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RELEVANT OPTICAL ISSUES OF THE SPM-TWIN TELESCOPES

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RESUMEN

La mayoría de los aspectos técnicos del Proyecto de los Telescopios Gemelos en SPM han sido resueltos por los proyectos de los telescopios Magallanes y MMT. Sin embargo, el "Telescopio de Gran Campo" será el primero de su clase, y se requiere investigar una solución óptica a partir de las soluciones del telescopio Magallanes. Adicionalmente se deben de investigar los requisitos para la óptica adaptiva en el "Telescopio de Campo Estándar". En esta contribución compararemos diseños conceptuales tanto para el campo amplio, como para la mejor solución para la óptica adaptiva en los Telescopios Gemelos en SPM.

ABSTRACT

Most technical aspects of the SPM-Twin Telescopes have been basically solved by the Magellan and MMT projects. However, the Spectroscopic "Wide Field Telescope" will be the first of its kind and an optical solution based on Magellan needs to be further investigated. In addition, the requirements for adaptive optics for the Standard Field Telescope need to be worked out. In this contribution we will compare optical wide field conceptual designs and the potential scope of AO for SPM-Twin.

Key Words: **INSTRUMENTATION: ADAPTIVE OPTICS**

1. CONCEPT DESIGN OF FOR THE WIDE-FIELD TELESCOPE

Unlike the Standard Field Telescope (SFT) which is basically an updated clone of the Magellan Design, the spectroscopic Wide Field Telescope (WFT) will be the first of its class (see González 2007). Hence, its technical feasibility under a Magellan-like concept had to be further investigated. In particular, it was important to verify that a telescope very similar to Magellan could deliver fields as large, or larger than 1.5°, under spectroscopic requirements.

As a guiding reference for the definitive conceptual and detailed designs of the WFT, the SPM-Twin project has explored the feasibility and potential performance of a myriad of optical designs, under optical concepts that do not impact on the Magellan structural or mechanical design of telescope and building.

A uniform set of optimization and evaluation criteria was applied to all optical solutions, to ensure a fair inter-comparison of their performance and feasibility. In particular, all designs avoid structural modifications of the Magellan telescopes (same dimensions, f/# of primary mirror, back-focal, etc.). Among the merit parameters considered were: complexity of the WFC and ADC refractive optics (number of lenses, size, curvatures, etc.), the compatibility with optical fiber feeding (f/#, plate scale, telecentricity, etc.).

1.1. *Optimization of a Magellan-like WFT*

Integrated design of telescope optics with single WFC and ADC. In this concept the telescope optics, the wide field corrector (WFC) and the atmospheric dispersion corrector (ADC), are designed and optimized as a single unit. This enables a tremendous gain in the ultimate performance, simplicity, and cost over conventional designs, where a generic telescope is first built and next generation instruments and WFC's are added onto it, or retrofitted, at a later time.

Figure 1 shows the quantitative gain of this SPM-Twin WFT integral design approach, in terms of the image quality (polychromatic FWHM) delivered by different optimization philosophies. For simplicity, only the f/4.5 solutions are shown, while the next subsection discusses the comparison of the potential f-ratios for the WFT.

A bare 2-mirror telescope, similar to existing large aperture telescopes like Magellan (or the Ritchey-Chretién solution shown in Figure 1), cannot yield fields much larger than a fraction of a degree with sub-arc-second quality as needed by our WFT. The performance of several self-similar 3-lens corrector systems, starting with a design to correct the fixed R-Ch telescope up to a design where the telescope and corrector parameters are optimized simultaneously, differs quite strongly. While correct-

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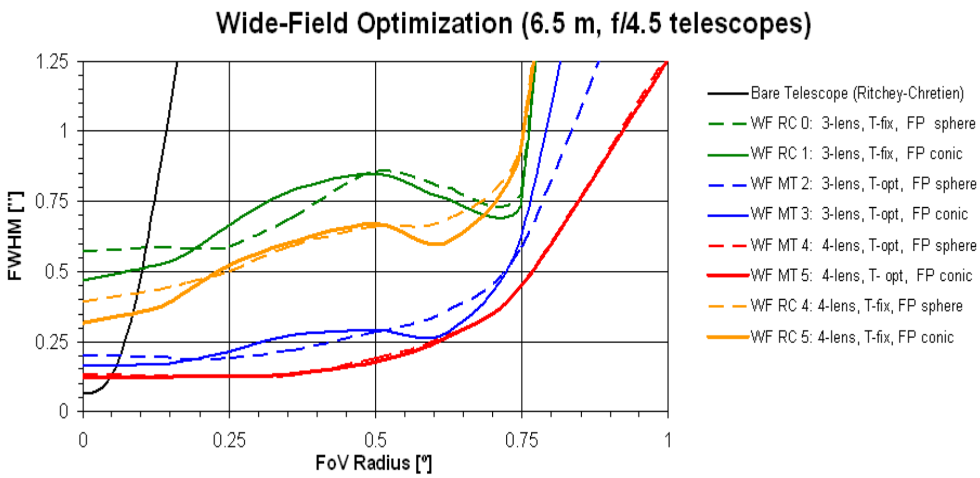

Fig. 1. Image quality (FWHM) delivered by different WFT telescope solutions (f/4.5 systems). A bare 2 mirror telescope (continuous line at left) cannot reach the sub-arc-second images required by the WFT. The design for a 1.5° FoV corrector for a standard Ritchey-Chretien telescope looks promising, but only through compromises of image quality across the field and forcing the solution to barely reach the edges of the field (green curves), even under the refinement of a more elaborate (complex and less efficient) lens correcting system (yellow lines). When the telescope and corrector are optimized as an integral system, far better and simpler solutions are reached (blue and red lines) even for corrected fields beyond 1.5°.

ing an existing bare telescope basically implies reaching a 1.5° field of view with sub-arc-second images at the expense of deteriorating the performance at the center, the integrated optimization allows for a far less compromising performance across the whole field, a more natural solution (not as forced to reach the field edges) and, as discussed below, simpler and more viable optical lenses.

1.2. *Mirrors and Optics Feasibility*

The particular case of an f/4.5 solution was shown before, since its plate scale (142 μm per arc-second) naturally couples with the numerical aperture of optical fibers and avoids an extremely large diffractive optics (about a meter in diameter for a 1.5° FoV). But faster and slower systems were also explored, searching for an optimal WFT solution.

Figures 2, 3 and 4 quantify the difficulty and performance of the different potential f-ratios of the SPM-Twin WFT. The optimal solutions call for a small modification of the conic constant of the parabolic Magellan primary mirror, but keep the focal distance fixed to the standard casting. The required hyperbolas do not deviate much from the generated parabola and are within the standard capabilities of the UA Mirror Lab. The secondary shape becomes more difficult the faster the system, but its size is basically determined by the field size (~2 m in diameter for 1.5°).

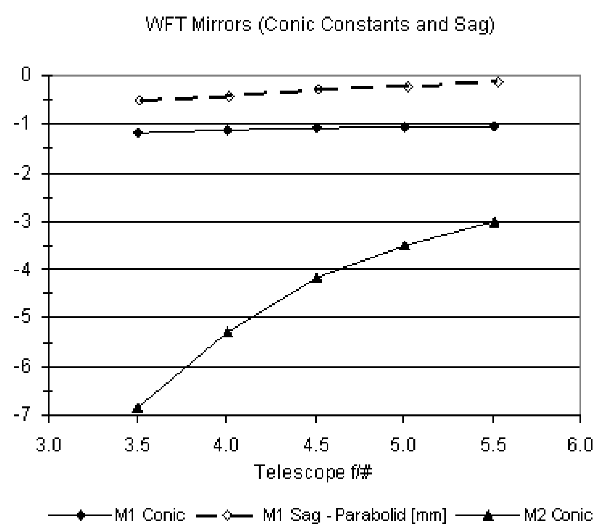

Fig. 2. Fast f-ratios are needed for the SPM-Twin WFT to minimize the size of the diffractive optics and instrumentation, but the conic constant — and difficulty — of the secondary mirror increase significantly with faster systems (black curve). Better solutions are reached if we allow the Magellan parabolic primary mirror to be slightly hyperbolic (red curve), and these solutions imply the removal of not more than 500 microns of glass at the edges of the generated parabola. These parameters are within the construction capabilities of the UA Mirror lab facility.

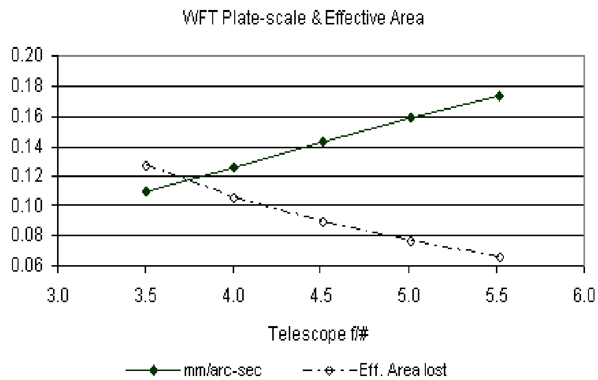

Fig. 3. The plate scale of the WFT (upper curve) should naturally couple to the diameter and to the numerical aperture of optical fibers for minimal focal-ratio degradation and to avoid the need and loses of pre-optics. The faster systems are better in this respect, but imply larger secondary blocking of up to 13% of the primary aperture (lower curve).

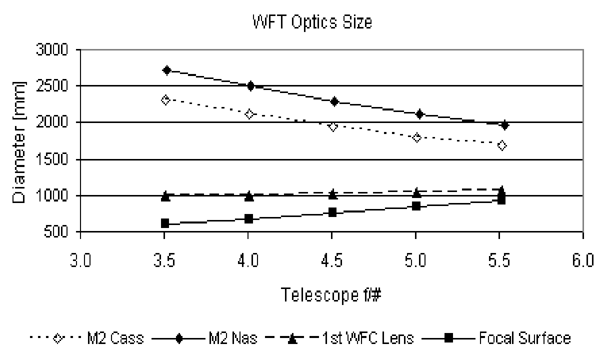

Fig. 4. The size of the optical elements is another relevant feasibility parameter of the SPM-Twin WFT. The focal plane diameter for a corrected 1.5° FoV (bottom curve) ranges from about 60 cm (f/3.5) up to slightly less than one meter, and is the characteristic size of the patrol area of individual spaxels and deployable IFUs. The diffractive optics of the wide-field and atmospheric-dispersion corrector have a maximum diameter of the order of one meter — large but feasible and significantly smaller than other wide-field projects (like LSSST and WFMOS). Finally, since the Magellan mechanical structure implies two very different back focal for the Cassegrain or Nasmyth foci, the required secondaries have different diameters (top curves respectively). The Nasmyth station of the Magellan structure limits the FoV to less than 1°; SPM-Twin considers as a first option the Cassegrain solution to avoid structural modifications and to take advantage of the smaller secondary.

The WFT final f-ratio will consider the optimal match with diameter and numerical aperture of the

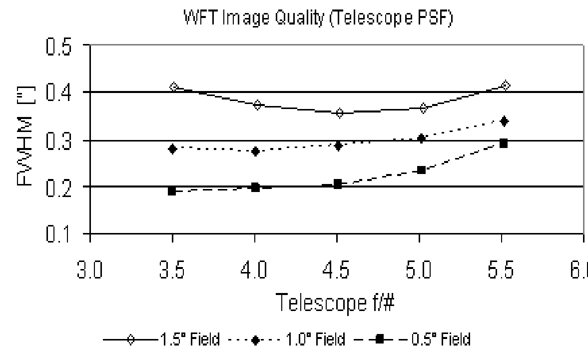

Fig. 5. Image quality, in terms of the full-width at half maximum (FWHM), delivered by telescope+WFC optimizations of different f-ratios. The image quality within a 1° field improves with system speed, but the FWHM of the outer 1.5° FoV reaches a minimum at ∼ f/4.5.

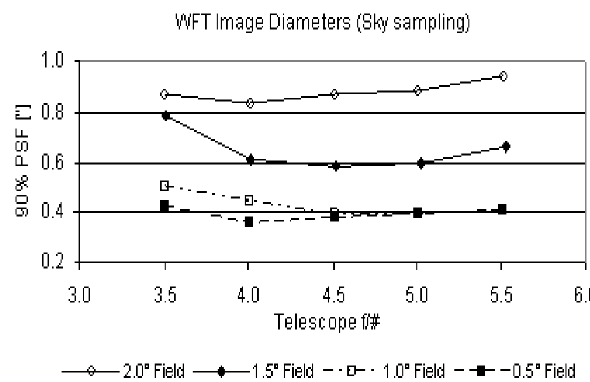

Fig. 6. Polychromatic 90% encircled-energy diameters as delivered by different WFT f-ratio solutions. This is a more relevant image-quality measure than FWHM for the spectroscopic SPM-Twin WFT. The optimal spaxel apertures of the WFT, considering extragalactic point-like sources, are between 1 and 3 arc-seconds, so the Magellan-like WFT provides an adequate error-budget. The wings of the point-spread function are harder to control than the FWHM, and systems faster than f/4.0 may perform better at prime focus. The coupled Telescope+WFC optimizations for a 1.5° system also deliver sub-arc-second 90% PEE diameters for a FoV as large as 2.0°, as can be seen by the natural behavior of the image deterioration in Figure 1.

optical fibers, in order to minimize the need for and complexity of any pre-optics. The faster systems imply narrower fibers and smaller corrector lenses and instrumentation, but the larger secondary decreases the effective area of the telescope, but not more than about 12%.

The SPM-Twin most likely will adopt the Cassegrain Station for wide-field spectroscopy. The

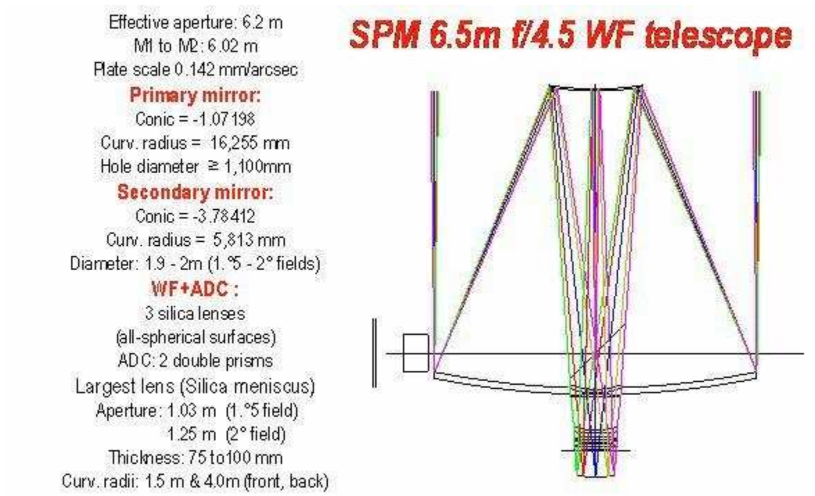

Fig. 7. Reference optical design for the wide-field spectroscopic SPM-Twin telescope (WFT).

compact Magellan telescope structure has the elevation axis too close to the primary to accommodate (without major structural modifications) fields larger than a degree in diameter at the Nasmyth stations. The longer back focal of the Nasmyth foci would also require a significantly larger wide-field secondary and consequently a smaller WFT effective aperture.

1.3. *Wide-Field Image quality*

The range of potential f-ratios for the WFT not only implies different technical compromises, as discussed above, but also delivers different optical wide-field performance. Image quality is usually quantified by the full-width at have maximum diameter (Figure 5) and in these terms, faster systems seem to perform better in the inner field but not so at the edges of the 1.5° FoV.

Nevertheless, for a spectroscopic telescope, the FWHM, for which a 2-D Gaussian PSF contains 50% of the energy, is not as important as the requirement to include all the light of point sources within each spaxel aperture. Figure 6 shows the polychromatic encircled-energy diameter that contains 90% of the light, and since the wings of the point-spread function are hard to control in fast systems, the optimal performance seems to be reached at intermediate f-ratios (around f/4 or f/4.5).

1.4. *Proposed optical design of the Wide-Field Spectroscopic Telescope (WFT)*

Given the discussion above, the reference design for the spectroscopic SPM-Twin Wide-Field Telescope adopts the f/4.5 Cassegrain Station solution shown in Figure 7.

In more detail (Figure 8), the Wide-Field corrector consists of three meniscuses like all-spherical silica lenses, and includes a double-prism atmospheric-dispersion corrector that can perform well at zenith distances up to 60°. The curvatures of the meniscus lenses are not difficult to manufacture. The double-prism corrector for atmospheric diffraction is particularly important for the WFT, given its wide spectral coverage (0.36 to 1.8 microns), since all wavelengths have to be sampled within the size of each spaxel sampling the FoV.

The potential wide-field atmospheric-dispersion correctors of WFT (Figure 9) are similar to, but larger than, the f/5 WFC of Magellan and MMT (Fata et al. 2004, and references therein). The SPM-Twin plans to work with the same developers on the details of the WFT corrector.

2. DESIGN FOR THE SPM-TWIN STANDARD FIELD TELESCOPE (SFT)

The SFT is basically a straight copy of the Magellan concept (Schectman 1994), since this is a well proven, highly efficient, general purpose and follow-up telescope. Magellan and MMT instruments and configurations can be adopted and interchanged, and the SPM-Twin SFT will build upon the experience of these two highly successful projects.

The SFT will be constructed for first light just as a standard Magellan telescope, but being complementary to the WFT capabilities, and since adaptive-optics astronomy will be more and more relevant in the near future, the SPM-Twin SFT has to be prepared for AO once this technique becomes of age. As mentioned above, SPM is a very competitive site for AO astronomy.

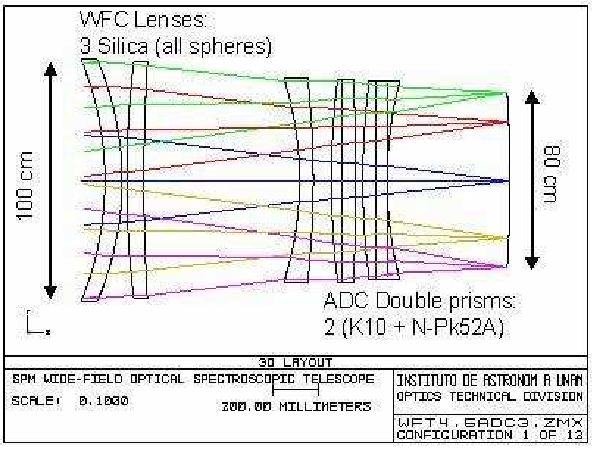

Fig. 8. Reference WFC for the SPM-Twin wide-field spectroscopic telescope. The curvatures of the spherical surfaces are gentle thanks to the coupled optimization of the telescope mirrors. The corrector glass is of one kind only (Silica), except for the ADC prism that requires two glasses of similar refractive index but very different dispersions for the variable correction of the atmospheric dispersion. The curvature of the prisms minimizes the spherical aberration that plane-parallel optics produce in a converging beam (Wynne 1993).

2.1. *The SPM-Twin AO*

Since AO performance depends strongly on seeing conditions, the performance will be specified for a Standard Seeing Scenario, corresponding to a seeing-limited image FWHM of 0.5 arc-seconds at 0.5 μm, and an equivalent turbulent layer at 5 km above the telescope, moving at a speed of 10 ms^{-1} . The d_0 parameter, a measure of focal anisoplanatism, is assumed to be 4 m at 0.5 μm.

The main scientific requirements for the high-order AO system include:

1. The primary requirement is for the on-axis Strehl Ratio (SR) at 2.2 μm to be at least 0.8 when the 'standard seeing scenario' applies and there is a guide star brighter than m_v=12 available on-axis.
2. Provision should be made for a Laser Guide Star (LGS), allowing an on-axis SR of at least 0.5 when the 'standard seeing scenario' applies and a natural guide star brighter than m_v=17 is available on-axis for measurement of tilt.
3. The system should also operate at wavelengths as short as 1 μm, and the SR degradation with respect to operation at 2.2 μm should be compatible with the change in wavelength.
4. The range of the wavefront measurement and correction should be sufficient so as not to degrade the SR possible for seeing as large as 1.65 arc-seconds.
5. The field of view within which it will be possible to search for a guide star should be at least 2 arc-minutes. Inside this field, there should be negligible vignetting and the reduction of SR due to optical aberration should be negligible.
6. The transmission to the science camera in the range 1-10 μm should be > 0.5.
7. The system stability should allow integration on the science camera of at least one hour.
8. It should be possible to optimize the system performance in real-time as a function of observing conditions, especially the seeing and guide star magnitude.
9. The AO operation should be compatible with queue observing. It should then be possible to take advantage of excellent seeing conditions. This requirement implies that the changeover to AO operation should be fast and straightforward. The AO control system should allow operation by trained but not necessarily highly specialized staff.

These requirements are based on what appears to be feasible given the current state of development of AO and LGS technology.

In addition, the entrance pupil area has a diameter of 6.5-m. It is required that the telescope provide excellent image quality, and that the main science instruments be easily interchangeable, in order to maximize operational efficiency. Adaptive optics will be employed to maximize image quality in the near infrared. The AO will be implemented in two stages:

1. Tip-tilt (and possibly fast focus) control should be available when the telescope starts operation (Day 1).
2. High-order AO should be available within two years of Day 1, and could be implemented using either an adaptive secondary mirror or a near-focus system for:
   (a) Conventional AO
   (b) Multi-conjugate AO
   (c) Ground-conjugate AO

An adaptive secondary would have the advantage of minimizing emissivity, and providing a corrected beam to any focus equipped with a wavefront-sensor. The MMT deformable adaptive-optics secondary is now in operation (Brusa et al. 2004, and references therein), and thus a similar system can be adopted by the SPM-Twin SFT. The performance of such a system is expected to reach large diffraction-limited fields with the SPM atmospheric profiles.

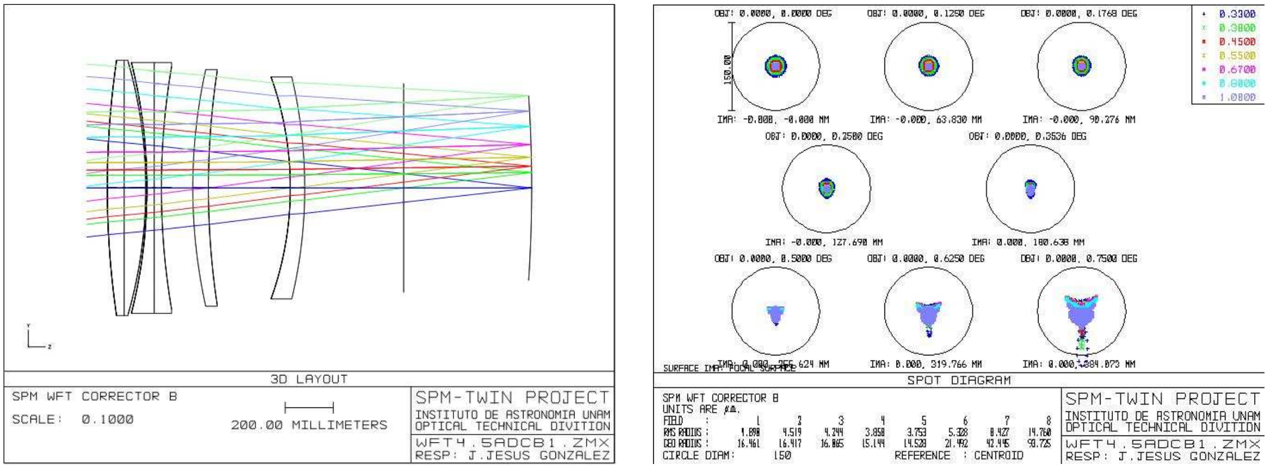

Fig. 9. WFT could also adopt a less-conventional but far more efficient WFC+ADC system. In this novel solution, the first meniscus is replaced by a pair of double prismatic lenses (ADC) giving a solution with less air-glass interface and easier to manufacture prisms. This system was also optimized to effectively correct atmospheric dispersion effects up to 60° zenith distances (right panel) with sub-arc-second images in a 1.5° FoV.

Near-focus systems have the advantage of being proven technology on existing telescopes, and are easier to calibrate and maintain.

The calibration of an adaptive secondary mirror would be facilitated by employing a Gregorian configuration, but this possibility has been rejected due to the cost incurred in constructing a longer telescope structure and dome. A good example of a non-Gregorian adaptive secondary has been developed for the MMT (Brusa et al. 2004) with very good results.

2.1.1. *Conventional Adaptive Optics*

Since multi-conjugate adaptive optics still requires further development, the present SFT concept will consider only conventional AO at first.

The principles of adaptive correction impose theoretical limits to what is achievable by an AO system. The correction worsens as the seeing deteriorates, as imaging wavelength gets shorter, and as the distance to the guide star increases.

The shape of the off-axis AO PSF, which mainly depends on the C_n^2 profile, has been analyzed by numerical simulations (Orlov 2007). The average C_n^2 profile observed with a generalized scidar at SPM, shows a very promising performance behavior with wavelength, seeing, and distance to the guide star. Obtaining the general shape of the PSF is relevant not only to its strong relation with the Strehl ratio but because of its potential use in the deconvolution algorithms.

2.1.2. *Ground-Conjugate Wide Field Adaptive Optics*

Ground-conjugate wide field AO is a new concept whose preliminary results show significant seeing improvement achieved over 10–20 arc-minute fields of view. After many years dedicated to single deformable mirror (DM), pupil-conjugated adaptive optics (AO) systems, new ideas are floating around for innovative concepts. Multi-conjugate adaptive optics systems are now in the making (e.g., Gemini South). Layer oriented MCAO schemes look promising. A specific proposal is being developed for a 6.5-m SPM-Twin AO system, which will reconcile most or all of the science and technical demands of SPM-Twin.

3. CONCLUSIONS

1. A wide field solution with fields beyond 1.5° are feasible with a 6.5-m Magellan-like telescope. They imply only optical differences, but no structural modifications to the Magellan design.
2. The correcting diffractive optics become simpler and more feasible with coupled optimizations with the telescope. A viable WFT solution implies a slightly hyperbolic primary very close to the cast parabola.
3. Although at the initial stage SPM-Twin will not concentrate efforts on adaptive optics, the SFT should consider the AO requirements right from the beginning for optimal performance and risk minimization.

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