# CELT INSTRUMENT WORKING GROUP
# QUARTERLY REPORT #2
# CELT Report #16

March 6, 2001

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## 1. MEETINGS & ACTIVITIES

Since the last Quarterly Report, the IWG has been very active.

*December:*

- Reviewed status of group – identified additional resources, assigned tasks

*January:*

- Co-chairs (McLean and Taylor) met with Chuck Steidel (co-chair of the Science Working Group)
    - Received draft SWG report on science goals and discussed these in the context of instruments
- McLean and Taylor began to meet on a more regular basis; also met with Dekany (AOWG)
- January 18, the full IWG met at UCLA and established Action Items for next Quarterly Report
- Caltech hired a student to work on source and system models

*February:*

- McLean, Taylor and Vogt gave presentations at the CELT Workshop at Caltech
- IWG researched technology issues, initiated modeling, worked on more detailed instrument designs and generated several intermediate reports

## 2. STATUS SUMMARY

A review of the report by the Science Working Group showed a significant overlap with the IWG's initial straw-man list of instruments, but revealed greater emphasis on spatial multiplexing in the seeing-limited case. The major science requirements can be met with the following suite of instruments:

A. Full field, Seeing-limited Mode (e.g. 0.6" apertures)

- High-Resolution Spectrograph (R>40,000)
    - object-multiplex factor ~100, fiber fed?
    - wavelength range 0.3 to 1 micron, but perhaps less important than below
- Intermediate-Resolution Spectrograph (R~5,000), sensitive to m~25 optical
    - object-multiplexed by ~1000, fibers or slits
    - wavelength range 0.3 to 1 micron; below 0.4 microns needed
- Low-Resolution Spectrograph (R~500), very faint objects
    - object-multiplex factor ~ 5000, fibers or slits; sky subtraction with fibers m~27?
    - wavelength range 0.4 -1.0 microns
- Medium-Resolution NIRMOS type instrument for near-infrared (< 1.8 microns) - no science case?

B. Multi-Conjugate Adaptive Optics Mode:

- Near-IR camera
    - FOV, stability of PSF and image quality harder to predict

    - Extremely large detector mosaics needed
- Near-IR Integral Field Spectrometer
    - R~5000, 0.9-2.5 microns
    - 1-2" per IFU; 5-10 units; fully deployable ver 120" FOV
- Mid-IR camera/spectrometer
    - high-resolution spectroscopy, R~200,000 + spatial resolution
    - wavelength range 8-21 microns
    - needs AO, but simpler system - must be diffraction-limited to beat space
    - 1024 x1024 array gives a few arcseconds FOV

Comments on MCAO:

- large fraction of the science can be done with a small field of view (FOV)
- no strong demand for the whole FOV to be covered at once => deployable integral field units (IFUs)
- diffraction limit at K is ~5 mas; implies multiple spectrographs and IFUs over 1 arcminute?

Other questions and issues still under consideration with an impact on instrumentation requirements are

(i) the benefits of Extreme AO - implies an IFU optical spectrometer
(ii) polarimetry - no case yet
(iii) tuneable filters - e.g. Fabry Perot for surveys, e.g. frequency switching (H-alpha) - no strong case
(iv) stationary IFU for AO use - gives largish field of view
(v) seeing-limited IFUs over 20' field? No strong science case yet.

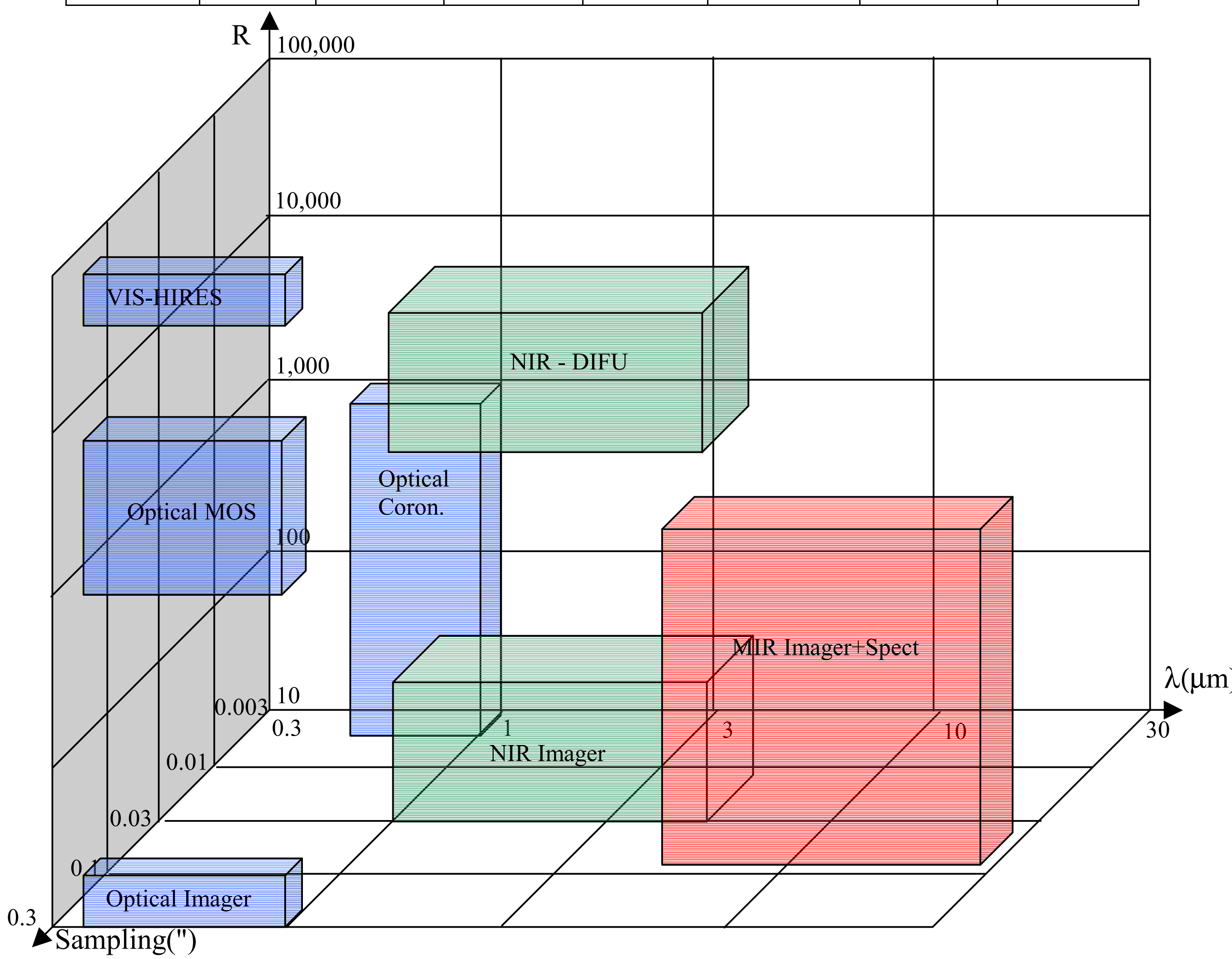
As already pointed out in earlier IWG reports and presentations, there are many challenges and complex design implications in meeting the science requirements. For example, how to build IFUs (cryogenic?) for AO, how to deploy these - this is an area which may need proto-typing - and, how to use fibers. Detector Systems is another concern. We need the lowest noise detectors and array-limited performance from a new generation of controllers. Faster readouts are needed to minimize loss of sky time.

At the end of this report is an Appendix with several papers containing intermediate results of IWG studies. This work will be refined and integrated into the draft IWG Final Report during the next quarter.

The following Table and Figure shows a summary of the phase space covered by these instruments.

# CELT Instrument Concept Parameters

| Name | Min λ | Max λ | Available FOV | Used FOV | Spectral Resolution | Sampling | Multiplex |
|---|---|---|---|---|---|---|---|
| Optical Imager | 400 nm | 1 µm | 20' | 20' | 10 | 0.3" | 1 |
| Optical MOS | 400 nm | 1 µm | 20' | 20' | 5000 | 0.3" | 1000? |
| HIRES | 400 nm | 1 µm | 20' | Single Object? | 50,000 | | ~few? |
| AO NIR Imager | 1 µm | 2.5 µm | 2' | ~1' | 5-100 | 0.003"-0.007" | 1 |
| AO DIFU | 1 µm | 2.5 µm (5µm?) | 2' | 0.5" | 5000 | 0.01-0.1" | 80 |
| MIR Imag+Sp | 8 µm | 27 µm | 2' | ~1' | 10-1000 | 0.03-0.07" | 1 |
| AO-Opt Coron | 600 nm | 1 µm | 30" | 30" | 1000 | 0.008"? | 1 |



**3. CURRENT ACTIONS**

The IWG is pursuing the following:

- More detailed instrument designs are being developed
  - Vogt has investigated in detail the design for CHRS – a super-HIRES instrument
  - Graham has studied options for a mid-IR Camera/Spectrograph
  - Larkin is investigating the NIR-IFU instrument
  - McLean is investigating the NIR MCAO camera concept
  - Taylor is working on multiplex techniques and the optical spectrographs
  - Kulkarni is investigating extreme AO issues
  - Guhathakurta is investigating the UV requirements
- Key technologies which are also being investigated are
  - Optical materials
  - Volume Phase Holographic gratings
  - MEMS
  - Detectors
  - Controllers – in conjunction with CARA/UCO/Palomar
- System modeling tools are being developed
  - Graham has provided IDL-based tools to Taylor
  - Jason Marshall has started work with Taylor at Caltech
- An outline of the final IWG report is now under construction by McLean and Taylor which draws together all the reports and includes
  - Instrument designs and costs
  - Technology issues and development requirements
- The IWG is also considering plans for proto-typing resources

**4. APPENDICES**

A1. Mid-IR Imager/Spectrometer – James Graham
A2. Diffraction-limited Near-IR Camera – Ian McLean
A3. Deployable Integral Field Spectrograph Possible Fiber Bundle Solution - James Larkin
A4. An Examination of the Viability of fibers instrumentation for CELT- Keith Taylor

## A1. Mid-IR Imager/Spectrometer – James Graham (UCB)

Goals: Diffraction limited imaging in the thermal infrared with performance optimized for the 8-13 micron window. Operation in the 20 micron window. Sensitivity limited by natural atmospheric emissivity.

Observing modes and design considerations:

- Wavelength range: 8-27 microns
- Broad band imager with interference filters (lambda/delta-lambda ~ 10)
- Cold pupil for rejection of out-of-beam thermal background
- Coronagraphic mode with occulting disk and rotating Lyot stop
- Grism spectroscopy
  - Ge grism to R ~ 1000
  - Ge R4 echelle to R ~ 4000
- Telescope focus located within dewar for cryogenic slits and occulting spot
- Nyquist sampling - broad wavelength range requires two cameras or variable magnification
  - 0.0344 arcsec/pixel at 10 microns
  - 0.0687 arcsec/pixel at 20 microns
- Final F-ratio: F/5.4 (demagnification = 2.77)
- Field of view: 70.4 x 70.4 arcsec (154 x 154 mm at F/15)

Optical design:
Broad wavelength range and high throughput suggests all reflecting, non-obscured optics.
Collimator: 3.8 degree FOV at F/15
Camera: 10.6 degree FOV at F/5.4
This combination of F/# and FOV implies that simple configurations such as a pair of OAPs provide inadequate control of aberrations for diffraction limited performance. Both optical elements probably need to be TMA's. The mid-IR camera design is not strongly influenced by the final focal ratio of the telescope. F/15 is acceptable.

Detectors:
The best detectors for this range are Si:As BIB devices. It is assumed that large formats will be developed for NGST and other applications. The following properties are assumed.

2024 x 2024 (55.3 mm x 55.3 mm)
Pixel pitch: 27 microns
Gap between pixels: 0 microns
Operating temperature: 8K
Dark current: 1 e/s
Read out noise: 4 e- rms
Well depth: 3e7 e-

Dimensions and mass of instrument:
Collimator diameter: 164 mm.  Diameter of pupil: 10 mm. Total optical path from cold focal plane to detector array: 410 mm
Cryogenic requirements at 8 K:
Volume ~ pi r^2 h ~ 8500 cm^3 (0.0085 m^3). Surface area ~ pi r h ~ 2100 cm^2
Power at 8 K ~ pi r h sigma T^4 /n ~ 70/n W, n = # of insulating layers
Mass of cryo (8K) optics. Assume 100% filling-factor of for 6061 Al alloy (2700 km/m^3): 23 kg

Dewar/optical bench dimensions: 45 cm diameter x 60 cm long cylinder
Dewar mass, assuming 6.35 mm walls: 170 kg
Electronics (preamps, level-shifters, ADCs, host computer VME rack and stepper motor control): 50 kg
Total dewar, & electroncs: 240 kg.

AO requirements: AO required --- r0 ~ 5 m at 10 microns: ~ 36 actuator system
AO emissivity must be minimized ( ~ < 0.04) or cryogenic AO required

Sensitivity:
Broad-band imaging at 10 microns (lambda/delta-lambda = 10):
30 micro Jy, 10 sigma, t = 10,000 s. Assumes 5% mirror emissivity.

Impact of telescope optical design on instrument: Field curvature --- use of TMA for the collimator and camera means that field curvature can be corrected internally.
Impact of telescope optical-mechanical design on instrument:
Inter-segment gaps/Mirror coatings/Cleanliness: need total emissivity < 5%
Control diffraction and scattering from inter-segment gaps for high contrast imaging.
Focal station: two mirror Cass preferred over three mirror Nasmyth

Observatory Impact
Compressor needed for closed cycle refrigerator

**A2. Diffraction-limited Near-IR Camera – Ian McLean (UCLA)**

**Requirements:**

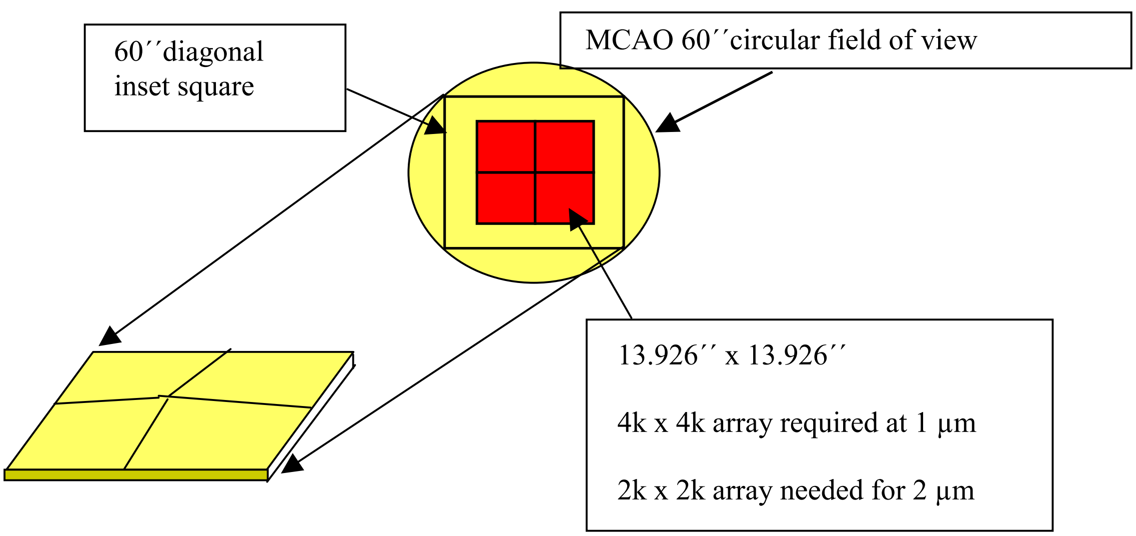
- Nyquist sampled PSF at 1 and 2 μm
  ==> 3.4 mas/pixel and 6.8 mas/pixel
- MCAO Field of View (FOV) = 60´´ diameter
  ==> physical FOV = 131 mm
- Wavelength range: 0.9 - 2.5 μm
  ==> HgCdTe detectors

**Derived Parameters:**

- plate scale telescope = 0.458 ´´/mm, therefore with 18 μm pixels: $2_{pix}$ = 8.25 mas - too coarse
- magnification system needed:
  - $FR_{cam}$ (1 μm) = 36, magnification = 2.4
  - $FR_{cam}$ (2 μm) = 18, magnification = 1.2

Detector size – assume 4k x 4k for now. Then the field of view is
4096 elements ==> 13.926´´ with 0.0034´´ at 1 micron
2048 elements ==> 13.926´´ with 0.0068´´ at 2 microns

**Four-shooter concept with twin-channel cameras**
Figure shows possible way to increase fraction of field of view used, given the assumption that the largest arrays available will be 4096 4096 pixels.

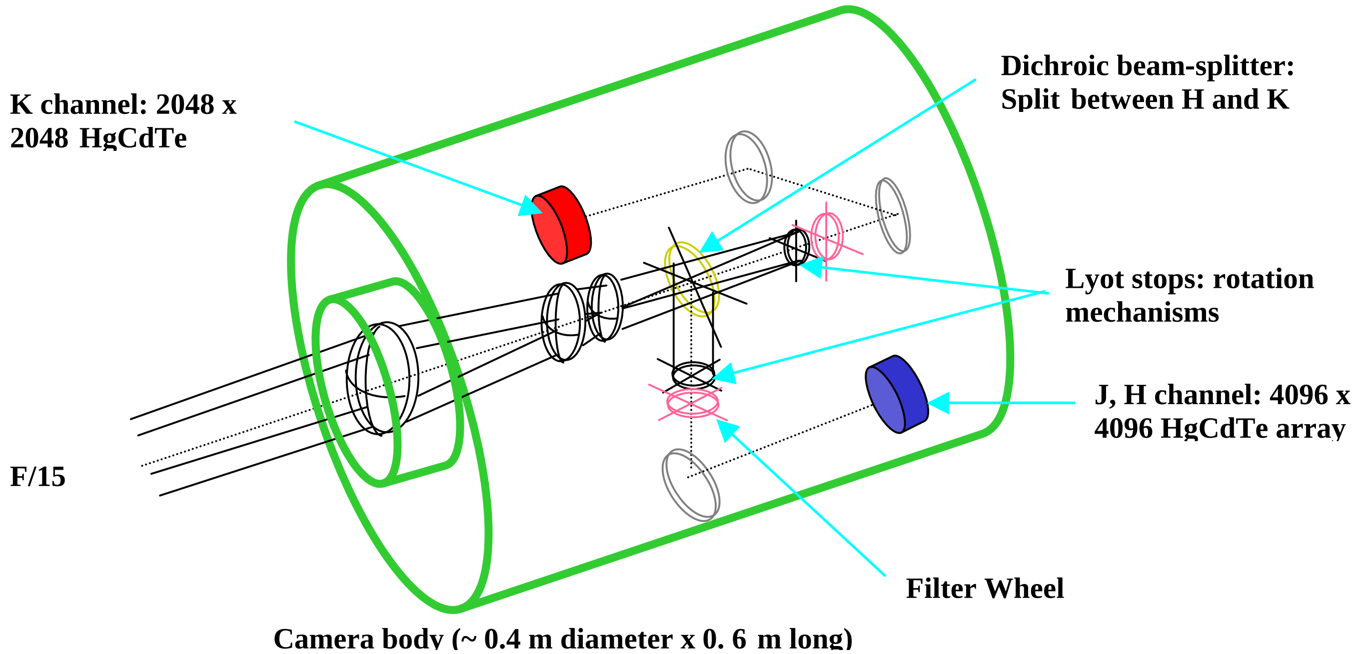



Four cameras are required, each with a ~14 arcsecond field of view. To further increase efficiency, each camera could be twin-channel using a dichroic beam-splitter to send J and H to one beam and K to the other.

Assuming that the 4kx 4k detectors are made by butting 2k x 2k arrays, then each camera has 5 2k x 2k detectors, giving a total of 20 2k x 2k arrays. There needs to be four identical electronic controllers, each capable of handling 5 arrays.

If the thermal background is noticeable, then the Lyot stops will have to rotate as the pupil rotates. Without this complication, there would be only two mechanisms (filter wheels) per camera.

One of Four Cameras:




4 mechanisms: 2 filter wheels and 2 Lyot stops

Cost Analysis:
- 4 cameras x 5 arrays (each 2k x 2k @ $0.25M) ==> $5.0M
- 4 sets of optics at $250k per set ==> $1M
- 4 dewars at $125k each ==> $0.5M
- 4 sets of electronics, each runs 5 arrays; @ $500k per set ==> $2M
- Labor costs (design, assembly & test, software) ~ 100 myr @ $100k/myr ==> $10M

**Total Cost $18.5M**

**A3. Deployable Integral Field Spectrograph Possible Fiber Bundle Solution - James Larkin (UCLA)** – DRAFT - February 18, 2001

## 1.0 Description of the Problem

The goal of the instrument is to provide a multiplexing capability of 50 or more, while also providing spectra of 2-dimensional patches with close to diffraction limited sampling and broad spectral coverage (1-2.4 microns). As section 2 describes, on of the fundamental problems facing such an instrument is sampling in the focal plane. The near diffraction limited scales desired require image slicing with ~20 micron elements in the default F/15 beam. Several approaches may prove feasible such as magnifying the field for mirror slicers or lenslets alone, or possibly using MEMs mirrors in an unmagnified field. I believe a good candidate technology, however, is the use of fiber optic bundles with lenslet arrays in a selectively magnified field (see below). It offers a compact, relatively affordable, and very flexible format while satisfying all of the design goals. In this first section several equations and tables are presented for later reference.

The fiber bundle approach is very flexible because different numbers of fibers can be bundled together into groups while still providing a linear feed to a spectrograph. Several commercial companies are actively producing fiber bundles of varied geometry for a wide range of applications, and fibers that will operate into the near infrared and that will work cryogenically are readily available. Bundles can be made with a square input pattern and linear output and can even be customized to remove some of the natural aberrations within grating spectrometers. The fibers are intrinsically flexible and so should be positionable. Fibers have a relatively small pitch so they can be used to slice images on scales that would be difficult with traditional mirror technologies, while being more flexible in reformatting than MEMs devices which can work on smaller scales.

In the current design, a total of 8192 fibers are used to feed 8 separate spectrograph modules (each 1024 fibers onto a $2048^2$ detector). These fibers can be arranged in a variety of bundle configurations and there is the flexibility to have different spectral resolutions in different modules, and different plate scales for different bundles. Some possible bundle configurations might be:

32x32 central bundle feeding a dedicated spectrograph module. This would be most useful for traditional single object work.

10x10 bundles could cover up to 82 objects simultaneously from the 8192 fibers. This might be the best option for faint galaxy or stellar cluster work.

20x20 bundles would over more spatial coverage than 10x10 but use 4 times for fibers in each bundle for a much lower multiplex advantage.

1.1 Useful expressions

**Angular Diffraction Limit**
The angular diffraction limit for a telescope can be expressed as follows:

$$\Delta\theta(\text{arcsec}) = \frac{0.262 \cdot \lambda(\mu m)}{D(m)}$$

So for the proposed 30 meter telescope, the table below gives the angular limits:

| CELT Diffraction Limit | |
|---|---|
| Wavelength | Resolution |
| 1.0 µm | 8.4 mas |
| 1.25 µm | 10.5 mas |
| 1.65 µm | 14 mas |
| 2.0 µm | 17 mas |
| 2.4 µm | 20 mas |

**Plate Scale**

The conversion from distance in the focal plane to angle in the sky is set by the plate scale and can be expressed as follows:

$$\frac{\Delta x(\mu m)}{\Delta\theta(\text{arcsec})} = \frac{D(m)\cdot F/\#}{0.206}$$

Where F/# is the focal ratio of the beam, D(m) is the telescope diameter in meters. For example, in the focal plane of an F/15 beam on a 30 meter telescope, 1 arcsec corresponds to 2.2 mm.

**Lenslet Pupil Images**

In the case of fibers, they have an intrinsically low fill factor due to their circular cross section and large cladding. In the current design we propose to use lenslet arrays coupled to their input to increase the fill factor to close to 100%. To do this, the lenslets' front faces are placed in the focal plane and they form a pupil image one of their focal lengths behind them. The diameter of this pupil image must be smaller than the fiber core in order to achieve high efficiency coupling to the fibers. So an important parameter is the size of these pupil images. In the end the size only depends on the focal length of the lenslets and the focal ratio of the beam that the lenslets are placed in:

$$\text{pupil size } (\mu\text{m}) = \frac{\text{focal length of lenslet } (\mu\text{m})}{\text{F/\# of input beam}}$$

As an example, the current design uses 150 micron pitch lenslets feeding 125 micron fibers with 50 micron cores. To produce a scale of 0.01" per element, the input focal ratio must be F/103 (see plate scale equation). To keep the pupil size under 50 microns, then the focal length of each lenslet must be less than 5.15 mm. This is no problem, and in fact a focal length of 1.2 mm is more attractive since it will produce an F/8 beam as the fiber input (1200/150=8) which is well matched to the fiber acceptance.

1.2 Focal plane size and focal ratio problems

The current specifications call for a 2 arcmin AO corrected field. In the output beam of the AO system (here assumed to have a focal ratio of F/15) this field is 0.26 meters in diameter (10.3 inches). This is relatively large but is manageable and even desirable given the desire to position many individual objects within the field. A problem immediately arises, however, in that the desired sampling is roughly 10 milli-arcsec which is only 22 microns in diameter. This would be fine for a detector array used in an imager, but is an awkward scale for image slicing.

In the past, one possible solution has been to magnify the desired field by making the beam very slow. If the slicing elements can be made larger than 100 microns, then several options become more attractive. But a problem immediately arises for CELT. If we magnify the field by a factor of 4 to get the sampling over 100 microns, then the 2 arcmin field becomes over a meter in diameter! This seems prohibitively large and reflects the fact that a 2 arcmin field with 10 mas sampling is over 12,000 samples on a side. This fundamental problem must be overcome by all of the CELT AO instruments.

## 2.0 Reimaging for each bundle

Reimaging the entire field is obviously problematic, but this is not absolutely necessary. We're proposing to place a small magnifying lens in front of each cluster of slicing elements. In other words, a small negative lens is placed in front of each bundle of fibers (note: the same solution might work for other slicing options). Figure 2.1 shows a possible solution as a ray trace from Zemax. In this case, the F/15 beam almost comes to a focus from the AO system on the left-most element. A small (2 mm diameter) doublet of fused silica and $CaF_2$ are placed 10 mm before the AO focus and are used to magnify the beam to F/103 and produce a final focus 40 mm to the right on the lenslet array. In this example, the lenslet array has 30x30 elements with a pitch of 150 microns and a scale of 0.01" per lenslet. A matched fiber bundle would be bonded on the back surface of the lenslet and would reorganize the light into a linear feed for spectrographs.

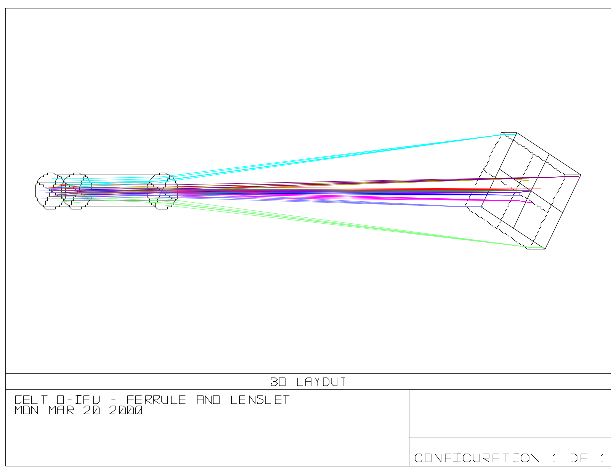



Figure 2.1. Zemax raytrace for a reimaging doublet used to magnify the AO beam onto a lenslet array (far right).

The lenslet array is made of fused silica and each element has a front radius of curvature of 0.528 mm. This forms a pupil image 1.728 mm on the opposite face of the array. This is where the fibers are bonded. Figure 2.2 shows the pupil images formed from some of the lenslet elements.

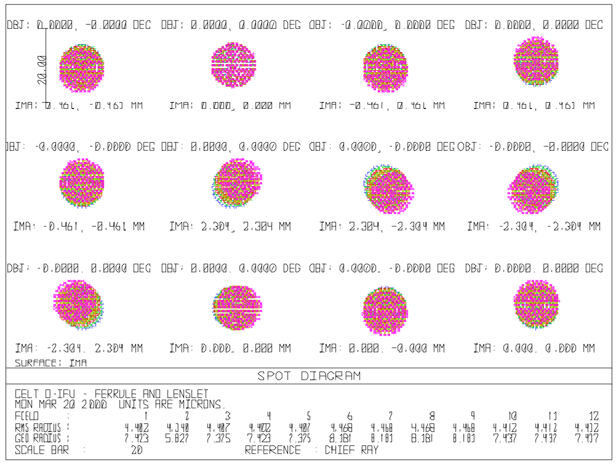



Figure 2.1. Zemax raytrace for a reimaging doublet used to magnify the AO beam onto a lenslet array (far right).

## 3.0 Backend Spectrograph(s)

One of the benefits of fibers is that not all of the fibers need to be brought to the same linear feed. For cost and complexity reasons, it is very attractive to have no more than 1024 fibers go to an individual spectrograph. This allows us to use $2048^2$ detectors with 2 pixels per fiber. These are relatively small detectors in the CELT scheme of things and traditional spectrograph designs are readily available. The amount of multiplexing is then principally decided by cost in terms of how many spectrograph modules to construct.

Each spectrographic module could be identical, or might have differences in spectral format (spectral resolution and wavelength coverage). But the camera and collimator are probably the same for each. The collimator element(s) would need to be matched to the ~F/8 output of the line of fibers. I believe it is advantageous to have the fibers in a slightly curving line to remove the natural spectral curvature inherent in diffraction grating spectrographs. This makes the spacing between fibers 150 microns, and needs to be mapped onto 2 pixels (36 microns for the Hawaii-2 array from Rockwell). This requires an F/1.9 camera which is challenging, especially if all reflective optics are desired (which they are), but is not impossible. The grating could be blazed between 6.35 and 6.5 microns following the design of several past IR spectrographs including the OSIRIS IFU for Keck. The orders are then shown in figure 3.1 below (for a 6.35 micron blaze wavelength). The detector would support full broad band coverage (J, H or K) with R>5000.

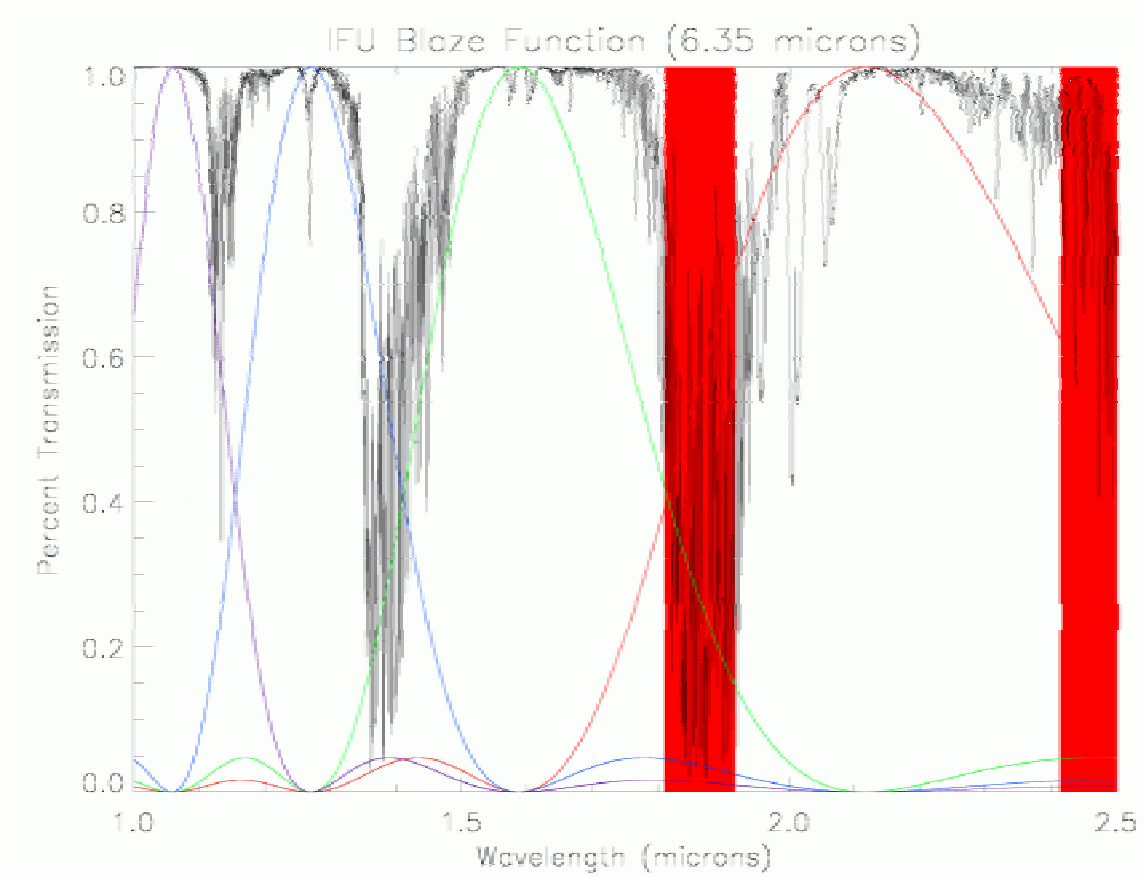



Figure 3.1. Wavelength coverage for each order of a grating blazed at 6.35 microns. Notice that each atmospheric band can be placed close to the center of a transmission order.

**4.0 Costs**

The cost of such a deployable IFU can be crudely calculated since most of the items needed are available today. With a baseline of 8 spectrograph modules and 8000 fibers, here are some baseline numbers:

| | | | |
|---|---|---|---|
| Optics | | | |
| each spectrograph module | $500,000 | | |
| Total for 8 modules | | $4,000,000 | |
| Fiber bundle of 10x10 | $10,000 (assumes some savings for bulk) | | |
| Total for 80 bundles | | $800,000 | |
| Initial Reimaging optics for cold pupil | $500,000 | | |
| Total Optics | | | $5,300,000 |
| Electronics | | | |
| Hawaii - 2 detector | $350,000 | | |
| Total for 8 detectors | | $2,800,000 | |
| 32 channel electronics | $100,000 | | |
| Total for 8 detectors | | $800,000 | |

| | | | |
|---|---|---|---|
| Computers, motors, misc | $100,000 | | |
| Total Electronics | | $3,700,000 | |
| **Mechanical, Vacuum & Cryogenic** | | | |
| Dewar, arm manipulators, pumps, cryoheads.... | | $3,000,000 | |
| **People** | | | |
| Programmers | $1,000,000 | | |
| Mechanical Engineers | $1,000,000 | | |
| Electrical Engineers | $500,000 | | |
| Total people | | | $2,500,000 |
| Grand Total | | | $14,500,000 |

**A4. An Examination of the Viability of Fibers Instrumentation for CELT**

**Keith Taylor (Caltech)** February, 2001

## 1. Introduction:

The use of multi-mode optical fibres in astronomy dates back to the early 1980s where they were pioneered on a number of ground-based optical/IR telescopes for use in multi-object spectroscopy. This was a natural usage for a technology that offered the capability of relaying light from a multitude of points in the focal plane of a telescope to a psuedo-slit of a spectrograph without the need for complex intervening optics. Many such systems were developed over the following two decades for the 4-metre class telescopes and, in a somewhat more limited fashion, we are now seeing the same technologies migrating to the 8-metres. However, while multi-object spectroscopy has risen in importance over the same period, there is an understandable reluctance to adopt the technology unless the scientific requirements absolutely demand their usage. Examples of this can be found on the VLT and Subaru where the very large fields of view (FoVs) make the use of conventional spectrograph optics impractical.

In this short article, we will be examining the reasons behind the perceived difficulties in using fibres and the developments in the technology that are leading to a re-assessment of their worth for multi-object spectroscopy in the context of CELT. We will also be examining the advantages and limitations of the use of fibres for near-IR integral field units as fed at an MCAO focus. But first we summarize the requirements placed on multi-object and MCAO-fed spectroscopy defined through deliberations with the CELT's Science Working Group.

## 2. Relevant SWG desiderata:

***UV/Optical, seeing-limited observations:***

It is important to note, in the context of fibres for CELT, that the interest in spatially resolved, IFU spectroscopy in the UV/optical is not strong. This is largely a consequence of the modest intrinsic spatial resolution (>0.3"; defined by the seeing limit) as compared to a typical size for faint galaxies (for example) which are, in general, only marginally resolved by the seeing disk. *[This is to be contrasted with a VLT instrument like VIMOS which has a very large, on-axis, IFU for 3D spectroscopy over relatively massive fields (~20").]* At this time, IFU spectroscopy for CELT, is exclusively the domain of MCAO feeds and hence is principally limited to the IR; an important subject for fibres which will be discussed separately.

Concentrating for now on the use of single aperture fibres for use in classical multi-object UV/optical spectroscopy, CELT's SWG has identified 3 generic instrumental requirements, as identified in Table 1.

| | Resolving Power | Object Multiplex |
|---|---|---|
| **Red-shift Engine** | R ~ 500 | M# ~5,000 |
| **Analytic spectrograph** | R ~ 4,000 | M# ~1,000 |
| **High dispersion spectrograph** | R ~ 30,000 | M# ~100 |

Table 1. Proposed modes of seeing-limited, multi-object spectroscopy for CELT

Common to these suggested configurations are a requirement for:

| | |
|---|---|
| Wavelength range: | 320nm < $\lambda$ < 1000nm (principally defined by CCD detector response) |
| Field of View: | 20' dia. (as defined by the CELT's RC Nasmyth focus) |
| Aperture size (a): | 0.3" < a < 1.5" (chosen to optimize S/N as $f^n$ of seeing and object size) |

While there is a high degree of latitude in defining these general requirements, they do give us a starting point in considering instrumentation that could satisfy this broad range of science goals. Implicit in defining such multi-object requirements is the assumption that limiting magnitudes will be compatible with spectroscopic optical train efficiency expectations of ~50% or higher which may be considered challenging for fibre spectroscopy; a subject we will return to later.

***Near-IR multi-object spectroscopy:***

Joint discussions between the CELT IWG and SWG have isolated the near-IR, MCAO-fed deployable integral-field units (or d-IFUs) as the most interesting capability for multi-object spectroscopy in the IR on CELT. We concentrate our fibre instrument considerations here to this arena.

We should first recognize that near-diffraction limited spatial resolution in the near-IR will require spectroscopic apertures of ~0.01" which translates to ~7µm at a typical f/5 input f-ratio for fibres. This places us thoroughly in the domain of single-mode fibres whose coupling efficiencies are very poor. In order to contemplate using multi-mode fibres at all for such purposes spatial sampling of 0.05" (ie: 35µm) must be considered as a useful lower limit unless greatly under-filled fibres, and hence under-utilized spectrographs are contemplated. As a general rule alternative technologies such as advanced image slicers (as pioneered, for example, by the MPIE's 3D group and the UK/ATC) should be considered. We are encouraged, however, to pursue fibre implementation of d-IFUs not only because they are simpler than their slicer alternatives, but also because of MCAO S/N studies performed recently (ref ???) which demonstrate photon starvation for R~5,000 near-IR spectroscopy towards the diffraction limit.

We would therefore suggest that fibre d-IFUs should concentrate on a domain with typical spatial sampling of 0.05" with ~16 individual IFU FoVs of ~1", deployed over an MCAO CELT field of 2' dia.

## 3. Problems with Fibres:

Much of the perceived limitation of fibres comes from the history of their implementation on optical telescopes. Many of the initial attempts at using fibres involved crude plug-plate devices where the fibres were not held rigidly in place; variations in gravity loading at a cassegrain focus very easily caused subtle mis-alignments in the fibre's optical axis sufficient to compromise instrument efficiencies in an unpredictable and variable fashion. This led to early misgivings concerning overall efficiencies and sky-subtraction residuals. Furthermore, fibres were often retrofitted to existing long-slit spectrographs again leading to compromises in throughput. However their advantage in general information reformatting was obvious and once fibre technology had become accepted, ambitious instruments were designed to take maximal advantage of their capabilities. Again, for historical reasons, such projects (the 2dF, most prominently) explicitly traded object multiplex with photometric performance making compromises on spectrograph flexure and fibre packing on the detector that again severely impacted performance and photometric stability and it is only recently, with the advent of 8-metre fibre projects and the demand to stretch the magnitude limit of 2dF (for example), that attempts have been made to redress these unfortunately inaccurate perceptions.

Here we briefly summarize experience to date:

- Transmission:

The fibre transmission performance, as a function of λ, is primarily defined by the make-up of the fibre pre-form, however important advances have been made recently by various manufacturers. As an example, the throughput for 10m and 40m of Heraeus' STU fibre, optimized for UV performance, is given in Figure 1.

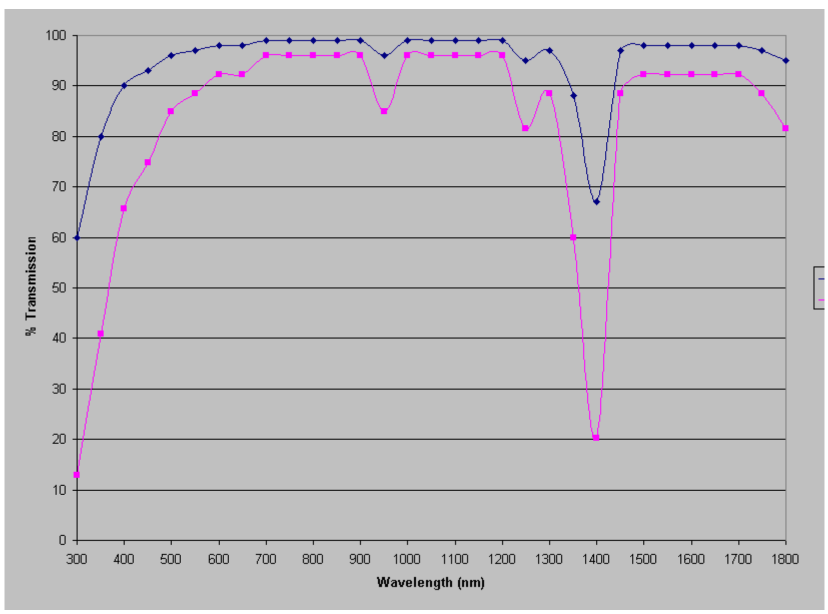



Figure 1: Transmission of STU fibres for 30nm<λ<1800nm

While relatively impressive peak transmission can be achieved, there are clearly deficiencies both the in UV and R bands that are further exacerbated by increased fibre length which will predictably impact when practical fibre spectrograph configurations and layouts are considered on the CELT Nasmyth platforms. Indeed there is often an unhappy trade-off between fibre transmission and the desire to take maximal advantage that fibres offer as a means of supplying a stationary, bench mounted, spectrograph thus alleviating the mechanical complexity of a directly mounted instrument which is subject to a changing gravity vector.

Furthermore, these peak transmissions do not take account of fibre end losses. While fibres can be A/R coated and so, in principle, these should be no more than an equivalent air-glass interface, in practice, great care must be taken to achieve a fine end polish to the fibres to prevent the scattering and alignment losses which dog many fibre instruments. This is a matter of care in assembly and manufacture and, as such, emphasizes the need for strict quality control in the construction of any fibre facility; a control which is easy to loose sight of in the rush to complete an instrument.

For fibres in the near-IR, low OH pre-forms usefully extended their range into the K-band while reducing the OH absorption troughs. However for $\lambda > 2\mu m$, $ZrFl_4$ (for example) is to be preferred, as demonstrated in Figure 2.

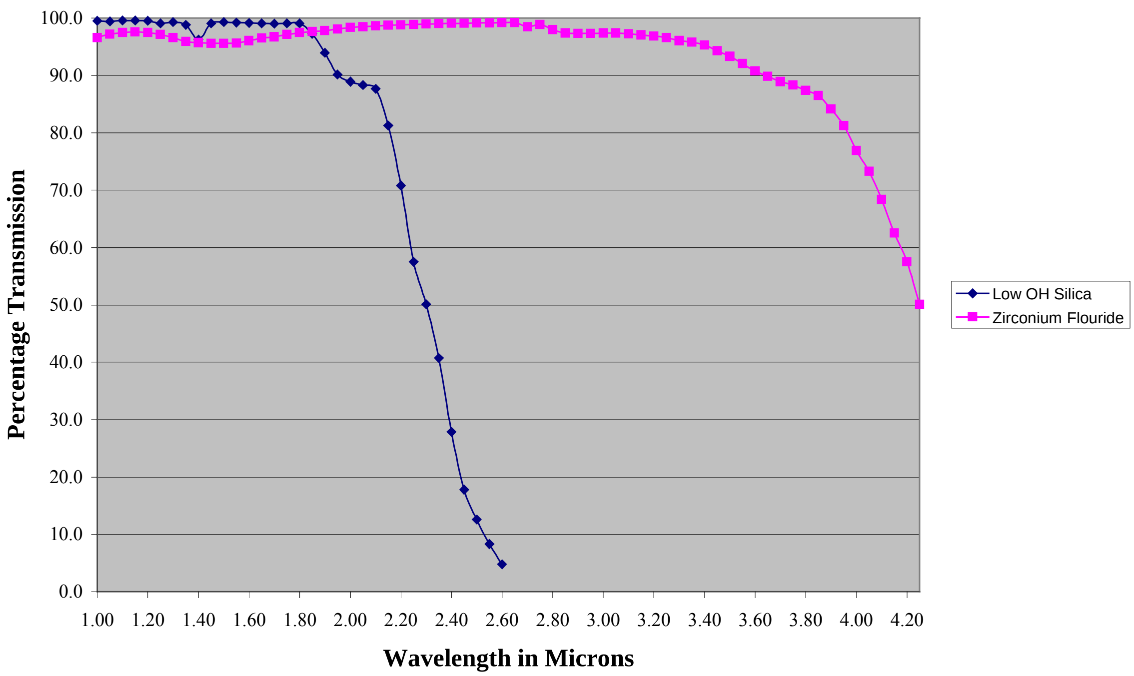



Figure 2. Transmission of low-OH and $ZrFl_4$ fibres for $1\mu m < \lambda < 4.2\mu m$

- Focal ratio degradation (or FRD):

FRD is the tendency to scatter transmission modes within the fibre and hence induce a degradation in the emergent f-ratio. Clearly this is a function, not only of input f-ratio but also of fibre input alignment, fibre length, local fibre stresses (especially at their ends) and subtle properties of the pre-form and drawing process. Indeed, in practice, it is quite difficult to predict with any degree of accuracy, the FRD of a particular fibre, however some general guidance is available from both the manufacturers and the astronomical fibre community as a whole.

An example of fibre FRD measurement is given in Figure 3 which demonstrate, for a variety of fibres, the *gathering* efficiency as a function of output f-ratio for an f/5.5 input. Clearly to maintain the AΩ product for a fibre system, throughput losses of typically ~25% are indicated. It is important to note, however, that light is not lost, it is simply scattered into lower (and higher) f-numbers. As demonstrated in Figure 3, a ~20% faster spectrograph collimator will collect ~90% of the light from the fibre and, provided the spectrograph design which is not otherwise limited (ie: typically at low dispersion), such mitigation is practically achievable.

It should also be noted, however, that FRD has the effect of infilling any central obstruction which could otherwise be used for folds in the collimator optical train. Fibre systems are therefore generally more suited to refractive collimator optics.

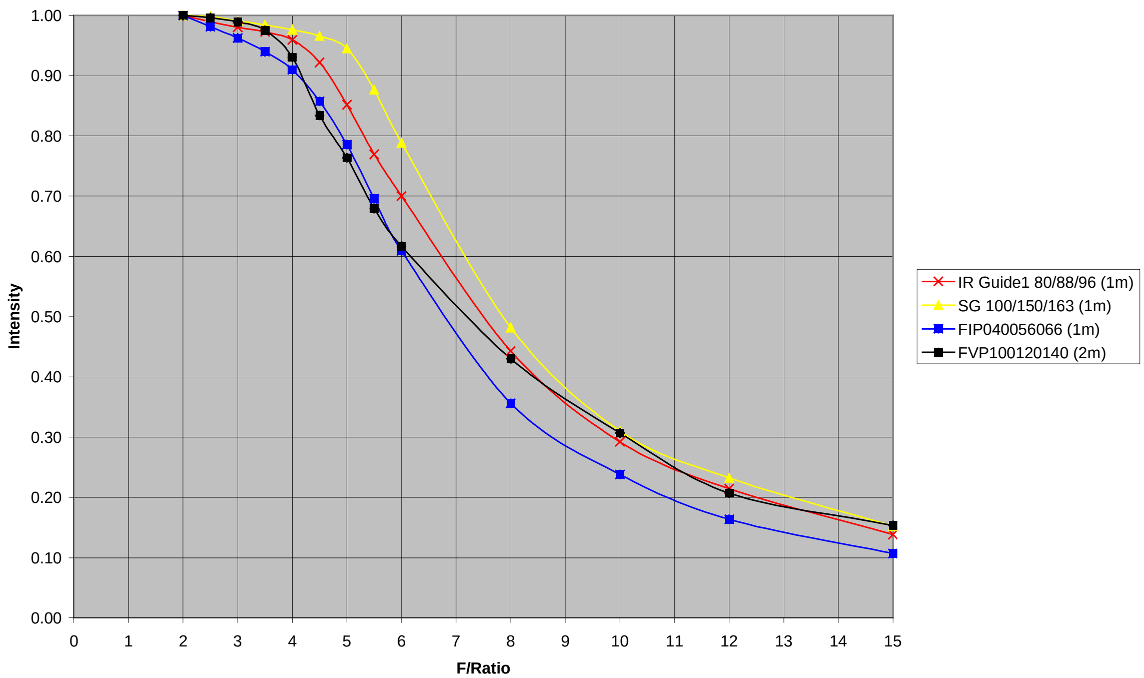



Figure 3. Example FRD curves for a variety of fibre types.

- Photometric stability:

As stated earlier, crude methods for fibre deployment severely compromised earlier attempts at effective spectro-photometry and sky-subtraction however, even for more recent fibre systems, fibre cross-talk together with spectrograph scattered light and flexure (for non-bench mounted instruments) has made ~1% (or better) sky subtraction difficult, if not unachievable; indeed standard 2dF procedures rarely give better than ~2% sky-subtraction residuals. What is not generally recognized is that such limitations are not intrinsic to the properties of the fibres themselves.

This has been indicated in a number of experiments that gave very stable (<1%) throughput measurements for fibres as telescopes were tracked across the sky. Most recently, however, definitively results produced from a combination of charge shuffling and synchronized aperture (telescope) nodding (performed with at the AAT with 2dF) have produced sky-subtraction residuals at the poisson limit (ref ???) demonstrating that, with appropriate procedures, fibre spectroscopy need no longer be considered deficient for faint object spectroscopy, provided system efficiency can be retained. Of course, a payment is extracted for such performance which generally translates into significantly lower object multiplex. Half (rather than ~5-10%) the objects have to be sacrificed to sky while, on-object integration is reduced by a factor of 2. Furthermore, since the subtracted sky spectrum is independent for each aperture, a further ~√2 degradation in S/N is imposed at the sky limit. These effects are substantial and can be translated directly into object multiplex losses. However they should be compared not to the maximum system object multiplex but to practical object multiplexes which could be achieved at the same magnitude limit by alternative procedures. This issue is covered in some depth by Bland-Hawthorn and Glazebrook (ref ???). Their conclusion is that *differential* techniques, as described here, promise significant practical (multiplex) gains over traditional *average sky* techniques as employed in both fibre and multi-slit spectroscopy.

## 4. Problems with Multi-slits (in the CELT context):

In order to achieve multi-slit spectroscopy over the full 20’ FoV of CELT, multi-slit masks of 2.6m in diameter will be required, assuming a default f/15 Nasmyth input. Of course the field optics will have to be similarly dimension making spectrograph mosaicking at a grand (if not totally impractical) level an inevitability. Furthermore, spectral resolving powers beyond R~5,000 will require collimated beams larger than ~500mm for 1$^{st}$ order, seeing-limited, high throughput, spectroscopy. Clearly this is not an easily contemplated instrument configuration and one can immediately see why the re-formatting character of fibres is so attractive in this context. While the prospect of satisfying the high-dispersion requirement of Table 1 is completely ruled out, before we give up entirely on intermediate and low-dispersion multi-slit work on CELT let us examine some possible ways forward.

- Tessellated spectrographs:

On order to get below 1m optics while sampling the full 20’ FoV, 7 or more independent spectrographs would have to mounted at the rotating Nasmyth focus. In principle, the same philosophy is adopted on a much smaller scale for the VLT’s VIRMOS spectrographs, where only 4 independent spectrographs are configured. Nevertheless, the optical and engineering design challenge to package multiple spectrographs at the Nasmyth location, while permitting successful acquisition of multiple fields and maintenance of differential alignment between the separate multi-slit masks, is extreme.

- A faster Nasmyth focus:

To make any significant difference to the size of the field optics, Nasmyth f-ratios approaching f/5 would be required. This would require a separate, interchangeable, secondary causing significant increase in telescope fabrication and operation costs and probably an unacceptable increase in secondary obscuration.

- Relay optics:

Alternatively, modest 3m, telescope sized, all reflective relay optics could be built to re-image the focal plane at f/5. While such a design, would have to accommodate the full 20’

FoV, it may be, in principle, realizable reducing the field optics of a multi-slit spectrograph to below the 1m scale. Inevitably, however, the effective central obstruction would be worse than the previous, already compromised, option.

This is, however, the only solution that could, even in principle, accommodate atmospheric dispersion compensation. The first prismatic doublet elements of 2dF are ~900mm in diameter and operate successfully at f/3.3. The optical design of such an ADC is beyond the present scope of this document, but it would be interesting to explore the practicality of such a device within the constraints of an f/15 to f/5 relay, as a worthy optical design exercise.

Beyond the focal-plane scale problems, we also have to confront a massive <500mm beam-size for the spectrograph(s). Again, availability of glass substrates becomes a problem in the manufacture of suitable dispersing elements, however, it is less hard here to imagine mosaic gratings in the manner of UVES (or CHRS, as proposed by Vogt for CELT). Nevertheless, we should recall that this huge, possibly tessellated, spectrograph with its grating mosaics will have to rotate, as DEIMOS, on the CELT Nasmyth platform unless some way of reflecting the optical axis to the vertical can be achieved. This again would seem to argue for an f/15 to f/5 relay given the basic geometrical constraints of folding a slower beam. Whether the relay itself can be configured to achieve this horizontal to vertical translation remains to be studied.

## 5. Fibre deployment:

This should be considered a *solved* problem in the context of the CELT Phase A study. A Nasmyth mounted fibre positioner is currently being fabricated for the VLT Unit 2 telescope. Its characteristics allow for ~500 fibre probes to be deployed across a ~850mm diameter field-plate. There is no doubt that a scaled up version could be mounted directly on a CELT Nasmyth location permitting an estimated ~1500 fibres to be deployed without significant change to the instrument architecture. The OzPoz positioner for the VLT is shown in Figure 4. It is shown with 2 field-plates, an active one at the telescope focal-plane together with a second field-plate in position for fibre re-configuration by its R;θ;z-axis robot. Further information on this device can be obtained from (ref ???).

Significant differences between the OzPoz positioner and its CELT equivalent are itemized as follows:

- The physical scale of the CELT positioner would be almost exactly 3 times that of OzPoz, given the latter's 25' FoV;
- The field-plate image scale for CELT would imply relaxed (~200um) fibre positioning tolerances which would translate into the faster fibre configuration times required for larger numbers of fibres;
- Attaining the 5,000 fibres required for the red-shift engine mode would require multiple outer pivot levels (3 sets) assuming no further increase in perimeter diameter was envisaged;
- The OzPoz field-plates are located at a corrected focal plane whose center of curvature is coincident with the telescope pupil. This makes the principle ray into the fibre always orthogonal to the image surface hence a permitting fibre placement with a simple curved R-axis robot. No such corrector would be possible for CELT and hence the principle ray will increasingly diverge from the normal to the focal surface with radius. This will add unfortunate, but not insolvable, complexity to the robotics. The original FEUGOS positioner, which was replaced in concept by OzPoz, had such a 5-axis robot head;

- The fibre probes themselves will be sufficiently large (~20mm dia.) to permit individual ADC elements on each probe. The added complexity and cost of such a device will have to be assessed with respect to the delivered increase in throughput;
- In order to decrease the fibre slit size with a view to decreasing the overall size of the spectrograph, each fibre aperture may be formed from a 7-hex array of smaller fibres.

None of these differences are intractable, however the lack of a CELT corrector places additional complexity and cost on the facility. As scaled from OzPoz, the CELT equivalent would occupy a roughly cubic space equivalent of ~100m$^3$ on the Nasmyth platform, would weigh something less than 10 tons and is estimated to cost in the vicinity of $5-10M, depending on the complexity of the robot itself.

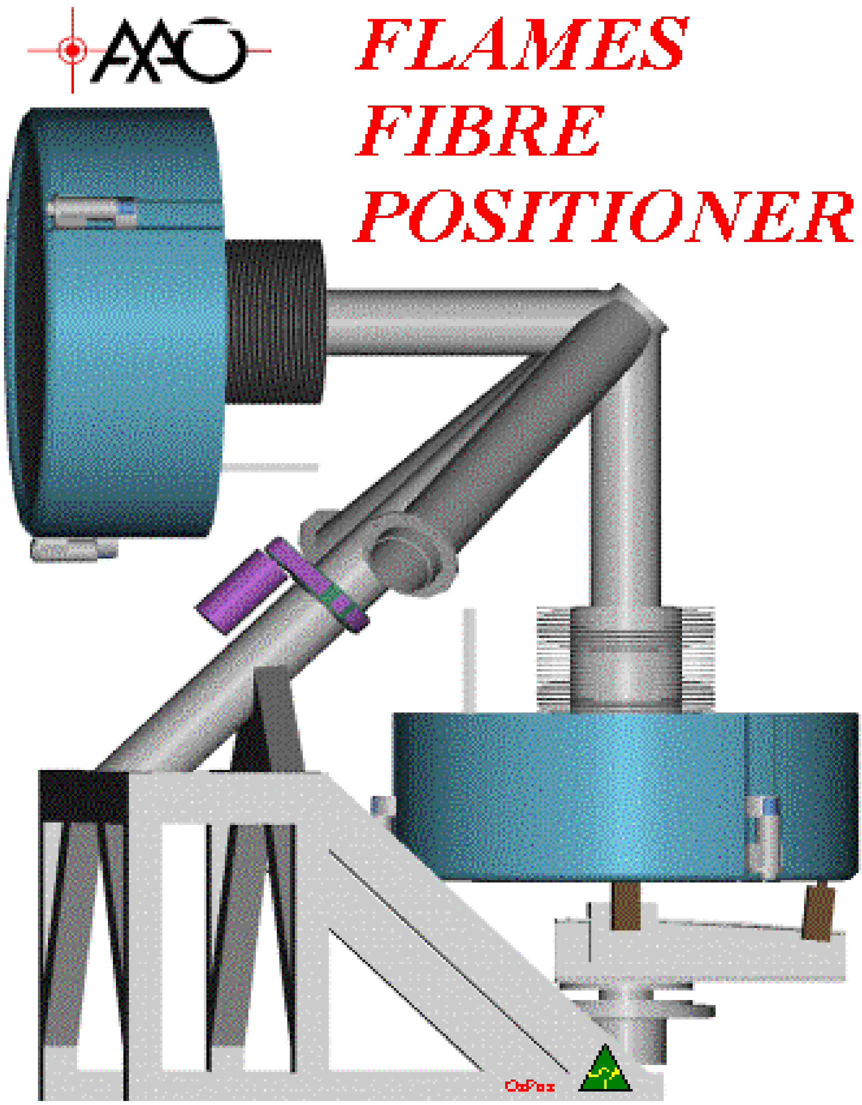



Figure 4. A view of the VLT's OzPoz facility (courtesy AAO)

## 6. Seeing limited UV/Optical fibre spectrograph:

An unresolved question common to all modes in Table 1 is "what is the optimal aperture size" spatially unresolved spectroscopy ?". We do not wish to address this question seriously here, however, we do have in train the modeling studies which are capable of directly addressing this issue. Of course, the results of such a study depend on a variety of instrumental and atmospheric parameters that can be more or less satisfactorily estimated however the intrinsic size of the target, generally zero for stellar and QSO work, is a parameter whose value can be finite and significant for faint galaxies. Earlier study of this type revealed optimal apertures of the order of 1" for seeing regemes in with modes in the 0.5" to 0.8" and or the purposes of this discussion we will keep to this 1" aperture figure. We will further assume an f/5.5 fibre input with light collected by an f/4.5 collimator, in line with Figure 3.

***The red-shift Engine:***

A single f/4.5 fibre feed would imply fibre cores of ~800μm which when imaged by an internal focus ~f/1.2 Schmidt camera would give spectral resolving powers R~500 with a ~150mm beam grism spectrograph using a 900 l/mm grating in 1$^{st}$ order. However a 4k$^2$ CCD mosaic could only support ~250 objects, given the ~15 pixels subtended by each fibre. A full 5,000 object multiplex not only has problems being supported by a positioner of the OzPoz type (see section 5), it also requires ~20 identical, but otherwise relatively modest, spectrographs to collect the data.

***Analytic spectrograph:***

In order to achieve spectral resolving powers R~4,000 with practical sized optics, not only has grating ruling frequencies to increase but the fibre aperture needs to be reduced by a factor of ~2. This is most readily and practically achieved by using a 7-hexagonal packed lenslet/fibre image slicer (ref ???) for each fibre aperture. A suitable spectrograph configuration (again with the same ~f/1.2, 4k$^2$ CCD mosaic, camera) can achieve the required spectral resolving power (R~4,000) with a 1$^{st}$ order grating ruled at ~2600 l/mm. This, of course, is outside the range of normal surface relief gratings but is well within the capabilities of VPH gratings (ref ???). While each object now results in 7 close packed fibres subtending a total of ~50 pixel, a mere ~12 of the previous 20 spectrographs are required to support the M# ~1,000 objects for the intermediate dispersion, analytic, mode as in Table 1.

***High dispersion spectrograph:***

The requirement for spectral resolving powers R~30,000 now places us in a different league of spectrograph. The classical approach would be to use an R4, high order (~100) echelle of sufficient beam diameter to give the required performance with a 1" aperture However, as has been demonstrated by Vogt (ref ???), this will require beam sizes of ~800mm, 20 grating mosaics and spectrographs the size of a tennis courts to achieve. Clearly the 7-hex lenslet/fibre image slicer gives a way of reducing this beam by a factor of ~2 which is already a very significant advance. Of course, no cross-dispersion could be allowed due to the multi-object requirement and order separation would have to be achieved through multiple order sorting filters as in the VLT's GIRAFFE fibre spectrograph. However, the advent of high ruling (<6000 l/mm) 1$^{st}$ order VPH gratings has the potential of offering another significant gain in throughput. Whether such gains are realized in practice remains to be seen and a traditional R4 echelle fall-back is always available.

The question remains as to how high an object multiplex is supportable by such a configuration. Again, assuming the f-ratio for the cameras, each projected 7-hex fibre slitlet subtends ~50 pixels implying an object multiplex M# ~75 objects for a single spectrograph which is not so far from the required M# ~100 objects defined in Table 1.

## 7. MCAO-fed d-IFUs:

To reiterate the general limits defined in section 2, we consider here fibre/lenslet d-IFUs with typical spatial sampling of 0.05" assuming ~24 individual d-IFUs each having FoVs of ~1" (each with ~320 lenslet/fibres), deployed over an MCAO CELT field of 2' diameter. Given the requirement for at least ~7λ cladding, 38μm core fibres fed at f/5.5 (equivalent to 0.05" sampling on CELT) and operating in the near-IR will have an outer clad diameter of ~66μm. In order to accommodate FRD in the fibres (as demonstrated in Figure 3) a somewhat faster, ~f/4.5, collimator will be required. This leads to a camera f-ratio of ~f/1.2 to match the pitch of the fibre slitlet to the 18μm pixels of the Rockwell HgCdTe arrays. While this is a relatively demanding camera specification, it may be achievable with internal Schmidt cameras or their variants. Note that the fibre core, itself, will be imaged to ~10μm, significantly smaller than a pixel, which is a reminder that fibre IFUs suffer a fundamental information packing problem not encountered with AISs (see section 2) which translates directly to a loss in object multiplex. AISs are, however, significantly more technically challenging and have none of the re-formatting advantages of fibres, highlighted in section 3. In addition lenslet/fibre d-IFUs can be fed by a variety of interchangeable fore-optics to give arbitrary spatial samplings finer than the 0.05" upper limit down to the diffraction limit; all that changes is the size of the telescope pupil imaged onto the fibre. Furthermore, deployment of lenslet/fibre d-IFUs is a more tractable problem that for AISs, given the flexible nature of fibres; this is true even at cryogenic temperatures (ref ???).

The goal in any such design is to optimize object multiplex and hence we have specified that each fibre is imaged to within a single pixel, however cross-talk between individual fibres within the d-IFU is not necessarily a serious issue since it mimics, at some level, the general sampling of information at the input to the d-IFU. With the specified f/1.2 camera, each d-IFU will then occupy ~320 pixels allowing ~6 d-IFUs per $2048k^2$ spectrograph and implying 4 identical spectrographs to service the 24 d-IFUs. Given the relatively small fibre entrance slits, relatively modest ~100mm beam spectrographs can achieve the required R~4,000 spectral resolving power, assuming 2-pixel limit resolutions. Considerably higher than this (towards a factor of ~2) can be retrieved from the intrinsic slit resolution if slit drizzling is employed.