Optical Design of MAAT: an IFU for the GTC OSIRIS Spectrograph

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ABSTRACT

The Mirror-slicer Array for Astronomical Transients (MAAT; http://maat.iaa.es) is an IFU for the OSIRIS spectrograph on the 10.4-m Gran Telescopio CANARIAS (GTC), spectrograph that has been operational for many years and is being upgraded. The Preliminary Design Review (PDR) phase is in progress. The spectrograph can be used for multi-objects spectroscopy using masks that are in a cartridge. The IFU will be in a box that will take the place of a few masks. It is based on the Advanced Image Slicer concept as for MUSE and KMOS on the VLT and many others. The field under study is 14.2" x 10" with a spaxel size of 0.254" x 0.303". Reflective and transmissive optics are under study due to the limited performances of both reflective and transmissive coatings in the range 360 nm to 1000 nm. The curvature and tilt of the slit creates additional challenges. Preliminary calculations give a resolution 1.6 times larger than with a standard slit of 0.6" because of the smaller size of the slices. This however assumes typical aberrations for the spectrograph. We intend to measure the wavefront of the aberrations by using 2 out-of-focus masks with pinholes along the slit, and then correct some of these aberrations with the IFU. A downgraded version of the IFU with a smaller field is also under study in case we need to simplify the project.

Keywords: image slicer, integral field unit, OSIRIS spectrograph, GTC.

1. INTRODUCTION

Integral field spectroscopy is now universally used on large telescopes. The GMOS IFUs on the GMOS spectrographs and NIFS have been in operation on Gemini for a very long time. A good example is the two very powerful integral field spectrographs of the VLT: KMOS and MUSE. While KMOS combines Multi-Object Spectroscopy with Integral Field Spectroscopy with its 24 IFUs, MUSE is the most powerful integral field spectrograph in the world on a fully steerable large telescope. We are now in the Preliminary Design Review (PDR) phase of a project of IFU for the OSIRIS spectrograph on GTC: The Mirror-slicer Array for Astronomical Transients (MAAT). Maat is the Egyptian goddess of cosmic harmony, peace, truth and justice. It is then well suited for the OSIRIS spectrograph. OSIRIS is an imaging and Multi-Object Spectrograph (MOS) using masks. It has a cartridge (also called juke box) with 13 slots, each for a mask. Some masks have a simple slit while others are multi-slit masks. The IFU will be in a box that takes the place of a few masks, probably 6 or 7. The structure of the box will use a standard frame normally used to hold a mask. The frame has the correct shape to fit in a slot of the OSIRIS cartridge. The box will be attached to that frame (Figure 1). In the day, the IFU can be inserted or removed and more masks inserted depending of the observations to be done in the next night. The IFU design will follow the concept of Advanced Image Slicer. At the slit, 3 different options of optics are under study because of the challenge created by the unusual characteristics of the slit. Because the telescope has a curved focal plane and the slit centre is very much off-axis with respect to the telescope, the slit is curved and tilted with respect to the direction of the beam. Another challenge is the large maximum incident angle on the reimaging mirror array of the IFU which can generate large aberrations if a standard design is used. We will present a solution to reduce that angle if the resulting aberrations are too large. Finally, there is the challenge of having a high IFU transmission for the whole range from 360 nm to 1000 nm while both reflective and anti-reflection coatings do not easily deliver a high efficiency for such a large range and such a blue end. Both reflective and transmissive optics are then under study. The present paper describes the status of the MAAT design.

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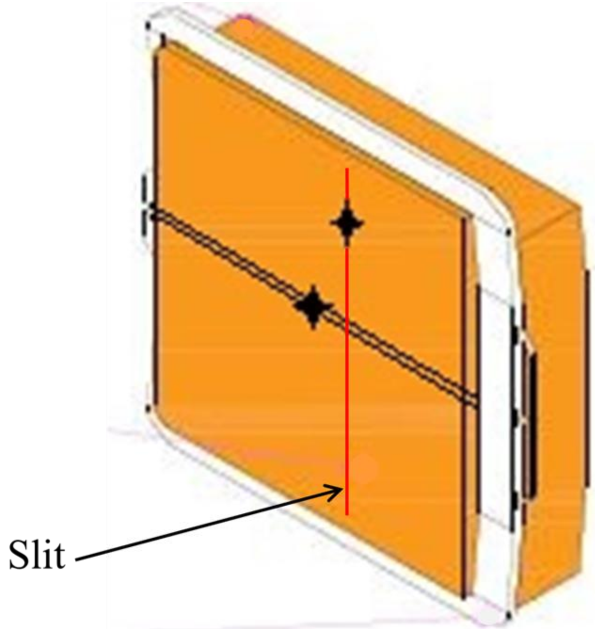

Figure 1. Preliminary mechanical design of the box. The standard mask frame is in white around the box. The apparent horizontal slit is in fact the back-image of the gap between the two 2k x 4k detectors. The top black star is the position of the telescope axis while the bottom is the OSIRIS axis.

MAAT will provide the GTC community with highly competitive unique observing capabilities complementary to the existing instrumentation, i.e. seeing-limited and wide-band IFS at low / moderate spectral resolution; all photons are collected, and a larger efficiency is obtained; it can perform absolute spectro-photometry; advantage on bad (any) seeing conditions since MAAT keeps its nominal spectral resolution regardless of the seeing; target acquisition with no overheads.

The science potential of MAAT is essentially unlimited as presented in detail in the White Paper on MAAT[15]. This includes the nature of the diffuse universe (the intergalactic and circumgalactic mediums), strong galaxy lensing studies, time-domain cosmography with strongly lensed quasars and supernovae, identification and characterization of EM-GW counterparts, exploration of the host galaxy environment of supernovae, binary masses and nebulae abundances, brown dwarfs and planetary mass objects, and synergies with worldwide telescopes and other facilities on La Palma. Furthermore, MAAT top-level requirements allow to broaden its use to the needs of the GTC community for a wide range of competitive science topics given its unique observing capabilities.

2. PRELIMINARY DESIGN

The preliminary design is based on the concept of Advanced Image Slicer (Figure 2). In the original design, the focal plane of the telescope is reimaged by fore-optics on an array of long and thin mirrors that slice the field in correspondingly long and thin images. This mirror array is called the slicing mirror. The beam from each slice is sent to a mirror that reimages the slice on the slit. A pupil of the telescope is imaged on that reimaging mirror by the slice mirror. This permits to avoid vignetting present on previous slicer designs. All slice images are side-by-side on the slit. A final mirror on the slit reimages the pupil at the right place in the spectrograph. Fore-optics are used to reimage the telescope focal pane onto the slicing mirror. Along the length of the slices, the spaxel width will be determined by the size of a pixel on the detector in the spectrograph spatial direction. In the spectral direction, it is the slice width that determines the size of a spaxel.

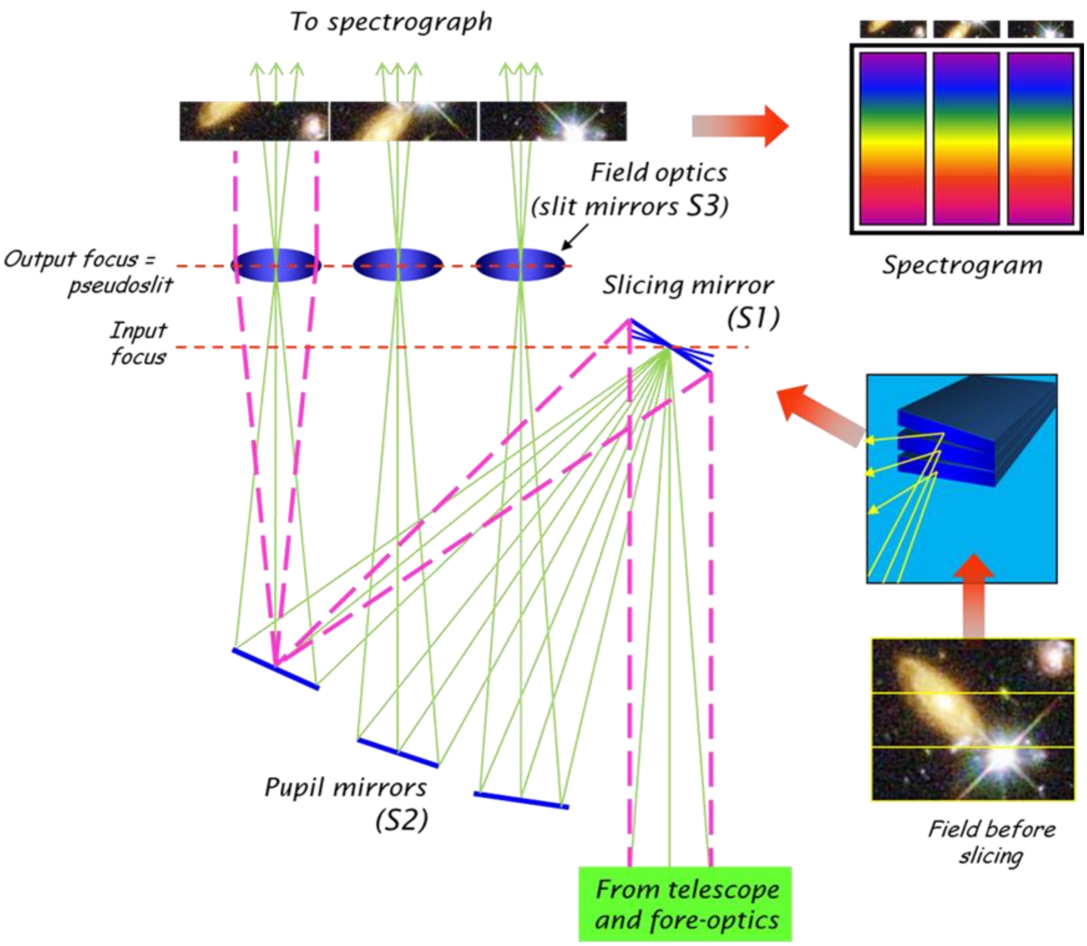

Figure 2. Basic principle of the Advanced Image Slicer.

A modification to the Advanced Image Slicer design was developed by the then Edinburg Observatory[14***]. They reasoned that only 2 mirrors are necessary to reimage the field and the pupil so 2 mirror arrays should be enough, not 3. They then removed the slit mirror array and replaced it by 2 long rectangular mirrors, and modified the curvature of the other optics accordingly. This simplifies the mechanical design and in principle reduces the cost but it brings some problems. First, it degrades the field and pupil image qualities; second, it is impossible to have a unique linear slit, the slit needs to be "staggered." Figure 3 shows the result. Apart from reducing the length of the spectra, it worsens cross-contamination because bright lines as OH lines can contaminate a region of faint lines in an adjacent slice image.

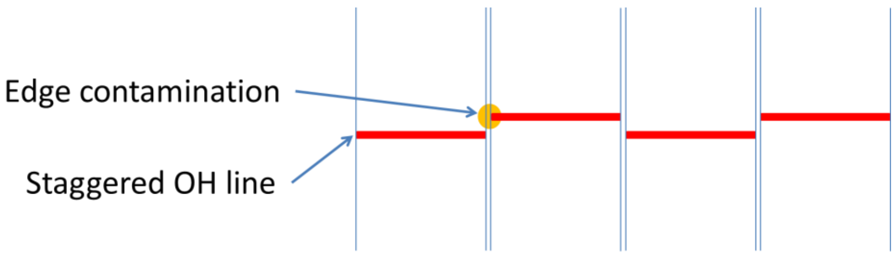

Figure 3. Sketch of the effect of a staggered slit in the version of the AIS developed by the then Edinburg Observatory. It represents the spectra from 4 slices where a bright OH line contaminates adjacent regions where faint lines can be present.

A possibly more important disadvantage that may cancel the cost reduction is that it makes alignment more difficult. Manufacturers have brought this point to us. For MAAT, it is not necessarily a serious problem because we are not working at the near diffraction limit design which asks for particularly high angular precision. Discussions with manufacturers are under way.

There is a third option that we are developing, one that keeps some of the advantages of the Edinburg version of the AIS while removing the staggered slit. There is again a slit mirror array but one that is of much lower cost because it is made of 2 staggered flat mirrors. The staggered slit is then replaced by a linear slit as in the standard design of the AIS. The field and pupil image degradation still remains however as the increased difficulty of doing the alignments. Figure 4 shows a sketch of the design. The 2 staggered mirrors are interleaved to create a simple slit mirror array. The 3 options are nevertheless under study. Note that there is not much difference between the staggered slit and staggered mirror options from an optical point of view. We present the staggered slit option in this paper.

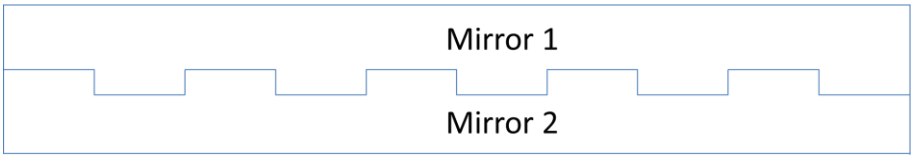

Figure 4. Layout of staggered mirrors creating a slit mirror array.

Figure 5 shows the layout of the staggered slit option. In green are the fore-optics. The first is the pickoff mirror, a 45° fold that captures the light coming from the telescope. The 2 following optics are mirrors that reimage the field on the slicing mirror which is in orange. Six slices are shown. Each slice mirror sends the light to a reimaging mirror (in red). To avoid vignetting typical to this version of the Advance Image Slicer concept, it is necessary to have 2 lines of reimaging mirrors. Each reimaging mirror gives an image of a slice on the slit of the spectrograph. For each line of reimaging mirrors, a long flat rectangular mirror sends the light in the spectrograph. One slit mirror is needed for each line of reimaging mirror because the incident angle of the beam on the slit is different for each of these lines. The angles of the slit mirrors are then slightly different from each other.

We can see in figure 5 that the horizontal incident angle of the beam from each reimaging mirror is not perpendicular to the edge of its slit mirror. This is the result of the slit being tilted with respect to the beam coming from the telescope. A horizontal incident angle is needed to get the light in the right direction after reflection. Since the slit is curved but the slit mirrors are flat, they are positioned at an intermediate position that minimizes the defocus on them. The slice images in the centre are real and in front of the slit mirrors but the edge images are virtual and behind the slit mirrors. The defocus on the slit mirrors increases the footprint so the slit has to be more staggered to avoid vignetting. This slightly reduces the spectral length on the detector but most gratings do not use the full length of the detector so there are no losses for these.

The only exception to the design described above is the optics of the last slice at the bottom of Figure 5. There was not enough space to fit all reimaging mirrors in the space envelope so the last slice uses the standard design of Advanced Image Slicer. A pupil is imaged on that reimaging mirror which permits to make it much smaller and a slit mirror with power permits to position the pupil at the right place in the spectrograph.

The layout shows that the maximum incident angle on the reimaging mirrors is quite large which can create aberrations. If they happen to be too large, we will add a flat mirror at the back of the box to increase its optical length by a factor of 2. The mirror would be on the right in Figure 5 and the reimaging mirrors at the left of the slit. The light from the slicing mirror would first hit this flat mirror and be reflected toward the reimaging mirrors. This would very significantly reduce the maximum incident angle.

Transmissive optics are also under study. The slicing mirror can in principle be made of off-axis powered slices that bend the beam through refraction but previous work done by the author shows that the deviation angle must remain small. It is not the case here so aberrations would result. The slicing mirror must then be reflective. The same is true for the reimaging mirrors. The other optics can be transmissive. The input pickoff and the slit optics can be total internal reflection prisms. The fore-optics can be made of lenses. In that case, the pickoff optics would be at a different position at the same height than the slicing mirror in Figure 5 but probably more to the right.

Figure 6 shows the layout of the slicing mirror. There are 33 slices of 0.303" x 14.2" for a total field of 10.0" x 14.2". The pixels on the detector are 0.127" which gives a satisfactory spectral sampling of 2.5 pixel. Along the slit, a good seeing of 0.6" would be oversampled with pixel so small which uselessly brings readout noise. A better approach is to bin the pixels by 2 then giving 0.254" effective pixels so a more reasonable sampling of 2.4 pixel per 0.6". The spaxels are then 0.254" x 0.303". The total slit length is 8.1' which is longer than the maximum value of 7.4' of the standard masks. This can be done because the box holding the IFU can have a more complex structure than a frame holding a mask. There is a small region that is slightly vignetted but it is in a corner of the field and the losses remains smaller than 20% everywhere. The red dotted line shows the size of a downgraded IFU that we are studying in case that we have to reduce the project goal. The reduced IFU would have 28 slices and a field of view of 8.5" x 12" which is still large enough to satisfy the science case. It would simplify the mechanical design of the box, improve the IFU image quality, reduce the cost and bring the IFU earlier on the telescope.

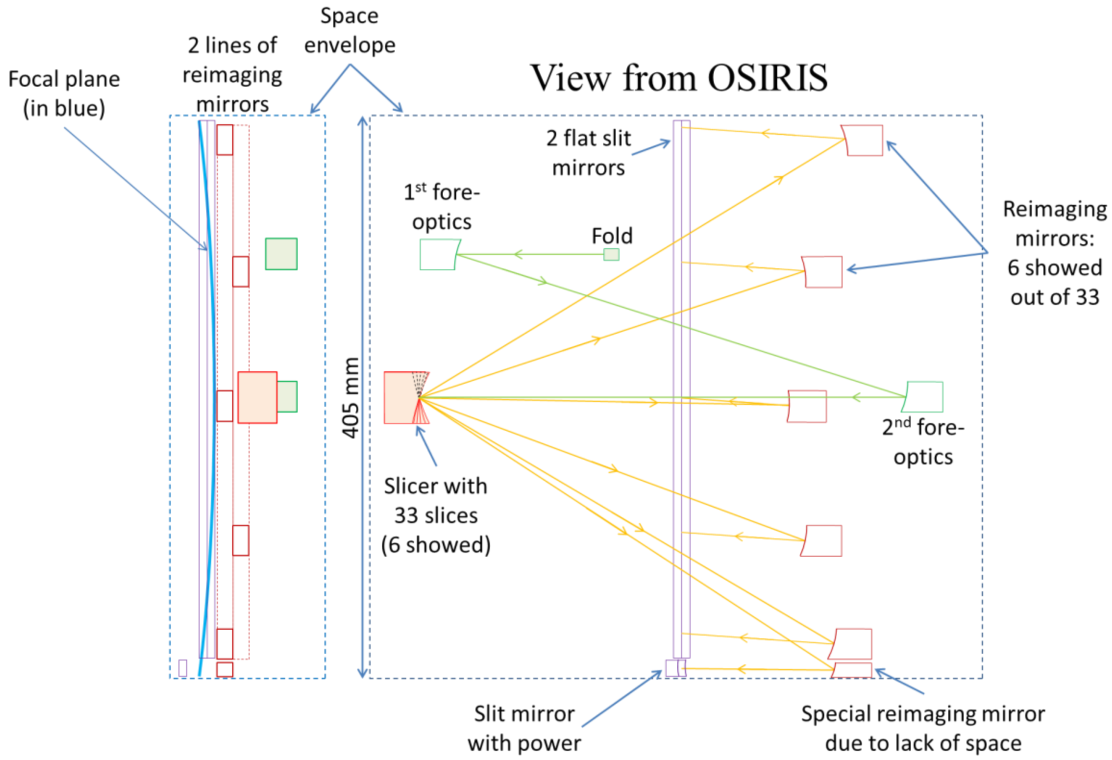

Figure 5. Layout of the inside of the IFU box showing top view from OSIRIS (right) and side view (left). Fore-optics are in green, slicing mirror in orange, reimaging mirrors in red and slit mirrors in violet.

Compared to a standard slit of 0.6", the slices of 0.303" increase the spectral resolution. Assuming a Gaussian spectrograph PSF of 0.3" in width, a reasonable value for a 0.6" slit, spectral resolution would be 1.6 times higher with the slicer than with the standard slit and all the light of the objects would be captured except for the losses in transmission of the IFU. This is however theoretical. The as-designed aberrations are known from the spectrograph optical design but this does not include the alignment aberrations which can easily dominates the PSF. Real measurements of the PSF on the detector must be done. We intend to measure the PSF by using 2 out-of-focus masks with a series of pinholes along the slit. Astigmatism for example would reduce the defocus in one direction and increase it in the perpendicular direction which would change a circular image into an ellipse. Note that the shape of the GTC primary is far more complex than a simple circle and diffraction effect cannot be discarded as shown in Figure 7 but the information is there and can be dig out with the proper software. Knowing these aberrations, modifications to the IFU can be made to correct at least some of them. This can be done because the real slit of the system is the set of slices on the slicing mirror. There is then additional optics in the "extended" spectrograph: the reimaging mirrors. Each of these mirrors reimages only a short slice image on the slit of the spectrograph so its aberrations do not vary much along that slice. Modifications to the reimaging mirrors can then correct the local spectrograph aberrations. Misalignments will mainly create defocus, coma, astigmatism and spherical aberration. Defocus and astigmatism can easily be corrected. Since the reimaging mirrors are toroidal due to the off-axis incident angle on them, the correction is simply done by changing some of the values given to the manufacturer. Coma and spherical aberration corrections would however mean making the reimaging mirror surface shapes more complex which would increase the cost.

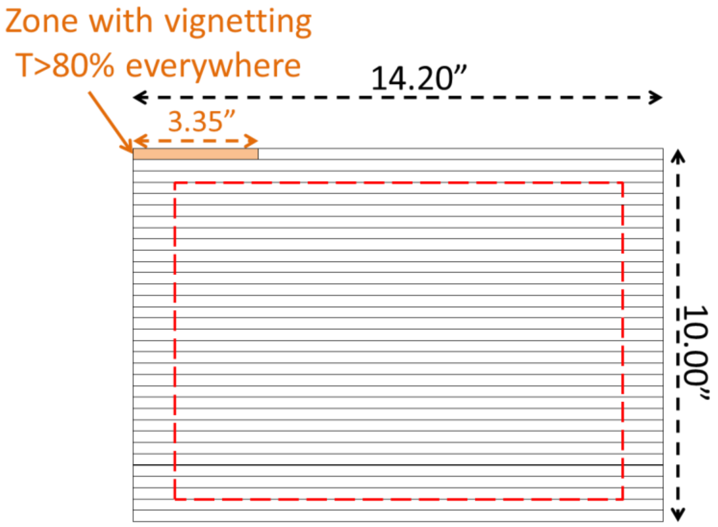

Figure 6. Layout of the IFU field showing the slices. The red dotted line shows the field size of a downgraded IFU also under study.

Figure 7. Out-of-focus images of a PSF with no aberrations using wave optics. The unusual shape is due to the shape of the GTC primary mirror.

3. CONCLUSION

The work done so far shows that an image slicer can be added to the OSIRIS spectrograph without any show stopper. The IFU would not only considerably increase the throughput of the spectrograph compared to a 0.303" slit that would scan an object in the sky but also increase the spectrograph resolution by probably a factor 1.6. To ensure this improvement, we intend to measure the spectrograph aberrations with out-of-focus masks and correct as much as possible these aberrations by modifying the reimaging mirror shapes. The IFU design has a series of challenges as the tilted and curved slit, the large incident angle on the reimaging mirror and the low efficiency of reflective and anti-reflection coatings over the 360 nm and 1000 nm range but none that cannot be solved.

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