Variation of the Near-IR sky continuum background from long-slit spectroscopy

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ABSTRACT

The amplitudes and scales of spatial variations of the sky continuum background can be a potential limit of the telescope performance, because the study of the extremely faint objects requires the subtraction accuracy below 1%. Thus, studying its statistical properties is essential for the design of next generation instruments, especially the fiber-fed instruments, as well as their observation strategies. Using ESO archive data of VLT/FORS2 long-slit observations, we analyzed the auto-correlation function of the sky continuum. As preliminary results, we find that the sky continuum background has multi-scale spatial variations at scales from 2” to 150” with total amplitude of ∼0.5%, for an given exposure time of 900s. This can be considered as the upper limit of sky continuum background variation over a field-of-view of few arcmins. The origin of these variations need further studies.

Keywords: Extremely Large Telescope, Fiber-fed spectrograph, Sky background, Long-slit, auto-correlation function

1. INTRODUCTION

The accuracy of sky subtraction down to 1% level is essential for the new generation fiber-fed instruments and multi-object spectrographs in the Europe Extremely Large Telescope (E-ELT),[1] for example, OPTIMOS-EVE (the Extreme Visual Explorer).[2] OPTIMOS-EVE is able to observe several objects simultaneously over a field of view of 7 arcmin. Thus it is important to know the statistical properties of the sky over this scale. Especially, we need to investigate the properties of the sky *continuum background* which is the ideal window to detection and study of very faint source of $J_{\rm AB} \sim 27$ out to redshift 6.[3] However, we know little about the properties of the continuum background, such as the temporal and spatial variations, due to its faintness and critical requirement of spectral resolution. Based on FORS2/LSS data in the ESO archive, we made a first attempt to investigate the variation of sky continuum background.

2. DATA

2.1 Raw data from ESO archive

We have used two different data samples for our study: the FORS2/MXU (multi-slit) and the FORS2/LSS (long-slit). For both data set, we choose only the grism of GRIS_1028+29 which provides a coverage from roughly 7730 to 9480 A, and a spectral resolution of $R \sim 2500$. At this resolution, we are able to extract some continuum regions clean of the sky emissions.

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For MXU data, we used data from the program ID: 072.B-0497(B) which studied the red giant stars in a dwarf galaxy WLM in the Local Group.[4,5] We have in total 40 individual exposures with 4 different plates. The effective field of view is $\sim 4.5' \times 4.5'$. After a first investigation, we found two limitations in using MXU data. First, within the slit length of about 8", there is a systematic variation which is not easy to correct; also the scientific object lies over most of the slit length which leaves very few useful sky regions. Second, the spatial sampling provided by each exposure is too low with typically 30 objects over 4.5×4.5 arcmin^2. With such a low sampling rate, the systematic uncertainties cannot be corrected properly.

We deeply analyzed the Long Slit Spectroscopy (LSS) observations. The slit has a geometry of $6.8' \times 1''$ which allows us to study the structure within $3.4'$ according the NyquistShannon sampling theorem. We did a general search for LSS observations of compact sources in the ESO database. We found 6 suitable large programmes related to the binary studies: 078.D-0719(A),079.D-0531(A),080.D-0407(A),082.D-0507(A), 083.D-0862(A),085.D-0974(A) and one about distant QSOs: 085.A-0714(A). All these data were observed between 2006 and 2010. In total we obtained 273 individual exposures (900s each), 3 exposures per night. We selected a sub-sample that includes 9 nights with at least 9 exposures per night. Table 1 gives a summary of the sub-sample.

Table 1. Summary of sub-sample

Dataset	Observation Date	N_{slit}[a]	$\text{Seeing}^{median}('')$	Duration[b] (hours)
D10	2007-04-15	10	0.86	4
D11	2007-04-17	9	1.15	4
D26	2009-04-14	11	0.91	4
D27	2009-04-16	9	0.97	9
D30	2009-04-23	12	1.39	4.5
D39	2010-05-30	9	2.88	4
D41	2010-07-08	9	0.51	3.5
D42	2010-09-06	9	0.69	3
D44	2010-09-09	12	0.55	5

[a] Number of individual exposures. Each of them has 900s exposure time.
[b] Time span from the first observation to the last for each night.

2.2 Data processing

The row data were reduced with *esorex* following the ESO standard pipeline by attaching to the aux files of the corresponding bias, flat-field, instrumental configurations. We obtained the calibrated 2D spectrum as shown in the upper panel of Figure. 1. We selected the region at ~ 9200 Å for our study, as shown in the lower panel of Figure. 1. The thicker red lines are the masks used for selecting continuum regions that are used in the following analysis.

First, we took the median value of the continuum according to the masks indicated in Figure. 1. Using the pipeline source detection we removed the objects in the slit. We manually checked each slit image one by one, removing the faint objects that are not detected by the pipeline, bad pixels as well as cosmic-rays. We normalized the flux to the mean value. This normalization is done for the two CHIPs separately, to avoid the possible calibration differences between them, as well as between the different observation epochs. Our immediate objective is to investigate the sky variation along the slit, as shown in the upper panel of Figure.2. A clear systematic variation of the flux along the slit can be seen. We checked and confirmed that this is a multiplicative component in the data. Using a median filer with a window of 10 arcsecs (~ 40 pixels), super-flat was extracted (the red line). The lower panel of Figure.2 shows the slit flux after the super-flat correction. Some of the remaining spikes and bad pixels were removed in the further analysis. To avoid the possible CCD edge effects, we removed 50 pixels from the ends of slit and the gap region between the two CHIPs.

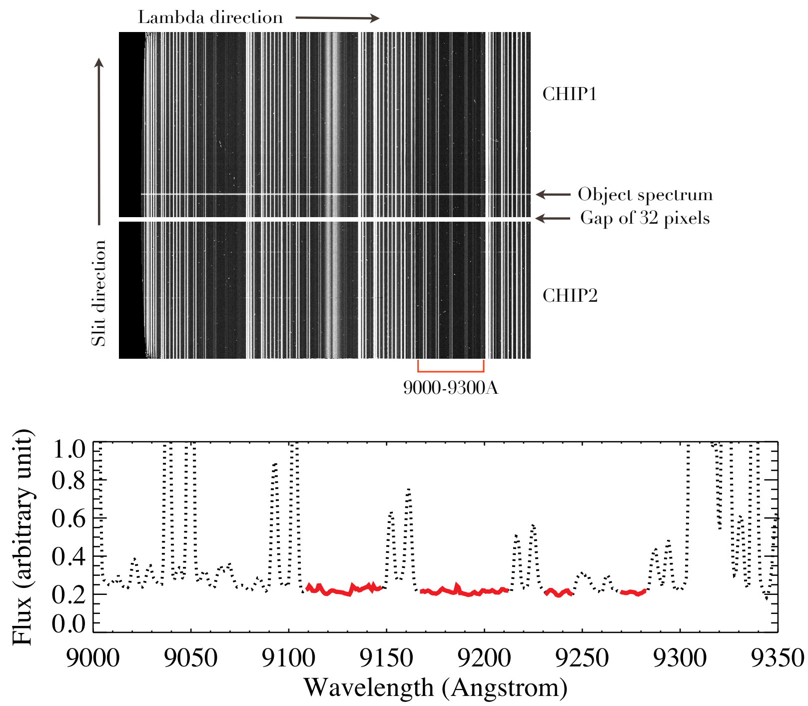

Figure 1. An example of LSS spectrum that is processed following the ESO pipeline. The upper panel shows a 2D spectrum, which is composed of CCD CHIPs with a 32-pixels gap in between. This is an observation of a stellar object which takes only a small area of the slit, leaving a large region of sky. A regions between 9000 and 9300 Å is selected for our study. Its spectrum is shown in the lower panels. The dotted lines are the slit spectra while the thicker red solid-line indicates the continuum regions that are used for analysis.

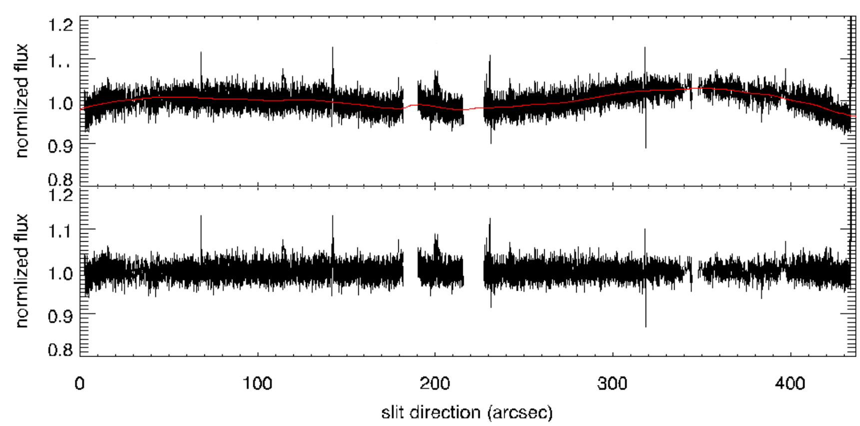

Figure 2. An example of 1D-slit flux before (upper panel) and after the super-flat correction (lower panel). The super-flat is shown as a red line, in the upper panel. Here we show the data observed on 23 Arp. 2009, which include 12 exposures.

3. METHODOLOGY

What we want is to measure is the spatial variations of the sky background continuum, $f(x)$.A The auto-correlation function (ACF) is the ideal tool to extract such an information statistically. We used a non-normalized ACF (Autocovariance):

$$R(l) = < |(f(x) - \mu)(f(x - l) - \mu)| >, \quad (1)$$

where μ is the mean of the data, x the spatial location, l the spatial scale to be investigated. A direct way is to analyze the full 2D-image of sky background.[6] Here, we try an indirect way analysing the long-slit observations. Obtaining the statistical properties of the sky background at a given scale (l) depends on the number of pairs at that scale, assuming the sky continuum background has an isotropic distribution. Using long-slit observations one should obtain the same ACF as the one obtained from 2D-image if we assume the sky variation is isotropic within the scale investigated. We assumed the sky variations can be modeled with Gaussian random fields (GRF). Using 4×4 arcmin^2 GRFs, we verified that both slit and image analysis will give the same information of spatial variations. On the other hand, the noise, due to the limited number of slit available, can be a limit in slit-based analysis.

We used the ACF^{sim} extracted from simulations to fit the ACF^{obs} of the observations. Since we used the non-normalized form of ACF, by fitting the ACF^{obs}, we are able to obtain both scales and amplitudes simultaneously.

4. ANALYSIS OF SPATIAL VARIATIONS

The noise level (RMS) is about 1.5% for the individual slits. Using Eq. 1 we may calculate the ACF for each slit at a resolution of 1 arcsec which is equal to the slit width of the observations. The ACF derived from a single slit is very noisy and gives no indication of any structures, suggesting that the signal the background fluctuations has much smaller amplitude. In order to achieve high enough signal-to-noise ratios (S/N), we derived the ACF per day by taking the mean of individual ACFs. In doing this, we made the assumption that the variation of sky continuum background is a stationary random process during the observation. In another word, with the daily ACF we are investigating the mean variation scales of the sky background during the observation period (see Table 1). The ACF of each dataset was calculated and shown in Figure. 4. The ACF^{obs} are fitted using simulated ACF^{sim} which are calculated from simulated GRFs with multi-scale spatial variations, see Figure. 3. To search the multiple components we used Levenberg-Marquardt minimisation*. We weight each points by the square-root of the pair counting at each scale. Due to the limited number of slits, the ACF function becomes too noisy over scales larger than 200 arcsecs. Thus we limit our analysis within this limit.

In Table 2 we summarize our preliminary results of ACF fitting. We notice that there is always a small scale component 2 arcsec. This scale might be linked to the PSF or very faint sources, such as stars and galaxies. The other larger scales, as seen in Figure. 5, range from 10 to 150 arcsec. There is a slightly concentration at 25 arcsecs. Note that the error bars for scale estimates vary from 10 to 50% depending on the S/N. The average amplitude of each scale variation is 0.2%. In Figure. 5 we show the distribution of the amplitude of variations as a function of scales. The large-scale component has a mean value of 35 arcsec and an amplitude of 0.3% with respect to the median continuum.

5. SUMMARY

In order to investigate the spatial variations of the sky continuum background, we analyzed FORS2/LSS archive data. By choosing observations of stars, we obtained large area of sky background for our study. The raw data were processed with the standard pipeline, and super-flat corrections.za Using ACF analysis, we detect the faint signals of spatial variations with total amplitudes of $\sim$0.5% at different scales from 2" to 150". The smallest scale at 2" is detected in all the data. The size of this scale is large than seeing (see Table 1) and not correlated with seeing. Thus, this might be linked to faint extended objects. Further tests are needed to confirm the origin of the these variations.

*IDL code by Craig B. Markwardt, http://cow.physics.wisc.edu/ craigm/idl/mpfittut.html

Table 2. ACF fitting results

Dataset	Component 1		Component 2		Component 3	
	scale (″)	amplitude (%)	scale (″)	amplitude (%)	scale (″)	amplitude (%)
D10	3.0	0.18	15.8	0.16	108.6	0.19
D11	1.2	0.31	17.6	0.25	120.0	0.10
D26	3.5	0.26	18.1	0.18	92.2	0.22
D27	1.9	0.35	30.3	0.27	138.0	0.20
D30	1.7	0.28	7.4	0.08	55.6	0.16
D39	2.6	0.33	87.4	0.36	—	—
D41	3.4	0.34	104.7	0.31	—	—
D42	2.1	0.38	26.6	0.17	109.3	0.35
D44	1.8	0.24	38.9	0.13	119.1	0.09

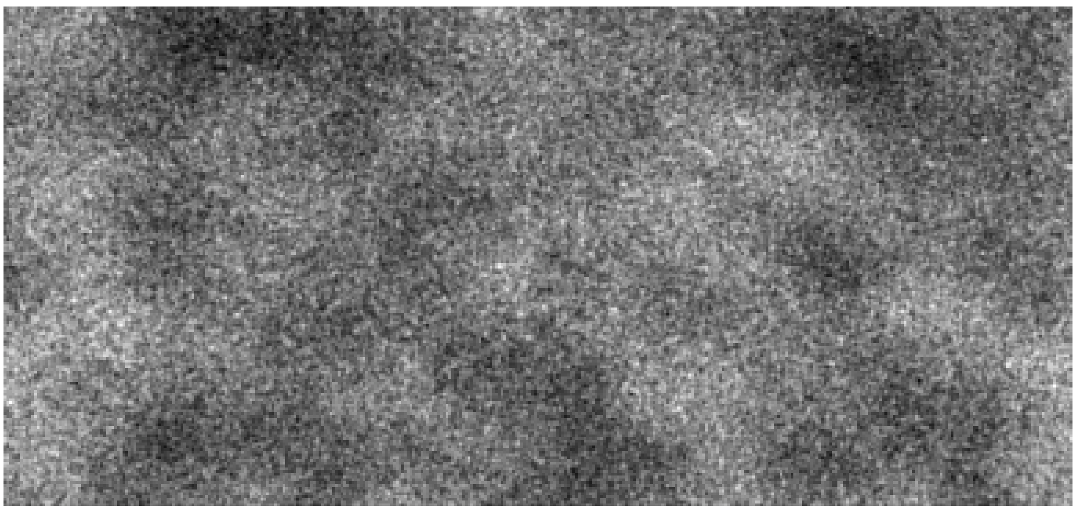

Figure 3. An example of simulated sky surface ($6.5' \times 3'$), a Gaussian random field with two spatial scales 1.4”, 30” (FWHM).

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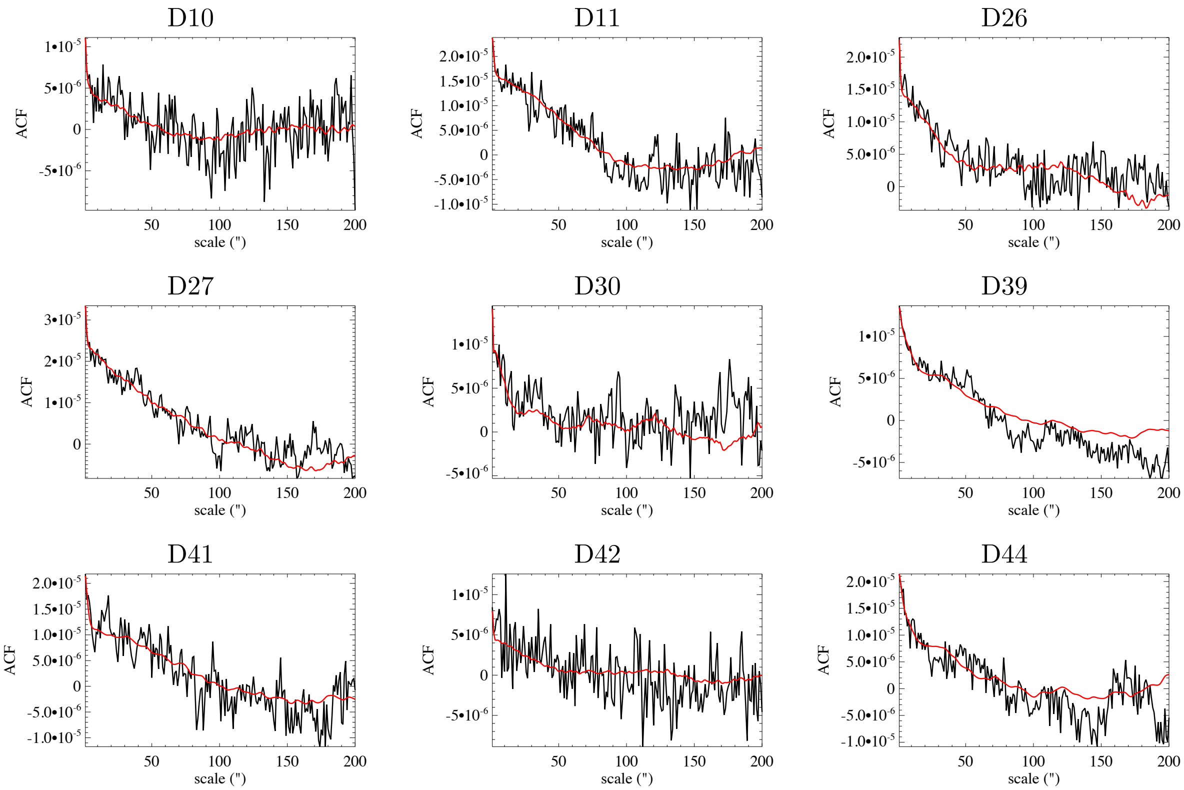

Figure 4. ACF^{obs} (black) and their fitting (red) using GFR simulations.

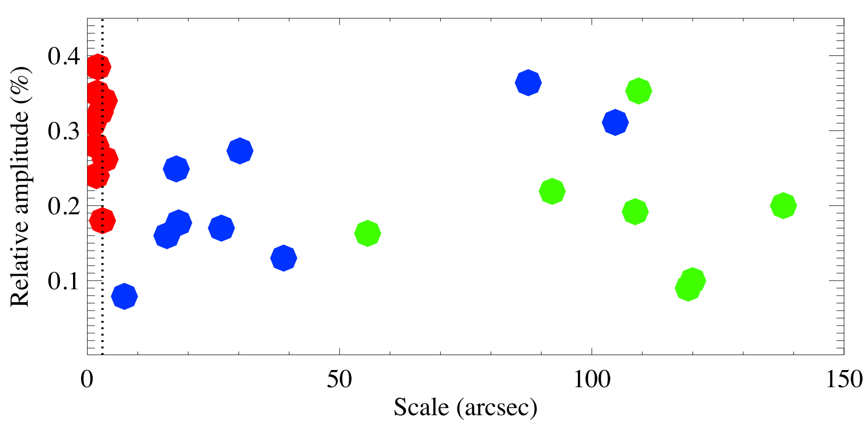

Figure 5. The distribution of the amplitude of variations as a function of their scales. The red, blue points represent the 1st, 2nd, 3rd components (See also Table 2). The dotted line indicate a scale of 3 arcsecs.