**Venice 2001**
**Beyond
Conventional
Adaptive
Optics**

# Optical design of a layer–oriented WFS for a 100m class telescope

Enrico Marchetti[a], Roberto Ragazzoni[b] and Philippe Dierickx[a]

[a]European Southern Observatory, Karl-Schwarzschild-Str. 2, D–85748 Garching bei München, Germany
[b]Osservatorio Astronomico di Padova, Vicolo dell'Osservatorio 5, I–35122 Padova, Italy

## ABSTRACT

Adaptive Optics is a fundamental requirement for Extremely Large Telescopes to achieve diffraction limited performance and large Field of View corrections. Among the different approaches to implement Multi Conjugate Adaptive Optics correction, the Layer–Oriented seems to be a very promising one due to the high versatility in Multi Object Wave Front Sensing, the easy optimisation of the sensing process for the Atmospheric parameters, the magnitude gain given by the intrinsic capability to co-add optically the light of the reference sources and the lower complexity in the implementation of the system. In this paper we present a possible optical design of a layer oriented Wave Front Sensor pyramid based for a 100–meters class telescope. The goal is to provide a feasible solution taking into account the problems related to the dimensions of the optics, to the re–imaging of the pupils given by the pyramids on the detectors and to the overall throughput of the system.

## 1. INTRODUCTION

Multi–Conjugate Adaptive Optics (MCAO) has been first proposed by Beckers (1988, 1989) to extend the correction Field of View (FoV) typically limited in the classical Adaptive Optics (AO) systems (Beckers 1993). In a MCAO systems several Deformable Mirrors (DM) are conjugated to different altitudes above the telescope and the atmospheric correction in done in a three–dimensional way. Each DM corrects the part of the atmosphere which it is conjugated to, even if the vertical discretization is somewhat rough. In order to reconstruct the vertical distribution of the atmospheric turbulence, different approaches have been proposed. Tallon and Foy (1990) introduced the concept of tomography to disentangle numerically the turbulence at fixed altitudes, using independent measurements obtained from an number of Guide Stars (GS) through classical Wavefront Sensors (WFS), like Shack–Hartmann or Curvature sensors. Later Ragazzoni, Marchetti and Rigaut (1999) introduced a more effective concept of *modal tomography* were the tomography approach is performed in modal way. The validity of the method has also been proven on the sky (Ragazzoni, Marchetti and Valente 2000) although in a preliminary form. At the same time the novel concept of *layer–oriented* has been introduced (Ragazzoni 1999; Ragazzoni, Farinato and Marchetti 2000) where many GS are simultaneously sensed with a single WFS with several detectors conjugated at the DM conjugation altitudes. The signal from each detector drives its corresponding DM allowing efficient closed–loop operations. Layer–oriented approach is extremely effective in terms of Signal–to–Noise Ratio optimization of the sensing process because it is possible to tune both the temporal and the spatial sampling for the temporal ($\tau_0$) and spatial frequencies ($r_0$) characteristic of the layer which the detector is conjugated to. Moreover the coaddition of the light of the GS in a single plane allows to lower the requirements in GS brightness and, in this way, to increase the Sky Coverage when Natural GS (NGS) are considered. It is clear why in the MCAO the WFS plays an extremely important role for the three-dimensional atmospheric turbulence sensing. In the layer–oriented approach any kind of pupil plane WFS could be suitable but a quite promising one is the Pyramid WFS (PWFS, Ragazzoni 1996). Furthermore an extention of the layer–oriented approach, called Multiple FoV (Ragazzoni et al. 2001a; 2001b), allow to significantly increase the Sky Coverage using a larger FoV for the ground conjugated detector to collect ligth from more stars. Extremely Large Telescopes (Gilmozzi et al. 1998; Nelson 2000) can strongly benefit from the layer–oriented approach and moreover the Multiple FoV concept gives really competitive Sky Coverages with respect to Laser GS based systems.

In this paper we present an optical concept of a Multiple FoV layer-oriented WFS for a 100–meter aperture telescope. The goal of this work is to show that such a WFS is feasible with existing technology and that there are no major show

---

Further author information: (Send correspondence to E.M.)
E.M.: E-mail: emarchet@eso.org

stoppers for its implementation. We'll give a detailed description of the optical solution and some suggestion for the coupling between the pupil images and the WFS detectors. Finally some consideration about the sky coverage of this system will be pointed out. It should be outlined that the concept presented here is extremely preliminary, and that considerable simplification may be possible.

## 2. FROM 10 TO 100 METERS: DIMENSIONS AND OPTICAL QUALITY

The problem to design a layer–oriented WFS for a very large aperture telescope arises from two main different reasons: the dimension of the optical elements involved and the strict contrainst on the optical quality both at the focal and the pupil planes.

The simple scaling of the existing optical designs (ragazzoni et al. 2001a; 2001b) produces very large optical elements. For a 8–meters class telescope the largest lens size in the layer–oriented WFS is about $\approx 200 \ldots 300$ mm and the simple scaling up to 100 m (12.5 times) gives lenses of $2.5 \ldots 3.7$ m. With the current technology the maximum diameter for a lens is around $\approx$ 1000 mm and moreover with a very limited number of materials (BK7 or Fused Silica). It is clear that the simple scaling is probably not the best way to solve the problem.

The Multiple FoV configuration is the source of the problems related to the optical quality. The major constraints imposed by such a WFS are:

- **large FoV**, at least $4'$;
- **high Strehl ratio** at the whole focal plane for pyramid positioning;
- **fast focal ratio** to reduce the size of the re–imaged pupil because of limited detector size;
- **reduced optical blur on the pupil** should be a small fraction of $r_0$.

The unfavourable scaling, the large FoV and the fast focal ratio make the optical solution complex if we want to use only the current available technology. In the next section we present a possible optical solution overcoming the problems mentioned above.

## 3. OPTICAL DESIGN CONCEPT AND GUIDELINES

The Multiple FoV configuration for two DM requires two different channels: the first channel has the detector conjugated to the ground layer and looking at an annular FoV surrounding an internal one that is also the target of the correction, while the second channel has two detectors looking at the internal FoV and conjugated to the ground and the high altitude layers. The main guidelines are listed in Table 1:

| | |
|---|---|
| Aperture size | 100 m |
| Focal ratio | F/25 |
| Maximum FoV | $4'$ ($\approx$ 2900 mm) |
| Wavelength range | 0.7–1.0$\mu$m |
| Fried parameter $r_0$ | 0.3 m @ $0.85\mu$m |
| Channel–1 FoV | $2'$–$4'$ annular |
| Channel–1 conjugation | 0 Km |
| Channel–2 FoV | $2'$ internal |
| Channel–2 conjugations | 0 and 10 Km |

**Table 1.** Main guidelines for the optical design. The focal ratio is assumed to be that of the IR science field.

Each channel consists in two optical subsytems: the focal reducer, to scale down the FoV size allowing the use of smaller optics for pyramids positioning, and the pupil reimager to re-image the beam footprints on the detectors conjugated at different altitudes. The specifications imposed to the subsystems of the channels are summarized in Table 2.

| | |
|---|---|
| **Focal reducer (both channels)** | |
| Focal ratio | F/7 ($4'$ FoV size $\approx 815$ mm) |
| Strehl ratio | $> 75\%$ |
| Vignetting | as small as possible |
| Largest lens size | $\approx$ 1000 mm (BK7 or Fused Silica) |
| **Channel–1 pupil re–imager** | |
| Focal ratio | F/1 (pupil size $\approx 116$ mm) |
| Optical blur | $< r_0/5$ |
| Largest lens size | $\approx$ 1000 mm (BK7 or Fused Silica) |
| **Channel–2 pupil re–imager** | |
| Focal ratio | F/5 (pupil size $\approx 291$ mm) |
| Optical blur | $< r_0/5$ |
| Largest lens size | $\approx$ 1000 mm (BK7 or Fused Silica) |

**Table 2.** Specifications for the subsyetms of the WFS channels.

## 4. CHANNEL–1 OPTICAL DESIGN

For the channel–1 (FoV $4'$) an hybrid reflective/refractive solution has been chosen and the optical layout is shown in Fig. 1.

The focal reducer consists of a 3–meter class F/2.7 annular spherical mirror placed at the F/25 telecope focus and collecting an annular FoV of internal radius of $1'$ and external radius of $2'$. The light of the internal $2'$ FoV is let pass through towards the channel–2. Close to the mirror focus, where the telescope pupil is re–imaged, a four 400–mm class dioptric objective provides a F/7 focus of high optical quality (Strehl $> 75\%$) over the whole FoV. The lenses have all the surfaces aspherical. The light is folded–out from the main optical axis by a $45°$ mirror that can be used also for the PWFS modulation. In Table 3 are listed the optical data of the focal reducer and in Fig. 2(left) the spot diagrams in the F/7 focal plane are shown.

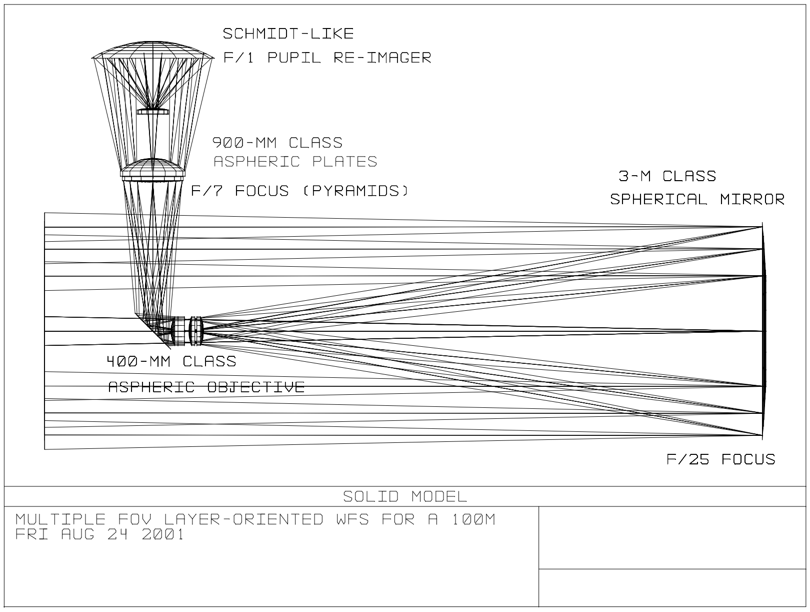

**Figure 1.** Channel–1 optical layout. The annular spherical mirror picks–up the external annular FoV that is re–imaged at a smaller focal ratio (F/7, $\approx 800$ mm size) for pyramid positioning. A Schmidt–like F/1 pupil re–imager provides to re–image the telescope pupil with an optical blur of $\approx r_0/6$. The spherical mirror has a central hole that lets the light pass through toward the Channel–2 (see Fig. 3).

The pupil re–imager is a Schmidt–like F/1 camera and consists of two 900–mm class BK7 aspheric plates placed just behind the F/7 focus (pyramids location) , a 1.6–meters class slightly conical mirror and a third 400–mm class aspheric plate faced to the pupil image plane. The pupil has a size of $\approx 116$ mm and $80\%$ of the Encircled Energy is included

| Surf.Type | Radius | Thickness | Diameter | Glass |
|---|---|---|---|---|
| Spherical | 16000.000 | 7800.00 | 3000.0 | mirror |
| Aspheric | 310.892 | 50.00 | 400.0 | BK7 |
| Aspheric | 288.399 | 100.00 | 400.0 | air |
| Aspheric | -426.514 | 50.00 | 400.0 | LF5 |
| Aspheric | -1040.308 | 100.00 | 400.0 | air |
| Aspheric | -352.255 | 50.00 | 400.0 | KFSNZ4 |
| Aspheric | 1142.538 | 100.00 | 400.0 | FK51 |
| Aspheric | -345.004 | 2308.50 | 400.0 | air |
| Image | 4096.583 | - | 800.0 | - |

**Table 3.** Optical data for the focal reducer of the channel–1. All the unit are in mm.

| Surf.Type | Radius | Thickness | Diameter | Glass |
|---|---|---|---|---|
| Spherical | 4893.967 | 50.00 | 900.0 | BK7 |
| Ashperic | 5099.945 | 200.00 | 900.0 | air |
| Aspheric | -638.612 | 75.00 | 900.0 | BK7 |
| Spherical | -664.404 | 1617.34 | 900.0 | air |
| Ashperic | -1664.247 | -783.30 | 1600.0 | mirror |
| Spherical | -994.595 | 50.00 | 400.0 | LASF35 |
| Image | -756.652 | - | 400.0 | - |

**Table 4.** Optical data for the for the pupil re–imager of the channel–1. All the unit are in mm.

within $60\mu$m corresponding to $r_0/6$. The optical data of the pupil re–imager are listed in Table 4 and the Encircled Energy plot is shown in Fig. 2(right).

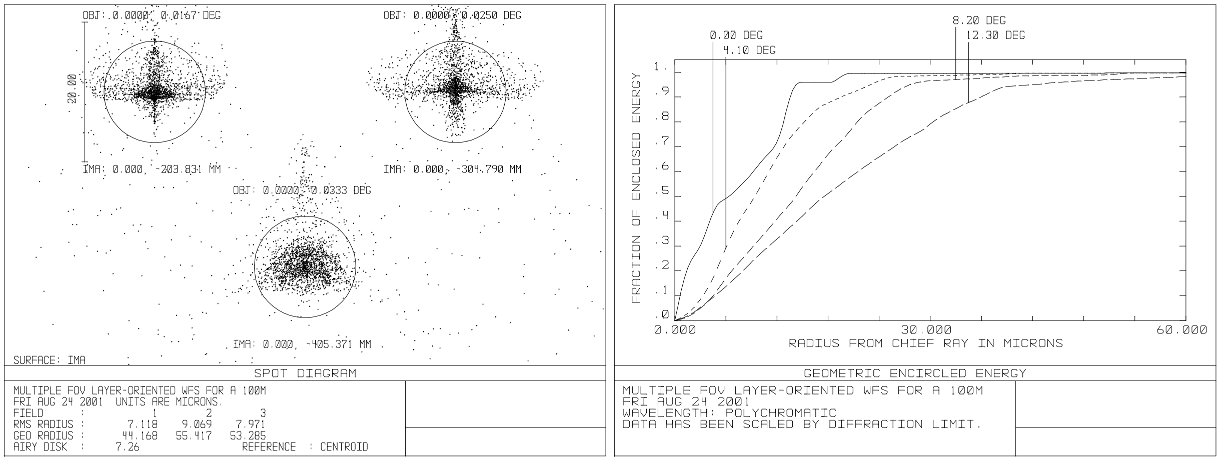

**Figure 2.** **Left:** spot diagram at the F/7 focus of the channel–1 focal reducer. The polychromatic Strehl ratio is $> 75\%$ over the whole FoV. **Right:** Encircled Energy at the pupil plane. The $80\%$ is included within a radius of $60\mu$m equivalent to $r_0/6$.

## 5. CHANNEL–2 OPTICAL DESIGN

Also for the channel–2 an hybrid solution has been adopted. The optical layout is shown in Fig. 3.
A 1.8–meters class F/4.4 spherical mirror, placed approximately 9 meters behind the F/25 focus, reflects the optical beams on a four 350–mm class aspheric lenses objective that re–images a F/7 focus for pyramid positioning with an overall Strehl $> 99\%$. Also in this case a $45°$ folding mirror folds the light out of the main optical axis and can be used for the PWFS modulation.

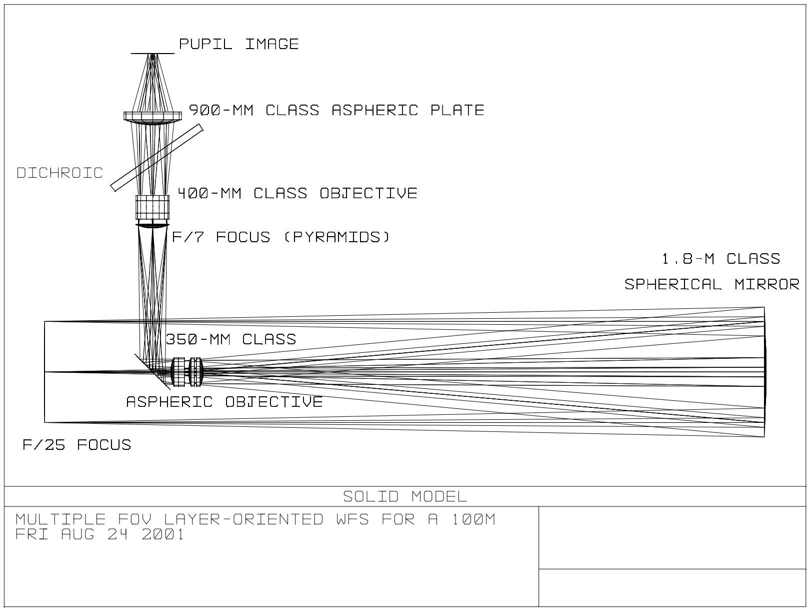

**Figure 3.** Channel–2 optical layout. The spherical mirro picks–up the internal part of the FoV that is re–imaged at a smaller focal ratio (F/7, $\approx$ 400 mm size) for pyramid positioning. A F/5 pupil re–imager provides an image of the telescope pupil with an optical blur of $\approx r_0/9$.

| Surf.Type | Radius | Thickness | Diameter | Glass |
|---|---|---|---|---|
| Spherical | 16000.000 | 7800.00 | 1800.0 | mirror |
| Aspheric | 335.990 | 50.00 | 350.0 | BK7 |
| Aspheric | 318.387 | 100.00 | 350.0 | air |
| Aspheric | -495.516 | 50.00 | 350.0 | LF5 |
| Aspheric | -1206.466 | 100.00 | 350.0 | air |
| Aspheric | -366.006 | 50.00 | 350.0 | KFSNZ4 |
| Aspheric | 2704.875 | 100.00 | 350.0 | FK51 |
| Aspheric | 377.663 | 2244.20 | 350.0 | air |
| Image | 7673.698 | - | 400.0 | - |

**Table 5.** Optical data for the focal reducer of the channel–2. All the unit are in mm.

The central $40''$ of the FoV are vignetted, but it doesn't significantly affect the sky coverage perfomances of the system (see Sect. 8). Table 5 lists the optical data of the focal reducer while Fig. 4(left) shows the spots diagrams at the F/7 focus. The first part of the pupil–reimager is a 400–mm class, four lenses objective with only one aspheric surface placed just behind the pyramids. After the objective a $45°$ dichroic splits the beam in two part, one per conjugated altitude, and finally two 900–mm class aspheric lenses (one per splitted beam) provide images of the beam footprints (diameter $\approx 291$ mm) on the detectors. $80\%$ of the Encircled Energy is contained within $100\mu$m (corresponding to $r_0/9$). The optical data of the pupil re–imager are listed in Table 6 while the Encircled Energy is shown in Fig. 4(right).
The whole optical train measures about 18 meters, a noticeable size but somehow reasonable if compared to the overall dimension of a 100–meters telescope.

| Surf.Type | Radius | Thickness | Diameter | Glass |
|---|---|---|---|---|
| Spherical | 633.227 | 50.00 | 400.0 | BK7 |
| Spherical | -8115.420 | 75.00 | 400.0 | air |
| Spherical | -6241.550 | 120.00 | 400.0 | BAFN10 |
| Spherical | -683.197 | 50.00 | 400.0 | KZFSN4 |
| Spherical | 363.960 | 130.00 | 400.0 | BAK |
| Aspheric | 2684.491 | 1000.00 | 400.0 | air |
| Spherical | 1138.408 | 150.00 | 900.0 | BK7 |
| Aspheric | 3141.917 | 640.80 | 900.0 | ai |
| Image | -2689.071 | - | 1000.0 | - |

**Table 6.** Optical data for the for the pupil re–imager of the channel–2. All the unit are in mm.

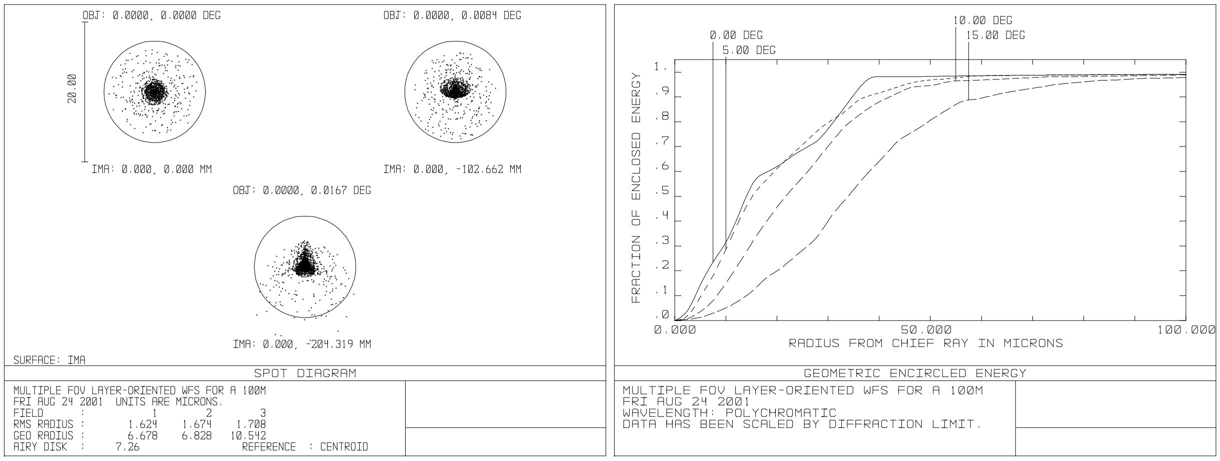

**Figure 4. Left:** spot diagram at the F/7 focus of the channel–2 focal reducer. The polychromatic Strehl ratio is $> 99$‘$\%$ over the whole FoV. **Right:** Encircled Energy at the pupil plane. The $80\%$ is included within a radius of $100\mu$m equivalent to $r_0/9$.

## 6. OPTICS MANUFACTURING

Even if the dimension of some optics are unusually large, none of them is too big or too complicate for available state of the art optical manufacturing technologies. Considering in detail what is included in the Multiple FoV layer–oriented WFS for comparison with already existing system we have: one 3.0–meters class mirror (ESO–NTT), one 1.8–meters class mirror (several telescopes), one 1.6 m fast focal ratio mirror (Palomar–Schmidt), four 900–mm class BK7 lenses (LBT Prime Focus, VLT M1 test lens), thirteen 400–mm class spherical and aspheric lenses (LBT Prime Focus) and two 350 mm folding mirrors.

All these optical components can be manufactured now with currently available technology and no major show stoppers can be seen for the optics procurement. Some example are shown in Fig 5.

## 7. DETECTOR COUPLING

The pupil dimensions as they are imaged by the WFS are too large to be coupled with available detectors or arrays of detectors. The size must be shrunk to fit a reasonable dimension for existing detectors. A possible solution to this problem is the use of Fiber Optics Tapers to couple the pupil plane with an array of detectors (see Fig 6). Fiber Tapers can be manufactured now with sizes up to 150 mm and they allow a maximum scaling of 10:1. The smallest focal ratio achievable with these devices is F/0.5 and the overall transmission is closer to $70\%$.

Fiber tapers can be arranged in arrays in order to cover a larger dimension and this solution is very attractive for our purposes. Using Fiber Tapers Arrays allows an easy decomposition of the pupil and, if every taper is coupled with one detector, there is no problem of light losses at the intermediate gap between detectors.

One can think to use state of the art detectors like very low Read Out Noise (RON) CCD recently developed for low light level imaging such as L3CCD of the Marconi Applied Technologies. These CCDs can achieve RON of the order of magnitude of $10^{-2}$ and they are very promising for WFS application. The largest format actually available is $576 \times 288$

**Figure 5.** **Left:** the ESO NTT a 3-meters class telescope. **Right:** 1-meter class BK7 lens of the LBT prime focus. The current available optical manufacturing technologies are well able to produce these optical components.

pixels ($20 \times 30\mu$m) and a size of $11.52 \times 8.64$ mm. Coupling an array of these CCD with Fiber Optics Tapers at the pupil images plane of the WFS can be considerd a solution not impossible to realize with the existing technologies. Table 7 lists the requirements in terms of fiber tapers and CCD for the two WFS channels.

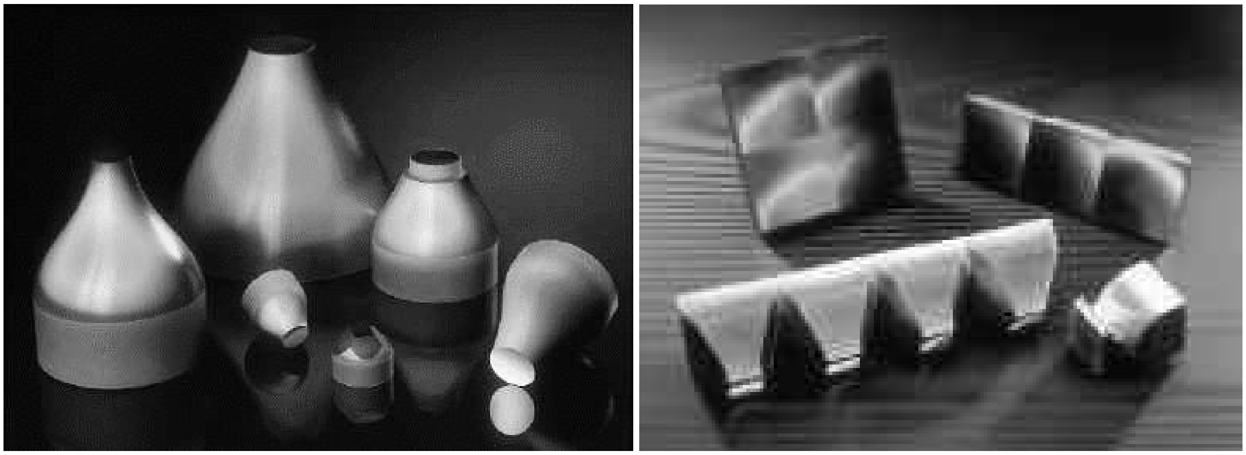

**Figure 6.** **Left:** Fiber tapers produced by Schott. These devices allow scaling factor up to 10:1 with a good optical transmission. **Right:** Fiber tapers arrays. It is a proimsing solution to effectively decompose the pupil image and to avoid the gap between the chips of a traditional detector array.

| Channel–1 | Input | Output | Channel–2 | Input | Output |
|---|---|---|---|---|---|
| Pupil size | 116 mm | 58 mm | Pupil size | 291 mm | 29 |
| Focal ratio | F/1 | F/0.5 | Focal ratio | F/5 | F/0.5 |
| Fiber tapers | 2:1 | | Fiber tapers | 10:1 | |
| CCD array | $4 \times 6 \times 6$ | | CCD array | $4 \times 3 \times 3$ | |

**Table 7.** Requirements for the detector coupling for the two WFS channels.

## 8. MFOV LAYER ORIENTED SKY COVERAGE

The Multiple FoV layer–oriented WFS has a FoV smaller than that considered in other papers (Ragazzoni et al. *this conference*; 2001b) and there is a further $40''$ central vignetting in the inner $2'$ FoV. We give here a preliminary estimate

of the system performance in term of sky coverage, taking into consideration the reduced and vignetted FoV.
We assume a correction at 800 nm, with an overall system efficiency of 0.1, a wind speed of 30 m/s and no dedicated optimization. In order to have a maximum Strehl ratio of 0.25, the limiting integrated magnitude at the ground conjugated detector can be defined for both channels. We considered a limiting integrated magnitude of $M_R = 15.1$ for the $4'$ annular FoV and $M_R = 17.5$ for the internal $2'$ FoV and using the Bahcall and Soneira model we computed the sky coverages listed in Table 8. It is worth noting that the gain in limiting magnitude of the pyramid when working in closed loop is not taken in cosideration so these sky coverages have still margins of improvement.

| Channel | $b = 90°$ | $b = 50°$ | $b = 20°$ |
|---|---|---|---|
| Annular $4'$ | 0.48 | 0.67 | 0.99 |
| Internal $2'$ | 0.46 | 0.63 | 0.98 |
| **Total** | **0.22** | **0.42** | **0.97** |

**Table 8.** Sky coverages for different galactic latitudes with the Multiple FoV layer–oriented WFS for a 100–meters class telescope. A galactic longitude of $90°$ is cosidered.

## 9. CONCLUSIONS

A tentative optical design for a Multiple FoV layer–oriented WFS for a 100–meters class telescope has been presented. The WFS provides a diffraction limited intermediate focus for pyramid positioning at the two channels looking at a different size concentric FoV. Fast focal ratio pupil re–imagers have been designed to provide sub–$r_0$ optical quality at visible wavelengths and the optics of the whole optical train are kept below the maximum reasonable size of about 1 meter. All the optics can be manufactured with the actual available techniques and materials and no major show stoppers are seen in the possibility to build such a WFS now. The dimensions of the re–imaged pupils are kept small and using fiber optics tapers it is possible to perform the coupling with an array of reasonable number of low RON state of the art detectors. Despite of the reduced FoV and the central vignetting, the sky coverage with this WFS is reasonably large and attractive.

## ACKNOWLEDGMENTS

This research has benefited from the support of the European Commission RTN program: "Adaptive Optics for the Extremely Large Telescopes", contract n.HPRN-CT-2000-00147.

## REFERENCES

Beckers J. M., “Increasing the size of tje isoplanatic patch size with multiconjugate adaptive optics,” in *ESO conference on Very Large Telescopes and their instrumentation*, M.–H. Ulrich, ed., pp. 693, 1988.

Beckers J. M., “Detailed compensation of atmospheric seeing using multiconjugate adaptive optics,” *Proc. SPIE* **1114**, pp. 215–217, 1989.

Beckers J. M., “Adaptive optics for astronomy – Principles, performance, and applications,” *ARA&A* **31**, pp. 13–62, 1993.

Gilmozzi R., Delabre B., Dierickx P., Hubin N., Koch F., Monnet G., Quattri M., Rigaut F., Wilson R.N., “Future of filled aperture telescopes: is a 100-m feasible?,” *Proc. SPIE* **3352**, pp. 778–791, 1998.

Nelson J. and Mast T., ”Giant Optical Devices ,” in *ESO Proocedings of the Bäckaskog Workshop on Extremely Large Telescopes* **57**, T. Andersen, A. Ardeberg and R. Gilmozzi, eds., pp. 1–11, 2000.

Ragazzoni R., “Pupil plane wavefront sensing with an oscillating prism,” *J. of Mod. Opt.* **43**, pp. 289-293, 1996.

Ragazzoni R., Marchetti E. and Rigaut F., “Modal tomography for adaptive optics,” *A&A* **342**, pp. L53–L56, 1999.

Ragazzoni R., “Adaptive optics for giants telescopes: NGS vs. LGS,” in *ESO Proocedings of the Bäckaskog Workshop on Extremely large Telescopes* **57**, T. Andersen, A. Ardeberg and R. Gilmozzi, eds., pp. 175–180, 2000.

Ragazzoni R., Marchetti E. and Valente G., “Adaptive–optics correction available for the whole sky”, *Nature* **403**, pp. 54-56, 2000.

Ragazzoni R., Farinato J. and Marchetti E., “Adaptive optics for 100-m-class telescopes: new challenges require new solutions,”, *Proc. SPIE* **4007**, pp. 1076–1087, 2000.

Ragazzoni R., Diolaiti E., Farinato J., Fedrigo E., Marchetti E., Tordi M. and Kirkman D., “Multiple Field of View layer oriented,”, *this conference*.

Ragazzoni R., Diolaiti E., Farinato J., Fedrigo E., Marchetti E., Tordi M. and Kirkman D., "Multiple Field of View layer oriented adaptive optics," *A&A submitted*, 2001b.

Tallon M. and Foy R., "Adaptive telscope with laser probe – Isoplanatism and cone effect," *A&A* **235**, pp. 549–557, 1990.