Slit Mask Integral Field Unit - 200um
Required information for the SALT Call for Proposal Phase 1

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1. **Introduction:**

The SMI-200 (Slit Mask IFU - 200um) is a new observing mode for RSS on SALT. SMI-200 consists of a retrofit to a long-slit-like cassette using fold prisms and fibre optics; it is inserted in the same manner as the cassettes for long-slits, MOS masks, or polarimetric apertures. The engineering commissioning for SMI-200 **(using the PG900 grating at 15.125 degree grating and 30.25 degree camera angle with 1x1 binning)** was successful. The instrument can now be used by the community on a "shared risk" basis. This document describes the technical information required to plan for observation using SMI-200. For detailed information about the technical parameters refer to Chattopadhyay et al. 2022 (SPIE, 12184/5V); for an update on the early commissioning results see Chattopadhyay et al. 2024 (SPIE, in press).

NB: SMI-200 spectral resolution and throughput is referenced to the so-called `1 arcsec' longlit mask (MASKID=PL0100N002). However, we have determined that PL0100N002 is actually 1.3 arcsec wide, presumably due to an error in fabrication. In this document, we refer to the currently used `1 arcsec' longslit mask (PL0100N002) as 1.3 arcsec longslit mask. Note the RSS simulator tool prediction for PL0100N002 assumes the designed width of 1 arcsec and not the actual width of 1.3 arcsec. This results in a simulator prediction for this mask that is too high in spectral resolution (×1.3) and too low in throughput (×1/1.3).

2. **Observing efficiency: When to use SMI-200**

Relative throughput: Any comparison to existing long-slit data should take into account differences both in solid angle and throughput (per unit solid angle). Each SMI-200 fibre has an area of 0.61 arcsec^2. For example, in the case of an idealized uniform, extended source, the light-gathering power of a single SMI-200 fibre is only 36% of the 1.3 arcsec long-slit in a 1.3 arcsec aperture along the slit. In addition, there are throughput losses from the fibre-optics, as follows. Development of the SMI-200 was particularly challenging given the small volume available to fit all the optical components. This led to focal-ratio degradation that reduced the median throughput to 58% in the accepted f/4.2 beam of the RSS collimator. On-sky we find the throughput of the fibres in the centre of the slit is close to 57% (matching lab measurements). However, the SMI-200 throughput diminishes significantly at the edges of the fibre pseudo-slit. This significantly lower throughput at the edge of the fibre slit is caused by a mismatch in telecentricity due to a design error (to be corrected in future SMI units, including a replacement for SMI-200). Currently 94% of the fibres demonstrate between 17-57% throughput (per unit solid angle) due to this mismatch; this is equivalent to 5-17% relative to 1.3 arcsec longslit in a 1.3×1.3 arcsec^2 aperture. The median throughput relative to 1.3 arcsec longslit is 11% while compared to 1 arcsec longslit it is 19%. The left and right half of the slit have a median throughput of 10% and 13% compared to the 1.3 arcsec longslit respectively (17% and 23% compared to 1 arcsec longslit). Because of the mapping between the fibre IFU and the slit, this creates a distinct pattern of relative throughput on sky. See Section 4.6 and Figure 5 for details. Note one half of the array has higher mean throughput than the other due to some asymmetry in the slit telecentricity.

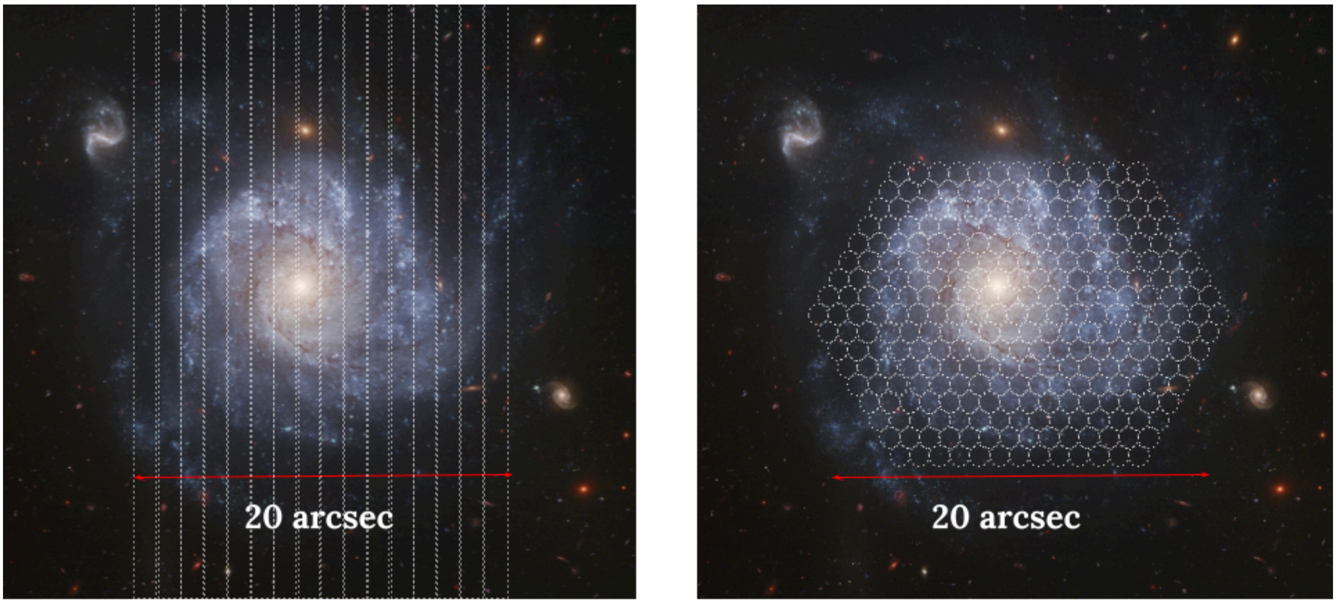
Sky coverage and simultaneity: Even with reduced throughput, SMI-200 is better suited for observing extended sources with diameter of the order of 20-60 arcsec due to the following reasons:

- **2.1.** The spectral resolution is 1.28 times higher than simulated 1 arcsec longslit and 1.67 times higher than the as built 1.3 arcsec longslit. (The effective width of a fibre is cos(30) × fibre core diameter.)
- **2.2.** To completely map a 20 arcsec diameter circular object with a 1.3 arcsec longslit requires 16 exposures (20 arcsec/1.3 arcsec), as illustrated in Figure 1. Such a large number of exposures is most often prohibitive for SALT given the tracker limitations. The median throughput relative to 1.3 arcsec longslit in a 1.3x1.3 sq. arcsec aperture is 11% (refer to figure 3), hence one would require 9 times the exposure length to get the same median SNR. However, this is at 1.7 times higher spectral resolution and 2.8 times higher angular resolution (area). Compared to a hypothetical 1 arcsec

longslit in a 1x1 sq. arcsec aperture, the relative throughput is 19% (refer to Fig 4), which defines 5x the exposure length with SMI-200 is required to get the same median SNR. However, this is at 1.3 times higher spectral resolution and 1.6 times higher angular resolution (area). Future SMIs with the minor tweak in telecentricity would provide the same depth of 1.3 arcsec longslit in just 6 exposures for similar sized objects again with the noted higher spectral resolution.

2.3. Other advantages of integral-field fibre spectroscopy over long slit spectroscopy that apply to the existing SMI-200 include

- reliable relative astrometric positioning of all apertures,
- non-varying sky conditions over the full 2D spatial coverage,
- seeing-independent spectral resolution (image structure is azimuthally scrambled),
- pupil-scrambling (for more uniform instrumental response and better sky-subtraction).



16 exposures of 1.3 arcsec long slit | **Single exposure with SMI-200**

Figure 1: Difference in spatial coverage for extended sources for 16 x 1.3 arcsec long slit exposures (left) versus one SMI-200 exposure (right). I.e., the 1.3 arcsec longslit would require 16 exposures to cover the same area of the galaxy covered by SMI-200 in a single exposure.

3. Total time to be requested:

The total requested time should include the following:

3.1. **Exposure time:** We recommend using the RSS simulator with the 1 arcsec longslit option and then use Figure 3 (to be updated) right panel to define the exposure based on the throughput. The SMI-200 median throughput relative to 1.3 arcsec longslit is 11% and relative to 1 arcsec longslit is 19%. Thus one would require 9x exposure time of the as built 1.3 arcsec lognslit while 5x exposure time of the simulated 1 arcsec longslit. Refer to section 4.6 for more details of the relative throughput value of each fibre.

3.2. **Flat fields:** A set of 5 flat field exposures should be taken after the target is observed to identify the fibre traces. For the commissioning setup the following flat field setup was used: 5s exposure time using both QTH 1 and 2 lamps with Neutral Density filter at 20%. This requires ~180 sec overhead time. However, one must note that the flat field exposure setting may vary for other instrument settings and tracker positions as well as the binning method. Refer to section 5.1 for more details.

3.3. **Arc frames:** Although we are making a wavelength calibration library to ensure adequate S/N in all fibers, a set of arcs taken right after the target is also necessary. For the commissioning setup a set of 2-3 ThAr arc frames of 20 sec exposure time were used with unbinned pixels. This amounts to ~180 sec + the readout time for the overhead time.

3.4. **Acquisition overheads:** The typical overhead for RSS with longslit mask is 600 sec to ensure proper slew, acquisition, spectrograph configuration and slit mask selection. For SMI-200, an additional overhead of 70 sec would be required. Refer to section 5 for more details.

Please note that the overhead times listed here are estimates, and they will be updated in upcoming semesters.

4. Technical description:

4.1. Sampling: The spatial sampling is 0.9 arcsec (circular diameter), and 0.61 $arcsec^2$ (area), as defined by the circular core fibre diameter. Centre to centre fibre spacing is 1.08 arcsec. For truly integral coverage, i.e., to fill the gaps between fibres, refer to Section 5.6 (Dithering) under operating principles.

4.2. Field of View: SMI-200 has a slightly elongated hexagonal field of view. The longest corner to corner distance is 22.3 arcsec; the smallest side to side separation is 17.6 arcsec. See Figure 2.

4.3. Spectral Resolution: We have measured spectral resolution in only a single grating configuration - PG900 grating at 15.125 degree grating and 30.25 degree camera angle. We find from arc and sky frames that the 1.3 arcsec longslit FWHM is roughly 1.67 times larger than SMI-200 FWHM, consistent with the above discussion. To estimate spectral resolution R = $\lambda/\Delta\lambda$ for any spectrograph and grating configuration for SMI-200, use the RSS simulator tool to compute the resolution for the 1 arcsec longslit (R_{las}). The SMI-200 spectral resolution $R_{SMI-200}$ = 1.28 R_{las}, i.e., 1.28 times the simulated resolution for the *simulated* 1 arcsec longslit.

4.4. Bandpass: RSS simulated wavelength coverage is applicable to SMI-200 for all grating and spectrograph configurations.

4.5. Mapping: The mapping of fibre location on slit in arcsec (the centre of the slit is marked as 0 arcsec) to on-sky location in arcsec can be found from Figure 2.

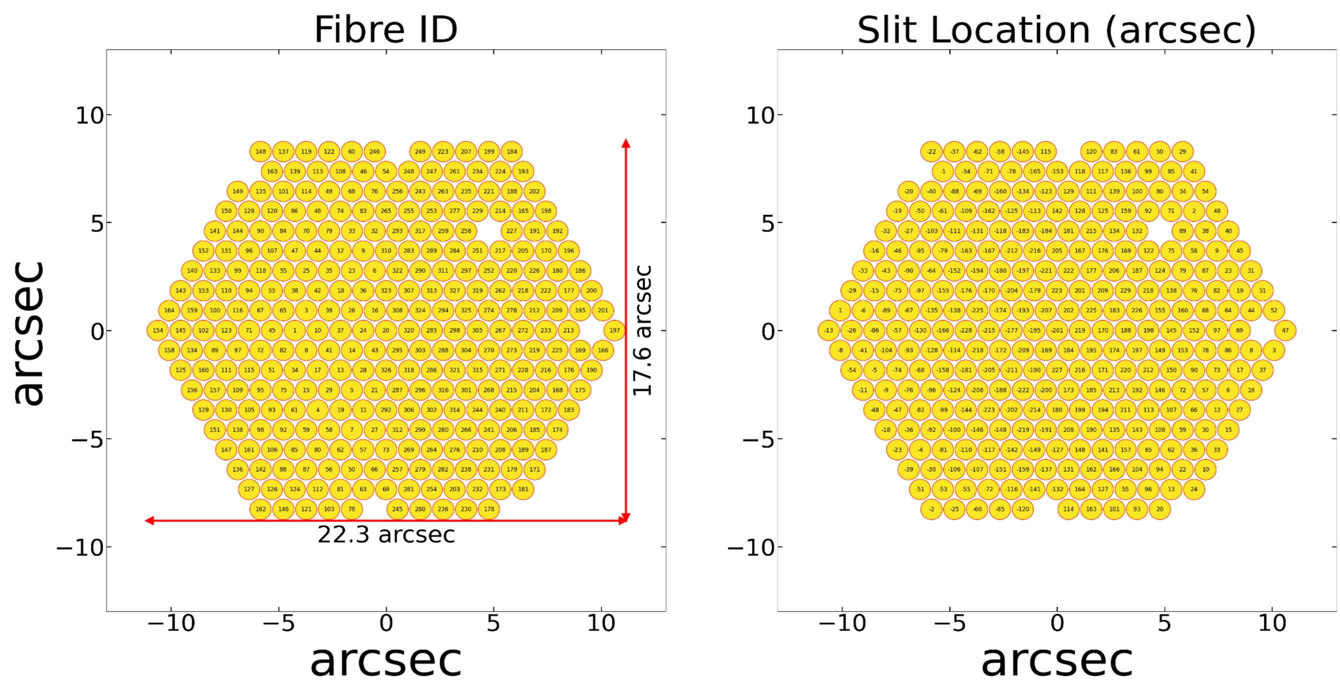


Figure 2: X and Y axis denote location of fibres on the sky. The annotated numbers inside each fibre footprint defines (right) the location of the same fibre at the slit which is at the input of the spectrograph in arcsec where 0 arcsec is the centre of the slit; and (left) the ID of the same fibre at the slit where 1 and 327 denote the lower end upper end fibre respectively.

4.6. Throughput: Each SMI-200 fibre has an area of 0.61 $arcsec^2$, so the throughput should be 36% of the 1.3 arcsec long-slit (1.3x1.3 $arcsec^2$). With 58% median throughput measured in the lab, we expected the overall relative throughput to be around 20%. However, due to a telecentric mismatch between SMI-200 and RSS, the effective fibre throughput diminishes significantly toward the edges of the fibre pseudo-slit (due to vignetting). This will be corrected in next generation SMIs. The below figure 3 measures the relative throughput when compared to a 1.3 arcsec longslit at camera angle 30.25 degree and grating angle 15.125 degree with PG900 grating. Figure 4 estimates the relative throughput compared to a 1 arcsec longslit. A relative throughput multispectral file will be provided to find the throughput at any spectral and slit location for the above configuration.

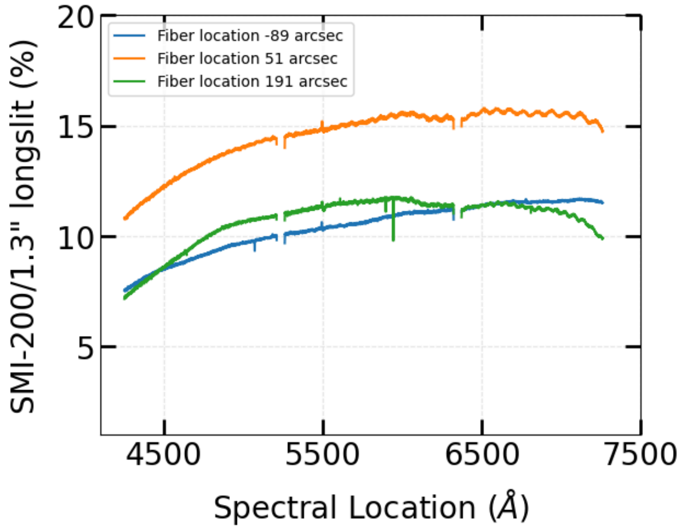


Figure 3: Measured SMI-200 relative throughput compared to 1.3 arcsec longslit in different (left) spatial locations and (right) spectral channels. The used configuration was 30.25 degree camera and 15.125 degree grating angle (PG900).

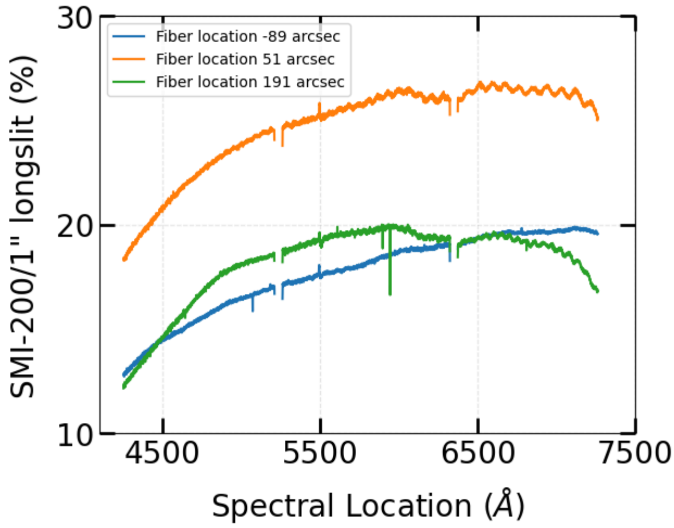


Figure 4: Estimated SMI-200 relative throughput compared to 1 arcsec longslit in different (left) spatial locations and (right) spectral channels. The used configuration was 30.25 degree camera and 15.125 degree grating angle (PG900).

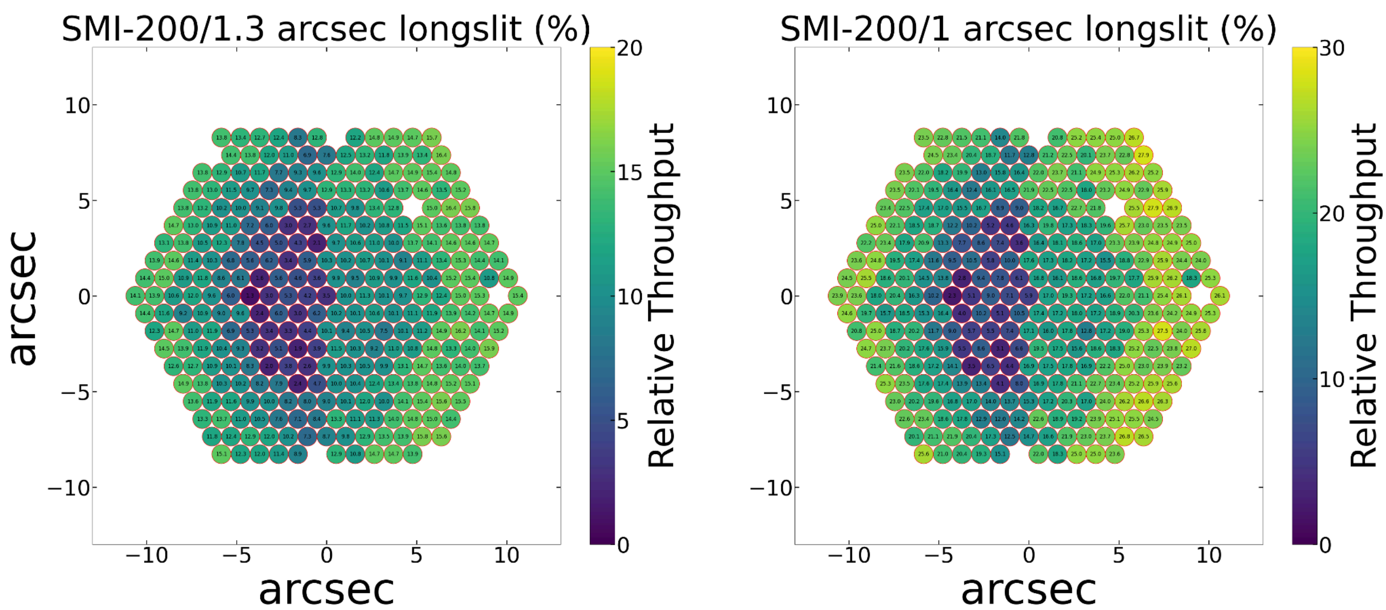


Figure 5: On-sky relative throughput distribution of SMI-200 compared to the 1.3 arcsec longslit. Use the right panel throughput to estimate the additional exposure time required compared to RSS simulation tool with 1 arcsec slit. Multiply the RSS simulated exposure time with sqrt(100/fibre throughput) to obtain the required exposure time.

5. Operating principle:

5.1. Calibration Exposures: Flat field exposures are necessary to extract traces of the fibres and the same traces are used to create multi-spectral files (similar to long slit spectra) from object exposures. Like other slit masks, SMI-200 is also selectable from the slit mask cartridge case. However, due to uncertainty in insertion mechanism, the location and orientation of fibre traces on the detector are not repeatable. Hence *every object exposure should be associated with a flat and arc exposures*. One should estimate an overhead of 180s each for flat and arc (include additional overhead for the arc readout times) exposures respectively. We will be building up a database of recommended ARC lamps and exposure times for different grating and spectrograph configurations.

5.2. Detector focus: SMI-200 is found to have an offset of 450 um from the best RSS camera focus position for a 1 arcsec longslit. The offset should be fixed for all observing configurations. An additional 15 sec overhead time must be included to achieve this detector focus offset.

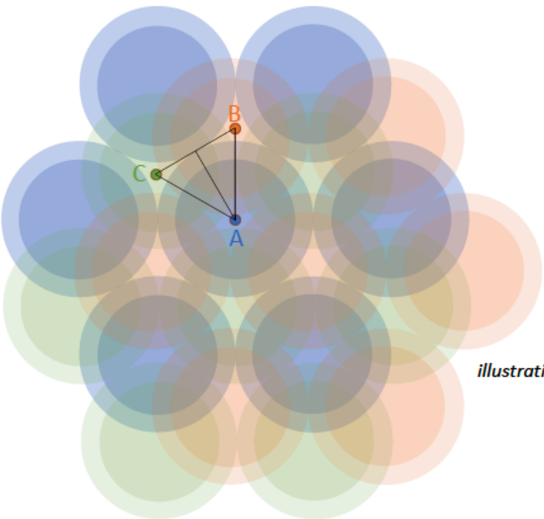
5.3. Telescope focus: No Adjustment of the telescope focus between long-slit masks and SMI-200 is required.

5.4. Focal plane offset: We have observed a star with a 1 arcsec longslit and SMI-200 in the same track (i.e. pointing accuracy was actively managed in a closed feedback loop). We initially placed the star at the centre of the longslit and then replaced the longslit with SMI-200. We found that there is a 2.86 arcsec offset radially between the longslit centre and SMI-200 centre. The SMI-200 centre is 2.7 arcsec east and 0.95 arcsec north of the longslit centre. An additional 30 sec overhead is required to perform the focal plane guided offset.

5.5. Target acquisition: Unlike longslits, SMI-200 doesn't have a reflective surface to image and monitor the location of the object relative to the longslit. It is advisable to first acquire the object on the longslit, start the tracking, apply the focal plane offset and then move in the SMI-200 to centre the target. The user may want to include this time (~70s) as an overhead.

5.6. Dithering: As described earlier, there are gaps between the fibres due to circular shape and hexagonal packing. If a user requires truly integral field coverage, it is advisable to perform a three point dither strategy. In this strategy one would observe the same object with three slightly different central target coordinates (called dithered coordinates) which are radially offset from one another by 0.62 arcsec as shown in figure 5. One of three dithered coordinates is the user supplied target coordinate (point A in figure 5). If dithering is requested, the observer would need to observe the same target with two other dithered coordinates (point B and C in figure 5) from the main coordinates supplied by the user as depicted in figure 5. The user may want to keep this in mind for the total requested exposure time and track length. The three dithered exposures can be combined with a python script (supplied with the phase 2 call) to form a cube with square pixels without gaps. The user must note that tracker guided offsets have about 0.1" accuracy and the overhead required for each guided offset is about 30 sec.

Standard 3-point dither pattern to fill interstitial gaps



X, Y relative offsets

Dither position	NIRWALS, SMI-300	SMI-200
A	0, 0	0, 0
B	0, 0.94”	0, 0.63”
C	-0.82”, -0.47”	-0.55, -0.315
Fiber : Core: Spacing:	300:300:370 µm 1.326” 1.636” (*s*)	200:220:240 µm 0.882” 1.091” (*s*)

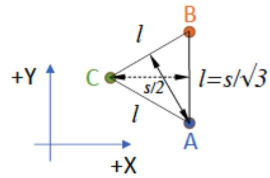


Figure 5: Dither pattern of the SMI-200 fibres to obtain truly integral field coverage. One may use 1/3rd of the total exposure time at each dithered location.

6. Data reduction recipe:

A data reduction recipe and cube formation method will be provided before the phase 2 submission. We will demonstrate the recipe through data reduced for a spectro-photometric standard star and a star-forming galaxy observed with SMI-200.