

INTEGRAL FIELD SPECTROSCOPY WITH THE GEMINI NEAR-INFRARED SPECTROGRAPH

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FEBRUARY 1996

1.0 Overview of Integral Field Spectroscopy

Imaging spectroscopy is not a new concept in astronomy. A classic example employed for decades is the scanning Fabry-Perot (FP) interferometer, which yields a data cube (x,y,λ) and permits relatively wide spatial coverage but is only effective across fairly narrow bandpasses. Another technique is slit stepping, in which a 1D long slit is stepped across spatially extended targets and a spectrum is recorded at each step. Like the scanning FP, fairly complicated data reduction techniques are used to recover both spatial and spectral information from the raw data recorded in these observations, with the net result being the generation of a data cube consisting of a series of essentially monochromatic images. Both FP scanning and slit-stepping have been successfully applied in optical and near-infrared instrumentation to support imaging spectroscopy.

Though such spectro-imaging is a powerful tool among the arsenal of techniques available to astronomers, past techniques like those mentioned above are certainly not trouble free. In particular,

- They are susceptible to variations in seeing or atmospheric transmission during the time that scans are made. In both FP and stepped-slit techniques, such changes in observing conditions inevitably propagate into a reduction in the spatial and spectral quality of final data cubes.
- Stepping a narrow slit across a complex region introduces low-level slit effects, compounded by key features in the region not necessarily being well centered in a slit as it is systematically stepped across a region.
- Both techniques intrinsically only record 2 of the 3 desired parameters simultaneously, hence demand a greater amount of time to complete compared to true 3 dimensional imaging spectroscopy.
- Considerable resources are being expended to provide an exquisite focal plane to instruments on Gemini. It is debatable if the best use of this focal plane is to cover >99% of it with a slit that is intended to step across targets to generate a datacube, instead of more efficient techniques.

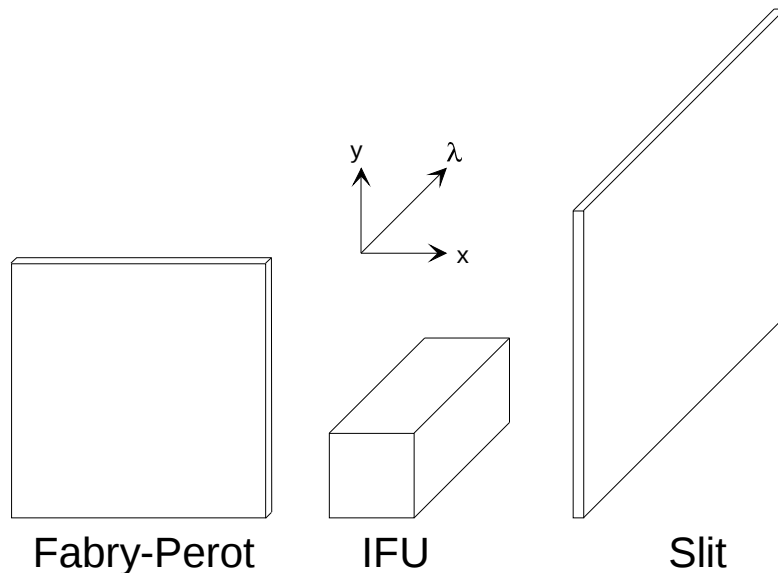


Figure 1 - The basic differences between 3 approaches to imaging spectroscopy are illustrated. The IFU approach represents a compromise between wide field narrow band FP spectroscopy and narrow field broad band slit spectroscopy.

So-called integral field spectroscopy represents a “middle ground” between FP and stepped-slit spectroscopy. Figure 1 is a characterization of how these three techniques compare. Integral field spectroscopy lacks the field coverage of FP scanning, but offers greater spectral coverage. Likewise, an integral field spectrograph lacks the broad spectral coverage (or high spectral resolution) that a stepped-slit spectrograph offers, but it delivers much more spatial information. A key difference between FP or stepped-slit spectroscopy and integral field spectroscopy is that the latter records all 3

parameters (x , y , λ) simultaneously, hence is not very susceptible to observing condition variations and is intrinsically quite efficient. Furthermore, integral field spectroscopy should not be viewed as a substitute for FP imaging or stepping a slit in a conventional spectrograph across an image, rather it is a compromise between competing factors in imaging spectroscopy and literally permits scientifically valuable observations that cannot be achieved with other techniques. For example, the amount of time needed to complete a FP scan across the same bandpass that is achievable with an integral field spectrograph can easily exceed a factor of ten. The same argument applies when comparing observing time required to achieve the same level of spatial coverage between a stepped-slit and integral field spectrograph.

The utility of imaging-spectroscopy in understanding complex, spatially extended regions is large, since it is possible to extract from the data cube a spectrum at any point in the imaged field, extract extremely narrow band images corresponding to unique spectral lines, or bin the final data cube to create broad band high signal-to-noise images. As an example, Figure 2 shows how both near-infrared narrow band images ($\sim 0.6''$ resolution) can be simultaneously recorded with high signal to noise spectra, permitting much more in depth analyses of morphologically complex targets than is possible with conventional slit spectrographs. These data were recorded with CFHT’s imaging FTS (Simons et al., 1994). Figure 2(a) shows AFGL 2688 in $\sim 2 \mu\text{m}$ continuum flux. It agrees well with previously made K-band images (e.g., Latter *et al.* 1993) and shows a pair of lobes, one of which is quite faint. A fiducial mark has been added to Figure 2(a) to help identify the center of the object, where the central red giant is located. The morphology of AFGL 2688 takes a radical departure when viewed in H_2 . Figure 2(b) shows the difference between an image centered on the relatively strong H_2

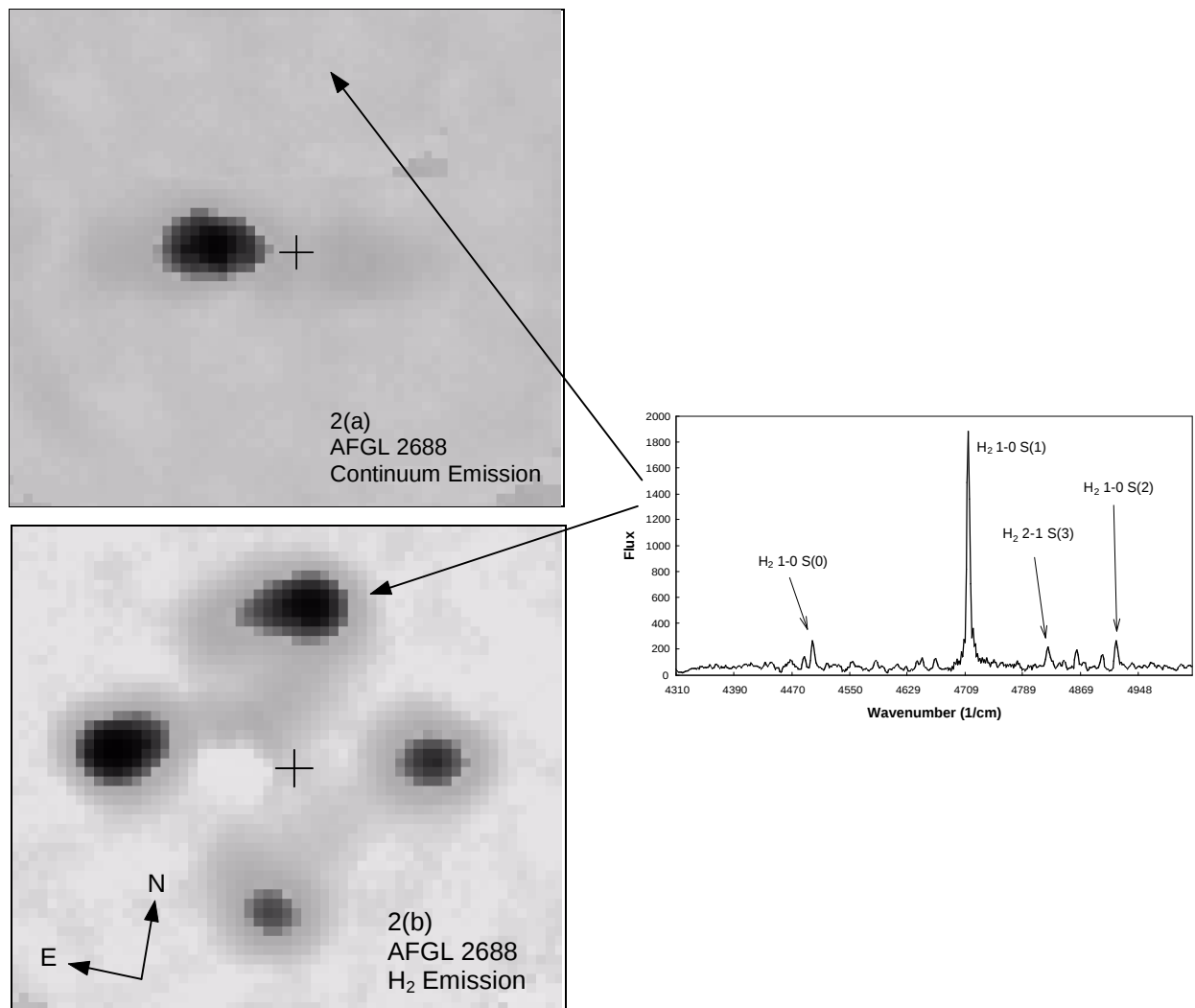


Figure 2 - At top left (a) is an image made in continuum ($\sim 2 \mu\text{m}$) flux of AFGL 2688. A single bright lobe of emission is obvious. Just opposite the fiducial mark, which lies approximately at the location of the central star, is a much fainter lobe. Below left, in (b), is the same object but in the line emission of H₂ S(1). In this case the emission comes from four completely different lobes exterior to the central continuum lobes. Note that (b) has had a continuum image subtracted off. To the right is a spectrum of the area containing the brightest H₂ lobe. Also evident are weaker lines of H₂. The spectrum appears purely molecular in origin.

S(1) line and a continuum image. In this case 4 bright lobes well separated from the two that define the continuum flux are evident. A spectrum of the top brightest H₂ lobe reveals emission that is purely molecular in origin. Specifically, H₂ S(0), S(1), S(2), and S(3) are evident. Images made in these weaker molecular hydrogen lines reveal the same basic 4 lobe structure as seen in Figure 2(b). Using line ratios it is possible to derive excitation conditions within all of the H₂ lobes. Calibration of this scan indicates that line emission as faint as $\sim 1.5 \times 10^{-22} \text{ W cm}^{-2} \text{ arcsec}^{-2}$ for a signal to noise ratio of ~ 10 and resolving power of ~ 1000 is achievable with CFHT's infrared imaging spectrometer.

While an imaging FTS is clearly beyond the scope of any integral field spectrograph envisioned for Gemini currently, it is nonetheless useful to point out with real examples what performance levels are now being achieved in near-infrared imaging spectroscopy. This example (and those following) also demonstrate how many instruments have been developed in recent years to support imaging spectroscopy.

2.0 Various Technical Approaches

There are several possible approaches to building an integral field unit into an infrared spectrograph. Though arguably not as well established within the world-wide astronomical community as slit or FP spectroscopy, over a decade has passed since the first fiber based integral field spectrometer was built and tested (Vanderriest 1980). CFHT has been the focus of much of the development work in this field, with instruments like SILFID, TIGER, and ARGUS in the past, and the next generation instrument, OASIS, which will be a “work-horse” instrument for CFHT’s AO Bonnette in the future. Below, possible implementations for an IFU, in the context of the development work already completed by various French and German teams, is discussed. Relevant documents are attached to provide technical details and performance levels achieved for the approaches discussed. This technical note is therefore not intended to provide a detailed technical solution for the eventual implementation of an IFU in the NIRS, rather it merely outlines possible technical solutions to the problems, identifies key science areas which could benefit from this mode, and proposes baseline performance levels for whatever technical solution is selected. Ultimately the viability of the various techniques possible will have to be assessed, in the context of the performance of the NIRS/IFU combination, before a particular design can be selected. In the interim, the information provided here should at least help to define space requirements within the NIRS for an eventual IFU upgrade within the NIRS.

2.1 TIGER

The TIGER concept as explained in Bacon *et al.* (1995; see attached) was first tested at CFHT in 1987. The microlens concept prototyped in TIGER now acts as a critical part of the design in the next-generation integral field spectrometer, OASIS, at CFHT, which will include a Fabry-Perot mode, a fiber-fed lenslet mode, and a direct lenslet feed mode. TIGER is based upon the use of a microlens array in a magnified version of the entrance focal plane. Figure 3 shows the concept in detail. The lenslet array serves in effect as an image slicer, with each microlens creating an image of the exit pupil that is transferred to the final detector plane. Behind the microlens array is a collimator, grism, and camera, yielding a conventional grism spectrometer. TIGER is unusual in that the pupil is imaged onto the detector, not the focal plane. In practice this means precise centering of features within the grid of microlenses is not important as long as the PSF sampling is at least Nyquist limited (to properly illuminate each pupil; see Bacon *et al.* 1995). Each pupil image is dispersed into a separate spectrum with 7 pixels between adjacent spectra. Figure 3 shows the array of interlaced spectra produced at the final focal plane. Mechanically speaking this design is considerably simpler while yielding significantly higher throughput than fiber reformers achieve. One of the largest trades between a TIGER design and fiber-fed designs is that of

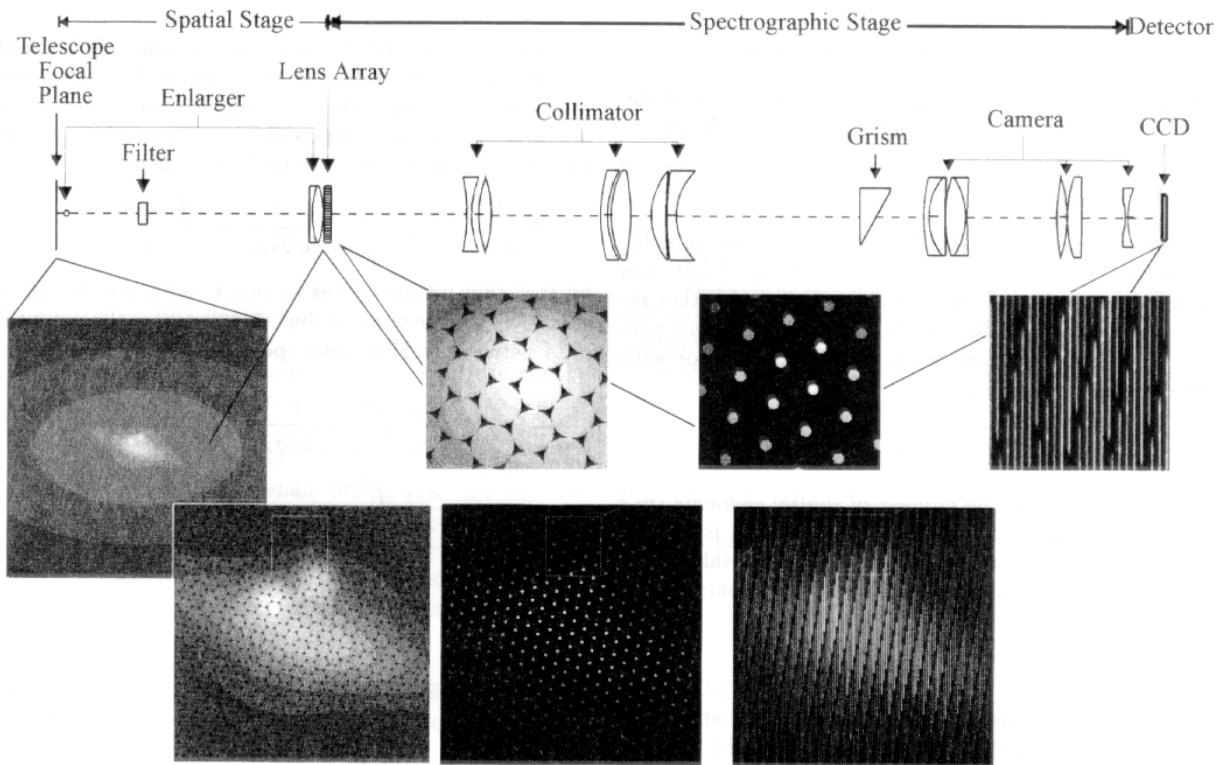


Figure 3 - Adapted from Bacon *et al.* (1995), the various stages in the TIGER design are shown.

reduction software, since fiber-fed designs reformat the focal plane into a series of spectra that are intrinsically easier to transform into a processed data cube than the interlaced spectra generated by TIGER. Considerable effort went into the TIGER reduction package (private communication), which has demonstrated that the instrument is capable of reconstructing a broad band image through the numerous separate spectra with no significant loss of spatial resolution. In principle it should be possible to either use or adapt the reduction package developed for TIGER for a system built for Gemini. Detailed formulae describing optimal pixel sizes, spectral parameters, etc. can be found in Bacon *et al.* (1995).

For Gemini's application in the near-infrared, a microlens array that transmits well out through $\sim 2.5 \mu\text{m}$ will be needed. Typically microlenses are generated through an epoxy replication process and the organic materials in the epoxy will absorb in distinct bands in the near-infrared. Manufacturing a microlens out of fused silica may be an option, if the substrate can be "infrared grade", hence transmissive out through the K-band. Likewise, mapping entire near-infrared atmospheric windows into the tightly spaced interlaced matrix of spectra generated by this technique will be difficult. Instead it may be necessary to use filters to select a particular region within atmospheric windows of scientific interest, in turn implying the need for additional filter slots in the spectrograph as part of an IFU upgrade option. Dedicating some small fraction of the pixels to off-axis sky sampling will be difficult, hence sky subtractions may either force the use of targets that are small compared to the field of view or separate sky integrations, reducing the efficiency of this approach.

2.2 ARGUS

Shortly after TIGER was tested and confirmed to be viable at CFHT, an alternate design called ARGUS was prototyped within the CFHT MOS. It uses optical fibers to slice the input focal plane and reformat it along MOS's slit, so that all spectra are aligned in parallel strips across the detector. Figure 4 shows the GMOS IFU concept, which is similar to what is used in ARGUS (note that unlike the GMOS IFU, ARGUS does not use lenslets on the ends of the fibers). A key advantage of this approach over TIGER is increased wavelength coverage. In GMOS the concept involves 0.2" pixels feeding ~1000 fibers that are aligned along the GMOS entrance slit. Microlenses are used at the back end of the fibers to yield a focal ratio that is compatible with the subsequent spectrograph in GMOS. As mentioned before, fiber losses in such a design can be significant compared to the more direct TIGER approach. At the cost of reduced wavelength coverage in a single integration, it may be possible to route fibers from a microlens to two slits, thereby expanding field coverage. Alternately, two lenslet arrays could be used to feed two slits, offering expanded field coverage but in two separate places on the sky.

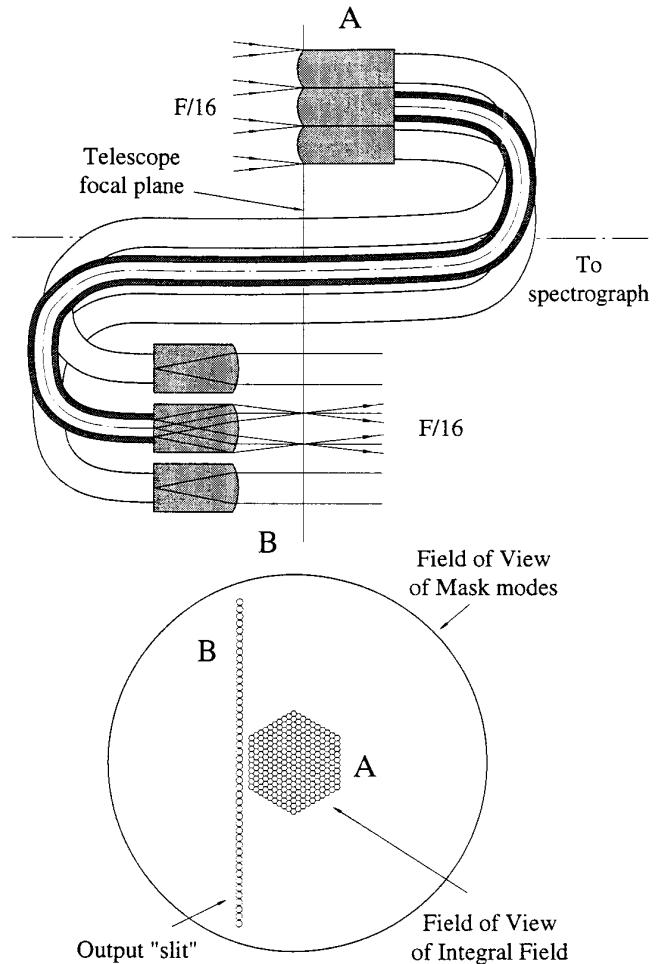


Figure 4 - The GMOS IFU concept is shown, adapted from the GMOS PDR documentation. Like the TIGER concept a lenslet array is used to slice the entering focal plane, but fibers are used to reformat the focal plane into a vertical strip, yielding spectra that are easier to manage from a processing perspective and offer longer wavelength converge than TIGER.

An infrared version of this instrument, called ISIS (Dallier *et al.* 1994), has been used successfully at CFHT as well. ISIS consists of a fiber bundle that is attached directly to the Cassegrain focus of the telescope, which feeds a fairly low cost bench mounted grating spectrometer, which in turn used the facility camera Redeye as the detector. ISIS was not used at K, due primarily to the high background resulting from the coupling of Redeye to the bench spectrograph. ISIS supports resolutions of 400, 2000, and 10000 at J and H but only has a ~60% fill factor with its 51 object fibers and 10 sky fibers. At CFHT ISIS has a 1 hr 10 σ sensitivity of J ~15-16 mag.

If used in the NIRS, several technical challenges would have to be solved for a fiber-fed IFU. Like TIGER, identifying a suitable microlens array that offers good

transmission from 1-2.5 μm will be needed. Perhaps even more importantly, infrared transmitting fibers would have to be identified and the fiber bundle would have to be stress relieved to assure that, when cooled, these rather delicate elements survive the types of g-shock that is typical of the NIRS environment, both in the lab and on the summit. Sky subtraction would be easier to manage than it would be with the TIGER concept, since (like the IFU mode of GMOS) separate sky fibers that accept flux well off the central axis of the IFU could be built into the system, permitting simultaneous object/sky acquisitions.

2.3 3D

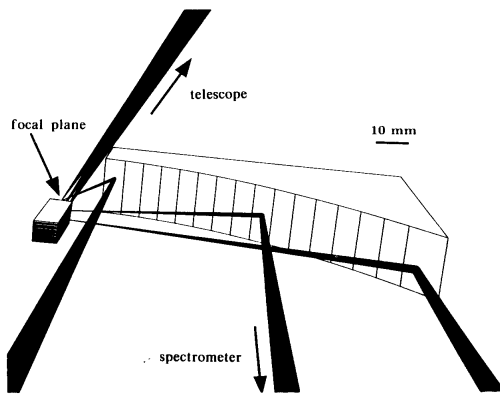


Figure 5 - Above is an illustration of how the 3D image slicer works through a pair of multifaceted mirrors to reformat the entrance focal plane. In reality a total of 16 separate slices are created. Both drawings are adapted from Krabbe *et al.* 1995.

The integral field spectrometer “3D” was developed at Max-Planck and has been used successfully on a number of science programs recently. It uses an unusual image slicer to reformat an 8x8 arcsec field into a line of images with a pixel scale of 0.5 or 0.3 arcsec, where it is dispersed by a fairly conventional grism based spectrometer at a resolution of 1000 (to map the entire H or K windows on a NICMOS3 array) or 2000 at K. Figure 5, derived from Krabbe *et al.* (1995; see attached) shows how the image slicer works. In 3D it operates warm at the forward focal plane of the instrument. The first element is a gold coated multifaceted mirror that splits a square shaped section of the entrance focal plane into 16 single strips that are directed into separate directions. From there the image slices are reflected off a hyperbolic faceted mirror which serves to co-align the pupils of the separate slices onto a common pupil. From the second hyperbolic mirror the sliced images are fed into the conventional linear slit of the spectrograph. The net result of the 3D image slicer and slit spectrograph is a complete spectrum for each image slice. Custom software is used to transform the spectral strips into a formatted data cube.

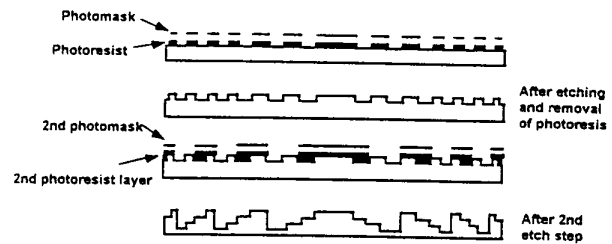
This design has the advantage of using all reflective optics, hence alleviates the problems associated with infrared transmitting lenslets or fibers. In fact, the lack of infrared transmitting fibers at the time 3D was under development in part drove the designers of this spectrograph in this direction. Fabrication of the mirrors used in this system is clearly a custom job, but scaling this technique up to accommodate the much larger ALADDIN array used in the NIRS (vs. the NICMOS3 array used in 3D) seems viable from a technical standpoint. Like the TIGER approach, sky sampling would be difficult for objects that are extended on the scale of the IFU field of view.

2.4 Binary Optics

Finally, an emerging technology on the commercial front should be mentioned. The field of binary optics, which was developed in large part to support military

applications, is just now becoming a commercially viable alternative to conventional optical elements. Binary elements are made through the same basic micro-lithography techniques employed in VLSI circuit fabrication, except the net result of successive etches of a substrate is to produce a transmissive diffractive optical element, not an electrically conductive circuit. Figure 6 illustrates the basic procedure used in the fabrication of binary optics. The great utility of such optics is that they

can not only split up a focal or pupil plane into very small elements, but they can redirect those elements into new directions that would otherwise be impossible with conventional optics. Hence, in theory, a binary optic could offer the “best of both worlds” between designs like ARGUS and TIGER, i.e., it would be an elegant way to split up the focal plane into tiny elements with nearly 100% fill factor while being able to reformat the focal plane into a strip of sub-images, which could be directed into a spectrograph slit. Careful design may lead to the maximum packing of spectra onto the final detector of any of the techniques mentioned here. Dan Neal at Sandia National Labs has demonstrated high throughput (>95%) for binary lenses used as 8x8 Shack-Hartmann sensors (private communication). Sandia is in the process of turning over its technology to commercial vendors as part of the Federal government’s program of “technology transfer” to stimulate economic growth in high-tech sectors. Since one of the substrates that has been used at Sandia is fused silica, it might be possible to get a high efficiency binary optic made for the near-infrared. It should be noted that the throughput of a binary optic across the entire 1-2.5 μm range may be dominated by limitations in the diffractive mechanisms used to redirect light into a focal plane, not the transmissive properties of the substrate. Further contact with possible manufacturers of binary elements would be needed to estimate diffractive efficiencies for such elements across 1-2.5 μm bandpasses. Early estimates of costs for custom diffractive elements are at the few \$10K level.



$$N \text{ mask steps} = 2^N \text{ Phase Levels}$$

Figure 6 - Successive etches of a transmissive substrate yields microlenses with high efficiency that, when combined, serve multiple/complex functions on optical systems. Adapted from Neal *et al.* (1995).

3.0 Baseline Gemini NIRS IFU Design Specifications

Defining the detailed performance specifications of an IFU fitted into the baseline NIRS will have to wait until a particular technique is identified as viable (in terms of space available and compatibility with the baseline optical design). Nonetheless it is possible to propose some baseline parameters for the IFU mode and see how such a system could be used for some specific science applications. In much of what is assumed below the TIGER (fiberless) approach is assumed simply to explore parameter space.

Spatial Sampling: A scale of 0.05" per resolution element is suggested as a baseline specification. This is optimal for Nyquist sampling the tip/tilt corrected near-infrared image delivered by the Gemini telescopes. For adaptive optics applications a finer

sampling may be needed, though this leads to very small fields of view (see below). Designs which support more than one spatial sampling scale should nonetheless be considered since it is likely that a single field of view will not be optimal for all applications.

High Throughput: Adopting a design which yields high throughput, in terms of microlens fill factor and total flux transmitted, is suggested. This is consistent with the design philosophy of the baseline spectrograph and the Gemini telescopes in general, hence would make use of existing high throughput capabilities. To some extent this favors fiberless IFU implementations.

Wavelength Coverage: 1.0 - 2.5 μm should be covered, albeit split into a variety of much smaller windows in any one integration. Pushing the system to run in the thermal regime seems dubious due to the very high backgrounds implied, which will no doubt be a significant factor in the sensitivity of an infrared IFU. In any event there are certainly numerous astrophysically interesting applications for an IFU that is restricted to working in the 1-2.5 μm range.

Wavelength Resolution: A spectral resolution of ~ 2000 should be adequate to support a large number of applications. For reference, note that 3D supports $R \sim 1000-2000$ in its current configuration, and CFHT's imaging FTS operates in the $R \sim 10^{3-4}$ range, depending on the filter used and scan parameters selected. Such a resolution is also consistent with the science drivers already used to define the lower end of the resolution scale possible with the NIRS in its conventional single slit mode, but of course would allow for such performance in a unique spectro-imaging mode. For this level of resolution, and the assumed spectral length, several filters would be needed to fully sample a near-infrared atmospheric window, but in principle several interesting line features could be included in a single integration.

Field of View: Determining the optimal field of view requires a subtle trade between field of view and spectral coverage in any one integration. For a TIGER design, the number of lenses applicable to a given array size (n_x by n_y pixels), spectral length in pixels, L_s , and separation between spectra, δ_x , is given by the relation (Bacon *et al.* 1995) $N_{lens} = n_x n_y / (\delta_x L_s)$. The field of view scales as $sampling \sqrt{N_{lens}}$. For an ALADDIN array, assuming each spectrum occupies $\sim 1/4$ of the array width, and the same spectral separation is used as TIGER (7 pixels), N_{lens} is ~ 600 and the field of view is $\sim 1.2''$ for $sampling = 0.05''$. Though tiny, this field of view still has interesting applications on a telescope with the type of image quality Gemini should be able to deliver. Pushing to larger sampling (say $> 0.2''$) seems inconsistent with the design philosophy of the telescope and would probably lead to undersampling at the IFU with degraded overall performance.

4.0 Science Applications

Since the discovery of the Galactic center at infrared wavelengths by Becklin and Neugebauer (1968), unraveling the complex nature of this unique object has pushed ground based observing techniques to their limits. Striving for higher resolution infrared

images has been crucial in Galactic center research, particularly since the discovery of the peculiar compact radio source Sgr A* (Lo *et al.* 1985), which remains today one of the best candidates for a massive black hole known (Genzel and Townes, 1987). In the past few years a flurry of high resolution observations of the Galactic center have been made, thanks in part to recent advances in infrared array technology. In 1990 Simons *et al.* (1990) and Simon *et al.* (1990) published results from a series of lunar occultations that were observed with both infrared photometers and arrays. The resolution of the observations was $\sim 0.02''$, or ~ 200 AU at the Galactic center. These observations proved the stellar nature of the brightest components of IRS 16, which were previously speculated to be dense star clusters due to their extreme brightness. They did not, however, detect an infrared counterpart to Sgr A*. In 1991 Depoy and Sharp (1991) published images at J, H, K, and L with deconvolved resolutions of $\sim 0.4''$ and also failed to find any infrared counterpart to Sgr A*. More recently, Eckart *et al.* (1992, 1993, 1995) published H and K images of the Galactic center with $0.15''$ resolution and found a number of sources at the position of Sgr A* with a combined K brightness of ~ 13 mag. Also Close *et al.* (1992) found a point source within $0.2''$ of the nominal location of Sgr A* with $K = 13.3 \pm 0.5$ mag and $H = 15.5 \pm 0.5$ mag. Herbst *et al.* (1993) acquired high resolution images ($0.5''$ resolution) at K, L', and M. They found a possible counterpart to Sgr A* at K and L'. The Herbst *et al.* (1993) candidate is significantly fainter at K (14.5 mag) than the combined Eckart *et al.* (1993) sources or Close *et al.*'s (1992) candidate, probably indicative of the intrinsic problems of searching for a faint point source in a region as morphologically complex as the Galactic center. Finally, Simons and Becklin (1996) report on the detection of a possible infrared counterpart to Sgr A* at L' ($3.8 \mu\text{m}$) based upon a nearly diffraction limited image acquired through shift and add processing.

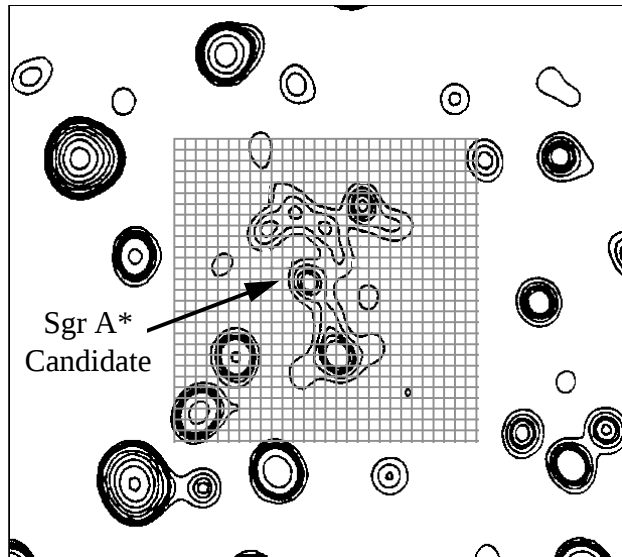


Figure 7 - The best image of an infrared counterpart to Sgr A* is shown, adapted from Eckart *et al.* (1995). This image has $\sim 0.15''$ resolution. Overlaid on this is a grid corresponding to $0.05''$ pixels in an IFU having a ~ 1.2 arcsec field of view.

Much of the research emphasis on the Galactic center in recent years has therefore been on achieving ever higher spatial resolution to disentangle the complex physical mechanisms at work in the Galactic center. A number of experiments have demonstrated that the enclosed mass within the central few arcseconds in the IRS 16 region is well in excess of $10^6 M_{\odot}$ (Sellgren *et al.* 1990). To date inadequate spatial and spectral resolution from ground based observations have made it impossible to pinpoint where this mass is located, e.g., is it in the form of a large number of degenerate stars or is it contained in a black hole? Accordingly Gemini will be a valuable tool for further dissecting this complex region. Though it is probable that NICMOS on HST will be used for further investigation of Sgr A*, the comparative spectroscopic capabilities of

NICMOS vs. an IFU-equipped NIRS on Gemini-South should leave Gemini with a clear advantage. A specific experiment that could be run would be to make an IFU observation of the ~ 1 arcsecond region centered on Sgr A*. The position of the candidate Sgr A* infrared counterpart Krabbe found is now tied in to the radio source at the ~ 0.1 arcsec level, hence with an infrared on-board wavefront sensor it should be possible to execute a precision offset from the bright nearby supergiant IRS 7 onto Sgr A* with adequate accuracy. Integral field spectroscopy of the target found by Eckart *et al.* (1995) at the CO ($2.3 \mu\text{m}$) absorption transition would in principle permit velocity measurements for each of the knots of emission seen in the immediate vicinity of Sgr A*, which could in turn pinpoint the enclosed mass at a *much* finer scale than has been possible to date, assuming these sources are in the immediate vicinity of the long suspected blackhole in this region. This could in turn lead to the critical discrimination between the unseen mass in the Galactic center being point-like (hence contained in a black hole) or distributed.

IFU applications extend to planetary science as well. Figure 8 shows an image of Io with the same grid of $0.05''$ pixels overlaid. The image was made with HST in the optical, though it has comparable resolution to what Gemini can achieve in the near-infrared. Figure 9 is a spectrum of Io with R ~ 4000 resolution in the K-band (Schmitt *et al.* 1994). This observation was made by placing an aperture in CFHT's FTS on Io and measuring the integrated flux from the surface of Io in a single beam, hence has no spatial information. Merging spatial information with spectra and chemical models would constrain remaining uncertainties about SO₂ frost grain sizes, depths, temperatures, etc., on the surface of Io, which has a direct bearing on the dynamics of this unique object in the solar system. An IFU observation would therefore permit a

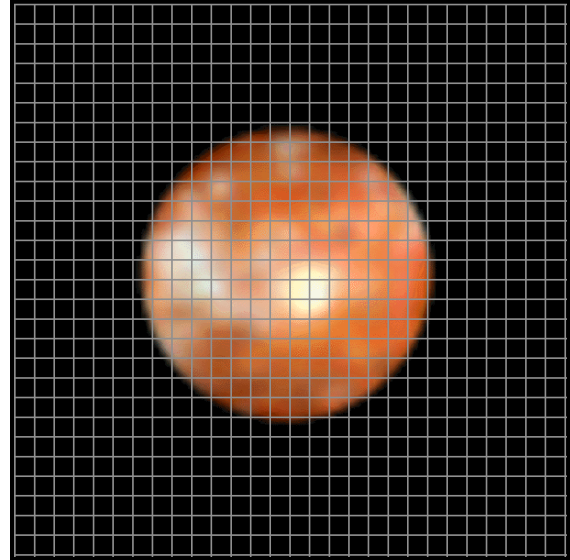


Figure 8 - A high resolution image of Io is shown, with an IFU grid consisting of $0.05''$ pixels superimposed. The image was made with HST in the optical but has comparable resolution to what can be expected from Gemini in the near infrared.

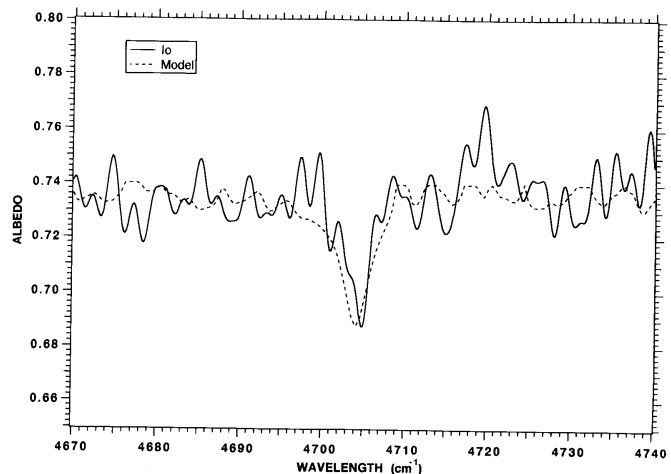


Figure 9 - A near-infrared spectrum of Io is shown compared with a synthetic reflectance spectrum, illustrating the recently discovered absorption line from SO₂ on the surface of Io. Mapping this line across the surface of Io, combined with high resolution imaging, would lead to a much better understanding of the volcanism on this satellite.

complete mapping of the surface composition of Io in the near-infrared and support a long term program of monitoring the geologic activity (volcanism, molten material flows, etc.) of an *extra-terrestrial* body with unprecedented sensitivity. Similar spectacular gains can be achieved for the other Galilean satellites, or Titan, orbiting Saturn, which has relatively transparent windows in the near-infrared and it might be possible to penetrate through the upper cloud deck of Titan, permitting for the first time near-infrared spectroscopy of surface features on Titan - a body suspected of having liquid on its surface, but never proven.

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