Instrumentation for the Giant Magellan Telescope

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ABSTRACT

A conceptual design for the Giant Magellan Telescope is being developed based on a primary mirror with 7 large segments to be fabricated using the borosilicate honeycomb mirror technology developed at the Steward Observatory Mirror Lab.

A number of key instrumental capabilities have been identified by the Science Working Group. It seems likely that the instrumentation for wide-field imaging and spectroscopy in the optical and near-infrared will have the greatest impact on the optical and mechanical design of the telescope. A number of conceptual designs for wide-field imaging spectrographs and wide-field fiber-optic spectrographs are being investigated. Some of these designs incorporate wide-field correctors.

In addition the opportunities for ground-layer correction using a Gregorian adaptive secondary mirror (which is conjugate to a point less than 200 m above the telescope) are being actively considered, and a program to empirically test the prospects for ground-layer compensation in progress.

1. Introduction

The conceptual design of the Giant Magellan Telescope (GMT) is being developed by an institutional collaboration which currently includes all of the partners in the Magellan 6.5-m telescopes: the Carnegie Institution of Washington, the University of Arizona, the Harvard/Smithsonian Center for Astrophysiscs, the Massachusetts Institute of Technology, and the University of Michigan. The size of the project is clearly so large that additional partners are actively being sought. A GMT board has been appointed, as well as a Science Working Group (SWG) and a Project Scientists Working Group (PSWG). The SWG is charged with identifying the key scientific goals of the facility, and the actual conceptual design work is taking place under the auspices of the PSWG. The SWG and PSWG are working together to define the key instrumental capabilities and to explore the feasible limits of various instrument concepts.

The primary mirror of the Giant Magellan Telescope will consist of seven 8.4-m diameter mirrors, with 6 identical off-axis segments arranged around a central on-axis segment. The baseline design of the telescope includes an adaptive Gregorian secondary which will conjugate to a height of about 150 m, which should be especially effective for ground-layer compensation and also provide a low-emissivity AO capability in the thermal IR. A detailed discussion of the organization of the project, the project plan, and the initial work on the conceptual design of the telescope is given in the paper presented at this conference by Matt Johns.

At a very preliminary stage of its work, the SWG has identified 6 instruments of particular scientific interest. They are: 1) a wide-field, seeing-limited optical spectrograph, with a field at least 10' in diameter and capable of observing at least 100 objects simultaneously, 2) a high-resolution, seeing-limited optical spectrograph with a resolution of at least 50,000, 3) a near-IR adaptive-optics imager with a field of 10", 4) a near-IR adaptive-optics integral field spectrograph, 5) a mid-IR adaptive-optics imager, and 6) a near-IR ground-layer adaptive-optics imager.

Given the experience with the current generation of 8-m class telescopes, it seems likely that the wide-field imaging spectrograph will be the largest and most complex instrument, with the greatest potential impact on the overall optical and mechanical design of the telescope. For this reason the PSWG has singled out this instrument for early consideration in order to help constrain the evolution of the conceptual design of the telescope as early in the design process as possible.

2. Field Correctors

The overall projected diameter of the seven-segment primary mirror is 25 m, with a filling factor, allowing for the space between segments and for the secondary obscuration, of about 70%. A reference focal length of 18 m has been adopted for the early design work, but it is possible that this value will be modified somewhat as the interaction with the design of the instrument suite becomes better defined. Secondary focal ratios in the range from f/6 to f/10 have been considered during the early work on the design.

The primary and secondary mirrors will be made aplanatic in order to provide a completely diffraction-limited field over the central arc-minute, for work with adaptive optics. But it is very likely that the wide-field spectrograph will require a field corrector in order to provide acceptable image quality over a 10' or larger field. The diameter of the focal surface is such that it should still be possible to provide field correction by using very large fused-silica or optical-glass lenses, up to a maximum feasible diameter of about 1.8 m. Such transmissive correctors are much easier to implement and to work with than reflective designs which have been proposed and in some cases implemented on other telescopes. A characteristic of transmitting correctors is that they introduce very little net power to the optical system.

Three classes of transmissive corrector have been considered, each one with advantages and disadvantages. It is possible that more than one type of corrector will be implemented for the GMT. For this reason an important constraint on the design of the telescope is that it should be possible to add or remove different correctors from the telescope depending on the choice of instrumental configuration.

The first type of corrector is a single Gascoigne[1] (aspheric) corrector plate. This design has the advantage of adding only 2 glass-air surfaces to the system. Correction of fields up to about 20' in diameter is feasible, although the design works best if the parameters of the primary and secondary mirrors are allowed to vary by a small amount from the fully-aplanatic case. When the Gascoigne corrector is removed from the telescope there is a small amount of (overcorrected) residual coma. This coma will probably need to be corrected for AO work, but there are at least several conceivable ways to introduce the correction: either in the re-imaging optics which are likely to be part of an AO system anyway, certainly in any system with an intermediate cold-stop; or by introducing a small corrector element sized appropriately for the AO field on the way to the secondary focus. The small corrector could be made from exotic IR-transmitting materials if necessary, something which is certainly not feasible for the wide-field corrector.

The second type of corrector consists of two spherical meniscus lenses. The optical performance of this corrector is somewhat better than that of the Gascoigne corrector, and the figures of the primary and secondary mirrors can be left in the fully aplanatic configuration.

A third type of corrector incorporates a strong field lens near the telescope focal plane in order to render the curved secondary focal surface "telecentric." In this condition the chief ray is perpendicular to the focal surface (or nearly so) at any field position. The telecentric condition is essential if the wide-field spectrograph or some other instrument is to be implemented using multiple optical trains in a fly's-eye arrangement. It is also very convenient, although perhaps not essential, for use with certain types of fiber positioners. The field correction in a design of this type is still provided by two spherical meniscus lenses, but the spacing between the lenses becomes critical and the optical performance is not quite as good as for the non-telecentric designs.

Figure 1 shows the optical layout for one of the telecentric corrector designs. The field diameter is 24' and the largest element is 1.75 m in diameter. The rms image diameter is 0.07" at the edge of the 24' field. The last surface of the corrector, which is closest to the focal surface, is aspheric. This is necessary in order for the very strong field lens to create a high quality image of the exit-pupil, which is equivalent to satisfying the telecentric condition to high accuracy. The exit-pupil, which is shown in the diagram, is 0.4 m in diameter. Because the aspheric surface is so close to the focal surface, the required tolerance on the accuracy of this surface is not very stringent.

An additional consideration for the wide-field correctors is the provision of atmospheric dispersion compensation. In some designs it is necessary to provide very large elements of two different types of glass. It is possible to incorporate the dispersion-compensating elements directly into the corrector lenses, or to add them as separate plano or nearly plano

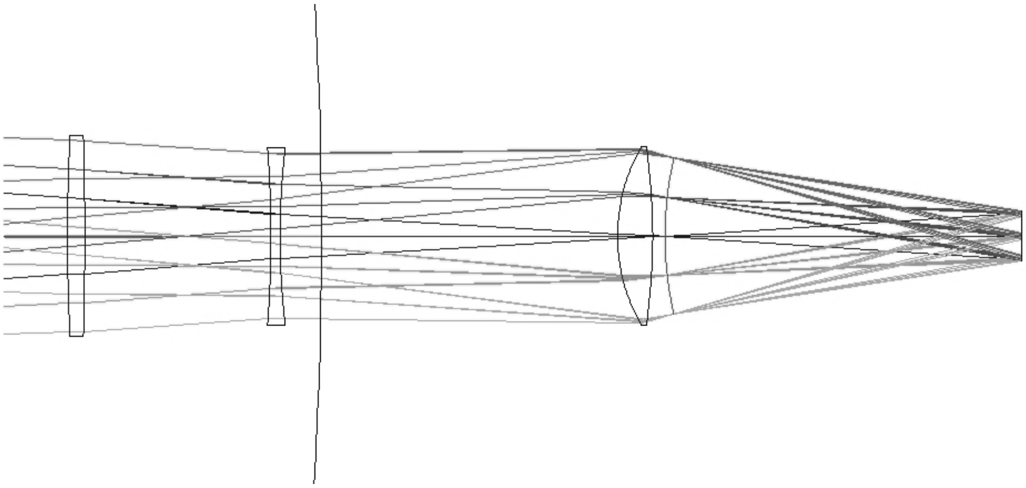

Fig. 1. Optical layout of telecentric field corrector for the GMT, with a field diameter of 24'.

prisms to an uncompensated field corrector. This is an area which urgently requires further attention in the GMT design effort.

3. Wide-Field Spectrographs

Several approaches are being considered for wide-field spectroscopy. These include single, very large imaging spectrographs (basically extensions of the IMACS[2] design), intermediate-sized fly's eye spectrographs (extensions of the VIMOS[3] or DEIMOS[4] designs), as well as fiber systems, possibly incorporating fiber image slicers, feeding multiple spectrographs with fiber inputs (extensions of 2dF[5] or OzPoz[6]).

3.1. Optical Materials

Without using image slicers, an imaging spectrograph will need to have a collimated beam diameter of *at least* 250 or 300 mm in order to provide adequate dispersion (equivalent to an 80 or 100 mm beam on an 8-m telescope). For very wide-field designs using transmitting optics, it will be necessary to obtain lenses using a variety of optical materials with diameters of at least 500 mm and preferably larger. It is clearly in the interest of all of the extremely large telescope projects to explore the prospects for obtaining large pieces of optical glass. The manufacturers of optical glass, particularly Schott and Ohara, have indicated a willingness to engage in significant development programs, sponsored by the ELT projects, in order to improve the availability of materials in large sizes. However it is important for the ELT projects to refine their optical designs to the point where specific families of the most important kinds of glass can be singled out for such a development program.

Fused silica can probably be obtained in sizes comparable to the ULE boules used to fabricate the Gemini primary mirror blanks. Sizes up to 1.8 m in diameter and 150 mm thick are probably possible using current manufacturing capability at Corning. Very large pieces of the most common crown and flint glasses, like BK7 or F2, are produced by Schott on a regular basis. These blanks are typically about 1 m in diameter and several hundred mm thick, and can be slumped or puddled to larger diameter if the total volume of glass is preserved.

Calcium fluoride is a particularly advantageous optical material which is essential to many optical designs for instruments on the current generation of 8-m class telescopes. It can be obtained in diameters of 350 or perhaps 400

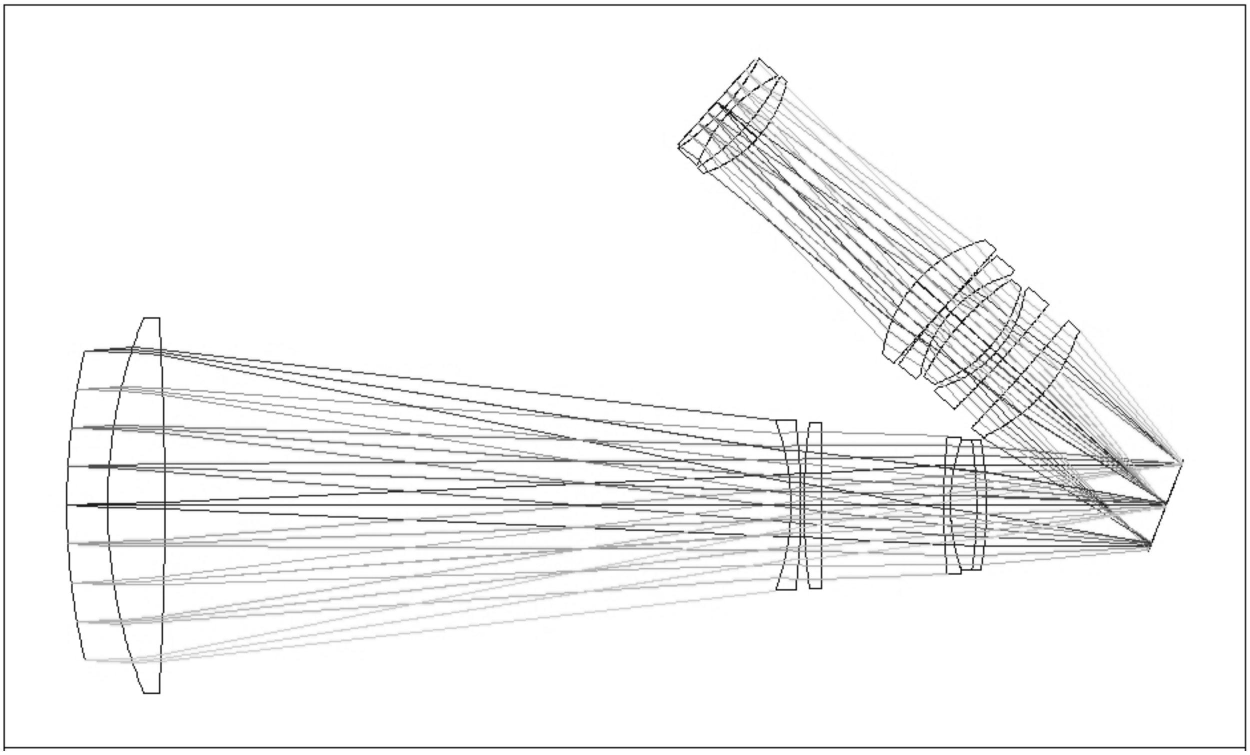

Fig 2. Optical layout of an imaging spectrograph with a 13' field and 250 mm collimated beam. The length of the instrument from the telescope focal surface / aperture plate to the mirror / reflecting grating is 3.4 m.

mm with thickness up to about 100 mm. Because the crystal-growth process requires extremely high thermal homogeneity, the time required to grow such large crystals is very long, typically several months. Moreover the thermal time-constant scales like the square of the diameter, so the prospect for obtaining much larger pieces of CaF2 appears to be poor. A significant development program, with an inevitable time scale of several years, would be required even to explore the possibility of obtaining material with a diameter of 500 mm.

For this reason the most important class of glasses to explore may be the fluorocrown (FK or FPL) types, which can sometimes be substituted for CaF2 in certain optical designs. Many instruments derive most of their net optical power from CaF2 or the fluorocrown glasses (often from a combination of the two) and are then achromatized to high order using a variety of other glasses. It would be very useful to review a wide range of current optical designs in order to identify a few families of glass which might be generally useful in providing this achromatizing function.

3.2. Imaging Spectrograph

The design of the IMACS spectrograph for the Magellan 6.5-m telescopes incorporates a collimator which is closely matched to the field curvature produced by a specific choice of Gregorian secondary mirror. This matching allows the collimator to obtain much higher optical performance (field diameter and image quality) than that of any other imaging spectrograph. The required properties of the secondary mirror are specifically a function of the collimated beam diameter. It is possible to design such a collimator for the GMT as well.

A spectrograph based on one such design is shown in Fig 2. It was developed at a time when the back focal length of the telescope was somewhat longer than is currently being considered, with a secondary focal ratio of f/10. The field of view is 13' in diameter, corrected by a single aspheric plate which is not shown in the diagram. All of the optical surfaces in the collimator and camera are spherical. The large field lens and the two single lenses in the collimator are made from fused silica. The triplet is made from BaK2 glass and CaF2, with a diameter of 400 mm. The parallel beam diameter is 250 mm. The optical layout is shown with a plane mirror for use in imaging mode, which would be replaced with a reflecting grating (presumably a 4-element mosaic) for spectroscopy. One possible design for the camera is shown, based on a design from the blue side of the UVES[7] spectrograph. The 5 air-spaced elements at the front of the camera are FPL51 glass and fused silica, except for the center element which is CaF2, again with a diameter of 400 mm. The two elements in the field flattener are both fused silica. A 36 CCD mosaic of 2K x 4K devices would be required in order to provide reasonable coverage of the camera focal plane.

In order to keep the sizes of the optical elements from growing even larger, there is a moderate amount of vignetting (20%) at the edge of the 13' diameter field, although there is no vignetting over the central 8'. The rms image diameter of the complete optical system is 0.2", and the wavelength range is 3600A to 1 micron. With a 1200 g/mm grating in first order the resolution is 4000 for a 1" slit at 8600A, and the spectral coverage is 2000A. Because of anamorphic pupil distortion the vignetting in spectroscopic mode is somewhat greater (20% at the center of the field).

The conclusion of this design exercise is that it should be possible to produce a spectrograph, using materials which are likely to be obtainable, with field coverage and wavelength resolution comparable to that of many of the imaging spectrographs which have recently been built for 8-m class telescopes, but which is appropriate for use with a telescope of very much larger aperture. If such a spectrograph is to be part of the instrument complement for GMT, the spectrograph design needs to be refined in order to precisely specify the appropriate diameter (and focal ratio) of the secondary mirror. However the desired secondary mirror diameter is likely to be between 3 and 4 m.

The strong field lens which forms the first element of the collimator is similar to the strong field lens in the telecentric corrector shown in Fig. 1. In principle it is possible to design a single large collimator for the telecentric corrector which has the field lens in front of the focal surface instead of behind it. So far the optical performance of such a collimator design is not as good as for the configuration shown in Figure 2. However the performance improves very rapidly with decreasing field size, and the telecentric corrector can be used very successfully with a 2 x 2 fly's eye, for example, which would cover a somewhat greater area of the sky than a single large spectrograph.

3.3. Fiber spectrographs

An alternative method for multi-object spectroscopy makes use of fibers, possibly with robotic positioners similar to those for 2dF or OzPoz. Without image slicers the spectrographs would have to be quite large (perhaps scaled up from the fiber spectrographs for the MMT[8]), but could at least be bench-mounted. With image slicers, the spectrographs could be more modest in size, but a larger number would be required. It remains to be seen whether the overall cost of many small spectrographs, if they could be kept sufficiently simple, might be lower than the cost of a few very large ones.

In order to implement many small and simple spectrographs it would be desirable, for example, to keep a fixed dispersed format with a single grating in each spectrograph mounted in a fixed position. At red wavelengths the resolution must be relatively high in order to reject the airglow contained in the numerous night-sky emission lines, and an echellette configuration might accomplish this. In the blue such high resolution is not likely to be required, at least when working on the faintest objects.

The unit spectrographs could be built using very compact and efficient Littrow transmitting optics, similar to the configuration in the MIKE[9] spectrograph at Magellan. The cameras could have 150 mm diameter collimated beams which would not require mosaic gratings, and focal lengths of about 400 mm (f/2.67) which should be a very efficient focal ratio for transmission through the fibers (at about f/3) and injection directly into the spectrograph. The collimator/ camera focal planes, with a diameter of about 100 mm, would be large enough to accommodate a 2-CCD mosaic as well as a diagonal mirror for injection of light from the fibers. Suitable optical designs have been produced by Rebecca Bernstein for both the red and blue unit spectrographs. The optical layouts, shown once-through from the entrance-pupil to the focal plane, are presented in Fig 3.

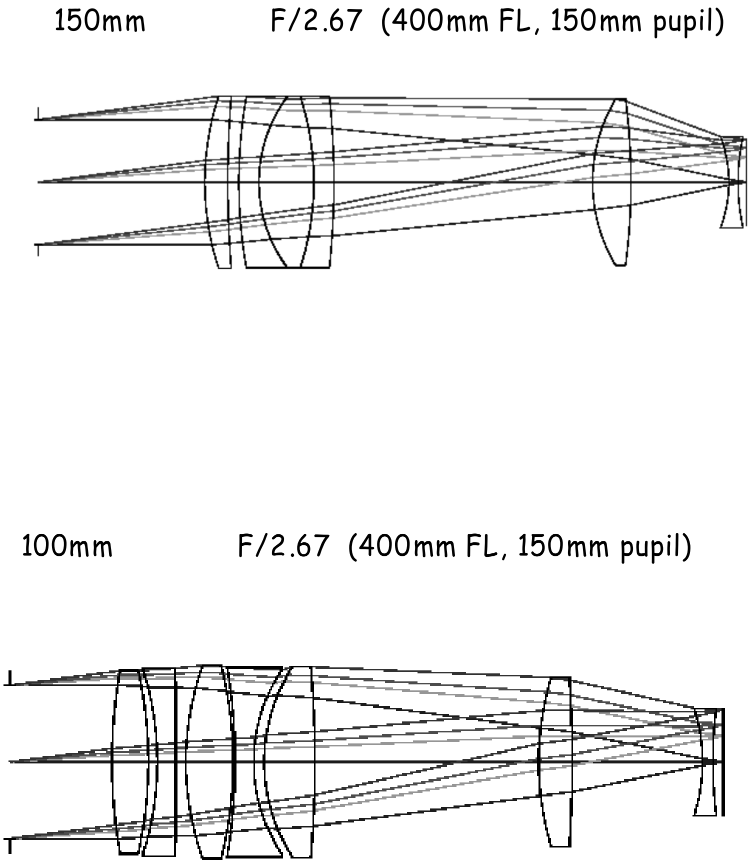

Fig. 3. Top: optical layout of a red unit spectrograph. Bottom: optical layout of a blue unit spectrograph

Each fiber-head would be a 7-fiber bundle with a total aperture of about 1”. The fiber tips would contain focal-ratio matching optics and possibly a dichroic beamsplitter. Charge-shuffling would be essential for obtaining the best possible sky subtraction in a fiber system. Allowing two heads per object, so that light is always being collected even when individual heads are being switched on and off target, and space for storing charge in the charge-shuffling mode, it should be possible to observe 5 objects with each unit spectrograph in the red, with a 4-order echellette format. In order to observe 100 objects it would be necessary to build 20 spectrographs. The situation is better in the blue, where a single order should suffice, and a total of 5 spectrographs would be required. The combination of the red and blue spectrographs would provide continuous spectral coverage over the entire optical band.

4. Ground-Layer AO

The PSWG expects the design of the GMT to be very specifically optimized for ground-layer adaptive-optics compensation. By minimizing the conjugation error the hope is that the field over which the ground-layer wavefront error is coherent will become large enough (possibly as large as 20’) that it will become possible to select several natural guide stars across the field at any position on the sky. The ground layer correction would just be the average wavefront error for these widely-separated guide stars, which will have to be about 14 mag or brighter.

The difficulty in making a reliable prediction concerning the performance of a GLAO system is that we do not have adequate data on the detailed behavior of the ground layer, covering a range of conditions and time of year. In particular we need to know the distribution of wavefront error with height above the ground, with an accuracy of better than 100 m. In order to obtain this information, we have begun a high-priority development program which will be carried out at one of the Magellan 6.5-m telescopes. A series of high-speed image analyzers will be deployed across the focal plane, which is 24' in diameter. Initially these image analyzers will be installed at fixed positions in order to observe stars in one of two bright open clusters, one of which will be observable at some time during almost any night of the year. The correlations between the wavefront errors measured for each of the AO guide stars will produce an accurate profile of the strength and height of the ground-layer wavefront error. Subsequently the wavefront analyzers will be modified to use fast CCD cameras of the highest possible sensitivity, and be made fully deployable. In this configuration they will be able to obtain information on the structure of the ground layer at any position on the sky, and will form the basis of a ground-layer AO guider suitable for use on the Magellan 6.5-m telescopes.

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