PROSPECTS FOR FIBREOPTICS IN FUTURE TELESCOPE INSTRUMENTATION

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Introduction

The importance and applied use of fibreoptics in astronomy has received rapidly growing attention in the past 5 years, particularly for instrumentation where the lightness, flexibility and simplicity of fibres, compared with classical optical systems, can be exploited to full advantage.

Angel [1] and Angel et al [2], who seem to be the first to have used an optical fibre to link a telescope to an instrument, also made the first proposal for the construction of a VLT (FLOAT) consisting of 40 independent mirrors linked to a single instrument via optical fibres. Since that time many authors, including Connes [3], Serkowski et al [4], Hubbard et al [5], Heacox [6], Hill et al [7], Vanderriest [8], Courtes [9], Tubbs et al [10], Gray [11], Lund et al [12], Schiffer [13], Watson et al [14], Vanderriest et al [15], and Felenbock et al [16], have proposed or reported various applications involving fibres with astronomical instrumentation.

Although a detailed description of some of the fibre instruments already developed for use in astronomy would fall beyond the scope of this paper, the complex nature of fibre beam transmission efficiency and its dependance on not only intrinsic fibre parameters but also on instrument design, is considered sufficiently important to merit attention at the beginning of this paper. In view of the contents of that discussion, the respective advantages and drawbacks of fibres, compared with conventional optics, are reviewed in § 1 of the paper. In § 2 the relative merits of optical fibres and classical optics are compared. A practical example is given in § 3 of the overall instrumental efficiency which can be achieved with a moderately long fibre link. In § 4 the question of seeing and VLT/fibre matching is discussed. Finally, in § 5 I and II, two design outlines are presented in which fibreoptics could be advantageously implemented in the instrumentation of a VLT.

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1. Fibre Transmission Properties

Of the many parameters to be considered when designing an astronomical instrument incorporating optical fibres, perhaps two of the most important would be (a) transmission efficiency as a function of wavelength and (b) fibre-induced focal ratio degradation as a function of input F ratio.

(a) Absorption in Optical Fibres:

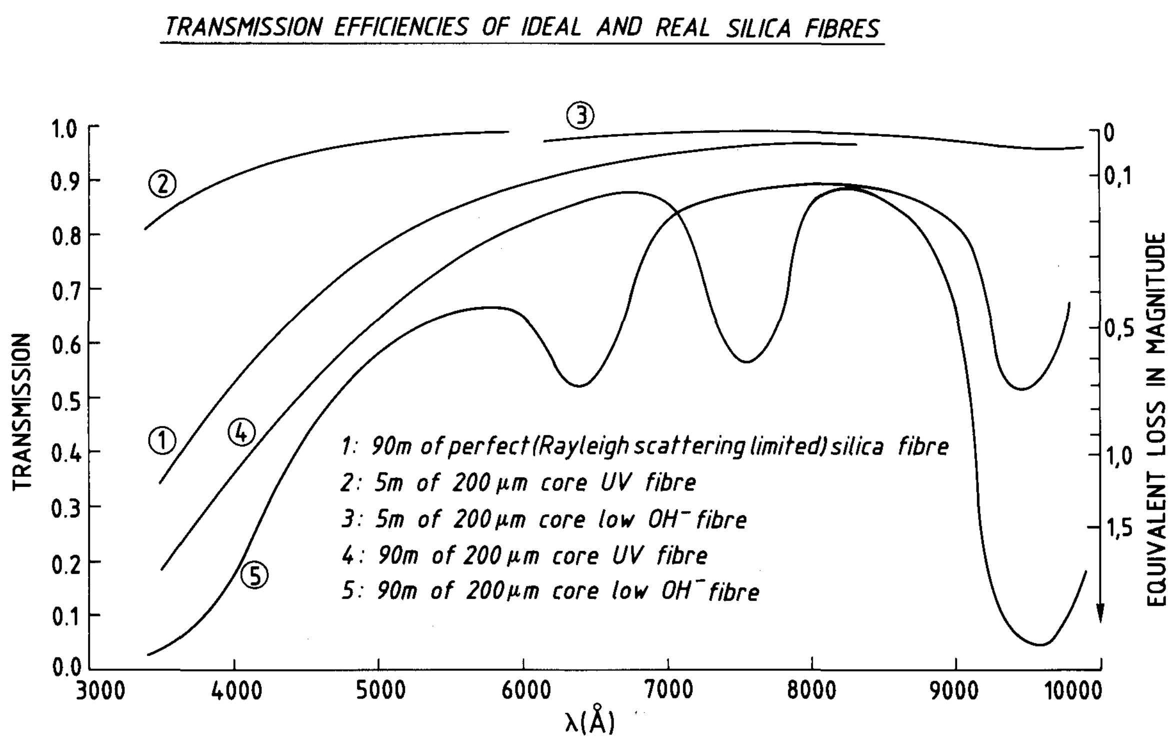
The overall transmission efficiency of optical fibres depends not only on material properties (which will be discussed here in detail), but also on parameters such as fibre core diameter, injection F ratio, bending, pressure, and quality of fibre endface preparation.

Of the two vitreous materials commonly used in the fabrication of optical fibres, i.e. multi-component glass and silica, the latter has the greatest potential for producing low loss fibres, particularly at ultraviolet wavelengths. High quality silica fibre preforms, containing negligible impurity traces, can nowadays be fabricated by a variety of methods. The intrinsic loss mechanisms in pure silica, as given by Horiguchi [17] are: Rayleigh scattering (loss $= 0.75/\lambda^4$ dB/km), the uv absorption tail (loss $\simeq 0.024.10^{1/2\lambda}$dB/km), and the infrared absorption tail (loss $\simeq 2.10^{12-22/\lambda}$dB/km) for which only the former is significant at wavelengths below 1.6 µm. The Rayleigh scattering mechanism is thus of predominant interest especially since it becomes very strong at blue and uv wavelengths, and can be strongly affected by the presence of dopants or even by the fibre drawing process (as discussed below). In order to make a useful fibre, the core must be clad with a low-loss material of slightly lower refractive index than the core. This is achieved either by increasing the core index by doping (normally with GeO_2 or P_2O_5) or by reducing the cladding index (normally with a SiF_4 or B_2O_3 dopant) or, in the case of plastic coated silica (PCS) fibres, by using a silicone resin for the cladding.

The former solution forces the Rayleigh scattering coefficient upwards by virtue of lattice rearrangements in the silica (Jeunhomme, [18]), to a value typically around $A \simeq 2.2$, as opposed to $A = 0.75$ for pure silica (Pinnow et al [19]). This implies a worsening of the dB/km losses which is equivalent, for example, to a reduction from 76% to 45% in transmission efficiency for a 40 m length of fibre at 4000 Å. Doping of the cladding has a weaker effect on transmission losses, the extent of which is dependent on the number of reflections encountered by a ray travelling down the fibre. In this sense the choice of a large core diameter and small injection F ratio will reduce absorption and mode leakage losses.

Whether the core and cladding be doped or not, silica fibres containing very low OH^- ion concentrations are found to exhibit uv absorption losses far in excess of those predicted by Rayleigh scattering, which can be measured in the bulk material. This strongly increased uv absorption is always accompanied by an attendant resonant absorption peak (Fig. 1), centered at 6300A, which has a maximum strength typically around 150 dB/km. This phenomenum, although not completely understood, is believed by Kaiser [20] to be brought about by rearrangements of the regular crystalline lattice structure present in annealed bulk silica. The lattice rearrangement, which occurs during the rapid cooling experienced during the fibre drawing process, can however be reversed (Kaiser [20], Guerder [21]) by annealing the fibres at 700°C, or by introducing controlled quantities of the OH^- radical during production of the bulk silica; an OH^- concentration of 200 ppm induces complete disappearance of the 6300A drawing peak and restores the fibre uv transmission towards that observed in the bulk material.

In view of these findings and the foregoing discussion concerning the influence of dopants on fibre transmission, it can be seen that "wet" (i.e. moderately OH^- doped) PCS fibres can exhibit, despite their mechanical and FRD drawbacks, the greatest potential for making low loss uv fibres.



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This recovery of uv performance is gained however at the expense of broad and rather strong harmonics of the OH^- resonance absorption, centered at 7500 Å and 9500 Å as can be seen in curve (4) of Fig. 1. An example of such "wet" fibres is given by the French company FOI fibre types PCS or ASW. The former is marketed as a so-called "uv" fibre.

(b) Focal Ratio Degradation in Fibres:

The phenomenon commonly known as "focal ratio degradation", due to the combined effects of diffraction and microbending, also deserves careful attention when designing an astronomical instrument using optical fibres. Focal ratio degradation (FRD), which is the degree of angular spreading of the fibre output beam profile when compared with that of the input beam, is equivalent to a degradation of the transmitted beam entropy. The influence of this entropy degradation becomes decreasingly significant with increasing fibre injection F ratio, as shown in Fig. 2. Focal ratio degradation of the telescope beam is similar in effect to a deterioration of the atmospheric seeing; in the case of spectroscopy, either a loss of received energy is incurred if the collimator has the same F ratio as that of the injected beam at the telescope focal plane or, if negligible light is to be lost, a faster collimator and larger grating must be installed with an attendant loss in spectral coverage or resolution.

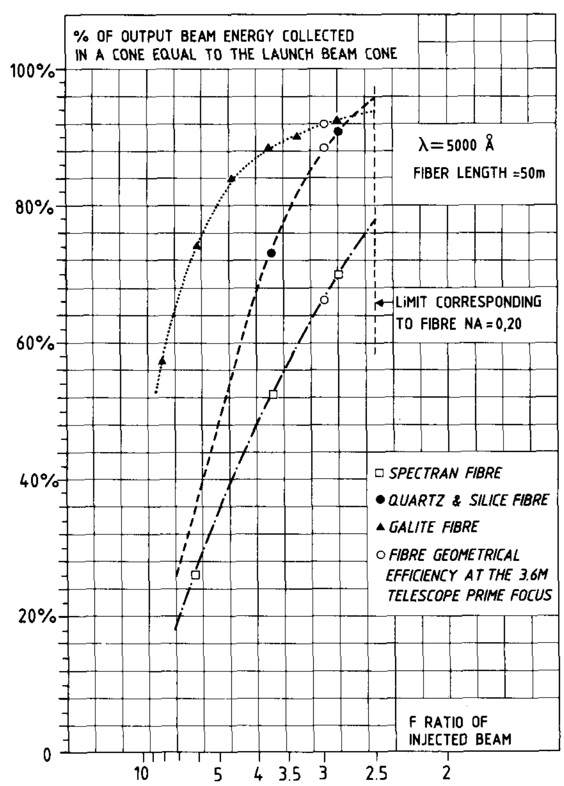

Fig. 2 Variation of beam transfer efficiency due to focal ratio degradation in 3 different all-silica fibres.

Whereas diffraction effects are determined simply by the fibre core diameter, microbending (a term which describes the integrated effects of core/cladding interface imperfections and departures from cylindricity) is determined largely by the fibre type and by the technique used in the manufacturing of the fibre preform. Generally speaking, all-glass and all-silica fibres, especially those drawn from preforms made by an axial vapour deposition process, exhibit less FRD than PCS fibres. The degree to which microbending contributes to the FRD is generally dependent on fibre length (the shorter the better), and can be sensitive to external influences such as bending and pressure. The use of a tight jacketing around the fibre can also increase FRD and mode leakage losses.

Experimental measurements of the dependence of FRD on input focal ratio, for different fibre types, have been conducted by various authors including Angel et al [2], Heacox [6], Barden et al [22], Gray [23] and Powel [24].

2. Fibres or Conventional Optics?

Clearly, with sufficient ingenuity, a large number of mirrors, prisms, lenses and diaphragms could be used to replace any optical fibre. Even the highly useful "image scrambling" property of fibres, sometimes exploited in high precision radial velocity measurement spectrographs (e.g. Serkowsky et al [4]), can also be replaced using a fast rotating prism (Connes [3]).

With exception to the major considerations of transmission efficiency discussed in (a) and (b) of the above section, it can be useful to compare fibres and conventional optics on the basis of several other important factors, as described below:

* Size:
  The extremely small size of fibres makes them rather fragile and difficult to handle. On the other hand, they can be easily introduced into small confined spaces. In applications where independent light sources need to be combined in a closely packed arrangement (such as in the example shown in Figs., 4 and 5, or in multi-object spectroscopy) fibres can provide a convenient solution.

* Flexibility:
  The flexibility of fibres has many mechanical advantages in astronomical instrumentation. Perhaps that which springs most readily in mind is the possibility of isolating instruments from the telescope, thereby eliminating

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the need to build heavy and rigid structures which must be intermittently attached to and removed from the telescope. Some instrument changeovers, for example from one type of spectrograph to another, could be effected in a matter of minutes. This feature is discussed further in § 5-I.

* Image scrambling:
  By virtue of the fact that practically all rays incident onto a fibre can be classed as skew rays, they can all be considered to have followed a quasi-helical path through the fibre. This means that for a small bundle of adjacent parallel rays incident to one end of the fibre at an angle θ to the axis, each individual ray will exit, having undergone many thousands of internal reflections, in uncorrelated helical path positions in such a way as to lie in a cone defined by the angle θ. A detector placed in the far field of this exit beam will see a slightly blurred ring of light whose intensity distribution will remain virtually unchanged, irrespective of the position of the incident bundle on the input face of the fibre. This property, known as "image scrambling", can be very useful in applications where the symmetrical and time-invariant illumination of an instrument is desired, as, for example, in high resolution spectrographic radial velocity determinations.

* Spectral calibration:
  By feeding calibration sources through the same fibre as that used for observations, all transmission anomalies of the optical system (except for that of the primary mirror), can be corrected for. In the case of fibre-fed spectroscopy using a CCD detector, it is thought that the immobility of the fibre output end and the geometrically identical conditions of illumination, for both observation and flat field or sky background corrections, may enable bothersome CCD fringing patterns to be virtually eliminated.

* Alignment and guiding:
  By injecting a white-light source into the input of a fibre link, the beam at the output end can be adjusted to achieve a correct and perfectly stable alignment with the instrument. Whereas with some instrument feeds (such as the coudé mirror train), several lenses or mirrors must be periodically checked and aligned, no such adjustment is required with a fibreoptic feed. This inherent simplicity can make a fibre link a particularly attractive alternative to some types of coudé train, for which a servo-controlled mirror is needed (as would be the case at the ESO 3.6 m telescope).

Guiding of a fibre-linked telescope can be readily achieved using a TV camera focussed on the fibre input. Ideally, this end face should be masked with some sort of inclined reflective diaphragm with a hole just larger than the diameter of the fibre core, as done in the ESO coudé link used as an example in the section below.

* Cost

  The cost of optical fibres suitable for use in astronomical instrumentation falls roughly between 4 and 10 DM/m (between US $ 2 and $ 4 per metre), depending on the manufacturer, the type of protective cable (if any) around the fibre, and the fibre outer diameter. The cost of mechanical connectors, telescope and instrument adaption components, and various optical adaption components (e.g. focal reducers, image slicers) will vary with every different project. In many situations, however, a fibre linked instrument can prove considerably cheaper than the alternative solution involving classical optical components. In the case of multi-object fibre spectroscopy, the multiplex advantage of obtaining many tens of spectra simultaneously from different points in the sky can represent enormous savings in terms of telescope time and running costs.

3. Example of the ESO 40 m Fibre Link

Recent tests of a 40 m optical fibre link, coupling the ESO 3.6 m telescope to the auxiliary telescope (CAT) high resolution spectrograph (CES), described in detail elsewhere by Lund et al [25], have confirmed the usefulness of this solution as an alternative to a 4-mirror coudé train. The link, as depicted below in Fig. 3, consists essentially of a 133 μm optical fibre, a 10.5 x magnifying beam projector, and an image-slicer of the Modified Bowen Walraven type.

The transmission losses incurred at different parts of the link (as well as those to be expected from the alternative solution of a 4 mirror coudé train) are indicated by figures in brackets. The combined transmission efficiency of the link, with exception to the fibre itself, amounts to 71%. This could be increased to about 75% by applying antireflection coatings to the image slicer. The wavelength dependent fibre transmission losses are given approximately by curve no.(5) in Fig. 1. Although this curve corresponds to a low OH^- fibre, 90 m in length, the potentially higher efficiency of the 40 m fibre is fairly

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well compensated for by the higher loss/m incurred due to its smaller core diameter, (133 μm instead of 200 μm). To summarise, the fibre link is found to have an efficiency better than that of a train of 4 untreated aluminium mirrors (of combined reflectivity ≈ 0,52), for wavelengths above 5000 Å. Clearly, a long fibre link does not provide an efficient solution for blue and ultraviolet wavelengths.

4. Matching Optical Fibres to a VLT

In accordance with the presentations of D. Enard given in these proceedings, a VLT design using 4 primary mirrors of 8 m diameter is assumed.

Following the discussions of the first section in this paper, it should be clear that in designing a fibre instrument, precautions should be taken to ensure

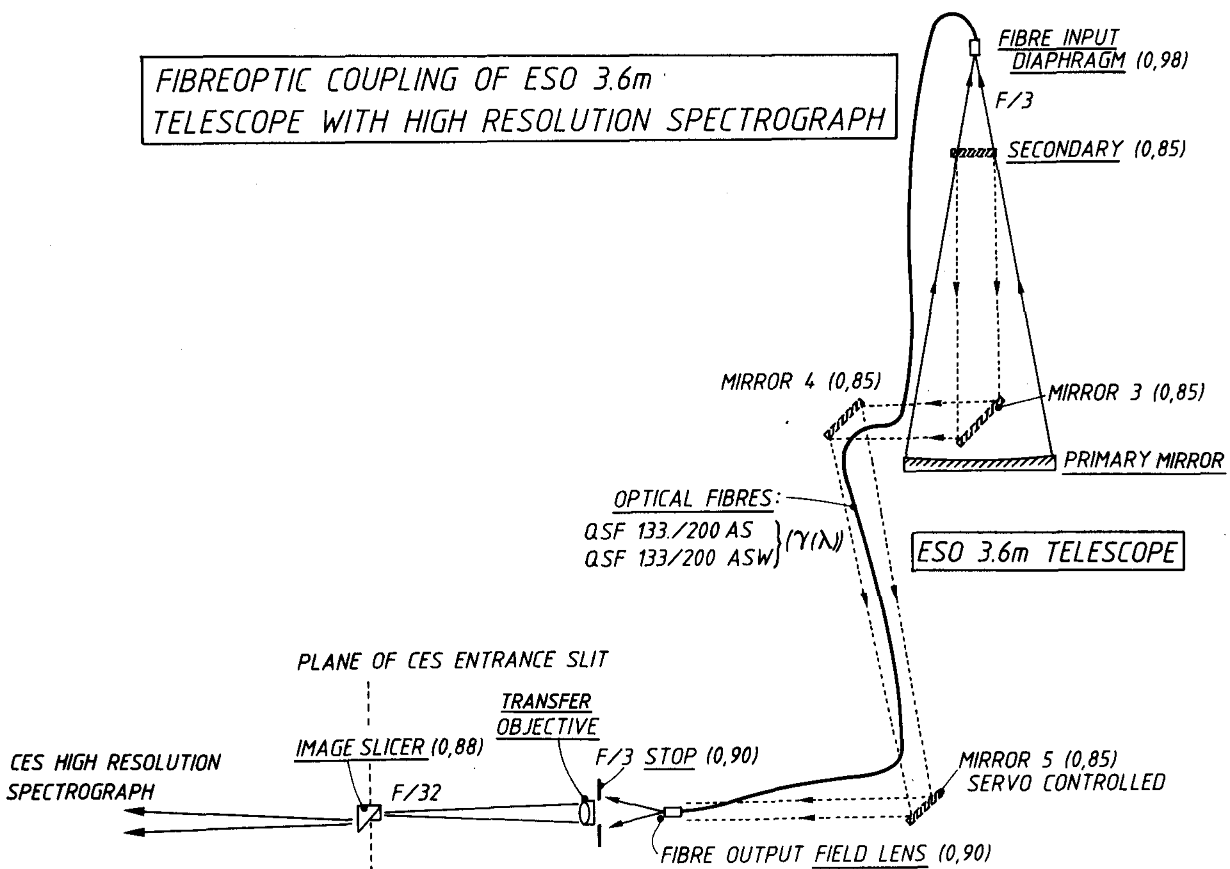

Fig. 3 ESO 40 m fibre coudé link for high resolution spectroscopy

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that a fairly high injection F ratio is used at the fibre input. From Fig. 2, an injection ratio of F/3 or faster is seen to be efficient in the case of most all-silica fibres. The numerical aperture of such fibres being typically 0.20 or less (i.e. F/2.45 or slower), it would be unadvisable to design for an injection beam much faster than F/3, since this would lead to an increased sensitivity to bending losses (coupling of the highest guided modes to unguided, lossy modes). For the purposes of this example, an injection ratio of F/3 will be used. The above considerations would then lead to the following expression for the needed fibre core diameter (ϕ), as a function of the seeing FWHM (α), and the telescope diameter (D) and focal length (f).

$$\phi = f.\alpha(\text{rad})\ (\text{m/rad}) = 4.85\ .F/D\ .D.\ \alpha(\text{arcsec})\ (\mu\text{m/arcsec}) = 116\ \mu\text{m/arcsec}\quad (\text{at } F/3)$$

As has been pointed out by Enard [26], the choice of a site with excellent seeing will be essential if a VLT is to be exploited to its full potential. Nevertheless, according to a recent report of Walker [27], star trail measurements performed at various high quality astronomical sites around the world indicate that the quality of seeing is rarely better than 1.5 arcsec for more than 50% of the time. It would thus seem reasonable, even for an excellent site, to choose a fibre having a core diameter equivalent to a sky diaphragm of at least 1.5 arcsecs (since a circular diaphragm of "x" arcsec diameter admits only 50% of the photons in an incident "x" arcsec Gaussian seeing image). Bearing these facts in mind, and considering the core diameters of currently available good silica fibres, the following table provides a selection of fibres which should permit satisfactory matching to a VLT, according to the value of seeing FWHM;

FIBRE CORE DIAMETER (μm)	SEEING FWHM FOR WHICH 50% OF PHOTONS ARE COLLECTED	SEEING FWHM FOR WHICH 80% OF PHOTONS ARE COLLECTED
100	0.8 arcsec	0.6 arcsec
133	1.2 arcsec	0.8 arcsec
150	1.3 arcsec	0.9 arcsec
200	1.8 arcsec	1.2 arcsec

From the above table, it can be seen that the choice of a 200 μm core fibre (1.8 arcsec on the sky) would enable most of the incident energy in the seeing disc to be collected during around half of the observations at a very good site. For the case of a VLT design using a primary mirror of different diameter, the required fibre core size is derived in accordance with the ratio of that diameter to 8 metres, and with the values given in the table above. The flexibility of fibres could allow the designer to provide several fibres of different core diameter, to be selected just before each observation in accordance with the prevailing seeing conditions.

The problem of matching the fibre output beam entropy to an instrument deserves careful study, and the reader should refer to the relevant paper given by Enard in these proceedings. In the case of high resolution spectroscopy, the use of a low loss image slicer would be necessary for the efficient matching of the fibre core geometry to that of a long narrow slit. If the simultaneous coupling of several telescopes to a single spectrograph is desired, this can be conveniently achieved with optical fibres and an appropriately designed image slicer. An example of this type of VLT/spectrograph matching configuration is illustrated in Fig. 5.

5. Two VLT-Instrument Coupling Designs Using Optical Fibres

Whereas from the discussions in § 2 it can be seen that fibres have many useful properties, it is clear from the text of § 1 and § 3 that in order to reduce fibre absorption losses to a minimum, only short lengths (~ < 10 m) should be used. In the light of these discussions, it is apparent that the most effective use of fibres in the design of instrumentation for a VLT would come from short lengths, used in such a way as to make the best use of their properties of small size, flexibility, and lightness. Some examples of this type of application would be designs aiming at:

* freeing some of the mechanical constraints in the rigidity and alignment requirements of instruments

* allowing rapid interchangeability of instruments

* enabling light from different telescopes to be conveniently assembled and fed to a common instrument (as in the image slicer example Fig. 5)

* enabling light to be collected from different objects in the focal plane of a telescope and arranged together in a single instrument (multi-object spectroscopy)

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As an inspiration for the design of future VLT instrumentation, two applications for which fibreoptics would exhibit one or more of the above features are outlined in the paragraphs below:

I Interchangeable VLT Instrument Coupling System

This system, as depicted in Fig. 4, could possibly provide an elegant solution to the problem of incoherently coupling the independent beams originating from 4 separate telescopes into a single spectrograph. It is assumed that the images collected at the telescopes are each transfered to a central instrument cabin by means of a collimated beam. The beam transfer, as described by Enard in these proceedings, would be achieved using small dielectrically coated mirrors. Selectable sets of off-axis parabola + fibre, optimised for either "blue" or "red" wavelengths, are then used to couple the collected light into one of two spectrographs (depending on the wavelength band of interest), via image slicers perhaps of the type shown in Fig. 5. Since as little as 5 m of fibre could suffice in this set-up, fibre absorption losses would be small and indeterminant in the selection of the wavelength bands for the two optimised spectrographs. The modes of use offered by this type of instrument coupling could be very diverse, since it would be possible to point the telescopes either to the same object or to independent objects, and to selectively feed the fibre output beams not only to these two spectrographs, but also to a variety of different instruments. The provision for fibre selection on the basis of varying seeing conditions, according to criteria such as those given in the Table above, could also be envisaged. For the sake of clarity, the possibility of coupling a telescope beam into a selection of different fibres is indicated only for the bottom right beam in Fig. 4.

The supports used to mount each fibre/parabola pair can allow for precise prealignment of each fibre with the mirror focus, thereby reducing the guiding problem to that of monitoring the star position on the fibre input face. the fibre output beams can be prealigned with the various instruments (occasional verifications being done during daytime), thus ensuring a high degree of alignment simplicity, and enabling the telescope beams to be rapidly coupled with any chosen instrument. The need for a precise and mechanically stable alignment of each telescope beam with its various instruments is completely eliminated.

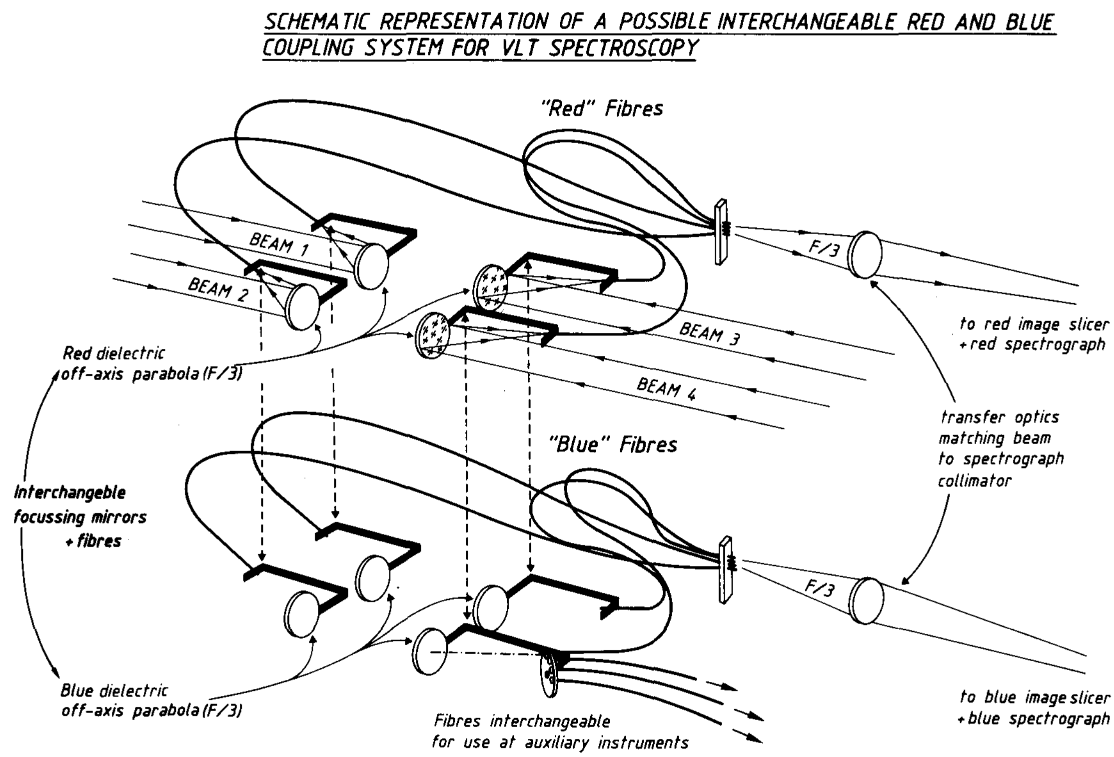

Fig. 4 Proposed VLT light coupling system based on short lengths of optical fibres. The relayed beams from each telescope can either be combined to feed a single instrument, or connected independently to a selection of auxiliary instruments. Fibre flexibility affords a relaxation in alignment tolerances.

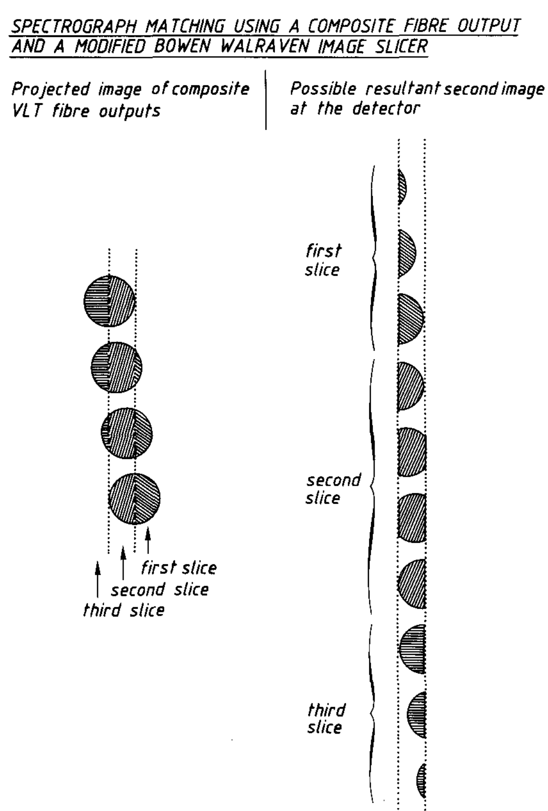

Fig. 5 For combined telescope spectroscopy, as depicted in Fig. 4 above, the fibre output beams can be matched to the spectrograph entrance slit requirements using an image slicer as depicted here. The modified Bowen-Walraven slicer rearranges the image into a predetermined number of slices. When used with a two-dimensional detector such as a CCD, simultaneous exposure from independent sources can be made possible by means of software recombination of the appropriate pixels (at each wavelength) for each respective spectrum.

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II FASTAR (Automated Multi-Object Spectroscopy)

The principle of multiple-object fibre spectroscopy was first described in 1980 by Hill et al [7] from the Steward Observatory when they introduced their fibre Medusa. More recently, the idea of automating the positioning of the individual fibres in such an instrument was described by Hill et al [28], who named their device the "MX Spectrometer". Other groups are developing automatic fibre positioning systems for the Mt. Palomar Observatory and the Anglo Australian Observatory. For use as a VLT instrument, an automated type of multi-object spectrometer would be desirable in the sense that it could enable the control and setting up of the instrument to be achieved from a remote location. This is not possible with a precision-drilled "starplate" system such as Medusa or Optopus.

The following concept, due to Enard, Huster and Lund, could provide a solution to some of the inherent drawbacks and complexities present in other automated designs. The AAO is investigating a similar scheme, known as AUTOFIB, which uses magnetic rather than vacuum clamping.

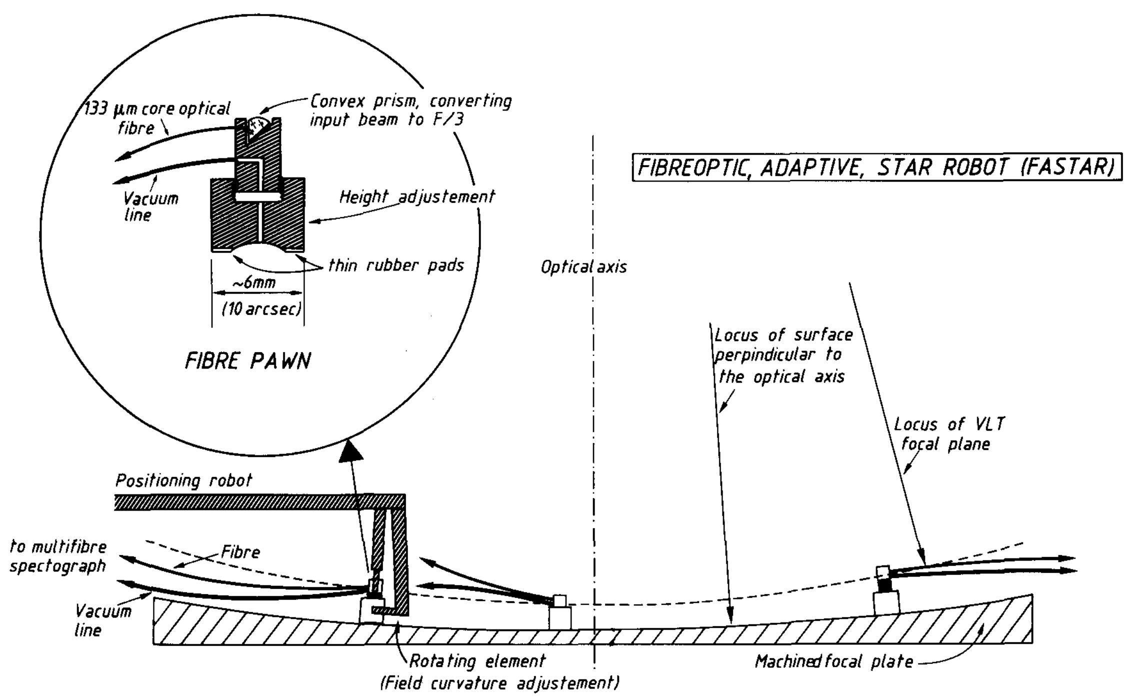

Fig. 6 Automated multiple object spectroscopy (FASTAR) using a single positioning robot and small pneumatically held fibre pawns.

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Fig. (6) depicts the proposed FASTAR (Fibreoptic Adaptive Starplate Robot), in which a single robot is used to position a large number (50 or more, depending on the spectrograpy geometery and detector size) of independent fibres at different object positions within the accessible field of view. The difficulty of correcting for field curvature and maintaining parallel alignment of the optical and fibre axes is overcome by incorporating a height adjustment into the pawns, and milling a spherical focal plate with a radius of curvature equal to the apparent pupil-focus separation. A small prism, figured on its input and output surfaces to serve the additional purpose of a telecentric focal reducing lens, is mounted at the top of each pawn so as to direct the beam at right angles to the focal plane. Fixation to the focal plate is ensured by means of suction pressure within a small cavity at the base of each pawn.

In order to benefit from a convenient field scale, enabling closely spaced objects to be simultaneously sampled, the FASTAR system could be placed at a VLT Nazimuth focus where, assuming an F ratio of F/15, the plate scale would be 580 µm/arcsec (for an 8 m primary mirror). Whereas the prism focal reducer would ensure a fibre input beam close to F/3, the above field scale would relax the needed positioning accuracy of the robot to about ± 100 µm (~ 0.15 arcsec). If an outer diameter of 6 mm could be achieved for the pawns, the maximum sampling density available with this system would correspond to 10 arcsecs on the sky.

6. Conclusions

If a VLT is to be used to its utmost potential, all possible steps should be taken to minimise the loss of photons. For this reason, and in the light of the discussions in § 1. above, optical fibres should be used only in instrument designs requiring relatively short lengths. On the other hand, as suggested in § 2. and § 5., fibres have many useful properties which should be exploited in the design of future telescopes.

Acknowledgements

I wish to thank D. Enard for many fruitful discussions, and G. Huster for his contribution to the FASTAR concept.

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Discussion

G.J. Odgers:
Would you like to compare your coudé efficiency with that of the CFHT which uses image slicers and a small-mirror coudé train?

G. Lund:
The direct throughput of our fibre is probably marginally inferior to the CFHT high-efficiency coudé mirror train at red wavelengths. In the blue, it is definitely inferior because of the poor blue/UV transmission of fibres over long distances. However, the combination of a fibre with an image slicer not only permits all the light leaving the core to be imaged onto the detector, but also eliminates the problem of guiding which is often an important source of inefficiency. The image slicer also reduces photometric errors which can

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otherwise occur due to variations in slit illumination. In view of these facts, I would say that the ESO fibre feed is probably as good as or better than a dielectrically coated coudé feed, for wavelengths between 5000 Å and 9000 Å. The fact that fibres have quite poor transmission below 4500 Å nevertheless prevents them from providing a universally acceptable solution.

J.E. Noordam:

Have you experimented with single-mode fibres for phase-stable transportation of light? The application would be interferometry between different telescopes.

G. Lund:

No, I have not experimented with such fibres. I also believe they are entirely unsuitable for use in astronomical interferometry, for the following reason: The most important problem of monomode fibres, as far as astronomical applications are concerned, is their "light carrying capacity" or entropy (E), which can be expressed according to the product of their core diameter (d) and maximum input acceptance angle (θ_o). For a typical monomode fibre, d = 7 μm, and θ_o = 0.02 rad. The input beam entropy which can be accepted by the fibre is then:

$$E_f \propto (2.d.\theta_o)^2 = 0.078\ \mu m^2\text{-ster.}$$

On the other hand the "entropy" provided in the beam from a 1 arcsec star, collected by an 8 m VLT is given as:

$$E_t \propto (D.\phi)^2 = (8.10^6\ \mu m \times 5.10^{-5}\ rad)^2 = 1.6\ 10^5\ \mu m^2\text{-ster.}$$

The number of such monomode fibres required to collect all the light coming from this 1 arcsec source is:

$$N = E_t/E_f \simeq 2.10^6\ !!$$

B. Foing:

In the FASTAR concept, can the separation between the elements be decreased to less then 20 arcsec, and then allow a spectroscopic imaging of small extended sources? Can the concept of a long slit spectrograph be extended with lines of adjacent fibres at the telescope focus?

G. Lund:
The FASTAR is at present merely a speculated system. If fibre pawns as small as 6 mm in diameter can be made, this would allow a spatial resolution of 10 arcsecs to be achieved at the F/15 focal plane of an 8 m VLT.

An alternative solution for the analysis of small extended sources could be provided by a closely packed bundle of bare fibres whose output ends would be arranged in a straight row at the entrance to the spectrograph. Taking the example of the 133/200 µm fibres we have often used, and assuming a tightly packed bundle with a focal reduction to F/3, this would lead to separations of nearest fibre centres equivalent of 1.7 arcsecs on the sky. Rather than using a round bundle, a straight line of fibres could also be used as you suggested.

H. Wöhl:
Did you measure the changes in fibre transmission for different bending?

G. Lund:
I have not quantatively measured these effects. From geometric reasoning it can be shown that the relative change in exit angle for a ray propagating through a bend is $\Delta\theta/\theta_i \simeq d/R$, where θ_i is the ray injection angle, d is the fibre core diameter and R is the radius of curvature. For a 200 µm core fibre, a single bend of radius 2 cm will thus increase the exit ray angles by about 1%. The loss mechanism in question is that of "mode stripping", which occurs when θ_i approaches or exceeds the acceptance angle θ_o defined by the fibre numerical aperture, NA = sin θ_o ($\simeq$ 0.2 for all-silica fibres). The likelihood of modestripping occurring will depend on the proximity of θ_i to θ_o, and on the number and sharpness of the bends. Thus, if light is injected with a low NA into the fibre, the influence of bending on transmission losses will be considerably reduced. On the other hand, as discussed in § 1-(b) of the report, the phenomenon of focal ratio degradation must also be taken into consideration when determining the injection F ratio to be used in astronomical applications. An injection F ratio of around F/3 (NA = .16) should minimise the combined effects of mode-stripping and focal ratio degradation losses in all-silica fibres.

It is in all cases advisable to avoid designs where pressure can be applied to the fibre, since this can strongly enhance the effects of "microbending" which leads to strong leakage of light through the fibre cladding, as can be observed in the laboratory by squeezing a laser-illuminated fibre between the fingertips.

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