# ATISE: A MINIATURE FOURIER-TRANSFORM SPECTRO-IMAGING CONCEPT FOR SURVEYING AURORAS AND AIRGLOW MONITORING FROM A 6/12U CUBESAT

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## I. INTRODUCTION

The nanosatellite ATISE is a mission dedicated to the observation of the emission spectra of the upper atmosphere (i.e. Airglow and Auroras) mainly related to both the solar UV flux and the precipitation of suprathermal particles coming from the solar wind through the magnetosphere. ATISE will measure specifically the auroral emissions, and the airglow (day- and night) in the spectral range between 380 and 900 nm at altitudes between 100 and 350 km. The exposure time will be 1 second in auroral region and 20 s at low latitude regions. The 5 year expected lifetime of this mission should cover almost a half of solar cycle (2 years nominal). This instrument concept is based on an innovative miniaturized Fourier-transform spectrometer (FTS) allowing simultaneous 1 Rayleigh sensitivity detection along six 1.5°x1° limb lines of sight. This 1-2kg payload instrument is hosted in a 12U cubeSat where 6U are allocated to the payload and 6U to the plateform subsystems. This represents a miniaturisation by a factor of 500 on weight and volume compared to previous Arizona-GLO instrument for equivalent performances in the visible. The instrument is based on microSPOC concept developed by ONERA and IPAG using one Fizeau interferometer per line of sight directly glued on top of the half of a very sensitive CMOS Pyxalis HDPYX detector. Three detectors are necessary with a total electrical consumption compatible with a 6U nanoSat. Each interferometer occupies a 1.4 M pixel part of detector, each is placed on an image of the entrance pupil corresponding to a unique direction of the six lines of sight, this in order to have a uniform illumination permitting good spectral Fourier reconstruction from fringes created between the Fizeau plate and the detector itself. Despite a limited 8x6 cm telescope, this configuration takes advantage of FTS multiplex effect and permits us to maximize the throughput and to integrate very faint emission lines over a wide field of view even if the 1 second integrated signal is comparable to the detector noise.

## II. SCIENTIFIC GOALS AND MISSION REQUIEREMENTS

The science Requirements are :

- producing 6 contiguous 1.5°x1° field of view
- with a spectral domain between [350,900nm]. This allow to get the main part of the Vegard Kaplan N2 band in the lower part of the spectra and to get the O-844 nm line which is important in auroral region.
- The spectral resolution at 600nm must be lower than 1nm. Hence : $R=\lambda/\delta\lambda=600$ at 600nm. This allow to disentangle the vibrational line of the molecular bands. The rotational structure is not reachable at these spectral resolution.
- The detection threshold of each line must be 5 Rayleigh ($1\ R = 1.10^6$ photons.cm-2.s-1) and the sensitivity 1 R.

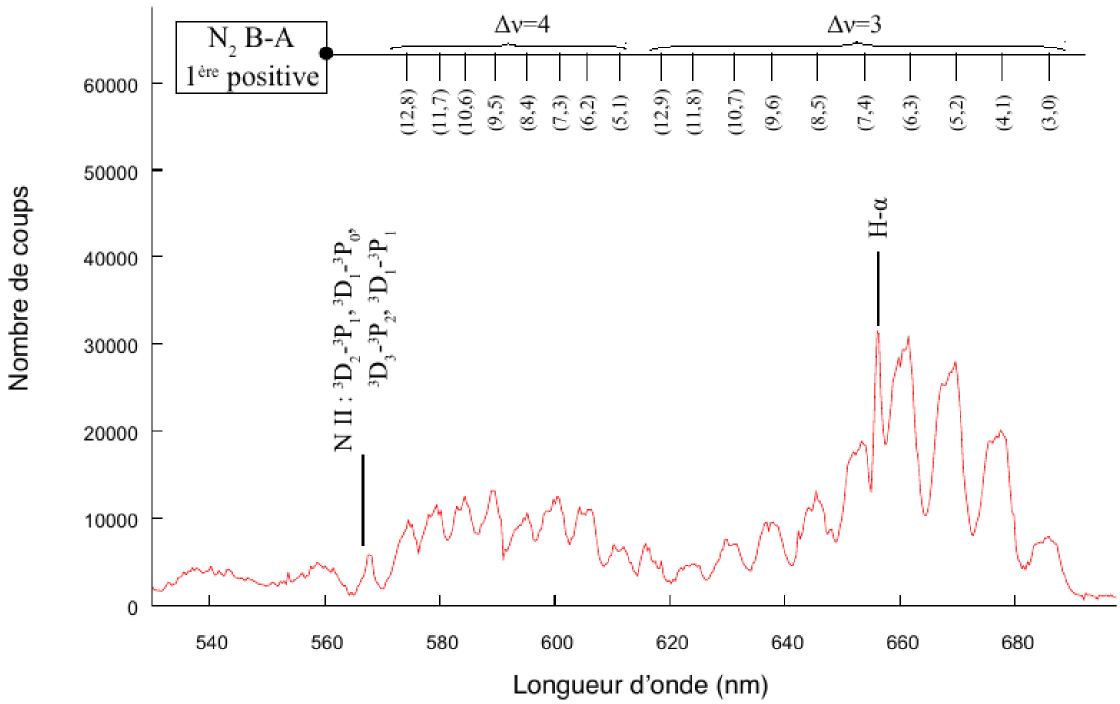


**Fig. 1.** Spectrum of the auroral simulator planeterrella (ref papier Jean) between 520 and 700 nm. The resolution is around 1 nm. The spectrum of the aurora is somehow different since forbidden transitions also appear in aurora and airglow mainly $O^1S$ at 557 nm and $O^1D$ triplet at 630, 639 and 639 nm

## II. INSTRUMENT PRINCIPLE AND DESCRIPTION

ATISE instrument is based on the MICROSPOC principle that was described in [1] by S. Rommeluère & al. It is made of a two-wave interferometer glued in front of the detector. Rays coming from infinite are partly reflected by the detector face and the substrate face as illustrated in fig. 3a make interferences detected by the active layer of the detector. Contrarily to a classic optical instrument, the goal of ATISE is not to make an image of each field of view, but to obtain an area which is uniformly illumined on each detector (those area on the detector are called "plage de Fabry" [2]). To this end, the optical instrument can be viewed in two parts : first, a system focuses the entire field of view on the focal plane. In those 6 areas, we Micro lenses divided then the input light in 6 contiguous field. These micro lenses are positioned to project an image of the entrance pupil on the detectors. Thus, we obtain on each detector uniformly illumined area of each field, which are perfectly delimited, due to the pupil imaging through micro-lenses. As we will see further, the aperture (which is characterized by the f-number : N=focal/diameter) of the micro-lenses is the fundamental parameter of the design of this instrument. The aperture of the beam is yet strongly related to the nature of the spectrometer and to the expected spectral resolution.
A µ-SPOC Fourier transform spectrometer is selected, in accordance with the mission specifications. This miniaturised Fizeau interferometer use the principle of Fourier Transform spectroscopy to produce spectra, that we are going to explain and illustrate in this paragraph.

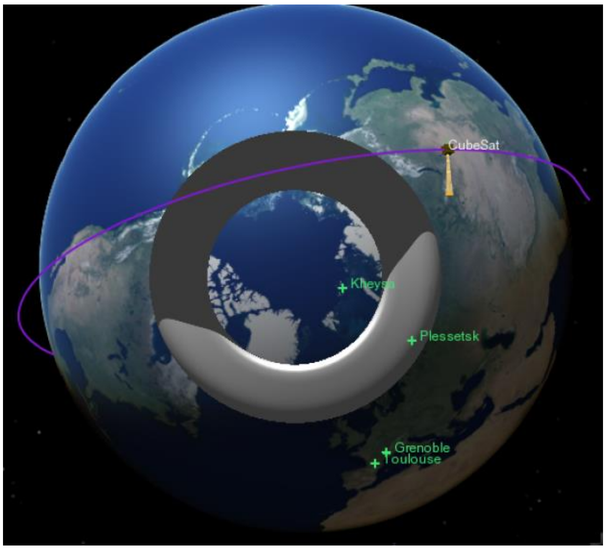


**Fig. 2.** ATISE will observe aurorae on 70° inclined orbit at an altitude around 650km

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*A. Optical design*

Main entrance lens is 81x69 mm wide with 650mm focal lens focalizing 6°x1.5° field of view focal plane after 3 reflections on folding mirrors. In the focal plane, a line of six 19x12mm lenses integrates flux on each 1x1.5° sub field of view, each of them making an uniform image of entrance pupil with flux integrated in each field. Fig 4b shows these illuminated zones on the three detectors assembled contiguously. The instrument strength is to maximize optical acceptance of spectrometer up to the spectral resolution limit. For this geometry, an auroral 1 Rayleigh emission gives 1500 photons integrated on 1400x1088 detector zone. We will show further that it is compatible with the goal of 5 Rayleigh sensitivity for 3e RMS of detector including 1s dark current (total RMS 3e).

*B. Mechanical design*

Fig. 3. shows a sketch of 6U ATISE payload with 2U dedicated to field imager, on board electronic. During next study phase, all optical part support and baffles will be designed. Detectors need to be regulated at 0°C +/- 0.1.

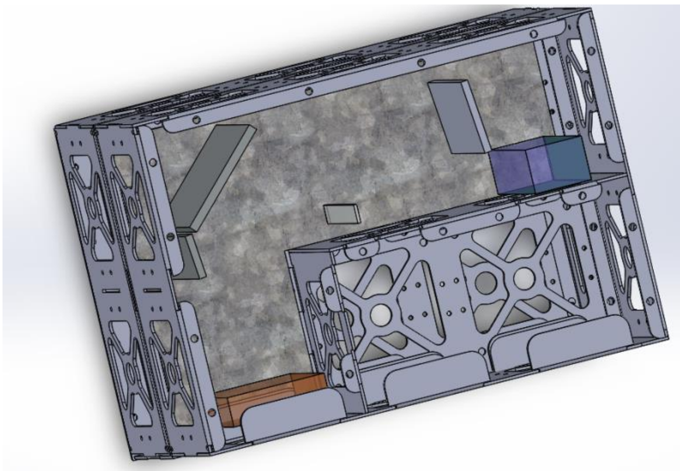

**Fig. 3**. ATISE Mechanical implementation for optical test assembled with 6U plateform.

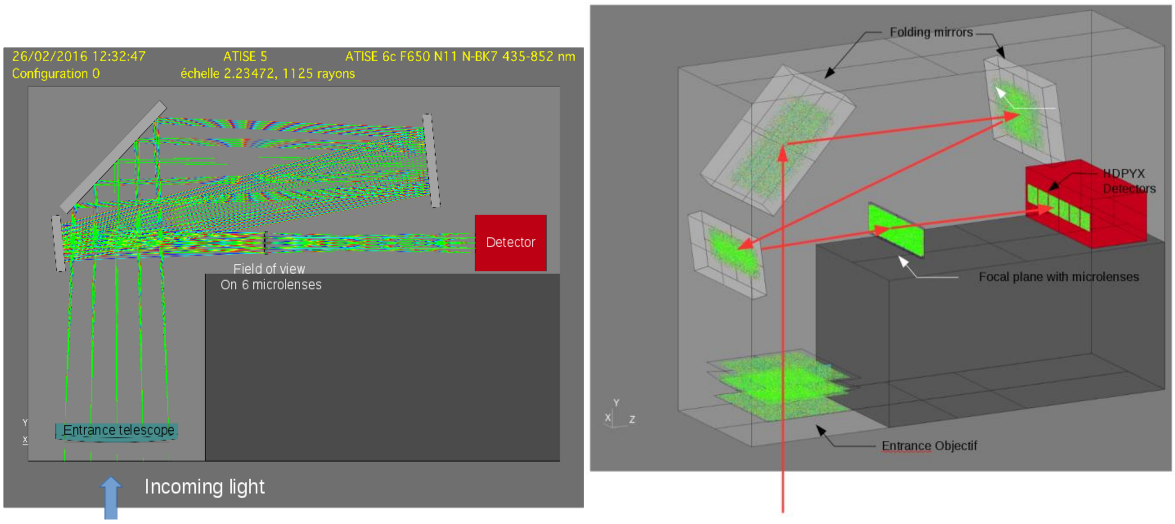


**Fig.** 4. **a)** ATISE optical schematic. **b)** Perspective view showing light distribution on each optical surface. The optics forms an image of entrance pupil on detector which create an uniform illumination corresponding to one of six line of sight.

### *C. Spectrometer design*

The µ-SPOC spectrometer consists of a two-wave interferometer (a Fizeau interferometer) a semi-transparent glass plate assembled on top of a detector. The hypothesis that only two waves interferes depending of the reflectivity of the prism and the natural reflexion of the uncoated detector, as we will see further (contrast of fringes). A monochromatic beam coming from the infinite on a substrate which has the height *e* reflects off the detector and interferes with itself with an optical path difference (OPD) , where n is the optical index of the substrate (Fig 5a). The reflectivity coefficient maximizing two waves detection is set between 25% and 50% thus, the Fizeau finesse is comprised between 2 and 4. For glass plate part, a quaterwave single layer Ti02 gives 42% of reflexion as it has been design in [2]. The second face of interferometer is assumed by the natural reflectivity of detector which is also 40%. Both reflectivity giving a fringe contrast of 66%. The 2808x1088 pixel detectors are divided in two zones of 1400*1088 pixels. On each zone, the fringes will be sampled along the 1400 pixels fast axis giving possibility to reach R=700 spectral resolution at 365nm wavelength. The detector pixel size is 10x10µm. the size of one Fizeau plate is 14x10mm. in front of each interferometer the entrance pupil is imaged with 15x12mm microlens with 100mm focal then the interferometer is illuminated by f/8 beam which is compatible with the R=600 spectral resolution at 600nm.

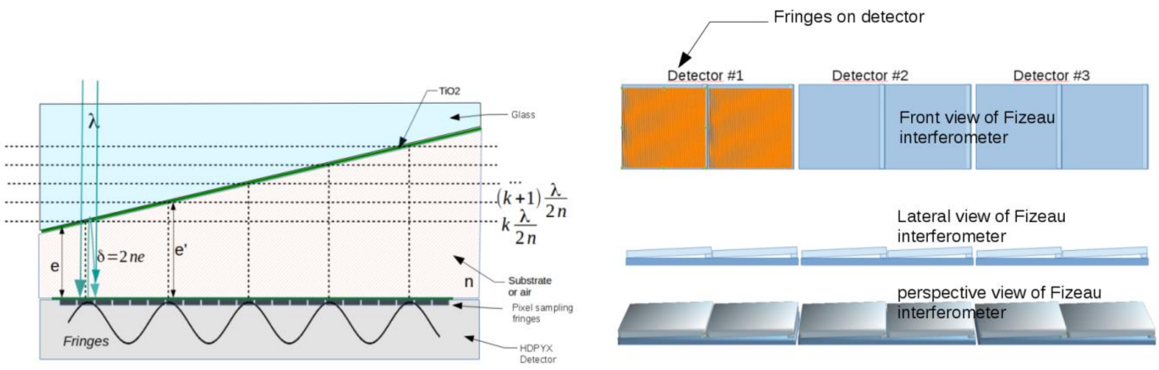


**Fig.** 5**. a)** SPOC principle : A semi-transparent plate is set on top of detector. Light coming from observed field of view reflects both on semi-transparent plate and detector itself. Fringe pattern formed by interference is measured by detector. Fourier transforms of this image gives the spectra corresponding to whole field of view concern by this way. **b)** An HDPYX detector is divided in two zone with one interferometer by zone. 3 detectors permits us to select 6 lines of sight

## III. SPOC PROTOTYPE AND FIRST LABORATORY TESTS

The first SPOC prototype composed by a 75mm plano-convex lens has been assembled with Pyxalis HDPYX Sensor a 130µm spacer has been used to incline the plane in front of detector providing inclination compatible with ATISE spectral resolution.

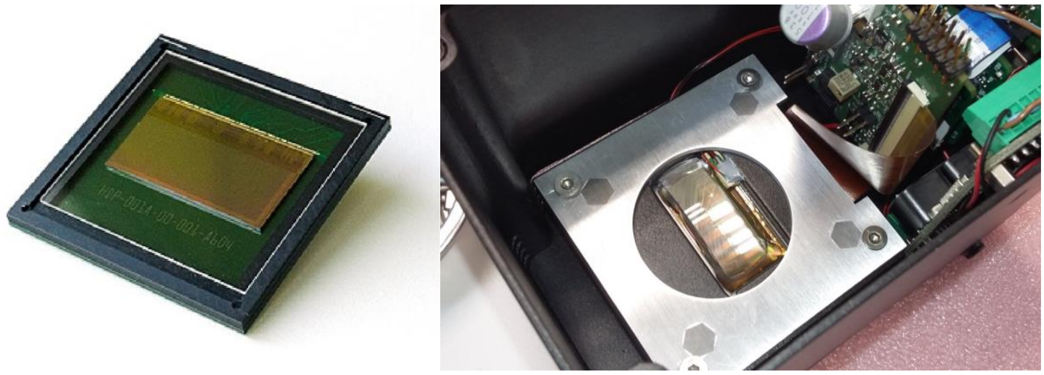

**Fig.** 6**. left)** Pyxalis HDPYX Sensor in BGA, Ceramic Ring configuration; **right)** tested SPOC configuration , a 60nm TiO2 layer has been deposited on plane of plano-convex lens. An optical fiber is set at focal plane of the lens to obtain flat illumination.

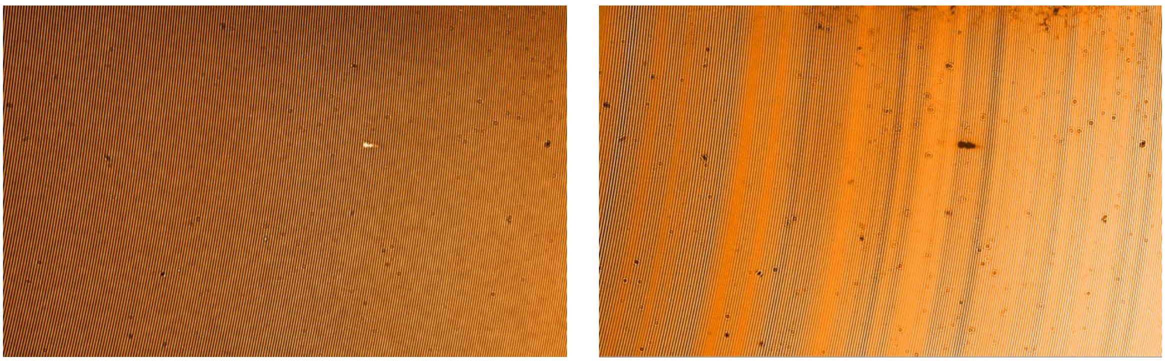

**Fig.** 7**. left)** Observed Fringes of neon's 703nm spectral line on SPOC; **right)** Observed fringes of whole neon'spectra

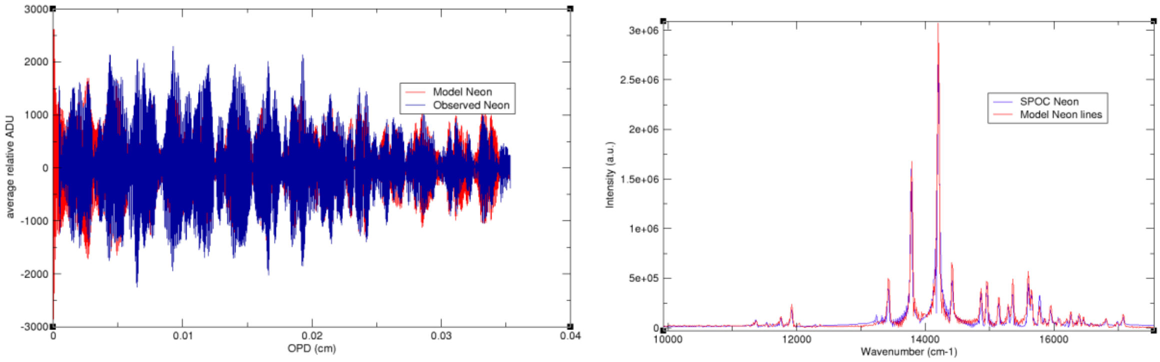


**Fig.** 8**. left)** Reconstructed interferogram. Only the positive part of interferogram is measured. **right)** reconstruction of neon'spectra surimposed to theoretical neon spectra.

II. PERFORMANCES VERIFICATIONS

*A. Detector characterization*

Two versions of electronics has been tested, the first one version is very compact but not yet optimized regarding performances demanded by ATISE mission but this first prototype gives us these first encouraging images with 24e readout noise. A second electronics used by detector manufacturer gives 2.5 e readout noise which is the nominal readout noise without external perturbations and well stabilized alimentations. This electronic cannot be used yet for these optical tests but will be available later. The functioning temperature has been set to 20°C to avoid condensation. Some tests are under progress to determine the right functioning temperature in order to have 3e in 1second exposure time i.e. less than 2e of dark current. The temperature of the Fizeau and detector assembly will be set close to 0°C in satellite to fulfill the 3e noise specification in 1 second.

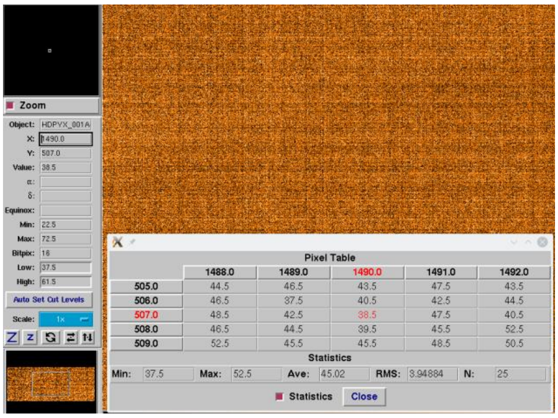


**Fig.** 9**. left)** HDPYX dark image in High gain configuration showing 4 ADU RMS corresponding to attended 2.5e read out noise.

In ATISE, the detector will be essentially used in high gain configuration with 10ke sample on 14bits ADC. The full well capacity of pixel is 100ke can provide 120dB dynamics compatible with observation of very strong solar events.

*B. Spectra reconstruction*

Mainly, three parameters are necessary to reconstruct the spectrum:

- Exact depth between Fizeau plate and detector reflection face principally the detector silicon interface with metallic deposition for pixel's electronic. This depth depends of wavelength because of TiO2 layer and passivation layer.
- Chromatic Pixel Photometric response depending of instrument transmission, Fizeau plate reflection coefficient and detector quantum efficiency.
- Chromatic Fringe contrast which depends also of reflectivity of Fizeau Plate and detector reflectivity.

The calibration of these values for each pixel is obtained from two measurements:

- Observation of simple emission spectra such Neon lamp or high altitude night glow dominated by OI 630nm emission unresolved triplet at ATISE spectral resolution.
- Observation of broadband flat-field on integrating sphere, Moon or solar light reflecting on desert or ocean surface

After this calibration, the 1 dimensional interferogram is obtained by averaging every pixel contribution on a equidistant OPD distribution between optical contact (OPD=0) and maximum OPD.

### *C. Spectral resolution*

The spectral resolution of Fourier Transform spectrometer depends only of the maximum sampled OPD. In our case, the Fizeau sampling starts at minimum optical distance at mechanical contact between detector surface and Fizeau plate surface. This minimum distance is around 1 micron according to passivation layer depth of detector. This mean that we don't measure the first fringe but this is not necessary for emission line spectra such aurorae. The maximum OPD distance is given by the depth of spacer set on the opposite side i.e. the angle of interferometer is 0.5°. This angle corresponds to a Shannon sampling of 700 fringes at 365nm which is the shorter wavelength.. If this medium is vacuum, this depth is 125µm if this medium is optical glue, n=1.5 and the depth is 82µm. SPOC sample one side interferogram, the full spectral resolution is attained when the interferogram is symmetrized before Fourier transform or to use directly the Cosine transforms. In two cases, the knowledge of absolute value of OPD is required. The pattern of neon's fringes of fig. 6. is sufficient to determine absolute OPD values. The spectral resolution is 1.5nm at 703 nm corresponds to the ATISE goal.

### *D. Low illumination Sensitivity*

ATISE will observe at limb integrating aurora oval from the side as shown in the Fig. 2. The expected brightness is estimated to be 10kR i.e. 10^8 photons/s on each line of sight. This represents 5e6 photon on 1s exposure on detector. A very first laboratory experiment has been made observing an argon and neon discharged lamp which represents similar emission lines. The readout electronic is not yet optimized and the readout noise has been actually measured at 25e , this means that we has obtain similar results introducing 5e7 photons in the systems.

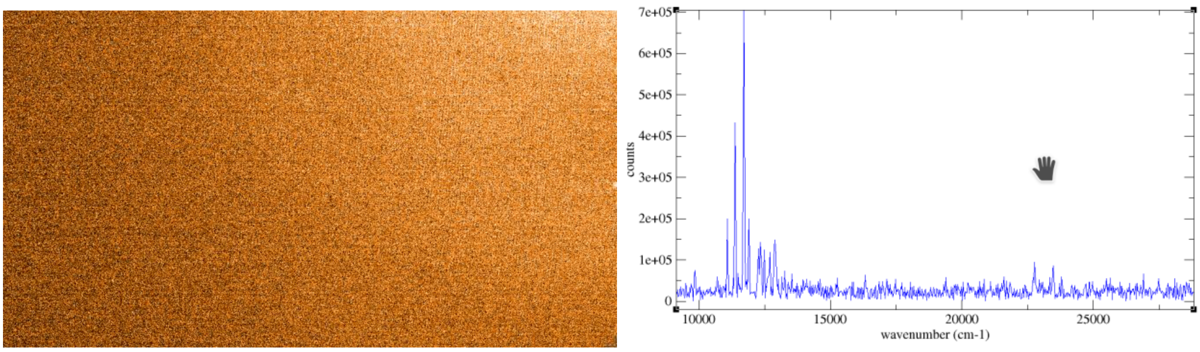


**Fig.** 10**. left)** Under low flux illumination corresponding to flux receive in 1s exposure of aurora .Fringes visible on fig. 7 are not visible but are sufficient to build a usable spectra after Fourier transforms.

Fainter distinguishable lines represent 50R that is equivalent to the ATISE's 5R requirement according the actual experimental noise excess that will be corrected during next study phases.

## IV. CONCLUSIONS

ATISE is an innovative spectrometer taking advantage of detector progress. It permits us to design small and powerful instruments to surveying aurorae and upper atmosphere airglows. Strengths of this concept if its ability to integrate very faint diffuse emissions under a large solid angle contrary to slit spectrometers. The new HDPYX CMOS detector has an exceptional dynamics especially optimized for Fourier spectrometry with low readout noise. It is well adapted to ATISE to follow large dynamic events without saturations. The uncoated detector is well adapted to play a role of semi-transparent mirror , we exploit this feature to win a 40% of transmission. The measurements accuracy don't depend of optics stability but only of the stability of the assembly of Fizeau interferometer to detector which not requires 0.1° thermal regulation on a very small volume and weight.

AKNOWLEDGMENTS

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