The SOAR IFU Spectrograph

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1. INTRODUCTION AND SCIENTIFIC OBJECTIVES

1.1 Introduction

We present the project of an optical spectrograph equipped with a 1300-element Integral Field Unit (IFU), that will be one of the main instruments of the SOAR (4m) telescope. The project is in large part funded by the Sao Paulo State agency FAPESP, and conforms the specifications of the Scientific Advisory Committee (SAC) of SOAR. 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, which is bench mounted in the present case. A prototype with 512 elements has been constructed as a result of a collaboration between the University of São Paulo, the Laboratório Nacional de Astrofísica (LNA), and the Anglo-Australian Observatory. The results already obtained with the prototype, as well as the results of the SPIRAL spectrograph in Australia, makes us confident that we can build an excellent instrument. The same basic techniques of the prototype will be used to mount the 1300 elements IFU at the LNA.

The purpose of the instrument is to best exploit SOAR's excellent angular resolution (about 0.15 arcseconds, with tip-tilt correction) in cases where complex extended objects or objects in crowded fields are studied. The proposed unit will permit simultaneous spectra to be taken of all parts of moderately extended objects like HII regions or distant galaxies. Strong motivations for high spatial resolution are the study of velocity fields and of ionization structure in HII regions, AGNs, and planetary nebulae.

An IFU spectrograph is expected to be competitive at this spatial 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 especially useful in crowded fields like globular clusters or the Magellanic bar, allowing simultaneous observations of many stars. The spectral resolution must be
sufficient for studying the metalicity of stars (at R > 6000), or abundances ratios like [$H\alpha$/Fe] (at R > 15000).

There are already several IFU spectrographs 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, etc), and others in construction, like VIMOs for the VLT and GMOS for GEMINI.

1.2.1 The specifications from the SAC

The SAC, through the its partner representatives, reviewed some 120 observing proposals from astronomers of the partners institutions, in order to define the set of initial instruments for SOAR. These included two optical spectrographs: the High-Efficiency Optical Spectrograph, which is being constructed by the University of North Carolina, and the High-Spatial Resolution Optical Spectrograph, presented here. The main requirements, as stated by the SAC, are next reproduced.

1.2.2 Main requirements

- 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, with one octave (factor 2) interval on the detector at once

-R up to 30,000

-Throughput: 15% at $\lambda > 350$ nm (including CCD + telescope)

-Flexure: <0.04 pix/hr

-Sky subtraction: 1% residuals over 180^0 field rotation

A large range spectral of resolving powers is needed. The lowest resolution derives from the requirement to cover one octave in wavelength (a factor 2) in a single spectrum. This is the maximum wavelength coverage that can be attained with the grating order m=1. With a CCD of 4000 pixels, and line width defined by 2 pixels, this corresponds to a resolution of about R = 2000 in terms of $\lambda/\Delta\lambda$ where$\Delta\lambda$ is the FWHM wavelength resolution. 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 ($\lambda > 0.8\mu$m), 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. Between the two extreme spectral resolution specifications mentioned above, a choice of resolutions capable of 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 system with capability of changing the magnification is desirable.

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

1.2.3 Possible future options or upgrades mentioned by the SAC:

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. 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 new 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 sequenti ally.

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

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

1.3. Driving decisions: optical fibers, VPH gratings, CCD

This section briefly describes the line of arguments that led to the choice of the present optical design the of the spectrograph. The optical design is presented in the next section.

The requirement for high efficiency recommended us the use of VPH gratings, which are more efficient than classical gratings, and the use of order $m = 1$ only. The need for high efficiency also prompted us to look for optical designs of the collimator and camera with a minimum of absorption. The first all-transmissive design included a too large number of lenses and had a poor transmission. Finally, we adopted an off-axis catadioptric collimator, which minimize the number of transmissive elements; the off-axis geometry avoids the central obstruction (usually, catadioptric systems must be large, to minimize the obstruction problem). The camera needs to be relatively compact, since its angle must be remotely adjustable, and an all-transmissive design was adopted.

One critical requirement of an IFU-based spectrograph is the focal ratio of the collimator, which must match the output focal ratio of the fibers. As focal ratio degradation in fibers is minimized for beams of focal ratio 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 high resolution. However, too small fibers may present larger transmission losses and are technically more difficult to deal with and to couple to the lenslet system. 50 µm fibers have been tested successfully with SPIRAL at the AAO and with the prototype at LNA, are also under development at the University of Durham for the GMOS IFU.

We propose to use 50 µm fibers, with 5µm thick cladding. This preserves the minimum cladding thickness of 5 λ at 1 µm, with a usual 10:1 core/cladding ratio. The center-to-center separation will be 75 µm, and the total height of the 1300 fibers column will be 98 mm. This determines the diameter of the beam about 100mm, and the focal length of the collimator about 500 mm.

At the other end of the spectrograph, the image of the fibers output must match the CCD characteristics. The project will use a 4k x 4k CCD (a mosaic of 2 4kx2k CCDs), with pixel sizes 15µm. To match the spectral resolution to 2 pixels sample on the CCD, or 30 µm, the focal length of the camera must be about 300 mm.

To fulfill the requirement specified by the SAC of covering the total wavelength range in 2 steps, we specify the intervals 0.35-0.65 µm and 0.60-1.2 µm, allowing for some overlap. With a 4k x 4k CCD, at the lowest resolution, a 300nm range will be covered by 4096 pixels; with the ideal dispersion, 2 pixels would correspond to 0.15 nm. This corresponds to about R= 2300 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, and b) the total number of pixels of the CCD and total wavelength coverage required.

We are discarding the use of an échelle grating. Such a grating does not seem to be a good solution, since we cannot separate the orders with a cross-disperser, as it is usually done. In our case, the CCD is already completely filled with spectra from individual fibers. To use only one order (with a small spectral coverage), we would have to introduce a very large number of filters, or a tunable filter, which complicates the project. In addition, we would have to put the camera at a small angle from the collimator, in a geometry which is very different from that required by the VPHs.

Considering the strong variation in resolution with wavelength, for a given grating, a number of gratings must be provided, in order to be able to offer a relatively large resolution (R > 15000) at almost all wavelengths. A choice of 6 interchangeable gratings was designed.