Image Slicing with Infrared Fibers

J. E. Larkin¹, A. Quirrenbach², & J. R. Graham³

¹Department of Physics and Astronomy, University of California, Los Angeles, 8371 Math Sciences, Los Angeles, CA. 90095-1562
²Center for Astrophysics and Space Science, University of California, San Diego, 9500 Gilman Drive, La Jolla, CA 92030-4111
³Department of Astronomy, University of California, Berkeley, Berkeley, CA 94720

Abstract.
We are proposing to build a new integral field instrument (OSIRIS) for use with the Keck Adaptive Optics System. It will utilize a large (1024 element) fiber optic bundle to slice the field and feed a standard infrared spectrograph with a spectral resolution of 5000. To improve the fill factor of the fiber bundle, we plan on coupling it to a matched lenslet array. The spectrograph will have three plate scales of 0.′′05, 0.′′10 and 0.′′20 per pixel, and full broad band spectra will fit on a single 2048×2048 infrared array. Other innovations include using some of the fibers for pseudo-slits and sky measurements and non-uniform spacing for the "linear" feed to the spectrograph.

1. Design Goals

Among the most important design goals for the OSIRIS instrument was to have a sampling close to the diffraction limit of the Keck Telescope (0.′′02 to 0.′′07 in the near-IR). The only ways of achieving this is to either have very small physical sampling (0.′′05 = 36.4 µm at F/15) or a large focal ratio (0.′′05 = 1 mm at F/412). The first option requires new technologies and one must worry about diffraction effects deteriorating image quality. The second option makes the spectrograph very large and potentially costly. As you'll see, we’ve opted for a compromise of moderate focal ratio and sampling size.

Many of the potential science targets are on the order of one arcsecond across and one of our design goals was to encompass all or most of a target in a single exposure. With samplings on the order of 0.′′05, this requires at least a 20×20 grid of spatial samplings or at least 400 individual spectra. To avoid spectral overlap, for most geometries this requires at least a 1024 square array.

The instrument also needs to have a spectral resolution of at least 4000. This requirement is set both by the spectral sampling needed on many of the science targets (~ 75 km/s) and also on our desire to suppress OH emission lines. Between 1 and 2.2 µm the dominant source of background is the forest of atmospheric OH lines (e.g. Herbst, 1994). The continuum emission actually
reaches a minimum near 1.6 microns where scattered light and thermal emission cross. Because the OH lines are narrow and discrete, we can separate them by going to high spectral resolution. At a resolution of 4000 approximately 90% of our pixels will be free of bright emission lines and will thus have greatly reduced backgrounds.

A conflicting requirement is broad band spectral coverage (z, J, H and K). This is an efficiency requirement so that each setting has $\Delta \lambda/\lambda \sim 0.2$. Coupled with the high spectral resolution, this requires approximately 2000 spectral pixels.

Finally, the spectrograph needs to work throughout the near infrared from 1 to 2.5 microns are therefore requires full cryogenic performance (77 K). This requirements places many difficulties with the design including the need for cryogenic optical couplings, cryogenic motors and mechanisms, temperature compensation in the optical alignment and restrictions on the optical components that are available.

2. Image Slicing Technique

With the requirement of diffraction limited sampling mentioned above, we found that we had three viable image slicing techniques. The first would be to use micromirrors (MEMs) to carve up the field. This is a promising avenue, but we have not seen any concrete designs for coupling a micromirror to a spectrograph. One of the largest problems with these devices is that each mirror tips about an individual axis so the optical path lengths from different elements are different. This makes it difficult to collimate the light. Micromirrors also require complex electronics and software to control. Other concerns such as fill factor, repeatability, cryogenic operation and technical maturity also made us decide against micromirrors.

A second slicing solution would be the use of a lenslet array in a Tiger style instrument (Bacon et al. 1995). That is use the pupil images formed by a lenslet array placed at the focus to feed a spectrograph. The lenslets are rotated so that their spectra don’t overlap. This is a good option if the desire is for large spatial coverage with modest spectral coverage. The difficulty arises in that spectra from the bottom of the array must be prevented from overlapping with spectra from the top or middle of the array. One solution would be to make a fairly long and narrow lenslet array (10×50 for example) but that would not meet our goal of 1” spatial coverage in both axes.

The third slicing option we considered is a fiber optic bundle. These have now matured into a somewhat standard commercial product in which fibers can be arranged in complex geometric patterns at the input, and then reorganized into a linear (or pseudo-linear) pattern for feeding a spectrograph. They offer the advantages of a fine sampling scale (100 $\mu$m), no spectral overlap between fibers, and the ability to dedicate some fibers to simultaneous measurements of the sky. The primary disadvantage is modest fill factors ($\sim 40\%$). To compensate for this we have combined options two and three and designed around a fiber bundle and matched lenslet array placed at the AO focus. The lenslet is used to achieve a much higher fill factor, while the fibers gives increased sampling flexiblity and a more optimized arrangement into the spectrograph.
Fiberoptic manufacturers have begun creating elaborate fiber bundles for high speed switching applications, and we have identified one company, Fiberguide Industries, that can produce almost arbitrary fiber patterns. The basic process is to define a hole pattern in a computer and use it to direct a laser to cut a precision set of holes in a thin metal plate. The hole spacing can be as small as 150 microns and positional accuracies are better than 4 microns. The fibers are then individually polished and inserted into the holes. The output end is done similarly with essentially any mapping of input to output hole patterns. Fiberguide Industries has an infrared transmissive fiber (Anyhroguide G) that operates from 0.4 to 2.4 microns and has a temperature range from -190°C to 350°C; ideal for our application. We anticipate a fully cooled optical assembly to just above LN2 temperatures.

Based on certain optical limitations it is difficult to use more than one fiber per two spatial pixels, even with underfilling of each pixel. We are therefore proposing a 1024 fiber bundle with a fairly elaborate input and output arrangement. The primary input component will be a 28×28 fiber rectangular bundle (784 fibers total). Extending from this bundle in the four cardinal directions are 52 fibers yielding pseudo-slits of total length 52 + 28 + 52 = 132 fibers. These "slits" can be aligned along an extended object’s major and minor axis to extend the spatial coverage of the instrument. The final 32 fibers are placed in four bundles of 4×2 fibers each at the extreme corners to provide simultaneous sky coverage for many compact objects. The arrangement is shown in figure 1.

At the output the fibers are staggered to allow a horizontal spacing of 100 microns while maintaining the minimum 150 micron fiber-fiber spacing. Since an arbitrary fiber spacing is possible with bundle technology, we plan on an output pattern that is not exactly evenly spaced and that has a gentle curve from one end to the other. This allows us to remove much of the spectral curvature and distortion of the optics that is inherent in slit spectrographs. So it is hoped...
that the spectra on the detector will have a very uniform spacing and spectral features will lie roughly along rows of the device.

### 2.1. Lenslets

A fundamental problem with fiber bundles is the low fill factor due to the round shape of the fibers and the thick claddings and jackets. We are proposing to remove this problem by placing a matched lenslet array in front of the fiber bundle. The fibers are then at the pupil images of the lenslets making the instrument a pupil spectrograph. Adaptive Optics Associates can manufacture custom lenslets with the desired 150 micron spacing with better accuracy than the fiber bundle. Rectangular lenslets have > 98% fill factor and should have high coupling efficiency. For the infrared, AOA recommends their sapphire substrates with the lenslets formed from infrared transmissive epoxy. AR coatings will be applied to both faces.

A potential problem is the alignment of the lenslets with the fiber bundle and maintaining this alignment when cold. We hope to alleviate this problem by rigidly mounting the lenslets to the face of the fiber bundle. The lenslets can be fabricated such that their focal plane is at their back surface. By fastening this to the fibers, alignment should remain good during cooldown. We will investigate several fastening strategies including ir-epoxy, and mechanical clamping.

For most of the plate scales we recommend, the alignment requirement is relaxed a bit because the spot size generated by each lenslet is significantly smaller than the fiber core itself. So we underfill each fiber and small misalignments don’t create light losses. The spot size for each lenslet is essentially the pupil diameter formed by the lenslet since each lenslet is in the focal plane. The pupil size is given by:

\[
pupil \text{ size (microns)} = \frac{\text{lenslet focal length (microns)}}{\text{input focal ratio}}
\]

As shown below, the input focal ratio for the primary fiber spacing of 0′.05 per fiber is F/61. To achieve a pupil size under the 50 micron core size, we need a lenslet focal length less than 3.05 mm. For the coarser plate scales of 0′.1 and 0′.2 per fiber, the pupil would be too big, however, resulting in a loss of light. At the same time too small of a focal length will result in a very fast focal ratio at the detector. We are therefore recommending a focal length of 1.5 mm, which matches the 0′.1 pupil with the fiber core. It does mean that there will be a 75% loss of light for the coarsest scale of 0′.2 per fiber. As will be shown, a focal length of 1.5 mm for the lenslets requires a focal ratio at the detector of F/3.6 which is difficult but doable.

### 3. Spectrograph Design

#### 3.1. Front-End Reimaging Optics

The angular scale that corresponds to each fiber is determined by the F/## of the beam as it reaches the lenslet array. A simple relationship can be obtained:
\[ \frac{\Delta \theta (\arcsec)}{\Delta x (\mu m)} = \frac{0.206}{D(m) F/\#} \]

where \( D(m) \) is the diameter of the telescope in meters, \( F/\# \) is the focal ratio at the lenslets, and \( \Delta \theta / \Delta x \) is the angular scale in arcseconds per micron. So for a 150 micron lenslet separation, a 10 meter telescope and a focal ratio of 15, the angular scale per lenslet is 0.206 arcseconds. This is a good sampling for a non-AO mode, but with a diffraction limit at 1 micron of under 0.025 arcseconds, it is necessary to change the plate scale before the lenslet array. It is also difficult to form a good cold pupil or baffle system after the fiber bundle, so the primary baffling is performed in the front-end optical elements.

**Table 3.1:** Plate Scales

| Magnification | Focal Ratio at Lenslets | Angular Scale per Fiber | Central Field | Length of “slits” |
|---------------|-------------------------|-------------------------|---------------|------------------|
| 1:1           | F/15                    | 0.206                   | 5.76          | 27.2             |
| 1:2           | F/31                    | 0.100                   | 2.8           | 13.2             |
| 1:4           | F/62                    | 0.050                   | 1.4           | 6.6              |
| 1:10          | F/155                   | 0.020                   | 0.56          | 2.64             |

Table 3.1 gives the four possible plate scales and their corresponding focal ratios. The fields of view of the central 28×28 fiber patch and the lengths of the "slits" formed by long 1×132 fiber stripes is also given in arcseconds. For full sampling of the diffraction limit, we would need a scale per fiber of ~0.01, but then the field of view becomes very small, and we believe that for that scale, the other AO instrument NIRC2 is more appropriate in most scientific applications. But a field of 0.56 is actually not too small to consider for certain applications like faint field galaxies where the diameters can be under 0.5. But the scale that we recommend as the primary choice is a 1:4 magnification that yields 0.05 fibers and a 1.4 central field of view. This is ideal for most of the scientific programs and although it slightly undersamples the diffraction limit at all of the selected wavelengths, it does maximize the energy per fiber for point sources and allows for very high resolution on extended sources. The "slit" lengths of 6.6 are also quite reasonable for investigating the major and minor axes of extended sources such as AGN and the nuclei of Ultraluminous Infrared Galaxies.

There will, however, be occasions where a larger field of view will be desirable so coarser samplings should be considered. Since the front end will consist of a pair of infrared doublets that are of very low cost compared to the overall instrument, we are recommending that a simple turret be used to rotate in different reimaging optics to select different plate scales. We recommend three selectable scales for the instrument of 0.2, 0.1 and 0.05 arcseconds per fiber in a three position turret. Good repeatability of this mechanism is important but not critical since any motion of the lens assemblies would simply change the field of the fiber bundle by a small amount. So no spectral shifts or loss of light would occur due to position errors. The turret also provides the future option that additional scales can be created, and three selected for each run. This would give a powerful non-AO capability to the instrument as well, although there can be significant light loss at the fiber coupling with the coarsest plate scales.
3.2. Grating

For maximum reproducibility, we have selected to use a single non-rotating grating. But we still desire high efficiency across each infrared spectral band, and no order overlap within each broad band. This is achievable by blazing the grating to a blaze wavelength of 6.35 microns. The third order then peaks at 2.12 microns, fourth at 1.59 microns, fifth at 1.27 microns and sixth at 1.06 microns. These are ideally situated in the K, H, J and z bands, respectively. A blaze function for such a grating is shown in figure 2.

3.3. Filters

Since an entire broad band fits onto the detector at once, narrow band filters are not needed. So the only filters required are broad band K (2.0-2.4 microns), H (1.5-1.85 microns), J (1.15-1.35 microns) and z (1.00-1.12 microns). We plan on placing these in a filter wheel just in front of the grating, essentially at the pupil plane. This gives uniform wavelength blocking across the field. Ray tracings for standard one inch filters have demonstrated that flatness requirements are quite modest since filters begin as highly polished substrates. Most surface deviations are then due to warping which are matched between the front and back surface.

3.4. Detector

Essentially every advantage of the integral field unit is tied to the use of a 2048×2048 infrared device. Good OH-suppression requires a spectral resolution of 4000 or higher. It also requires a highly reproducible spectral format to assist with software extraction of uncontaminated pixels. Together these requirements mean full band coverage without a moving the grating. For a resolution of 5000, this requires roughly 2000 pixels in each spectral channel. If a 1024 array were used, then either the resolution would need to be halved with considerable loss.
of scientific capability and essentially all OH-suppression, or the grating would need to be scanned across the array which would decrease observing efficiency and degrade spectral extractions.

The spatial coverage is also dependent on the number of fibers in the bundle. We’ve found it difficult to use more than one fiber for every two columns of the array without significant spectral overlap. If a 1024 array were used, then this would correspond to only 512 fibers arranged in a central 20×20 fiber bundle. With 0.05 fiber sampling, the field would be one arcsecond on a side. This is marginal for many of the science goals. A 2048 array would allow 1024 fibers arranged in the 28×28 fiber bundle with 240 fibers for the extended linear ”slits” and sky patches described above. This is a significant improvement in field size and relaxes many of the pointing accuracies required for targets such as the Kuiper belt objects.

Rockwell has recently begun fabricating multiplexers for a new Hawaii 2 infrared array that has a 2048×2048 format. Quantum efficiencies are expected to be greater than 80% for the 1-2.5 micron version, with a read noise of ~2.5 electrons. The detector pitch will be 18 microns yielding a total array physical size of 37 millimeters. The multiplexer can support either 4 or 32 readout channels with pixel clocking rates of roughly a megahertz. Since all of science goals make use of the OH-suppression, it is anticipated that long exposure times will be the rule, so it is not necessary to support a fast readout mode. We therefore believe that a one hertz maximum frame rate is more than sufficient allowing us to use only 4 readout channels. This greatly reduces the cost of the electronics.

4. Science Drivers

The OSIRIS instrument combines four powerful capabilities: high spatial resolution with the Keck adaptive optics system, medium resolution (R~5000) infrared spectroscopy, integral field capability, and OH-suppression. Taken together these capabilities allow us to dig much deeper into many pressing astrophysical problems. Below we have identified several scientific programs which should greatly benefit from this instrument.

4.1. Extragalactic Science

Faint field galaxies like those observed in deep imaging surveys are very compact, often with radii well below 1". Integral field observations of these objects can determine internal dynamics, star formation rates, redshifts, and Hubble Type simultaneously. These observations are crucial in determining the merger rates and evolutionary processes in the first generations of galaxies. Although the surface brightness per fiber will be quite low, the backgrounds are also down by a factor of 400 compared to a square arcsecond so many of these objects can be observed in reasonable timescales (hours).

Another related group of objects are the host galaxies of quasars. Only with high spatial resolution can the faint disks of galaxies be seen in the glare of quasars. Recent observations suggest that mergers and galaxy interactions may play a key role in the feeding of material in the central supermassive blackhole. An integral field instrument can study not only the emission features of the
Faint field galaxies become very small at high redshift and can have core diameters well below 1". As this pair of images from Roger Thompson (Univ. of Arizona) shows, the infrared and optical morphologies are sometimes quite different.

quasar itself, but also measure the morphology, and spectrum of the galaxy and determine star formation rates, masses, metallicities, etc...

Active Galaxies are also an ideal target for the integral field spectrograph. At the resolution of the proposed instrument (0.05) the narrow line regions of some nearby Seyfert Galaxies should be resolvable. This would allow us to directly test the standard model in which AGN have a supermassive blackhole, an accretion disk and two populations of clouds (narrow line and broad line) which orbit at different distances from the center. OSIRIS should be able to spatially and spectrally separate out the narrow line clouds from the more centralized broad line region. OSIRIS should also be able to study nuclear star formation in AGN and spectrally image the interaction between the central engine and surrounding regions.

4.2. Planetary Science

Although the planets are vastly closer than the extragalactic targets, many solar system targets do have interesting structures on subarcsecond scales. Obvious targets include the moons of the Jovian planets and asteroids. The largest moons, such as Titan are roughly 1" across, and there is intense interest in their surface chemistry. Titan has a dense methane cloud layer which can best be penetrated in the infrared, and appears to have a surface covered in hydrocarbons. With OSIRIS, one could measure surface chemistry at over 500 independent locations within a few hours. The moons IO and Ganymede are also of great interest.

Kuiper belt objects present a different opportunity for OSIRIS. Although we don’t anticipate resolving these tiny objects, there is still significant gain to be had by going to high spatial resolution. Chief of these is a great reduction in
the background. The integral field nature of OSIRIS also reduces the need for accurate tracking and positioning since there are effectively no slit losses.

4.3. Galactic Objects

Within our Galaxy, there are countless varieties of objects, many of which have structural and spectral properties ideally suited for OSIRIS. Perhaps chief among these are faint stellar objects and brown dwarfs. For free floating objects, the reduced background of the high spatial resolution would allow for more sensitive measurements. For faint objects near brighter companions, the pseudo-coronagraphic nature of an integral field instrument (and the capability to put in a real coronagraphic set of stops) gives great advantage in determining the spectral properties. OSIRIS not only offers the ability to study such objects but also to find them in the first place. By imaging the central 1” to 2” around stars, one could use a spectral filter to search for objects that are spectrally different from the primary. Such a filter could be formed from a weighted summed set of spectral channels where the brown dwarf or low mass companion would be expected to be significantly different from the primary, such as in the methane or water bands.

The Galactic center is a unique environment where massive stars are born in compact clusters, and where orbital motion is directly observable around the central blackhole. It is also highly obscured with approximately 30 magnitudes.
of visual extinction. Infrared spectra encompassing the central cluster (<1” in diameter) could determine the 3-dimensional kinematics as well as the spectral types of this unique grouping of stars.

5. Instrument Summary

The OSIRIS instrument is an integral field infrared spectrograph designed for the Keck Adaptive Optics System. It will utilize the latest infrared detectors and state-of-the-art fiber bundle technologies to achieve high spatial resolution, integral field imaging, very faint object sensitivity, moderate resolution spectroscopy (R~5000) and a limited long slit capability. All of this is achieved with an innovative yet straightforward and easy to use instrument.

Because of the great amount of information in each frame, only very limited observing modes are required. The large array means that a full broad band spectrum is contained in each exposure. By proper grating selection this is further simplified in that a single fixed grating can be used for all bands (z, J, H and K). The band is easily selected by changing the order sorting broad band filter. Thus, within the spectrograph portion of the instrument, the only moving part is a simple filter wheel with five positions corresponding to z band, J band, H band, K band and a closed position. In each position, a complete spectral image is obtained with 2048 spectral channels and 1024 spatial channels.

Within each exposure is an R~5000 spectrum of a 28×28 pixel patch of the sky, plus vertical and horizontal slit coverage of 1×132 pixels. At this resolution, OH emission lines that dominate the background in the J and H windows are well separated. By coadding only those spectral channels without OH-emission lines (about 90% are clean) a very deep infrared image can be extracted for the 28×28 pixel field (1.4”×1.4” in the primary adaptive optics mode). But in addition to this image, full spectral coverage is of course present.

The OSIRIS instrument is not only powerful scientifically but also quite modest in cost and complexity. It draws upon much of the experience of previous Keck instruments especially NIRSPEC (McLean et al, 1998). Due to a simpler detector readout, it actually has simpler electronics requirements than the NIRSPEC instrument allowing us to essentially clone most of the vital electronics. Because of the expected low backgrounds and long exposures, the detector can be clocked out relatively slowly, about 1 hertz per frame, meaning that we only need to use a four channel readout scheme. We also anticipate only two or perhaps three cryogenic mechanisms of fairly simple design.

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References

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