Fibre Optic Positioning Device for the NGST Multi-Object Spectrograph

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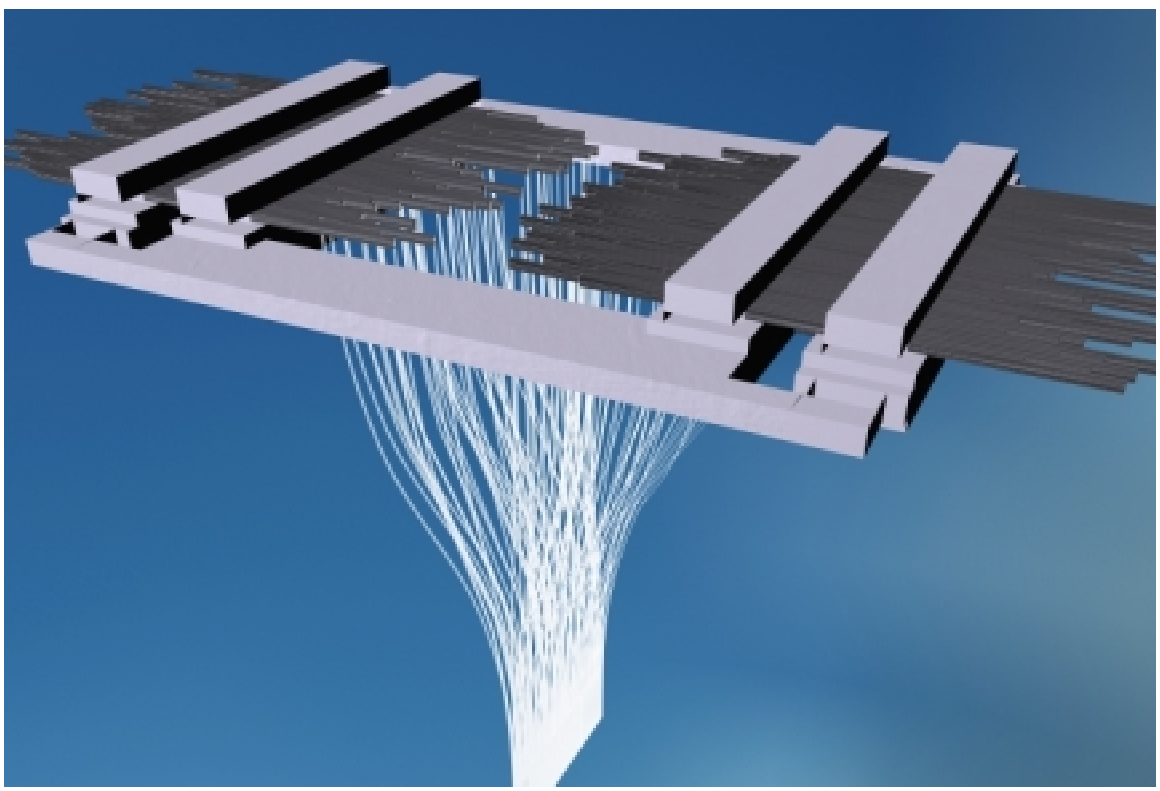

Abstract

In the scope of a prior contract, researchers at the University of Victoria's Space and Subsea Laboratory reviewed a broad range of alternatives for producing a slit mask for the space-based NGST which could be changed *in situ* for each observation. The results of that work indicated three approaches which appeared viable. Subsequent discussions with NRC staff led us to focus further efforts on the fibre-based approach which had been roughly outlined in our prior report. The purpose of the present work was to flesh out the design and bring it to the next level of definition. This report then summarizes that work, aimed at the preliminary design of a fibre-based reconfigurable slit mask for the NGST NIR Multi-Object Spectrograph (MOS).

The design requirements specified by NRC staff are first outlined, and the conceptual design of the reconfigurable slit mask is then presented. In this design, movable fibre bundles collect the incoming NIR light and reformat it for the CCD array. This design is a compromise solution in which the key priorities are: flexibility in 'slit' positioning; simplicity of mechanical design; and fault tolerance.

Two key issues are identified for further study in this work: the adequacy of fibres for transmission of NIR light at cryogenic temperatures; and the design of a mechanism to position the fibre 'slits'.

Time and resources did not allow us to study the issue of fibre adequacy in detail, and so our work in that area consisted of a review of the existing literature, as well as contacting other researchers who had prior experience in this area. Our investigation indicates that there have been substantial advances in NIR fibres for cryogenic operation during the past decade. Although there is still little information available in the public domain, all indications are that such fibres will be available in the time frame of NGST. Our main conclusions in this area, if this design is to be pursued, are that (a) better ties should be established with other groups working in this area, and (b) in-house tests of fibre properties (optical and mechanical) at cryogenic temperatures should be undertaken.

The bulk of our time and resources was channelled toward the design of a positioning mechanism for the fibre 'slits'. Our conceptual design for this device consists of (approx.) 150 bars which can be moved to programmable positions in the focal plane. In the interest of reliability and accuracy of motion, piezo-electric actuators are used for all actuation and flexures are used for all joints. The coordinated ('inchworm') actuation of a group of actuators is used to move each bar. Each bar is independent from all other bars and failure of one bar or group of actuators will not interfere with the others. Furthermore, the design allows the incorporation of redundant actuators for fail-safe operation.

A proof-of-concept device was constructed to demonstrate the viability of this approach, at least at room temperature. The device incorporates two movable bars and is controlled by a laptop PC via a custom-built set of amplifiers. The driving software accommodates different frequencies of operation and allows individual actuators to be turned off to simulate failures. It is recommended that further work on the fibre positioning device focus on the issue of operation at cryogenic temperatures.

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1. Introduction

A preliminary investigation into creating a slit mask for the NGST MOS was completed by the Space and Subsea Robotics Laboratory at the University of Victoria in January, 1999 [1]. A diversity of methods was considered and three of these were identified as the most promising: laser machining, ionized particle deposition, and reconfigurable arrays of fibre optic bundles. Following the review of those results by DAO, the UVic group was tasked with performing a more detailed investigation of one of the more promising alternatives, the fibre optic bundle solution, culminating in a proof of concept device. This report summarizes the results of this work.

Several factors form the basis for selecting the fibre optic solution to create slit masks for NGST MOS:

- In-situ manufacturing methods such as laser machining and ionized particle deposition inherently involve the production of waste material, which could contaminate the optics of the NGST.
- A reconfigurable array of fibre optic bundles does not require the storage and manipulation of raw materials.
- Fibre optic technology has been accepted in the astronomical community, and a basis of expertise has been developed over the last 15-20 years.

To briefly summarize the fibre optic solution, the slit mask is made up of fibre optic bundles which are to be placed in the focal plane at the desired slit locations. The design of such a device involves two critical aspects: optical fibres capable of transmitting near-infrared (NIR) wavelengths at cryogenic temperatures and a mechanical positioning device for placing fibres in the focal plane. The latter must be subject to the constraints and criteria specified below.

Constraints:

Mask area	180 x 180 mm
Number of slitlets	> 100
Nominal slitlet size	2 mm x 200 μm
Positioning accuracy	< 10 μm
Relative positioning accuracy	20 - 50 μm
Reconfiguration time	< 20 min
Operating environment	30K, vacuum

Criteria:

- Minimize heat generation
- Minimize power consumption
- Maximize the focal plane fill factor
- Maximize the number of slitlets

With regard to the optical fibres, several research groups and companies are currently working on developing fibres for NIR wavelengths. These fibres are being examined for their optical (throughput, FRD) and mechanical (strength, bend radii) properties. At this time, the Space and Subsea Robotics Laboratory at the University of Victoria is not equipped to test NIR fibres at cryogenic temperatures. As part of this work, a survey was conducted for availability of fibres suitable for the present application. It was found that this technology is developing rapidly and it is likely that fibres will be available to meet the NGST operating conditions. The results of our survey of NIR fibres are given in Section 2.1, and the remainder of this report focuses on the development of a manipulator which is capable of positioning many fibre optic bundles in the telescope focal plane.

2. Conceptual Design

The goal of this design work is to develop a concept for a device that is capable of positioning fibre optic bundles or slitlets within the telescope focal plane. Figure 2.1 presents the components of the conceptual design:

- *Frame*: surrounds the focal plane and provides a platform to support the rest of the components.
- *Blade flexures*: connect the carriage to the frame. The blade flexures allow a small range of carriage motion in one direction.
- *Carriage*: generates the stepwise motion of the movable rods
- *Upper and lower carriage covers*: seal the cavity inside the carriage. The lower cover acts as a mounting plate for the clutch piezos. The upper cover acts as a sliding surface for the movable bars.
- *Movable bars*: support the fibre slitlets.
- *Guide posts*: constrain the motion of the movable bars.
- *Clamping bar*: used as a foundation for the clutching of the movable bars.
- *Clutch piezos*: are contained in cavities in the frame and the carriage. These piezos are used to press the movable bars against a clamping bar.
- *Actuator piezos*: are used to pull the carriage towards the frame. One side of the actuator piezo is fixed to the frame the other is coupled to the carriage.

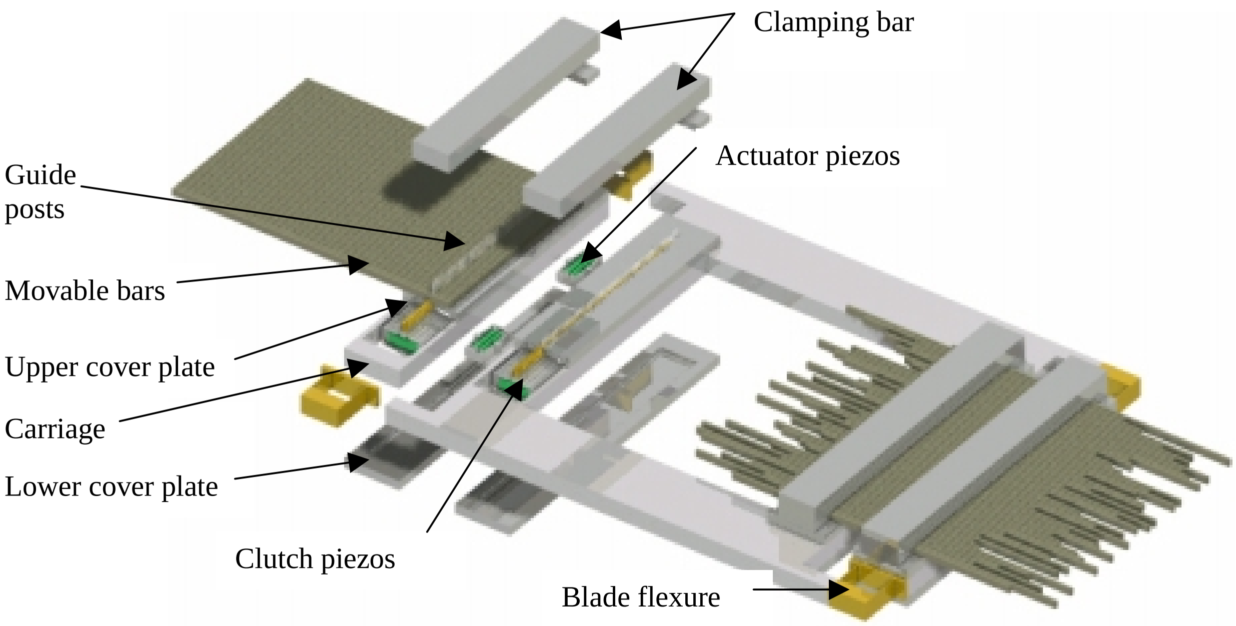


Figure 2.1. An exploded view of the conceptual fibre optic manipulator.

Each slitlet is assumed to be a linear array of fibres which collect light from a rectangular region that is 2mm x 200μm. It is assumed that the slitlets are oriented in the same direction, and are located in one or more columns or banks. This is a common arrangement used in slit masks for ground based spectrographs. For the conceptual design, we have chosen to move the slitlets across the focal plane in a linear fashion from two sides. This results in two banks of slitlets, with 60-90 slitlets per bank, as illustrated in Figure 2.2.

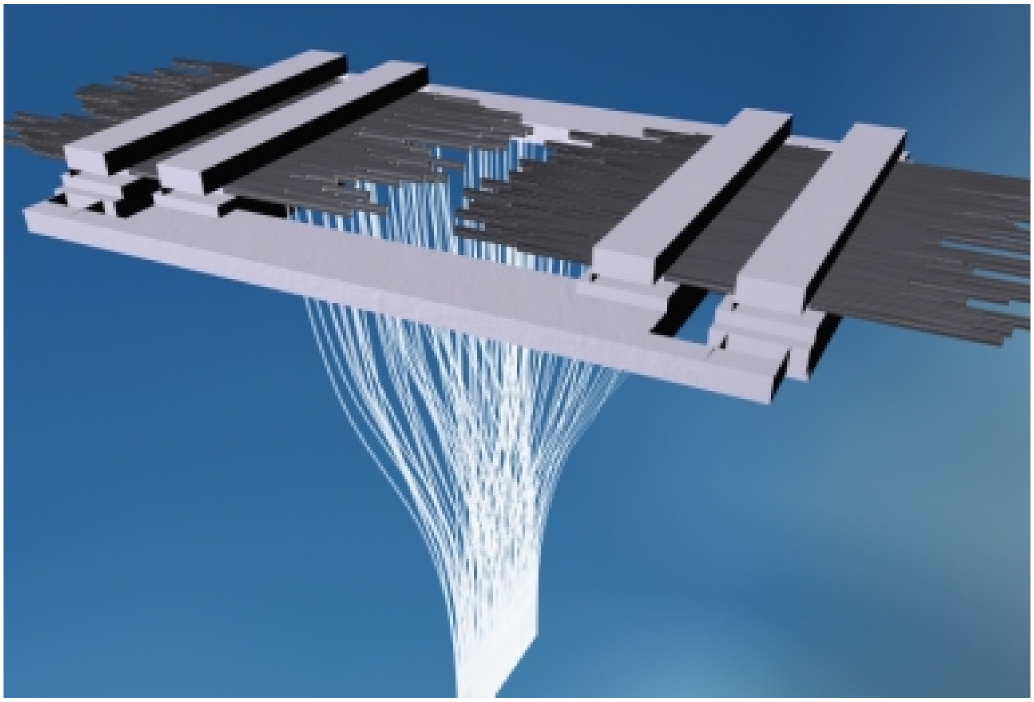


Figure 2.2. Conceptual design of NGST MOS fibre manipulator

Each individual bundle of fibres is attached to the tip of a movable bar which is actuated using "inchworm" linear motion. This type of motion has been used for actuation by companies such as Burleigh Instruments. However, it has been significantly altered in this device to actuate multiple bars in parallel. The movement of a single bar is achieved through the co-ordinated action of three piezo electric actuators. Each bar has two "clutch" piezos which are used to clamp the bar to either a fixed or movable surface. The third piezo is an "actuator" which moves the sliding bars across the focal plane. Since the stroke of piezo actuators is very limited (microns), the movable bars are translated in small steps. Long stroke linear motion is achieved by taking thousands of steps. One cycle of this motion is shown in Figure 2.3 in section view. The clutch piezos move vertically to clamp the movable bar against the upper surface while the actuator piezo moves horizontally to generate the translational motion. By co-ordinating the motion of the piezos, the movable bar is made to move one step to the right.

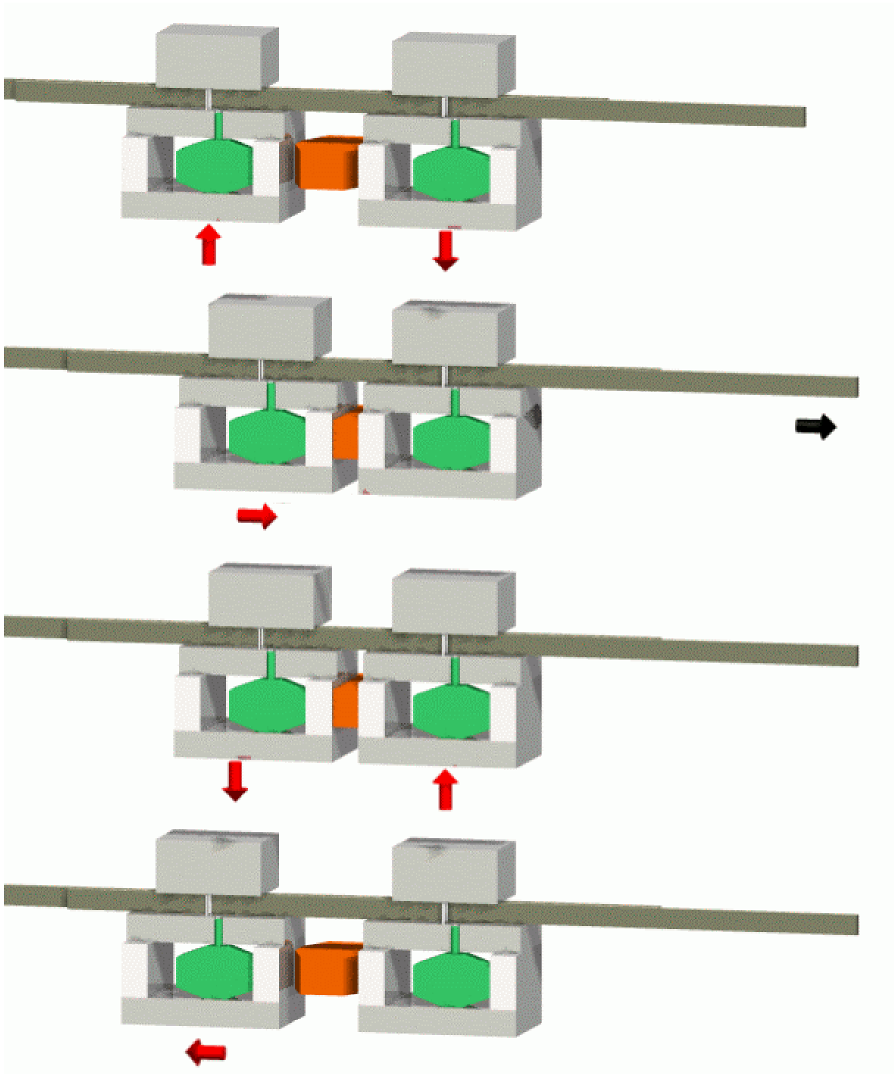


Figure 2.3. Linear motion using piezo actuators and "inchworm" motion

While the movable bars control the position of the slit inlet, the output of all the slitlets is reformatted in one long slit at the entrance to the spectrograph. This has certain astronomical advantages over conventional slit mask spectroscopy, most notable is the ability to create high resolution spectra which utilize the entire detector area.

Rows of lenslets attached at the inlet of the fibres create the "slitlets". These lenslets could be used to collect light from a rectangular region and direct it into the core of each fibre (see Figure 2.4). They could simultaneously be used to change the input f/# of the beam to reduce the FRD effect and maximize the fibre throughput. Additional rows of fibres and lenslets could be added to give 2D spatial information. Output microlenses could also be used at the entrance to the spectrograph, reformatting the beam to the desired f/# and maximizing throughput.

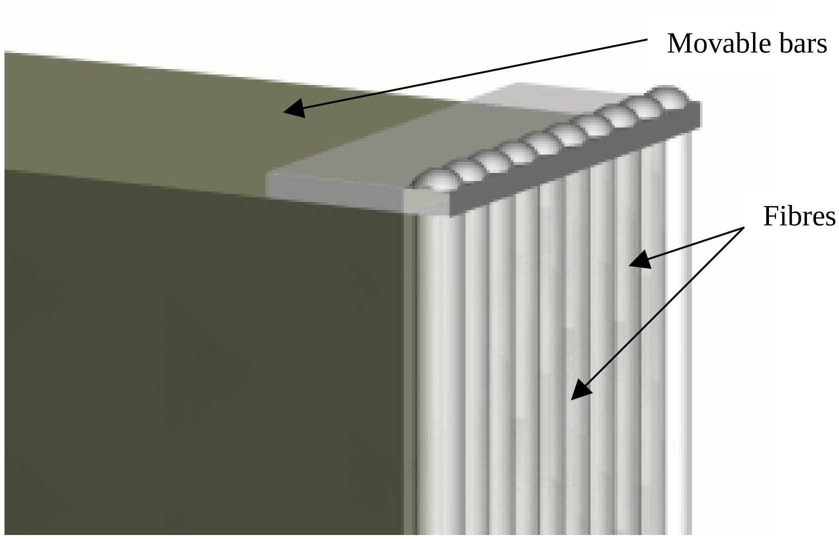


Figure 2.4. Fibre optic slitlet with attached lenslet

Central to the proposed design concept is the use of infrared fibre optics for making up the slits, and the application of piezo electric actuators to move fibre bundles to desired locations. As noted in the Introduction, a survey of available fibre optics technologies has been conducted, the results of which are presented in the following section. In Section 2.2, we discuss the piezo actuators used in the proof of concept device. Our design also incorporates a number of desirable features such as safety, redundancy and it offers the flexibility to include many additional options. Since these topics are central to the success or failure of the device, they are discussed in more detail in Section 2.3.

2.1. Near-Infrared Fibre Optics

A detailed investigation of fibre optic technology has been performed which focussed on:

1) Summarizing the extent of past cryogenic testing of suitable NIR transmitting fibres.
2) Determining the design issues for the application of glass fibres on the NGST MOS unit.
3) Finding optical fibres with suitable transmission characteristics in the NIR band.

2.1.1. Past and Present Cryogenic Developments

Near infrared (NIR) transmitting fibre optics is a relatively new technology. In the past most of the NIR observation performed with fibre based systems has been limited to wavelengths less than 2.2μm, as this was the upper limit on the transmission of ultra low OH^- silicate fibres. For transmission in the 1-5μm band of wavelengths two materials are prevalent, zirconium fluoride glasses and chalcogenide glasses. While there is some documentation regarding the mechanical (bend radius, tensile strength, elasticity) and optical properties (throughput, FRD, NA) of IR fibres provided by manufacturers at room temperature, there is virtually no documentation regarding the behavior of these fibres at relatively standard cryogenic temperatures (liquid N_2).

The only literature that has been found regarding cryogenic experimentation was an effort of Ken Levin at Infrared Fibre Systems (IFS) and Dave Glenar at the Goddard Space Flight Center [2][3]. They tested the transmission properties of IFS fluoride fibres at liquid N_2 temperatures, but did not publish any testing of the fibre mechanical properties. Their documented experimentation led to Ball Aerospace ordering bundles of IFS fibres for use in the NICMOS unit of the HST. Ball completed in house vibration and temperature experiments, but we have not been able to locate these results to date. Eventually the fibres were eliminated from the NICMOS design. The IFS fibres are currently being used by the Goddard Space Flight Center in the development of the CIRCLE suite of instruments for the Rosetta comet lander mission [4]. A bundle of IFS fibres is to be used as a cable for a remote sensor and deployed into holes drilled into the comet surface. Dave Glenar and researchers at the JPL are currently faced with similar problems to those posed by this project: to characterize the optical and mechanical behavior of the IFS fibres at a cryogenic operating temperature. That project is focussing on 400μm core IFS fluoride glass fibres.

Some additional astronomic projects are also driving more experimentation with NIR fibres. At the Anglo-Australian Observatory (AAO), David Lee and Roger Haynes will be commencing cryogenic testing of low OH^- silicate and fluoride glass fibres in June of 1999 as part of the development of the Gemini IR IFU/MOS unit. These silicate fibres are good (<1dB/m attenuation) out to wavelengths of 2.2μm - 2.5μm. David Lee at the AAO has already completed some informal tests in which silicate fibres were manipulated in liquid N_2 baths to test their flexibility. No noticeable changes in the flexibility of the silicate fibres were reported. In [5] and [6] it is presented that glasses by nature shouldn't show large changes in their mechanical properties when cooled from room to cryogenic temperatures. This gives us basis to hope that the fluoride fibres will maintain a good portion of their flexibility at the operating temperature of the NGST.

2.1.2. Commercial Supply of NIR Transmitting Fibres

Chalcogenide or fluoride glass fibres are known to be significantly more fragile than optical fibres constructed from silicate glasses. They also appear to be less readily available. Five suppliers of chalcogenide and/or fluoride glass fibres have been located:

Seiche River Photonics/Le Verre Fluore (LVF)

Redondo Beach, CA, USA

Contact: John Bessey

ph: (310) 849-0001 fax: (310) 798 0897

email: brekilien@worldnet.att.net

Institute Nationale Optique (INO)

Sainte-Foy, QC, CA

Contact: Jocelyn Lauzon or Serge Caron

ph: (418) 657-7406 fax: (418) 657-7009

email: lauzon@ino.qc.ca, scaron@ino.qc.ca
www.ino.qc.ca

Amorphous Materials Inc. (AMI)

Garland, TX, USA
Contact: Greg Whaley
ph: (972) 494-5624 fax: (972) 272-7971
email: GegWhaley@aol.com
www.amorphousmaterials.com

Infrared Fibre Systems (IFS)

Silver Spring, MD, USA
Contact: Ken Levin
ph: (301) 622-9546 fax: (301) 622-7135
email: info@infraredfibresystems.com
www.infraredfibresystems.com

Galileo Corp.

Sturbridge, MA, USA
Contact: Brian Lincoln
ph: (508) 347-4204 fax: (508) 347-3849
email: BLincoln@Galileocorp.com
www.galileocorp.com

From the constraints and criteria of the NGST MOS Phase I study, the necessary throughput of the fibres must be ≥90%. The following transmission plots, and additional product information have been provided for comparison.

LVF

Seiche River Photonics is the North American supplier of Le Verre Fluore fibre optic products. Le Verre Fluore is based in Brittany, France and is believed to be the first supplier of commercial zirconium fluoride glass fibres. They produce three different IR fibres (fibre guides): IRguide-1, IRguide-2, and IRguide-3. It should be noted that the lower limit on the range of temperatures over which the LVF fibres can be used is in the cryogenic realm. Under standard atmospheric conditions, the LVF products have compared favorably to their chief competition, the IFS fibres. However, in [7] the LVF and IFS products were both tested for FRD effect, and the LVF product was noticed to exhibit a worse FRD effect. However, it was believed that this was due to impurities in the fibre at that time which created fluctuations in refractive index.

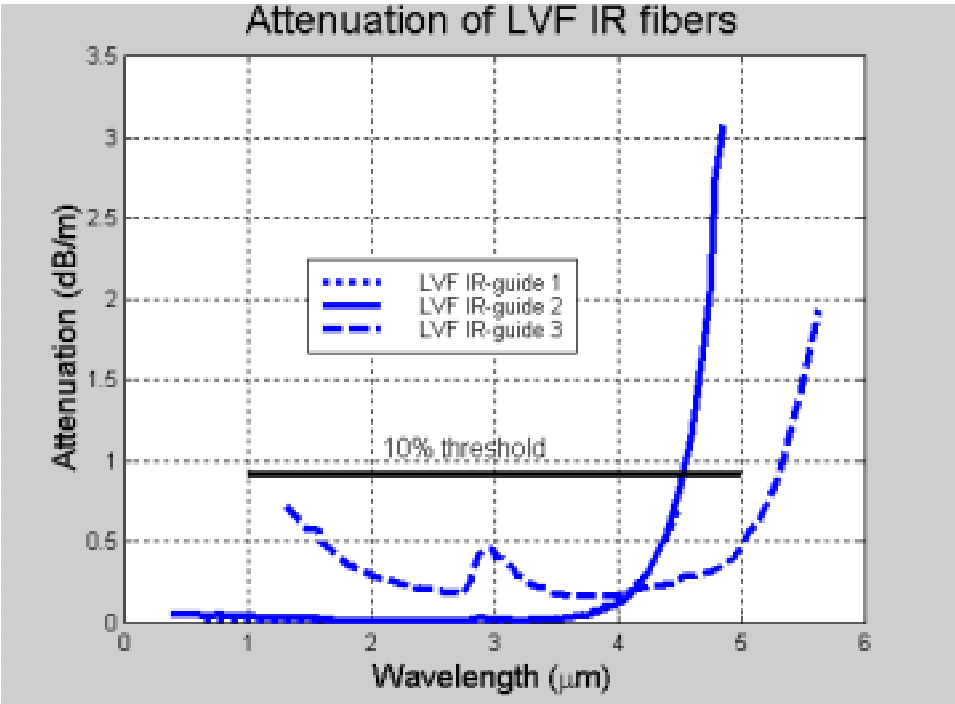


Figure 2.5. LVF IRguide fibre transmission at room temperature.

LVF - IRguide Fibre	
Numerical aperture*	0.2 - 0.45
Core diameter	70, 100, 150, 200μm
Temperature range	63K - 323K

*Numerical aperture can be specified in any order placed to LVF.

INO

INO is a private non-profit corporation established by the NRC. Much of the research performed at INO is aimed at determining fluoride glass structures that optimize the mechanical performance of the fibres. In conversation with Serge Caron, minimum bend radii of 4mm have been quoted for 60μm core / 125μm clad fibres. INO has also performed informal cryogenic tests by immersing the fluoride fibres in liquid N_2. No mechanical failure was noted in these tests. INO is currently implementing the necessary quality control technology for the commercial production of high quality ZBLAN fluoride glass fibres. The attenuation characteristics of the INO fibre are shown in Figure 2.6. INO has expressed an interest in collaborating on the NGST MOS project.

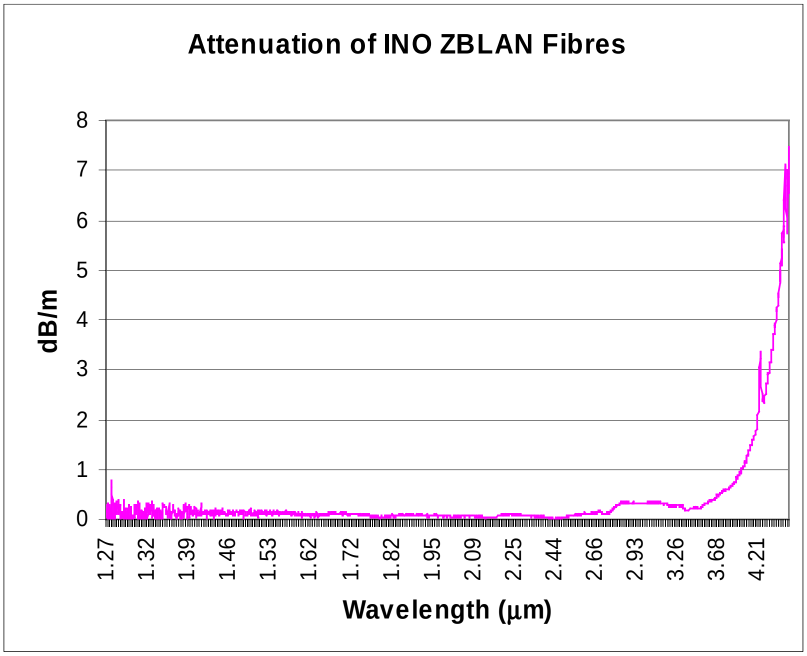


Figure 2.6. Attenuation data for the INO 60µm core / 125µm glass core glass clad fibre.

AMI

Since 1990 AMI has been manufacturing chalcogenide glass fibres. The chalcogenide glasses are compositions of arsenic, selenium, and tellurium. They feature two products, a C1 fibre for near to mid-IR transmission (2.5µm -10µm) and a C2 fibre for near-IR transmission (1µm -5.5µm). Conversation with experts in astronomical fibres revealed the opinion that chalcogenide fibres are unlikely to be able to compete with the transmission offered by fluoride glass due to the absorption spikes in their transmission plots, which are shown in Figures 2.7 and 2.8.

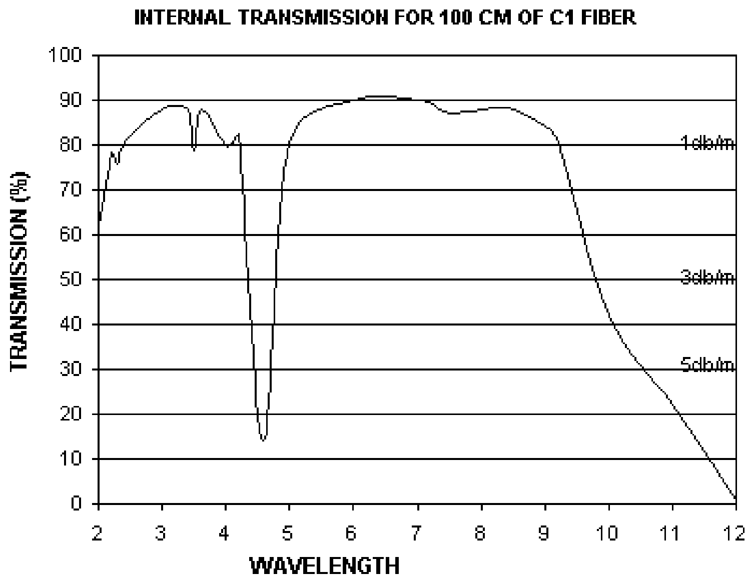


Figure 2.7. AMI - C1 fibre transmission

AMI - C1 Fibre	
Numerical aperture	0.5 - 0.7
Core diameter	< 100, 100, 250 μm
Index of Refraction (n)	2.81 - 2.82
$\Delta n/\Delta T$	$3x10^{-5}$/K
Bend Diameter (@ core diameter)	0.2 cm (100 μm) 1.6 cm (500 μm)
C.T.E.	23.5/K
Temperature range	< 443K

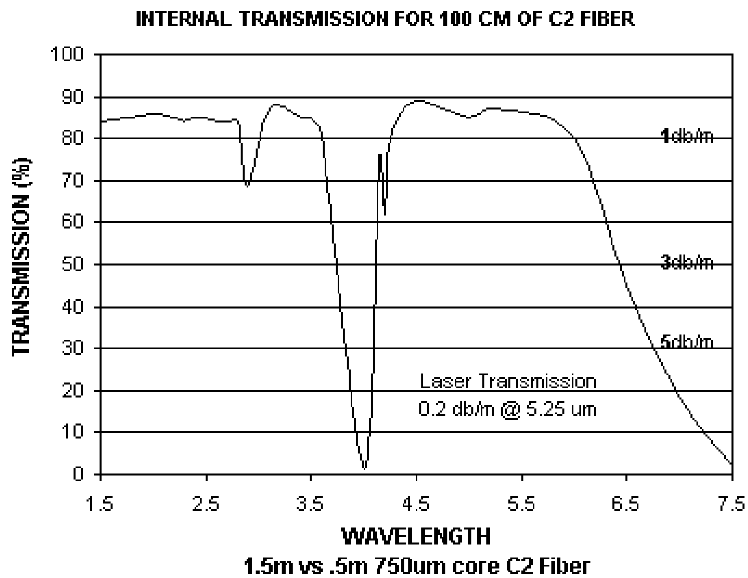


Figure 2.8. AMI - C2 fibre transmission

AMI - C2 Fibre	
Numerical aperture	0.5 - 0.7
Core diameter	< 100, 100, 250 μm
Index of Refraction (n)	2.38 - 2.41
$\Delta n/\Delta T$	0.9×10^{-5}/K
Bend Diameter (@ core diameter)	0.2 cm (<100 μm) 1.6 cm (500 μm)
C.T.E.	21.4/K
Temperature range	< 481K

IFS

IFS is the best known North American supplier of NIR transmitting fibre products. The IFS products have been well documented in literature [7], and results of cryogenic transmission testing of these fibres have been published [2] [3]. In [7] it was revealed that the IFS fibres exhibited less FRD effect than the LVF products. Figure 2.9 gives the attenuation plot for the *SG* (sensor grade) type fibre produced by IFS for both plastic and glass clad fibres. For reasons that are outlined in Section 2.3, and the better performance of the glass clad product, we are focussing on the glass clad fibre.

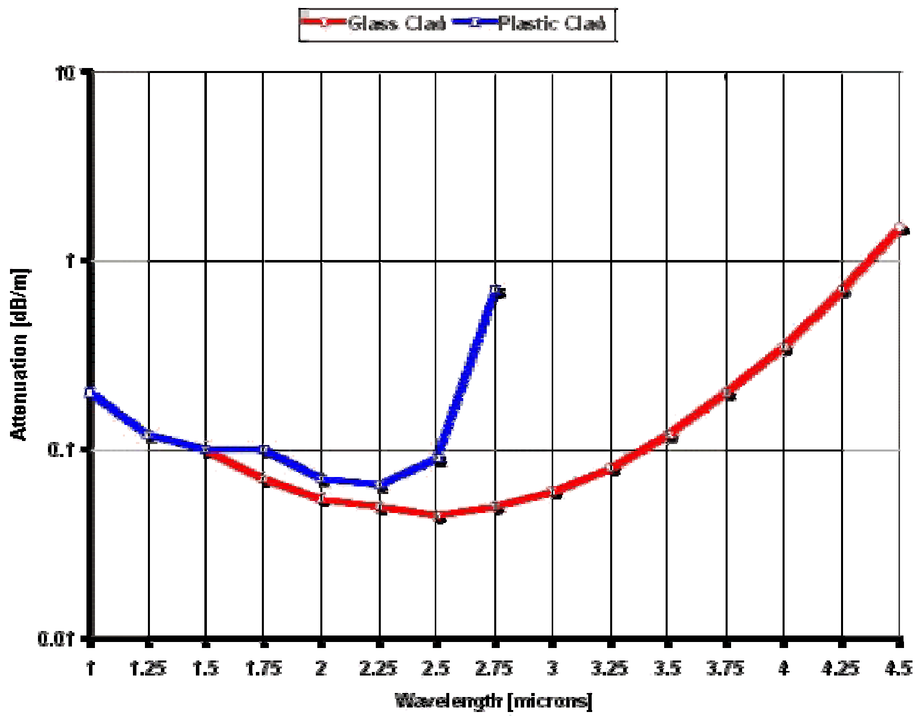


Figure 2.9. IFS - SG fibre attenuation

IFS - SG Fibre	
Numerical aperture	0.22 (glass clad) 0.6 (plastic clad)
Core diameter	100, 200 μm
Bend Diameter (@ core diameter)	1.2 cm (200 μm)
Temperature range	< 523K

Galileo

The Galileo Corp. produces both chalcogenide glass and heavy metal zirconium fluoride glass (HMFG) fibres. While the transmission bandwidth of the chalcogenide fibres is wider (1μm -10μm), the transmission borders on the 90% constraint. Also, it is noted that for both suppliers of chalcogenide glasses (AMI and Galileo), a sharp attenuation spike is evident at 4.2μm - 4.5μm depending on the specific chalcogenide fibre. As this spike is a characteristic for chalcogenide fibres from two independent manufacturers, it is believed to be a reflection of phonon absorption that is inherent with the chalcogenide structure. Figure 2.10 also illustrates how the transmission of the low OH^- silicate glasses degrades drastically at 2.2μm.

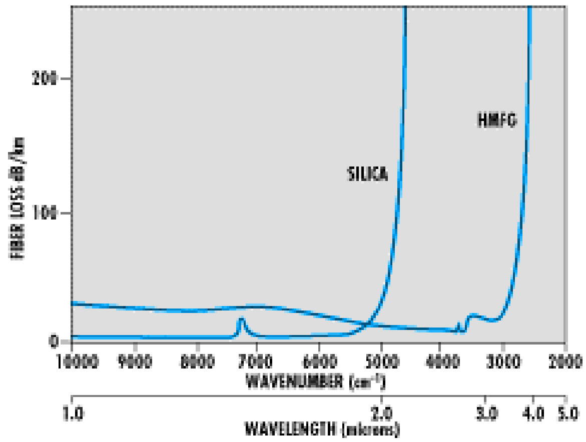


Figure 2.10. Galileo Silica and HMFG fibre attenuation

Galileo - HMFG Fibre	
Numerical aperture	0.37
Core diameter	250 µm
Bend Diameter (@ core diameter)	10 cm (250µm)
Temperature range	253K - 358K

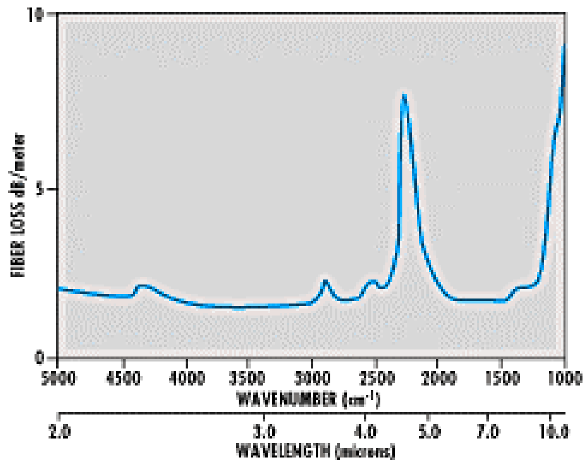


Figure 2.11. Galileo Chalcogenide fibre attenuation

Galileo - Chalcogenide Fibre	
Numerical aperture	>0.3
Core diameter	750 µm

Bend Diameter (@ core diameter)	20 cm (750μm)
Temperature range	253K - 358K

2.1.3. Design Issues / Optical Performance

In conversation with Dave Glenar at the Goddard Space Flight Center, it was highlighted that any mechanical failure of fibres at cryogenic temperatures would likely be preceded by degradation in the fibre's optical properties caused by any internal mechanical stresses. Thus, it is his belief that maintaining the optical performance of the fibre at the cryogenic operating temperature becomes the limiting requirement. A description of the criteria which will determine the optical performance of any NIR fibre, and the manner in which temperature dependent mechanical properties affects each, is given below.

Transmission

In [3] it was noted that the transmission of IFS fluoride fibres improved when the fibre was cooled to liquid N_2 temperatures. This was attributed to a decrease in the phonon absorption of the material, the prime mode of attenuation at longer wavelengths. This suggests that the transmission/attenuation curves given above could show an extension in the range of adequate transmission. Generally adequate transmission is defined by attenuation <1dB/m (90%).

Focal Ratio Degradation (FRD)

Focal Ratio Degradation (FRD) is the transfer of light energy in a fibre from one mode to another that is a result of inconsistencies in core diameter and refractive index along the length of the fibre. Such variations cause propagating rays to reflect off the core-cladding interface with varying angles of incidence, and cause higher order modes of propagating light (light that is incident on the core-cladding interface with a large angle of incidence) to be lost to the cladding [8]. Fibre systems with fast input focal ratios (numerically small f/#) exhibit less FRD. The FRD effect always acts to decrease the output f/# (or speed up the output).

During the transition to cryogenic temperatures, the cladding may contract about the core of the fibre if there is a significant difference in the thermal expansion coefficients between the core and cladding material. If such a stressing of the core material occurs, small microbends can develop which increase the FRD effect. Thus even if the FRD is characterized for a fibre and aft optics are designed to contain the speed of the fibre output, the drop to cryogenic temperature can cause the FRD effect to worsen, the aft optics to be overfilled, and the throughput to drop significantly. For this reason it is desirable to keep the materials used for cladding and core as homogeneous as possible. Thus, only glass core-glass clad fibres have been considered.

It is well recognized that the mounting of the fibres has a great effect on the level of FRD that is experienced. With identical lengths of fibres, different levels of FRD have been recorded [8]. Such differences can be induced by inconsistencies in how the fibre ends are fixed to a manipulator tip. The number of variables present in any FRD characterization make published or documented FRD results questionable. For example, experiments at the AAO have shown a 10% decrease in throughput at cold temperatures that is attributed to FRD, while work at Durham University has shown no appreciable increase in the FRD effect with change in temperature.

Numerical Aperture (NA)

In order to limit the contraction of the cladding onto the core, as mentioned above, the fibres being considered are a glass core/glass clad fibre. Unfortunately, this also results in a relatively small difference between the index of refraction between core and cladding material, and thus smaller numerical apertures and acceptance cones for the fibre candidates. This acts as a limit on the speed of the image at the input to the fibre. Since the FRD effect can be reduced/eliminated by speeding up the input at the fibre inlet [8], a small numerical aperture will act to create a more significant FRD effect. Thus the greater the difference between the index of refraction of the core and the cladding, the better. Another way to combat the negative effects of a small numerical aperture is to increase the core diameter. In this approach we are constrained by the slit width constraint of 200μm. Should this constraint be flexible, it could be advantageous to increase the slitlet width. Another option is to use lenslets. Lenslets would have to be mounted onto the fibre ends or drawn from the fibre core material itself in a manner described in [9]. This latter approach would remove the problems associated with bonding the lenslets to the fibre in a cryogenic environment.

Thermal Dependence of the Index of Refraction (n)

The propagation of light down a fibre depends on the phenomenon of total internal reflection. Thus the index of refraction of the core is greater than that of the cladding. However, the index of refraction of a material is dependent on temperature. As the temperature drops the index of refraction of the cladding can increase, and the attenuation jumps significantly. It is possible that the wave guiding capability of the fibre will be lost completely, and that any transmission will become due to reflection off of a buffer coating. This phenomenon is material dependent. Given the IFS testing at liquid nitrogen temperatures showed an improvement in transmission, one could hypothesize that the fluoride fibres should not lose their waveguiding capabilities at the NGST operating temperature.

Flexibility

It has been shown that, at room temperatures, macrobends (large scale bends or curves in the fibre) do not contribute to the FRD effect. However, if cooling to the operating temperature should significantly increase the Young's modulus of the core or cladding of the fibre, any macrobending of the fibre induced by manipulation of the fibre inlet will generate additional stress which can create microbends [8]. It is believed that the most significant restriction on the flexibility of the cable will be the flexibility of the buffer coating at the operating temperature [10]. This opinion is reinforced by the good mechanical performance of silicate glass fibres after being dipped in liquid N_2 in the AAO tests. Due to the relatively small motions required of the inlets of the fibre slitlets, it is not expected that the manipulation of the fibre will create significant problems.

Mounting fibre Inlets

In order to avoid stress induced by microbends, low shrinkage, slow curing epoxies are recommended when attaching the fibres to a manipulator tip or stationing fibres in a hardwired configuration. Even when using such adhesives, it has been found that the curing of the epoxy can increase the FRD and cause the throughput of the fibre to overfill the aft-optics designed for the normal FRD of the fibre [8]. A popular method of mounting fibres is to use precision grooves in a thermally matched metal ferrule, and tack the fibre in place with one or two beads of low shrinkage epoxy, well away from the fibre end. Ian Parry of the Institute of Astronomy at Cambridge University has used this simple approach in the COHSI unit, and he claims it performed adequately [11].

There is also insufficient publicly available data to address another issue: how a curved section of fibre will behave when cooled. We have questions as to how the thermal contraction of the fibre will affect the curvature of any section of fibre. By understanding the changes in curvature that a curved section of fibre will undergo when cooled to 30K, an optimal mounting scheme can be determined to link the focal plane to the spectrograph. The mounting of the fibres may also affect the manipulator design in terms of the fibre terminations at the tip of the manipulator(s).

2.1.4. Summary

Although there is very little published, quantitative data regarding the optical and mechanical performance of NIR transmitting glass fibres, the possibility of using fibres in the NGST MOS seems favorable for a couple of reasons. Firstly, fibre technology in the 1-5μm range is rapidly evolving. This is evidenced by the development of the IRguide-3 fibre at LVF, which has a suggested permanent operating temperature of ≥63K. Secondly, the development of the CIRCLE suite of instruments and the NIR fibre probe for the Rosetta comet lander mission demonstrates that the aerospace community believes that glass fibres can be employed in space applications. This is also supported by the cryogenic testing of fibres at the GSFC in the late 80's. In fact, glass fibres have already been considered for use in space with the NICMOS unit of the HST.

The choice of fibres for this project seems to be limited to various fluoride glass products. These fibres demonstrate transmission that is a few percentage points better than the alternative product, chalcogenide glasses. Chalcogenide glasses also exhibit characteristic attenuation spikes at 4.2μm - 4.5μm, depending on the particular molecular makeup of the chalcogenide glass. Although fluoride glasses have a shorter range of transmission, they do perform adequately (<1dB/m) out to 5μm. One can also expect the range of transmission to increase by at least 0.3μm due to the decreased phonon absorption capability of any glass fibre at cryogenic temperatures. The choice of fibres must also be constrained to those of a glass core, glass cladding construction. By maintaining a more homogeneous composition, the effects of thermal expansion (increase in the FRD) can be minimized.

It is evident that the optical requirements of a fibre used in the NGST MOS will provide the strictest performance criteria. By achieving the transmission requirements and exhibiting the minimal FRD inherent in any fluoride glass fibre, a fibre must avoid initial stages of mechanical failure, let alone total mechanical failure. The final choice of fibres must await complete optical and mechanical characterization at cryogenic temperatures, as is being conducted by researchers at the INO, AAO and GSFC/JPL.

The positioning device discussed in the remainder of this report could be used as a test bed for the evaluation of new fibre products, and thus would be a valuable contribution to the scientific community and to the progress of the NGST MOS project.

2.2. Piezo Electric Actuators

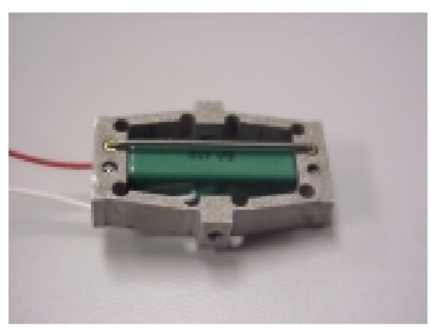
Piezo actuators were chosen for our conceptual design because they offer some unique advantages. Firstly, piezos are a solid-state ceramic which undergo a dimensional change (expansion) when a voltage is applied across it. This implies that the device has no inherent friction or wear associated with its operation. It requires no moving parts or lubrication, and is therefore straightforward to space-qualify. Secondly, as a result of the small scale motion, high resolution positioning is possible. Piezos are commonly used for optical alignment and sub-micron positioning. Next, unlike other actuators, piezos have already been demonstrated to work in cryogenic conditions. They do suffer from a decrease in stroke length at reduced temperatures, but otherwise retain acceptable performance [12] [13]. Finally, piezo actuators are a primary technology being studied for the adaptive optics aboard the NGST [14]. This means that significant research and development is already underway to develop piezo actuators for cryogenic, vacuum conditions.

For the proof of concept device, it was apparent that piezo actuators with a large stroke would be beneficial. Therefore, two commercially available devices with integrated motion amplification structures were studied. These products were the APA-100S from Cedrat Recherche, and the FPA-100 from Dynamic Structures and Materials. As shown below, these actuators utilize a flexible metal casing to amplify the motion of the piezo stack. Due to the geometry of the casing, the output of the piezo actually contracts (instead of expands) when the voltage is applied.

Cedrat Recherche SA,
AMA Department
Zirst, 38246 Meylan Cedex, France
Tel (33) (0)4 76 90 50 45,
Fax (33) (0)4 76 90 16 09
http://www.cedrat-grenoble.fr/actuators/actua.htm

(APA-100S Actuator)

Dynamic Structures and Materials, LLC
309 Williamson Square
Franklin, TN 37064
Tel: (615) 595-6665
Fax: (615) 595-6610
http://www.dynamic-structures.com



(FPA-100 Actuator)

Figure 2.12. Possible cryogenic piezoelectric actuators.

2.2.1. Specifications and Power Consumption

Each of the two devices considered has a nominal stroke length of 100μm at room temperature. The APA-100S actuator has the more favorable performance specifications which are listed below. These reflect the assumed performance at 30K, where the stroke is reduced by approximately 50%-80% [13] [15].

APA-100S actuator	
Size	5 x 10 x 25 mm
Stroke (@ 30K, assumed)	20μm
Resolution	< 1μm
Voltage	200V
Capacitance	0.73μF
Blocked force	20N
Resonant frequency	1.6KHz
Response time	2ms

Using these specifications, it is possible to estimate the power consumption of each piezo based on the voltage, capacitance and frequency of operation. In the extreme scenario, a movable bar carrying the fibre bundles is required to translate across half the focal plane (90mm). By taking 20μm steps, this is equivalent to 4500 steps. If the motion is to be completed in 10 minutes, this would require an operating frequency of f = 7.5Hz. Since the piezo ceramic behaves like a capacitor, the power consumption of each piezo can then be calculated using the following formula:

$$P = V^2 (2\pi f) C$$

With the values quoted in the specifications and the calculated frequency f, the power consumption of each piezo is found to be P = 1.38W. It is important to note that this power is not all dissipated as heat at the focal plane. Indeed, the majority of it is dissipated as heat in the electronic amplifiers which control the piezos. These amplifiers will need to be located in the "warm" part of the satellite, away from the thermally sensitive instruments. There is, however, a small amount of heat dissipated by the piezos themselves at the focal plane. The amount depends on the dielectric loss of the piezo ceramic material. Fortunately, Cedrat Recherche has stated that this loss decreases sharply at low temperatures, and expects that a low-loss piezo material would only dissipate approximately 0.01W at the focal plane. This small amount of heat may need to be removed from the focal plane with a conductive or radiative cooling system. It should be noted that this heat is only generated when the piezo is active. In our slit mask design, the actuators are only active during reconfiguration, and are all inactive during exposure.

2.3. Safety and Redundancy

Since the NGST will be placed in orbit that prevents servicing missions, all components must be designed for maximum safety and redundancy. This means that in the event of equipment failure, the satellite can continue to function with the maximum capability possible. To address the issues of safety and redundancy, the conceptual design of the fibre manipulator includes several notable features.

2.3.1. Independent Movable Bars

Referring to Figure 1.1, the movable bars are arranged side by side in a linear arrangement on two sides of the focal plane. Each bar has its own set of guide posts and clutch piezos. In the event of a clutch piezo failure, the bar can no longer be reconfigured for observations, but will not interfere with the remaining bars. The clutch piezos can be designed such that if failure occurs, they will remain in either the clamped or unclamped state. It seems desirable to have one clutch nominally clamped when unpowered while the other is unclamped when unpowered. This would prevent binding of the carriage in the unlikely event that both clutches on a single movable bar failed.

2.3.2. Redundant Actuators

One of the most interesting aspects of this design is the use of redundant actuators. Although two *clutch* piezos are required for each movable bar, one is not restricted to use a single *actuator* piezo. In the minimal case, only one actuator is needed to move all the bars on one side of the focal plane. However, in practice, several actuators can be mounted in parallel for redundant operation. In this case, if one actuator piezo fails, another could take over the function of moving the bars. For example, our proof of concept device described in Section 3 incorporates two actuator piezos which can be operated individually or together.

The key to the feasibility of this redundancy concept is to ensure that a failed actuator can not impede the performance of the remaining active devices. The conceptual design incorporates a special type of connection which achieves this goal. When the actuator is activated it contracts and pulls the entire movable carriage towards the focal plane. When the voltage is removed, the spring force in the flexures returns the carriage to its original position. Although the actuators are capable of pulling on the carriage, they are not rigidly attached. If an actuator fails, the carriage would be translated by the other actuator piezos and a gap would simply form between the malfunctioned piezo and the carriage. In this way, the failed actuator would become mechanically uncoupled from the system.

2.3.3. Other Technologies

It is worth noting that piezo actuators represent a safe, conventional technology for actuating the fibre manipulator. Although other options exist (e.g. electric motors with ball screws) these devices have friction, wear and often require lubrication. Their long-term performance at cryogenic temperatures may be questionable.

Other options such as MEMS devices being studied in the USA and at Simon Fraser University (SFU) utilize a comparatively exotic technology which is unproven at cryogenic temperatures. In the concept being pursued at SFU, micro shutters are opened by thermal actuators etched in a silicon substrate. These actuators move by using the differential expansion of two parts heated by an electric current. The researchers at SFU have noted that during operation, the silicon substrate became "red hot" due to the prolonged high frequency operation. This heat generation could have obvious detrimental effects on both the mechanical components and on the quality of observations. Compared to MEMS solutions, a mechanical piezo driven manipulator is a safe, conventional device.

2.4. Additional Options

During the development of the conceptual design, it became evident that many additional options could be incorporated to improve the performance of the device. Many of the options presented here have not yet been explored in detail and are left for further research.

2.4.1. Image Slicer

One interesting concept is to incorporate an image slicer into the same package as the fibre positioner. It has been proposed that the image slicer could be mounted in the centre of the focal plane, between the movable bars. This arrangement would naturally restrict the motion of the fibre slitlets in the central region, but is an acceptable trade-off. A preliminary design incorporating the fibre slitlets and image slicer is shown in Figure 2.13, created by EMS Technologies in Ottawa.

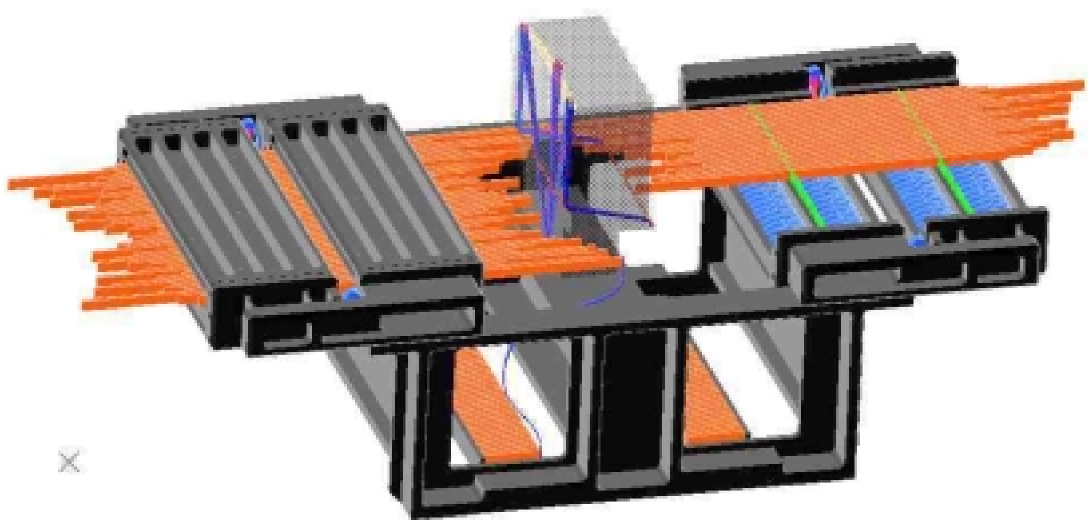


Figure 2.13. NGST MOS fibre manipulator with additional image slicer (courtesy EMS Technologies)

2.4.2. Optical Position Feedback

To achieve high accuracy positioning of the fibre slitlets, some form of position sensing would be required. Several methods of position sensing have been put forward, for example, using the instrument's CCD detector or installing an optical feedback device such as a linear encoder. A linear encoder uses an LED and a photo-transistor along with a strip of opaque material containing thin slits at regular intervals. The strip moves between the LED and transistor and generates a square-wave signal at the transistor. By counting the number of pulses of the wave, the exact position of the bar can be determined. This type of device could be easily attached to the back end of each movable bar.

2.4.3. Multiple Fibre Sizes

It is not necessary to have only one fibre slitlet at the end of the movable bar. Multiple slitlets could be arranged which have different fibre sizes, or are optimized for different wavelengths of light. In this way, the device could be used for limited "3D" observations which combine spatial and spectral information. Since the fibres can be reformatted at the entrance to the spectrograph, multiple slitlets can be used to extend the performance of the device. A movable bar with two slitlets (and two rows of fibres) is shown schematically in Figure 2.14.

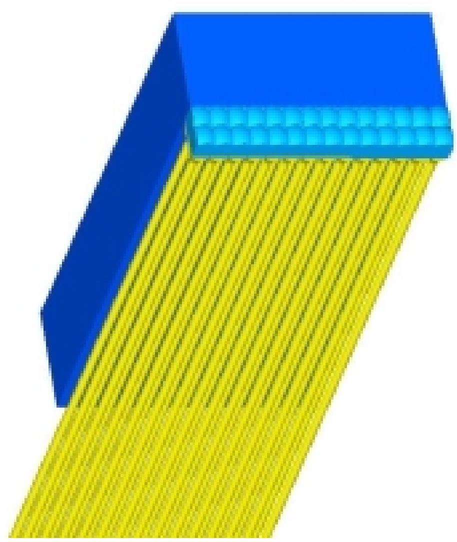


Figure 2.14. Movable bar with two fibre slitlets

2.4.4. Long-Stroke Operation

One drawback with the current design is that the piezo actuators must be activated in a cyclic fashion for the duration of the movable bar's motion. This may require thousands of cycles for a single reconfiguration and contributes to increased heat production and decreased lifetime of the piezos. One solution to this problem is to retain the clutch piezos in their current configuration, but replace the actuator piezos with a long-stroke linear actuator such as a stepper motor and ball screw. Also possible in this application are the Burleigh inchworm actuators and the New Focus Pico motor, both of which are being considered for actuation of the NGST's deployable mirror. With this arrangement, the movable carriage could be translated over the maximum required stroke (90mm), and would require only one cycle. During the motion, the clutch piezos would clamp or unclamp at the required time to position the movable bars. Since only one large step is taken, each clutch piezo must operate for only one cycle per reconfiguration. The obvious benefits are decreased heat production and increased actuator life.

3. Proof of Concept Device

In order to test the fibre manipulator concept, a proof of concept device was designed and built. Due to budget and time constraints, this device is capable of actuating only two movable bars without fibres. In most other respects, though, the device was built to reflect the design for the complete slit mask. Following are photographs of the device showing various components and the final assembly.

The principle differences between the conceptual design and the proof of concept device as constructed are: only two movable bars, the supplier of the piezos, and the arrangement of the clutch piezos. As mentioned before, time and budget constraints limited the number of movable bars to two. A third bar was included (as seen in the following figures) to demonstrate issues such as spacing and guiding, but this bar is not actuated. This also means that the movable bars were only placed on one side of the focal plane. In the actual design, the bars would move across the focal plane from two sides.

The piezo actuators chosen for this design were the FPA-100 series supplied by Dynamic Structures and Materials. The APA-100S actuators from Cedrat Recherche were preferred due to slightly better performance characteristics and an overall smaller size, but they could not be delivered within the time constraints of this project. One result of using commercially available actuators is that the clutch piezos were greater than 3mm in width. This meant that the clutches had to be mounted with an orientation of 90^{o} to the desired direction. For a device with only two movable bars, this did not pose a problem, but for the final design the issue of packing of piezos must be addressed. In all other respects, the proof of concept device was built to closely reflect the final design.

3.1. Component Photographs

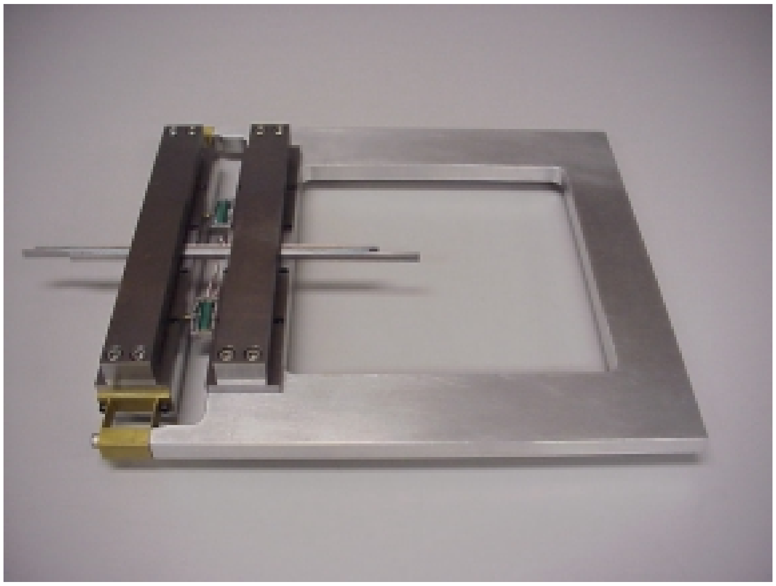


Figure 3.1. Final assembly of fibre manipulator.

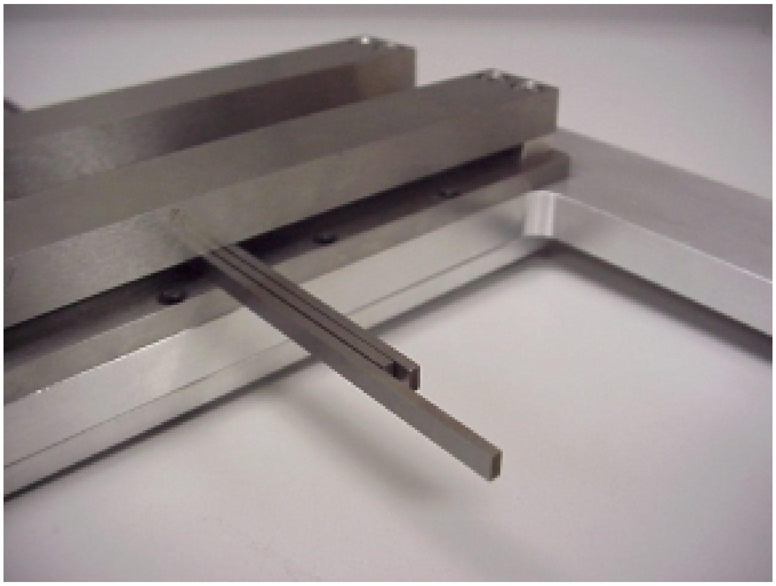


Figure 3.2. Assembled device showing three movable bars.

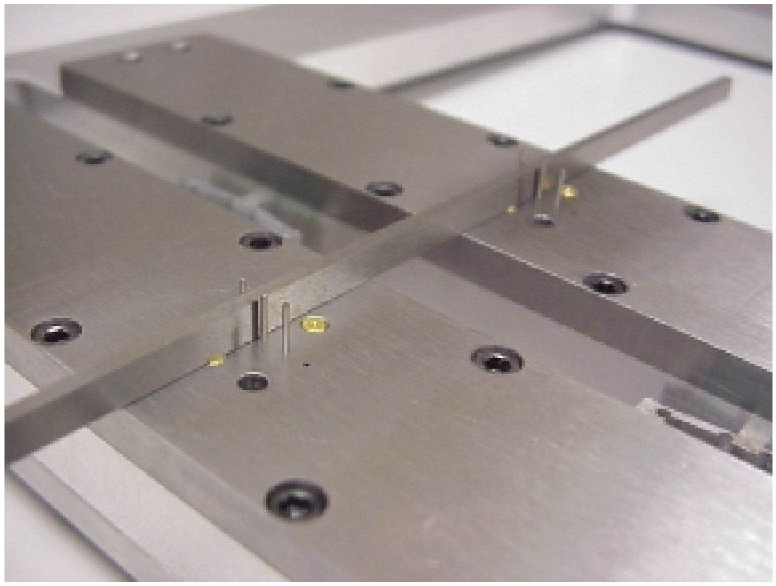


Figure 3.3. Movable bar, guide posts and clutch posts.

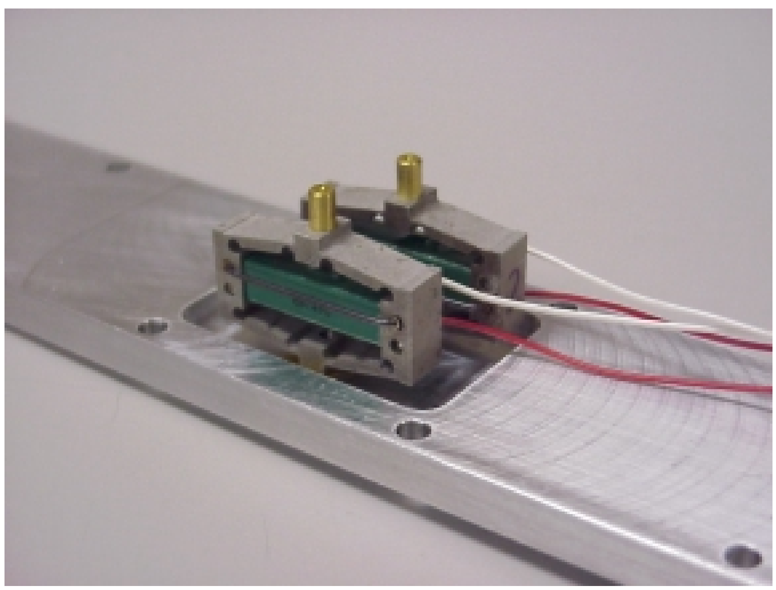


Figure 3.4. Clutch piezos on mounting plate.

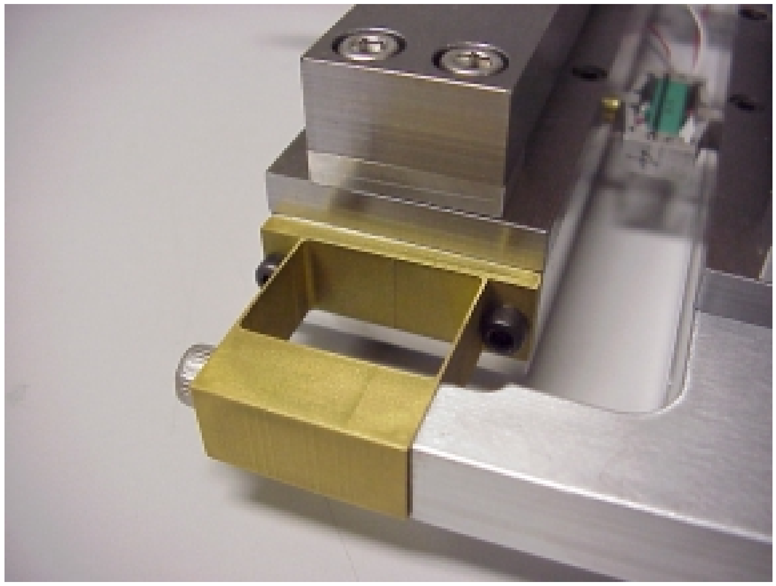


Figure 3.5. Movable carriage mounted on flexure hinges.

3. 2. Piezoelectric Controllers

In order to control the six DSM actuators of the prototype manipulator, six independent amplifiers were constructed. To generate the fixed increments of motion of the slider bars it was only necessary to run the actuators between two states: an *on* state corresponding to delivery of 150V by the amplifiers, and an *off* state which corresponded to a 0V signal. The amplifier inputs were 0V or 5V signals supplied by the digital channels of a parallel port of a standard personal computer. Two types of amplifiers were constructed: those dedicated to the control of the clutching piezos, and two amplifiers which were responsible for controlling the actuator piezos.

3.2.1. Controlling the Clutching Actuators

The prototype amplifiers allow for adjustments to be made to the peak voltage which they deliver to the clutching piezos. Dynamic Structures and Materials has supplied calibration curves, located in Appendix A, which describe the extension generated by each actuator during a 20Hz voltage loading cycle. These plots illustrate how there is variation in the extension of each actuator. In order to accommodate these variations in the performance of the six actuators, each amplifier circuit is equipped with a 50kΩ, 10 turn potentiometer which provides $\pm$10V at the piezo input voltage. This allows for the differences in the performance of the actuators to be accounted for. This mode of adjustment also allows for very fine tuning of the stroke of the clutching actuators to ensure that the clamped and unclamped states are achieved. Although we did not need this adjustment during our operation of the prototype manipulator, it could prove very useful in situations where thermal expansion must be accounted for.

3.2.2. Control of Carriage Actuators

Although the amplifiers we have constructed deliver a square wave signal, the capacitive nature of the actuators result in a rise time of 5-8ms. In order to ensure smooth carriage motion, the ability to adjust this rise time has been provided in the amplifiers that are dedicated to the carriage actuation.

Simulations of the carriage motion developed using Simulink have shown that as the carriage moves into a new position, it will oscillate about that position at a frequency much higher than the frequency of the control signal. The frequency of this oscillation is directly related to the relatively high stiffnesses (10^5N/m) of the structures which support the carriage: the set of translational flexures, and the actuator which drives the carriage motion. The simulations have also shown that the magnitude of these higher frequency oscillations can be decreased by allowing for longer rise times in the application of the “on” or 150V control signal. This degree of freedom is accomplished with an additional 50kΩ, 10 turn potentiometer.

3.2.3. Frequency Issues

Referring to the table of constraints presented in Section **1**, the sequencing between the “on” and “off” states of the actuators which drive the carriage must be completed at 1-10 Hz. This allows for the breadth of the focal plane to be easily covered in the requisite 20min. In this range of frequencies, the piezoelectric actuators are being driven well below their bandwidth of normal operation (>200Hz). This allows us to make use of two advantages. Firstly, the input waveform delivered to the actuator by the amplifier can be very sharp. This allows us to deliver a square wave form with a 150V peak to the actuators, without risking the decreased life expectancy that is associated with the use of this type of input at higher frequencies. At such low frequencies, we are also able to operate over the entire 150V operating range with a constant bias. At higher frequency operation it is the manufacturer’s suggestion that the 150V range of the actuators be accomplished between -20V and 130V. The lower overall voltage in this range prevents additional heat dissipation within the actuator and helps increase actuator lifetime.

3.3. Performance

Once the mechanical parts were assembled, all electrical connections were made and the device was tested. As expected, the manipulator was able to translate two movable bars across one-half of the focal plane. Some simple testing led to the following observations:

Length of a single step	50μm
Max. frequency (with existing PC)	5 Hz
Max. time to reconfigure (90mm stroke)	6.5 min

It was noted that positioning accuracy was only 1-2 mm, which is larger than expected. There are two main causes for this. First, the movable bar may "miss a step" from time to time due to excessive friction in the sliding surfaces. Alternately, the stroke length setting in the driving software may be slightly inaccurate. This would cause an incorrect calculation of the number of steps required to complete the motion.

Regardless of the reason, this observation points to the need for some type of position sensing and feedback control.

Based on the performance of the manipulator, it is felt that the concept of using piezo actuators to manipulate multiple fibre slitlets has been proven. Additional work should focus on cryogenic operation, positioning accuracy and thermal emissions.

4. Conclusions

A reconfigurable slit mask device has been designed and proof-of-concept constructed in the Space and Subsea Robotics Laboratory at the University of Victoria. The device uses fibre optic bundles to form slits in the focal plane for the NGST MOS. Positioning of fibres is achieved by means of two types of piezo electric actuators---one to clutch the movable bars carrying the fibres and the other to actuate the supporting carriage. A survey of existing fibre optics technologies revealed favourable findings in terms of availability of fibres capable of NIR transmission. As well, research on fibre optics performance at cryogenic temperatures is progressing rapidly.

The performance of the design was demonstrated with a two-slit mask proof of concept device. The device functioned successfully although it did not meet the positioning accuracy specifications due to lack of position feedback. The design of the complete slit mask incorporates a number of advantages, such as redundant actuation, possibility of using position feedback and different slit sizes to further improve MOS functionality.

5. Recommendations

There is still substantial work to be done to ascertain whether the conceptual design presented here will be a viable solution for the NGST MOS slit mask. First and foremost, since the design inherently assumes the existence of appropriate optical fibres, such fibres must be identified. Since a number of research groups and companies have already performed work in this area, it would be advantageous to contact them, perhaps form alliances with them, and obtain any quantitative data they may have. Once that is done, experimental testing of candidate fibres at cryogenic temperatures should be performed to support and complement any data obtained. In particular, the following properties must be quantified as being satisfactory for the purpose of the NGST slit mask: (a) mechanical strength, bend radius, stiffness, ductility, and fatigue life, and (b) optical transmission, focal ratio degradation, and numerical aperature. Methods for mounting the fibres on the rod ends without inducing thermal stresses at cryogenic temperatures must also be identified, as well as the design and construction of lenslets for channeling the light at the fibre inlets.

The design of the fibre positioner presented here is less crucial because, even if it turns out not to be viable, another approach could likely be proposed for this function. Nevertheless, assuming that the conceptual design presented here does form the basis for the final selected design, a number of items still remain to be investigated. First and foremost, the adequacy of piezo-electric actuators for operation at cryogenic temperatures must be ascertained. It is well known that the stroke of such actuators is reduced, but more quantitative data must be obtained for the specific actuators being considered, at 30 K. As well, the heat dissipation of these actuators, in the focal plane, must be quantified. It would likely be desirable to enlist one or more of the piezo manufacturers to custom-design an integrated actuator/flexure for this application. Hopefully, the actuators could be made more compact to improve the packing efficiency in the final design. As well, the amplifier and control circuitry should be redesigned to allow more accurate positioning of the actuators (as opposed to the on/off control used in our proof-of-concept device), though this is expected to be straightforward. Some means of sensing the position of the bars must also be devised to allow closed loop control of the bar positioning.

Further work needs to be done on the remainder of the positioning device for operation at cryogenic temperatures---in particular, choosing and sizing of materials for the frame, rods and flexures. Some analysis should also be performed to identify potential vibration problems of the rods both during operation and during launch. Finally, if the idea proves attractive, further work could also be done on the incorporation of an image slicer into the overall design.

6. References

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[13] http://ngst.gsfc.nasa.gov/Hardware/meetings/techchal2.html

[14] NASA awards contracts for the Next-Generation Space Telescope, news release no. 98-014. Technical Report, March 24 1998.

[15] Editors, The New Melles Griot Nanopositioning Guide, Melles Griot, pp. 1-1 to 3-11, 1993.

Appendix A: Piezo Calibration Curves

Part Number: FPA-100 UVIC 1
Calibration Data: 21-Jul-99
Calibration by: M. Samuelson
Actuator mass: 7.70g

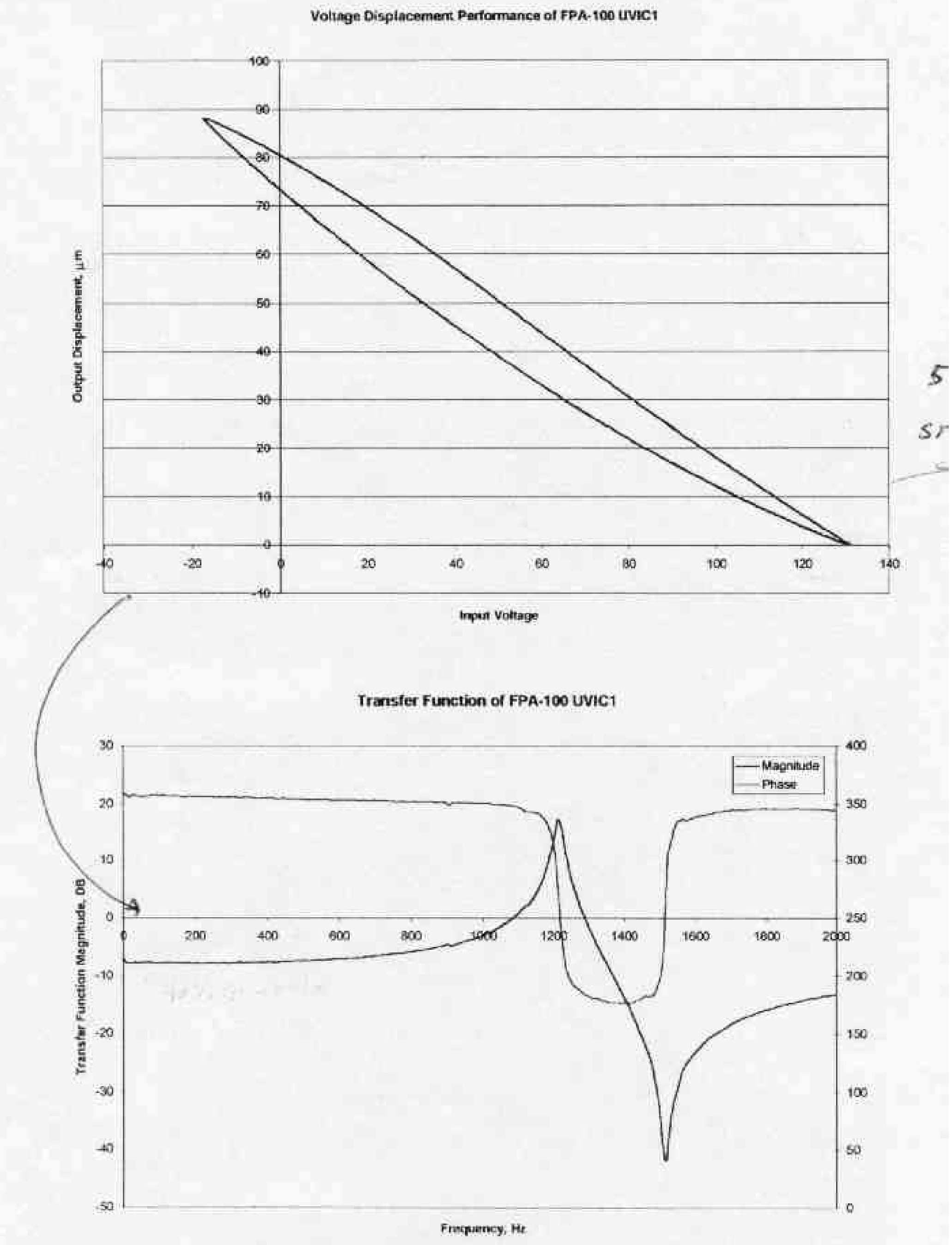
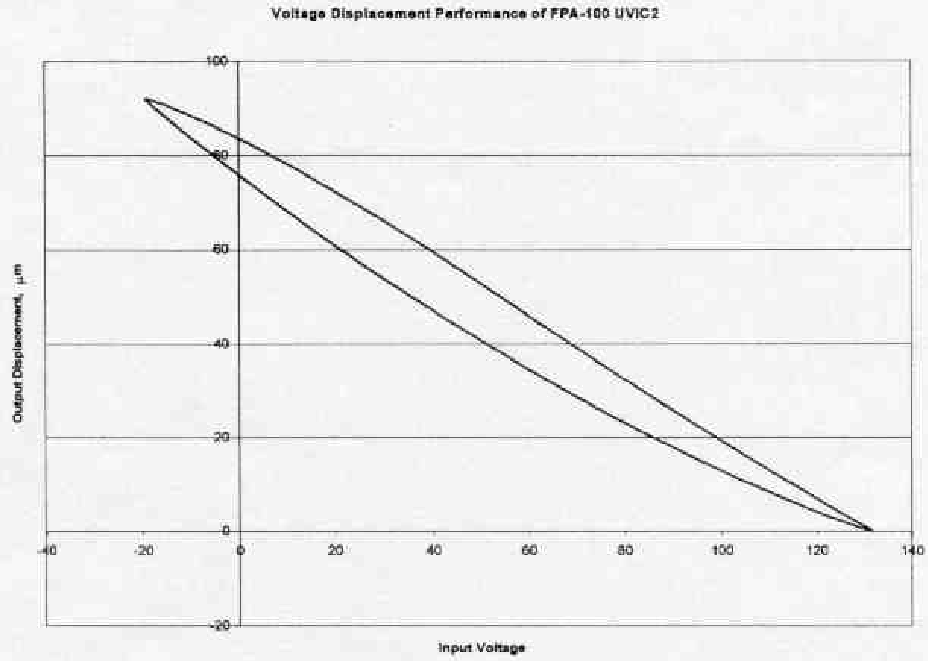


Figure A.1. Piezo 1 calibration curve

Part Number: FPA-100 UVIC 2
Calibration Data: 21-Jul-99
Calibration by: M. Samuelson
Actuator mass: 7.65g



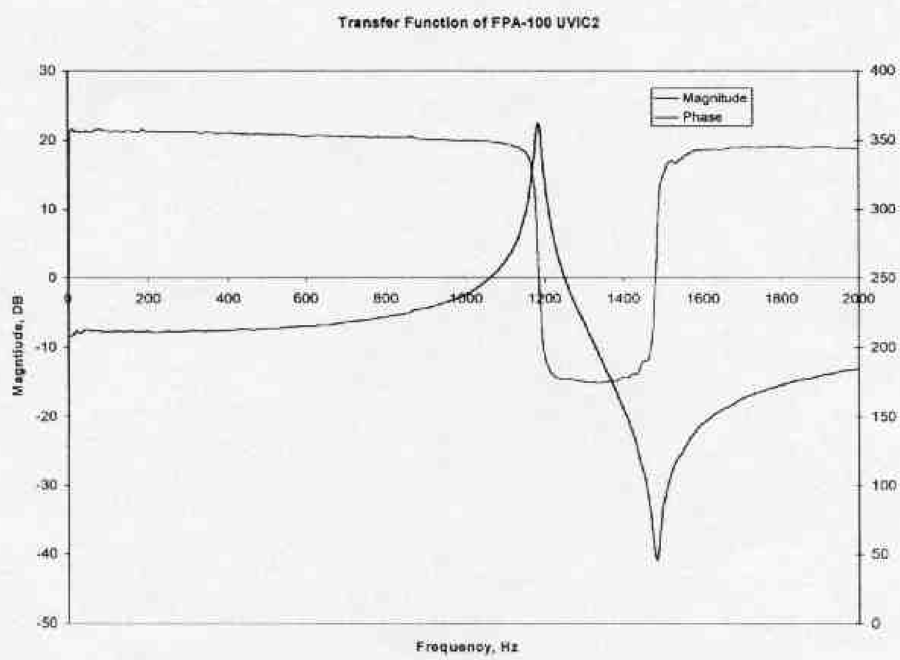


Figure A.2. Piezo 2 calibration curve

Part Number: FPA-100 UVIC 3
Calibration Data: 21-Jul-99
Calibration by: M. Samuelson
Actuator mass: 7.70g

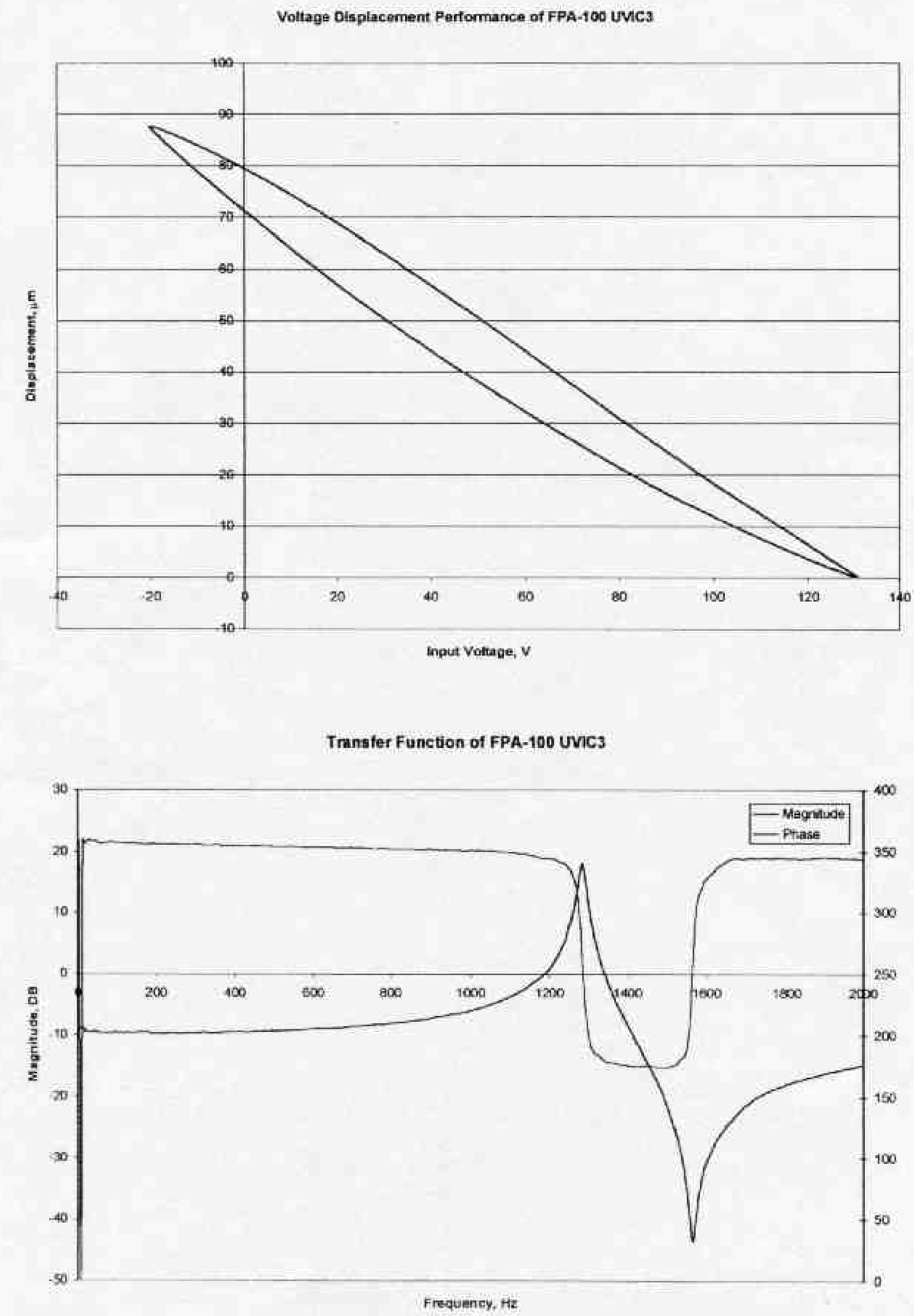
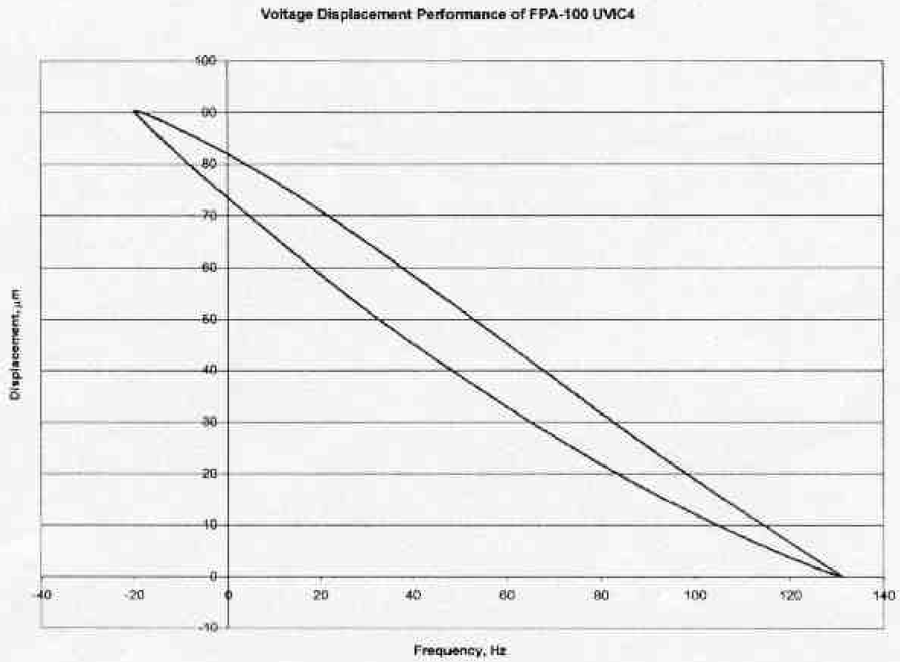


Figure A.3. Piezo 3 calibration curve

Part Number: FPA-100 UVIC 4
Calibration Data: 21-Jul-99
Calibration by: M. Samuelson
Actuator mass: 7.65g



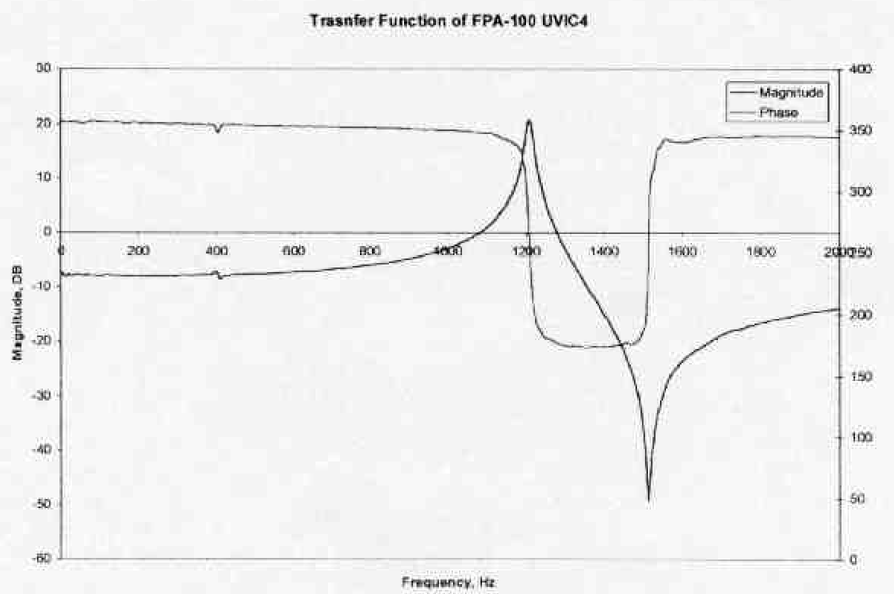
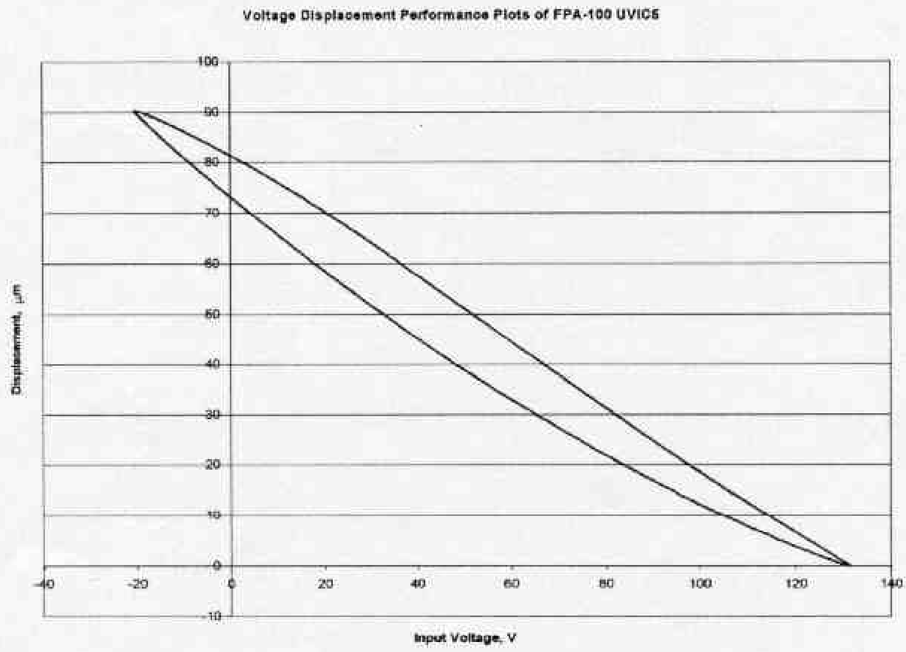


Figure A.4. Piezo 4 calibration curve

Part Number: FPA-100 UVIC 5
Calibration Data: 21-Jul-99
Calibration by: M. Samuelson
Actuator mass: 7.65g



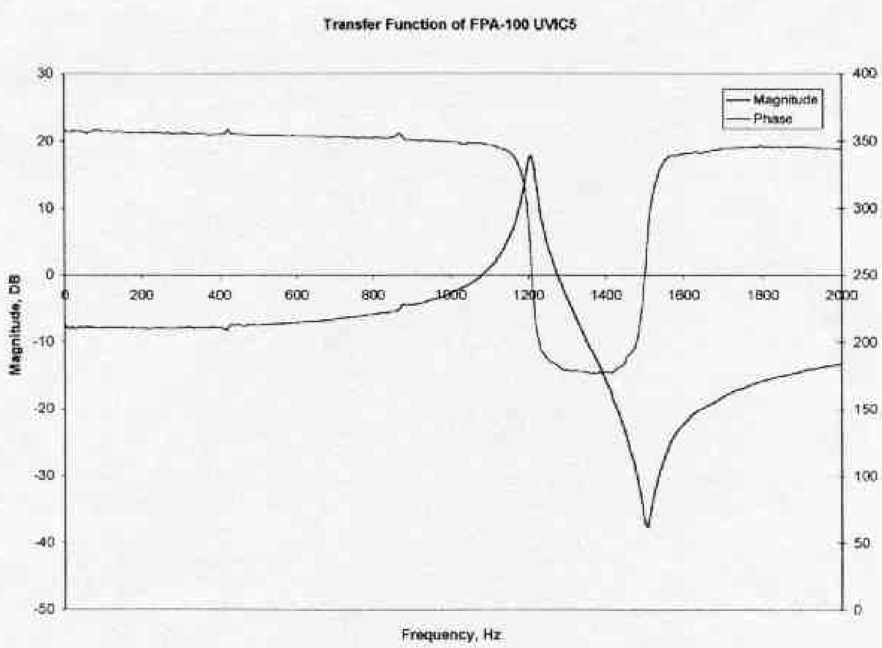
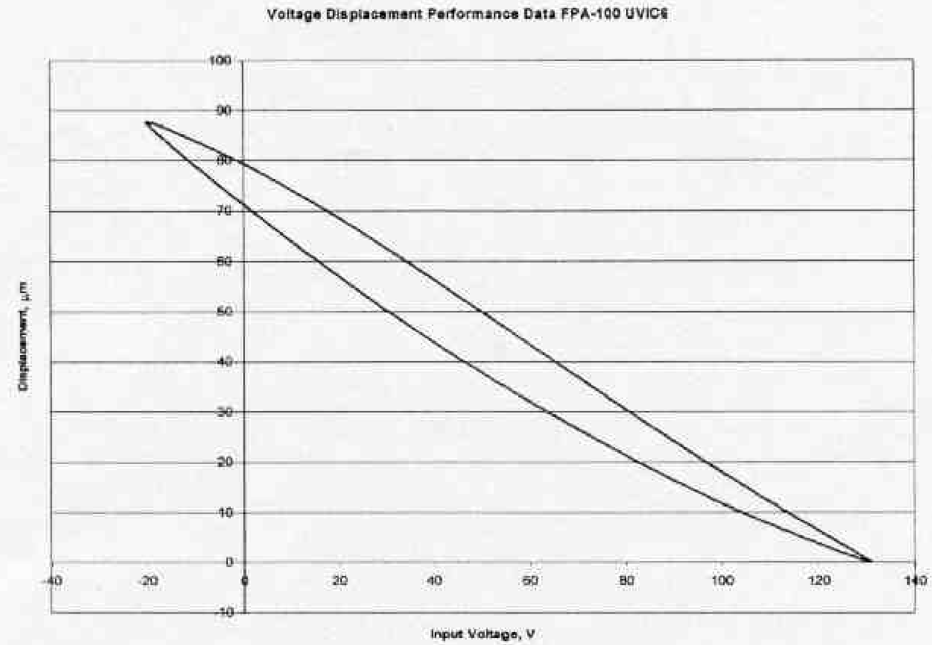


Figure A.5. Piezo 5 calibration curve

Part Number: FPA-100 UVIC 6
Calibration Data: 21-Jul-99
Calibration by: M. Samuelson
Actuator mass: 7.65g



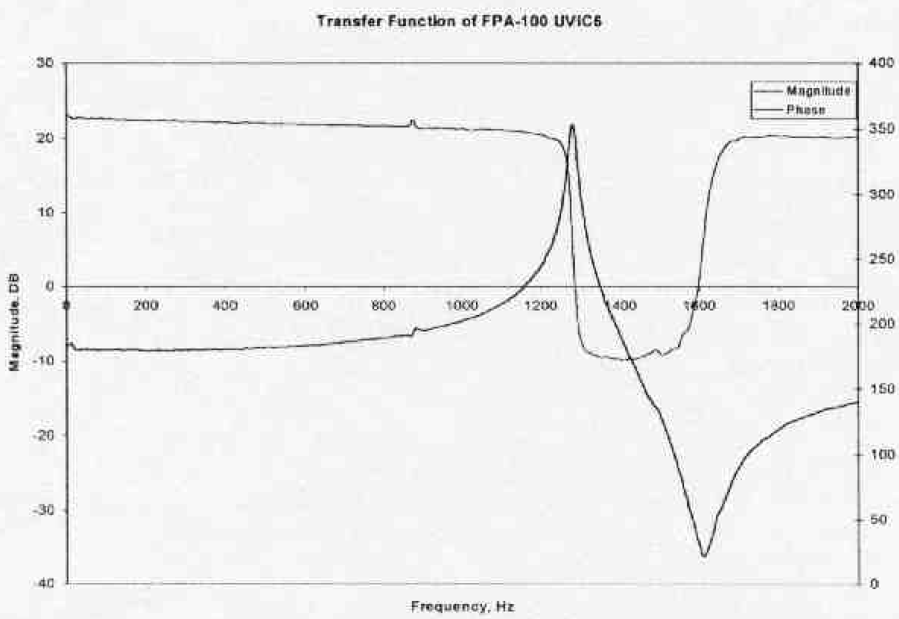


Figure A.6. Piezo 6 calibration curve

Part Number: FPA-100 UVIC 7
Calibration Data: 21-Jul-99
Calibration by: M. Samuelson
Actuator mass: 7.65g

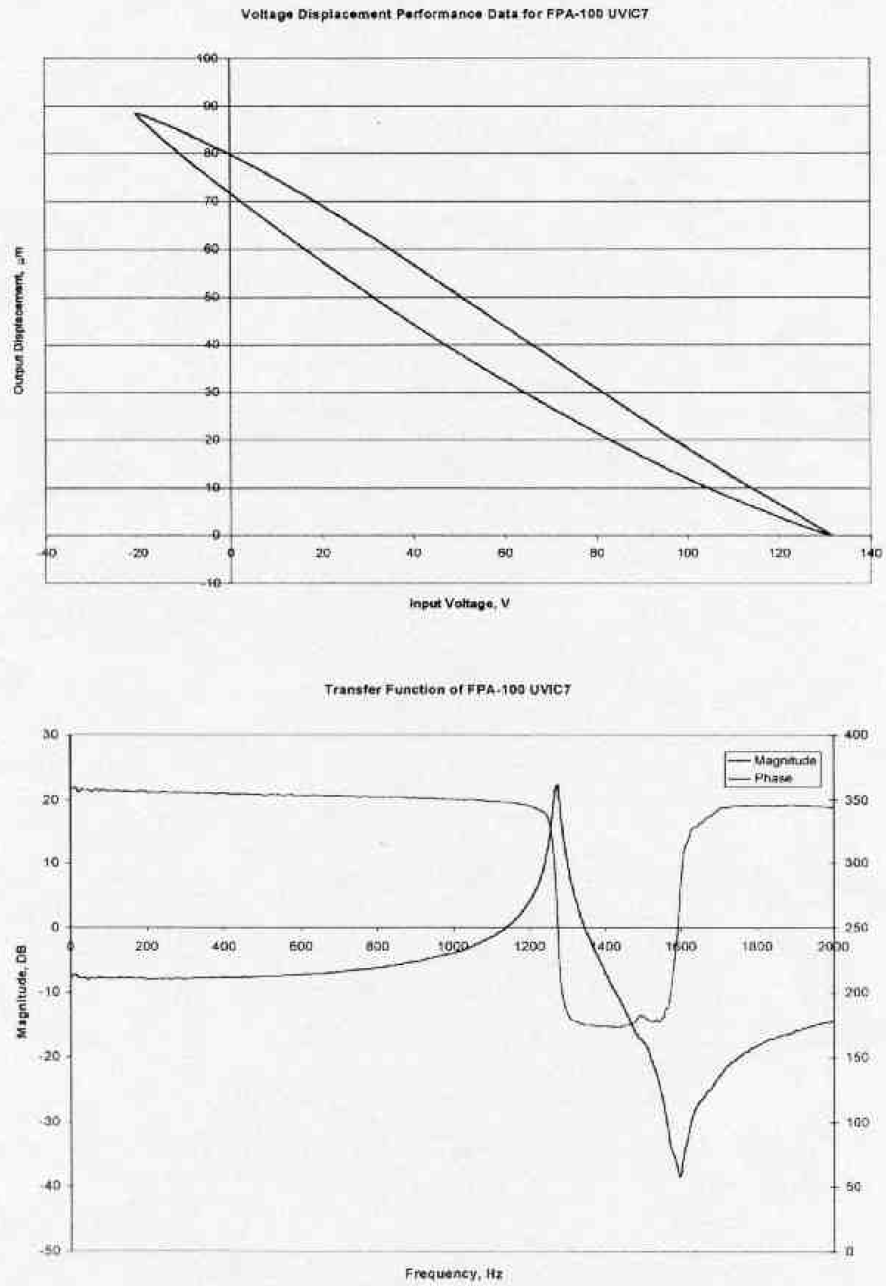


Figure A.7. Piezo 7 calibration curve

Appendix B: Computer Control System

The fibre manipulator is controlled using a PC running Windows 95/98. This computer is connected to the piezo amplifiers via the parallel port. Unfortunately, due to restricted access to the parallel port under WinNT, the control software does not run with that operating system. To simplify use, a graphical user interface was developed to specify the desired motion and customize the settings.

Running the program

- In Windows 95/98, open the *Start - Programs* menu.
- Click on the *Run NGST Prototype* link. A dialog box will appear as shown in Figure B.1.
- To insert or reposition the slider bars by hand, click on the *Settings* button.
- A second dialog box will appear as shown in Figure B.2.
- Click on the Clutch 1, Clutch 2, Clutch 3 and Clutch 4 boxes to turn on (retract) the clutch piezos. The slider bars should now move freely into position.
- Click on *Close*.
- To activate the device, drag the two trackbars to the desired locations and press *Move*.

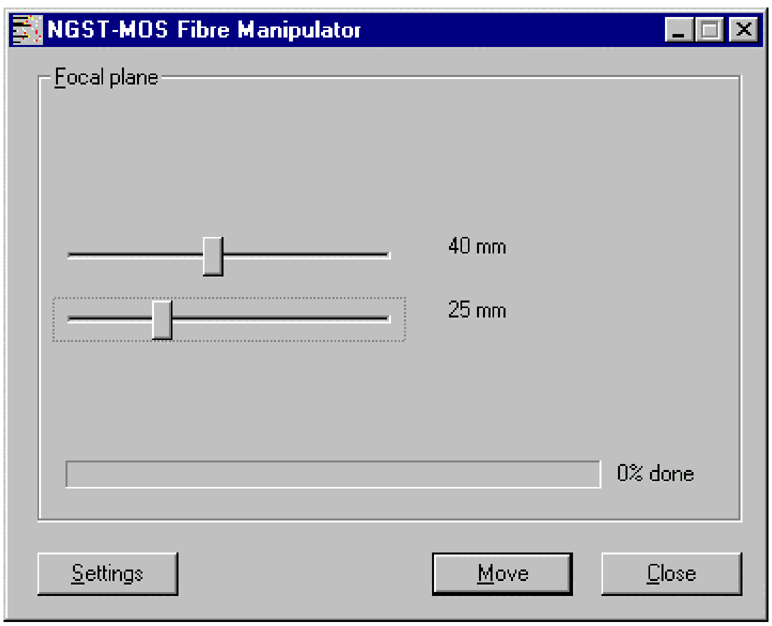


Figure B.1. Control program main window

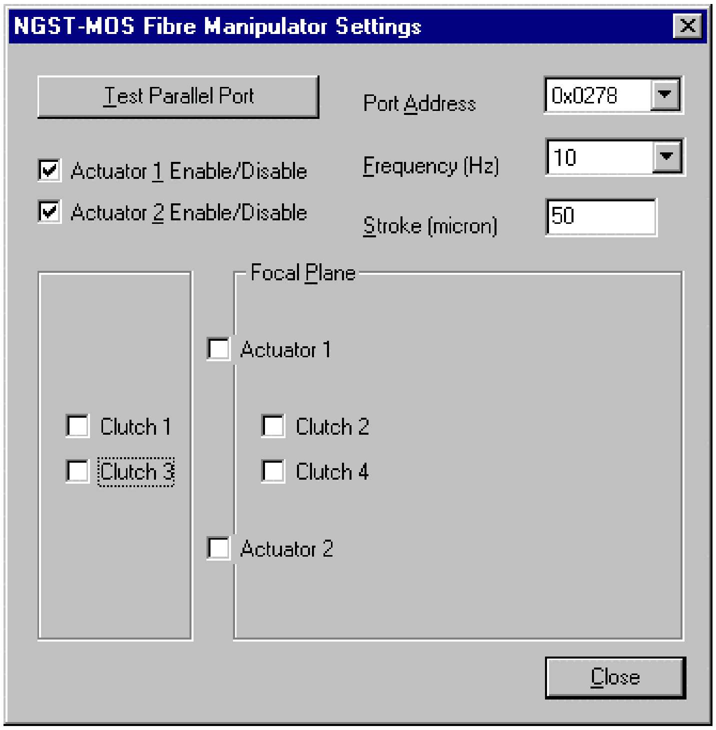


Figure B.2. Settings window

Software Troubleshooting

If nothing happens when you press *Move,* there may be several causes:

- The cable connections are not fully contacting. Verify that all cables are fully connected.
- The power is not on. Plug in amplifier and turn on power switch.
- The parallel port setting is not correct. Look in the *Windows Control Panel* under *System, Device Manager* for a folder called *Ports*. Expand this folder, highlight LPT1 and press *Properties* then *Resources*. Take note of the input/output range. It should resemble something like 0x0378. Next open the NGST controller program and press the *Settings* button. In the *Port Address* list box, highlight the parallel port I/O address that was listed in the *Control Panel*. Close the *Settings* dialog box and re-try the program.

CAUTION - The *Test Parallel Port* button is meant to test the connections and address settings of the software. However, the input impedance of the parallel port has not yet been measured. If the impedance is very low, then pressing the *Test Parallel Port* button may cause the port to short circuit. For the present, DO NOT USE this feature.

Customizing the motion

The Settings dialog box allows the user to change many of the settings used in the control program such as stroke length, frequency and number of actuators used.

- To change the frequency, click on the down arrow and select one of the options. Depending on the speed of the computer, it may not be possible to achieve some of the higher frequency motions.
- To change the stroke length used in the program, click in the edit box and type the new value (in microns). This value should be edited if the observed motion is different from the desired motion.
- The actuator enable/disable feature can be used to turn off or on one of the actuators and demonstrate the redundant operation. The program only permits one actuator to be turned off at a time.

As mentioned above, DO NOT USE the *Test Parallel Port* button. Until the input impedance of the parallel port is determined, this feature should not be used or else damage to the computer may result.