"Va et Vient" (back and forth) spectroscopy with CCDs: a new approach to faint object spectroscopy on very large telescopes

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ABSTRACT

The signal to noise ratio of very faint object spectroscopy is discussed in the context of the gain in limiting magnitude attainable on very large telescopes at low spectral resolution. It is shown that if the multiplicative errors resulting from the sky subtraction are not corrected, deeper spectroscopy will not be obtained by increasing the telescope size. A new CCD observing technique, which we call "Va et Vient" spectroscopy, is described in detail. This is a beam switching method where the elementary exposures are short enough to freeze the sky temporal fluctuations, and where the CCD is read only after a series of a few dozen of exposures. During the integration, the signals from the object field and the reference sky are separated by shifting the charges onto the CCD along the columns. Analytical evaluations are confirmed by laboratory tests and show that this technique is photon noise limited even at high flux and thus can lead to deeper spectroscopy. We give estimates of the results that can be achieved with the new generation of very large telescopes.

1. INTRODUCTION

With the coming of new instrumentation and new detectors, very faint object photometry has become a challenge for different groups, especially those working in extragalactic astronomy. A lot of results have been obtained since Tyson's[1] or Cowie et al.[2] pioneering works, the most impressive being in the field of gravitational lenses and their use to detect and identify the nature of dark matter as illustrated by Bonnet et al.[3].

In order to have access to more details on the spectral energy distribution of faint objects (B>24), one has to move from multi-band photometry to low resolution spectroscopy. For the very large telescopes, the scientific challenge is of importance as for example, deep spectrophotometry opens windows on the evolution and the nature of very faint and distant objects, providing better knowledge of luminosity functions and strong constraints on evolution models (Cowie et al.[2], Lilly et al.[4]). A new generation of efficient spectrographs for faint object spectroscopy are now working or are under construction, thanks to efficient coatings, high quantum efficiency and low read out noise large CCD's and multiplex gain using multiaperture masks or fiber optics. They can typically reach a limiting magnitude B $\sim$ 24 corresponding to a brightness of about 10% of the sky brightness.

The purpose of this paper is to discuss different methods and their limitations in faint objects spectroscopy and to propose a new technique which we call "Va et Vient" (back and forth), that is easy to implement on CCD's and can lead to a gain of a few magnitudes, depending on parameters like spectral resolution, spatial scale, wavelength domain. In the first part we briefly discuss the signal to noise ratio (S/N) attainable in faint object spectroscopy when the sky background is dominant over the signal and how the different sources of noise can be lowered. In the second part, we compare the "Va et Vient" to long slit spectroscopy. In the third part we describe the "Va et Vient" and its implementation on a telescope. Results of laboratory tests are discussed in the fourth part. In the last part, we discuss the performances and applications of the "Va et Vient" with different observing parameters.

2. SIGNAL TO NOISE RATIO IN VERY DEEP SPECTROSCOPY

To do spectroscopy on very faint objects, high signal to noise ratio, which means high flux, has to be reached on the sky background. Consequently, its subtraction is the dominant noise source, although the S/N on the object is low. The situation is quite different from high resolution spectroscopy where the high signal to noise is expected on the object itself.

In the following, the discussion will assume a constant brightness through the slit for the sky and the object, and the photon noise dominated by the sky since the objects are typically ten times fainter than the sky.

2.1 S/N limitations in faint object spectroscopy

To recover the object spectrum, the reference sky has to be recorded at high flux and subtracted from the signal, the non poissonian noise components can be dominant and may lower the S/N expected from the photon and CCD readout noises only. A similar problem has been solved in very deep photometry, using techniques like "shift and add" described by Tyson[1] or Cowie et al.[1]. This method has proved to be very efficient, the main photometric limitation coming from the spatial fluctuations of the sky. As shown below, this kind of technique could be applied to faint object spectroscopy but it is not perfect and different approaches have to be looked for.

The discussion will use ϕ for the flux recorded per spectral element and time unit, subscript (O) holding for the objet and (S, S') for the sky under the object and the reference sky. Φ is the integrated flux per spectral element during the total exposure and φ is the flux expressed in energy units per $cm^2/arcsec^2/\text{Å}/sec$. A spectral element is defined as the sum of n pixels along the slit and m pixel in the slit halfwidth as we consider two spectral elements in the slit image. Assuming constant brightness and constant spectral distribution within the spectral element scale (which is a zero order approximation), ϕ is simply expressed by the relation:

$$\phi = n\, m\, \frac{\pi D^2}{4}\, \eta\, p\, w\, \delta\lambda\, \varphi \tag{1}$$

where D is the telescope diameter in cm, p the pixel size in arcsec, w the slit width in arcsec, η the efficiency of the whole chain from the atmosphere to the instrument and the CCD, $\delta\lambda$ is the dispersion in $\text{Å}/pixel$ giving $R = \lambda/(2m\delta\lambda)$ the spectral resolution at the observed wavelength λ, fixed by the slit width. Estimation of the object signal Φ_O, after sky subtraction, is given by

$$\Phi_O = \phi_O T + (\phi_S - \phi_{S'})T \tag{2}$$

where T is the exposure time and $(\phi_S - \phi_{S'})$ are the residuals of the sky subtraction which will be considered as noise components noted μ in the following expression:

$$N = \sqrt{\sigma_{CCD}^2 + \sigma_{ph}^2} + \mu_{sky} + \mu_{flat} + \mu_{lines} \tag{3}$$

where the usual photon noise and readout noise are kept under the square root. Except the photon noise, the noise components are considered systematic and are simply added. This is the right way of writing the errors for several experiences on the same pixel when adding several exposures. In fact the S/N is often measured on a set of pixels in a wavelength range so that the errors are randomized and can be quadratically added to the photon and readout noise. In any case, neither approach significally changes the conclusions of the discussion. The noise components and other points related to the "Va et Vient" are discussed in more details in a paper by Cuillandre et al.[5].

Let us formally express these different components to the first order: $\sigma_{ph} = \sqrt{u\phi_S T}$ is the photon noise. $\mu_{flat} = \varepsilon\phi_S T\sqrt{v+\alpha^2}$ is the noise due to the accuracy ε in the flatfielding process, α being the brightness ratio between the object and the sky. u and v are constants depending on the observing mode used. In case of beam switching spectroscopy, u is set to 2 and v to 0. In case of long slit spectroscopy, both u and v are set to 1 when the sky reference is averaged along the slit and set to 2 in the other cases. $\mu_{sky} = \beta\phi_S T$ is the noise component due to temporal and spatial relative variations β of the sky brightness. $\mu_{lines} = \omega\phi_S T$ is the noise due to the possible spectral shift, resolution and slitwidth changes between the sky reference and the object field which apply on the first derivative of the sky line profile. Using these definitions, a general formulation of the S/N can be written

$$\frac{S}{N} = \sqrt{\phi_S T}\frac{\alpha}{\sqrt{u + \frac{2nm\sigma^2}{\phi_S T} + (\beta + \frac{\varepsilon}{\sqrt{n\,m}}\sqrt{v+\alpha^2} + \frac{\omega}{\sqrt{m}})\sqrt{\phi_S T}}} \tag{4}$$

Everything being perfect, considering only the photon noise, this expression can be reduced to

$$\frac{S}{N} \propto \frac{\alpha\sqrt{T}D}{\sqrt{R}} \tag{5}$$

which is an increasing function of the telescope diameter, of the square root of the exposure time and of the inverse of the resolution. In a perfect world, getting fainter could be simply achieved by longer exposure time, a larger telescope and smaller resolution. In fact, when increasing the flux in the complete expression (4), because of noise components proportional to the sky background, the S/N tends to an upper limit

$$\frac{S}{N}^{lim} = \frac{\alpha}{\beta + \frac{\varepsilon}{\sqrt{n\,m}}\sqrt{v+\alpha^2} + \frac{\omega}{\sqrt{m}}} \tag{6}$$

which depends only on the multiplicative sources of noise and explicitely of the sampling of the spectral element through n and m parameters. The fundamental point is that this limit no longer depends on the exposure time nor the telescope size leading to a big worry on very large telescopes. Since everything being kept constant, the only gain from increasing the collecting area could be to reach this limit more rapidly without getting fainter, solutions to reduce the magnitude of the multiplicative noise sources are needed.

To analyze things more deeply, let us rewrite φ assuming a spectral distribution $f(\lambda)$ expressed as an expansion limited to the first order. After integration, the flux per spectral element, assuming 2 spectral elements in the slitwidth is given by

$$\phi = n\,m\,\frac{\pi D^2}{4}\eta\,p\,w\,\delta\lambda\,<f>\,[1 + \frac{1}{2}\frac{<\partial f/\partial\lambda>}{<f>}\delta\lambda\,(1 + 2\rho + w/p)] \tag{7}$$

where ρ is the spectrum shift in fraction of a pixel which results in different line sampling and $\delta\lambda$ is the dispersion in Å/pixel.

In this expression, the instrumental - $(w, \delta\lambda, \rho)$ - and sky - $f, (\partial f/\partial\lambda)$ - parameters can vary between the object field and the reference sky leading to residuals after sky subtraction, so that corrections, through calibrations must be applied before. The instrumental parameters are calibrated through the flatfielding (w) and the spectral calibration $(\delta\lambda, \rho)$ and the sky parameters are estimated through sky monitoring.

Expression (7) shows two quite different regimes. In the case of the sky continuum, $\partial f/\partial\lambda$ can be assumed to be null at the scale of the spectral element and the residuals can be kept at very low level (say a few thousandths) since the calibration applies to linear and independant terms. In the case of sky lines, depending of the slope of the line profil and the spectral resolution, the residuals can reach a few percent of the total flux because simple calibrations no longer apply to higher order terms.

Other variations are due to the fluctuations of the signal itself through f. Since the sky spectrum is made of several independant components (Wise & Gilmore[6]), it is well known that its amplitude can vary by a few percent at a scale of a few arcsec (Ellis & Parry[7]) and that its spectral fluctuations, very different in the continuum and in the lines, can vary all along the night with time scale ranging from a few minutes to hours. Expression (7) shows that in the lines, because of the fluctuation of non linear term and the fluctuations of f and $\partial f/\partial\lambda$, the residuals can not be perfectly corrected by simple calibration procedures, even by monitoring the sky. A better correction would imply a modeling of the sky spectrum.

This discussion shows that the depth of faint object spectroscopy is very dependent of the technique used and of the quality of the instrumentation. Much care has to be carried on the spectrograph design, as for example its optical distorsion, its stability or the slit quality and alignment (as in high resolution spectroscopy). Since the correction of the residuals can not be perfectly done, methods have to be found to minimize the residuals.

2.2. Possible strategies for improving deep spectrophotometry

Given the observing parameters (resolution, sampling, scale), different strategies are possible to overcome these problemsand some have already been used. Obviously, the first way is to use conventional observations and correcting the different subtraction errors during data reduction.

Reducing the spatial fluctuations of the sky is generally done by observing the sky near the object and modeling the sky under the objects (Horne[8]).

This holds whatever the observing technique and will no longer be discussed below. Temporal fluctuations for long exposures are reduced by recording the sky reference and object field at the same time, like in long slit spectroscopy, or by monitoring the sky fluctuations in beam switching spectroscopy. Neither is perfect since in the first case, the sky reference and object field being recorded at different places on the CCD, the sky subtraction is affected by the spatial errors (μ_{flat} and μ_{lines}) and in the second case, the temporal changes cannot be perfectly corrected as they are not sampled the same way (see discussion above).

A second approach, is to observe in such a way that spatial and temporal errors are minimized. Attempts have been made to randomize the spatial noise sources (Cowie & Lilly[9]) using a "shift and add" method along the slit, but the gain is limited to the square root of the shifts number. A gain of ten (2.5 magnitudes) would imply about 100 shifts along the slit.

The best solution is to use a beam switching observing mode to remove the spatial errors but with exposures that are short enough compared to the timescale of the sky fluctuations to sample the temporal errors. A similar technique was used earlier by Boksenberg[10] with a photoncounting detector (IPCS) with very low readout time and negligible readout noise. The difficulties in adapting this technique to conventional CCD's that are superior in terms of quantum efficiency and image stability, come from their readout time (a few seconds to a minute) and their readout noise which has to be small enough for each elementary exposure to be in the photon noise regime in a short exposure time (1 to a few minutes). In general cases (depending on the telescope size, resolution and scale), this exposure time would be too long compared to the sky fluctuations.

2.3. The "Va et Vient" technique

Following a procedure used in photopolarimetry by Mac Lean et al.[11], we propose using a beam switching technique, alternatively recording the object field and the sky reference on the same CCD pixels, with a short period compared to the sky fluctuations, reading the CCD only at the end of a sequence of several cycles, by using the possibility of shifting the charges along the CCD columns in both directions. The object field and sky reference spectra are integrated through the same slit, on the same pixels but are recorded on two different strips on the CCD. The interest of this technique is to save readout noise and the time lost by reading the CCD when working with periods of a few minutes (to freeze the sky fluctuations) since, except for the systematic errors which are removed by the sky subtraction, each elementary exposure is in the photon noise regime, provided the charge shifts are noiseless. Another advantage compared to the "shift and add" technique is that the data reduction procedure is simpler because both spectra are on a single image.

3. GAIN REACHABLE BY THE "VA ET VIENT" ON LARGE TELESCOPES

In order to describe this concept, let us compare the expected performances of the "Va et Vient" to classical long slit spectroscopy in terms of signal to noise ratio and the possibility of going deeper. In terms of efficiency, other considerations would have to be taken into account, such as the mutiplex facility of the different techniques.

3.1. Comparison to long slit spectroscopy

In the long slit spectroscopic mode, the signal to noise ratio can be calculated from expression (4) just keeping the flat fielding ε and sampling ω terms because the object field and sky reference are not recorded through the same part of the slit, the same spectrograph path and the same pixels. u is set to 0 since the sky is averaged before subtraction. As the flux increases, the S/N tends to an upper limit (see expression (6) with β=0) which depends only on the residual parameters (ε and ω) and the object to sky ratio (α), so that working on a very large telescope would not reach fainter spectrophotometry. The only gain would be the time needed to reach this limit.

In the case of the "Va et Vient", the S/N is calculated from expression (4) where the only multiplicative residuals are the temporal sky fluctuations (β), as the object field and reference sky spectra are recorded through the same slit on the same pixels. The flat field accuracy ε apply only to the object signal. u is set to 1 since the sky subtraction must be done pixel per pixel. If the sampling period is small compared to the sky fluctuation, the "Va et Vient" mode can be considered as working in a photon noise regime even at high flux, when increasing the telescope size or the exposure time or decreasing the resolution. In this way, large telescopes at very low resolution will lead to deeper spectrophotometry.

Limitations on the flux and the exposure time, will be given by the saturation effects on the CCD, which must always work in the linear regime but higher flux can be attained by summing several exposures after reduction.

3.2. Gain of the "Va et Vient"

The gain of the "Va et Vient" over the long slit mode, under the same overall conditions, is simply expressed in terms of magnitude G_{VV} at a given signal to noise ratio k:

$$G_{VV} = 2.5\, log\, [\frac{1 + (\varepsilon/\sqrt{nm} + \omega/\sqrt{m})\sqrt{\phi_S T}}{\sqrt{2} + \beta\sqrt{\phi_S T}}(1 - k\,\varepsilon/\sqrt{nm})] \qquad (8)$$

The gain is an increasing function of the flux which tends to $1/\sqrt{2}$ at the zero level because the sky subtraction is made pixel per pixel in the "Va et Vient" instead of removing a sky averaged or modeled on several pixels in long slit spectroscopy. At high flux per pixel (which means low resolution, large collecting area, long exposure time), the gain tends to the expression:

$$G_{VV}^{lim} \simeq 2.5\, log\, \frac{\varepsilon/\sqrt{n} + \omega}{\beta\sqrt{m}} \qquad (9)$$

The last expression shows that at high flux (low resolution, large telescope), the gain is dominated by the sampling residuals (ω) on the sky lines and the spectral element sampling m.

These simple analysis confirms the interest of the "Va et Vient" in faint object spectroscopy when, as shown by expression (5), everything must be done to increase the flux per pixel, which means working at low resolution, with a spectral element of a few pixels.

4. IMPLEMENTATION OF THE "Va et Vient"

4.1. Implementation of the "Va et Vient" on a CCD

This is a very simple operation as soon as the physical structure of the CCD enables charge shifting along the columns in both directions, which is the case with the four phase thinned Thomson CCD that we use for our laboratory test. The implementation on modern controllers is a minor change since programming the clock phases is easy. Parameters to be given are the shifting period, the number of periods to be done, the number of lines to be shifted. In a true telescope experiment, the controller must be linked to the telescope's control system as the telescope must be offseted synchronously with the charge shifts. On the spectrograph, a short slit has to be used in order to perfectly mask the CCD outside the used zone, generally a few columns. We discuss later about the possibility of multiaperture spectroscopy.

At the laboratory, the experiment was carried out using a back illuminated Thomson CCD (TH7895 512×512 pixels) and a controller developed by ESO.

4.2. How the "Va et Vient" works

The principle of the "Va et Vient" is illustrated in figure 1. Time increases from left to right. In the first drawing, the object $(S + O)$ is centered on the slit and the first elementary exposure is made. When it is finished, the shutter is closed and, as shown on the second drawing, the telescope is offset to put the reference sky (S') into place on the slit while the integrated charges are shifted in a masked region of the CCD. Then an elementary exposure is made on the reference sky on the same pixel as before and the shutter closed. The third drawing shows a situation which returns to the first, so that a new integration on the object field through the same pixels can be added to the first one. The fourth drawing shows the second integration on the reference sky. The fifth drawing illustrates the fact that, thanks to the charge shifting, at the end of the complete integration, after a series of cycles, the signals are recorded in two independent strips, one with the object field spectrum and the

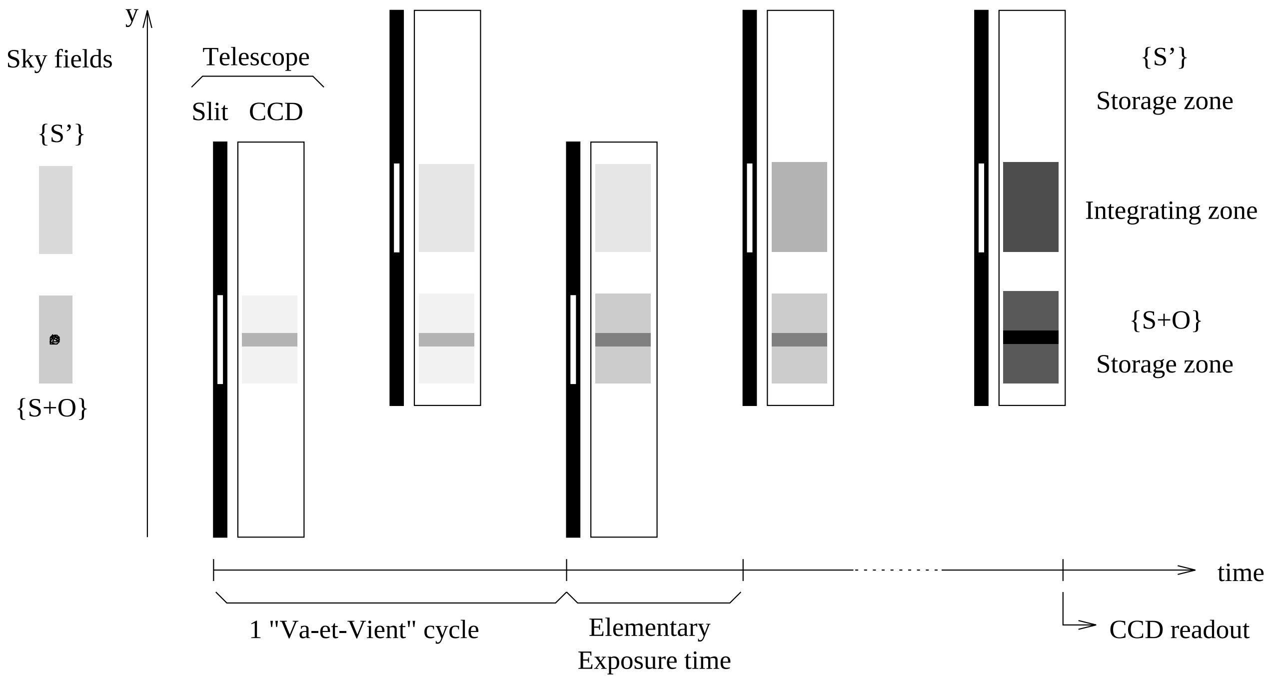

Figure 1: Principle of the "Va et Vient" technique with a single slit

other with the reference sky spectrum. As shown on the picture, three zones are really needed on the CCD, the integration zone under the slit image, and on each side, a storage zone for the object field and the sky reference spectra.

The sky reference is perfectly removed from the object field spectrum pixel per pixel as for both spectra the correspondence between one pixel and the wavelength is the same, which means the same quantum efficiency and the same sampling on the sky lines. This is important as we will discuss some particular applications of the technique.

4.3. Results of laboratory tests

Results obtained under the same conditions with long slit spectroscopy and "Va et Vient" are compared after standard data reduction fitted to each technique.

4.3.1. The experimental set up

The experimental set up is shown in figure 2. We used a simple spectrograph made of two objectives and a grism with a 25 Å/pixel dispersion and a 4 pixel slit width, leading to a very low resolution of 100Å. The sky spectrum as shown in figure 3 (curve a) is simulated by a halogen lamp and a neon lamp giving lines whose amplitude can be varied. The galaxy spectrum, as shown in figure 3 (curve b) is simulated by a halogen lamp filtered by a blue filter and can be attenuated. The galaxy and sky are combined through beam splitters. The telescope offset is simulated by switching off the galaxy (reference sky exposure) or switching on the galaxy (object exposure). The same sky is used in both integrations, without any spatial changes but temporal changes are allowed, because of the lamp stability (better than 1%) or more drastically by tilting an interference filter in front of the neon lamp, which provides wavelength dependent variations on the sky emission lines. The flux have been adjusted to be comparable to about one hour exposure on a four meter telescope.

Figure 2: Laboratory ”Va et Vient” optical bench

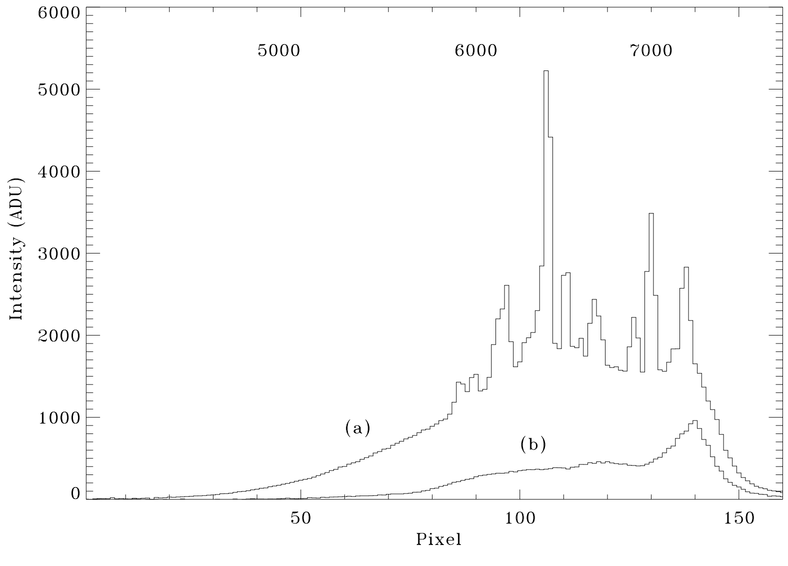

Figure 3: Sky (a) and object (b) artificial spectra; a wavelength scale is given above in Å

4.3.2. Is the "Va et Vient" noiseless?

The first test was to check that the clocking and charge transfers did not add measurable noise to a normal operation. On a telescope, a typical exposure of one hour will result in about 30 to 60 shifts of no more than 100 rows. The "Va et Vient" noise was estimated by comparing the variance of a bias read in normal conditions to a bias read after 60 shifts of 100 lines. The result was smaller than 1 electron rms. To check the charge conservation, a sharp profile has been conservatively shifted 1000 times by 100 rows. The comparison of the MTF of the profile before and after the shifts allows us to compute a charge transfer efficiency (CTE) of 1-3.10^{-6}, well in the range of the Thomson characteristics showing that the transfer function is not affected by the charge shifting.

4.3.3. Data reduction procedures

We used standard data reduction for faint spectroscopy: bias subtraction, flat fielding, sky subtraction and wavelength calibration. In the case of long slit, after bias subtraction and flat fielding, the reference sky has been averaged over 60 rows (photon noise of the object field is kept) and subtracted with an optimal algorithm as proposed by Horne[8]. The resulting object spectrum is then added over 5 rows corresponding to the spatial extension of the object. In the case of the "Va et Vient", after bias subtraction, the reference sky is removed pixel per pixel, then the resulting object spectrum is flatfielded and added over 5 rows.

4.3.4. "Va et Vient" gain

The gain of the "Va et Vient " mode over the long slit mode is shown in figure 4. The mean S/N was measured on a wavelength domain from 5800 to 7200 Å, after removing a very high S/N normalized spectrum of the simulated galaxy alone. As expected, less than 1 at very low flux (must be $\sim$ 0.7 at flux 0), the gain of the "Va et Vient" increases with the flux.

As shown on Figure 4, curve a, the gain measured with the skylines switched on (skyline domain) is rapidly higher than 1 and regularly increases with the flux. On curve b, the gain measured with the skylines switched off (sky continuum) increases with the flux but more slowly and as expected, the long slit is better than the "Va et Vient" up to a high flux.

Fitting expression (8) to the laboratory results gives us typical values for the parameters in our experiment: $\varepsilon \simeq 0.005$, $\beta \simeq =0.003$ and $\omega \simeq= 0.025$. These laboratory results confirm that the "Va et Vient" is noiseless and that its maximum efficiency is reached in low resolution spectroscopy in the red spectrum where the sky is dominated by the emission lines. We can use the analytical analysis made above, to infer the attainable results in different conditions. As already mentioned, the "Va et Vient" is very simple to implement on a telescope and the data quite simple to reduce because they are all on a single exposure. A first attempt on a telescope was made at ESO for a few hours on the red arm of EMMI (Cuillandre et al.[5]), but the dispersion was too high (10 Å/pixel) and we did not have enough time to saturate the signal to noise ratio, even in the long slit mode, so that new observations have to be made.

5. DISCUSSION

In this chapter we will compare long slit to "Va et Vient" spectroscopy with the different observing parameters, telescope size and exposure time. Calculations are made using a flux of 1.5 $10^{-6} photons/cm^2/arcsec^2/$Å$/sec$, typical of the continuum sky in the V band. A factor of 2 is taken for the I band which is dominated by the sky lines. The whole chain efficiency is taken 0.2, the pixel size 0.5", the slitwidth 1.5", the spectral element 6×1.5 pixels and the dispersion per pixel 30 Å,

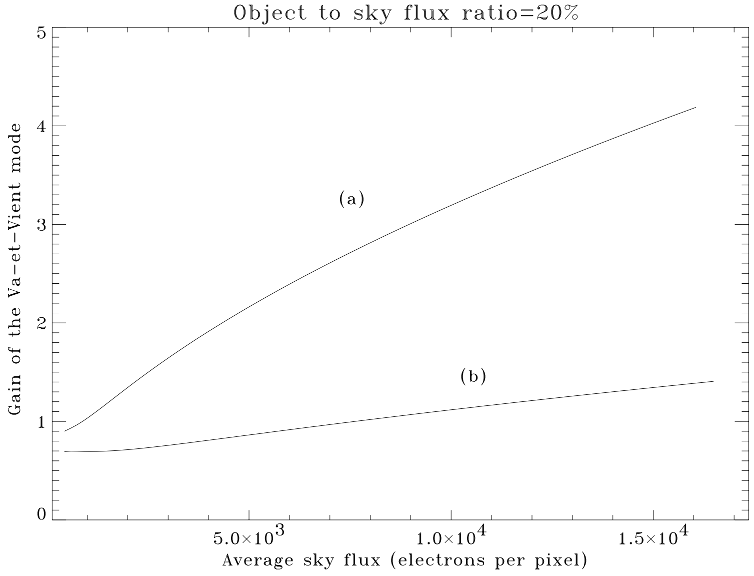

Figure 4: Experimental laboratory gain of the Va et Vient over the long slit spectroscopy in sky lines spectral domain (a) and in the continuum (b).

which gives a resolution of 100 at 9000 Å. The flux is calculated for an extended object, on a spectral element as defined above and for a single exposure and the magnitudes are given per $arcsec^2$.

The flatfielding accuracy ε and the sky temporal fluctuation parameter β are set respectively to 0.01 and 0.002, values which seem easily attainable with some care during the observations but which do not imply too much effort during the data reduction process.

5.1. Going deeper

Results are given in table 1 for three different values of the parameter ω: first line is in case of the continuum, the others in case of sky lines. Results are given in case of long slit and "Va et Vient" spectroscopy for the magnitudes $\Delta\mu_{VV}$ and $\Delta\mu_{LS}$ attainable at a S/N=3 above the sky on a 1 hour exposure made on a 4 meter telescope, the gain in magnitude G_{VV} of the "Va et Vient" over the long slit mode and finally the integration time, T_{VV} and T_{LS}, required to get the multiplicative residuals equal the photon noise.

ω	$\Delta\mu_{VV}$	$\Delta\mu_{LS}$	G_{VV}	T_{VV}	T_{LS}
0	4.04	4.11	-0.06	9.1h	1.6h
0.02	4.31	2.92	1.39	4.55h	0.024h
0.05	4.31	2.12	2.19	4.55h	0.005h

Table 1

Long slit spectroscopy and "Va et Vient" are very comparable in the continuum but in the sky lines, even with a four meter telescope, the long slit spectroscopy noise is dominated by the sampling problems in a few minutes and increasing the exposure time is not an efficient way to get higher magnitude.

The evolution of the magnitude per $arsec^2$ attainable above the sky versus the flux, in the red where the sky spectrum is dominated by the lines, is shown on figure (5) versus the quantity

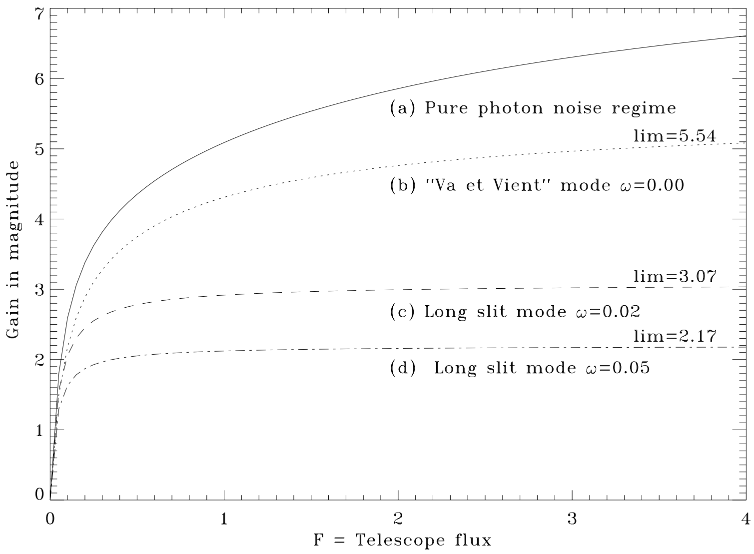

Figure 5: Gain in magnitude over the sky in the "Va et Vient" mode and the long slit mode for $\omega = 0.02$ and $\omega = 0.05$

$F = (D\sqrt{T})/4$, for the spectral element and parameter values given above. F equals 1 for a one hour exposure on a 4 meter telescope (or a 15 minutes exposure time on a 8 meter telescope). Curve a is expected for pure photon noise, curve b is the result for the "Va et Vient" and curves c and d are the results for long slit spectroscopy. The limit attainable is given for each curve.

This figure clearly illustrates the gain of the "Va et Vient" method when increasing the telescope size or (and) integration time at very low resolution. In long slit spectroscopy, the magnitude is limited to 3.07 magnitudes above the sky for $\omega = 0.02$ but the curve shows that increasing the exposure time above half an hour on a 4 meter telescope is not an efficient way to reach this limit. This would be worse on a 8 meter telescope. Curve b shows that a magnitude of about 5 above the sky could be expected from the "Va et Vient" technique because its efficiency to about F=3, which means an exposure of 2.2h on a 8 meter telescope.

5.2. Other applications

In the laboratory, we checked that with the "Va et Vient", the sky subtraction was kept very efficient in the case of a large misalignment of the slit (several degrees)which is a very interesting result because it opens the possibility of working with curved slits on faint elongated objects like gravitational arcs in cluster of galaxies. Such spectra have already be done (Soucail et al.[13]) but with the limitations on the signal to noise ratio of long slit spectroscopy.

We also checked that, as expected, the fringes on the CCD due to the sky background lines in the red part of the spectrum are better removed by the sky subtraction in the "Va et Vient" mode than in long slit spectroscopy, even with a good modeling of the background.

The "Va et Vient" is a beam switching method, which means using half the time on the object and half the time on the reference sky. To save time, it is possible to use two adjacent slits, so that when the object is integrated on a slit, the sky reference is integrated on the other and alternatively. This way, the sky is integrated half the time on each side of the object. The room needed on the CCD in this case is four times the size of the elementary slit since two storage zones and two integrating zones are needed. The final result is a spectrum of the object field and on each side a spectrum of the reference sky with a level intensity half of the object field spectrum. Moreover, this mode presents the advantage of reducing the temporal sky variations to a second order value as the sky fluctuations are sampled two times. The "Va et Vient" should always be used in this mode, enabling to push back further an eventual S/N limit as discussed above.

The "Va et Vient" mode can be used in multiaperture spectroscopy provided a very clever selection of the objects is made because a reference sky is needed on each side of the objects and at the same distance for all objects. Since the sky subtraction is made pixel per pixel, the slits do not have to be much longer than the object size. However, gaps of a few pixels have to be maintained between the different zones in order to correct any background and to prevent any charges from being transferred from a zone to the other during the shifting. Taking these parameters into account, we can hope observing simultaneously up to 20 faint objects in a 7'×7' field.

6. ACKNOWLEDGMENTS

This work was supported by the Centre National de la Recherche Scientifique and the Université Paul Sabatier. The authors wish to thank Sandro D'Odorico (ESO) for the engineering time allocated on the NTT for testing the "Va-et-Vient" spectroscopy and the technical staff in Garching and La Silla. We also thank J.P. Dupin, F. Beigbeder, G. Ratier, B. Altieri and T. Pourthié for their work during the installation of the optical bench and the laboratory tests and to M. Dantel-Fort for her help in the data reduction.

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