SITELLE: A wide-field imaging Fourier transform spectrometer for the Canada-France-Hawaii telescope


Dépt. de physique, de génie physique et d’optique, Université Laval, Québec, Qc, Canada G1K 7P4 and Centre de recherche en astrophysique du Québec (CRAQ)

ABSTRACT

We describe the concept of a new instrument for the Canada-France-Hawaii telescope (CFHT), SITELLE (Spectromètre Imageur à Transformée de Fourier pour l’Étude en Long et en Large de raies d’Émission), as well as a science case and a technical study of its preliminary design. SITELLE will be an imaging Fourier transform spectrometer capable of obtaining the visible (350 nm – 950 nm) spectrum of every source of light in a field of view of 15 arcminutes, with 100% spatial coverage and a spectral resolution ranging from $R = 1$ (deep panchromatic image) to $R = 10^4$ (for gas dynamics). SITELLE will cover a field of view 100 to 1000 times larger than traditional integral field spectrographs, such as GMOS-IFU on Gemini or the future MUSE on the VLT. It is a legacy from BEAR, the first imaging FTS installed on the CFHT and the direct successor of SPIOMM, a similar instrument attached to the 1.6-m telescope of the Observatoire du Mont-Mégantic in Québec. SITELLE will be used to study the structure and kinematics of HII regions and ejecta around evolved stars in the Milky Way, emission-line stars in clusters, abundances in nearby gas-rich galaxies, and the star formation rate in distant galaxies.

Keywords: Fourier transform spectroscopy, hyperspectral imagery, planetary nebulae, supernova remnants, galaxies

1. INTRODUCTION: THE Imaging FTS in context

There are basically two traditional approaches to obtaining spectral information on extended astrophysical objects. Imagery with filters allows the observer to map a target in selected wavelength ranges and to extract the required physical information by comparing the relative flux of the sources in these bands. This technique is used to obtain color-magnitude diagrams of star clusters or resolved galaxies (Johnson UBVRI broad-band filters for example), or to map abundance, temperature or density gradients in nebulae or gas-rich galaxies (using narrow-band interference filters centered on specific emission lines such as Hα, [NII] or [OIII]). Images of the targets in the different band passes must be obtained one after the other, rejecting each time all photons excluded by the selected filters (up to 99.8%). Moreover, this technique is severely limited in terms of spectral resolution and is limited to face-on galaxies. Dispersive spectroscopy with slits allows a much finer spectral resolution at the expense of spatial information on the targets. The use of multi-object spectrographs (Sloan [1]; 2dF [2]) and integral field spectrographs (GMOS-IFU on Gemini [3]; or VIMOS-IFU [4]) on large telescopes has revolutionized data collection by allowing respectively to obtain spectra of a large number (up to 1000) of objects dispersed in a large field or to spatially sample relatively small (of the order of 10 arcseconds) objects. An integral field spectograph allowing observations across a relatively large field of view (41 x 33 arcseconds at a spectral resolution $R \sim 1000$), SAURON [5], has revolutionized the study of late-type galaxies [6], and a similar, but much more complex, instrument, MUSE, is being built for the VLT. High spectral resolution of single lines are also performed with instruments such as Fabry-Perot interferometers [7] to determine, for instance, the rotation curves of galaxies.

A large number of research programs would benefit from an instrument capable of simultaneously obtaining spatially resolved, high quality spectra on extended areas (of the order of 10 arcminutes) and with a resolution up to $R \sim 10^4$. Fourier transformer imaging spectroscopy is very promising in that regard. Based on the principle of the Michelson
interferometer, Fourier Transform Spectrometers (FTS) are extremely efficient because all photons are collected and analyzed. Moreover, by using appropriate optical configurations, it is possible to transform the traditional one-pixel FTS into a truly integral field spectrometer [8]. Although FTS are most widely used in military and chemical industries, they have also been very successful in planetary exploration (on board the Mariner, Voyager and more recently Cassini spacecrafts [9]) and in the analysis of the Earth’s atmosphere (a recent example being the ACE-FTS instrument on board the SCISAT-1 remote sensing Canadian satellite [10]). The use of FTS in astronomy is not widespread, mostly because of the technical difficulties in building such instruments, but some examples need to be mentioned. The FTS at Kitt Peak’s Mayall telescope was used the 1970’s and 1980’s to provide exquisite spectra of late-type stars [11c,11b]. At the CFHT, the high-resolution FTS was widely used on a large variety of planetary and stellar programs. Made able to work on an imaging mode in the early 1990’s, the called BEAR, it provided integral field spectra such as planetary nebulae, massive star clusters and star-forming regions in a 24 arcsecond field of view [11e], see section 1.2. Other examples include the FTS built by D. Naylor (U. Lethbridge) on the JCMT [11a,11c], an FTS for SPIRE, one of three instruments to fly on ESA’s Herschel Space Observatory [12], a far-infrared FTS on the Japanese satellite AKARI, a mid-IR FTS (CIRS) on the Cassini spacecraft and for the near-IR, PFS on Mars Express with a copy on Venus Express. We should also mention another imaging FTS prototype, working in the visible part of the spectrum that was built at the Laurence Livermore Lab [13], but which development ceased about a few years ago.

The advantages and disadvantages of the imaging FTS technique, as well as the relative merit of different approaches to 3-D imagery are discussed by Ridgway & Braul [14] and, more recently, by Bennett [15]. The development of imaging FTS in astronomy was given a strong incentive during the early definition phases of the NGST (now known as the James Webb Space Telescope): astronomers supported by the three participating space agencies (NASA, ESA and the Canadian Space Agency) presented studies of imaging FTS at the NGST Instrumentation meeting in Hyannis in 1999 september [16, 17, 18].

SITEILLE (Spectromètre Imager à Transformée de Fourier pour l’Étude en Long et en Large de raies d’Emission, or Imaging FTS for the study of emission lines) will be the second Fourier transform spectrometer attached to the Canada-France-Hawaii telescope. The adventure of the FTS at CFHT started in Oct. 1977 when a convention to build a high resolution Fourier transform spectrometer for the infrared domain (1 – 5µm) was signed between the CFH Corporation and CNRS. This was based on the experienced previously gained with such an instrument at the OHP 193-cm telescope and with a visiting instrument on 5-m Palomar telescope. The new FTS, capable of a resolution up to 5x10^5 at 2µm (60 cm maximum optical path difference), was delivered at Mauna Kea in Jul. 1980. However, it was able to really start its scientific life only in 1983 when the f/35 infrared Cassegrain focus, for which it was designed, was fully ready. Some highlights of the FTS in the high-resolution mode were the first detection of the molecular ion H_3^+ in the jovian aurorae [20], the spectroscopy of the Venus night-side [21], and the detection of the hot and cold gas on the line of sight of a set of embedded high-mass young stellar objects [22]. In parallel, the possibility of adapting the FTS to an imaging mode was considered as early as 1990 with a first test with a CCD camera. The instrument being initially built with a step-by-step data acquisition mode, it was potentially easy to adapt it to this mode. Besides an optical coupling of the camera to the FTS, a synchronization of the camera data recording with the scanning of the optical path difference of the interferometer had to be made. The final mode, named BEAR, was developed with the near infrared CFHT camera Redeye equipped with a 256x256 HgCdTe mosaic. An optical interface imaged the two output beams side-by-side on the single camera, using 128x256 pixels. Since the FTS was not initially designed for the imaging mode, the field of view was small, 24'' in diameter, but with all the capabilities of resolution of the instrument.

The operation of the BEAR mode, completed by the full development of the specialized data reduction package, really started in mid-1996 and was available until the decommissioning of the infrared focus at the beginning of 2001, which meant the end of the FTS. The main astronomical targets for BEAR were the planets Venus and Jupiter, young planetary nebulae (Figure 1), reflection nebulae, star forming regions, the inner region of the Galactic Center, providing on all these sources unique results with spectral imagery at 10 km/s resolution in the K band [23,24]. With the capability of shifting back and forth from the standard mode to the imaging mode the FTS at CFHT had a versatility which explains its unique longevity. It triggered numerous collaborations between the members of the three CFH scientific communities. The BEAR instrument opened the door to another method of doing integral field spectroscopy, which can be continued by the access to a wide field, a specific property of an imaging FTS, which will be fulfilled by SITEILLE.
2. SPIOMM, A PROTOTYPE FOR SITELLE

The design of SITELLE will directly benefit from our combined experience with BEAR and SPIOMM (Spectromètre Imageur de l’Observatoire du Mont-Mégantic), an imaging Fourier transform spectrometer attached to the bonnette of the 1.6-m telescope of the Mont Mégantic Observatory (OMM) in southern Québec. Because SITELLE will essentially be an improved version of SPIOMM, working in the same wavelength range, we present in this section the main characteristics of SPIOMM, its concept and some science highlights to provide the reader with a flavor of what to expect from SITELLE.

SPIOMM is capable of obtaining the entire visible spectrum (from 350 to 850 nm) of every light source in a 12 arcminute (circular) field of view of the 1.6-m OMM telescope. The spectral resolution is variable, depending on the need of the observer, from R = 1 (broad-band image) to R = 25 000; the spatial resolution is limited by the seeing (pixel size = 0.5"); CCD camera as detector with 1340 x 1300 pixels), resulting in ~ 10^6 spectra. The dual input, dual output design of SPIOMM ensures that virtually every photon collected by the telescope reaches the detector and is analyzed; a by-product of the spectral data cubes is therefore a very deep panchromatic image of the targets. Its early development phase was presented by Grandmont, Drissen and collaborators [25-28].

SPIOMM was developed at Université Laval (F. Grandmont’s Ph. D. thesis) with close collaboration with ABB-Bomem, a world leader in the development FTS and Québec City-based Institut National d’Optique (INO), with grants from the Canadian Foundation for Innovation, NSERC, FQRNT and the Canadian Space Agency. Although SPIOMM saw first light in 2004, numerous stability and electronics problems inherent to a prototype postponed the acquisition of the first usable science cubes to early 2007. SPIOMM is unique in the world, offering the largest field of view of any integral field spectrograph; by comparison, Gemini’s GMOS-IFU can sample a field of smaller than 10 x 10 arcseconds (4000 times smaller than SPIOMM) with a maximum resolution of R = 5000. Currently, only one output port is used on SPIOMM. The detector is a LN₂-cooled, Princeton Instruments VersArray CCD, with 1340 x 1300 pixels covering a field of view of 12 arcminutes x 12 arcminutes. The CCD is read at 100 kHz to reduce the readout noise and the pixels are binned 2x2 during readout to increase the S/N ratio and reduce the readout time.

We have now demonstrated [29] that the concept behind SPIOMM is sound and viable, and that such an instrument is capable of producing high quality hyperspectral data cubes over a very extended field of view. We present below some recent results obtained with this instrument.

2.1 Recent science highlights from SPIOMM

Since its first light in 2006, SPIOMM has been used to map several dozen objects, ranging from nearby star-forming regions such as the Orion nebula and W4 to nearby galaxy clusters such as Stephan’s quintette. One of the most interesting target, both from a scientific point of view and to demonstrate the capabilities of SPIOMM, are supernova remnants. Supernova remnants, which are the remains of the explosion of massive stars, display five strong emission lines in the 650 – 680 nm wavelength range of various intensities and Doppler shifts. While the stellar material in the oldest ones, such as NGC 6992 (~ 10 000 years old), is now pretty well mixed with the interstellar medium and has considerably slowed down, the youngest supernova remnants of the Milky way, such as the Crab nebula (1054 AD) or Cassiopeia A (~ 1667 AD) are still expanding at very large velocities. Spectra of such young objects are therefore very complex due to the overlapping of filaments moving at different Doppler velocities: in some regions, up to three filaments overlap, meaning that 15 emission lines are observed with SPIOMM. We have developed an algorithm that allows us to deconvolve the complex spectra and obtain a 3D view, in all of the strongest emission lines, of these objects.

The Crab nebula data have already been published[29], and we are now working on recent data cubes of Cas A. Figure 1 shows some results obtained for a much older, kinematically more quiet, supernova remnant NGC 6992. The lines of [NII] and [SII] are very strong and the nebular morphology is often very different from one line to the next. NGC 6992 represents the western part of the much extended Veil nebula. Six adjacent fields have been mapped so far, and we intend to complete the 3D mosaic of this region in the fall of 2010. Our data reveal a very complex structure of filaments resulting from the interaction between the stellar ejecta and the diffuse, inhomogeneous, interstellar medium. Filaments of pure hydrogen.
Fig. 1  (Left) - Doppler map of the Hα line in one region of the supernova remnant NGC 6992. Velocities vary between -20 km/s and +30 km/s. (Right) - Electron density of the gas for the same region, based on the ratio of the [SII] 671.6 and [SII] 673.1 nm lines, assuming an average temperature of 8 500K. Both frames are 12 arcminutes on a side.

With its wide field of view and large spectral coverage, SITELLE will be the ideal instrument to perform measurement of narrow emission lines in external galaxies. These measurements will help advance the field of abundance studies to reliable measurements of metal content in local and high redshift galaxies. Precise abundance measurements in star-forming regions require a good estimate of the gas temperature, which can only be obtained from faint emission lines such as [OIII] 436.3 nm. This line is too faint to be measured with SpIOMM, but will be within reach of SITELLE. Nevertheless, we have targeted so far half a dozen nearby gas-rich spiral galaxies, including M51 and NGC 628 (Figures 2 and 3), to measure metallicities of hundreds of HII regions with the so-called “indirect method” using strong emission lines.

Fig. 2  (Upper left) - Velocity diagram of the spiral galaxy M51, based on the centroid of the Hα 656.3 nm emission line from an SpIOMM data cube. (Upper right) - Image of the [NII] 658.4 / Hα 656.3 line ratio from the same cube. Notice the large ratio in the core of the galaxy, characteristic of shocks driven by the central Active Galactic Nucleus. (Bottom) - Spectrum of a typical HII region in M51 (black) with a simultaneous fit to the five emission lines (red): [NII] 654.8 nm, Hα 656.3 nm, [NII] 658.4 nm, [SII] 671.7 nm and [SII] 673.1 nm.
3. SITELLE

Following the publication of a feasibility study for an instrument similar to SPIOMM, but to be attached to the Canada-France-Hawaii 3.6-m telescope, named SITELLE (Spectromètre Imageur à Transformée de Fourier pour l’Etude en Long et en Large de raies d’Emission), we have recently secured funding to build this instrument from the Canadian Foundation for Innovation. Having learned from the design and use of SPIOMM, some significant improvements will be included in the new concept, including the servo mechanism and the detector technology. Taking into account the larger surface of the primary mirror, and the improved modulation efficiency and detector quantum efficiency, we estimate that SITELLE will be about 20 times more efficient than SPIOMM and will allow the mapping of fainter object as well as fainter emission lines. Our team has learned a lot from the development of SPIOMM and especially from its use on a regular basis at a telescope. All the potential improvements we have identified will be fully integrated in SITELLE. In particular, we expect:

- Better sensitivity in the blue.
- Use of two detectors, each with an improved quantum efficiency and reduced noise; not only will this at least double the signal, but it will also greatly improve the quality of the interferograms, which will directly be reflected in a reduced noise in the spectra, especially for continuum and absorption line studies.
- Better stability and improved modulation efficiency, especially in the blue-UV
- Ease of use and maintenance.

3.1 Science drivers
While the number of scientific programs for this type of instrument is potentially huge (from the study of individual stars in local star clusters to the search for high-redshift Ly-α emitters), we have chosen a series of typical projects to illustrate its scientific potential by advocating the enormous benefits provided by a systematic, complete 3D mapping of extended emission-line sources. The main science drivers for SITELLE are very similar to those of SpIOMM: the study of physical characteristics (temperature, density, kinematics) of nebulae surrounding evolved stars, supernova remnants and the diffuse interstellar gas in the Milky Way galaxy; abundance gradients and kinematics of nearby galaxies to understand their evolution; distant galaxies. The much higher throughput and efficiency of SITELLE at CFHT will allow us to map fainter emission lines, to broaden the study of galaxies to the absorption lines due to the presence of an old stellar population, and to extend the study of galaxies to much higher redshift in order to study, for example, the star-formation rate across the Universe.

3.2 Instrument requirements

The science requirements define the following technical requirements of SITELLE:

- **Wavelength range** - In the local universe, the [OII] 372.7 nm line defines the short wavelength requirement. It is used to measure the oxygen abundance in ionized nebulae. Many things conspire to make this line a real challenge for an Imaging FTS: The long wavelength limit is defined by the Ca triplet at 849.8 nm, 854.2 nm and 866.2 nm, which characterize the old stellar population in galaxies. In the case of the high redshift objects, the wavelength range accessible with the instrument defines the redshift range in which the Lyα line can be detected. The above-mentioned limits (370 – 870 nm) set this range to 2.0 < z < 6.15. A small gain will be obtained by extending the wavelength range to 350 nm – 950 nm (1.9 < z < 6.8).

- **Spectral resolution** - The cosmology projects do not require a high spectral resolution. The minimum resolution required for the analysis of the ionized nebula in the Milky Way and other galaxies, is set by the necessity to separate the [SII] 671.7 / 673.1 nm doublet, the Hα 656.3 nm from its [NII] 654.8 nm and 658.4 nm neighbors, and Hγ 434.1 nm from [OIII] 436.3 nm. This implies a minimum value of R = 1000. However, kinematics of HII regions and the studies of stars in clusters impose a more stringent requirement of R = 10⁴.

- **Field of view** - The maximum field of view of dispersive integral field spectrometers reaches one arcminute (SAURON, and the future MUSE). A FOV of 5 arcmin would represent a significant improvement. Most projects on stellar ejecta and nearby galaxies would also be feasible with a 5 arcmin FOV. However, for the study of extended HII regions in the Milky Way and the high-redshift galaxies, reasonable amounts of observing time require a FOV > 10 arcminutes, which set the constraints for SITELLE, with a goal of 20 arcminutes.

- **Spatial resolution** - Most of the projects presented here put the emphasis on the wide field observation of extended, diffuse objects and do not on the spatial resolution. However, observations of individual stars in clusters and distant galaxies require that the pixel size be no larger than the typical seeing, 0.6 arcsec. The panchromatic image quality (350 – 950 nm) should be no worse than one arcsec.

- **Sensitivity** - Two of the most stringent constraints in terms of sensitivity, from the science case, are the ability of SITELLE to detect the faint [OIII] 436.3 line, which is not always detected in HII regions, and its capacity to detect Lyman alpha emitters down to a flux of 4.3×10⁻¹⁷ ergs s⁻¹ cm⁻² (5 sigma detection) in a reasonable integration time (less than 4 hours).

- **High observing efficiency** - The readout time, combined with the displacement time of the interferometer should be a small fraction of the total on-target exposure time.

- **Filter wheel** - To increase the spectral resolution and reduce the photon noise from the sky or the intrinsic continuum of the objects, most observations will be performed with filters, either wide-band (cosmology, low resolution observations; Δλ ~ 100 – 200 nm) or medium-band (nebular analysis; Δλ ~ 10 – 50 nm). A standard set of filters, to be defined later, will be provided, and each user could choose the appropriate filter tailored to its needs.

- **Ease of use** - Based on our experience with BEAR and SpIOMM, an Imaging FTS is quite a beast to master. The first night at the telescope must start very early and a long series of adjustments must be performed before
the first scientific observation. Give the « guest instrument » status of SITELLE at the CFHT, it must be designed to be as user-friendly as possible. A « plug-and-play » device is our goal.

Table 1: SITELLE’s Preliminary Specifications

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectral Range</td>
<td>350 – 950 nm</td>
</tr>
<tr>
<td>Spectral Resolution</td>
<td>Better than 3 cm$^{-1}$ (ILS FHWM)</td>
</tr>
<tr>
<td>Detector type</td>
<td>2 × CCDs 16 bits, 2048 × 2048 pixels</td>
</tr>
<tr>
<td>Instrument Field of View (FOV)</td>
<td>20’ goal</td>
</tr>
<tr>
<td></td>
<td>10’ threshold (PFOV = 0.6”)</td>
</tr>
<tr>
<td>Panchromatic image quality</td>
<td>FWHM (350-950 nm) &lt; 1”</td>
</tr>
<tr>
<td>Instrument transmittance</td>
<td>&gt; 50% (both output ports combined)</td>
</tr>
<tr>
<td>Interferometer type</td>
<td>Dual output port</td>
</tr>
<tr>
<td>Scanning type</td>
<td>Servoed step scan</td>
</tr>
<tr>
<td>Operational temperature range</td>
<td>-15 to 10 °C</td>
</tr>
<tr>
<td>Humidity</td>
<td>0 to 100%</td>
</tr>
<tr>
<td>Mass</td>
<td>750 kg max</td>
</tr>
<tr>
<td>Torque</td>
<td>4500 Nm (750 kg @ 0.6 m)</td>
</tr>
<tr>
<td>Volume (width x width x length)</td>
<td>2×2×1.5 m</td>
</tr>
</tbody>
</table>

Phase A will begin shortly after the writing of this paper, but preliminary studies were performed as part of the feasibility study submitted to the CFHT. In particular, the final interferometer design will be chosen during phase I and cannot be presented here. In comparison to the SpiOMM specification, the SITELLE throughput stands as the main challenge. The CFHT primary mirror diameter is 2.2 times the one of Mégantic and the goal FOV is 1.7 x larger than the one of SpiOMM (0.8 x for threshold). Hence the SITELLE throughput requirements sits between 3.4 (threshold) and 13 (goal) times the one of SpiOMM which was already quite an achievement. We think this added challenge is surmountable given the much higher weight/torque limit of CFHT and larger budget. The volume limitations are very similar to the Mégantic ones and as such the SITELLE layout may require additional folding mirrors in the optical path. The remaining requirements are somewhat similar to values that have already been achieved with SpiOMM.

3.3 Optical design

The design of an IFTS with such emphasis on the imaging/throughput aspect obviously starts by attempting to meet the FOV and image quality requirement over the desired wavelength range simultaneously. This is a challenging task compared to similar astronomical instrument. One on side, wide field camera system can typically suffer from chromatic aberrations to some degree since band pass filter are typically used and allows for a focus correction. On the other side, Integral field unit spectrometer will typically image a much smaller FOV than SITELLE or, if not, allow for very coarse spatial sampling of it (hence poor image quality). All images acquired with an IFTS are meant to be panchromatic and take full advantage of all the available detector pixels for imagery. Band pass filters can still be used but primarily to reduce the photon noise in the spectra and not specifically to improve image quality.

The optical design process can be carried out almost independently from the interferometer design as the latter typically adds only folding or transmissive flat interfaces which effect on the optical performances are often negligible. However the IFTS configuration brings some additional requirements to the optical design such as the need to dispose of a
collimated beam section of sufficient length to place the interferometer. In this first optical design iteration, the free collimated space length was fixed at 1 meter.

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The input/output optical design’s intent was to converge to a solution that provided the largest FOV without compromising the wavelength range and image quality threshold as dictated by the science requirements. The SpiOMM design was used as a starting point. The proposed layout is composed of a triplet for input optics and 5 lenses in the output optics. The pupil size is a free parameter in the design. It is directly linked with the size and hence cost of the interferometer. However a small pupil makes the design of the output optics more difficult and may reduce the attainable FOV. The first design iteration fixed the pupil at 120 mm and a resulting FOV optimised over a diameter of 14.4 arc minutes. The image quality specification (panchromatic FWHM < 1 arcsec) is fully met with this preliminary design.

3.4 Scanning mechanism

The scanning mechanism must combine the following capabilities:
- Nanometer-level precision
- Travel range > 1.5 mm
- Fast response (kHz)
- No backlash
- Strong hold/push force

In order to achieve this kind of performance, a dual stage actuator scheme is proposed. For coarse displacement, one corner cube will be displaced by a long range, medium force and relatively slow piezo-actuator. Total displacement will be about ±0.75 mm around mechanical equilibrium position. Rectilinear and frictionless motion will be assured by a proper flex blade design. Blade thickness will be adjusted in order to get maximum stiffness and acceptable stress and required forces (taking into account the membrane effect). Initial calculations show that the blade stiffness required to properly hold the CC generate push force above the proposed actuator capacity. Hence, a simple flex blade based lever arm mechanism is used to increase the actuator force.

3.5 Observing procedure :

Standard calibration include, for each night :
- Bias frames; standard
- Flatfield exposures; standard
- Spectral calibration : the precise spectral calibration is internal to the system (laser metrology), so there is no need for external spectral calibration measurements.
- Flux calibration : observation of standard spectrophotometric stars
Before obtaining a data cube, the observer will have to specify:

- The exposure time per step;
- The spectral resolution; this will determine the number of steps.
- The wavelength range (defined by the filter);
- The detector read mode (full frame or a section of it; binning or not).

An acquisition can be paused at any time (clouds) and then restarted later, without any impact on the data quality. Two datacubes can also be combined to increase the S/N ratio. After each exposure, the computer will display:

- Both images (from the two output ports);
- The deep, combined image from all exposures (after, say, 10 steps);
- Spectra from selected regions within the FOV, with an increasing resolution after each step.

Storage: the typical size of a data cube is 10 Gb

3.6 - Data processing

The raw data consist of two series of CCD images of the targets (typically 100 – 500), one for each output port of the interferometer. The final product is a single data cube (RA, Dec, λ) from which spectra of individual objects, or monochromatic images of the targets can be extracted. Between the two datasets, the following steps must be followed:

- Standard CCD processing: bias removal, flatfield correction for each image.
- Alignment of the individual images. Unperfect telescope tracking or flexion in the instrument during the observations, however small, can cause slight drifting of the images which need to be corrected. This is done by measuring the centroid of a dozen stars in the field and shift every image accordingly.
- Correction for sky transparency variations.
- Spectral calibration.
- Combination of the two output ports and Fourier transform.

Most of these steps can be performed with standard IRAF procedures (imarith, imshift, daophot, imstack, …). We have however developed a complete package written in IDL to reduce SpIOMM data. If the proper calibration files (Bias, flatfield, calibration cube) have been taken before the beginning of the night, the whole procedure can be performed on a laptop computer in less than one hour. Data processing would in principle take longer with SITELLE because of the larger CCDs, although by the time SITELLE is installed, the speed and power of laptop computers will have increased.

3.5 – Detectors

As in all astronomical instruments, the detector is an essential component. In the case of an imaging FTS, two characteristics are especially important. As the datacube is built by acquiring multiple images of the target at different optical path differences, the readout time must be a negligible fraction of the on-target exposure time, and the readout noise must be small compared with the photon noise (from the target or the sky). Typical exposure times per step range from 10 seconds to one minute; the displacement of the interferometer’s moving mirror takes one second. Therefore, the readout time dominates the «dead time» between exposures; it must be kept to a minimum, ideally smaller than 2 - 3 seconds is required.

The total field of view and sampling specified in the requirements implies a 2k x 2k (13-15 μm pixels) detector for each of the two output ports. Moreover, the requirement for high sensitivity in the near UV ([OII] 372.7 nm line) implies a high quantum efficiency below 400 nm; this is now a regular feature of UV-enhanced, back-illuminated CCDs. Typical CCDs on the market (Princeton Instruments for instance) are capable of readout rates ~ 1 MHz (4 seconds readout time for a 2k x 2k CCD) but with a significant readout noise of 7 – 9 electrons. The readout noise can be significantly reduced, at the expense of slower rates. Both characteristics are above our requirements. A CCD equipped with four output amplifiers would reduce the readout time accordingly.
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