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NANO-VIPA : A MINIATURIZED HIGH-RESOLUTION ECHELLE SPECTROMETER, FOR THE MONITORING OF YOUNG STARS FROM A 6U CUBESAT

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INTRODUCTION

We introduce to astrophysical instrumentation and space optics the use of Virtually Imaged Phased Array (VIPA) to shrink échelle spectrographs and/or increase their resolution. The VIPA resembles a Fabry-Pérot etalon which, for an equal size, can be seen as an angular disperser with much greater dispersive power than common diffraction gratings. VIPA has already been much effective in various fields of research such as frequency comb spectroscopy [1], hyperfine wavelength demultiplexing [2,3], trace gas detection [4] and Fourier Transform pulse shaping [5]. Here, we report on both laboratory tests of a R=200000 spectrograph and on the design of a R=50 000 (@653nm) spectrograph which fits a 6U nanosatellite platform (1U= 10cm x 10cm x 10cm). The outline of our paper is as follows : in Part I, we make a theoretical presentation of the VIPA and describe an implementation in a cross-dispersed spectrometer. Part II shows the first results at R=200 000 we already achieved at the Institut de Planétologie et d'Astrophysique de Grenoble (IPAG). In part III, we present the science case of monitoring young stars that an early implementation would offer onboard a nanosat, and we briefly note the wider science landscape amenable with larger telescopes. Finally, part IV describes an actual design of a 6U satellite with a VIPA-based echelle spectrograph.

I PRINCIPLE OF A HIGH-RESOLUTION AND HIGH-THROUGHPUT ECHELLE SPECTROMETER BASED ON THE VIPA.

A. VIPA : Virtually Imaged Phased Array

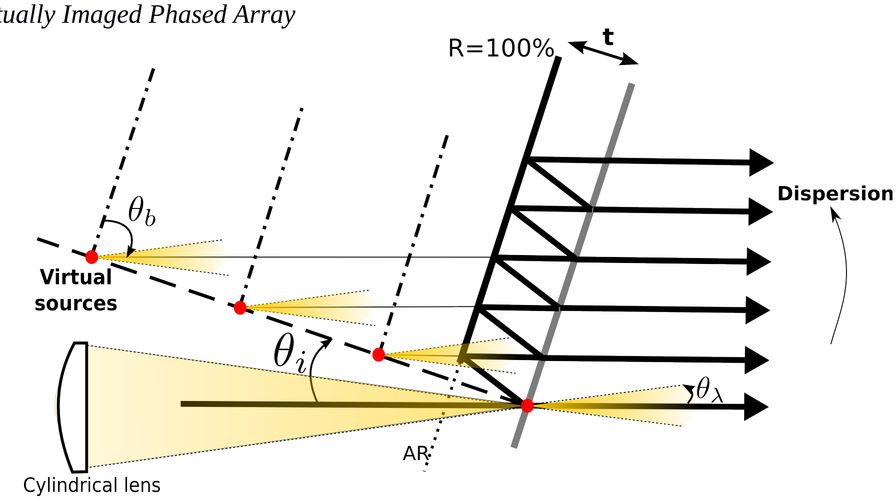


Fig. 1. : VIPA geometry, showing the multiple bouncing on the reflective plate and the equivalent virtual sources

The VIPA consists of two reflecting plates, as in a Fabry-Pérot etalon, of which the entry side (or back side) is coated with a nearly 100% reflective film except for an entrance window with antireflective coating (AR), and the exit side (or front side) which is coated with a partially reflective film (typically >95%). The space between the two reflecting faces can be filled with either air (air-spaced VIPA) or glass (solid VIPA) of optical index n. As it is represented in Fig. 1., a collimated input light is line focused with a cylindrical lens into the etalon, and experiences multiple reflections between the two reflective sides. Away from the front side these multiple beams interfere such that different wavelength propagate in different direction, much like a diffraction gratings [2, 6, 7]

Considering the virtual sources of Fig. 1., by analogy with the diffraction grating, the angular dispersion of the VIPA is proportional to $\tan(\theta_b)=\tan(\pi/2-\theta_i)=\cot(\theta_i)$. For $\theta_i=4°$, this factor is ~21.4 for a standard solid VIPA in fused-silica, whereas it is ~7.5 for a high-dispersive échelle-grating (blaze angle=75°) [2].

Thus, the crucial parameter of the spectrometer is the value of θ_i : the smaller θ_i is, the greater angular dispersion we have. More precisely, according to [7], the angular dispersion of the VIPA based on the paraxial wave theory is :

$$\frac{d\theta}{d\lambda}=\frac{-1}{\lambda_0(\tan(\theta_i)+\theta_\lambda)} \tag{1}$$

However, θ_i has a minimum value, below which the entry beam is vignetted by the AR window. During the design of the spectrometer, a compromise has to be found between the beam diameter of the input light, the thickness of the étalon, and the dispersive power of the VIPA, which is driven by θ_i .

B Properties and design of an echelle-spectrometer based on the VIPA

In such a spectrometer, the input collimated beam feeds a cylindrical lens, focusing the light on the VIPA. After the transmission side of the VIPA, the light is cross dispersed by a diffraction grating and focused on the detector, as shown in Fig.2. In our own instrument (Part II), the instrument was fed by a collimated optical fiber, and we used a blazed diffraction grating as a cross disperser.

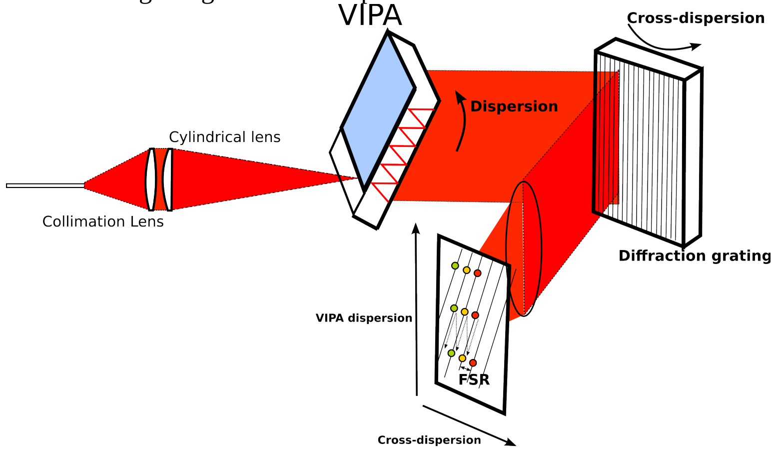


Fig. 2 : Principle of an échelle-spectrometer based on the VIPA. The optical design is analog to that based on a classical échelle-grating.

By replacing a common disperser (prism, or blazed diffraction-grating) with the VIPA - all other things being equal - the resolution (or respectively the compactness) will increase in the same proportion as the angular dispersion.

One other major advantage of the VIPA is his throughput : as the back side of the VIPA is 100%-reflective coated, the finite size of the beam and the finite angular spreads theoretically ensure that all the entrance light is transmitted to the detector. In fact, as the back side can't be 100%-reflective, the transmission depends of the reflectivity of both plates, assuming the equation T=(1-R2)/(1-R1R2) [8]. For our standard commercial VIPA, we measure a transmission of ~60% (and a global transmission of the instrument of ~10% with an instrument which can be optimized) : these preliminary results will be detailed in Part II. Thus, the VIPA seems to have a similar or better transmission than a classical échelle-grating.

Furthermore, contrarily to a diffraction grating which requires a high precision engraving, in the VIPA the virtual sources are “self-aligned” : the quality of the interference pattern relies only on the finesse of the VIPA (defaults in the reflectivity, parallelism, or irregularity of the plates), which seems easier and cheaper to produce than common diffraction gratings.

Finally, the optical design of such a cross-dispersed spectrometer is analog to that of an échelle grating spectrometer.

Design : First of all, the dimension of a pixel have to be compared to the dimension of the finest spectral element resolved by the VIPA. According to the Shannon criteria, we have :

$$2\,pix=f\,\frac{d\theta}{d\lambda}d\lambda \tag{2}$$

,where $d\lambda$ is the spectral bandwith of a pixel, f the focal of the projection lens, and pix the size of a pixel. As the resolution of the spectrometer has to be pixel-limited, the FWHM (in wavelength) of a transmitted peak of the VIPA has to be equal or smaller than the spectral bandwith $d\lambda$ of a pixel, fixed by his size . Finally, the *effective* resolution of the instrument in the case of a pixel-limited resolution is :

$$R_l = \frac{f}{(2\,pix(\tan(\theta_i)+\theta_\lambda))} \quad (3)$$

Thus, if the resolution of the VIPA R_{vipa} is greater than R_l , the resolution is pixel limited, otherwise the resolution is limited by the VIPA. Given that the ray-based analysis applies to the VIPA [9], the resolution of the VIPA follows the same equation than that of a Fabry-Pérot : $R=\lambda/d\lambda=pF$, where p is the interference order and $F=\pi\sqrt{(R)}/1-R$) the finesse of the VIPA : for a miniaturized instrument (small f), the resolution of the VIPA can be much greater than the pixel-limited above.

According to the law of dispersion of the VIPA, it may be noted that for small angles (<5°), a smaller value of θ_i will increase the angular dispersion of the VIPA, and possibly the resolution of the spectrometer, but not the resolution of the VIPA itself, which is equal to $pF=2t\cos(\theta_i)F/\lambda\approx 2t\,F/\lambda$. Hence, if the FWHM of the VIPA is much smaller than the spectral bandwidth of a pixel (which is not the case in a design, because of the loss of flux and possible Moiré effect), the resolution of the *spectrometer* could increase with a smaller θ_i ; otherwise, it will remain constant.

At last, it may be noted that the choice of F and t to achieve the resolution $R=pF$ has to be done carefully : indeed, a compromise has to be reached between the thickness t , θ_i , F_{cyl} (focal of the cylindrical length) and W (radius of the incident collimated beam prior to the cylindrical lens), to ensure there's no clipping of the input light. Furthermore, F_{cyl} and W also have an impact on the line profile along the dispersion direction. Indeed, the profile of an order on the detector is a Gaussian distribution with standard deviation :

$$\Phi=2*f*W/F_{cyl} \quad (4)$$

This standard deviation has to fit the size of the detector.

C Free Spectral Range (FSR) and cross dispersion

As in a classical Fabry-Pérot interferometer, the thickness of the VIPA sets the FSR, according to the relation : $\Delta\sigma=1/(2t\cos(\theta_i))$, valid for the small angle (θ_i and θ_l). As this FSR is smaller than that of a diffraction grating, the dispersive power of the cross-disperser has to be greater that of a classical échelle spectrometer.

E Summary of the design

In conclusion, since the dimension of t , θ_i , F_{cyl} , f and of the detector size are strongly entangled, their choice has to reach a compromise between the resolution of the spectrometer and its compactness. As the VIPA has a greater dispersive power than common diffraction gratings, the échelle-spectrometer gains resolution for the same size than a classical échelle-spectrometer, or compactness for the same resolution. An example of such an instrument and its first results on the spectrum of the Sun is provided in the next part.

II EXPERIMENTAL RESULTS ON A DEMONSTRATOR WITH EFFECTIVE R=200 000

A. Description of the instrument

Such a miniaturized high resolution échelle-spectrometer has been designed and lined up at the Institut de Planétologie et d'Astrophysique de Grenoble (IPAG). The platform size is 120 x 30 cm. The instrument has been designed to achieve a resolution R=570 000 , and was realized with standard components from Thorlabs, a VIPA from the company Lightmachinery, an astronomical SBIG camera, and a refurbished blazed diffraction grating.

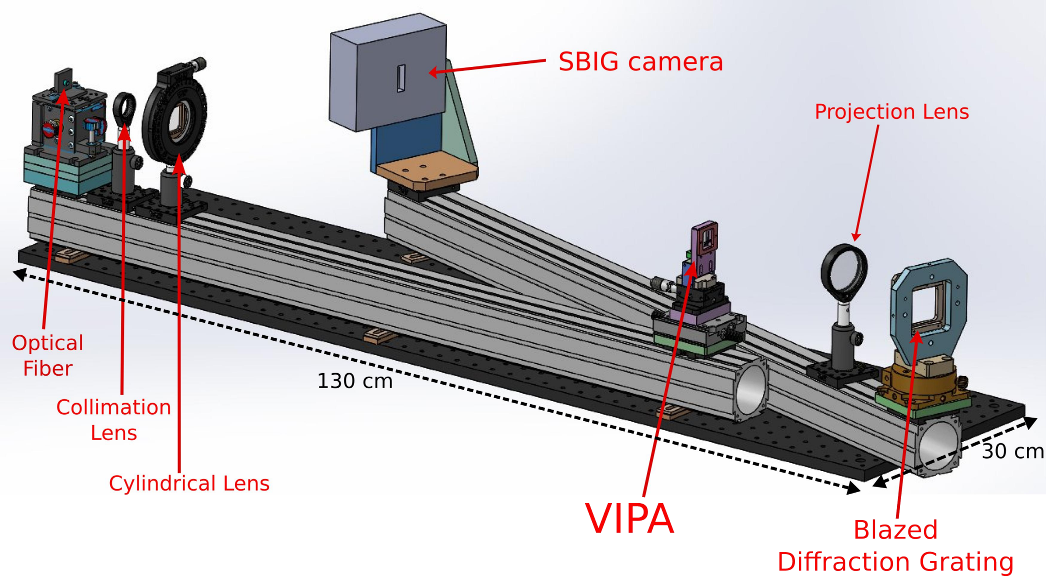


Fig. 3 : Model of the demonstrator intended to achieve R= 570 000

The VIPA has the following manufacturers specifications :

- Finesse =70
- FSR = 2.0 cm^{-1}
- thickness = 1.686mm in fused silica
- wavelength range : 600-725 nm
- θ_i = 4°

The focusing system has the following characteristics :

- single-mode optical fiber (mode-field diameter : 3.6µm-5.3µm, according to the Thorlabs specifications)
- collimation lens : Ø1” diameter with f=75mm
- cylindrical lens : f=700mm, H=30mm, L=32mm
- projection lens : Ø2” diameter with f=750mm

The current cross disperser is not optimized for our instrument : it is a blazed diffraction grating at **1µm** , with 600 lines/mm. The camera was a commercial SBIG CCD with a commercial Kodak KAF-3200ME, 2184 x 1472 pixels of 6.8 µm.

B. First results : Spectrum of the Sun with R=200 000

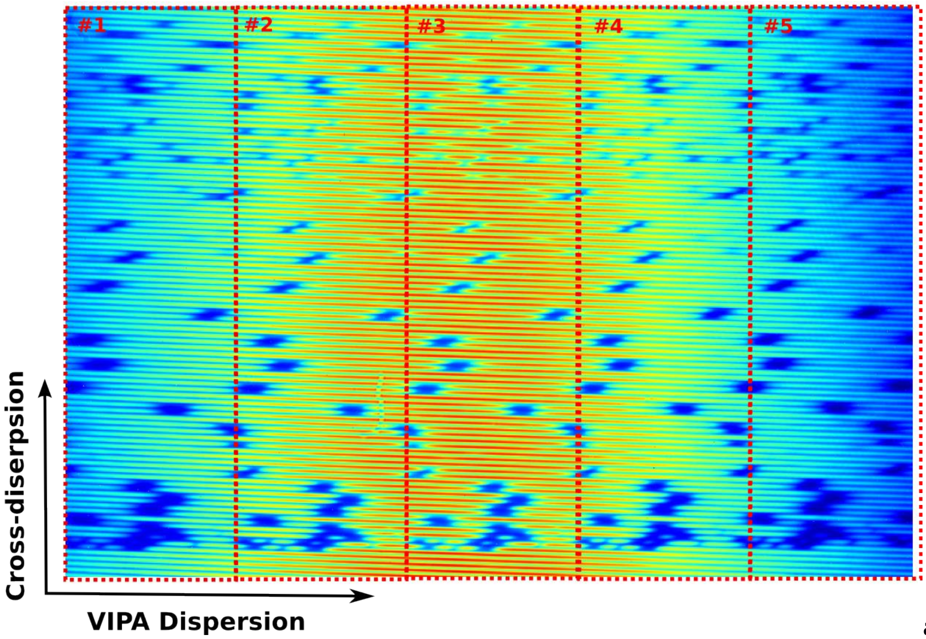
Our apparatus was linked with a single-mode fiber to a finder-scope with a diameter of 100mm. By comparing our spectrum to the Delbouille's reference spectrum of the Sun, and with simulated spectrum of the telluric lines above our observation site, we estimate to achieve a resolution R=200 000 (see Fig. 4 and Fig. 5). This value is more than twice smaller than the intended resolution, although the incidence angle of the VIPA of 4° and the optical collimation/focusing system ensures a good sampling of the spectrum, according the dispersion law of the VIPA and the pixel size. Given that our VIPA was a standard commercial components which was not calibrated, its finesse seems to be smaller than the manufacturer specifications. However, other parameters we yet have to identify may deteriorate the resolution of the instrument.

C. Photometry

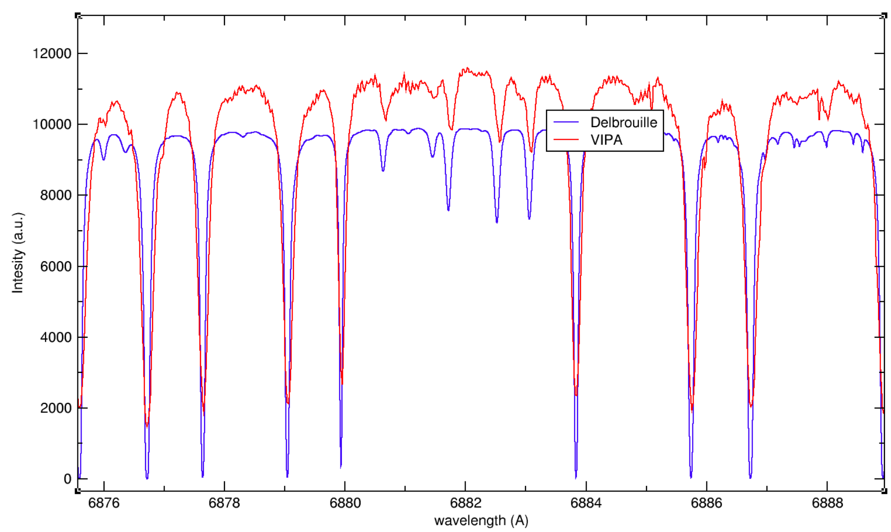
Preliminary results gives us a total transmission of 10%, and a total transmission of the instrument *without the VIPA* of 15%. These results do not take into account the loss in the fiber which feeds the instrument. These two results allow us to infer a transmission of the VIPA himself equal or better than 60%. It has to be noted that the transmission of the instrument is strongly determined by the quality of the injection of light in the VIPA. This result seems consistent with the properties of our instrument :

- the diffraction grating is blazed at *1µm* and is used with an incidence angle of 17° , which was not optimized for such an instrument : we estimate that about 30% or less of the incident light is reflected on the detector.

- given the size of the detector and the Gaussian profile of intensity on an order, 90% of the field is collected by the camera
- the quantum efficiency of the detector is 85%



a)



b)

Fig. 4a) : Extract of the spectrum of the Sun with the VIPA, in the region of the telluric oxygen lines. Each rectangle delimits the part of the spectrum of the Sun we observe : in this case, it is repeated 5 times (number of Airy peak of the VIPA on the detector, considering a monochromatic light), so the spectrum is repeated 5 times horizontally in these rectangles. **Figure 4b) :** Comparison with the reference spectrum of the Sun with R=1 000 000 (Delbouille L., Neven L., Roland G. (1972)). The data retrieval for this spectrum is the same than a classical échelle spectrum : after processing our image with a flat and a dark, each diffraction order (the horizontal lines on the image) are laid “end to end” to form the entire spectrum of the wavelength range considered. The only difference is that, as the entire spectrum is repeated 5 times horizontally (red rectangles), we average this 5 entire spectra. A comparison with the simulated atmosphere above our observation site is given in Fig. 5.

Hence, the throughput of this very first demonstrator is essentially limited by the cross-disperser, of which efficiency can be further increase. These first results and the physical structure of this Fabry-Perot interferometer allow us to say that the VIPA himself has a good transmission, which makes possible an échelle-spectrometer with similar or better luminosity than those based on a classical échelle grating, while providing high spectral resolution with a compact instrument. Taking advantages of the compactness of the VIPA and its very high resolution, these first results allow us to envisioned a range of instrument based on VIPA, from very high resolution on ground or in space – such as an instrument embedded on space telescope as James Webb

Space Telscope (JWST) - to a miniaturized échelle-spectrometer embedded in a nanosatellite. In the following part, we detail a science case which makes full use of this new opportunity, and, in Part IV, its possible design for a 6U platform.

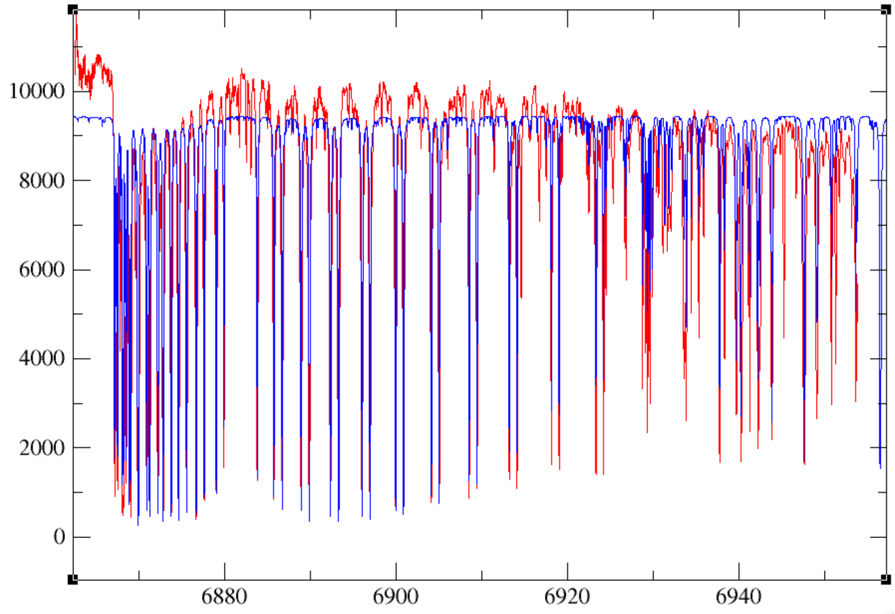


Fig. 5 : Complete wavelength range of the spectrum of the sun observed with the VIPA, and its comparison with a simulated spectrum of the telluric lines above our observation site, provided by the SkyCalc Sky Model Calculator (ESO).

III DESIGN OF A HIGH-RESOLUTION R=50 000 ECHELLE-SPECTROMETER FOR THE DEEP MONITORING OF YOUNG STARS IN A 6U PLATFORM

Young stars (T Tauri and Herbig Ae/Be stars), are still contracting and increasing their temperature to a point nuclear reaction can trigger in their core. In spite of the lack of nuclear reactions, these stars are emitting as much as, or even a larger, quantity of energy than normal stars, thanks to the gravitational contraction. Protoplanetary disks surround these stars in which planets are forming, and from which stars accrete gas and continue to grow. Close to the surface of the star (<0.1 ua), the accreting gas is heated by the star to large temperatures, and produces Hα line emission, which is the main observational criteria of these young stars. While Hα emission has been deeply observed in these objects, we do not understand how and where these lines are created. Many reasons can explain this paradox: (i) the shape of the lines is complex, indicating probably that more than one region is emitting in Hα with different physical, geometrical or dynamical properties, (ii) these lines can show strong variability on time scales of the order of hours to tens of days. It is however crucial to be able to understand the formation process of these lines at it would allow us to explore the most internal regions of these objects, still unreachable with high-angular resolving instrumentation, such as SPHERE/VLT or GPI/Gemini.

Spatial missions like Corot or Kepler allowed us for the first time to record quasi-uninterrupted light curves of young stars (Cody et al. 2014) and allowed considerable progress in our understanding of the photometric variability of these objects. In particular, it is now clear that in the young low-mass stars (T Tauri), the internal rim of the disk is not axisymmetric, can occult part of the star for certain line of sights, and that accretion is sporadic, irregular, and with a large disparity between two events (e.g. Souza et al. 2016). However, in the higher mass stars (Herbig Ae/Be), the picture is not that clear (e.g. Fairlamb et al. 2015). A few observational evidences may show that material from the disk could be accreted onto the star in the form of aggregate, proto-planets, or comets (e.g. Vural et al. 2014). To study the physical, chemical, and dynamical properties of accreted matter, we need high-resolution spectroscopy. High-resolution spectroscopy allows us to resolve in velocity individual lines and to identify their different components, and to study the chemical and physical properties of each component. Deep monitoring allows us to follow the temporal evolution of each component, and to perform tomographic images of the close stellar environment. Such imaging technique has started to be developed for the magnetospheres of massive stars (e.g. Grunhut et al. 2013). It has been successfully applied on ground-based data because the magnetosphere of massive stars are stable over decades. Sparse monitoring performed over many months or years are exploitable in those cases. In the case of young stars, each spectral event appear to be unique, and it is therefore necessary to follow it closely during its whole lifetime (of the order of days to weeks, e.g. Mendigutia et al. 2011, Alecian et al. 2013). However, such deep monitoring are almost impossible to perform from the ground, because of the day/night alternation and cloud coverage. It is therefore required to perform it from space.

Until recently such a project was impossible to perform because of the configuration of classical échelle spectrometers, too voluminous and heavy to be launched into space. The nano-VIPA, presented in this paper, provides us with an efficient solution at relatively low-cost, that can be considered to be launched into space and gives us the hope to make uttermost progresses in our understanding of the origin of the sporadic accretion onto young stars, on a relatively short time-scale.

We note that, on larger telescopes, other high-profile science cases can greatly benefit from our VIPA-based design. An exemple is the characterisation of exoplanet atmosphere through transmission spectroscopy. Indeed, as long as the individual spectral lines of the exoplanet atmosphere remain unresolved, which in practice means resolution up to R>500 000, the signal-to-noise of the detections is expected to increase both with the square root of the number of photons and with the square root of the spectral resolution. And therefore, whereas today the search for O2 in exoplanet atmosphere is believed to be at the limit of the forthcoming ELT capabilities [10], a higher-throughput / higher-resolution spectrograph such as a VIPA-based spectrograph might render that science case more practicable.

III EXTRAPOLATION TO A NANOSAT WITH R=50 000

A. Optical design

According to the equations (3) and (4), it is possible to reduce the dimension of the instrument with the same reduction factor as the resolution. A design is given in Fig. 6 and in the following table :

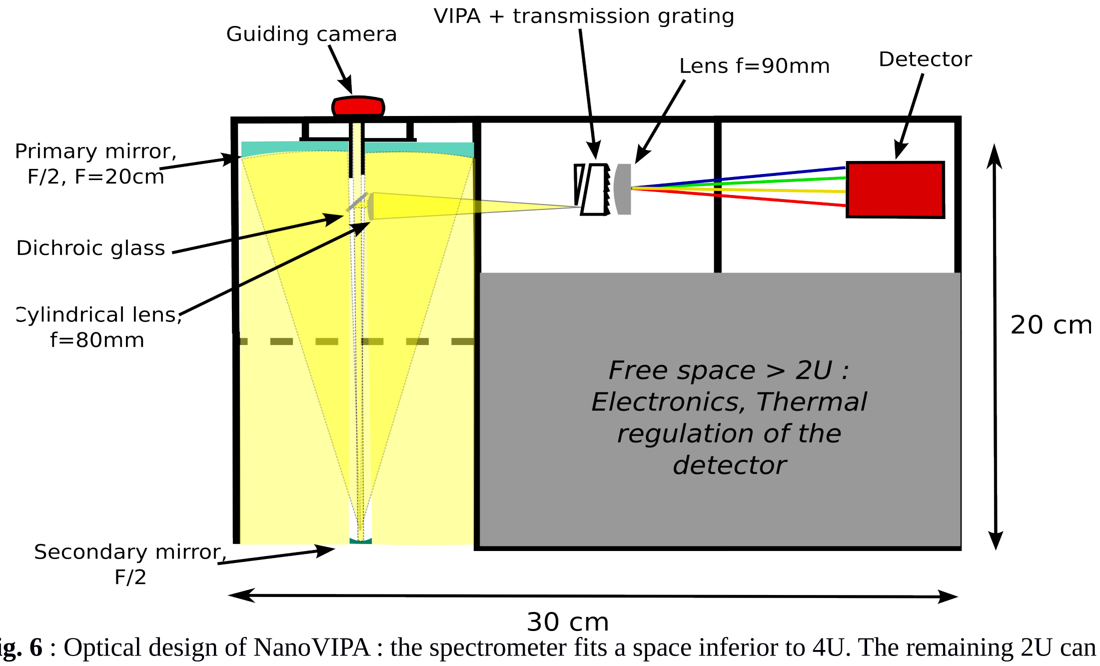


Fig. 6 : Optical design of NanoVIPA : the spectrometer fits a space inferior to 4U. The remaining 2U can be used to embed the electronics and the thermal regulation of the detector. The Guidance, Control and Navigation (GNC) system could be embedded in a surrounding 6U platform.

Afocal telescope and optics	VIPA , R=50 000	Detector
Primary concave mirror : Ø10cm, F/2, Secondary concave mirror : Ø 1 cm, F/2 Input beam radius : W=5 mm Input Cylinder Lens : F=80 mm Projection Lens : F=90mm	λ =653nm t=150µm, air-spaced $\theta_i = 5.1°$ Finesse : 110 FSR : 33cm-1 Vipa length >30mm Diffraction grating : 640 lines/mm	CCD height : 1125 pixels CCD width : 2200 pixels Size of a pixel : 10µm x 10µm Pixel bandwidth : 13.02pm

Assuming a general throughput of 30% for the complete instrument – this value could be possibly further increased with an optimized instrument – and a maximum exposure time of 1 hour with 3 electrons noise per pixel achieved with a thermal regulation of the detector, we obtain a Signal to Noise Ratio (SNR) superior to 30, which is the minimum to detect and analyze the fine structure of the Hα lines of young stars.

C. Critical points, further development

At this point, the instrument is no longer limited by the size of the spectrometer, but by that one of the telescope i.e the number of photons collected by the telescope. A significant critical point of the instrument will be the stability of the pointing device of the satellite, which will have to be on the order of 1 arcsec. Such a noise is not taken into account on the above photometric consideration of the SNR : we now have to design a stable pointing device for the satellite and estimate the noise related to the aiming. These considerations led us to allocate an entire 6U platform for a high-precision Guidance, Control and Navigation (GNC) system (leading us to a 12U nanosatellite, such as the ATISE mission, carried out by the Centre Spatial Universitaire de Grenoble [11]), and the possibility to incorporate an active optical system in order to limit the aiming noise.
The further development will consist in observing low-luminosity objects on ground-based telescope. These experiments will be led in parallel with the study of the fundamental properties (resolution, luminosity) of this new échelle-spectrometer, in order to improve the very first results presented in this paper.

V CONCLUSION

We have introduced the VIPA in the design of an échelle spectrometer for astrophysics, and demonstrated it has potentially similar or better performances than échelle grating spectrometer in terms of spectral resolution and/or compactness. Our first demonstrator has been designed and lined up at the IPAG and achieves a resolution R=200 000 and a throughput T=10%. Finally, we have presented a possible implementation for the nanosat standard 6U with R=50 000, with the monitoring of young stars as a first science case.

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