Image Slicer Performances from a Demonstrator for the SNAP/JDEM Mission, Part I: Wavelength Accuracy

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ABSTRACT. A space-adapted visible and infrared spectrograph has been developed for the SNAP (SuperNova/Acceleration Probe) experiment proposed for JDEM. The instrument should have a high sensitivity to see faint supernovae, but also a good redshift determination better than 0.003(1 + z), and a precise spectrophotometry (2%). An instrument based on an integral-field method with the powerful concept of imager slicing has been designed. A large prototyping effort has been performed in France that validates the concept. In particular, a demonstrator reproducing the full optical configuration has been built and tested to prove the optical performance both in the visible and in the near-infrared range. This article, the first of two, focuses on wavelength measurement, while the second article will report on spectrophotometric performance. We address here the spectral accuracy expected both in the visible and in the near-infrared range in such a configuration, and we demonstrate, in particular, that the image slicer enhances the instrumental performances in the spectral measurement precision by removing the slit effect. This work is supported in France by CNRS/INSU/IN2P3 and by the French space agency (CNES), and in the US by the University of California.

Online material: color figures

1. INTRODUCTION

Integral-field spectroscopy (IFS) is a powerful technique able to provide simultaneously the spectrum of each spatial sampling element in a given field of view (FoV). The principle consists of rearranging the 2D spatial field by means of an integral-field unit, and then using a classical spectrograph to disperse the light. Three types of integral-field unit exist: micro lens arrays, fibers combined with microlenses, and image slicers. The use of an image slicer is very suitable for measuring faint objects, thanks to its high efficiency and minimization of the constraint on the pointing accuracy. For about 10 years, two different image slicing technologies have been developed simultaneously. The first one uses a slicing-mirror stack in aluminum (“monolithic design”) and diamond-turning techniques. The second one uses individual mirrors on ZERODUR, assembled using optical-bonding techniques (molecular adhesion). Early prototypes have shown the potential of the image slicer in ground-based astronomy for infrared measurement (e.g., the instruments SPIFFI [Eisenhauer et al. 2000] or NIFS [Hart et al. 2003]). The aluminum monolithic approach is also planned for use in MIRI in the mid-infrared (Wells et al. 2006), and for NIRSpec in the near-infrared (Vivès & Prieto 2006) of the future James Webb Space Telescope (JWST). However, the aluminum has poor surface roughness quality, under 1.5 μm, which limits the use of this technology. The ZERODUR approach has also kept on maturing and has been developed in the visible range. A first prototype has been built and tested in the frame of the European Space Agency (ESA) for the NIRSPEC of the JWST, and has demonstrated the feasibility of an imager slicer for space application (Laurent et al. 2004). After further prototyping, this technology was selected for the Multi Unit Spectroscopic Explorer (MUSE) for the second-generation VLT (Laurent et al. 2006) working in the visible range. In the meantime, a complete IFS-slicer demonstrator of spectrograph has been designed, manufactured, and tested in the visible and infrared (IR) range for the SuperNovae/Acceleration Probe (SNAP). In this article, we present some results of this demonstrator both in the visible and infrared range.

The SNAP satellite is designed to measure very precisely the cosmological parameters of, and to determine the nature of, dark energy (http://snap.lbl.gov/). The mission includes the measurement of some 2000 supernovae (SNe) of Type Ia up to a redshift of z = 1.7. Details of the mission and the expected physics results are given by Aldering et al. (2004). Spectroscopy of each candidate supernova near maximum light is required to identify and to control intrinsic variations through spectral features. We need in particular to measure the velocity of the Si II line at a 400 km s⁻¹ level of precision. The spectrograph is also required to measure the redshift of the galaxy at a precision better than
0.003 \times (1 + z) for cosmology in the Hubble diagram. These requirements lead to a precision on the wavelength of 1 to 2 nm going from the visible to the infrared range (from 400 to 1700 nm). At last, the spectrograph is a key component of the calibration procedure. As the imager is saturating for stars brighter than $M_v = 18$, the spectrograph is used to transfer the calibration from fundamental standard stars ($M_v = 12–18$) to secondary standards ($M_v > 18$) at a 2% of precision. This requires a spectro-photometric calibration $\leq 2\%$ accuracy with a high control of the wavelength measurement to reconstruct the synthetic filter of the imager. We estimate that 1 nm wavelength accuracy is needed to achieve this precision.

The optical properties of the instrument will thus have to include high efficiency, very low noise, and accurate spectro-photometric calibration at 2% level. The slicer has been shown to have many advantages compared to a standard slit configuration, but this technology should be validated and its performances should be tested for space application. A large prototyping effort is going on in France to bring the technology to this level (Pamplona et al. 2008). In this article, we focus on the slicer’s optical properties in a full spectrograph configuration.

The SNAP project has designed a specific demonstrator, reproducing the spectrograph concept (Prieto et al. 2008) and including a new slicer unit. An optical bench prototype has been manufactured to evaluate the optical performance and to test the accuracy of the spectro-photometric calibration.

After describing the spectrograph concept and design, we present the demonstrator setup and the tools developed to test the optical performance. We describe a full simulation which includes the optical and detector effects, developed to test performances and adapted to the demonstrator to prepare procedures. The simulation is subsequently compared with data. We show that the optical characteristic and performance of the demonstrator are well reproduced, which proves that we effectively control the optical properties of the instrument.

We then present the first results in the visible and infrared focusing on the wavelength determination. We describe the wavelength calibration procedure, adapted to our configuration. We test the accuracy on the wavelength of a point-like source, and show that the wavelength can be recovered at better than 1 nm on the full range due to the slicer properties. We demonstrate than the slicer provides a natural method that corrects the classical slit effect without any additional mechanism.

### 2. SPECTROGRAPH DESCRIPTION

The instrument should be well adapted to a space environment (small, compact, light). To see faint SNe and galaxies, the instrument should have a low resolving power covering the visible and the near-infrared range, with very high optical and detector performance (the main limitation is the telescope diameter), and a constant resolving power in the 0.6–1.7 μm range. Each SN and its host galaxy should be exposed simultaneously to minimize exposure time.

Given the science drivers and specifications, we have conducted a trade-off study to choose the best instrument concept (Ealet et al. 2006). The requirement for simultaneous acquisition of SN and host spectra, and for the level of needed precision lead us to prefer a 3D spectrograph to a traditional long-slit spectrograph. The specifications are summarized in Table 1.

A 3D spectrograph reconstructs the data cube including the two spatial directions $X$ and $Y$ plus the wavelength direction. For each spatial pixel, the spectrum is reconstructed. Thanks to the large field of view ($3 \times 6'$), the pointing requirements are relaxed. The image slicer minimizes optical losses. Figure 1 shows the principle of this technique. The field of view is sliced along $N$ (for SNAP $N = 40$) strips on a “slicing mirror.” Each strip forms a subslit. The pupil mirrors makes the images of

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**Table 1**

| Specification                  | SNAP spectrograph (Visible) | SNAP spectrograph (Near-Infrared) | Demonstrator (Visible) | Demonstrator (Near-Infrared) |
|-------------------------------|-----------------------------|----------------------------------|------------------------|-----------------------------|
| Field of View                 | $3 \times 6$ arcsec$^2$     | $3 \times 0.75$ arcsec$^2$       | 344                    | 344                         |
| F-ratio                       | 347                         | 0.15"                           | Specific illumination unit | 0.15"                      |
| Resolution                    | $2 \times 3$ slices of $0.5 \times 10$ mm size | 5 slices of $0.5 \times 10$ mm size | One optical arm         | 1 optical arm               |
| Wavelength                    | [0.35–0.98 $\mu$m]          | [0.98–1.7 $\mu$m]               | [0.35–0.98 $\mu$m]     | [0.98–1.7 $\mu$m]          |
| Spectral Resolution           | 200                         | 70                               | 200                    | 70                          |
| Spectral Resolution           | 200                         | 70                               | 200                    | 70                          |
| Resolution                    | 9 $\mu$m                    | 18 $\mu$m                        | 9 $\mu$m               | 18 $\mu$m                   |
| Pixel size                    | Camera F-ratio = 12         | Camera F-ratio = 12              | Camera F-ratio = 12    | Camera F-ratio = 12         |
| Detector temperature          | Passive cooling             | Room temperature                 | 140 K                  | 140 K                       |
| Throughput                    | $\geq 40\%$                 | $\geq 40\%$                      | $\geq 40\%$            | $\geq 40\%$                 |

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Fig. 1.—Slicer principle: the FoV is sliced into \( N \) strips on a slicing mirror, creating \( N \) telescope pupil images in the pupil plane. Because of a tilt applied to each slice, the images are arranged along a line and form a pseudoslit. See the electronic edition of the \( \textit{PASP} \) for a color version of this figure.

each \( N \)-slice onto the slit mirrors. Thanks to a tilt applied to each individual slice, the image of the \( N \)-slices on the slit mirrors are arranged along a line, forming a “pseudoslit.”

The spectrograph then images the entrance slit onto the detector after a passage through a dispersing prism, for constant and low resolution (\( R \approx 100 \)) and high optical efficiency. The spatial and spectral resolution are optimized to maximize the signal-to-noise ratio (S/N) for the faint object (SNIa up to 26 mag at \( z = 1.7 \)). The spatial resolution is of 0.15 arcsec\(^2\).

The slit is imaged on 2 pixels in the visible, and only on 1 pixel in the IR to enhance S/N performance. Each slit thus covers 20 pixels in the spatial direction, and 1(2) pixel for IR (visible) in the dispersion direction. The spectrograph illuminates two HgCdTe detectors from Teledyne working from 1–1.7 \( \mu \text{m} \) and two visible CCD detectors from Lawrence Berkeley Laboratory (LBL) covering 0.4–1 \( \mu \text{m} \). The total size including detectors is \( 230 \times 250 \times 100 \) mm, for a weight of 10 kg; very small and compact, and thus well adapted to space.

Finally, the telescope point-spread function (PSF) is optimized to be diffraction limited at 1 \( \mu \text{m} \). The slicer sampling is optimized to have the size of the PSF FWHM at 1 \( \mu \text{m} \). Then, the PSF core, which is cut by the slit, has a size smaller than the slit width when \( \lambda \leq 1 \text{ \( \mu \text{m} \)} \). In the visible range, the slit function (i.e., the spectral resolution element, resulting from the convolution of the slit width and the spectrograph PSF) is close to be well-sampled in the Nyquist conditions (since the slit width is imaged on 2 CCD pixels as explained in the paragraph above). In the infrared range, the slit function is sampled on only 1 pixel (since the slit width is imaged on one IR detector pixel), in a non-Nyquist condition (in this article, we will call it an “undersampled configuration”). Thus, the wavelength measurement will be more difficult to obtain than in the standard configuration. Finally, this implies that we will have to take the slit effect into account (see § 6), both in the visible and infrared, because the PSF is always smaller than the slit.

3. THE DEMONSTRATOR

In order to validate the instrument performance in situ, we have built a complete prototype of an integral-field spectrograph in the visible and infrared range (Aumeunier et al. 2006). The demonstrator characteristics are the same as those of the onboard SNAP spectrograph: low and constant resolving power and undersampled PSF in the infrared range. Table 1 summarizes the main specifications of the spectrograph on board SNAP and of the demonstrator. The two main changes are: the FoV has been reduced to five slices for practical accommodation, and the telescope aperture and pointing system have been replaced by a steering mirror with a diaphragm. The diaphragm aperture is chosen to reproduce the telescope PSF size in the slicer plane. The steering mirror is equipped with a servocorel motor working in real time, and can scan the complete FoV in the two directions with an accuracy better than 1/70 of a slice width.

The input source is a QTH lamp combined with a tunable monochromator which produces emission lines of 5 nm width. The line positions are known to 0.35 nm and the width to 2 nm. Finally, optical fibers placed at the monochromator exit allow collimated point-like sources. The details of the setup are presented in Cerna et al. (2008). The construction and assembly was done during 2006–2007. Figure 2 shows a photograph of the complete demonstrator optical bench.

We conducted two campaigns of measurements. The first one was done at room temperature using a CCD camera (Apogee Kodak), the second in a cryogenic environment in the infrared range using the latest available HgCdTe detector with 2 K \( \times \) 2 K, developed by Rockwell/Teledyne (Barron et al. 2007).

A commissioning campaign was done to test the functionality of the setup. The results, presented by Cerna et al. (2008), confirm that the setup was working well. We focus in this article on the wavelength calibration procedure, test, and results.

4. SIMULATION

We have developed a complete simulation of the instrument that takes both the optical and detector effects into account. This allows us to verify our understanding of the optics. The simulation was used first to prepare tests and procedures, and to compare experimental data to validate the optical design and performance.

The optical simulation of the instrumental response is based on the modeling of the optical response of a monochromatic
point source. Its intensity, size, and shape are driven by optical effects such as diffraction, aberrations, and distortions, and varies with the spatial position within the FoV and the wavelength (§ 4.1). Then, the PSF is sampled on the detector, taking the pixel response into account (§ 4.3). From these PSFs, we can reconstruct the images of spatially extended sources.

4.1. PSF Modeling

To model the demonstrator PSF, we used the optical ray-tracing program, Zemax, which is used classically to describe light ray propagation according to the principles of geometrical optics. We here used a recent extension of Zemax, named POP (Physical Optics Propagation), to take into account the diffraction phenomenon. POP models the optical system by propagating the wavefront. The beam is propagated through free space between optical surfaces using Fresnel diffraction propagation and, at each optical surface, a transfer function is computed which transfers the beam from one side of the optical surface to the other (Zemax User’s Guide 2005). It provides the beam amplitude and the phase shift for any optical plane of the optical system.

In the IFS slicer, the telescope PSF is shared out on \( N \) “slices” and each part of the telescope PSF inside the slices is then convolved with the spectrograph PSF. Figure 3 shows the simulated PSF in the exit focal plane of the spectrograph in the visible and infrared range. We look at the PSF spread out on five slices when the point source is located at the center of the central slice. At this point, the PSF is symmetric and the PSF core, with more than 50% of the intensity, is imaged on only one slice. The adjacent slices contain the PSF rings. To minimize the pupil-plane diffraction losses, the pupil mirrors of the IFS slicer are oversized by a factor two (the aperture ratio on the detector is then \( f/6 \)). This allows us to have a high throughput in the exit focal plane. By taking into account the nearest adjacent slices, we can then recover more than 90% of the incident flux for the shortest wavelength and more than 85% for the longest wavelength, for any location of the point source within the slitlet.

4.2. Discussion of the PSF Modeling

The main limitation of the POP tool is that the PSF modeling is very sensitive to the beam sampling and the matrix size in the pupil plane to translate to the Fourier space. Inadequate control of these input parameters can result in the aliasing phenomenon on the exit PSF. To validate the PSF modeling, we checked the POP estimates with software developed in IDL\(^4\). The complex amplitude is, in this case, propagated through each optical subsystem (i.e., telescope, slicer unit, and spectrograph unit) using the Fraunhofer approximation. The aberrations are thus modeled, in the pupil function of each optical subsystem, thanks to the Zernike polynomial, where the Zernike coefficients are provided by Zemax. With such a model, we know that some approximations exists: for example, the pupil aberrations are not propagated from one optical subsystem to another one, and they are computed only from a theoretical ray going through

\(^4\) Interactive Data Language.
the pupil center of each subsystem. Nevertheless, as the SNAP spectrograph is diffraction-limited, these approximations are minor and we can have confident in the results obtained with IDL to estimate the level of the “mismodeling” with POP. By comparing the PSF computed by the two methods on different optical planes, we found only a small difference on the detector plane where the PSF image of POP presents a low asymmetry in log scale. This is due to the aliasing phenomenon and slightly affects the PSF center at the level of a tenth of pixel and the PSF width at about 5 μm. That shows that to use the POP tool with confidence, we need to further improve the control of the aliasing phenomenon. Nonetheless, the difference is not really restrictive for our application.

We conclude that the knowledge of the PSF with POP is sufficient to validate the functionality of the demonstrator (alignment, focus). Our final choice to use POP is mainly driven by simplicity. POP is directly linked to the optical design of Zemax; we use only one tool and one language, which makes the implementation easier and minimizes the errors. At the end, it goes faster to set up and to generate a library of PSFs. We still have to take into account the pixel response. The effects on the undersampled PSF may be equivalent or larger.

4.3. Simulation of Detector Effects

To sample on detector pixels, the simulation includes pixel response effects such as quantum efficiency, photon noise, read-out noise, and dark current noise. Furthermore, using the measurements made at the University of Michigan on the Rockwell
H2RG #40 infrared detector used for the demonstrator, we have also taken into account the intrapixel sensitivity variation, the charge diffusion, and the capacitive coupling between pixels (Barron et al. 2007). These variables may have significant effects, in particular on the undersampled PSF. The lateral charge diffusion is simulated with an hyperbolic secant function: $G(r) = \frac{1}{\cosh(r/l_\text{d})}$ where $r$ is the distance from the pixel center. The diffusion length value used is $l_\text{d} = 1.87 \text{ \mu m}$. The capacitive model assumes equal coupling to each of the four neighbor pixels and negligible coupling to the corner pixels (Brown et al. 2006). The coupling coefficient implemented in the model is 2% (Barron et al. 2007). Figure 4 shows the PSF computed from the optical simulation and the final PSF convolved with the pixel response. We see that the charge diffusion and the capacitive coupling affect mainly the PSF broadening (of around 1/6 of a pixel) but have insignificant impact on the line centroids. Consequently, we have to take these effects into account to compare the simulated and experimental PSF width, but this would not impact strongly the wavelength calibration.

4.4. Simulation of Extended Sources

The PSF gives the image on the detector for a monochromatic point-like source. For the demonstrator, we need to simulate the image of spectrally and spatially extended sources. These extended sources have been characterized by a brightness profile that describes the intensity distribution in the object plane. The image on the detector of such a source results from the convolution of the PSF with the surface brightness profile. To do that, we generate a library of PSF computed at different positions ($x, y$), and wavelength $\lambda$. Then we can extrapolate the PSF at any entrance point from this library. To be perfectly exact, we would have to extrapolate both the PSF shape and its intensity. However, the shape of the demonstrator PSF varies slowly, and it is sufficient to take the PSF shape of the library computed at the nearest source point ($x, y, \lambda$). Then we fit only the PSF intensity of the library as a function of the point source position and the wavelength, using a neural network (Tilquin et al. 2006). For the PSF library of the demonstrator, we generate 15000 images covering all the FoV (5 slices) and the wavelength range [0.43–1.7 \text{ \mu m}].

4.5. Conclusion

To completely validate the simulation, we have compared the PSF modeling with the demonstrator data. We have focused the tests on the infrared range where the pixel response is well known and can be taken into account in the model. Averaging over all the wavelength, we have recovered the PSF width with an accuracy of 1/6 of a pixel, taking into account the lateral charge diffusion and the capacitive coupling. The difference is due to a light defocus around $\approx 30 \text{ \mu m}$ above the focus specification of 50 \text{ \mu m}. This shows that we have a good understanding of the PSF and of the effects that can degrade the measurements. This comparison with real data shows that we can confidently use the simulation to test and develop procedures for instrument calibration and data reduction.

5. WAVELENGTH CALIBRATION

In this section, we describe the wavelength calibration procedure developed for the demonstrator using spatially extended sources (defined in § 5.2).

5.1. Principle

The spectrograph specifications for SNe, galaxy redshift, and spectro-photometry calibration presented in § 1 have led us to require a 1 nm level of precision on all wavelength ranges for the demonstrator. Figure 5 shows the shift of the light (of the detector, in pixels) for 1 nm of spectral deviation. In the visible range, the resolving power varies and is higher at shorter wavelengths; thus, 1 nm is covered from 2 pixels to one tenth of a pixel. The specification of 1 nm is then easier to reach at $\lambda < 500$ nm, where 1 nm is associated with a shift greater than 1 pixel. In the infrared arm, where the resolving power is flat of around 100, 1 nm always corresponds to a tenth of a pixel and at first sight, it will be more difficult to achieve the 1 nm of accuracy.

However, we have found with the simulation that it is possible to accurately recover the centroid of the emission lines for
the spatially extended source despite of the low resolving power, due to the special instrument configuration. Indeed, the lines of the extended source are broadened by the convolution with the slit function; this is our term for the instrument response after uniformly illuminating the entrance slit with a monochromatic source (namely, the slit function results from the convolution of the slit width with the PSF of the spectrograph). Even if the PSF is subsampled (around 1 pixel at 1 μm), as the FWHM of the PSF is equivalent to the slit width, the slit function spreads it at least over 2–3 pixels. This helps us to determine the spectral line center of the extended source on the detector, with a simple barycenter.

We have thus checked these performances to fit the dispersion curves from the demonstrator data (this section). In § 6, we will focus on the wavelength measurement of a point-like source, and we will show how to correct the slit effect. Here, we will not particularly address the case of an extended source, as it is a direct extension of the sources used to set the dispersion curves and they are less affected by the slit effect, since the entrance slit is lighted uniformly or in a symmetrical way.

5.2. Data Campaigns

The two campaigns of the demonstrator have been mainly driven by developing the spectro-photometric calibration adapted to the slicer spectrograph. To do the wavelength calibration, we used a standard emission line determination procedure. The emission lines are produced by using an halogen lamp combined with a monochromator. Such an illumination unit provides fine and accurate emission lines (0.35 nm of precision on the wavelength value with a 2 nm width) and prevents us from using blended lines that are more difficult to use in a low-resolving power configuration. To be independent of the source position in the entrance slit, we use extended spatial sources. As we cannot have directly extended sources with the demonstrator, we have “created” spatially extended sources by taking many images of the same point-like source scanning the FoV. But to minimize the acquisition time, the extended source covers only the central part of the FoV. Figure 6 shows the resulting image for a set of emission lines in the visible range.

The first campaign of the demonstrator at room temperature provided 23,000 CCD images in the visible range. The image processing is classical: we subtract a sky image, taking into account both the possible parasite light of the environment and the electronic noise of the CCD. For the second campaign at 140 K, we took 7000 infrared images, using a last generation Rockwell detector HgCdTe. The readout electronics was developed by the IPNL laboratory. We used a Fowler(N) sampling method. Fowler sampling data consist of a reset followed by multiple initial readouts (N frames or one burst), then an exposure, completed by an equal number of final readouts (N) (Fowler & Gatley 1990). The final image results of the difference between the mean of the two bursts of N frames. We correct each frame for bias (using a map of reference pixels), quantum efficiency, and conversion gain, and we correct the brightest pixels using a reference mask of hot pixels. We estimate the error of each pixel using the Poisson distribution.

5.3. Dispersion Curve Determination

The emission lines with well-known wavelengths are used to fit the dispersion curves. The spectral dispersion curves describe the relation $\lambda = f_{x_d}(y_d)$ at a given position $x_d$ between a wavelength at a detector pixel where $x_d$ is the position along
the spatial direction (detector rows) and \( y_d \) is the position along the spectral dispersion direction (detector columns).

Generally, the spatial distortions (iso-\( \lambda \) curves along the spatial direction \( x_d \)) are fitted to adjust the spectral dispersion curves along the spectrograph entrance slit. As shown in Figure 6, for the demonstrator, the spatial distortions are linear for a FoV of five slices (around 150 pixels). We observe also that the spatial distortions inside one slice (imaged at around 20 pixels) are negligible (less than 1 pixel). We choose then to use an original procedure that does not require us to fit the spatial distortions: we choose to fit one spectral dispersion curve for each slice, and as the spatial distortions are negligible in one slice, we fit only the spectral dispersion at the slice center. That means we have to determine five dispersion curves for the demonstrator.

Figure 7 shows the experimental dispersion curves fitted at the center of the five slices in the visible and the infrared range. We use a simple polynomial function of 5(3) orders respectively in the infrared(visible) range. Only eight emission lines separated by about 100 nm in the spectral range [900–1600 nm] have been used to fit the dispersion curves in the infrared range. In the visible range, where the resolving power changes, we use 10 emission lines in the spectral range [450–900 nm] by steps of 50 nm. The experimental curves have been compared with the simulation and have been found to be in a complete agreement at the 95% confidence level. This validates both the simulation and the experimental measurements.

6. WAVELENGTH MEASUREMENT OF A POINT-LIKE SOURCE

To test the accuracy of the calibration at the nanometer level, the dispersion curves have been used to measure the wavelength of a point-like source. Point-like sources, contrary to spatially extended sources, are sensitive to the positioning inside the slit. We therefore tested the ability to recover a line position without
an a priori knowledge of the source position in the visible and the infrared ranges.

An image slicer spectrograph has the same properties as a classical slit-spectrograph. In particular, the off-centering of a point-like source inside the entrance slit can create a shift of the line center on the detector. This is classically called the “slit effect” and can lead to an error on the measured wavelength.

We first estimated the slit effect using the simulation. We represent in Figure 8 the deviation of the measured wavelength compared to the true one in nanometers, when we move the point source inside the slice (e.g., in the slit): on the center of the slice, we recover the position within the specification (1 nm), but, close to the slice edges, we observe large discrepancies (up to 4 nm). In the infrared, as was shown in Figure 5, the resolving power is constant and 1 nm corresponds to 1/10 of a pixel. When changing the position inside the slit, the PSF is cut differently and the position can be shifted up to 4 nm. In the visible range, where the resolving power varies, the deviation depends more on the wavelength and increases when the resolution decreases. In this case, the error depends on the PSF size and on the position. Only low wavelength values where the resolution is high and the PSF is small are included in the specification. In other cases, the resolution decreases faster than the PSF increases, which translates to an evolving slit effect.

It is then clear that to be able to recover accurate wavelength values, we need to correct or control this effect for all wavelengths. We have thus developed a procedure that can recover a good accuracy thanks to the slicer properties.

6.1. Method

In a slit-spectrograph, the only way to correct the slit effect is to accurately know the position inside the slit. Nevertheless, in a spatial environment, we would like to relax on the requirement of the telescope pointing system. With a slicer, we can use the information of each slice to correct the slit effect and improve significantly the line determination without knowing the position of the object.

As the PSF spreads out up to five slices, we can find back the spectrum of the point-like source up to five slices on the detector. Instead of using one spectrum in the central slice, we can use the spectra imaged on different slices.

Thanks to the slicer “cut-out,” the PSF intensity distribution from one slice to another will vary with the point source position. This helps to recover the relative position of the point source onto the slicer plane by looking at the flux distribution between the slices. The result of the averaging is that we recover the position without knowing the light source position inside the slit, and so correct the slit effect without any new procedure or mechanism.

Furthermore, another advantage of this method is that the sampling of the spectrum on each slice is not the same in both the spatial and the spectral directions thanks to the spatial distortions. Averaging the spectra on five adjacent slices could act also like a “spatial or spectral dithering.” Also using the demonstrator data, we have tested the spatial dithering technique improvement compared to the average of the spectra on slices to achieve the required accuracy (§ 7).

7. RESULTS

We present now the measurement of “monochromatic” emission lines sources in the visible and the infrared range. To quantify the accuracy, we compute the difference between the true wavelength \( \lambda_t \) and the extracted wavelength \( \lambda_e \) of the observed emission lines: \( \Delta \lambda = \lambda_t - \lambda_e \). This absolute error \( \Delta \lambda \) is expressed in nanometer. This error includes both the error due to the accuracy of the dispersion curves and the error due to the accuracy of the lines center determination on the detector.

Practically, for \( N \) slices (\( N \leq 5 \)), we use a barycenter to extract the line center on the detector and we deduce the associated wavelength \( \{ \lambda_i \}_{1 \leq i \leq N} \) from the spectral dispersion curves. Then we deduce the final wavelength by averaging the \( N \) wave-
lengths \( \{ \lambda_i \}_{1 \leq i \leq N} \) weighted by the flux measured in each slice. We estimate first the error \( \Delta \lambda \) for a classical slit-spectrograph method, considering only the spectrum in one slice (central slice). Then we take the average of the wavelength extracted from each slice as explained previously.

Furthermore, the exposure time for the demonstrator has been adjusted to have a S/N of around 20–30, as required for SNe. In this way, we have enough flux in each slice to make the average of the spectra.

Figures 9 and 10 show the result as a function of the wavelength at two positions in the slice (slice center and edges) both for the visible and infrared ranges. At the slice center, averaging three slices has no impact on the error since we do not need to correct the slit effect. In contrast, on the edge, the value is shifted as expected by the slit effect and the averaging of the spectra on three slices allows recentering in the specification. In the visible range, we see that the slit effect increases with the wavelength, due to the resolving power, and it should be corrected. In the infrared range, as the resolving power is constant, the error due to the slit effect is constant over all the range (about 4 nm) and is also corrected to better than 1 nm.

We have observed that averaging of the spectra on five slices does not improve the accuracy on the wavelength. On the contrary, in the infrared range, the mean of spectra on five slices brings more error than the level of improvement since the most distant slices are dominated by the noise.

In Figures 11 and 12, we represent the error as a function of the slice position and compare it with the simulation both in the visible range at 610 nm and in the infrared at 1230 nm. We observe the same behavior at the center and edge of the slice: the simulation is in good agreement. Surprisingly, the error on the wavelength seems better with the demonstrator. We explain this deviation by the asymmetry of the simulated PSF which is responsible for at least 1/10 of the pixel shift on the PSF center (as we have detailed in § 4.2). This phenomenon can explain the observed fluctuations with the simulation.
Finally, we have also tested the “spatial dithering” technique. We simulate the spatial dithering by combining four images of one point-like source shifted in the FoV. The shift is in accordance with the jitter telescope (random shift with a Gaussian distribution of 0.03″ rms [root mean square]). The wavelength is computed from the average of the extracted wavelength of the four images. Figure 13 shows the measured error obtained with the demonstrator as a function of the wavelength when we apply the spatial dithering technique and when we do not, compared to the result of the three slice averaging. We observe no improvement on the measured error with the dithering technique.

We conclude that averaging the spectra on three slices is sufficient to achieve the expected accuracy, since averaging the three spectra acts as a spatial dithering. This works for a S/N of 20–30 by spectral bin at any position in the slit. For low S/N, when the point source is at the slice center, there is a very small amount of light inside the neighbor slices, but there is no slit effect, so no correction is needed and the average method is not required. When the point is not located at the slice center, the incident flux is shared on at least two slices, then the slice average method can be applied in most cases. Nonetheless, for the faintest objects, the random spatial dithering could improve the signal in each slice. This is not an extra constraint since it exists naturally with the telescope jitter and the two methods will be very complementary.

8. CONCLUSIONS

With the demonstrator, we have been able to prove that we can measure wavelengths at a precision of 1 nm in the visible and infrared ranges within the SNAP specifications, and this despite the low resolving power and the subsampled configuration in the infrared range. For spatially extended sources, we have shown that the emission lines on the detector are broadened by the convolution of the slit width with the spectrograph PSF. This improves the wavelength measurement compared to the low resolving power. For point-like sources, we have proved that it is possible to correct the slit effect thanks to the slicer properties, using the fact that each slice provides one spectrum of the source on the detector. We have also shown that, as soon as there is enough light on more than one slice, the spatial dithering is not needed since the averaging of the spectra on three slices allows measurement of the wavelength of emission lines with an accuracy better than 1 nm, even in a subsampling condition.

The proposed procedure does not require us to know the position of the source, or to extract it precisely inside a slit. This means that, thanks to the slicer, we can also relax the requirement of the telescope pointing system. In a long-slit spectrograph, the telescope should be pointed at 0.01″ to achieve
1/10 pixel precision. In a slicer, we can relax this requirement without necessarily degrading the accuracy of the wavelength measurement. This simplifies the calibration procedure without adding any procedure or mechanism. All these results have also been checked with the detailed simulation of the instrument, which will be a good tool now to develop a detailed data reduction.

This last result allows us to be confident about the extraction of emission lines in a subsampling configuration when we use a slicer. The redshift, measured from the galaxy emission lines, can be thus recovered with extended source at better than \( \approx 0.003 \times (1 + z) \) in all configurations (visible and infrared). Furthermore, using the slice average method, we have shown that a point-like source line can be also measured at 1 nm of precision. That means, for SNe, that we expect to be able to measure the Si II absorption feature of SNe Ia at a precision of \( \approx 400 \text{ km s}^{-1} \) throughout the redshift range. This should help the spectro-photometry calibration of stars at 2% accuracy, which will be addressed in a future article.

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