High-Spatial Resolution (IFU) Optical Spectrograph

Proposal for SOAR - October 1, 1998

Principal Investigator: Jacques Lépine, University of São Paulo

Table of contents

Page

1 INTRODUCTION 1

2 SCIENTIFIC REQUIREMENTS 2
 2.1 MAIN REQUIREMENTS FROM THE SAC 2
 2.2 POSSIBLE FUTURE UPGRADES 3

3 DESIGN OF THE BENCH SPECTROGRAPH 3
 3.1 GENERAL CONSIDERATIONS 3
 3.2 CHARACTERISTICS OF THE GRATINGS 6
 3.3 RESULTS OF PRELIMINARIES STUDIES 7

4 THE IFU AND FORE-OPTICS 8
 4.1 THE IFU 8
 4.2 THE FORE-OPTICS 10

5 THE CONTROL SYSTEM 11

6 THE PROTOTYPE 12

7 CRITICAL AREAS 13

8 COSTS 13
 8.1 THE PROTOTYPE 14
 8.2 THE SOAR IFU SPECTROGRAPH 14

9 TIME SCHEDULE 15
 9.1 THE PROTOTYPE 15
 9.2 THE MAIN SPECTROGRAPH 16

10 PERSONNEL AND INSTITUTIONS INVOLVED 17

APPENDIX A1: THE COST WBS 19

1. INTRODUCTION

To best exploit SOAR's excellent angular resolution in cases where complex extended objects or objects in crowded fields are studied, we propose an optical spectrograph equipped with a 1500-element Integral Field Unit (IFU). An IFU consists of a 2-D array of microlenses fully covering the focal plane over a modest field of view, each lens feeding an individual optical fiber that takes the light to the spectrograph. Such a unit will permit simultaneous spectra to be taken of all parts of some extended object such as a moderately distant galaxy or HII region. Since the spectrograph is bench-mounted, it can be constructed in a short time, and easily modified. The spectrograph will accommodate volume-phase holographic (VPH) gratings in transmission as well as a conventional reflection échelle grating. Use of narrow fibers allows narrow slits, so high spectral resolution ($R \approx 30{,}000$) is possible with a modest (90 mm) beam size. An IFU spectrograph is expected to be competitive at this resolution, not only for extended objects but also for stellar spectroscopy. In a slit spectrograph, the slit width must be kept to a minimum to obtain high resolution, but this has the disadvantage of vignetting much of the seeing disk in non-optimal seeing conditions. This limitation does not exist in a IFU spectrograph, since all the light of a star is used. The IFU spectrograph will be specially useful in crowded fields like globular clusters or the Magellanic bar, allowing simultaneous observations of many stars. Another motivation for high resolution is the study of velocity fields in HII regions, AGNs, and planetary nebulae.

The main components of the IFU spectrograph are sketched in Figure 1.

There are many IFU spectrographs already in operation (eg. the TIGER at the CFHT, Bacon et al., 1995, OASIS by the same group, HYDRA at the WIYN telescope, Barden and Armandroff, 1995, WYFOS at the WHT, SPIRAL prototype at AAT, etc), so that the risks and difficulties can be estimated.

The present proposal is the result of a joint effort of Brazilian institutions (IAG-USP, LNA, UFSC). We intend to exchange informations with the SOAR partners, to adopt similar solutions for the control systems, to benefit from the tests that are going to be performed on VPH gratings at UNC, and from the expertise of the CTIO staff on fiber optics spectrographs.

The strategy proposed is to build a prototype IFU spectrograph which will have many of the features requested by the SAC (Scientific Advisory Committee). The prototype will be cheap, and capable of serving as a testbed for the challenging aspects of the final SOAR IFU spectrograph. It will be assembled in about one year, and tested at the 1.6m LNA telescope. The final SOAR spectrograph, equipped with an IFU with a larger number of fibers, with all the gratings needed to fulfill the range of resolution recommended by the SAC, and with computer control for all the adjustable components, will be designed while the tests of the prototype are made, and the suggested modifications will be incorporated in the project.

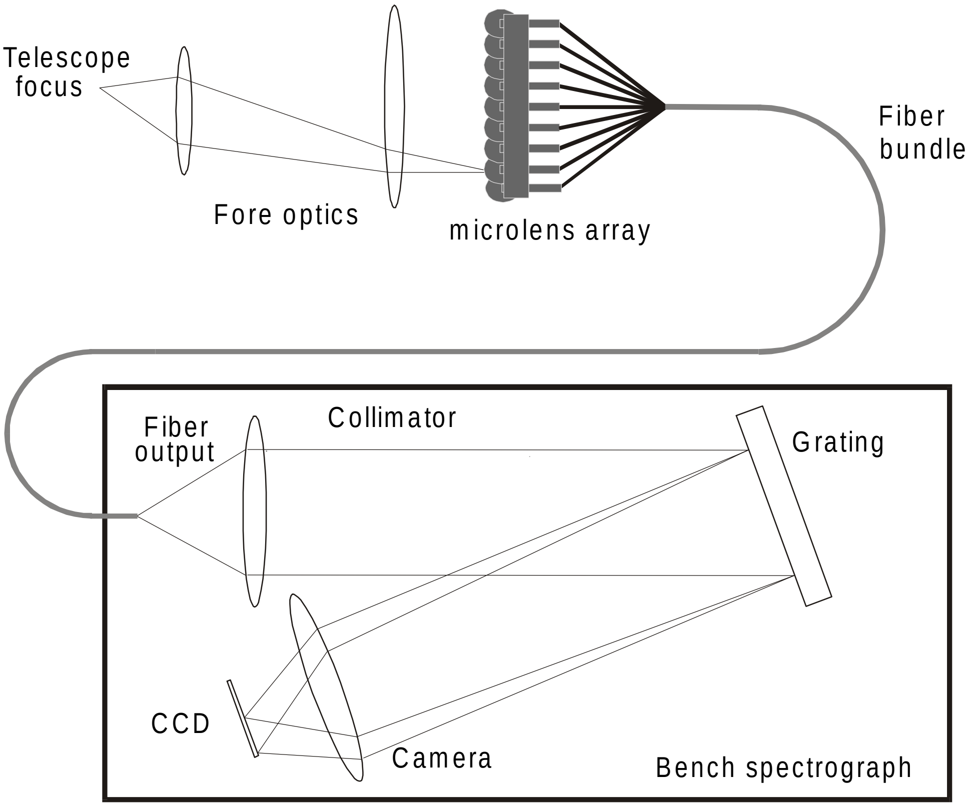


Figure 1. Sketch view of the IFU spectrograph, showing the fore-optics, the IFU, the fiber bundle and the bench spectrograph.

2. SCIENTIFIC REQUIREMENTS

2.1 Main requirements from the SAC

- 2D-coverage of a 5 x 10" field with 2-pixel sampling matched to the best quartile, center field, tip/tilt stabilized images, which corresponds to 0".15/pixel at about 1000nm. In the case of an IFU, a minimum of 1500 contiguous spatial elements (lenslets) is recommended. The lenslets should oversample the image so as to preserve the spatial resolution of the telescope with no loss of light between the fibers.

-wavelength coverage 0.35-1.05µm.

- A large range of resolving powers is required. The lowest resolution derives from the need to cover one octave in wavelength (a factor 2) in a single spectrum. With a CCD of 4000 pixels, and line width defined by 2 pixels, this corresponds to a resolution of about R = 2000. The other extreme fixed by the SAC is a resolution of about R = 30000. This would enable observations "between" the individual atmospheric OH lines in the red (λ >0.8µm), allowing much fainter objects to be observed in this spectral region. This resolution is also desirable for stellar spectroscopy, mainly for studies of chemical abundance. A choice of resolutions covering all the scientific requirements, like R= 2000, 6000, 12000, 30000, can be achieved by interchanging gratings.

-A fore-optic system is required to speed-up the telescope beam from f/16 to about f/5, to feed the fibers, and at the same time to provide the correct spatial sampling (0.15" per fiber). A switchable system with the capability of changing the magnification is desirable.

The SAC also recommends multiple fibers in fixed sky pattern (or applicable sky suppression strategy).

Other minimum capabilities, specified by the SAC:

1. >15% throughput at <350nm (including CCD+ telescope).

2. very low flexure: <0.04 pix/hr.

3. sky subtraction: 1% residuals over 180^o field rotation

Program options:

Provision for slit translation. It is intended to allow different fiber feeds; e.g. an eventual telescope upgrade to a bench-mounted adaptive optics system, and another directly from the telescope focal plane. This could be handled by a manual interchange mechanism.

2.2 Possible future upgrades:

1. An additional goal will be to have several separate IFUs that could be remotely deployed in the focal plane so that different objects, or different areas of the same extended object, can be studied spectroscopically with high spatial resolution. This capability is not found on any existing telescope, and will offer part of the widefield capability of imaging spectrographs without the drawback of having to observe each wavelength sequentially.

2. Operation to 1.4µm using warm fibers and a cold spectrograph

3. Adaptive optics feed with spatial scale < 0.08"/pixel to ensure 2 pixel sampling of top-quartile, center field, AO corrected images.

3. DESIGN OF THE BENCH SPECTROGRAPH

3.1 General considerations

This section describes the arguments leading to the specification of the optical components of the main part of the spectrograph, mounted on a bench. The design is that of a classical spectrograph possibly incorporating VPH gratings. Figures 2 and 3 show preliminary designs of the collimator and camera (preliminary design by Gilberto Moretto).

One critical requirement of an IFU based spectrograph is the focal ratio of the collimator, that must match the output focal ratio of the fibers. As focal ratio degradation is minimized for beams of focal ratio of about f/5 or faster, this value will be adopted.

Another driving requirement is the diameter of the optical fibers. It is desirable to use fibers with small diameter, in order to minimize the total length of the equivalent slit and consequently the diameter of the beam. In addition, small fibers result in smaller images at the camera, turning it easier to obtain higher resolutions. However, too small fibers may have large transmission losses and are technically more difficult to deal with and to couple to the lenslet system. SPIRAL has successfully used 50 µm fibers.

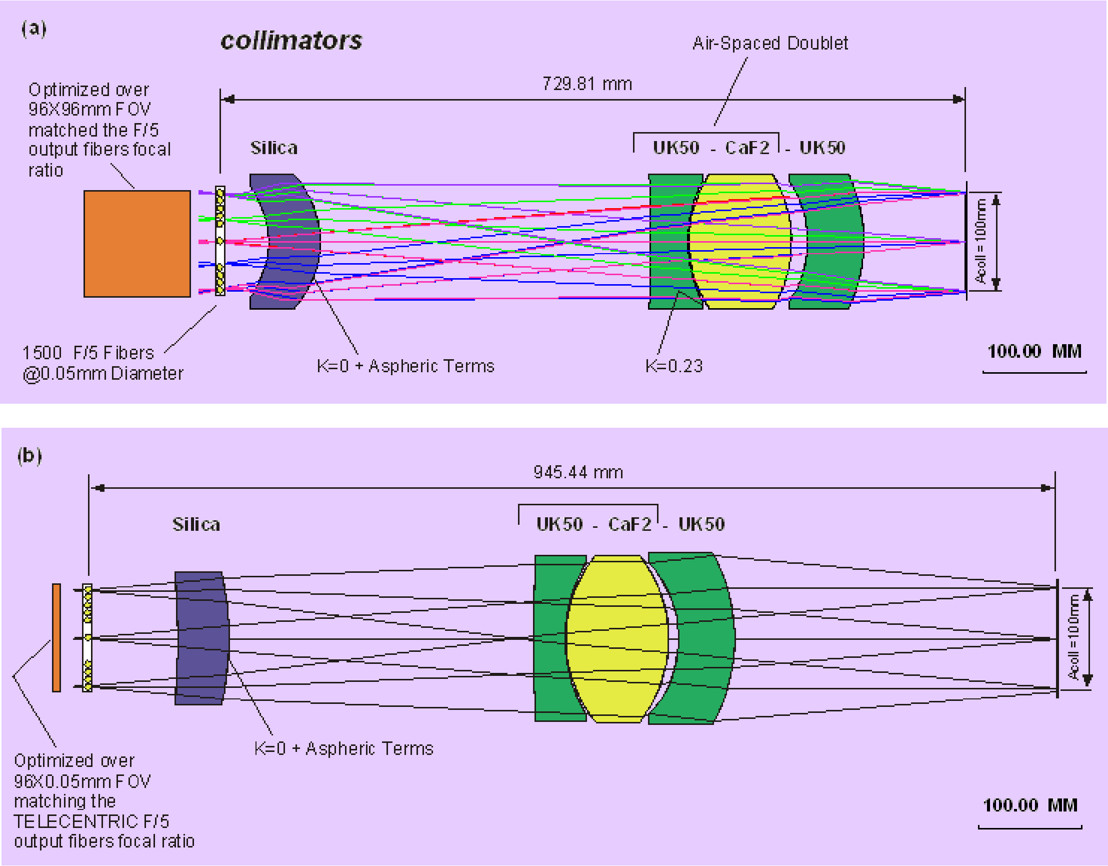


Figure 2- Preliminary design of two possible collimators

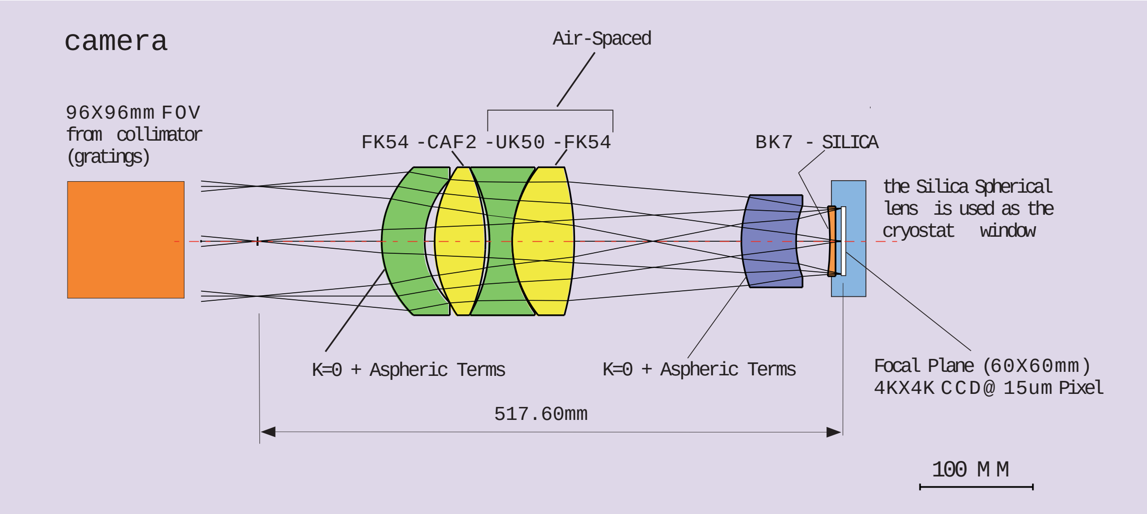


Figure 3- Preliminary design of the camera

IFUs based on ~50µm fibers are also under development at the University of Durham. The GMOS IFU that is expected to be completed in 1999/2000 is a result of the experience on other IFUs constructed in their program. We propose to use 50µm fibers, with 5µm thick cladding. This preserves the minimum cladding thickness of about 5λ at 1µm, with a usual 10:1 core/cladding ratio. The center-to-center separation will be ~ 60µm, and the total height of the 1500 fibers column will be ~90 mm. This determines the diameter of the collimated beam of about 100mm, and the focal length of the collimator about 500mm.

At the other end of the spectrograph, the image of the fibers output must match the CCD pixels. The project is considering a 4k x 4k CCD, with pixel sizes 15µm. To match the spectral resolution to 2 pixels sample on the CCD, or 30 µm, then the focal length of the camera must be about 300 mm.

The angular dispersion of the spectrograph is:

$$di'/d\lambda = m/a \cos(i')$$

where *i'* the angle of diffraction with respect to the normal to the grating, *m* the order used and *a* the separation between the grooves. In the configuration discussed here, the resolution is determined by the dimension of the image of the fibers on the CCD, and not by the diameter of the beam (or the size of the grating), as it is often the case in spectrographs. If the diameter of the beam is about D=100 mm the dimension Δx of the corresponding Airy disk is given by $\Delta x = f_2 \lambda / D$, where f_2 is the focal length of the camera, about 300 mm . Even for λ =1µm, Δx is about 3µm, much smaller than the image of a fiber on the CCD.

The maximum spectral range in an order *m* is given by the condition:

$$(m+1)\lambda = m(\lambda+\Delta\lambda)$$

Only $m = 1$ fulfills the condition of covering a factor 2 wavelength interval in one spectrum. The use of the first order is also convenient to maximize the throughput. The total wavelength range required can be covered in 2 steps: 0.35-0.65µm and 0.60-1.2µm, allowing for some overlap. With a 4k x 4k CCD, at the lowest resolution, a 350nm range will be covered by 4096 pixels, with the ideal dispersion; 2 pixels would correspond to 0.17 nm. This corresponds to about R= 2000 at 350 nm. The proposed design offers a good match between the resolution determined from a) the size of the pixels and the size of the image of the fibers on the CCD, or from b) the total number of pixels of the CCD and total wavelength coverage required.

3.2 Characteristics of the gratings

The density = 1/ a of grooves (mm^{-1}) of the grating is given approximately by:

$$\rho = 100 \cos(i')/\Delta\lambda$$

where $\Delta\lambda$ is the resolution expressed in wavelength (nanometers) corresponding to 2 pixels of the CCD (30 µm), and considering a focal length 300 mm for the camera. For $\Delta\lambda$= 0.17 nm, which corresponds to the lowest resolution case discussed above (R = 2,000) this gives about 500 grooves/mm. Adopting a set of four reflection gratings, to provide resolutions R = 2000, 6000, 10000, 30000, the first three of them, with sizes 100x120 mm, and groove densities about 500, 1500, 2500, could be common gratings. They should be specified with blaze angles such that the output is maximized for the order $m = 1$. Examples of efficiency curves for different conventional gratings are shown in the HYDRA/WIYN users manual (Barden and Amandroff, 1995). Peak efficiencies are usually above 60%, but for the largest groove densities the efficiency may vary strongly with wavelength. Eventually, a larger number of conventional gratings might be necessary to cover the full wavelength and resolution with high efficiency.

The use of a Volume Phase Holographic (VPH) grating in the reflection or in the transmission is considered . The VPH technology is evolving rapidly (Barden et al., 1998), and possibly high efficiency can be obtained at high groove densities. If used in transmission mode while other gratings are in reflection mode, this would require a large variation of the position angle of the camera, so eventually the use of VPH gratings only could be preferable. Such a decision will depend on the cost and characteristics of VPH gratings. VPH gratings have the advantage of presenting large efficiency other a wider wavelength range; this could decrease the number of gratings needed in the project. The efficiency of a VPH grating is illustrated in Figure 4.

For the lowest resolution, considering a conventional reflection grating with $\rho = 500$ grooves/mm, with an angle of incidence about 5^o, the m =0 order will be at 5^o from the normal, and $m = 1$ at about 15 ^{o} from the normal; the angle between the incident and diffracted beam (20 ^{o}) is sufficiently large to avoid blocking of the incident beam by the mechanical support of the camera. For larger resolutions this angle increases, and obviously the position of the camera must be able to rotate around the center of the grating.

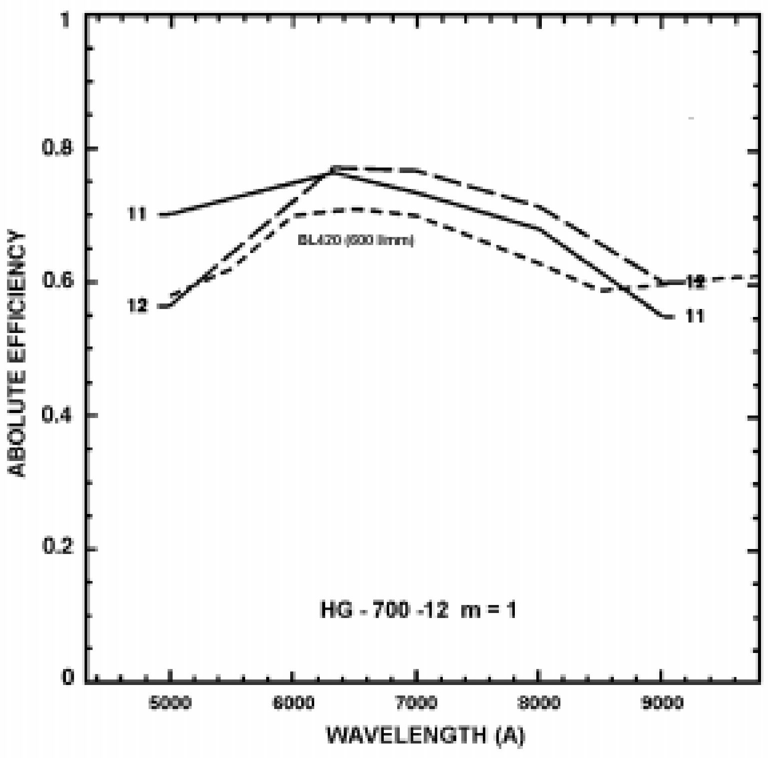


Figure 4: Comparison of a 600 l/mm VP grating at gratings tilts of 11 and 12 degrees to a diamond ruled, 600 l/mm, reflection grating blazed at 800nm (BL 420)

To reach a resolution R= 30000 at 350 nm, Δλ = 0.012 nm, and ρ= 7700 gr/mm. This is a too high density for a classical grating. In this case, we must consider the use of an echelle grating in the R2 configuration. It would be used like a conventional reflection grating. Preliminary calculations show that using orders 22 to 58, one can cover the wavelength range .34 µm to 1.0 µm. At a given position of the camera, a large number of orders will be superimposed. Different solutions can be used to select the desired order: a cross disperser, a set of narrow band filters and/or a Fabry-Perrot tunable filter.

3.3 Results of preliminary studies

The preliminary design of the proposed optics for the spectrograph (Figure 2), shows that for a large range of wavelengths, the fraction of the encircled energy within 30 µm (2 pixels of the CCD) is about 80%. (Figure 5).

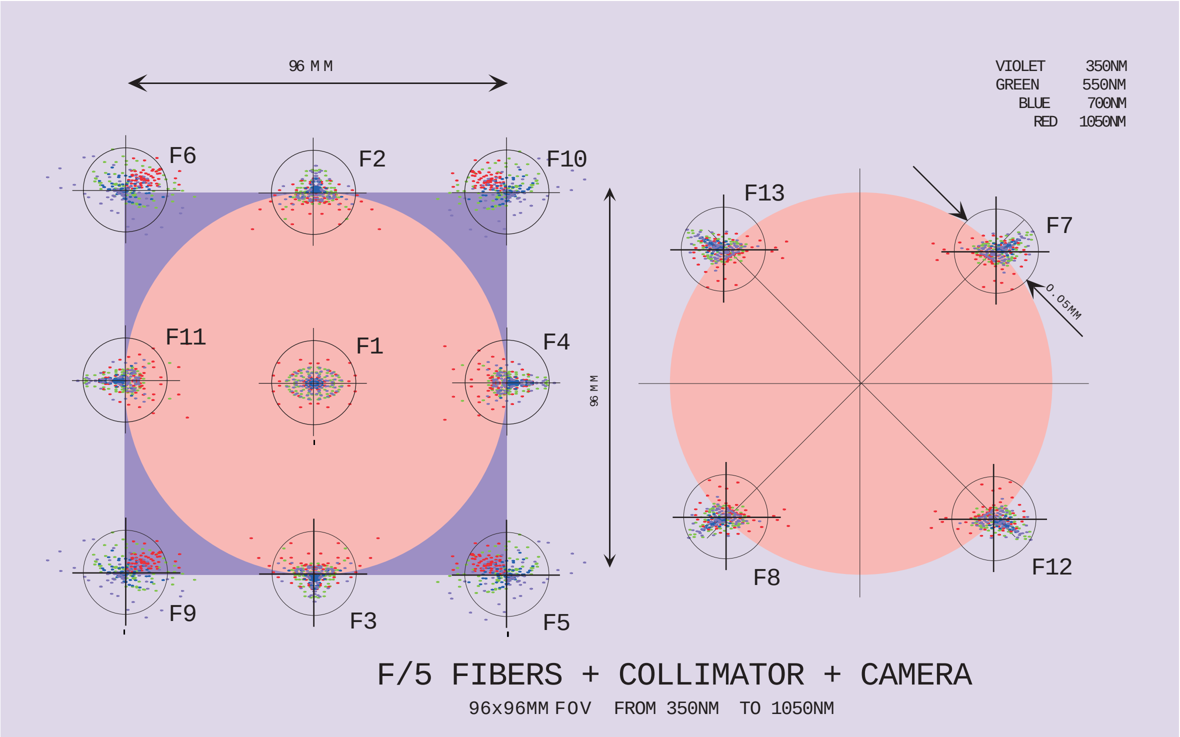


Figure 5: Encircled energy diagrams at several field positions.

4. THE IFU AND FOREOPTICS

4.1. The IFU

The IFU is the image reformatting device that takes pixels from a two-dimensional region at (or near) the focal plane of the telescope and rearranges them to form a single line of pixels for input to a spectrograph. Optical fibers are ideal for the construction of such devices for two reasons: they offer an easy way to rearrange positions, and they allow the spectrograph to be mounted on a bench near the telescope, without worrying about flexures, lack of space, etc. High quality optical fibers are now available, with good transmission over the wavelength range needed in this project. A transmission curve for a 10m long fiber is shown in Figure 6.

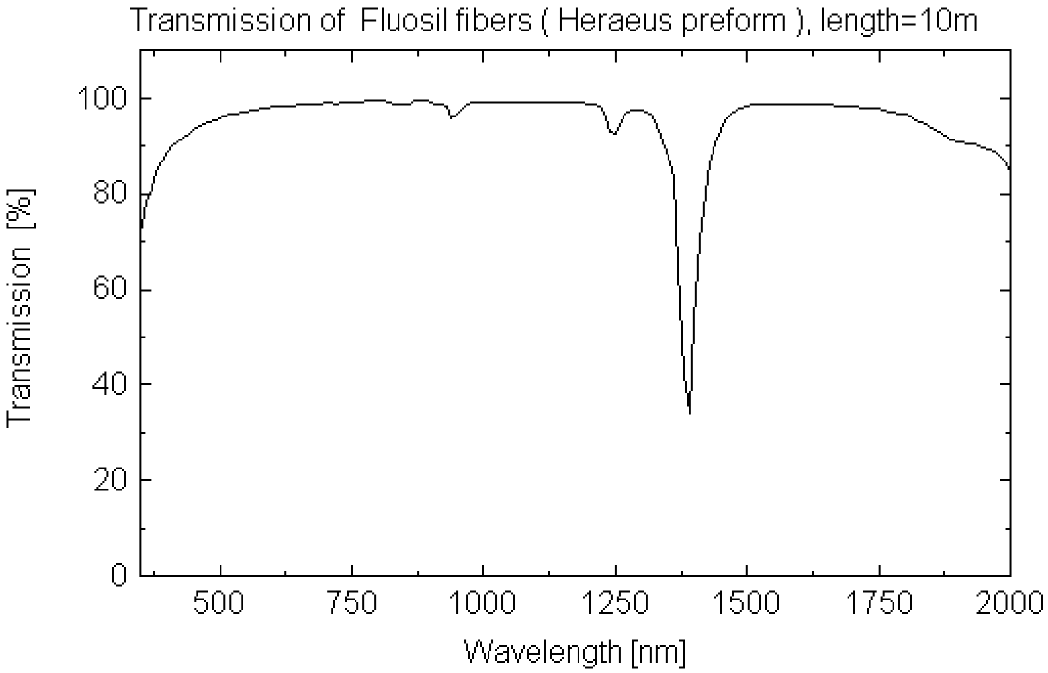


Figure 6: Transmission curve for an optical fiber that can be used in this project.

We plan to use a lenslet array to feed the fibers; the lenslets produce an image of the telescope pupil at the input of each fiber, smaller than fiber diameter, so that the loss of light is minimized. A convenien size of the lenses is 1 mm. The VIMOS IFU instrument to be used at the VLT, with 6,400 elements, is being entirely manufactured by LIMO (Lissotschenko Mikrooptic GmbH), using a system of crossed cylindrical lenses. Another possibility is to use arrays of microlenses made by Adaptive Optics Associates.

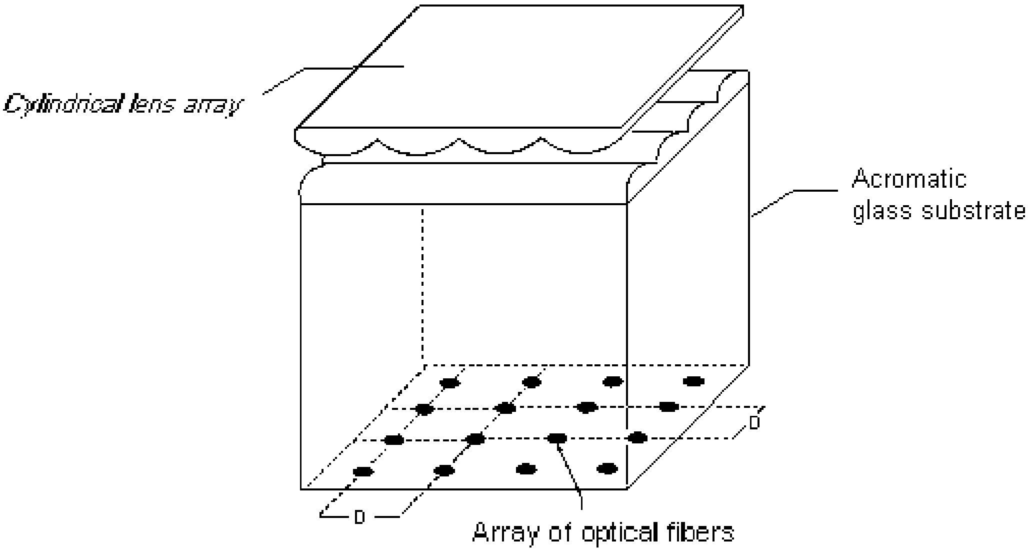


Figure 7. The lenslet array obtained with crossed cylindrical lenses manufactured by LIMO

One possibility considered in this proposal is to use the crossed cylindrical lenses system manufactured by LIMO. The cylindrical lenses can be manufactured with aspheric surface profiles producing diffraction limited performances, and the array can be made achromatic with the use of a high dispersion glass substrate, ensuring high throughput at all wavelengths. A schematic of a crossed cylindrical microlens array as produced by LIMO is presented in figure 7. But since the technology of IFU construction is evolving rapidly, the team will continue to examine other possibilities for the lenslet construction.

The coupling of fibers to the lenslet arrays will use the technique which is presently being used by Tom Ingerson at CTIO for the construction of an IFU spectrograph for the Blanco telescope. The fibers extremities are introduced and cemented in steel jackets (steel tubes used for hypodermic needles) and polished. The jackets are introduced in an array of holes in a steel block, and the fibers are fixed on a glass substrate with UV-cured cement.

4.2. The Fore-optics

4.2.1 The main IFU fore-optics

The input lenslet array segments an image formed by the telescope, pre-enlarged by fore-optics. The purpose of the fore-optics is to magnify the focal plane of the telescope to the scale that is required by the microlens array sampling. The fore-optics consists of a magnification lens and a field lens. The field lens is used to provide telecentric correction to the magnified beam (the light must feed the lenses parallel to the axis of the fibers).

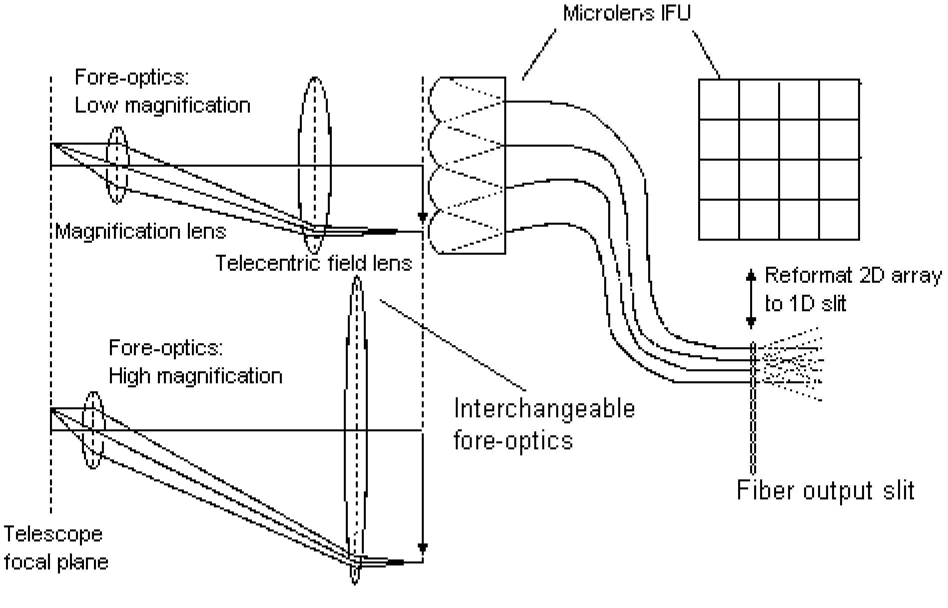


Figure 8: A sketch of a two-magnifications interchangeable fore-optic system

In the present case, the intention is to match 0.15” of the sky, which is about 48μm in the focal plane, to 1mm lenses; this corresponds to a magnification of the order of 20. It is convenient to have at least two interchangeable fore-optics systems, so that the system is still well adapted for relatively bad seeing conditions (still good for stellar spectroscopy) and/or observations covering a larger field. The second fore-optics system should have a magnification about 10, so that 1 pixel is about 0.30”. Since the SAC recommends to make provision for a 0.08”/pixel scale to be used with AO, a third switchable magnification will be included (or at least space for it), in a rotating system with three sets of fore-optics lenses. The three fore-optic systems, with magnification 10, 20 , 40, will be mounted on a rotating wheel.

4.2.2 The sky IFU fore-optics

For observations of extended objects, sky subtraction is a major concern, since very often, regions of the sky not contaminated by the object, are only found at distances larger than the size of the IFU. The only solution is to have a second IFU with a small number of pixels (like 5 x 5), which can be positioned at a few arc minutes away from the object, by remote control. The “sky” IFU must be built with the same technology of the main one. However, we should use separate fore-optics , to be able to reach sufficiently large distances from the object. For the sky IFU, a small fore-optics system can be designed, so that it is easily displaced in the focal plane; a single magnification (20) corresponding to the most frequent magnification used with the main IFU is sufficient, since the sky spectrum does not depends on magnification.

The question of the spacing between the main IFU and sky IFU is next shortly discussed. The size of the main IFU lenslet array will be about 50mm, so that the diameter of the field lens of the main IFU can be chosen about 60 mm. The fore-optics of the sky IFU, with smaller diameter, can be designed so that it can reach distances of the order of 80 mm from the center of the main IFU, about 4 arc minutes in the sky, which is a convenient distance for sky measurements.

5. THE CONTROL SYSTEM

Besides the control of the CCD, the components which have to be controlled are the change of fore-optics (rotating wheel with 3 positions corresponding to different magnifications), the position of the sky IFU in the focal plane, the change of grating and position angle of the grating, the angle of the camera (or grating output beam) with respect to the input beam, and focus of the camera. If dithering of the slit (fiber output) is adopted to produce finer pixel sampling (multiple exposures with the image shifted by sub-pixel amounts), then a fine control of the slit position is also required.

The system will provide remote control, including status feedback, for all mechanisms within the instrument.

The control system is considered to consist of the following major components:

1. A Local Controller. that provides high level control and supervision of the instrument. It will take commands from either a human user or a high level control computer and convert them in to the required actions. It will monitor the status of all mechanisms allowing the user to know the condition of the instrument ant any time.

2. A motor drive system. This converts commands from the local controller into correct drive signals for the mechanism actuators. It also provides some feedback information from position and limit switches.

3. Mechanism actuators. These are the motors.

4. Position encoders. These provide precise position information for mechanisms where this is important.

The solution proposed is to control the instrument mechanisms with LabVIEW. The controller would be a PXI (National Instruments) chassis that has a Pentium PC in the 1st slot and 7 PXI/compact PCI slots.

6. THE PROTOTYPE

The main purpose of the prototype is to test the IFU itself. At present, there is no IFU in operation with such large number of fibers, as planned for the SOAR spectrograph. The quality of the crossed 1mm cylindrical lenses produced by LIMO, the coupling of 50µm fibers, the effect of cross-talk and light scattering, the performance of sky subtraction, are all issues that the team proposing this project would like to know more deeply before deciding about all the details of the final project. In addition, the prototype will stimulate the development of data reduction procedures, which are needed to handle the large simultaneous number of spectra. Besides the laboratory tests, real observations will be made with the 1.6m telescope and produce feedback from the observers.

It only makes sense to build a prototype if it can be ready in a short time and at low cost, compared to the final project. Several crucial components are available at the LNA which will facilitate the construction of the prototype. An optical fibers spectrograph is currently under construction (an INPE/LNA collaboration - Francisco Jablonski is the PI) to be used at the Observatório do Pico dos Dias. Four gratings covering a nice range of resolutions is avaliable to test the prototype. The whole mechanical mount capable of rotating the gratings under computer control is available and could be easily adapted on the prototype bench.

On the other hand, a 2k x 2k CCD (SITe SI424AB - 24µm pixel size) is being purchased by the PRONEX project of IAG-USP, to be used at LNA for wide field imaging. The PIs of this project are Laerte Sodré (IAG-USP) and Francisco Jablonski (INPE). They agree to make this CCD available for the prototype.

The prototype does not need to meet the same specifications of the SOAR spectrograph to reach its goal, which is mostly to test the IFU itself . The wavelength range can be smaller (0.4-1µm) to allow less severe specification of coatings of the collimator and camera. There is no need to reach R= 30000, but whatever the available gratings allows. The beam can be smaller, since a smaller number o fibers will be used. The optical components will therefore be less expensive.

The largest contribution to the cost and to the construction time of the prototype will come from the IFU itself. A 500 fibers prototype is planned. Assuming a maximum of 500 fibers per bundle, the 500 fibers prototype IFU is a real test of the 1500 fibers IFU for the SOAR spectrograph.

7. CRITICAL AREAS

The major challenge of this project is the construction of the IFU itself. What will be the fiber-to-fiber differences in transmission, is there some scattering of light in the lenslet array, is there some “cross-talk” between lenslets? The problem may appear, for instance, when a point source with strong emission line contaminates neighboring pixels.

The throughput specifications constitute another challenge. SPIRAL obtained a 15% throughput efficiency, and preliminary calculations indicate that the goal of 20% can be attained.

The use of an échelle grating to reach R= 30 000 resolution may offer some difficulties. The usual cross-dispersion to separate orders cannot be applied since the CCD is filled with 1500 spectra. A large-amplitude cross-dispersion would turn the optical design more complicate. A Fabry-Perrot tunable filter to separate orders could be a solution. Eventually, it could be preferable to use a conventional grating at order m =3.

Concerning the focal plane mount for fore-optics, there is some difficulty to accommodate at the same time a rotating system with 3 sets of fore-optic lenses with different magnifications, and the possibility of future expansion with several deployable IFUs. The use of several IFUs in future expansion will require anyway a new design of the focal plane arrangement.

The data handling is also a challenge. Enough storage capacity must be provided to keep flat fields, calibration spectra and sky spectra.

8. COSTS

The detailed Work Breakdown Structure (WBS) is presented in appendix A1. The total cost including contingency and overhead is 1.5 million dollars.

We propose use in-house staff for scientific and system design, as far as possible, and use external engineering help where that is cheaper and more efficient. The salaries are lower than US standards, but are only roughly estimated in dollars due to fluctuations in the change rate. The overhead was considered to be 48% for all charges except equipment, in order to be consistent with other SOAR proposals. The overhead takes into account expenses covered by the institutions involved in the project (LNA, IAG, INPE) that are not displayed in the cost breakdown, like administration, installations, communications, etc.

A demand for funds for this project is being submitted to the São Paulo State Research Agency FAPESP; it does not include neither overhead and contingency costs, nor the management costs in WBS-9, but it includes external services costs, like optical design, etc.

8.1 Prototype

In the case of the prototype, items of different nature like mechanical design, optics, travel, etc, are gathered in a single worksheet, in order to display separately the cost of this part of the project. The prototype will make use of a CCD, gratings and optical bench, currently available at LNA, but the IFU and fore-optics system must be constructed. The major items are manpower for assembling and testing of the microlens array /fibers coupling. The travel expenses include frequent São Paulo- Itajubá displacements, other travels inside Brazil and 2 travels São Paulo- CTIO.

8.2 The SOAR IFU spectrograph

Mechanical, optics, electronics : The detailed WBS are in appendix A1. The manpower required for design, assembling, etc. is estimated based on the experience on development of astronomical instruments at LNA. The costs of optical components, mechanical and control components are based on catalogs and current experience; the costs of optical components will depend on the final design.

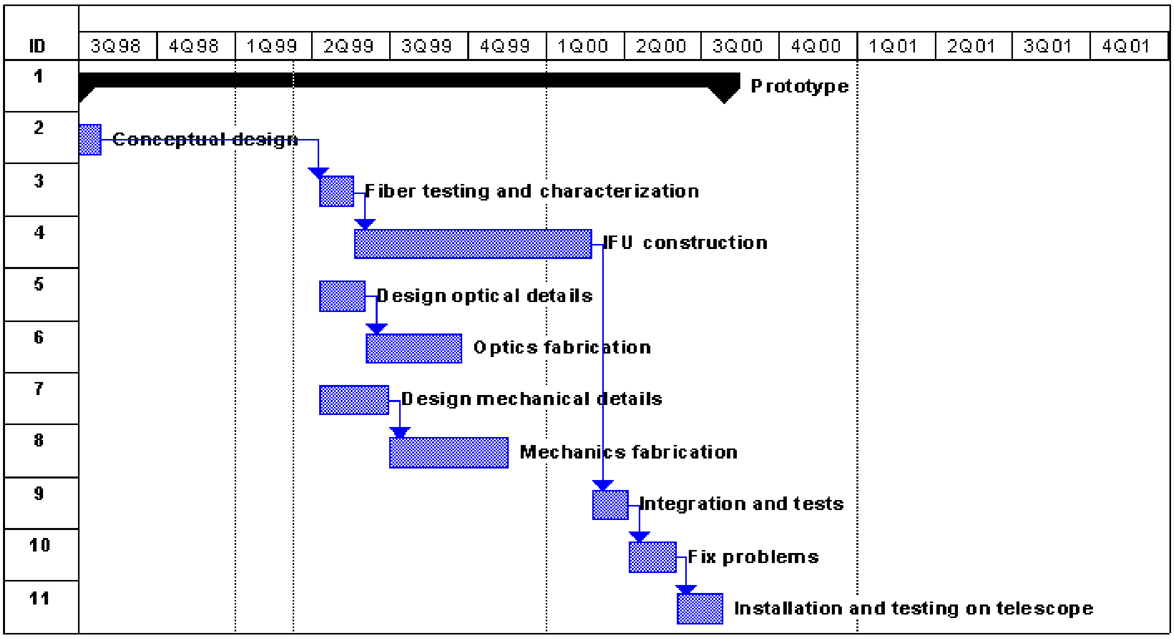
Support equipment and supplies: although some laboratory equipment is available at the LNA, additional equipment is needed to test efficiently the transmission characteristics of lenses, coatings, fibers and epoxy, from UV to NIR, and for fiber polishing and alignement of optics.

Management, reporting and documenting: the effort involved in these items is similar to that of other SOAR instrument proposals.

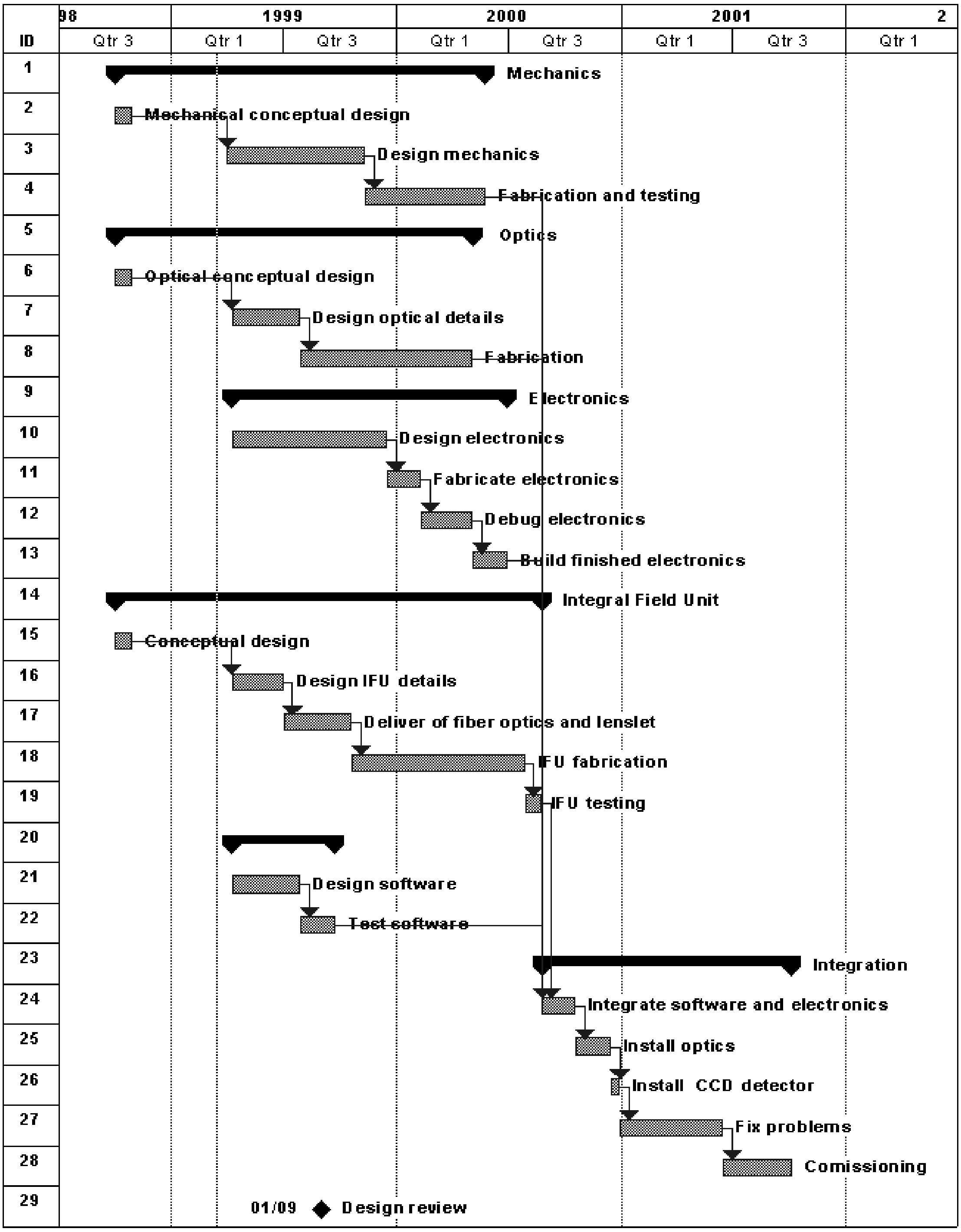
Travel: the IFU spectrograph will be built at the LNA (Itajubá) and São Paulo University; in close contact with CTIO. Travels between São Paulo to Itajubá will take place about twice a month, with 2 days stays. Other displacements in Brazil include Rio-São Paulo and Florianópolis- São Paulo.

9. TIME SCHEDULE

9.1 The prototype



9.2 The main spectrograph



10. PERSONNEL AND INSTITUTIONS INVOLVED

1. University of São Paulo:

   - Jacques Lépine (PI), see more comments below.
   - Beatriz Barbuy : Chair of the Astronomy Department; has experience in high resolution spectroscopy, will participate in management.
   - Jane Gregorio-Hetem, astronomer, has experience in observations and data reduction; will work on calibration and reduction software .
   - Cesar Strauss, electronic engineer, will work on control systems (hardware and software).
   - Marcos Diaz, member of the SAC, will participate in tests and commissioning of prototype and final spectrograph

2. LNA (Laboratório Nacional de Astrofísica):

   - Clemens Gneiding: is an experient instrumentation scientist. Will be responsible for the management of the mechanical and optical design and assembly.
   - Francisco Rodrigues, head of Technology Division of LNA, will be responsible for the management of the control system.
   - Antonio Cesar de Oliveira, optical engineer, recently obtained a post-doc fellowship from the São Paulo research agency FAPESP. He will stay 6 months at Cerro Tololo and 6 months at the AAT, working with experts in fiber optics spectrographs.
   - Rodrigo Prates Campos has long experiencie with optical instrumentation and will work on the IFU mounting
   - other engineers and administrative support

3. Universidade Federal de Santa Catarina

   - Antônio Kanaan is a pos-doc with fellowship from CNPq; Will participate in the optical and mechanical design and electronic control .

4. INPE (Instituto Nacional de Pesquisas Espaciais, São José dos Campos):

   - Francisco Jablonski, is the PI of a bench spectrograph using optical fibers that will be commissioned at LNA by the end of this year, from which the prototype IFU spectrograph will benefit. He is also the PI of the project of a near-infrared camera that will enter operation this year. He will manage the construction of parts of the spectrograph at INPE.

- René Laporte, optical engineer, was responsible for the optical design of the CCD camera with focal reducer for wide field imaging under construction for the Observatório do Pico dos Dias. He will participate in the optical design of the prototype and final version.

5. Observatório Nacional:

   - Natalie Stout, astronomer, will work on software development for data reduction

External consultants: Tom Ingerson (CTIO), Keith Taylor (AAT), Gilberto Moretto (SOAR optical designer)

The PI has experience in the development of instruments mostly in radioastronomy (for instance a mm radiotelescope, and an acousto-optic bench-mounted spectrograph using a Bragg cell which was the subject of the thesis of his student Nori Beraldo, among other projects). He has no previous experience in the construction of optical spectrographs in particular; but possesses theoretical knowledge of the subject, being responsible several times for the graduate course “Observational Astronomy” at the IAG-USP. He has observational experience in spectroscopy (observations of T Tauri stars with the coudé spectrograph at the LNA), and management experience (chair of Department for 4 years). The PI will act as a manager, all the technical decisions being discussed with the team.

Several members of the team listed above have experience in the development of optical astronomical instrumentation (most of the instruments are in operation at the telescopes of the Observatório do Pico dos Dias and where developed with the LNA facilities). Additional members of Brazilian institutions are going to participate in the project when specific duties are established.

All the institutions involved in this proposal have mechanical and electronic shops. INPE in particular is a space research agency capable of constructing artificial satellites and balloon experiments. There are several small companies near INPE at São José dos Campos that can be contracted to construct mechanical or electronic parts of the project.

Appendix A1

WBS for the prototype

1 Prototype

		Unit cost	M&S total	Contingency			Overhead		
				%	cost	Total cost	factor	M&S	M&S+cont.
Mech design	3 m.mo	2500	7,500.00	10	750	8,250.00	0.48	3600	3960
Mechan. shop	4 m.mo.	2500	10,000.00	10	1000	11,000.00	0.48	4800	5280
Optical design	2 m.mo	2500	5,000.00	10	500	5,500.00	0.48	2400	2640
IFU assembling	6 m.mo	2000	12,000.00	10	1200	13,200.00	0.48	5760	6336
Integration, tests	6 m.mo	3000	18,000.00	10	1800	19,800.00	0.48	8640	9504
Softw. Develop.	4 m.mo	3000	12,000.00	10	1200	13,200.00	0.48	5760	6336
Optical components			10,000.00	10	1000	11,000.00	0	0	0
misc. cements,jackets, etc			2,500.00	10	250	2,750.00	0	0	0
Lenslet array			1,500.00	10	150	1,650.00	0	0	0
Optical fibers			5,500.00	10	550	6,050.00	0	0	0
Travel			6,800.00	10	680	7,480.00	0	0	0
Total prototype			90,800.00			99,880.00		30960	34056

WBS for the SOAR IFU

2 Mechanical

		Unit cost	M&S total	Contingency			Overhead		
				%	cost	Total cost	factor	M&S	M&S+cont.
Mech. design	6 m.mo.	5,000.00	30,000.00	10	3000	33,000.00	0.48	14,400.00	15,840.00
Thermal design	1 m.mo.	5,000.00	5,000.00	10	500	5,500.00	0.48	2,400.00	2,640.00
Mech. shop	6 m.mo.	3,000.00	18,000.00	15	2700	20,700.00	0.48	8,640.00	9,936.00
Assembling	4 m.mo.	5,000.00	20,000.00	15	3000	23,000.00	0.48	9,600.00	11,040.00
Optical bench			10,000.00	25	2500	12,500.00			
enclosure & suspension		3,000.00	3,000.00	25	750	3,750.00			
computer controlled mechanisms			50,000.00	25	12500	62,500.00			
static supports			5,000.00	25	1250	6,250.00			
field rotator			10,000.00	25	2500	12,500.00			
misc metal, screws etc			5,000.00	25	1250	6,250.00			
Total mechanical			156,000.00			185,950.00		35,040.00	39,456.00

3 Optics

	Unit cost	M&S total	Contingency			Overhead		
			%	cost	Total cost	factor	M&S	M&S+cont.
Optical design 3 m.mo.	5,000.00	15,000.00	10	1500	16,500.00	0.48	7,200.00	7,920.00
Installation 2 m.mo.	5,000.00	10,000.00	15	1500	11,500.00	0.48	4,800.00	5,520.00
IFU assembling 6 m.mo	3,000.00	18,000.00	15	2700	20,700.00	0.48	8,640.00	9,936.00
Camera &collimator		40,000.00	15	6000	46,000.00	0		
echelle grating	20000,00	20,000.00	15	3000	23,000.00	0		
Lenslet array	3,000.00	3,000.00	15	450	3,450.00	0		
Gratings 3 convent. or VPH	7,000.00	21,000.00	20	4200	25,200.00	0		
fore optics		8,000.00	10	800	8,800.00	0		
optical fibers 11 km		20,000.00	15	3000	23,000.00	0		
jackets		1,000.00	15	150	1,150.00	0		
coatings		5,000.00	15	750	5,750.00	0		
cements & epoxy		2,000.00	15	300	2,300.00	0		
spectral filters 3	6,000.00	18,000.00	15	2700	20,700.00	0		
ADC		3,000.00	15	450	3,450.00	0		
Cross disperser		3,000.00	15	450	3,450.00	0		
Total optics		187,000.00			214,950.00		20,640.00	23,376.00

4 Electronics

	Unit cost	M&S total	Contingency			Overhead		
			%	cost	Total cost	factor	M&S	M&S+cont.
Electron.design 6 m.mo	5,000.00	30,000.00	10	3000	33,000.00	0.48	14,400.00	15,840.00
CCD detector & control		220,000.00	15	33000	253,000.00	0	0.00	0.00
encoders		8,000.00	10	800	8,800.00	0	0.00	0.00
motors		5,000.00	10	500	5,500.00	0	0.00	0.00
misc connectors, wiring		5,000.00	15	750	5,750.00	0	0.00	0.00
thermal control system		5,000.00	15	750	5,750.00	0	0.00	0.00
mounting & testing 6 mo	5,000.00	30,000.00	10	3000	33,000.00	0.48	14,400.00	15,840.00
Total electronics		303,000.00			344,800.00		28,800.00	31,680.00

5 Software & Computers

	Unit cost	M&S total	Contingency			Overhead		
			%	cost	Total cost	factor	M&S	M&S+cont.
Develop. data acqu 3 mo.	5,000.00	15,000.00	25	3750	18,750.00	0.48	7,200.00	9,000.00
Develop mech. Control 3 mo.	5,000.00	15,000.00	25	3750	18,750.00	0.48	7,200.00	9,000.00
Dev. data red., calibr. 8 mo.	5,000.00	40,000.00	25	10000	50,000.00	0.48	19,200.00	24,000.00
PXI computer+chassi		12,000.00	10	1200	13,200.00	0	0.00	0.00
workstation		15,000.00	10	1500	16,500.00	0	0.00	0.00
Total software		97,000.00			117,200.00		33,600.00	42,000.00

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6 Installation and Comissioning

	Unit cost	M&S total	Contingency			Overhead		
			%	cost	Total cost	factor	M&S	M&S+cont.
shipping		3,500.00	23	805	4,305.00	0.48	1,680.00	2,066.40
Installation		8,000.00	13	1040	9,040.00	0.48	3,840.00	4,339.20
Commissioning 8 m.mo	5,000.00	40,000.00	20	8000	48,000.00	0.48	19,200.00	23,040.00
support after install 4 m.mo	5,000.00	20,000.00	20	4000	24,000.00	0.48	9,600.00	11,520.00
subsitance at obs. 12 mo	1,000.00	12,000.00	10	1200	13,200.00	0.48	5,760.00	6,336.00
Total installation		83,500.00			98,545.00		40,080.00	47,301.60

7 Support Equipment & Supplies

	Unit cost	M&S total	Contingency			Overhead		
			%	cost	Total cost	factor	M&S	M&S+cont.
Zemax license	2,900.00	2,900.00	0	0	2,900.00	0.48	1,392.00	1,392.00
LabView license	2,550.00	2,550.00	0	0	2,550.00	0.48	1,224.00	1,224.00
AutoCad license	3,000.00	3,000.00	0	0	3,000.00	0.48	1,440.00	1,440.00
Lab Spectrometer	3,000.00	3,000.00	25	750	3,750.00	0	0.00	0.00
Lab camera	1,800.00	1,800.00	25	450	2,250.00	0	0.00	0.00
Fiber polisher	2,000.00	2,000.00	25	500	2,500.00	0	0.00	0.00
Light sourcces and detectors	4,000.00	4,000.00	25	1000	5,000.00	0	0.00	0.00
Alignment facility	6,000.00	6,000.00	25	1500	7,500.00	0	0.00	0.00
Laptop computer	3,000.00	3,000.00	25	750	3,750.00	0	0.00	0.00
Misc tools & supplies	5,000.00	5,000.00	25	1250	6,250.00	0	0.00	0.00
Total support		33,250.00			39,450.00		4,056.00	4,056.00

8 Travel

	Unit cost	M&S total	Contingency			Overhead		
			%	cost	Total cost	factor	M&S	M&S+cont.
Sao Paulo-Itajuba & vice-versa		4,000.00	25	1,000.00	5,000.00	0.48	1,920.00	2,400.00
Other displacements in Brazil		2,400.00	25	600.00	3,000.00	0.48	1,152.00	1,440.00
Sao-Paulo CTIO		2,400.00	25	600.00	3,000.00	0.48	1,152.00	1,440.00
Brasil-USA and vice-versa		16,000.00	25	4,000.00	20,000.00	0.48	7,680.00	9,600.00
Total travel		24,800.00			31,000.00		11,904.00	14,880.00

9 Management, Reporting & Documenting

		Unit cost	M&S total	Contingency			Overhead		
				%	cost	Total cost	factor	M&S	M&S+cont.
P.I.s	12 m.mo.	6,000.00	72,000	10	7,200.00	79,200.00	0.63	45,144.00	49,658.40
Secretary	9 m.mo	2,000.00	18,000	10	1,800.00	19,800.00	0.48	8,640.00	9,504.00
Design review	2 m.mo	5,000.00	10,000	10	1,000.00	11,000.00	0.48	4,800.00	5,280.00
Documenting	4 m.mo	3,000.00	12,000	10	1,200.00	13,200.00	0.48	5,760.00	6,336.00
Total management			112,000			123,200.00		64,344.00	70,778.40

Budget summary by WBS item

	M&S	M&S+cont	overhead	overh.+cont
Total prototype	90,800.00	99,880.00	30,960.00	34,056.00
Total mechanical	156,000.00	185,950.00	35,040.00	39,456.00
Total optics	187,000.00	214,950.00	20,640.00	23,376.00
Total electronics	303,000.00	344,800.00	28,800.00	31,680.00
Total software	97,000.00	117,200.00	33,600.00	42,000.00
Total installation	83,500.00	98,545.00	40,080.00	47,301.60
Total support	33,250.00	39,450.00	4,056.00	4,056.00
Total travel	24,800.00	31,000.00	11,904.00	14,880.00
Total management	112,000.00	123,200.00	64,344.00	70,778.40
GRAND TOTAL	1,087,350.00	1,254,975.00	269,424.00	307,584.00

M&S+cont+overhead= 1,524,399.00