GOHSS: a Fibre–fed Multiobject NIR Spectrograph for the Italian Galileo Telescope

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Abstract

We present the concept and preliminary design of the Galileo OH Subtracted Spectrograph [GOHSS], a multifibre NIR spectrograph for faint objects. The instrument represents a collaboration between the Institute of Astronomy, Cambridge [IoA] and the Observatories of Naples and Rome and will be a second–light instrument for the 3.6m Galileo telescope [TNG] located on La Palma.

The NIR spectrograph accomplishes OH night-sky suppression in a different way from the hardware solution used by both OHS\textsuperscript{3} and COHSI\textsuperscript{10}. GOHSS provides a multi-echelle design with software subtraction capable of yielding $\sim 28$ spectra in J+H bands at a spectral resolution $\mathcal{R} \sim 3000$. Such a resolution is the minimum necessary to reduce the impact of atmospheric OH lines.

1 Scientific Aims of the Instrument

A number of key scientific programs can benefit from a significant reduction in the background in the J and H bands. These can be essentially grouped into three classes: redshifts and spectral studies of galaxies, spectral properties of quasars, the study of faint, cold or obscured stars. In the following we will illustrate some programmes in the first of these categories.
High Redshift Galaxies, Their Counts, Properties and Evolution

In recent years there has been considerable progress in determining the counts, colours and redshift distributions of faint galaxies. Such studies are crucial for the theory of structure formation. The current limits for ground-based counts are $B \sim 27 \div 28$ mag [9], while the 4-m redshift samples have painstakingly reached $B \sim 24$ mag [1], $I \sim 22$ mag [6] which represents a hard instrumental limit in the visible band. Further progress has been possible through the use of the unique combination of Keck + HST. HST has provided new insight into the morphological appearance of high $z$ galaxies including those faint sources in the publically-available HDF. Some high $z$ candidates located with Lyman-limit imaging techniques [11] have been spectroscopically confirmed by Keck exposures [12]. A gap emerges, however, between the progress to $z \approx 1$ secured from 4-m surveys and limited data now available at $z > 2$. From various considerations, the bulk of the star formation activity appears to have occurred in this little-explored region for which NIR spectroscopy is crucial.

The main scientific targets of GOHSS are:

1. **Redshift Measurements of Faint Galaxies.** For $z > 1.1$ the [OII]3727 emission line (a principal line for the redshift determination) leaves the visible band, whereas to observe the Ly$\alpha$ (often very weak or absent) requires $z > 2.2$. Consequently **without low resolution spectroscopy in the J and H bands, it is very hard to determine the redshifts of normal galaxies in the range $1 \leq z \leq 2$**. A multifibre device would make practical the simultaneous spectroscopy in the same exposure.

2. **Study of the Star Formation Rate (SFR) at High Redshift.** Spectroscopy in the J and H bands allows the measurement of the H$\beta$ line (providing the ionization level) and the equivalent width (EW) of the H$\alpha$ line in the range $0.5 \leq z \leq 2$. The latter line is **one of the most reliable tracers of star formation** and its measurement in many distant galaxies would provide crucial information in understanding the rates, timescales and modes of galaxy formation including environmental effects, the role of different IMFs etc.

3. **Redshift Measurements of Gravitational Arcs.** Over the past few years, spectacular examples of gravitational lensing have been provided through the identification of giant arcs. Such arcs arise from spacetime curvature induced by the gravitational field of the dark matter in rich galaxy clusters. Their importance is twofold. Firstly, when the redshift of the lensed object is known, it is possible to accurately model the potential well of the cluster and determine the dark matter distribution. Secondly, the cluster itself acts as a natural telescope: the lensing phenomenon amplifies the apparent luminosity of lensed objects which become observable at greater distances than unlensed field objects. However, spectroscopy of such arcs present a challenge to most spectrographs as the arc morphologies are not easily accommodated within a single long-slit. This problem can be alleviated by using an Integral Field Unit [IFU].

4. **Galaxy Redshift Measurements along the Line of Sight to Quasars.** An efficient way to find galaxies at high redshift is to perform imaging observation in the K band around quasars at medium redshift, or to select objects in absorption with metallic lines (typically CIV) along the line of sight. In this case, the infrared spectra of these objects confirm which source is the absorber as well as yielding useful information about the SFR. In this case, an IFU used so that the spectral width $\Delta \lambda$ is centred on important lines in the damped absorbing cloud restframe could yield interesting results.
2 Technical Solutions

2.1 Hardware vs Software Solution

In undertaking a feasibility study of the instrument, we have quantitatively compared the hardware suppression vs software subtraction. The former solution involves the suppression of OH lines by means of a physical mask at an intermediate high resolution spectrum and the subsequent recombination in white light to feed a low resolution imager-spectrograph. Such a solution has been implemented by the Japanese group at Kyoto [8] [4] and by Io in the case of COHSI [10].

The second solution adopts a high resolution ($R \gtrsim 3000$) approach which allows the registration of the spectrum directly on the detector. By selecting regions uncontaminated by the OH lines and rebinning in case of weak signals, the need for hardware suppression is avoided. This solution, which offers significant advantages, has not been implemented thus far because of the high costs of the large format IR detectors and their relatively high dark current. However, the situation with regard to these problems is rapidly changing and this progress makes the software suppression method now preferable. Other, less direct methods e.g. blocking filters do not appear yet satisfactory [2], [5]. We note that the software solution is also envisaged for the VLT [7], although with the use of slits instead of fibres, a much larger multiplexing than adopted here and, of course, at considerably increased cost.

![Diagram](image)

Figure 1: Main modules of GOHSS

2.2 Optical Design

The optical design of GOHSS has passed through several reviews and modifications since its first conceptual design based on that of COHSI, the (hardware) OH Suppressor Spectrograph nearing completion at IoA. The scientific aims and conceptual requirements described above lead to a modular design. In Figure 1 we show the overall layout of the three main components: the fore–optics, the IR fibres and the dispersing optics.

The fore–optics section is intended to modify the f/11 beam of the 3.5m Galileo telescope and provide a suitably enlarged scale to allow the positioning of the IR fibres along with their interface optics, i.e. the lenslets. The fore–optics consists of two simple doublets. By replacing the first doublet and readjusting the lens separation, the spatial scale can be varied. This is likely to be extremely useful in transporting the instrument to different telescopes, such as the LBT.

In multiobject mode GOHSS will most likely have a plug-plate fibre system with a single fibre per galaxy. To feed the light into the fibre efficiently a micro–lens is used to image the
telescope pupil on to the fibre at f/4, significantly reducing focal ratio degradation (FRD).

A small field stop ahead of the microlens and in the telescope focal plane samples $\sim 1.5''$. With a final camera focal ratio of f/1.2, a single fibre corresponds to two pixels. Allowing for some residual FRD and possible misalignment in the optics, conservatively we will adopt three pixels for the spatial coverage.

The instrument specifications are defined primarily by the scientific aims. For the optical design, the most important specifications are:

- Spectral resolution of $\sim 3000$. This is dictated by the nature of the OH sky spectrum. This criteria could be lessened somewhat when observing in the J band where the OH lines are more sparse. In this case, it is possible to trade spectral resolution for extension towards shorter wavelengths.

- The MOS mode requires a fibre aperture of $\sim 1.5''$ because of the inherent size of the target galaxies. A minimum of 20 – 25 fibres is necessary to provide significant gains.

- The simultaneous spectral coverage should be $1 \div 1.8 \mu m$.

The conclusion from several optical designs studied by I. Parry and F. Piché at IoA is that the most promising configuration is the cross-dispersed echelle.

The optical scheme is shown in Figure 2. Fibres from the telescope are aligned along a slit at the focal plane of a Schmidt camera (Figure 3). The f/5.5 primary mirror generates a 150 mm diameter beam which is then projected onto the grating. The spectrum is then projected onto the relay mirror (situated at the Schmidt camera focus) and re–collimated by the primary mirror. It then passes through a cross–disperser prism to properly distribute the orders onto the detector. After cross-dispersion the spectrum is imaged onto the detector by an f/1.2 camera. The detailed layout for a single fibre spectrum is shown in Figure 3.

The number of photons per pixel detected from the sky background is very low so it is vital that GOHSS contributes significantly less than this in terms of the background due to thermal
emission from within the spectrograph. From detailed considerations we find that in order to keep the thermal background to an acceptably low level, the temperature of the spectrograph has to be maintained between \( \approx 217\text{K} \) and \( 236\text{K} \) or \( \approx -56\text{°C} \) to \(-37\text{°C}\).

### 3 Expected performances

Assuming the following efficiencies for: Atmosphere + TNG: \( \epsilon_1 \approx 68\% \); multifibre system: \( \epsilon_2 \approx 81\% \); spectrograph: \( \epsilon_3 \approx 64\% \); camera: \( \epsilon_4 \approx 40\% \), we obtain total efficiencies of: \( \epsilon_{\text{Tot}} = \Pi_{i=1}^{4} \epsilon_i \approx 14\% \). Now, with a 4\( m \) class telescope (TNG) the software solution allows to work in BLIP (Background Limited Instrumental Performance) conditions in the J and H bands once the detector dark current [DC] is below \( 0.05 \text{ e}^-/\text{s} \). With a 8\( m \) class telescope (VLT), the instrument would always be in BLIP conditions, even with high DC values \( (>0.15 \text{ e}^-/\text{s}) \) and low overall efficiencies \( (<10\%) \). Therefore, the relative efficiency \( S/W \) vs \( H/W \) is always \( >1 \) in case of low DC, before considering possible OH scattering problems associated with the hardware mode.
The SNR in the left panel of Fig. 4 does not take into account the possibility of software rebinnig (or more advanced methods to extract the signal). Nonetheless, an increase in SNR of a factor $\sqrt{f_{\text{rebin}}}$ is realised, where $f_{\text{rebin}} \simeq R_{\text{c,orig}}/R_{\text{c,low}}$. Furthermore, it can be $f_{\text{rebin}} \sim 6$ when $R_{\text{c,orig}} \sim 3000$ and $R_{\text{c,low}} \sim 500$. This is shown in the right panel of Fig. 4, where we show the continuum SNR as a function of object brightness under the assumption of fibres of area $1''$ square (diameter of $1.3''$). Notice that a “typical” faint galaxy has angular extent of $\lesssim 2''$, therefore an approximate conversion in limiting magnitudes is given by subtracting $\sim 1$ mag from the abscissa scale. This is compensated by the fact that most of the information is typically stored in lines of remarkable EW, an aspect which is being studied with more detailed simulations of spectra.

It is important to note that, when one limits to a single band (i.e. J or H), the GOHSS multiplexing could double, reaching a number of possible targets of $\sim 50$ in a single exposure. This can be exploited in the study of distant clusters of galaxies, where the main aim is to determine if a galaxy belong to the cluster. Moreover, it becomes feasible to study the SFR as a function of density and time, because the $H_\alpha$ line can be studied for cluster members and compared to the general behaviour in the field, a spectral counterpart of the Butcher–Oemler effect. The multifibre mode is then essential, given the crowding of targets.

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