Sky background subtraction with fiber-fed spectrographs

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ABSTRACT

Fiber-fed spectrographs can now have throughputs equivalent to slit spectrographs. However, the sky subtraction accuracy that can be reached on such instruments has often been pinpointed as one of their major issues, in relation to difficulties in scattered light and flat-field corrections or throughput losses associated with fibers. Using technical time observations with FLAMES-GIRAFFE, two observing techniques, namely dual staring and cross beam switching modes, were tested and the resulting sky subtraction accuracy reached in both cases was quantified. Results indicate that an accuracy of 0.6% on the sky subtraction can be reached, provided that the cross beam switching mode is used. This is very encouraging regarding the detection of very faint sources with future fiber-fed spectrographs such as VLT/MOONS or E-ELT/MOSAIC.

Keywords: *Extremely Large Telescope, Sky background, Sky subtraction, Spectroscopy, Fiber-fed spectrographs*

1. INTRODUCTION

One of the key science drivers for the future instrumentation of the VLT and E-ELT is to study faint galaxies in the early universe at very high redshifts[1,2]. The detection and spectroscopic follow-up of these sources will require an accurate and precise sky subtraction process. For instance, in its deepest observations, VLT/MOONS will study sources as faint as H_{AB}=25 in their continuum and emission lines in ~ 16 hr of integration time, while E-ELT/MOSAIC[3] will push this limit up to J/H_{AB}~30 in emission, and up to J/H_{AB}~27-28 for continuum and absorption line features[4,5]. These features will be typically observed between bright OH sky lines. However, the NIR sky continuum background is found to be J_{AB} or H_{AB} ~19-19.5 in dark time conditions[6], i.e., hundreds to a thousand time brighter than the sources to be detected in the continuum. While the expected relatively bright emission lines with rest-frame equivalent widths larger than ~15 nm should easily emerge above this background[5], continuum and absorption line detections might clearly be hampered by possible systematic residual signal left by the sky subtraction process. For the future detection of such faint sources, it is therefore critical to check that sky subtraction techniques are accurate enough, i.e., that one can actually reach accuracies at a level of a few tenth of percents at least.

In this respect, slit spectrographs have long been considered as much more accurate than fiber-fed spectrographs. This is mainly due to two different kind of issues: (i) fiber-fed spectrographs, if not carefully designed, can result in significant loss of light compared to slit spectrographs (e.g., fiber cross-talk on the detector, or Focal Ratio Degradation which results in a change of aperture at the output of the fibers), and (ii) it is more difficult to achieve an accurate sky subtraction process with fibers than with slits. Recent developments in fiber technology and careful designs of fiber-fed spectrographs can control the issues of the first kind. For instance, good spacing of fibers of the detector can avoid significant cross-talk, while fiber-fed spectrographs can now potentially reach global throughputs similar to those of classical multi-slit spectrographs[1].

However, issues related to the accuracy of the sky subtraction remain, and this turns out to be particularly problematic when dealing with faint sources. Perhaps the two most important effects often associated with fibers further limiting the accuracy of the sky subtraction compared to slits are (1) sky continuum variations between the position of the object and the position at which the sky is measured (due to the finite coverage of the fibers in the focal plane and the minimum practical distance of closest approach), and (2) variations in the fiber-to-fiber responses (due, e.g., to PSF variations, fringing, or FRD). We refer to, e.g., Sharp & Parkinson[7] for a detailed description of the factors limiting the sky subtraction accuracy with fibers. After the end of the E-ELT phase A instrumentation studies, we undertook an effort to better characterize these two important potential caveats.

2. CHARACTERIZING THE SKY CONTINUUM SPATIAL VARIATIONS

The signal from the sky is difficult to predict and subtract in the near-IR (NIR), mainly because of its high variability in space and time. Variations of about 15% in amplitude are typical over scales of a few degrees[8]. These variations are clearly dominated by the flux fluctuations of the bright and numerous OH emission lines, and, at second order, by the intensity variations of absorption bands produced by molecules of water and other component of the Earth's atmosphere. Between these telluric emission and absorption lines, the sky signal has a continuum level about ~19-19.5 mag_{AB} in the J or H bands, the origin of which is still poorly understood. It could be due to a pseudo-continuum associated with instrumental residuals, e.g., diffuse scattered light from the wings of bright emission lines within the spectrograph[9], or to continuum radiation from constituents of the atmosphere. To our knowledge, the spatial and temporal variability of this sky continuum has never been characterized.

We first investigated these issues using archival VLT/FORS2 narrow-band imaging and spectroscopy. Over timescales of a few tens of minutes, the sky continuum background was found to exhibit spatial variations over scales of ~1″ up to ~150″, with total amplitudes below 0.5% of the mean sky background[10,11]. At scales of ~10'' or below (on which the sky is likely to be measured with future fiber-fed spectrographs), the amplitude of the variations is found to be ~0.3-0.7%. Note that this should still be considered as an upper limit to real sky continuum variations, since scattered light and noise variance can be difficult to mitigate in such low signal-to-noise data. Regardless, this is a very encouraging result, which suggests that sky background subtraction can, in principle, be achieved with an accuracy of a few tenths of a percent.

3. TESTING SKY SUBTRACTION WITH CROSS BEAM SWITCHING OBSERVATION

Reaching such accuracy still requires dealing with the variations in fiber-to-fiber response. For this purpose we requested ESO technical time on FLAMES-GIRAFFE, which is the ESO optical workhouse multi-object fiber-fed instrument at VLT/UT2. Such tests reveal that accuracies of few tenths of a percent can indeed be reached, provided that a cross beam-switching observing sequence is used (see Fig. 1). In the following, we describe the observations conducted and the results obtained.

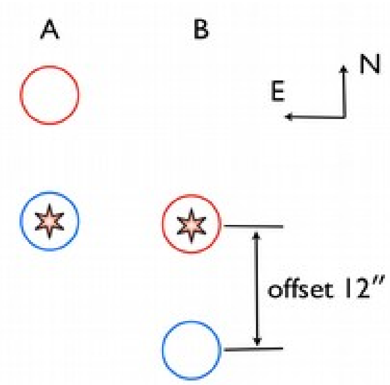

Figure 1: Illustration of cross beam switching observations. The astrophysical object of interest is represented as a star. The fibers are positioned in pairs in the focal plane, with distances of 12'' between two fibers of each pair along the North-South direction. Such a pair is represented as red and blue circles. The observing sequence consists in dithering the telescope from position A to position B by 12'' such that the object (and the sky) is always observed within one of the two fibers of a given pair.

We undertook technical observations with FLAMES-GIRAFFE on March 8th 2012, using the Medusa-fiber mode with clear conditions and a seeing of ~0.9''. The fibers were distributed on blank or faint galaxies over a 20'x20' region in the zCosmos field[12]. Seventy fibers were distributed in pairs separated by 12" and oriented along the North-South direction as illustrated in Fig. 1. Three of these pairs were "pure sky" meaning that no object was observed in any pair of fibers. Preliminary results from these three pairs were presented by Rodrigues et al.[13].

The LR8 GIRAFFE setup, which covers 820 - 940 nm with a spectral resolving power of R=6500, was chosen to obtain spectra at NIR wavelengths. The target field was observed at low airmass (< 1.2), i.e., when it was relatively close to the meridian with an hour angle of less than ~30 minutes. During the observations the moon was located ~28 degrees away from the target field, contributing about 50% to the sky continuum background flux. The total continuum background of the observations reaches $mag_{AB} \sim 19.7$ arcsec^{-2}, which is very similar to the J-band sky continuum brightness in dark conditions[6] and therefore particularly well-suited for our purposes.

The observations were carried out using a cross beam switching configuration in which the telescope was offset by 12" along the North-South direction three times in a row (see Fig. 1), resulting in an A-B-A-B-A-B sequence. FLAMES does not have a template for cross beam switching observations, so the telescope guiding had to be switched off during all the dithered B exposures. In principle, the pointing error during offsets is better than 0.2", which is much smaller than the diameter of the fibers (1.2''). However, in order to prevent any risk of significant misalignments between objects and fibers during the dithered B exposures, an A-B-A-B-like sequence was preferred instead of the usual A-B-B-A-like sequence. This preserved the signal-to-noise ratio and only resulted in larger overheads. Each individual (A or B) exposure was 10 minutes long. The three consecutive A-B sequences obtained represent a total effective exposure time of one hour, immediately after which attached flat-field exposures were acquired.

4. DATA ANALYSIS

Basic reduction steps were done using the ESO pipeline (bias correction, flat-fielding, wavelength calibration and extraction of 1D spectra). We focused on the sky continuum background since targets will be observed between the sky emission and strong telluric lines[14,15]. Seven spectral regions free of sky emission and absorption lines were defined (see Fig. 2) to test the accuracy of different sky subtraction strategies. To increase the statistics but limit the impact of the object spectrum, we limited the analysis to 15 pairs with object I_{AB}-band magnitudes fainter than 21. The mean magnitude of these 15 objects is found to be I_{AB}=21.88, which corresponds to a continuum flux that is ~7 times fainter than the contribution from the sky continuum. To compare the sky continuum subtraction accuracy reached using cross beam switching observations, we also reduced the data in order to mimic a simpler staring mode observing strategy. Both observing and reduction methods are detailed below.

In staring mode observations, an object and the nearby sky (12″ away in the present case) are observed with a pair of fibers simultaneously. For each object in the sample, we derived two spectra by combining the three A exposures and the three B exposures, respectively. The resulting exposure time of each spectrum is 30 minutes. Here, there is no point in combining all A and B exposures together since, by definition, in staring mode the sky is sampled on only one side of the object and that the object and sky are observed with different fibers which would lead to large residuals. Since the objects have fluxes that are significantly fainter than that of the sky continuum (see above), a simple A-B difference can be considered as a first order estimate of the residuals from the sky subtraction process (i.e., from using different fibres).

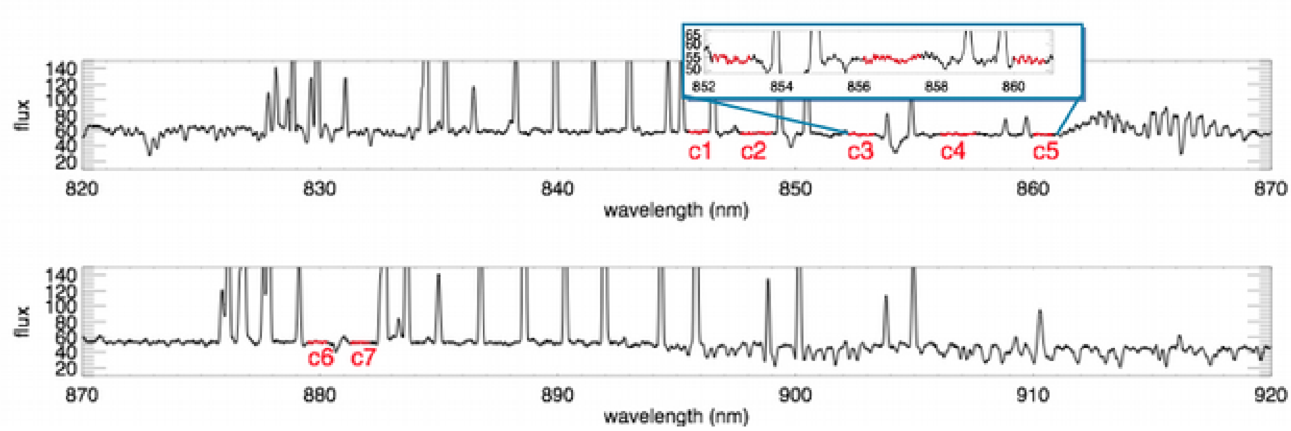

Figure 2: Sky spectrum from 820 to 920 nm obtained after combining 72 sky fibers. OH emission lines and atmospheric absorptions, i.e., telluric lines, can be seen almost everywhere. Only a few relatively clean continuum regions are left with the red c1 to c7 regions selected for further analysis.

In cross beam switching mode, the telescope is dithered by 12″ along the North-South direction between the A and B positions. During the three consecutive A-B sequences, a given object is always observed by one of the fibers of the pairs alternately. Within an single A-B sequence, the object spectrum can be extracted twice (once in A and once in B) and subtracted one from another. Conversely to the staring mode, one can combine all the six exposures to produce a one-hour integration time spectrum. In cross beam-switching mode, object and sky are observed by the same fiber but at different times, and the sky is sampled on both sides of the objects. Finally, if one combines all the exposures of all the objects together, one can actually simulate the result of a 15 hr-long on-sky spectrum. Combining all the measurements in the seven distinct spectral windows can mimic a simulated integration time of up to 105 hours. This is sufficiently long so as to sample deep integration times for future VLT or E-ELT observations (i.e., of few tens of hours). In absence of any residual systematic effect, one would expect that the resulting signal-to-noise ratio of the combined spectrum is reduced by a factor 3.8 (if one combines the 15 exposures together) and 10 (if one combines all the exposures of all objects together), respectively.

5. RESULTS

For each exposure of each objects, we estimated the residual local error in each spectral window after sky continuum subtraction (i.e., the accuracy of sky subtraction) as the relative mean between the object and sky spectra (divided by the mean sky). As argued above, considering all such measurements for all exposures of all objects in the sample simulates a 105 hour integration. The resulting mean expected accuracy on the sky subtraction process as well as its associated uncertainty are shown in Fig. 3. We found in this case a mean accuracy of 0.6±0.2%. In comparison, the accuracy is degraded by a factor of ~ 10 when using the simple staring-mode observations. This confirms the preliminary analysis conducted by Rodrigues et al.[13], i.e., that cross beam switching observations allow us to reach sky subtraction accuracies of a few tenths of a percent.

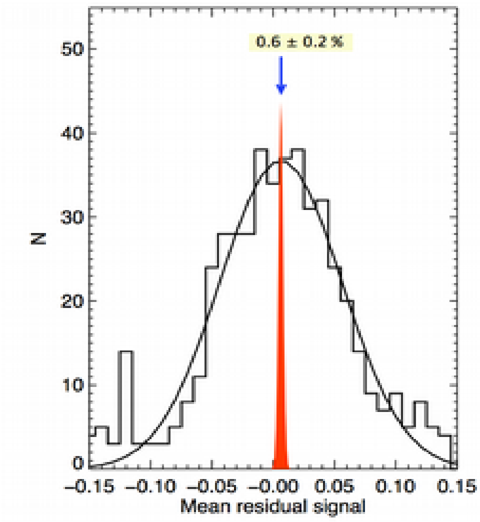

Figure 3: Histogram of the mean residual signal measured in each spectral window of all exposures of all objects observed with FLAMES-GIRAFFE. The mean value estimates the mean residual error signal, i.e., the accuracy of the sky continuum subtraction, obtained with simulated 105-hr long exposures. The red region represents the uncertainty associated with this value, which was derived using the standard error of the mean, i.e., as the standard deviation of the distribution divided by the square root of the sample size.

We also investigated the exposure time needed to reach the noise floor at which the signal-to-noise ratio of the observations becomes limited by systematic effects associated to sky continuum subtraction inaccuracies. For this, we repeated the above measurements in samples of different sizes, which simulate different integration times, as argued above. Results are shown in Fig. 4. At short integration times, the local residual error is dominated by random errors associated to photon noise. It is expected from simple Poisson statistics that this error decreases as the square root of the integration time, until it reaches a floor[7]. Given the limited size of our sample, it is difficult to measure such a decrease precisely, but a gradual decrease followed by a floor can indeed be seen in Fig. 4. This floor is reached after 10-25 hr of integration time at a value of 0.6%. At such large integration times, the local residual error starts being dominated by systematic effects from the sky continuum subtraction. This trend is similar to that found by Sharp & Parkinson[7] at 600 nm, with a ~0.3% floor after 70-100 hr of integration time. Besides, we note that the 0.6% floor in residual local error is very close to the measured variations of the sky continuum background obtained by Puech et al.[10] and Yang et al.[11], which range between ~ 0.3 and 0.7%. This could indicate that long exposure observations can really remove most of the instrumental inaccuracies and reach the physical limit due to sky continuum variations. The 0.3% floor found by Sharp & Parkinson[7] could be due the smaller variations in the 600nm sky continuum compared to the 900nm wavelength we are probing here.

It is important to recall that the results reported here were obtained on 1D spectra with non-optimal conditions. It is likely that using more advanced procedures in the data reduction[7] and with more control on the instrument design regarding the potential sources of inaccuracies detailed above, one might be able to lower the floor at which signal-to-noise ratio is limited by such systematic effects, and possibly to shorter integration times. Moreover, these results support the idea that controlling and measuring instrumental scattered light would remain the main obstacle to accurate spectroscopy of faint sources. We argued above that these results should apply up to the J band, but it will be important to confirm these results and characterize the sky continuum variations at even longer wavelengths, where the impact of scattered light keeps increasing.

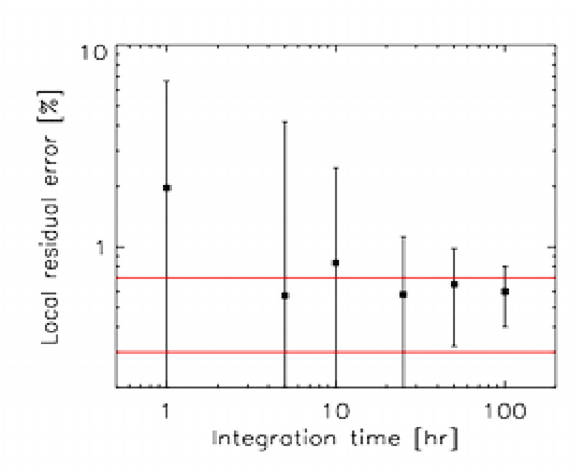

Figure 4: Local residual error as a function of integration time. The black line illustrates a decrease as the square root of integration time. The two horizontal red lines represent the range of variations found at ~10'' scales in the sky continuum background[10,11].

6. CONCLUSION

The results reported here strongly suggest that the issue of the sky continuum subtraction is not a show-stopper for the study of very faint sources with fiber-fed spectrographs. Given the flexibility of these systems, it is likely that they will play a very important scientific role in the future generation of multi-object instruments such as MOONS for the VLT[16] or MOSAIC for the E-ELT[3]. The results reported above (see also Yang et al.[17]) will be implemented soon in the *websim* end-to-end simulator[18]. This tool was heavily used during the E-ELT Design Reference Mission[19,20], the E-ELT instrument phase A studies[1,21,22], and now in preparation of the E-ELT /MOSAIC consortium[4,23]. Accounting for all possible systematics in the background signal subtraction, in particular how to measure and optimally correct for diffuse scattered light, will be essential to accurately assess the future performances of fiber-fed spectrographs.

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