COHSI: The Cambridge OH Suppression Instrument

F. Piché, I. R. Parry, K. Ennico, R. S. Ellis, J. Pritchard, C. D. Mackay, R. G. McMahon

Institute of Astronomy, Madingley Rd, Cambridge, CB3 0HA, UK

ABSTRACT

One of the main limitation to the study of faint objects in the near-infrared (1 - 2 μm) is the luminous, varying sky background from very narrow OH emission lines originating in the Earth's upper atmosphere. This source of background contributes 95% - 98% of the total sky counts in the J & H atmospheric windows.

We present the optical layout of the Cambridge OH Suppression Instrument. COHSI is designed to deliver OH suppressed, R = 500, spectroscopy for both J & H spectral bands simultaneously providing an integral field mode and a multi-object mode. COHSI also has an OH suppression imaging mode. A modular approach has been selected for COHSI with the instrument consisting of three components. The first section consists of simple re-imaging lenses and a lens array interfacing the telescope to a set of optical fibers. This decouples the design of COHSI's main components from the telescope allowing COHSI to be easily used with different telescopes and making it free from flexure problems. The second section of COHSI is the OH suppression "filter" itself. The size of this section is significantly smaller than in other similarly planned instruments. The third and final module of COHSI is the cryogenic low-resolution imaging spectrograph.

Keywords: OH suppression, near-infrared, spectrograph, fiber

1. PURPOSE AND REQUIREMENTS

The main scientific aim of COHSI is to extend the optical galaxy redshift surveys conducted with LDSS-2[1] and Autofib[2] to redshift $1 < z < 3$. At such distances, the usual spectral features used to determine galaxy redshifts (Hα, Hβ, [OIII]5007Å, [OII]3727Å, …) are displaced into the near-infrared.

Unfortunately, in the near-infrared, the sky background is much higher than at optical wavelength, as well as highly variable. In the 1.0 - 1.9 μm wavelength range, 95% - 98% of the sky emission originates from 100 - 150 very narrow OH lines emitted in earth's upper atmosphere (~90 km altitude).[3,4,5,6] If we could somehow remove these strong emission lines, without loosing too much instrumental throughput, the remaining background would be much lower resulting in surveys with greatly improved sensitivity. Furthermore, removing the OH lines leaves a smoother background spectrum, thus giving redshift surveys which are more evenly sampled in redshift space. This is what COHSI is designed to achieve. The idea of removing the OH airglow lines from the near-infrared background is called OH suppression and was pioneered by Maihara and his collaborators.[7,8,9]

The design requirements for COHSI are a final spectrum with a resolution reasonably well matched to the width of galaxy spectral features (R ~ 500). Because unambiguous determination of galaxy redshifts requires that at least two spectral lines be identified, and since these lines usually fall in different atmospheric windows, simultaneous coverage of J & H is required. Numerical simulations demonstrate that the filtering/suppression process has to operate at an effective resolution of $R \geq 4000$ for a maximum OH suppression efficiency to be achieved.[10] We also wish to have an instrument that can be readily adapted to any large telescope with minimal modification. Finally, the following observing modes should be available: integral field (2-dimensional) spectroscopy, multi-object spectroscopy and OH suppressed imaging.

2. OVERALL LAYOUT

The requirements listed above led us to a modular design for COHSI. Figure 1 presents an overall layout of the three main components of COHSI. The first module contains the fore-optics which match the telescope scale and f-ratio to the OH suppressor module. This is the only part of COHSI that is telescope specific. This interface feeds the heart of

COHSI: the OH suppressor module. Once the light input from the telescope has been "cleaned" of the OH sky emission, it is then fed into the cryogenic imaging spectrograph. This final module generates either the low resolution spectra needed for redshift determinations or an OH suppressed image.

3. THE FORE-OPTICS

3.1. Single object/ integral field spectroscopy

Because of the size of COHSI's OH suppressor and the requirement of easy adaptability to different telescopes, we opted for an instrument fed entirely by fiber optics. An f/6.5 input into the fibers was chosen giving some allowance for a moderate amount of focal ratio degradation (FRD).

Figure 2 presents the fore-optic design for the single object/integral field unit (IFU) interface with UKIRT. The design concept for this module is based on the image segmentation mode of SPIRAL.[11] It consists of two simple doublets which modify UKIRT's f/35 beam, providing the right magnification to obtain the desired spatial sampling scale at the lenslet array front face, and positioning the exit pupil at infinity. Both doublets are composed of a positive calcium fluoride (CaF_2) lens coupled with a negative SCHOTT glass lens. Either LaF20 or BaF51 may be used for the second lens.

By replacing the first doublet with a new doublet, and re-adjusting the lens separations, the user will be provided with a choice of spatial scale of 0.15", 0.35" or 0.55" per lenslet/fiber on UKIRT. In principle, any scale up to 0.6"/lenslet can be accommodated. The second doublet remains unchanged whatever the scale. Doublet #1 has to be changed so as to properly position the telescope pupil at the focus of doublet #2.

Each hexagonal lenslet consists of an SK2 - SFL57 doublet. These are then matted onto a slab of SFL57 in a configuration appropriate to the type of observations performed with COHSI. Details of the lenslets are shown in Figure 2's inset. The first planned module will have 100 lenslets distributed in a pattern with a length to width ratio of ~2. This interface configuration has the advantage over bare fiber coupling of an effective 100% collecting efficiency. Because the telescope focal plane is re-imaged onto the front surface of the lenslet array, there is no loss of spatial coverage from cladding and the packing fraction.

3.2. Multi-object spectroscopy and imaging

In the case of multi-object spectroscopy, the important concern is the angular size of the "aperture". Since galaxies are extended objects, the choice of "aperture" size has to take in to account the typical size of the objects in the sample observed, the fiber positioning error, the effect on spectral resolution and the amount of sky background introduced. Taking all of these factors into account leads to an aperture size of between 1.1" and 1.4". For the multi-object spectroscopy mode, two options are available to us.

The first option (option A) is to use a micro-lens on each fiber to change the telescope f-ratio (f/35 for UKIRT) to ~f/6.5 matching the focal ratio of the OH suppressor unit. On UKIRT this requires input fiber diameters of 140 μm for a 1.2" scale. This in turn necessitates 240 μm diameter output fibers from the OH suppressor unit, which, once fed into the cryogenic spectrograph, leads to a slight reduction of the effective spectral resolution down to 400. On larger telescopes, this is an unattractive option as the input fiber diameter required is even bigger.

Option B is to have a set of 90 μm fibers. In this case a microlens on each fiber feeds the light in at f/4 to minimise FRD losses (equivalent to 1.2" on the sky) and the IFU fore-optics are used to re-image the output end of each fiber onto 7 hexagonal lenslets in the lenslet array. The advantage of this method is that the input fiber to COHSI's OH suppressor remains at 80 μm diameter, thus preserving the full R = 500 spectral resolution irrespective of the telescope characteristics. Because each object observed is re-imaged onto seven individual fibers, the multiplex gain is less in this case than in option A. A maximum of ~20 galaxies could conceivably be observed. For UKIRT's restricted field of view of ~ 4 arcminutes diameter, this limitation does not really come into play. The multiplex gain is limited by the number of detector pixels available in the spatial direction and can therefore be increased in principle by upgrading to a 1024x1024 array.

The fore-optics configuration for the imaging mode is discussed in section 5.2.

4. THE OH SUPPRESSOR MODULE

4.1. The Schmidt Camera

The heart of the OH suppressor module is a Schmidt camera with a 87 cm primary mirror and a BK7 aspheric plate (48 cm diameter) to correct spherical aberrations (Figure 3). The primary mirror as well as the two mask mirrors are gold-coated for maximum infrared reflectivity. The input f-ratio of the suppressor is f/5.5 allowing for some FRD in the input fibers. The overall size of this module is 2 m x 1 m x 1m. The suppressor is essentially 2 spectrographs end-to-end. The first one creates a high resolution spectrum at the mask and the second one undisperses the light back to a white light slit image. Light passes through the Schmidt 4 times: collimator for grating G1 (1), camera for the mask (2), collimator for grating G2 (3) and camera for the suppressed slit image (4).

The unsuppressed light is fed into the suppressor from the center of the mask mirror and is directed towards the primary mirror which acts as collimator to the first grating (G1). The beam diameter is 150 mm, the grating ruling is 400 λ/mm, and the grating is blazed at 1.2 µm. The gratings are used in first order Litttrow configuration for maximum efficiency (91% at peak blaze). This grating generates the high-resolution spectrum which is then projected onto the mask mirror via the primary mirror. The spectral resolution is 4500 - 7500 (from 1.01 µm to 1.80 µm respectively). At the mask, only the clean section of the spectrum, between the OH lines, is sent back toward the primary mirror to be collimated onto a second grating (G2), identical to the first one. This grating reconstitutes back a white light image of the input fiber slit. This image is projected, by the primary mirror, onto the output fiber slit situated adjacent to the input slit.

Conceivably gratings G1 and G2 could have slightly different ruling frequencies such as to generate the final R = 500 spectrum directly, without the need for COHSI's third module. We opted not to go down that route mostly due to thermal emission considerations. In this alternate configuration there is no cold pupil nor cold slit. The detector sees the full amount of thermal emission from the Schmidt camera. As a consequence of this, the entire Schmidt camera would require cooling to a least -50^{o} C in order to keep the instrumental thermal emission below the sky background level between the OH lines. Such a configuration would also loose the OH suppressed imaging capability available to COHSI.

4.2. Mask mirror and fiber module

The details of the mask and fiber module are shown in Figure 4. As can be seen, the J & H spectra do not overlap. There is no unnecessary loss of spectral coverage attributable to blocking OH lines from the other band spectrum. The fiber module is situated in the middle of the mask in the conveniently situated 1.4 µm atmospheric water absorption band. To generate the 0.3 mm offset of the output slit image relative to the input fiber slit, grating G2 is slightly tilted with respect to grating G1's orientation. This introduces a slight residual spectrum at the output slit which is small compared to the image quality delivered at the output fiber slit. The output fibers are 180 µm in diameter to make allowance for the image quality delivered by the Schmidt camera (~80 µm full image spread) and some tolerance in the relative positioning of the input and output fiber slits. Optically, the fiber slit is part of the same spherical surface as the J & H mask mirrors are. The fiber slit unit is itself made up of a pair of fiber slits offset from each other by 0.3 mm. Each input fiber has its own associated output fiber.

The mask mirror is actually made up of two parts: the J-mask mirror and the H-mask mirror. Each is a spherical surface 55 mm high and 135 mm wide. Once installed at the focus of the Schmidt camera, spectra of the night sky will be taken to map the position of the OH lines onto the masks. Once mapping is completed, the reflective surface of the mirror will be burned away with a laser, turning these sections of the mirror non-reflective. The width of the burned region in spectral space is somewhat dependent on the strength of the OH lines. Stronger OH-lines also have stronger wings (in absolute units) thus requiring a wider portion of the spectrum to be blocked than for weaker lines for which the wings may not be significantly stronger than the sky background between the OH-lines. Simulations show that an average blocking width of approximately three resolution elements is optimum[10].

Because of the larger input fiber diameter for multi-object spectroscopy option A, the mask spectral resolution is degraded down to 3300 - 5450. This is still high enough for efficient OH suppression. Since the width of a resolution element is increased, a new mask with wider "burned-out" region is required.

5. THE CRYOGENIC SPECTROGRAPH

5.1. Spectroscopic mode

The optical layout of the cryogenic imaging spectrograph is presented in Figure 5. It is a fully refractive design with a single collimator and a dichroic beam splitter re-directing the J and H spectra onto two NICMOS III IR arrays. The fiber slit is cold and situated inside the dewar.

Most of the optical power is in the three doublets made up of a positive barium fluoride (BaF_2) lens and a negative SF2 lens. Since we are not concerned about wavelengths greater than 1.8 μm, there is no need to use the BaF_2- IRG2 combination[12]. Most of the standard flint glasses of SCHOTT's F and SF classes can be substituted in place of IRG2, with little degradation to the doublet's optical performance, with a higher instrumental throughput, and at a much reduced cost .

The spectrograph input fiber slit is a spherical surface with a radius of curvature matching the field curvature of the collimator doublet. This reduces the collimator design to a single doublet without the need for an additional field corrector lens. The f-ratio of the J & H cameras were fine-tuned independently to spread the spectrum (1.01 μm - 1.35 μm for J, 1.44 μm - 1.80 μm for H) across the full widths of the detectors, making maximum use of the detector space available.

The two grisms are manufactured by Diffraction Products, Inc. The grisms' glass substrates (SCHOTT F5 and BaK5 for the J and H grisms respectively) were selected such that the central wavelength of the spectrum is undeviated for stock item rulings. Thus, there is no need to re-adjust the camera orientation between spectroscopic and imaging modes. Each camera has an internal focus mechanism operating by moving the camera doublet together with the adjacent SK2 lens as a single unit along the optical axis. This allows us to change from spectroscopic to imaging mode with a straightforward re-adjustment of the camera optics.

5.2. Imaging mode

In the imaging mode, the grisms are moved out of the way and filters are inserted into the light path, just ahead of the field lenses (see Figure 5). There are two imaging modes.

The first option (option A) is to use some fore-optics to generate a small field of view imaged at f/6.5. In this case an input fiber size of 50 μm gives a spatial scale of 0.42"/lenslet on UKIRT. The suppressor has a very large field of view in the direction perpendicular to the dispersion direction (~55mm) and can therefore process the light from a large number of fibers. Furthermore, by imaging in only one band instead of both the J and H bands, it is possible to have two fiber "slits". An additional H-mask has to be made for this mode. A total of 1600 fibers can be used giving a 40x40 fiber array on the sky. The fibers are arranged in a loosely filled array with an inter-fiber gap of 1 fiber diameter. Thus 4 exposures are required to give a fully-interlaced 80x80 suppressed image. There are enough pixels in the detector array to also allow a very low resolution spectrum (R=50) to be obtained for each image point by putting in a prism in the collimated beam.

The second configuration (option B) is simply the single object/IFU spectroscopy mode with the grisms removed. The advantage of this configuration is that no extra fiber feeds have to be made and a variety of image spatial scales are available, irrespective of the telescope particulars. As mentioned in section 3, this option does not suffer from fiber packing losses. Its one drawback is the limited number of lenslets available.

The imaging quality of the cryogenic imaging spectrograph, shown in Figure 6, is more than adequate for the NICMOS III arrays. This will make alignment of the optical train easier. As can be seen in Figure 6, the camera design is not fully achromatized for the imaging mode. This is deliberate in order to keep the thickness of the BaF_2 lenses as low as possible.

6. DISCUSSION

Table 1 summarises the main characteristics of COHSI's different possible observing modes on UKIRT.

TABLE 1. COHSI'S OBSERVING MODES

Observing Mode	Input Fiber Size (μm)	No. of Fibers	Output Fiber Size (μm)	Fiber Scale	Spectral Resolution	FOV
Single Object / Integral Field	80	100	180	0.55"	500	4" x 8"
Multi-Object Spectroscopy A	140	60	240	1.2"	400	4'
Multi-Object Spectroscopy B †	80	14	180	1.2"	500	4'
OH Suppressed Imaging A	50	1600	150	0.42"	filter	34"x34"
OH Suppressed Imaging B	80	100	180	0.15" - 0.55"	filter	Variable
Low Resolution Spectroscopy	50	1600	150	0.42"	30 - 50	34"x34"

† In this case, input fiber size refers to the diameter of the input fiber feeding the OH suppressor, number of fibers refers to the number of objects which could conceivably be observed, and fiber scale refers to the scale at the input of the large diameter fiber at the front of the fore-optic unit.

The overall throughput of COHSI, including detector quantum efficiency, but excluding the telescope itself, is calculated to range from 14% to 5%. The highest value coincides with the peak blaze wavelength of gratings G1 and G2. The lowest value is at 1.8 μm where the grating efficiency is declining and substrate absorption for four passes through the 20 mm thick BK7 aspheric plate starts to be significant.

Theoretical estimates of OH suppression factors (ratio of unsuppressed to suppressed sky background) are 30 and 50 for J & H respectively[10]. Maihara et al.[8] achieved a suppression factor of ~20 at H with their prototype. With an improved mask design and a flexure free system, background suppression factors of at least 25 and 35 at J & H respectively are quite realistically achievable. The sensitivity gain expected from COHSI, over a low resolution spectrograph, is given roughly by $(\varepsilon f)^{1/2}$, where ε is the ratio of COHSI's throughput to that of the low resolution spectrograph, and f is the background suppression factor achieved by COHSI. Assuming a throughput for the low resolution spectrograph of 40%, the suppression factors given above, and COHSI's throughput values given earlier, we calculate COHSI's gains to be 3.0 (1.2 mag) and 2.1 (0.8 mag) at J & H respectively.

We calculate COHSI's sensitivity for multi-object spectroscopy option A given the following assumptions. We assume a suppressed background of 1000 photons/m^2/s/μm/$arcsec^2$. This number is about twice the suppressed background measured by Maihara et al.[3], thus allowing for some scattering and imperfect blocking in the OH suppressor unit. The total integration time is 9600 s made up of 8 individual 1200 s exposures. The detector read noise is 15 e^- and the dark current is 0.5 e^-/s. The telescope collecting area is 3.8 m diameter primary. The telescope throughput is 70% and COHSI's throughput was given previously. The light from the object is expected to fall onto ~9 pixels. The calculated 3 sigma detection limits, given the above assumptions, are 22.2 magnitude and 20.9 magnitude for J & H respectively.

The imaging sensitivities are calculated using the same characteristics described above except for those listed below. The total integration time is 1800 s made up of two individual 900 s exposures. When taking interlacing into consideration, this gives an overall observing time of 2 hours. The scale is 0.42"/fiber and the seeing is assumed to concentrate 66% of the object light onto a single fiber. The five sigma detection limits are 24.3 magnitude and 23.0 magnitude for J & H respectively.

As of June 1996, COHSI's optical design has been completed and the various optical components are being manufactured. The mechanical engineering work (dewar, OH suppressor frame, lens mounts, etc…) is currently progressing. Integration and assembly of the various components is planned for August - October 1996. First light is expected on UKIRT for semester 97B.

7. ACKNOWLEDGMENTS

This project is supported by PPARC grant GR/J79300. We also wish to express our gratitude to Dr. A. K. Velan for his generous donation to this endeavour. Finally, we wish to express our gratitude to J. Rogers, R. Dace, and D. Malloy of the Mullard Radio Astronomy Observatory for contributing their expertise in dewar cryogenic design to this project.

8. REFERENCES

1. K. Glazebrook, R. Ellis, M. Colless, T. Broadhurst, J. Allington-Smith, N. Tanvir, "A faint galaxy redshift survey to B = 24.", *Mon. Not. R. Astron. Soc.* **273**, 157-168 (1995)
2. R. S. Ellis, M. Colless, T. Broadhurst, J. Heyl, K. Glazebrook, "Autofib Redshift Survey - I. Evolution of the galaxy luminosity function.", *Mon. Not. R. Astron. Soc.* **280**, 235-251 (1996)
3. T. Maihara, F. Iwamuro, T.Yamashita, D. N. B. Hall, , L. L. Cowie, A. T. Tokunaga, A. J. Pickles, "Observations of the OH airglow emission.", *Publ. Astro. Soc. Pac.* **105**, 940-944 (1993)
4. S. K. Ramsey, C. M. Mountain, T. R. Geballe, "Non-thermal emission in the atmosphere above Mauna Kea.", *Mon. Not. R. Astron. Soc.* **259**, 751-760 (1992)
5. E. Oliva & L. Origlia, "The OH airglow spectrum: a calibration source of infrared spectrometers.", *Astron. Astrophys.* **254**, 466-471 (1992)
6. M. C. Abrams, S. P. Davis, M. L. P. Rao, R. Engleman, J. W. Brault, "High-resolution fourier transform spectroscopy of the Meinel system of OH.", *Astrophys. J. Suppl. Ser.* **93**, 351-395 (1994)
7. T. Maihara, F. Iwamuro, D. N. B. Hall, , L. L. Cowie, A. T. Tokunaga, A. J. Pickles, "An OH-airglow suppressor spectrograph: Design and prospects." in *Infrared Detectors and Instrumentation*, A. M. Fowler, Editor, Proc. SPIE **1946**, 581-586 (1993)
8. F. Iwamuro, T. Maihara, S. Oya, H. Tsukamoto, D. N. B. Hall, L. L. Cowie, A. T. Tokunaga, A. J. Pickles, "Development of an OH-airglow suppressor spectrograph.", *Publ. Astro. Soc. Japan*, **46**, 515-521 (1994).
9. T. Maihara, F. Iwamuro, S. Oya, H. Tsukamoto, D. N. B. Hall, , L. L. Cowie, A. T. Tokunaga, A. J. Pickles, "OH-airglow suppressor for SUBARU telescope: OHS for SUBARU" in *Instrumentation in Astronomy VIII*, David L. Crawford, Eric R. Craine, Editors, Proc. SPIE **2198**, 194-200 (1994)
10. T. M. Herbst, "Numerical evaluation of OH-suppression instruments.", *Publ. Astro. Soc. Pac.* **106**, 1298-1309 (1994)
11. M. Kenworthy, I. Parry, K. Taylor. "SPIRAL: Single object spectroscopy for the AAT." this volume.
12. E. Oliva & S. Gennari, "Achromatic lens systems for near infrared instruments." *Astron. Astrophys. Suppl. Ser.* **114**, 179-182 (1995)