A User–oriented Comparison of the Techniques for 3D Spectroscopy

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1 Introduction

3D spectroscopy attempts to get closer to the fundamental goal of astronomical observing techniques, which is to **record the direction, wavelength, polarization state and arrival time for every incoming photon over the largest field of view**. In fact using 3D spectroscopy, the wavelength and the incoming direction in a 2D field of view are recorded in a (x,y,λ) data cube, in contrast with standard techniques which either do imaging over a 2D field, or spectroscopy along a 1D slit. There are two main ways of doing 3D spectroscopy: the best one is to simultaneously record both direction and wavelength, while in the other case these are not recorded at the same time, but scanning in one of the 3 dimensions is required. Clearly the latter throws away some of the incoming photons, therefore requiring longer exposure times, and has problems with variable observing conditions. Nevertheless it can be useful for some particular applications.

2 Simultaneous Techniques

Integral field spectroscopy (IFS) rearranges over a 2D detector the spectra coming from every pixel in a 2D field of view. Therefore it provides a straightforward way to fill the (x,y,λ) data cube. The rearrangement of the spectra can be done with microlens arrays (e.g. SAURON (2)), fibre–lenslet arrays (e.g. IFS in GMOS (1)), or image slicers (e.g. SINFONI (8)). It is becoming a popular technique, since most modern spectrographs on large telescopes have IFS capability. IFS in general has the advantage of providing great flexibility in the choice of the spectral resolution and wavelength range and of being easily fed by adaptive optics systems. The main disadvantage is the limited field of view, since the number of spatial elements is limited by the number of pixels along one side of the detector. This drawback is at least partially overcome by an obvious development of IFS: the field of view, particularly for IFS using fibre–lenslet arrays, can be separated in several disjoint regions, for example to cover several galaxies in a cluster. Examples of this development are the multiple IFS of GIRAFFE (9), and the even more flexible programmable IFS concept (5). Because of its flexibility, IFS is suited to a large number of applications, from kinematical studies of the Galactic centre to stellar population and kinematical studies of distant galaxies (10).

Also **slitless spectroscopy** is capable of simultaneously recording a (x,y,λ) data cube: originating from the objective prism technique, used on Schmidt telescopes for more than fifty years, it is easily implemented in modern imaging (focal reducer) spectrographs by removing the slit. Therefore it records spectra of all objects over the whole field of view, which can be quite large, like the 14'x14' field of VIMOS (12). The disadvantages are the high sky background, since on every detector pixel the sky is integrated over the whole wavelength range, and the overlap of spectra in the dispersion direction. Still this technique is particularly useful for surveys and searches of special objects, when the sky background is very low, like in space or in small atmospheric windows. For example it has been successfully used with ACS on the HST for GRAPES, a spectroscopic survey of the Hubble Ultra Deep Field down to an AB magnitude limit of $z = 27.2$, leading to the discovery of a large number of emission line objects over a huge redshift range, like AGN and Lyman α galaxies (15). In this case the effects of the spectra overlap has been substantially reduced by taking spectra at various position angles. An example of the use of slitless spectroscopy from the ground is the search for Lyman α emitters at z=6.5 in the atmospheric window centred at 915 nm. In this case the spectral range can be limited to the 20 nm width of the window by using a narrow-band filter. Therefore both the sky emission and the spectra overlap are greatly reduced and very faint emission line objects can be found down to a line flux of $2 \times 10^{-17} erg\ cm^{-2} s^{-1}$ (11).

Energy–resolving detectors are imaging arrays where each pixel has some energy resolution. Therefore these are true 3D devices capable of simultaneously recording the (x,y,λ) data cube, and no spectrograph is necessary. Being mostly photon-counting detectors, they also have a very good temporal resolution. Their main disadvantages are the very limited spectral resolution and field of view. Two different technological approaches are being explored in the optical range: the Superconducting Tunnel Junctions (STJ (14)) and the superconducting transition-edge sensors (6). Currently STJ detectors using tantalum metal films have a good quantum efficiency in the optical range (about 70%), but have a resolution $\frac{\lambda}{\Delta\lambda}$ of only about 20 and a total number of pixels of about 100. The latter could reasonably be increased to 10000. High speed energy-resolved observations of rapidly variable stars and optical pulsars have been obtained with STJ detectors, and their use as order sorters in an intermediate resolution spectrograph (not 3D) has been investigated (7).

Although purists may not consider **multi–object spectroscopy** as true 3D spectroscopy, since it does not completely cover a 2D field of view, it does however produce spectra of many objects in a large field, and very suitably fulfils the needs of many applications, making it the most popular 3D technique. Practically all telescopes have MOS instruments, using either a fibre positioner coupled to a spectrograph, movable slitlets, or a multi-aperture plate. The latter implementation has advantages in terms of better sky subtraction and throughput than fibres, and a larger number of objects and better positioning flexibility than slitlets. A good example is VIMOS on the VLT (12), which is capable of simultaneously recording spectra of 1000 objects over a 14'x14' field of view. The disadvantages are that it requires prior imaging (and mask preparation), that objects have to be preselected (not good for object searches), and that it is not capable of a complete 2D coverage of extended objects.

3 Scanning Techniques

Tunable imaging filters cannot simultaneously record the data cube, but require scanning in wavelength. The most used in astronomy is the Fabry–Perot filter, which uses interference between two glass plates (4). They have very good imaging capability, a large field of view and good spectral resolution. They suffer from the so–called phase problem: the central wavelength is not constant over the field of view. Therefore reconstructing the (x,y,λ) data cube is not straightforward. Fabry–Perot filters have been used for a large number of applications mostly on nearby galaxies and nebulae.

Imaging Fourier Transform Spectroscopy (IFTS) is a special technique using the interference of two optical beams. Although it requires several exposures by scanning a movable mirror, and the reconstruction of the (x,y,λ) data cube is not straightforward, but requires heavy computation, nevertheless the scanning does not imply any loss of photons, which are all recorded over the full field of view and wavelength range (3). A disadvantage compared to the simultaneous 3D techniques, like the IFS, is that the readout noise affects the final data cube not just once, but a number of times equivalent to the number of spectral elements. Also each spectral element suffers the sky noise of the whole bandpass. Therefore IFTS is competitive when a reduced number of spectral elements is required over a large field, as, for example in kinematic studies of the Galactic centre. One of the few examples of IFTS used in astronomy is BEAR on the CFHT (13).

Scanning long–slit spectroscopy does not require a new instrument, but uses a normal long-slit spectrograph. It does not simultaneously fill the data cube, but can be used for very elongated objects, like edge-on galaxies, when only coarse information is required in the second spatial direction.

4 Selection of the Most Suitable Technique

Although advantages and disadvantages can be found (see Table 1), it is hard to say which technique is best. One has rather to find the technique which most efficiently fills the (x,y,λ) data cube for each specific application. In most cases the data cube is largely empty. However it is exactly in these empty spaces that one can make serendipitous discoveries.

Table 1. Synopsis of the techniques for 3D spectroscopy

Technique	Advantages	Disadvantages	Applications
IFS	Simultaneous (x,y,λ) Spectral flexibility Disjoint regions possible	Limited f.o.v.	Galactic centre, distant galaxies, etc.
Slitless spectr.	Simultaneous (x,y,λ) Normal spectrograph Large f.o.v.	High sky background Spectra overlap	Surveys Searches for objects
Energy–res. det.	Simultaneous (x,y,λ) No spectrograph Good temporal res. Good efficiency	Very limited $\frac{\lambda}{\Delta\lambda}$ Very limited f.o.v. Under development	Rapid variables Optical pulsars
MOS	Normal spectrograph Spectral flexibility Very large f.o.v.	2D field not covered Prior imaging Mask preparation	Large redshift surveys
Tunable im. filters	Large f.o.v. Good spectral res.	Scanning in λ Variable central λ	Nearby galaxies Nebulae
IFTS	No loss of photons	Scanning required High sky background Heavy computations	Galactic centre
Long slit scanning	Normal spectrograph	Scanning required	Very elongated objects

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