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Feasibility study of an image slicer for future space application

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ABSTRACT

This communication presents the feasibility study of an image slicer for future space missions, especially for the integral field unit (IFU) of the SUVIT (Solar UV-Visible-IR telescope) spectro-polarimeter on board the Japanese-led solar space mission Solar-C as a backup option. The MuSICa (Multi-Slit Image slicer based on collimator-Camera) image slicer concept, originally developed for the European Solar Telescope, has been adapted to the SUVIT requirements. The IFU will reorganizes a 2-D field of view of 10 x 10 arcsec^2 into three slits of 0.18 arcsec width by 185.12 arcsec length using flat slicer mirrors of 100 µm width. The layout of MuSICa for Solar-C is telecentric and offers an optical quality limited by diffraction. The entrance for the SUVIT spectro-polarimeter is composed by the three IFU slits and one ordinal long slit to study, using high resolution spectro-polarimetry, the solar atmosphere (Photosphere and Chromosphere) within a spectral range between 520 nm (optionally 280 nm) and 1,100 nm.

Keywords: Solar-C, SUVIT, image slicer, IFU, MuSICa, IFS.

1. INTRODUCTION

During the last decade, the development of integral field units (IFU) has relieved standard long slit spectroscopy offering the possibility to obtain the spectra of the points of a surface, independently of its geometrical shape, simultaneously. This technique is known as Integral Field Spectroscopy (IFS). IFS has been implemented in the state-of-the-art spectrographs of the largest night-time telescopes and, recently, it is being implemented in solar spectrographs too [1]. This technique is being also applied to space instrumentation, such as NIRSpec [2] at James Webb Space Telescope [3] or SNAP [4].

There are different alternatives of integral field units (Figure 1), such as: microlenses, optical fibers or image slicers and they can also be combined between them.

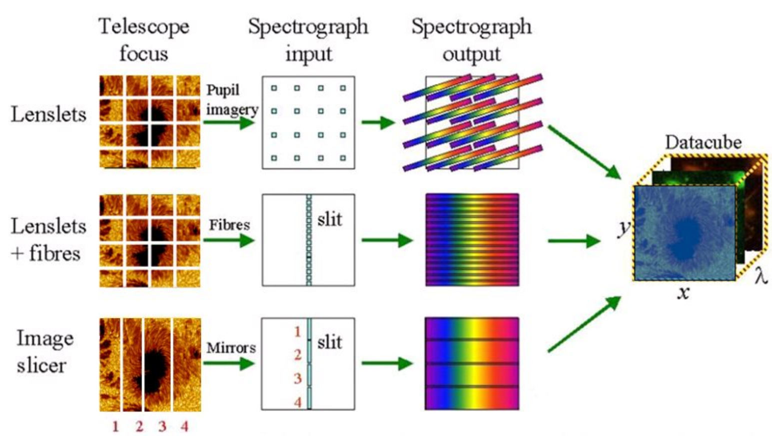

Figure 1. Alternatives of integral field units (IFU): microlenses, optical fibers and image slicer. These alternatives can also be combined as the use of fibers with input and output microlenses.

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The image slicer concept improves some aspects of the other IFU alternatives, such as:

- The spectra obtained using microlenses are overlapped in the detector. This does not occur using image slicers.
- The focal-ratio degradation characteristic of optical fibers is not produced using image slicers, which can preserve the f-number or can change the final focal-ratio using its own optical components.
- The loss of light transmission in the infrared spectral range for optical fibers is solved with an adequate coating for image slicers.
- In addition, optical fibers are depolarizing elements.

The spectra overlapping obtained using microlenses could be solved by software. Other points as the focal-ratio degradation of fibers can be characterized at laboratory but, no doubt, image slicers are an optimum choice for instruments designed for polarization studies. Based on these points, image slicers are being studied as a backup option for the IFU of SUVIT spectro-polarimeter, on boarding Solar-C mission.

For studies of 2-D regions using standard slit spectrographs, it is needed to scan the image of the telescope across the entrance slit and obtain the spectra in sequential observations. Integral Field Spectroscopy (IFS) is a useful technique for solar physics considering the time scales in which the structures evolve in the Sun, which can be larger than the exposure time and, thus, the observed structures can go out of the slit field of view during the exposition. For example, at SUVIT, the time estimated for the observation of a spicule using a slit spectrograph with a width of 0.2 arcsec width by 5 arcsec length is 250 seconds, requiring 10 scanning positions. This implies a scanning speed of about 14 km/sec what is too slow. For studies of a bidimensional region, IFS has to be applied. However, since slit spectroscopy has advantage for observations of photospheric B and chromospheric Doppler, SUVIT will present both options: three slits generated by an integral field unit (IFU) and one ordinal slit, increasing, thus, its performance.

2. IMAGE SLICER CONCEPT

In general terms, an integral field unit reorganizes a bidimensional entrance field of view into one or more slits that illuminate a spectrograph, obtaining the spectra of all the points at the same time and, thus, under the same conditions. In particular, an image slicer uses arrays of mirrors (for pure reflective image slicers) with different orientations to reflect each part of the entrance field of view and send them with different angles to a mirror of the next arrays. Thus, the optical path of each sliced part of the field of view is defined by the reflection using one mirror of each array and composing a piece of the generated output slit, which is obtained by the aligned distribution of the focusing beams associated to each part of the input image. An image slicer is located at the telescope image focal plane and its output is the instrument object focal plane. An image slicer is an optical system that: decomposes a 2-D field of view, generates a pupil image for each beam associated to different parts of the image and focuses the beams, so that the output slit is generated by the alignment of the images of each one of these beams.

The number of surfaces of an image slicer depends on the concept itself. For Solar -C an adaptation of the design of the image slicer for the European Solar Telescope (EST) [5] is considered. This concept, called MuSICa [6], minimizes the number of optical components needed for multi-slit capability, so it is optimum for SUVIT [7]. The base concept of MuSICa to generate a slit uses three arrays of mirrors: slicer mirror array, collimator and camera mirror arrays. The first one is an array of flat mirrors that divides the entrance field of view into thin slices. It is located at the telescope image focal plane. Collimator and camera mirrors are spherical. The collimator mirrors generate a pupil image for each sliced part of the field of view at their focal length, between them and the camera mirrors. As a characteristic of this design, the different pupil images are overlapped. At that position a mask with one circular aperture is placed to avoid scattered light contribution. The camera mirrors focus the beams one on top of the other generating the output slit. In addition they can make a focal-ratio conversion and send the pupil to infinity. The proposed image slicer is a telecentric system. As well as the pupil mask, a field mask at the slicer mirror array will be used to minimize the stray light contribution. MuSICa offers multi-slit capability. For this purpose, the image at the telescope focal plane has to be 'divided' into as many parts as the number of slits to be generated, eight in the case of EST (and three in the case of SUVIT). This is done using an array of eight flat mirrors, as many mirrors as the number of slits, with different orientations. The 2-D field of view is then sliced into eight 2-D sub-fields and each sub-field is the entrance field of view for an image slicer, composed by:

slicer mirror array, collimator mirror array and camera mirror array, which generates one slit. This array of flat mirrors is called macro-slicer. Thus, the multi-slit IFU is composed by a macro-slicer and eight image slicers. Since for MuSICa either macro-slicer or slicer mirror array are flats, they can be combined, integrating the slicer mirror array of each image slicer over its corresponding mirror of the macro-slicer. So the macro-slicer acts like a mechanical mounting with the appropriate angles. This minimizes the number of surfaces needed to satisfy the multi-slit capability since macro-slicer and slicer mirrors have to be located at focal plane, due to both of them slice image and if they were not combined, the macro-slicer would be integrated at focal plane and a reimaging system would be needed to generated a focal plane for the slicer mirror array. This combination avoids three surfaces.

MuSICa image slicer presents several advantages: it is a telecentric system that sends the output pupil to infinity keeping the plate scale on the detector; collimator and camera mirrors are distributed in two columns whose length is equivalent to that of the generated slit what reduces the angles of incidence and improves the optical quality; collimator and camera mirrors are placed in front to each other but with antisymmetric correspondences, so that the pupil images are overlapped and the pupil mask, used to avoid the contribution of scattered light, has only one circular aperture. The symmetry of the MuSICa's layout facilitates the alignment and the fabrication, reducing the costs.

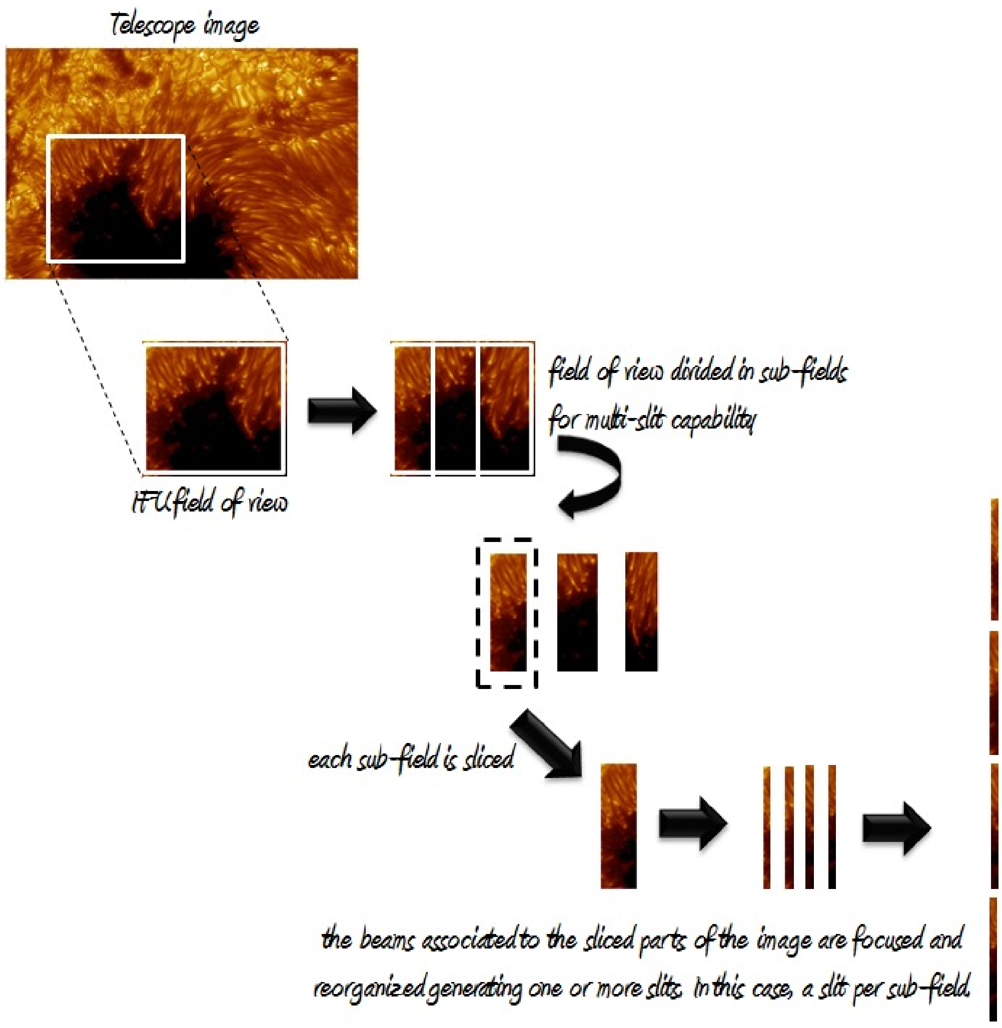

Figure 2. Scheme of a multi-slit image slicer concept. The entrance 2-D field of view is sliced in as many sub-fields as the numbers of generated slits. Each sub-field is itself sliced by the slicer mirror array and the beams associated to the sliced parts of the sub-field are focused (using spherical collimator mirrors to generate a pupil image and spherical camera mirrors to focus the beams) and distributed composing a long slit. A slit per sub-field is generated, three in this case.

3. APPLICATION TO SUVIT SPECTRO-POLARIMETER

After the success of the Hinode mission, the new Japanese-led solar mission, Solar-C, will obtain crucial information about the lower solar atmosphere at an inclined geo-synchronous orbit, observing the Sun 24 hours per day with high spatial resolution and high precision polarimetry. Its three science instruments are: SUVIT (Solar UV-Visible-IR-Telescope), EUVS (EUV/FUV high throughput spectroscopic telescope) and XIT (X-ray imaging (spectroscopic) telescope).

SUVIT will study phtotospheric and chromospheric magnetic field and plasma characteristics and it is focused on the analysis of gas dynamics and magnetic fields from photosphere to the upper chromosphere, and to understand dynamical evolution of elementary structures of magnetized atmosphere. It will allow the study of: the origin of the Sun's dynamic atmosphere, fundamental MHD processes, such as reconnection, wave or acceleration and the mechanism of explosive phenomena, like flares.

SUVIT is a 1.4 m aplanatic Gregorian telescope at diffraction limit. It will contribute to solar community with magnetic fields measurements in the chromosphere and the resolution of structures with 0.1 arcsec for the first time from space. It covers a spectral range from UV to near infrared, from about 380 nm (optionally 280 nm) to 1.1 μm.

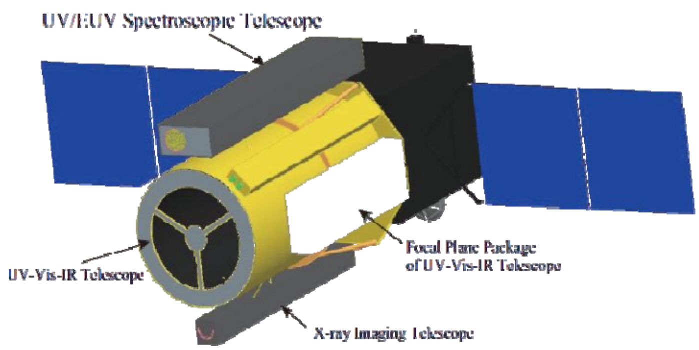

Figure 3. Solar-C mission layout and its three science instruments: SUVIT (Solar UV-Visible-IR-Telescope), EUVS (EUV/FUV high throughput spectroscopic telescope) and XIT (X-ray imaging (spectroscopic) telescope).

At SUVIT image focal plane three instruments are integrated: a broadband filtergraph (BF), a narrowband filtergraph (NF) and a spectro-polarimeter (SP) with a polarimetric sensitivity of 10^{-4} in Ca II 854 nm and He I 1083 nm for chromospheric magnetic field with an integration time of about 10 seconds and 10^{-3}–10^{-4} in 525 nm for photospheric magnetic field. The requirements for the spectro-polarimeter are summarized in Table 1.

Table 1. Requirements for the SUVIT spectro-polarimeter.

SUVIT spectro-polarimeter requirements	
Field of View	Slit scanning polarimetry: 184 arcsec x 143 arcsec IFU polarimetry : 10 arcsec x 10 arcsec
Sampling scale	Slit: 0.07 arcsec, IFU: 0.18 arcsec
Spatial resolution	Slit scan: 0.14 arcsec IFU mode: 0.14 arcsec (along slit) x 0.36 arcsec (across slit)
Spectral resolution	Slit mode: R= 100,000 – 210,000 IFU mode: R= 96,000
Integration time	1-20 sec

The field of view requirement is 184 x 143 arcsec^2 for slit scanning polarimetry and 10 x 10 arcsec^2 for IFU mode. The sampling scale is 0.07 arcsec, the spatial resolution is 0.14 arcsec for slit scan and, for IFU spectro-polarimetry, 0.14 arcsec along the slit by 0.36 arcsec across the slit; the slit width is 0.07 arcsec and 0.18 arcsec for slit and IFU modes, respectively. The spectral resolution is R=100,000-210,000 for slit option and R=96,000 using IFU and the exposure time for polarimetric observations is 1-20 seconds. The current layout of the spectrograph is shown in Figure 4 and the technical parameters for the spectrograph are presented in Table 2. The maximum total mass of the spectrograph is 100 kg and the length 180 cm approximately.

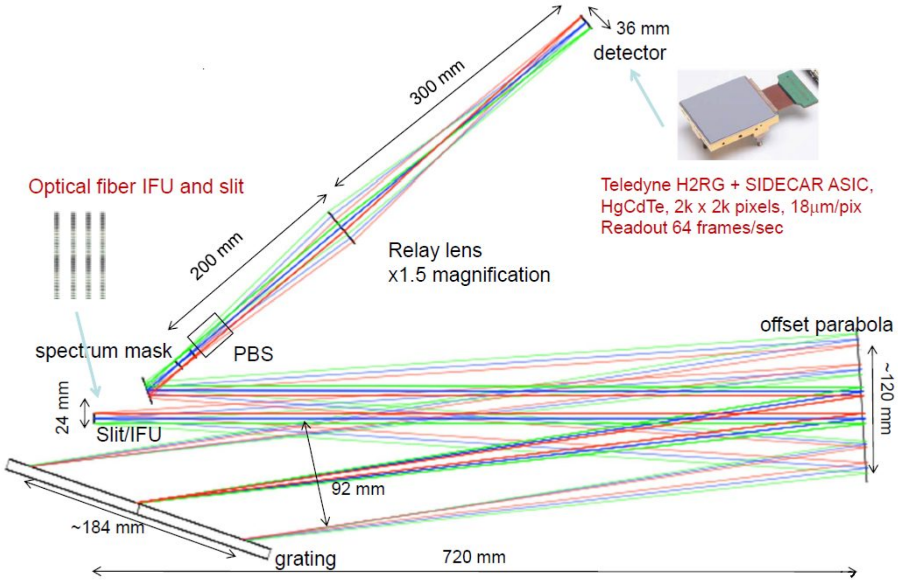

Figure 4. Current layout of the SUVIT spectrograph.

Table 2. Spectrograph technical parameters.

Spectrograph technical parameters	
Focal length	720 mm
Focal-ratio	23.57
Grating size	100 mm x 200 mm
Grooves density	110 / mm
Spatial sampling	0.07 arcsec
Pixel size	18 µm (12 µm x 1.5 magnification)
Slit width	12 µm
Detector	2k x 2k

4. PRELIMINARY OPTICAL LAYOUT AND RESULTS

A feasibility study of the adaptation of the MuSICa image slicer of the European Solar Telescope (EST) to the requirements of SUVIT has been done as a backup option for the integral field unit. This study includes a preliminary ZEMAX optical design of a single slit image slicer. The requirements and main characteristics considered for the IFU layout are presented in Table 3.

Table 3. Requirements and main characteristics for the preliminary calculation of an image slicer for Solar-C.

Requirements and main characteristics for the preliminary calculation of the image slicer	
Field of view	10 x 10 arcsec^2
Slicer input sampling	0.18 arcsec
Slicer width	100 µm
Entrance focal-ratio	F/76.4
Number of generated slits	3
Wavelength coverage	280 nm (TBD) – 1100 nm

The entrance field of view (FOV) is 10 x 10 arcsec^2. The input sampling is 0.18 arcsec/slice. The thinnest slicer mirror whose fabrication is currently feasible is considered, 100 µm, and the image slicer entrance focal-ratio considered for this calculation is F/76.4. The telescope effective focal length calculated considering an aperture of 1.4 meters is 107 meters. The bidimensional field of view is reorganized into 3 slits and, for that, the entrance field of view (10 x 10 arcsec^2) is divided into as many sub-fields of view as the number of generated slits (3). A square 10 x 10 arcsec^2 field of view leads to three sub-fields with 3.33 x 10 arcsec^2, what implies 19 slicer mirrors for each sub-field. The concept of image slicer applied for this calculation presents a symmetric layout with the mirrors of each array organized in two columns. Thus, an even number of mirrors is recommended. The recommended number of slices in which the field of view is cut is sixteen. Sixteen slices with 100 µm width and 0.18 arcsec/slice implies an entrance field of view of 99.96 arcsec^2 (8.64 arcsec width by 11.57 arcsec length), reorganized into three sub-fields of 33.32 arcsec^2 (2.88 arcsec width by 11.57 arcsec length). For this first preliminary study, a 1:1 image slicer has been designed using the entrance focal-ratio F/76.4. The entrance field of view (99.96 arcsec^2 for the considered layout) is divided into three at the telescope image focal plane to generate three sub-fields of view, each one of them is reorganized into a slit. This field division is done by the macro-slicer, composed by three flat mirrors. Later, an array of slicer mirrors per sub-field of view cuts it into very thin sixteen slices. As mentioned before, since for MuSICa both, macro-slicer and slicer mirror array are flat, they can be combined. The way in which we propose this combination is to use the macro-slicer only for the orientation of the sub-beams. Thus, it does not need to be an array of three flat mirrors, but it only needs to be a mounting for the slicer mirror arrays with so many faces as the number of field divisions. The angle of orientation of each face depends on the required separation between the generated slits. The aperture of the pupil mask has a diameter of ≈ 6.55 mm, in which the pupil images associated to each part of the sliced field of view are overlapped. The characteristics of the calculated parameters for each image slicer component are presented in Table 4. Although a 1:1 image slicer has been considered for the feasibility study, the IFU can be designed to make a focal-ratio conversion, if required.

Table 4. Calculated parameters for a preliminary 1:1 image slicer design.

MACRO-SLICER	
Entrance field of view	99.96 arcsec^2 (8.64 arcsec width by 11.57 arcsec length)
Number of faces	3
FoV per face	33.32 arcsec^2 (2.88 arcsec width by 11.57 arcsec length)
Size of each face	1.60 mm width by 6.428 mm length
SLICER MIRROR ARRAY	
Size of the array	1.60 mm width by 6.428 mm length
Number of mirrors	16 (distributed in 2 columns)
Curvature	Flat
FoV per slicer mirror	2.083 arcsec^2 (0.18 arcsec width by 11.57 arcsec length)
Size of each slicer mirror	100 µm width by 6.428 mm length
COLLIMATOR MIRROR ARRAY	
Number of mirrors	16 (distributed in 2 columns)
Curvature	Spherical
Focal-ratio	F/76.4
Focal length	500 mm
PUPIL MASK	
Number of apertures	1
Pupil diameter	≈ 6.55 mm
Position from collimator mirrors	502.18 mm
CAMERA MIRROR ARRAY	
Number of mirrors	16 (distributed in 2 columns)
Curvature	Spherical
Focal-ratio	F/76.4
Magnification	1
Focal length	500 mm
GENERATED SLIT	
Number of generated slits	3
FoV per slit	33.32 arcsec^2 (0.18 arcsec width by 185.12 arcsec length)
Size (F/76.4)	100 µm width by 102.848 mm length

Figures 5 to 8 present the ZEMAX layout of the image slicer. Figure 5 shows the first two components: slicer mirror array and collimator mirrors in two different views. Collimator mirrors are distributed in two columns to reduce the off-axis distances. Collimator mirrors generate a pupil image per beam and all these pupil images are overlapped, as shown in Figure 6. Figure 7 shows, on the left, the symmetry of the layout, from collimator to camera mirrors, which are distributed in front to each other with antisymmetric correspondences and, on the right, the generated slit between the two columns of camera mirrors and alternating focusing beams of each column to compensate the angles. The whole layout, including all the optical components, is presented in Figure 8.

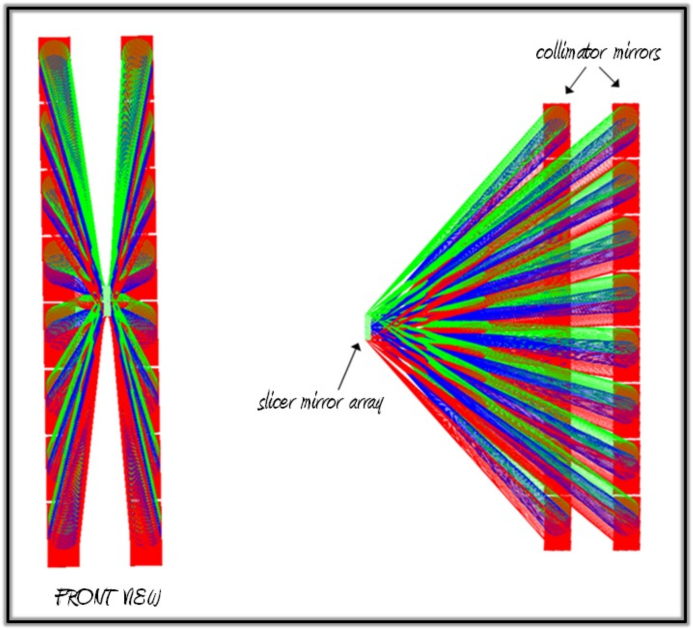

Figure 5. First image slicer step. At the telescope image focal plane the slicer mirror array decomposes the entrance field of view into sixteen thin slices and sends each part of the field of view to a collimator mirror. Two different views are presented.

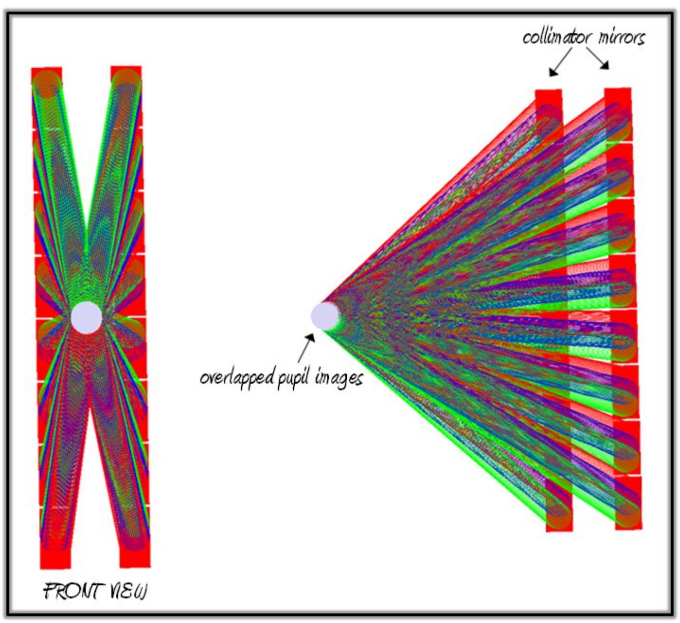

Figure 6. Collimator mirrors generate a pupil image for each sliced part of the field of view at their focal length. The design of this image slicer overlaps the pupil images

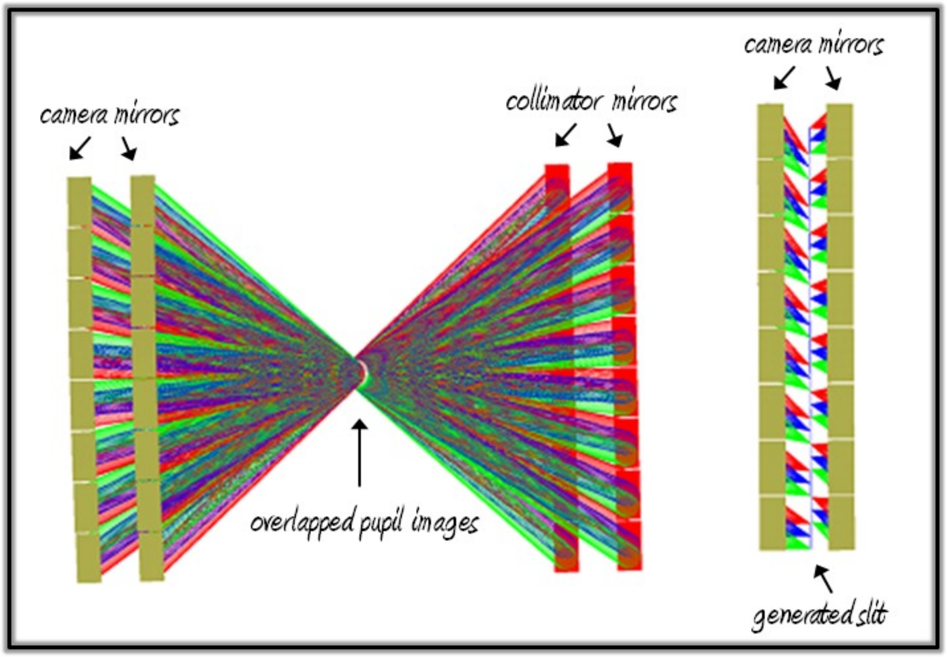

Figure 7. On the left the collimator and camera mirror arrays are shown, with the overlapped pupil images between them. On the right, the output slit is presented, generated by the camera mirrors and alternating focusing beams of each column to compensate the angles.

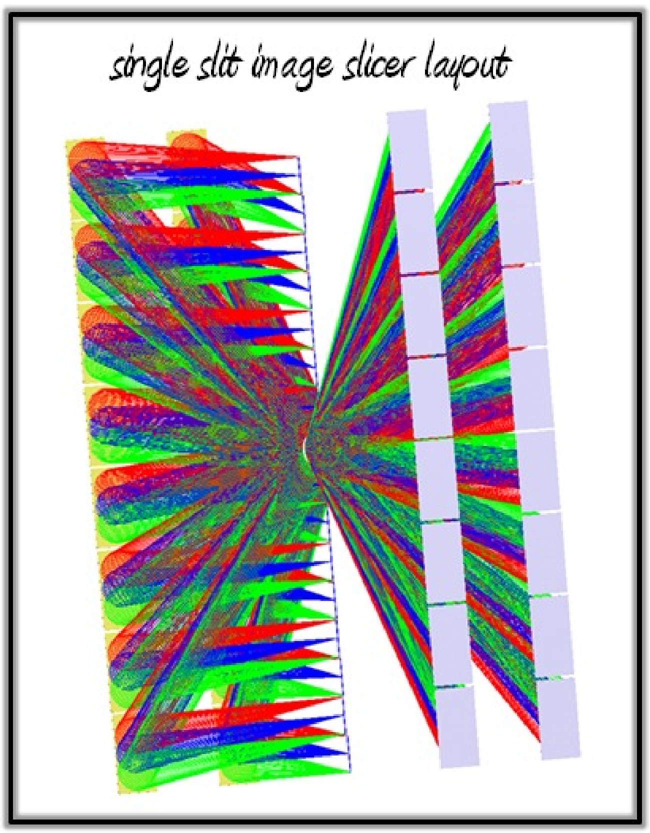

Figure 8. Complete design of a single slit image slicer, based on the MuSICa concept.

After the IFU, orthogonal polarizations should be divided with the beam splitter of the polarimeter for spectropolarimetry measurements.

This preliminary layout presents an optical quality at diffraction limit as shown in the spot diagram of Figure 9, where each column represents a piece of the generated slit and the circle is the Airy disk. The four slits for the spectro-polarimeter, the three slits of the IFU and the ordinal slit, can be accommodated with the restrictions of the separation of the slits in the detector and the available volume for the IFU. It is expected that the design of the multi-slit image slicer presents bigger spot sizes due to the angles will increase, however, the geometrical distribution of the optical components can be fixed to control the optical performance and a result of optical quality at diffraction limit is also expected in that case.

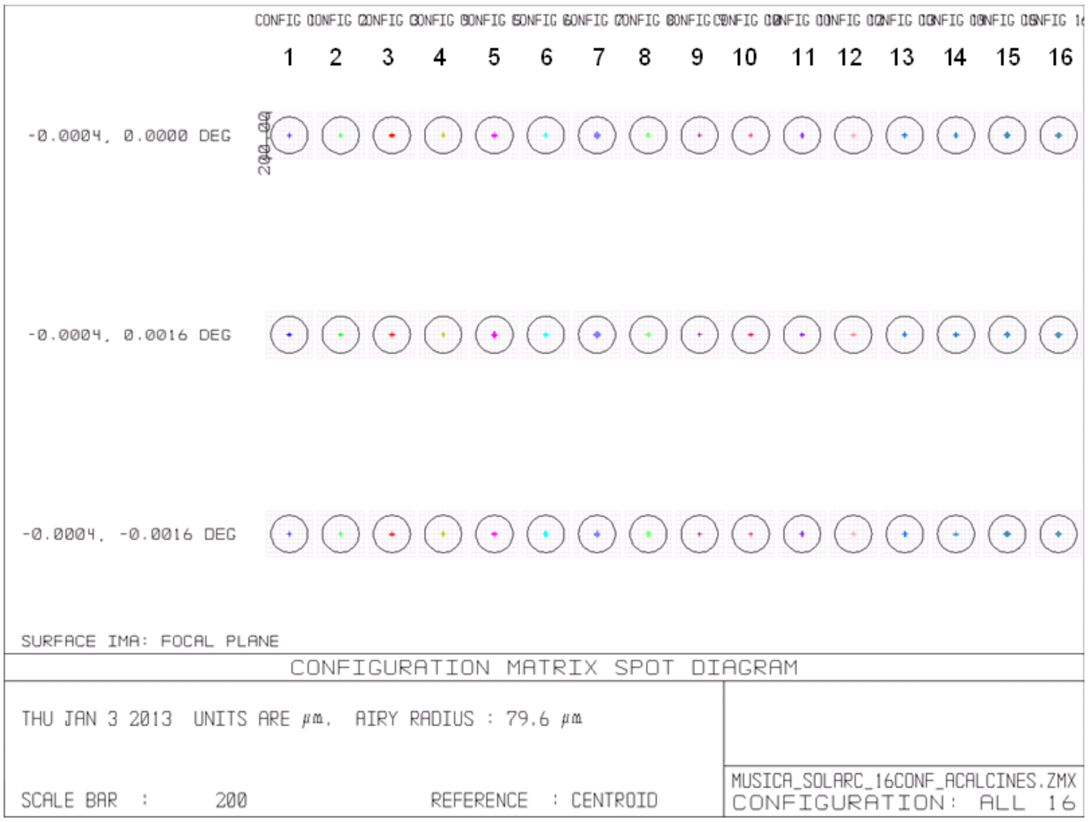

Figure 9. Optical quality at diffraction limit of the preliminary optical design of an image slicer for SUVIT based on the concept of MuSICa layout for EST. Each column represents the image of each configuration, this is a piece of the output slit. The circle is the Airy disk.

5. MANUFACTURING RESTRICTIONS AND FUTURE PERSPECTIVES

MuSICa image slicer, whose concept is adapted for Solar-C will be fabricated in zerodur glass, whose coefficient of thermal expansion is nearly zero and the polished finish is really good, what improves the performance in terms of stray light. Further studies should be done for material and coatings especially for space. Materials must be low outgassing and optical elements should be durable to radiation. Verification tests are required for coatings, like mechanical strength or thermal cycling.

This communication presents a first layout for a single-slit IFU. The final multi-slit will be composed by three image slicers like the one here presented, with the appropriate distribution based on the separation between the slits in the detector and the available volume.

As for everything in space, image slicers should be tested before on Earth. A prototype image slicer of MuSICa for the European Solar Telescope is currently under design for the 1.5 m GREGOR solar telescope using slicer mirrors of 100 µm. It is expected to start its fabrication at the end of 2014 and to have the prototype around April 2015. This prototype will confirm the possibility to manufacture slices with such thin widths and the viability of this alternative of integral field unit for solar physics applications. A multi-slit image slicer prototype for the European Solar Telescope, also for GREGOR solar telescope, using three slits is expected for a near-future within about three years.

6. PHYSICAL OPTICS PROPAGATION ANALYSIS

Diffraction effects can be analyzed using ZEMAX and POP tool, Physical Optics Propagation. For POP study the 1.5 m diameter of the telescope has been considered and it can be propagated through the different optical elements of the image slicer. In this preliminary study the diffraction effect at one slicer mirror has been analyzed. Since the focal-ratio is not still fixed and neither the width of the slicer mirrors, for which the smallest size currently feasible has been considered, this study has been repeated for three slicer mirrors width: 200 µm, 100 µm and 50 µm. The focal-ratio considered for this preliminary layout is F/76.4. The PSF has been calculated for the largest wavelength of the interval, for which its Airy disk is bigger and thus, is more problematic to have an acceptable percentage of the light within the slicer mirror. Thus, the PSF diameter at 1 µm wavelength is 186.416 µm. For that reason, a slicer mirror of 200 µm, which is currently feasible, has been considered as the first case for POP study. The minimum width that can be manufactured at the present is 100 µm, which is the size considered for the image slicer prototype for EST that will be coupled at GREGOR telescope. This is the second case considered. And the third case is 50 µm, which is the width expected for the image slicer of EST.

POP study has been done for a field point centred in a slicer mirror. The diffraction pattern at a slicer mirror and the PSF are presented in Figure 10.

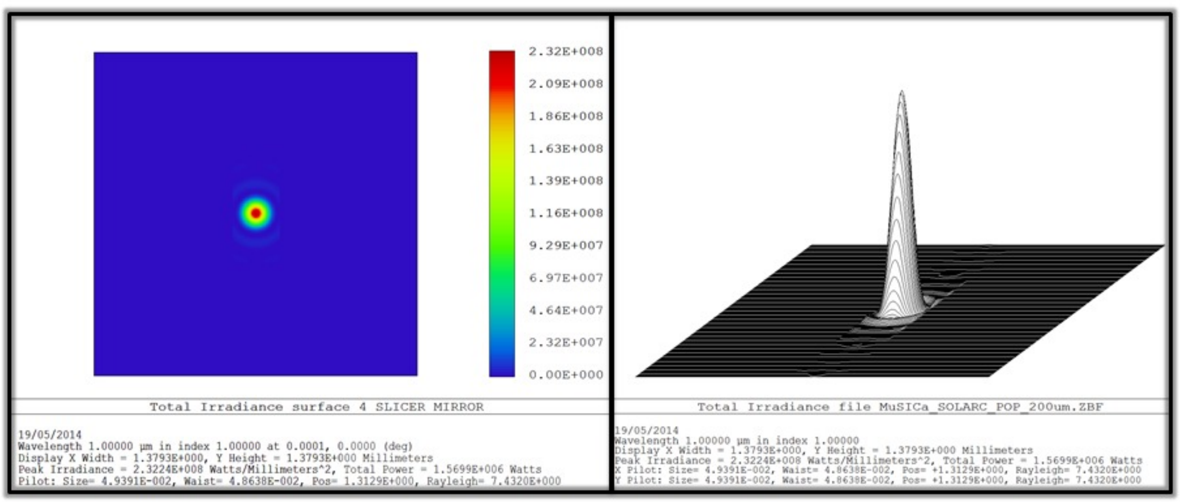

Figure 10. On the left the diffraction pattern at a slicer mirror of 200 µm width is shown and on the right the associated PSF is presented. Both obtained using POP tool of ZEMAX.

A comparison of the diffraction pattern at a slicer mirror with the three considered sizes is presented in Figure 11 represented in logarithmic scale (log-5).

If the focal-ratio for the instrument is fixed based on the width of the slicer mirror, thus a focal-ratio F/40.98 is suggested if slicer of 100 µm width are used and F/20.49 for slicers of 50 µm. This guarantees at least the 83.3% of the light within the slicer mirrors. For the focal-ratio mentioned in Table 2, F/23.57, the diameter of the PSF at 1 µm wavelength is 57.51 µm and this would be the width of the slicer mirrors or the minimum one for the 83.3% of the energy.

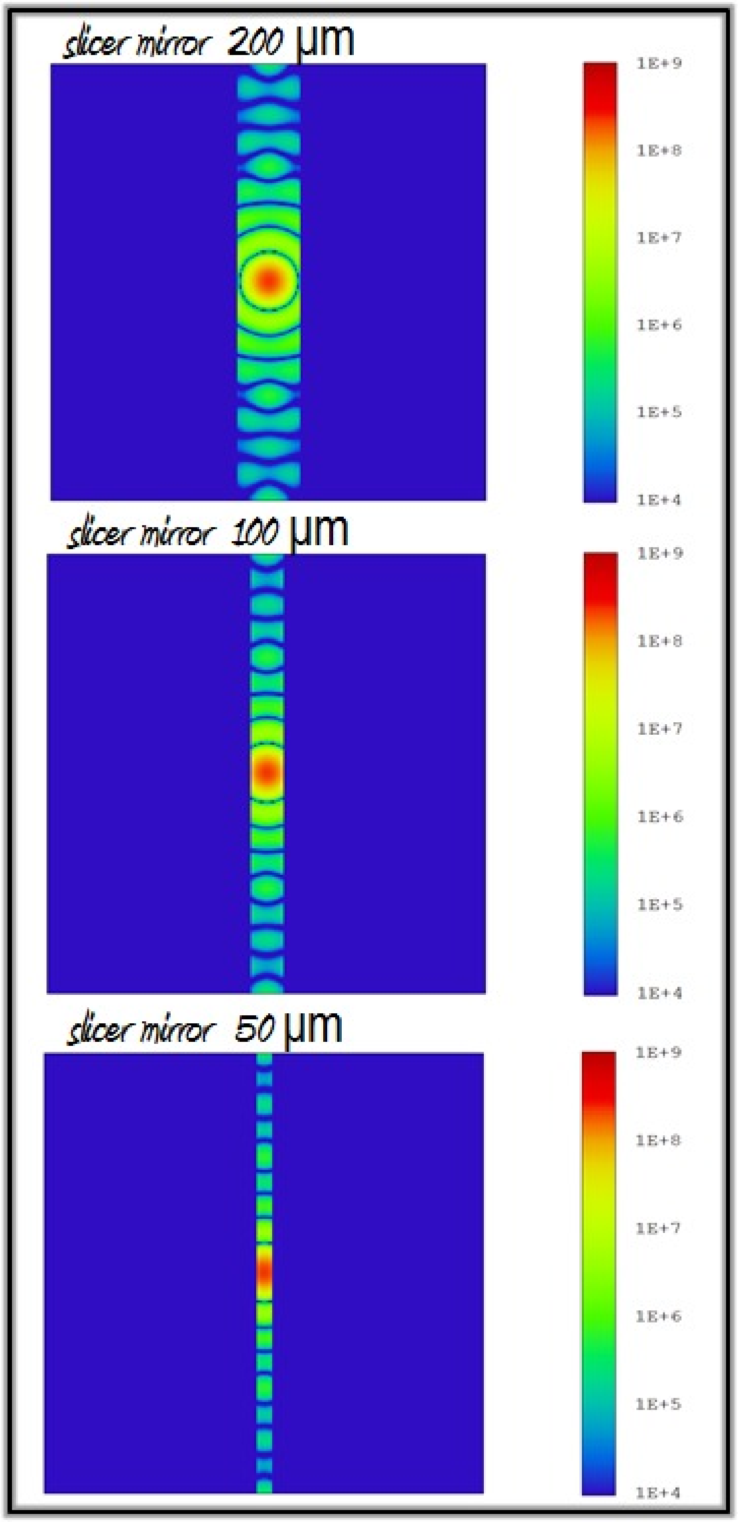

Figure 11. Diffraction pattern of a field point centred at a slicer mirror of a 1.5 m pupil (telescope pupil) represented in logarithmic scale (log-5). Three sizes for the slicer mirror have been considered: 200 µm, 100 µm and 50 µm. The first Airy disk is only contained within the slicer mirrors for 200 µm width considering a focal-ratio of F/76.4. This study has been done using POP tool of ZEMAX at a 1 µm wavelength.

7. CONCLUSIONS

This communication presents the feasibility study of an image slicer based on the concept designed for the European Solar Telescope, for future space missions, especially for the integral field unit of the SUVIT spectro-polarimeter on board Solar-C mission. This proposal is a backup solution for SUVIT, whose current concept for the IFU is optical fibers.

The preliminary ZEMAX layout shows the feasibility of the adaptation of the MuSICa's image slicer layout to the requirements of SUVIT with an excellent optical quality at diffraction limit. The four slits for the spectro-polarimeter, the three slits of the IFU and the ordinal slit, can be accommodated with the restrictions of the separation of the slits in the detector and the available volume for the IFU. It is expected that the design of the multi-slit image slicer presents bigger spot sizes due to the angles will increase, however, the geometrical distribution of the optical components can be fixed to control the optical performance and a result of optical quality at diffraction limit is also expected in that case.

The thinnest slicer mirrors already manufactured have been considered for this layout, whose width is 100 µm, however, the diffraction effects at a slicer mirror have been studied for three different widths: 200 µm, 100 µm and 50 µm. The first Airy disk, evaluated at 1 µm, is only contained within the slicer mirror for 200 µm for a focal-ratio F/76.4. A focal-ratio F/40.98 is suggested if slicers of 100 µm width are used and F/20.49 for slicers of 50 µm. This guarantees at least the 83.3% of the light within the slicer mirrors. For the focal-ratio mentioned in Table 2, F/23.57, the diameter of the PSF at 1 µm wavelength is 57.51 µm and this would be the width of the slicer mirrors or the minimum one for the 83.3% of the energy.

An image slicer is an excellent proposal of IFU for the spectro-polarimeter of SUVIT.

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