specific parameters for this device are the tilt angle and the actuation voltage. The tilt angle determines the separation between the input beam and the output beam and therefore the possible numerical aperture of the instrument. A large tilt angle also reduces the scattered light of the array entering the output pupil. However, the fabrication process is not compatible with the use of very thick sacrificial layers on top of the substrate, limiting the tilt angle. The two discrete positions are typically rotated  $\pm 10^\circ$  with regard to the substrate plane, producing a  $40^\circ$  beam separation. The second parameter is the actuation voltage: its value has to be low enough for matching the performances of integrated driving electronics.

MDM are constituted by a reflective surface with an underlying set of actuators driven in the linear portion of the electrostatically induced motion. For MDM, key aspects are inter-actuator spacing, inter-actuator coupling, actuator bandwidth and low driving voltage. High order wave front correction needs a large number of actuators. The size of conventional Si wafers limits the maximal size of single deformable mirrors, increasing the required density of actuators. Typical inter-actuator spacing could be in the range 200-500  $\mu\text{m}$ . An inter-actuator coupling factor can be defined as the ratio of the motion of an actuator with no voltage applied to the motion of a neighboring actuator in action. If this factor is close to 1, there is too much redundancy, the effective actuator number is drastically reduced and high-order deformations cannot be corrected properly. If this factor is zero, sharp slopes are present on the surface, usually on top of the actuator location, resulting in larger residual wave front errors. If this factor is 20-30 %, the surface has a smooth overall shape with low residual errors.

For both MMA and MDM devices, three additional parameters are of interest: the optical surface quality, the driving electronics and the actuator bandwidth. As these micro-optical components include mirrors, their surface quality must be excellent. We have developed an original method based on Foucault's knife-edge test for the surface characterization of individual MMA micro-mirrors. The driving electronics is also a challenge as the high number of actuators integrated on a semiconductor substrate leaves individual actuator driving impossible. The driving circuit has to be integrated on the wafer or directly bonded to the optically active elements. The driving voltage must then be as low as possible, a few tens of volts is preferable to the several hundreds of volts often used in present-technology devices. The design of driving circuits requires much attention in order to match the needed bandwidth, and to be compatible with the technology employed to realize the mobile mirrors on top of the electronic driving circuit. Finally, the bandwidth of these components must match the specific requirements.

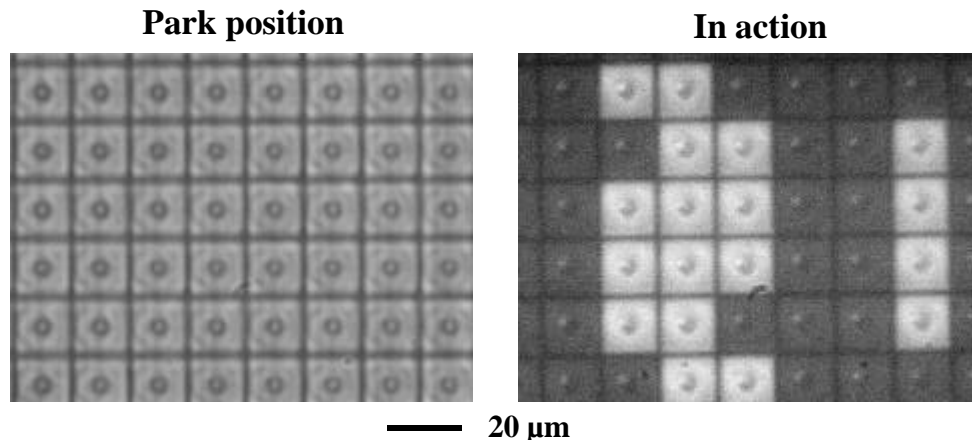
#### 4.4.4.2. Micro-Mirror Array for Multi-Object Spectroscopy

In order to obtain spectra of hundreds of objects simultaneously, MOS require a reconfigurable multi-slit device. Conventional masks are made by laser cutting or by using complex fiber-optics-based mechanisms. A promising solution is the use of an MMA for generating reflecting slits (Burg 1998, Burgarella 1998). By placing the MMA in the focal plane of the telescope, the light from selected objects is directed towards the spectrograph, while the light from others objects and from the sky background is blocked in a light trap (Fig. 25). MMA allows remote control of the multi-slit configuration in real time.



**Figure. 25:** Principle of Multi-Object Spectrograph with a Multi-Mirror Array.

We have based our work on a most impressive MOEMS realization, the MMA designed by Texas Instrument for video projection, which is an array of 1K x 1K, 17  $\mu\text{m}$  pitch bistable mirrors (Hornbeck 1995). A picture of the micro-mirrors is shown in Fig. 26. These electrostatically driven mirrors can occupy two discrete positions (ON and OFF), rotated  $\pm 10^\circ$  with regard to the substrate plane. The switching time is a few microseconds. Using this MMA, any required slit configuration might be obtained with the capability to match point sources or extended objects (Fig. 21). In the park position, i.e., without driving voltage applied, the micro-mirrors are undeflected, parallel with the substrate. In action, the micro-mirrors in the ON position direct the light toward the spectrograph and appear bright, while the micro-mirrors in the OFF position are dark.



**Figure. 26:** MMA in park position and in action with various “slit” shapes.

The Laboratoire d'Astrophysique de Marseille (LAM) is the only European laboratory to have participated in the NASA study of a near infra-red MOS equipped with tiltable micro-mirror array (MMA) for NGST (NGST-MOS study, PI John MacKenty). With the aim of including this micro-optical device in a MOS, we have directed our studies along three lines:

- Surface characterization of individual MMA micro-mirrors by an original method based on Foucault's knife-edge test.
- MMA optical modeling by ray tracing.
- Optical design for the MOS including two different concepts.

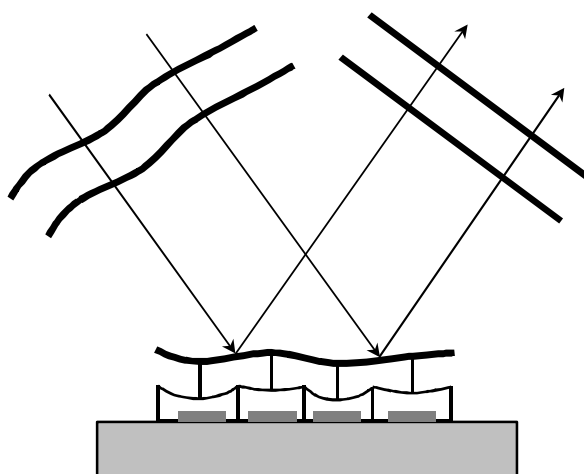
For testing micro-optical components, development of accurate surface characterization methods is essential. The most commonly used techniques for surface characterization are based on interferometry, but on a micron-sized regular array with deep discontinuities the results obtained are dramatically affected by diffraction effects. To overcome these effects, we have introduced a novel surface characterization method with an incoherent light source (Zamkotsian 1999-1, 1999-3), based upon Foucault's knife-edge test (Foucault 1859). We have used this technique to characterize the MMA designed by Texas Instruments (Hornbeck 1995). Our measurement indicates a maximum slope below 1 mrad and surface deformations smaller than 2 nm. Each micro-mirror has a "palm-tree" shape, which can be explained by strain relaxation in the thin aluminum layer constituting the mirror surface. A slope map for 8x6 micro-mirrors reveals slight mirror-to-mirror shape variations, notably due to combinations of tilt and astigmatism (Zamkotsian 1999-3).

Optical design of the multi-object spectrograph requires a ray-tracing equivalent of the MMA. Using the non-sequential ray tracing ability of the Synopsys program, we have simulated a block of nine micro-mirrors with individual tilt angles, and, by locating blocks of micro-mirrors in critical field locations, we are able to properly design an MMA-MOS. We have studied different concepts for the MOS: a spectrograph with focal reduction, and a unit-magnification spectrograph preceded by a focal adaptator (Zamkotsian 1999-2, 2000-2).

#### 4.4.4.3. *Micro-Deformable Mirror for Adaptive Optics Systems*

The second major application of MOEMS in future instrumentation is in the field of deformable mirrors. LAM is involved since June 2000 in the European Research Network on the conception of Adaptive Optics systems for Extremely Large Telescopes. The micro-deformable mirrors (MDM) of these systems should be able to reach a large number of actuators ( $> 100\,000$ ) and small inter-actuator spacing (few  $100\,\mu\text{m}$ ). Due to limitations in conventional technologies, we have based our new deformable mirror concepts on MOEMS technology. We are currently engaged in the definition of required technologies, materials and tests structures. These compact, lightweight and low-consumption deformable mirrors with on-chip electronics will enable the correction of wave front perturbation in highly integrated astronomical instruments (Fig. 27).

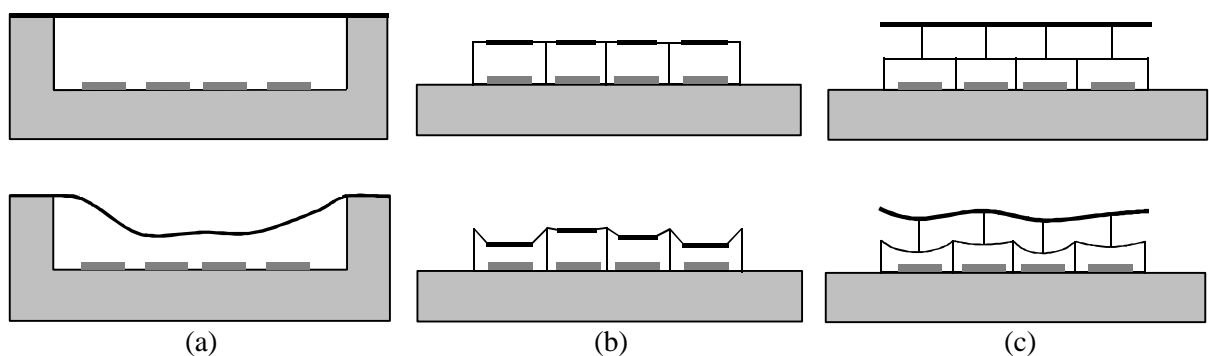
**Figure 27:**  
Principle of wave front correction using a Micro-Deformable Mirror (MDM).



Three main MDM architectures are under study in different laboratories. First, the bulk micro-machined continuous-membrane deformable mirror, studied by Vdovin from Delft University, is a combination of bulk silicon micromachining with standard electronics technology (Vdovin 1997). This mirror is formed by a thin flexible conducting membrane, coated with a reflective material, and stretched over an electrostatic electrode structure (Fig. 28 (a)). Local deflections of the membrane are obtained by applying different voltages to the electrodes. This deformable mirror has a continuous flexible mirror with a very good surface quality and a large deflection, but for a low inter-actuator coupling, inter-actuator spacing  $l < 1$  mm cannot be reached, reducing therefore the number of possible correction modes. The thin and large suspended flexible mirror is also rather fragile and removing fabrication stresses is very difficult. Finally, increasing the surface of the suspended membrane is not obvious.

Second, the segmented, micro-electro-mechanical deformable mirror realized by Roggeman (1997) at University of Michigan and Cowan (1998) at Ohio Air Force Research Laboratory consists of a set of segmented piston-only moving surfaces, fabricated in dense array (Fig. 28 (b)). The piston-like motion is obtained by applying a voltage between the active mirror area and an underlying address electrode. Due to the large static background, the segmented deformable mirror has a low optical efficiency (typically 40%) and large interference effects. The driving voltage is remarkably low (15 V), but the actuation efficiency (stroke/driving voltage) is comparable with the previous architecture. This device offers the highest degree of freedom and simplest control algorithms because each segment is completely independent. The segment density can be adapted to the needed aberration correction (low order, high order) and the piston motion can be increased with a larger gap between the electrodes.

Third, the surface micro-machined continuous-membrane deformable mirror made by Bifano (1997) at Boston University is based on a single compliant optical membrane supported by multiple attachments to an underlying array of surface-normal electrostatic actuators (Fig. 28 (c)). This type of deformable mirror allows a continuous control of the membrane's local deformation with nanometer precision at the attachment points, and a frequency response exceeding 50 kHz. The number of actuators is not limited and they can be driven with an underlying electronics in the silicon substrate. High optical efficiency and minimal diffraction effects can be achieved. Main disadvantages of this architecture are small-scale print-through deformations on the optical surface due to the fabrication process, weak inter-actuator coupling and rather high driving voltage. The resulting actuation efficiency is lower than the values obtained with the two previous architectures, mainly due to the stiffness of the structure. Another critical issue is the realization of a mirror layer without any stress, since the deposition of a thin layer on a large surface cannot be achieved without residual stress. The solution adopted by Perreault (1999) is a segmented tip-tilt mirror with anchoring posts shared between four square adjacent segments in order to ensure the optical phase continuity of the mirror. Unfortunately, this solution leads to diffraction effects already discussed in the second type of MDM. This is certainly the most promising architecture, but low actuation efficiency and mirror surface quality need further improvement.



**Figure. 28:** Three different architectures of MDM, in the rest position (upper panels) and in action (lower panels).

These three architectures, bulk micro-machined MDM, surface micro-machined continuous membrane MDM and segmented MDM, are the three main electrostatic MDM architectures. However, their performances do not at present reach the values required for an optimum system. We are therefore studying new MOEMS-based MDM architectures in close collaboration with opto-electronics research laboratories, and we plan to realize first test devices by the middle of next year.

#### 4.4.4.4. References

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## 5. Management

### 5.1.1. Telescope study group

#### 5.1.1.1. *Scientific consortium*

|                                |  |
|--------------------------------|--|
| <b>Science Team</b>            |  |
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| <b>Farrokh Vakili</b>          | Observatoire de la Côte d'Azur           |
| <b>David Valls-Gabaud</b>      | Observatoire Midi – Pyrénées             |
| <b>Christian Veillet</b>       | Canada-France-Hawaii Telescope           |
| <b>Frédéric Zamkotsian</b>     | Laboratoire d'Astrophysique de Marseille |



#### 5.1.1.2. Industrial constellation

Concerning the realization of large astronomical telescopes, a high industrial expertise already exists in Europe as demonstrated with the achievement of the 8-10 m class telescope projects (VLT, Gemini, Grantecan). SAGEM-Reosc has world leadership in large optics manufacturing, and we are working closely with that company for our study. Their remarkable expertise in manufacturing 8-m optics perfectly complements the proposed concept using 6-8 m segments.

Many European mechanics companies have also been involved in the recent large telescope projects. The Belgian AMOS proposed a detailed design for the VLT Unit Telescopes, and has been selected to build the VLT Auxiliary Telescopes. This company is associated to the NG-CFHT study, and will perform mechanical and thermal studies during phase 2.

For some key technologies, such as adaptive structures and micro-optics, the needed expertise already exists in France and in Europe. Adaptive structure concepts have already been developed for space based and military projects, and large consortia of the European space industry are well advanced in this domain. Another key component for segmented telescopes is the high-accuracy magneto-mechanical sensor for segment phasing. The French company FOGALE is well placed in the field of non-contact sensor technologies, and participate in the VLTI project. Micro-optics is still mainly a research field, but its industrial development is quickly evolving. We are currently working in close collaboration with LAAS, a major micro-technology research laboratory in France.

#### 5.1.2. ROM cost

A preliminary ROM cost, based on the Grumann report (1997), has been established, leading to a total cost of 100 millions dollars, excluding instruments. This cost is compared with the old CFHT facility and other existing large telescope projects in Table 1. One can notice that, even with an additional 10% increase, the cost of a 16-m telescope would be only 4 times higher than the price of the old CFHT, for a 16 times larger collecting surface. This relatively low-cost, as already mentioned by other authors, comes from the fact that the cost index ( $\$/d^2$ ) decreases as the collecting surface increases.

| Telescope  | CFHT      | Gemini    | Keck I    | NG-CFHT   |
|------------|-----------|-----------|-----------|-----------|
| Period     | 1973-1979 | 1992-1998 | 1986-1992 | 2002-2010 |
| Cost (M\$) | 27        | 87.5      | 63.5      | 96        |

**Table 1:** NG-CFHT cost comparison with other large telescope and historical CFHT

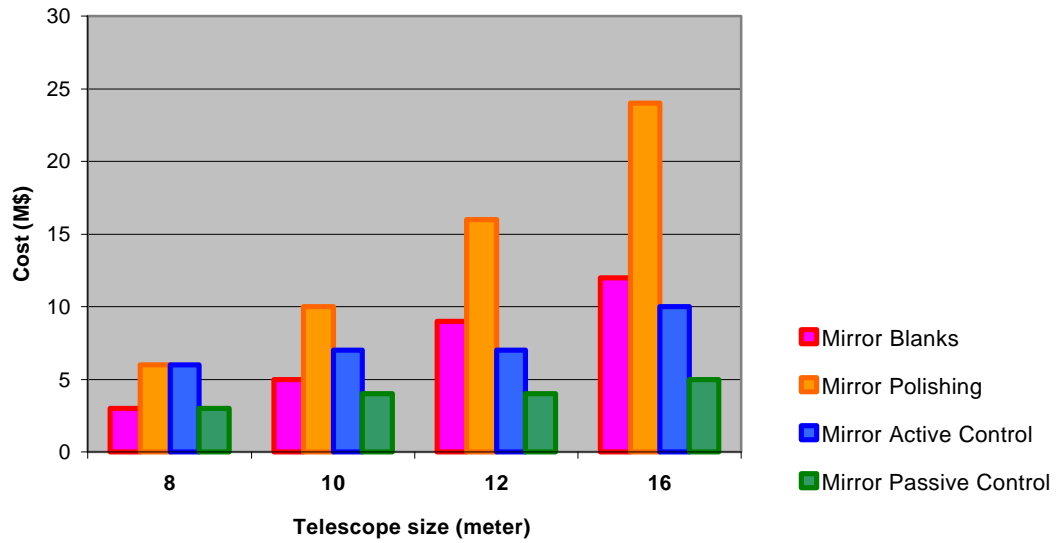
The detailed cost for a 16 m NG-CFHT has been obtained by extrapolating the estimations made by Grunmann (1997) for an 8 to 12 m facility (Table 2). The total cost is a function of the mirror diameter and not the surface, which allows the budget per collecting area (cost index) of a 16-m to be half that of an 8-m telescope.

| Telescope diameter                   | 8 m       | 10 m      | 12 m      | 16 m        |
|--------------------------------------|-----------|-----------|-----------|-------------|
| <b>Design &amp; Management</b>       | 8         | 8         | 8         | <b>8</b>    |
| <b>Mirror Blanks</b>                 | 3         | 5         | 9         | <b>12</b>   |
| <b>Mirror Polishing</b>              | 6         | 10        | 16        | <b>24</b>   |
| <b>Manufacture - Telescope</b>       | 7         | 7         | 8         | <b>10</b>   |
| <b>Site Preparation</b>              | 2         | 2         | 2         | <b>2</b>    |
| <b>Enclosure</b>                     | 9         | 9         | 11        | <b>15</b>   |
| <b>Erection/Running in</b>           | 4         | 4         | 4         | <b>5</b>    |
| <b>Mirror Active Control</b>         | 6         | 7         | 7         | <b>10</b>   |
| <b>Mirror Passive Control</b>        | 3         | 4         | 4         | <b>5</b>    |
| <b>Software-Hardware Controls</b>    | 5         | 5         | 5         | <b>5</b>    |
| <b>Total (no instruments)</b>        | <b>53</b> | <b>61</b> | <b>74</b> | <b>96</b>   |
| <b>Cost index (\$/d<sup>2</sup>)</b> | .83       | .61       | .51       | <b>0.38</b> |

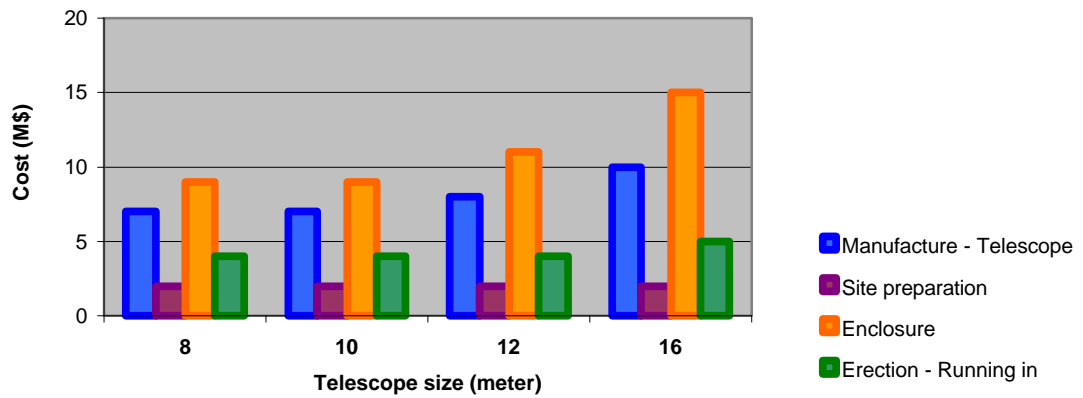
**Table 2.** NG-CFHT cost comparison for different telescope size (M\$). The total cost of a 16-m telescope, without instrumentation, will fit in a 100 M\$ envelope. Cost estimations for 8- to 12-m telescopes have been extracted from Grundmann, 1997, “Report on Option for use of the Existing Pier with a New Telescope”.

Figure 29 and 30 show graphical representations of the cost estimates for optics/mirror control and mechanics/building sub-systems, respectively. If the cost of optics manufacturing increase strongly with the diameter, some other items, as mirror passive control or site preparation, have a very slow increase or remain constant with the telescope size.

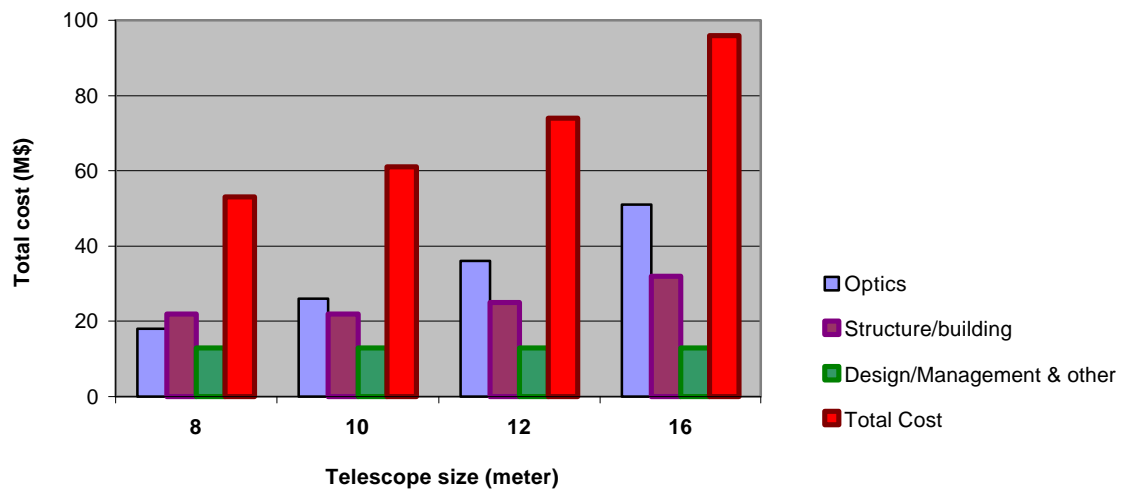
The total budget is presented in Figure 31, including the total of the two previous sub-systems as well as the costs for the design phase, the project management and software/hardware developments (other). One can notice that the optics, including manufacturing and active control, always represents half of the total while the design/management cost is relatively constant.



**Fig. 29:** Comparison of optics costs, including mirrors and controls, for different NG-CFHT diameters



**Fig. 30:** Comparison of mechanics costs, including building and enclosure, for different NG-CFHT diameters



**Fig. 31:** Comparison of total costs, including Design/Management, for different NG-CFHT diameters

### 5.1.3. Planning

A tentative planning has been made, indicating first scientific light by the end of 2009. The planning assumes project funding from January 2002. The main drivers for the planning are structural design and optical fabrication. These items are closely linked, and it is risky to freeze the optical design and blank specifications before the mechanical design is well defined. We have reserved two years for this work, allowing the four years of optical fabrication to start in 2004.

Operation of the old telescope may be continued until the beginning of 2005. At that point, the old telescope must be dismantled in order to allow building works on the new dome to start in 2006. The blind period is 3.5 years before first engineering light by the end of 2008.

We will review and refine the planning in Phase 2, notably according to the scientific pressure, political support, and funding availability.

|                      | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 |
|----------------------|------|------|------|------|------|------|------|------|------|------|------|
| Call for prop        | x    |      |      |      |      |      |      |      |      |      |      |
| 21 Ann Meet.         | x    |      |      |      |      |      |      |      |      |      |      |
| Final report         |      | x    |      |      |      |      |      |      |      |      |      |
| Kick-off             |      |      | x    |      |      |      |      |      |      |      |      |
| Phase A (Pre-study)  |      |      |      |      |      |      |      |      |      |      |      |
| Optics               |      |      | --   |      |      |      |      |      |      |      |      |
| Systems              |      |      | ---- |      |      |      |      |      |      |      |      |
| Structure            |      |      | ---- |      |      |      |      |      |      |      |      |
| Build/dome           |      |      | ---- |      |      |      |      |      |      |      |      |
| Control              |      |      | ---- |      |      |      |      |      |      |      |      |
| R&D structure        |      |      | ---- |      |      |      |      |      |      |      |      |
| R&D AO               |      |      | ---- | ---- |      |      |      |      |      |      |      |
| Phase B (Pre-design) |      |      |      |      |      |      |      |      |      |      |      |
| Optics               |      |      | --   | --   |      |      |      |      |      |      |      |
| Systems              |      |      |      | ---- |      |      |      |      |      |      |      |
| Structure            |      |      |      | ---- | ---- |      |      |      |      |      |      |
| Build/dome           |      |      |      | ---- | ---- |      |      |      |      |      |      |
| Control              |      |      |      | ---- | ---- |      |      |      |      |      |      |
| R&D structure        |      |      |      |      | ---- | ---- |      |      |      |      |      |
| R&D AO               |      |      |      |      | ---- | ---- | ->   |      |      |      |      |
| Phase C (Design)     |      |      |      |      |      |      |      |      |      |      |      |
| Optics               |      |      |      | --   |      |      |      |      |      |      |      |
| Structure            |      |      |      |      | ---- |      |      |      |      |      |      |
| Build/dome           |      |      |      |      | ---- |      |      |      |      |      |      |
| Control              |      |      |      |      | ---- | ---- | --   |      |      |      |      |
| Phase D (Fab)        |      |      |      |      |      |      |      |      |      |      |      |
| Optics               |      |      |      |      | ---- | ---- | ---- | ---- |      |      |      |
| Structure            |      |      |      |      |      |      | ---- | ---- |      |      |      |
| Build/dome           |      |      |      |      |      |      | ---- | ---- | -    |      |      |
| Control/electronic   |      |      |      |      |      |      | --   | ---- |      |      |      |
| Transport            |      |      |      |      |      |      |      |      | -    |      |      |
| Integration          |      |      |      |      |      |      |      |      | ---- |      |      |
| 1st light eng        |      |      |      |      |      |      |      |      | *    |      |      |
| Tests                |      |      |      |      |      |      |      |      |      | ---- |      |
| 1st light sci        |      |      |      |      |      |      |      |      |      | *    |      |
| Dismantling          |      |      |      |      |      | ---- | -    |      |      |      |      |

## **6. Appendix: REOSC-SAGEM report**

SAGEM/REOSC optical fabrication feasibility study.