Next Generation Space Telescope (NGST)

Report of the NGST Task Group

October 1997

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1. Summary

In its report released in 1995, the Survey Committee established by ESA to update the long-term plan for Space Science, presently known as the “Horizons 2000 Programme”, discussed the future prospects for Optical Space Astronomy in Europe and concluded that ESA should continue its participation in the Hubble Space Telescope (HST) and assure an involvement in possible successor programmes.

In 1996, the scientific case for a large aperture space telescope was laid out in a report by the “HST and Beyond” Committee, a team of American astronomers set up to consider the needs of the astronomical community after the end of the HST mission foreseen in 2005. This Committee identified two major goals to be addressed in the coming decades : (1) the detailed study of the birth and evolution of normal galaxies such as the Milky Way throughout the life of the Universe and, (2) the detection of Earth-like planets around other stars and the search for evidence of life on them. While the second goal requires the development of space interferometry and is not addressed in the present report, for the first one, the US Committee recommended that NASA develop a space observatory based on a 4 m or larger aperture telescope, optimized for imaging and spectroscopy, operating at the diffraction limit over the wavelength range 1 to 5 microns. This large telescope, now known as the Next Generation Space Telescope (NGST), would be ideally suited to study galaxies up to redshifts of z=10, corresponding to less than 1/10 of the current age of the Universe. Such a large space telescope operating in the 1-5 μm range will offer two unique advantages (i) high angular resolution at the shortest wavelengths and (ii) enhanced sensitivity through the low background of the cold space environment. Because of the limited size of space telescopes to date, high resolution has been restricted to terrestrial telescopes that are hampered by the (relatively) high background generated by the ambient temperature conditions, and by strong atmospheric OH glow. The two main advantages of NGST should be exploited by the instrumentation suite that the telescope carries : the basic complement of instruments must therefore include a wide field camera imaging in the 1-5μm domain and a versatile spectrograph for single and multiple-object work in the same waveband.

Since the advent of the concept for the NGST and the ensueing scientific and technical feasibility studies carried out by NASA, European astronomers have applied considerable pressure on ESA to participate in these studies and consider a substantial European involvement in NGST.

In mid 1996, NASA formally invited ESA to cooperate in the studies initiated in the framework of their “Origins” programme of which NGST is a major element.
In the meantime, ESA’s advisory bodies discussed the issue of a possible European involvement in this ambitious project, in the difficult context of a revised and more flexible implementation of the Horizons 2000 Programme. As a result, the Space Science Advisory Committee (SSAC) recommended to set up an ad-hoc team, the NGST Task Group (NTG), comprising a small number of European Astronomers, supported by ESA personnel, to assess the technological developments related to NGST in the context of high priority scientific programmes. Emphasis was placed on opportunities for a sufficiently visible albeit not unrealistically costly European involvement.

The NTG activity extended over the period from April to September 1997 during which the group held four meetings at ESA HQ. The group took a comprehensive look at the possible areas for European involvement. With due consideration given to the programmatic constraints, the NTG evaluated the scientific and technical interest of the European Astronomy community and identified three main areas for further studies, a mission based on lower background orbits and on the usefulness of solar electric propulsion, the scientific instruments and a deployable telescope. This preliminary report does not claim to cover all the scientific areas of interest towards a European participation in NGST : in particular, in the area of instrumentation, emphasis has been given here to integral field spectroscopy, a domain of great interest for NGST, in which Europe is playing a leading role. Of course, other types of scientific investigations remain open and could be considered.

In order to maximize their return, the studies recommended by the NTG in the present report should be coordinated as soon as possible with NASA in the context of NGST's preparatory activities.

This report summarizes the analyses and the conclusions reached by the NTG.

The members of the NGST Task Group were :

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The terms of reference of the NTG were as follows :

- provide an independent assessment of the overall NGST programme (including the cost aspects) by verifying the technological choices in connection with the scientific priorities. In particular, assess the risk reduction and performance implications of alternative technological choices (e.g. a monolithic primary mirror vs a deployable one) and of alternative launchers (e.g. Ariane 5 vs Atlas II);

- identify possible areas for ESA involvement taking into account the multiwavelength availability or development of European astronomical facilities;

- advise ESA on technological developments of interest to European Industry and to other ESA projects;

- monitor the NGST programme evolution in the US and provide timely information on technical and scientific progress;

- report to Advisory Bodies and ESA on a regular basis.

2. A brief scientific overview

Understanding how galaxies formed and evolved is one of the major issues of current astrophysical research. We have yet to reach look-back times corresponding to the epoch of galaxy formation. Existing cosmological models are still largely unconstrained by direct observations at high redshifts, while their predictions have become more and more detailed. We need to push our observational limits to probe the universe at greater depth and observe large samples of the progenitors of galaxies like our Milky Way, to be able to understand the complete sequence of events that has led to the galaxies that we know today.

Another topic of major interest is the mapping of the universe at various epochs. The cartography of galaxies in the neighborhood of our galaxy has revealed that galaxies are distributed in sheets, walls, groups, clusters and super-clusters. All these structures have evolved under the gravity induced by the mass distribution. The sequence of evolution is here again poorly known and the early stages of structure growth are critical to our understanding of the evolution of the universe. Maps of vast volumes of the universe at epochs spanning most of its life are critically needed to make progress.

When and how are galaxies formed ? How are the building blocks of large scale structures assembling over time ? Answering these questions can only come from a new generation of large observatories in space. The current pace of technological development for astronomy on the ground and in space is prodigious. The Hubble Space Telescope has provided extraordinary pictures of the universe, and new very large observatories on the ground are now becoming operational for detailed analyses of remote galaxies. However, atmospheric absorption and image distortion are limiting the penetrating and resolving power of large ground based telescopes, while the Hubble Space Telescope has too small an aperture and reduced infrared capabilities. A significant leap in our exploration of the universe can only come from a very large, 8 meter aperture class telescope, in the cold environment of space. This time machine will allow to probe out to the origins of galaxies.

These arguments led to the Next Generation Space Telescope concept as presently studied by NASA. Europe has a consistent record of excellence in many fields connected with the NGST, both scientifically and technologically. European astronomers have conceived and operated some of the major space observatories dedicated to study the heavens. They participate currently in the HST and they are operating some of the major ground based observatories while putting into operation the largest telescope in the world, the Very Large Telescope of ESO.

The access to these excellent facilities has allowed Europe to claim a greater share of the outstanding science output over the past several years. In particular, the field of cosmology has benefited enormously from these developments, and very significant results have been obtained by European teams in the areas of galaxy evolution, AGNs, large scale structures, etc. This collective expertise has built a solid technological and scientific foundation upon which European participation in the NGST can be firmly anchored.

3. European expertise and potential contributions to NGST

3.1 Introduction

Over the last decades, Europe has developed considerable expertise in many areas relevant to an ambitious space project such as NGST. In the first phase of the study, the NGST Task Group (NTG) has taken a wide look at all the possible areas for a European involvement based on scientific and technical considerations only. Thus, in this early phase, NTG did not take into account constraints such as a predetermined maximum financial participation, level of visibility of the European involvement, participation of as many ESA member states, as possible etc. Figure 3.1 shows a block diagram of the overall NGST system, and the many areas of possible European involvement as identified by the NTG. The following sections highlight all these areas in various degrees of details.

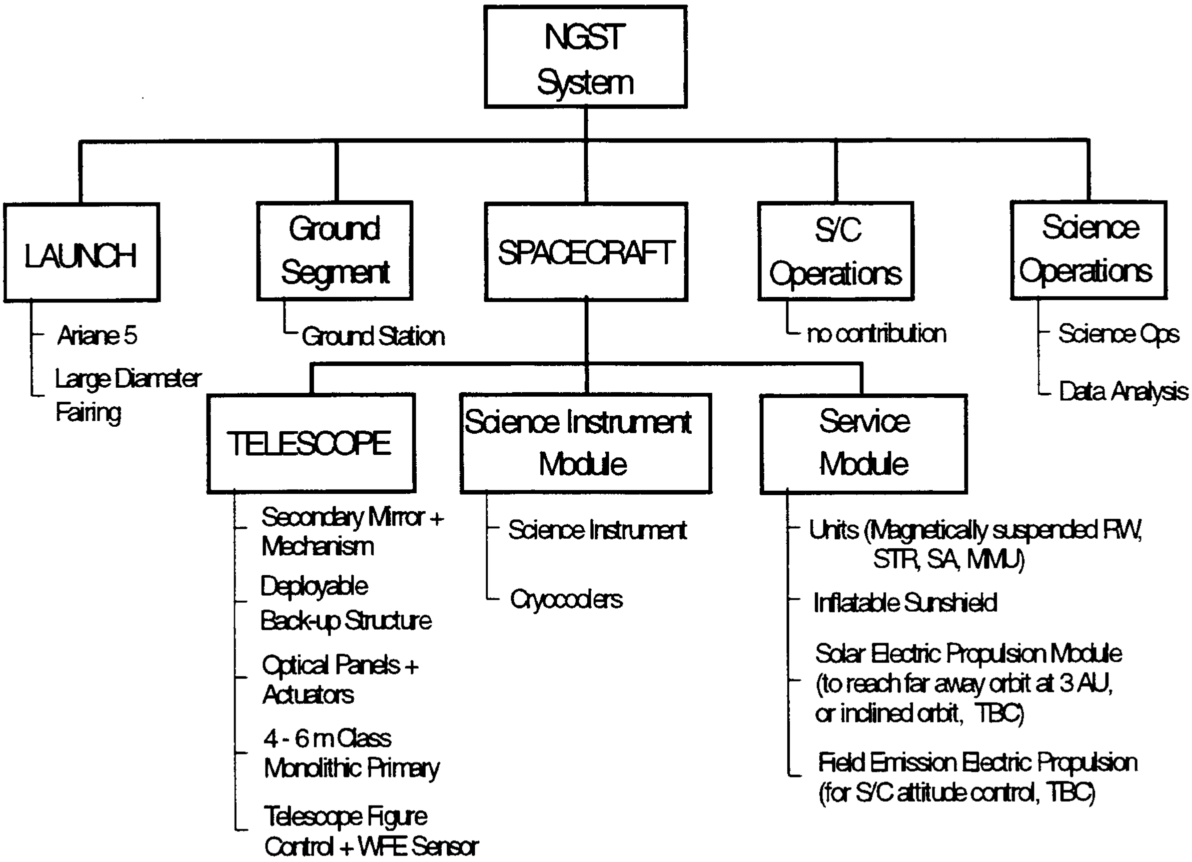

Figure 3.1 – *Possible European contributions to NGST*

3. 2 European expertise in instrumentation

Since the sixties European astrophysics has expanded both in its international impact and in the capability to build major facilities and instruments. Besides ESA’s participation in HST, in particular with the Faint Object Camera, many space astronomy missions have been successfully exploited such as IUE, IRAS, ROSAT, Hipparcos and ISO. Several more are in their developement or preparatory phase, XMM, INTEGRAL, FIRST, Planck. Many ESA member states are in the vanguard of ground based large telescope building in both the VLT and Gemini projects. These achievements build on the outstanding contributions made by European 4m class telescopes : AAT, Calar Alto 3.5m, CFHT, NTT, UKIRT, WHT and ESO 3.6m. Through these developments European institutions have acquired a long-standing capability in the development and operation of world class instrumentation. There exists in Europe a lively cadre of astronomical instrument builders that are ready and able to contribute to the scientific success of NGST. In many fields European groups lead the world eg. in the construction of panoramic combined imager spectrographs in the ultra-violet, optical and infrared.

The scientific and technical expertise for European groups to provide a state-of-the-art instrumentation suite on the NGST is in place. In Chapter 4 we have focused particularly on the potential of integral field spectroscopy, a technology in which European groups lead and which is a natural technique to exploit the high angular resolution and low background provided by the NGST.

3.3 Telescope

In Europe there exists extensive experience in building large actively controlled ground-based telescopes and Europe is leading in this field. In addition, especially within the framework of the preparatory programme for FIRST, a number of developments concerning technology for large space telescopes have taken place in Europe over the last decade. Among these are the following which could be applicable to the NGST telescope:

- Deployable Telescope Technology

Up until July 1990 the baseline telescope for FIRST was an 8-meter diameter Cassegrain telescope with a deployable primary, designed such as to fit in the 3.65 m diameter Ariane 4 fairing. A study by Dornier, in cooperation with Sener, established as a preferred concept, the inclined panel concept consisting of a central sawblade-like dish with a maximum outer diameter of 3100 mm and 16 panels each on a single one degree-of-freedom hinge. Once deployed it provides a fully circular filled aperture. For FIRST, the panels consisted of Carbon Fibre Reinforced Plastic sandwich panels supported by a truss backing structure. Such a concept could be envisaged for NGST, but of course, an actively controlled optical surface would have to be provided on top of the backup panels (glass, nickel, beryllium, etc). A mockup was built consisting of a central part and of two panels, including hinges, latches, drives, etc. After the decision to decrease the FIRST telescope diameter to 4.5 m (which eventually became 3.5 m) the technological activity on the deployable concept was discontinued. This concept has the advantage over the proposed deployable NGST concepts that it minimises the deployment complexity through the use of simple one degree-of-freedom hinges and provides a fully filled circular aperture.

- Lightweight Deformable Mirror

In an ESA-funded study from 1987 to 1990, Matra Marconi Space (France) has studied a 4 m diameter active mirror for space applications operating at wavelengths down to 0.5 µm. In that study, the mirror consisted of a stiff backing structure supporting a thin (20 mm) solid Zerodur meniscus via 250 actuators equidistributed across the mirror surface, the mirror shape being monitored in orbit with a Shack-Hartmann wavefront sensor whose output is processed for calculating the 250 point forces to be applied for correction of the mirror. In order to validate the thin mirror realization technology and the mirror control loop, a demonstration mirror was successfully realized with the recommended “thinning after polishing” technique : it was a Zerodur meniscus of 820 mm diameter, thickness 5 mm and radius of curvature 5 m. The mirror was supported by 30 motorized actuators, 81 manual actuators, initially devoted to gravity compensation and 3 fixed points at the mirror edge. The actively corrected mirror using all 111 actuators showed a wavefront error of Mon, 2 Oct 1905/10.

In fact, the NGST concept proposed by Roger Angel (Lockheed study) for a 6-m diameter monolithic telescope is basically identical to the MMS concept although the proposed thickness of the meniscus is much less (3 mm) in order to save mass.
In addition, Europe has pioneered the technology of actively corrected mirrors for ground-based applications :

1) In the 80's ESO developed a 1 m diameter, 20 mm thick active mirror which served as demonstration model for the 3.5 m diameter mirror of the New Technology Telescope which is in operation in Chile since 1989. The Very Large Telescope (VLT) now about to be completed, is based on the use of four 8 m diameter, 175 mm thick mirrors, controlled by 150 actuators.

2) The Gemini telescopes have “thin” meniscus mirrors similar to those of the VLT. The entire support system including its control and guiding and acquisition unit was developed by UK laboratories and industry.

Considerable experience therefore exists in Europe, not only in the field of optical technology but also in that of figure control. Sensing concepts and algorithms developed for ground-based applications can be easily used for a space-based active mirror.

- Servo-controlled lightweight mirrors

There exists a long standing experience in using lightweight servo-mirrors for space- and ground-based applications. Dornier recently developed the secondary mirror units of the VLT. These units are based on 1.2 m lightweight beryllium mirrors controlled over 5 degrees of freedom including two fast tracking tilts.

- FIRST Telescope Backup Technology

Although at present it is envisaged that NASA provides the telescope for FIRST, various technologies are being investigated in Europe within the framework of the FIRST telescope development. Among these, the most promising is the SiC technology and MMS (France) has nearly completed a 1.3 diameter SiC demonstrator reflector. In addition, Dornier/IABG have developed the C/SiC technology to produce ultra-lightweight mirrors. Although not required for FIRST, previous experience has shown that SiC and C/SiC mirrors can be polished to optical quality and a light-weight SiC or C/SiC mirror could possibly be envisaged as secondary mirror for the NGST telescope.

- XMM Mirror Technology

Media Lario has successfully employed the replica technique by nickel electroforming over an optically finished mandrel in order to produce thin and light-weight mirror shells for X-ray projects like SAX, JET-X and XMM. Such ultrathin face sheets could be envisaged as the optical panels for the NGST primary mirror.

Possible European contributions to the NGST telescope : a summary

Given sufficient resources in terms of development time and money, Europe would be technically capable of providing a complete telescope for NGST. However such a major contribution does not seem to fit within the constraints set by the fact that NGST will be a NASA-led mission with limited ESA contribution and an envisaged launch in 2007.

However, based on the above summary of European developments with respect to large telescopes (in space), it is well conceivable that Europe contribute parts of the NGST telescope, with NASA being responsible for the overall telescope.

Possible ESA contributions of such “parts” which could be envisaged are listed below:

a) Provision of the secondary mirror with its linear and angular position control mechanism

The secondary mirror could be based on the aforementioned SiC technology, but also Beryllium or light-weighted glass-type mirrors could be possible candidates since there exists experience on these types of mirrors in Europe. The mirror adjustment mechanism, which has to operate at cryogenic temperatures would constitute a new development but experience from other mechanism developments in Europe could be used. Recent studies in the US seem to show that actuators can accurately be made to work under cryogenic conditions.

b) Provision of the deployable back-up structure for a deployable 8-m class telescope

The deployment concept could be based on the inclined-panel Dornier development for FIRST with the necessary adaptations for operation at cryogenic temperatures and in-orbit fine panel adjustments necessary for telescope figure control.

c) Provision of the optical panels for a deployable telescope and their actuators

In the concept of an actively controlled primary mirror it could be envisaged that Europe provide the optical panels which will be mounted on the back-up structure via actuators. The panel and figure control concept could be based on the deformable mirror technology as developed by MMS, where a full-size thin glass-type shell would be produced which, by water-jet cutting would be cut in panels in order to guaranty equal radius of curvature of all panels. As a second possibility the thin nickel shell technology as developed for X-ray mirrors could be considered.

The cryogenic actuators for mirror figure control would constitute a new development but could be based on already existing technology.

d) Provision of a 4-6 m class actively-controlled monolithic primary

Such a mirror would be based on the MMS light-weight deformable mirror concept, which has also been proposed by Roger Angel in the Lockheed study.

It is clear that a monolithic mirror is the cheapest and minimum risk solution, however, its maximum size depends on the maximum fairing diameter of the launch vehicle. The largest shrouds currently available can accommodate payloads approximately 4.5 m in diameter. Larger monolithic mirrors would require the development of larger shrouds. However, placed in a low-background orbit far from the Earth (3 AU), a 4-m class telescope could possibly be acceptable: further trade-offs are to be studied in this case.

e) Overall telescope figure control

Finally, based on experience in Europe with ground-based actively-controlled telescopes and on the experience gained during the deformable mirror activity in MMS, which also included the development of a Shack-Hartmann wavefront sensor, it is conceivable that Europe provide the telescope control including the wavefront error sensor. Europe could also provide the actuators if need be.

Any of these contributions would constitute an important aspect of the NGST telescope and as such, European participation would be very “visible”. In addition, possible future European astronomy missions requiring large, precise telescopes in space would benefit from the developments started in the framework of a European contribution to the NGST telescope.

3.4 Spacecraft

The NGST spacecraft may in fact be considered to consist of three modules/assemblies :

- the telescope itself;
- the science instrument module accommodating the science instruments;
- the service module providing the normal services such as power conditioning and supply, attitude control, data handling and communications.

While the telescope issue has been considered in the preceding paragraph (3.3), whereas a possible European instrument is described in Chapter 4, the present paragraph concentrates on the service module.

Relatively small European participation in the NGST Service Module could be envisaged by provision of **specific units** with simple interfaces such as magnetically suspended reaction wheels (not available in the US), startrackers, solar array or solid state recorder. Such contributions would only constitute a minor share in NGST and would not enhance the mission or be very visible.

Another possibility for participation in the NGST Service Module is the **sun shield**. Most NGST options studied so far use a very large inflatable or deployable sun shield to protect the telescope and science instrument module from direct solar radiation.

Since 1979 Contraves has developed the technology of inflatable space rigidised structures under a series of ESA contracts. This technology aims at the realisation of large expandable structures of low mass, high stiffness and high packaging efficiency. Although development activities were concentrated on two applications, i.e. antenna reflectors and truss type structures like the FIRST thermal shield, the technology is quite flexible and can be applied to a wide range of geometrical configurations not requiring high in-orbit accuracy and stability.

European participation in NGST could be envisaged also by the provision of a **Solar Electric Propulsion Module (SEP)**. Such a separate propulsion module could be used to attain a more favourable orbit with regards to the zodiacal light, like a 1AU * 3AU orbit or orbits inclined to the ecliptic. Detailed analyses will be required to assess the potential of solar electric propulsion for NGST.

Several ion thrusters are available in Europe for such an application. The Radio-Frequency Ion Thruster (RIT), a German development, was flight tested on the Eureca platform and is presently being qualified for use on Artemis. The Stationary Plasma Thruster (SPT) developed by FAKEL in Russia has been successfully used on several Russian spacecraft and SEP in France is presently commercialising this thruster in Europe. Other developments are underway in Europe.

Finally, the use of **Field Emission Electric Propulsion (FEEP)** as developed by ESTEC/Centrospazio is worth considering for spacecraft attitude control as it could eliminate the need for reaction wheels which are the main source of microvibration aboard the spacecraft. The feasibility of using FEEP for attitude control depends on the magnitude of the disturbing torques and the slew requirements.

3.5 NGST Operations

Apart from experience in the operation of its own astronomy satellites, ESA has experience in sharing part of the operations with NASA in two major cases, IUE and HST.

In the case of IUE, the share regarded the entire operation, including the ground segment, the data processing and the archive. The coordination was extremely successful to the point that,

after the decision by NASA to discontinue to support IUE operations, the European segment was able to assume the entire responsibility for the IUE project. The ESA/NASA collaboration on this project is continuing on the production of the IUE Final Archive. In the case of HST, the collaboration which is most relevant for the NGST, is the one provided through the ST European Coordinating Facility. Indeed, since its constitution in 1984, the ST-ECF, as a mixed ESA/ESO Group, have been exposed both to the scientific operations of the HST and to the evolution of the operations of large ground facilities, as the ESO VLT.
In particular, the ST-ECF participated directly in the development and operation of the initial HST' archive system which was jointly developed by the ST-ECF and the STScI. Support was also given in the development of the HST scheduling engine. More recently, new concepts in the operation of the calibration pipeline and of the archive were independently developed by the ST-ECF. Particularly relevant to future projects is the use of realistic software models of the scientific instruments in the calibration and quality assessment of the data (for example, the model of the HST Faint Object Spectrograph, developed by the ST-ECF, was essential for a correct evaluation of the scattered light affecting the spectral background). A similar model is now being developed for the new STIS Instrument for which a "direct" traditional calibration of all its observing modes would be too expensive in terms of calibration observing time. It is now planned to integrate the Instrument modelling concept in the HST Archive.
When ESO started to design the VLT Operation System, it became clear/that the different modules which are needed for the operation of a complex astronomical facility (Phase I & II proposal preparation, scheduling tools, routine instrument calibration, performance monitoring, scientific archive operation) cannot be developed independently from each other, even if a detailed interface was defined. On the basis of the ST-ECF "hands on" experience, ESO designed for the VLT a "data flow end-to- end" model which is currently being implemented by its Data Management Division.

Naturally, because of the technological evolution, more advanced software design techniques (Object Oriented Methodology) have been adopted for a more transparent design, easier maintenance and easier possibility of modifications and evolution of the system, on the basis of growing experience. The local experience of the ST-ECF, which had to accommodate 4 major upgrades of its archive system since its first implementation, was instrumental in having modularity and flexibility as major guidelines in the design of the VLT system.

Because of its orbit, NGST operations are much more similar to a VLT-type Observatory than to HST. Actually, while the large ground facilities (VLT, Gemini, ...) will have to accommodate fast changes of schedule in order to take full advantage of the changing seeing conditions, NGST will enjoy more stable observing conditions and, because of pointing constraints, much less frequent slewing manoeuvres.

Because of this similarity, a natural area of collaboration between ESA/ESO and NASA on the NGST, is the development of its "data flow" system. In fact, by the time NGST flies, VLT will have been several years into routine operation. Because of its highly modular design and because it will have gone through severe operation testing, the VLT system seems ideal for being used as the basis for the development of a NGST operation environment. The only module which would need to be developed specifically for the NGST, is the telescope/instrument operation, the rest (proposal handling and preparation, scheduling, calibration, archive, etc.) can just be re-used with minor adaptation.

An additional advantage of this approach is that the implementation can start ~ 2 years from launch, avoiding early investment in hardware and software which otherwise can rapidly become obsolete.

Although not functionally required, a share of NGST operations between two ground segments in the US and in Europe (similar to the IUE concept) is a possibility which could be considered, particularly if NGST will be in a L2 orbit.

3.6 Launch

The provision by ESA of a standard Ariane 5 launch vehicle for NGST is the simplest way of contributing to NGST. It minimises technical and management interfaces and could have advantages for the NGST mission and in science. However, as was already noted by SSAC, it is not the most attractive way to participate in the project. It would not provide a scientifically visible role of Europe in NGST, and it would not stimulate European industry in the development of new and challenging technologies which also might be of benefit for future ESA missions.

There are however several advantages of using an Ariane 5 launcher for NGST. The most obvious one is the increased payload capability in terms of mass. The Atlas IIAS launch vehicle, which was adopted as the baseline launcher in the NGST studies conducted in the US, allows for a spacecraft mass of approximately 2800 kg, assuming an orbit around L2. Ariane 5 could launch a much larger total mass (about 4600 kg(1)). Although the US studies concluded that the Atlas capability would be sufficient, margins are rather small and would require a severe and costly mass control policy during later stages of the project.
The US studies have chosen an L2 orbit as baseline; other possibly interesting orbits could be envisaged if an Ariane 5 launcher were used, e.g. in combination with solar electric propulsion as described already. For example, an orbit with aphelion at 3 AU has important scientific advantages as it would eliminate most of the infrared “foreground” radiation due to the solar system’s zodiacal dust. The Atlas capability into such an orbit is approximately 1760 kg, while Ariane 5 would allow for a spacecraft mass of about 2500 kg[1]. As such far-away orbits have other technical problems (power, telecommunications), 1 AU orbit, inclined to the ecliptic are another alternative not suffering from these technical problems and still offering a significant reduction in zodiacal light for inclinations in excess of 10%. The Atlas capability into a 10%-inclination orbit at 1 AU is 1540 kg while Ariane 5 could place a spacecraft of about 2200 kg[1] into such an orbit.

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[1] values to be checked, in particular after the launch of Ariane # 502

4. Instrumentation for the NGST: a European perspective

4.1 1-5 μm spectroscopy with the NGST

Instrumentation for the NGST should reflect the goals of its core science program: to study distant galaxies, at z>2 , their structure and dynamics, their evolution, and to use this knowledge to form a comprehensive picture of the early evolution of the universe, including the formation of the first stars and galaxies. The operating wavelengths encompass the range 1-5 μm, wavelengths at which the rest-frame visible light from these highly red-shifted objects is observable. To carry out its scientific goals, NGST needs to obtain spectra of a large number of galaxies with as high an efficiency as possible. Consequently, the suite of instruments should make it possible to conduct detailed spectroscopic surveys of large parts of the sky to very faint levels, taking advantage of the high sensitivity and extremely low background of the NGST.

We have informally evaluated the scientific interest of European astronomers and investigated the potential interest of instrumentation groups and concluded that a spectrograph with multi-object and integral field capabilities would be highly desirable scientifically. Furthermore, this is an area where European groups lead technologically. In this chapter, we outline the types of spectrographs (paragraph 2), generic advantages of integral field spectrographs (paragraph 3), list the type of scientific investigations they can address (paraprah 4), review the work at present underway (paragraph 5), define areas where technology development is required to construct a successful NGST instrument (paragraph 6) and finally outline the specifications of a possible NGST instrument. The appendix provides details of integral field instrumentation efforts in Europe.

4.2 Choice of spectrographic instrumentation

Instrumentation to carry out spectroscopic studies of a large number of objects falls into two categories: multi-object spectrographs and integral field spectrographs. Some multi-object spectrographs use a fiber-laying robot (e.g. 2dF at the AAT) to position the multiple apertures in the field of view. While this approach makes very efficient use of detector area, it is ill-suited for adaptation to space telescopes. The other commonly used approach is to create a slit-mask with multiple slits coincident with source positions, which is placed at the telescope focus (e.g. LRIS at Keck, MOS at the CFHT).While this approach is viable for space telescopes, it suffers from excess background and rather inefficient use of detector area. Furthermore, the multiplex gain which can be achieved is limited in dense fields, where the spectra tend to overlap. In view of these constraints, we felt that an integral field instrument would be better suited to the requirements of the NGST. However, our choice is a subjective one, and should not be viewed as a design constraint on possible instrument developments. It is likely that multi-slit and integral field designs could be combined in the NGST instrument payload to maximize versatility and efficiency. The rest of this chapter, will, however, concentrate on integral field instruments.

4.3 The advantages of integral field spectrographs

The concept of an integral field spectrograph centers on the desire to map spectroscopically reasonably large contiguous areas of sky, over extended wavelength ranges, at a variety of resolutions. Scientific applications such as the kinematic mapping of galaxies (to search for black holes or halos; the mapping of emission lines in AGNs (to identify the source(s) and nature of the ionizing radiation) are well served by such a concept. A pioneering project was the TIGER instrument at CFHT which measured the mass of the black hole at the center of M31. In the infrared these kinds of studies can be extended to dusty environments such as the nuclei of spiral galaxies (that possibly harbour black holes), to regions in which stars are forming today and to the distant universe where many of the useful diagnostic lines are shifted into the infrared. They offer several generic advantages over conventional spectrographs some of which are especially valuable for operation in space.

1. Simultaneous spectra of a two dimensional field with 100 % filling factor can be taken in a single exposure.

2. They incur no slit losses, collecting all the light from an extended object in a single exposure.

3. As one can routinely recover an image of the object after observing, there is no requirement to place the slit exactly on the object. At the high angular resolutions at which the NGST will work, particularly in obscured regions, this simplifies acquisition considerably.

4. The interpretation of spatially resolved spectra with respect to an image is straightforward.

5. The spectral resolution is limited not by the size of the region of sky studied but by the of the subapertures into which the image is divided.

6. The high multiplex gain in dense fields, simultaneous background determination, and effective use of limited detector area provides substantial efficiency gain over conventional spectrographs.

4.4 Scientific Programmes for an Integral Field Spectrograph on NGST

4.4.1 Panoramic spectroscopy of faint field galaxies

The observations of the Hubble Deep Field (HDF, Williams et al, 1996) have dramatically shown that even a field which appears relatively empty in shallow surveys is densely populated at faint magnitudes. More than 200 galaxies are detected per arcmin^2 to I=26. These faint galaxies can be used to trace the history of star formation in the universe in the last 10 billion years (see e.g. Madau, 1997). The Hubble observations were done in broad bands from the UV to 1 µm. The density and nature of objects to be found in an equally deep infrared survey are still unclear. The deepest ground-based imaging surveys have reached K, which is sufficient only for the strongest IR emitters.

The picture is going to change in the near future as observations made with NICMOS of small fields and with wide field instruments at 8 to 10 m class telescopes will push the limit by more than one order of magnitude. By using both the optical and infrared data we want to answer the crucial questions:

1. What is the history of star formation ?

2. To what extent does dust affect the luminosity function at the different epochs?

3. What is the fraction of evolved stars, and hence the evolutionary history of different types of galaxies? The infrared observations are essential to clarify this question and to assess the stellar mass for systems at z Æ 1.

4. What is the earliest epoch of galaxy formation? The IR is needed to push the limit of detectability to $z > 4.5$

In all these cases, infrared spectroscopy is required up to a limiting magnitude that only an NGST can provide. Additionally, the telescope will extend by more than 4 mag. the depth of broad band surveys at the same wavelengths obtained by any 8 m class telescope on the ground.

The galaxy density at infrared wavelengths for K ~ 26 is expected to be close to the value observed in the I band by the HST and ground-based visual-red surveys. This high galaxy density creates severe problems for traditional long slit or multi-slit spectroscopy, as several slit configurations will be required to cover all the galaxies, and most slits are very likely to include the main target but also nearby contaminating objects which could affect the background correction. An Integral Field Spectrograph with subarcsec angular resolution and up to 120"x120" field as tentatively outlined in this document would allow us to gather simultaneous information on all objects in the field to the required magnitudes and still obtain a good sampling of the background. The spectral resolution required for this application is ~ 200. Higher values (R up to 3000) would be desirable for the study of emission line objects. An illustrative application of IFS in dense fields is shown in figure 4.1 which shows the Hubble Deep Field as will be viewed by the VLT VIRMOS-IFU, with 6500 elements covering 1 arcmin^2.

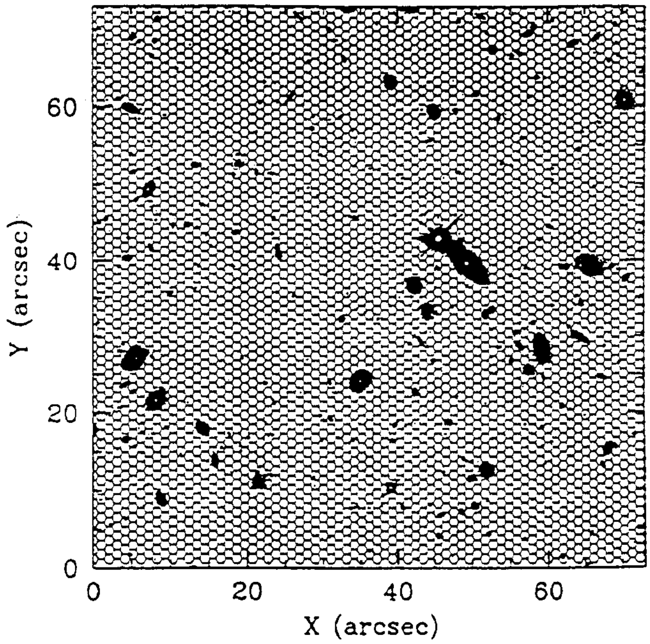


Figure 4. – *A section of the Hubble Deep Field as will be imaged with the VIRMOS integral field unit. It will provide 6500 spatial resolution elements spanning 1 arcmin^2.*

4.4.2 The evolution of the fundamental plane

An Integral Field Unit (IFU) with the high spatial resolution of the NGST will allow us to obtain spatially resolved velocity information on very distant galaxies. The size of z ~1-3 galaxies is typically 1-2 arcsec. With a resolution element of 0.1-0.2 arcsec, one can hope to obtain ~ 100 velocity measurements per galaxy, enough to derive a velocity field (e.g. Kelson et al., 1997). The construction of the fundamental plane thus becomes possible out to very large redshifts. This calls for diffraction limited sampling of a small area of sky at R ~1000.

4.4.3 The distribution of star formation inside galaxies at large z

The evolution of the star formation rate, as determined from deep ground based redshift surveys (Lilly et al, 1995, Le Fevre et al., 1995, Ellis et al., 1996, Steidel et al., 1996), indicates that the peak of star formation is probably in the redshift range 1.2-2.5 (Madau et al., 1996). The identification of the main physical phenomena at play remains unclear. The passive evolution of stars, the fading of galaxies after the first burst of star formation, the successive mergers and interactions, and the link to the central AGN, all could combine to produce the effect seen, on e.g. the luminosity function. The NGST will enable us to quantify the relative importance of these phenomena (and possibly unveil others), from the location of the sites of strong star formation in very distant galaxies. Is the star formation confined to the core, or proto-core? Is it evenly distributed in the (proto)-disc, or in clumps? Or is it located at the sites of strong interactions between galaxies or triggered by major or minor mergers? Spatially resolved spectroscopy is critical to address this issue. This work calls for the detection of emission line regions over small areas and considerations of detectability again suggest working at the diffraction limit at R~1000. Figure 4. 2 shows complementary studies of nearby clusters using IFUs at ground based telescopes.

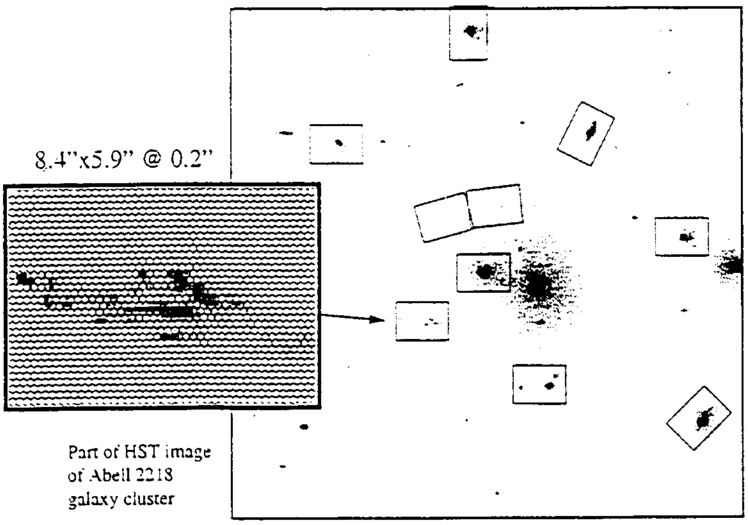


Figure 4.2 – *Integral field spectroscopy of the Abell 2218 cluster, as will be performed by the GMOS Integral Field Unit (IFU) at the Gemini telescopes. Ground based studies of nearby clusters will complement observations of high redshift galaxies made with the NGST.*

4.4.4 The evolution of the mass function of galaxies

Considerable progress has been made in the use of the weak gravitational shear to obtain mass and mass distribution estimates for clusters as well as for galaxies. At the resolution and depth of the NGST, weak shear measurements, coupled with redshift measurements of the deflectors, will allow the mass function of galaxies out to the largest redshifts to be measured. This application requires a spectral resolution R~ 200, but with the widest field of view possible.

4.4.5 Distant clusters of galaxies

The evolution of clusters of galaxies remains poorly known beyond z= 0.5. The NGST will allow us to conduct detailed observations of a large number of distant clusters to study (i) the evolution of the comoving cluster density, of fundamental importance to constrain cosmological models, (ii) the evolution of the dynamical properties (assembly of clusters vs. time), (iii) the evolution of the mass distribution from virial and strong lensing analyses, (iv) the evolution of the cluster galaxies, in a high density environment to be compared with the evolution of field galaxies. These cluster observations require wide field coverage, albeit at low spectral resolution.

4.4.6 Detecting black holes in AGNs

In the past couple of years, evidence has been mounting for the presence of super massive black holes in the nuclei of normal and active galaxies. Both gas kinematics (e.g NGC 4258, Miyoshi et al. 1995) and stellar dynamics (NGC 3115, see Kormendy and Richstone 1995 for a review) have been effectively used to probe the gravitational potential in the nuclear regions of galaxies. NGST, with its high resolution at near infrared wavelengths, will allow us to conduct such observations for normal galactic nuclei which are obscured by their dusty disks at visible wavelengths. Indeed, if the quasar population, peaking at z~2, represents a phase in the life of every galaxy, most nearby galaxies should harbour dark masses greater than a million solar masses. At the other end of the redshift range, NGST could probe galactic nuclei at z>2, looking for the progenitors of quasars.

For nearby AGNs the NGST would provide spatial resolution close to the postulated limits for the dusty molecular tori surrounding the central dark mass, which lie at the center of AGN unification theories. NGST observations would dramatically improve our understanding of AGN physics, including the relationship between tori and jets, the link between the BLR and NLR, collimation mechanisms and nuclear fueling. Detailed studies of AGNs require observations at the telescope diffraction limit, with a field of view large enough to cover the entire nuclear region (4x4 arcsec), with a spectral resolution exceeding 2000.

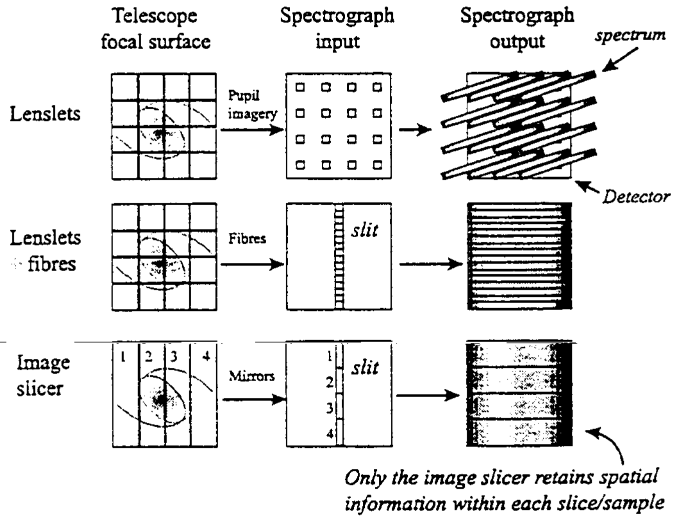
4.4.7 Proto-planetary disks

Stars in their early phases of evolution are surrounded by envelopes and disks with typical sizes of ~500 AU. These disks are, in particular in the earliest phases of the stellar life, dense enough to obscure the central object. TTauri is another, more typical, example of a (Young Stellar Object) YSO, in this case a binary system, surrounded by diffuse material (Herbst et al. 1996). The angular sizes of the disks range from 0".1 to 1" at typical distances of nearby galactic star forming regions. Using NGST, we will therefore be able to separate the disk/envelope and their associated gas jets from such young stars thus allowing us to study separately the evolution of both components relative to each other. The complex spatial and dynamical structure of these disks and envelopes require integral field spectroscopy in order to determine the velocity structure of the stellar environment and other quantitative parameters like dust and gas masses. The obscured central, sometimes multiple, star itself often can only be studied and characterized in light reflected and scattered by the envelope. It will be possible for the first time to characterize these stars and compare them with theoretical pre main sequence evolutionary tracks.

4.5 Integral Field Spectrographs

4.5.1 Image slicing techniques

There are three main types of integral field spectrographs that are characterized by the method used to map the plane of the sky into the spectrograph:



Only the image slicer retains spatial information within each slice/sample

Durham University AIG

Figure 4.3 – *The three main techniques of integral field spectroscopy*

1.a **Lenslets only**: The input to the spectrograph is a series of pupil images formed by a lenslet array placed close to the telescope focal plane following an enlarger system. The problem of overlap between the spectra is alleviated by tilting the dispersion axis slightly with respect to the principal axes of the lenslet array. The archetypical system is TIGER (Bacon et al., 1995) (figure 4.4). These designs are the simplest examples of integral field spectrographs but although they permit a large number of sub-apertures to be observed at once the length of each spectrum is limited.

1.b **Lenslets + Fibres**: By combining the lenslet array with optical fibres the patch of sky can be re-formatted into one or more slits to feed a spectrograph. They provide a means to achieve a 100% filling factor and to speed up the telescope beam so as to minimize focal ratio degradation (which otherwise results in non-conservation of étendue leading to loss of spectral resolution). These designs allow more versatile spectroscopy to be undertaken (a wide range of resolutions and numbers of spectra can be accommodated in a single design). The GMOS design (Allington-Smith et al. 1997a; figures 4.2 and 4.5), the VIRMOS-IFU (figure 4.1) and the SINFONI design (figure A.1) adopt this approach.

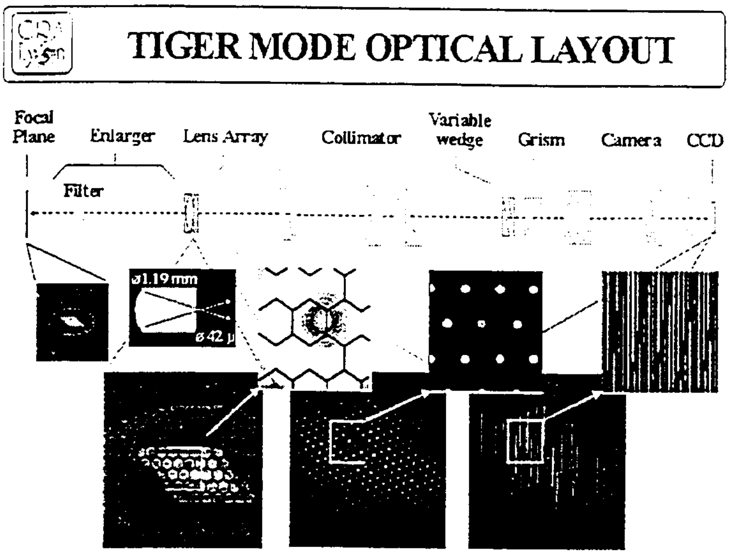


Figure 4.4 – *Illustration of the principle of a lenslet-only integral field spectrograph: TIGER*

(An earlier variant on this theme is the use of unlensed fibres which reformat the field of view into a single fibre slit. But, lacking lenslets, they do not provide a contiguous field and offer less efficient coupling to the telescope.)

3.c **Image slicer**: These designs use arrays of small mirrors (image slicers) to reformat the light from a patch of sky into the spectrograph. These designs provide the highest throughput, but they have large physical slit lengths requiring bulky spectrograph optics. The MPE 3D spectrometer (Weitzel et al., 1996, figure 4.6) pioneered this technique. A recent design (Content 1997) offers enhanced performance within a smaller package.

We summarize the integral field spectrograph projects in Europe underway and planned in the table in the Appendix. Further details of each instrument are also present in the Appendix.

4.5.2 The detectors

The Integral Field Spectrographs discussed above will operate in the 1-5 μm spectral interval, which is the primary choice of wavelengths for the NGST. At these wavelengths, the preferred detector is an InSb array which has high efficiency through the entire region. Arrays of this type in the format 256x256 have been used for astronomy for some time. They are manufactured by SBRC in the USA but in Europe both ESO (Finger et al., 1996) and ROE (Puxley et al. 1994, Sylvester et al. 1997) have extended experience in their characterization and testing.

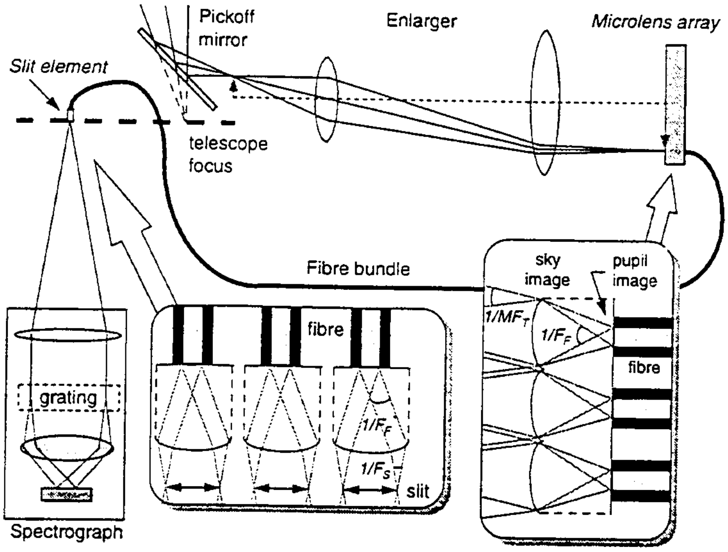


Figure 4.5 – *Illustration of the principle of a lenslet + fibre system : the GMOS IFU*

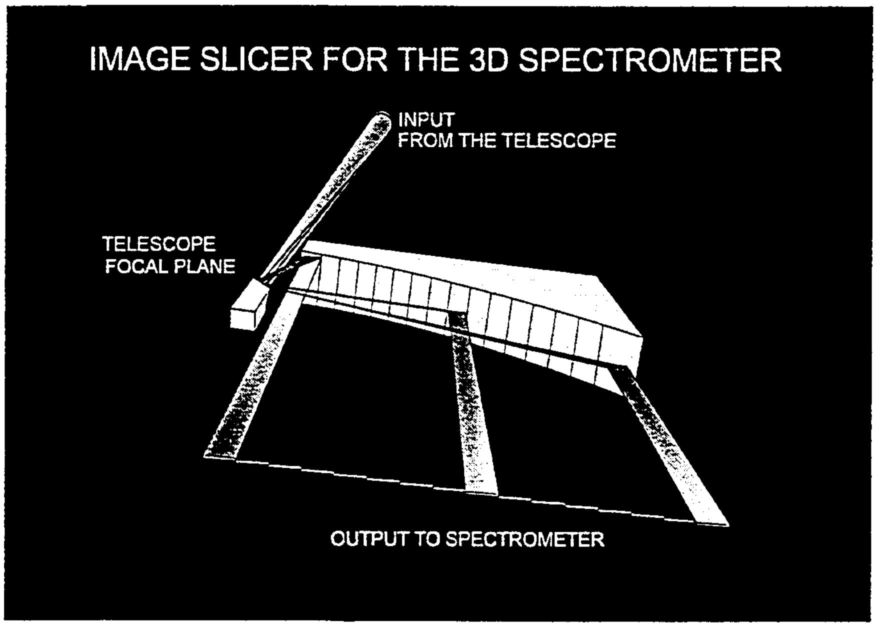


Figure 4.6 – *Schematic diagram illustrating the principle of operation of the MPE 3D Image Slicer*

At wavelengths longer than 2 μm the thermal noise dominates in ground based observations and requires very fast read-out control systems which the two european groups mentioned above have also successfully developed (Meyer et al., 1996; Sylvester et al. 1997). More recently, InSb arrays of the 1024x1024 format (ALADDIN) have been produced and they have been used at selected observatories. This detector would be the building block for larger arrays to be used for the 1-5 µm NGST instruments. The performances (dark current, read-out-noise, efficiency) are sufficiently close to the ones that are ultimately desired. The European groups would have the competence to characterize and integrate these detectors into the instrument and guide manufacturing of the cameras in industry. For the Integral Field Spectrographs discussed above we would require at least one 8096x8096 mosaic and perhaps more. As shown in the NGST report (1997) a modified version of the present 1024x1024 arrays could be used for 2048x2048 mosaics, which could be mounted on a common baseplate with gaps in between for the wiring connections.

The final instrument proposal might envisage a splitting of the 1-5 µm range into two separate optical paths to optimize the coating and material choices and/or to obtain full wavelength coverage. In this case, use of the HgCdTe IR arrays for the range 0.8 to 2.5 µm becomes attractive. The 256^2 NICMOS array of this type has already flown successfully on HST. The same manufacturer has started an RD contract for a 2048 monolithic array. ESO is one of the partners in this contract, the 2048^2 array being the baseline option for the VLT NIRMOS instrument.

For both the InSb and the HgCdTe arrays, it is unlikely that a single 8096^2 monolithic array or a contiguous array mosaic would become available. This will have to be taken into account in the design of the instrument.

4.6 Technological Developments aimed at an IFS for NGST

Technology assessments need to be carried out to evaluate the optimum technique for realizing an IFS in a cold (~30 K) environment in space. Although several different schemes for image slicing have been developed over the last few years, only few of them provide throughputs greater than 90%. The telescope size dramatically affects telescope costs, especially for a space telescope like NGST. Hence, the instrument package must provide the highest possible throughput, utilizing all the light collected by the telescope.

There are several facets of lenslet+fibre systems which may prove problematic in a cold space environment. The fibre/microlens coupling is vulnerable to temperature cycling, although the integrated lenslet+fibre (flared fibre) approach taken by SINFONI shows promise at wavelengths shorter than 2.5µm.

In contrast, the lenslet only systems are relatively simple but require a high quality microlens array. However these systems are limited in terms of the length of spectrum.

The image slicer approach, which potentially offers the best performance, relies on the construction of a multiple-mirror system which requires careful alignment which must be maintained as the system is cooled. The primary problem is the large slit length, which may possibly be overcome by `advanced' designs using complex mirror assemblies.

To summarize, the main technological developments which are required are as follows.

- Development of high-quality monolithic microlens arrays suitable for either the lenslet or lenslet+fibre approach. Present arrays are generally not monolithic and generate too much scattered light. Fused silica is probably the best material forœ 2µm while ZnSe is preferred for longer wavelengths. Monolithic construction is required to combat problems with differential thermal expansion. European industrial manufacturers need to be made aware of these requirements.

- For lenslet+fibre systems, the system must be able to withstand low temperatures and temperature cycling (between terrestrial manufacture/testing and operation in space). Not only is it necessary to examine the performance and robustness of the fibres but also the junction between fibres and microlenses. The latter problem can be avoided by forming the lenslets from the fibre ends themselves (as done for the SINFONI design) or the lenslet/fibre interface adapted to eliminate thermal stress. Further experiments, along the lines of those done for the SINFONI development, need to be carried out.

- The optimum fibre type for transmission over the full wavelength range needs study. Fused silica is the best candidate for œ 2.5 μm. Zirconium fluoride has been used at longer wavelengths but is much more expensive and fragile. Alternative fibre types for the longer wavelengths should be actively explored.

- Although image slicer IFUs have been successfully built and are in operation (MPE 3D), versions of the design to give larger formats and higher resolution while fitting within a small volume have not yet been built. However, developments such as the AIS proposed by Content (1997) (funded for testing a warm prototype at UKIRT in 1999) are now underway. Potential problem areas are the construction of the multiple-mirror system, to maintain alignment of the system during cool-down and the construction of the slicing mirror which requires very thin, optically figured segments.

- The primary wavelength range of NGST will be 1-5 μm. Although a single detector (InSb technology) for this wavelength range is available, there is a severe lack of infrared transmissive materials and broad band anti-reflection coatings which cover the entire range. Further effort toward developing new infrared glasses and broad-band coatings should be strongly encouraged.

4.7 Baseline IFU for the NGST

4.7.1 Modularity of an IFU approach

The IFS concept meshes very well with classical multi-slit spectrograph designs. One may be able to conceive of one single instrument, which will allow the following modes in a confocal configuration:

- Direct Imaging
- Multi-slit spectroscopy (e.g. with multi-mirror)
- Integral Field Spectroscopy

4.7.2 High Level Specifications

In a single exposure, the instrument should achieve the following:

- Field (high spatial resolution mode) 4x4 arcsec^2 (0".03 sampling) required, twice the field and/or finer sampling desirable

- Field (low spatial resolution mode) 1 x1 arcmin^2 (0".3 sampling) required, 2x2 arcmin^2 desirable

- Wavelength Range: 1-5 μm, possibly split into two bands of 1-2.5 μm and 2.5-5 μm

λmax/λmin > 2 required in a single exposure

- Spectral Resolution: R=200 to R=2000 essential, up to 5000 desirable

- Baseline detector 8196 x 8196 pixels InSb mosaic

The largest IFU designed to date is possibly the VIRMOS IFU for the ESO VLT, which has 6000 spatial elements, and uses a 4096x8196 detector. In contrast, the high resolution mode described above has at least 18000 spatial elements, while the wide field mode has at least 40000 spatial elements. A simple comparison of available detector area with the desired number of spatial and spectral elements, keeping in mind that Nyquist sampling requires two detector pixels per resolution element in both spatial and spectral dimensions, shows that detector area has to be used very efficiently. In the wide field mode at low spectral resolution, the number of available detector pixels barely exceeds the minimum number required. Clearly, novel schemes to effectively use the available detector area and/or develop larger array mosaics are required.

4.7.3 Expected Efficiencies and Predicted Performances

The proposed instrument must have a very high efficiency if the advantages of the lower background, higher angular resolution and large collecting area are to be fully exploited. The instrument optical train (including any possible fiber link) should have a transmission higher than 80%. This is a challenging goal because of the difficulty of obtaining high efficiency coatings through the entire 1-5 μm range. Coupling of microlenses to fibers, if needed, is also an efficiency-critical item. The gratings should have a peak reflectance exceeding 80%. A few gratings might be needed if this value has to be achieved through the entire spectral range. Finally, the InSb detectors of smaller size already in operation do have QE higher than 80% over the entire spectral range of interest.

A preliminary performance estimate for low resolution spectroscopy with an efficient spectrograph can be derived using the same approach outlined in the NGST report (1997). For a 6-8m telescope, $\lambda/\Delta\lambda=200$, we could expect to reach a K magnitude of 26 (10σ per resolution element) in three hours.

5. Conclusion and Recommendations

Following the above general analysis, based on the overall block diagram of figure 3.1 illustrating the many possible domains of European involvement in NGST, three main areas for further investigation presently emerge. These are :

1. a mission concept based on the use of low background orbits, alternative to the baseline L2 type orbit;

2. the implementation of an instrument design for multi-object near IR spectroscopy; and

3. the use of European deployable telescope technology.

The NTG believes that these three areas could, taken together or separately, constitute the backbone of a visible ESA participation in the NGST, compatible with a level corresponding to an F-type mission proposed in the new implementation of the Horizons 2000 program.

In order to achieve a valuable, while still realistic, ESA participation in important scientific aspects of NGST, the NTG recommends that ESA initiate, in close coordination with NASA, the following studies :

- a concept study for a 3 AU, or alternative low background orbits, concentrating on their specific problems and critical areas, i.e. launch and transfer, power supply, telecommunications. In addition, scientific trade- offs with the alternative baseline L2 orbits should be conducted;

-two studies on the scientific instrumentation,

one devoted to a single instrument with emphasis on multi-object spectroscopy in the primary 1-5 microns wavelength region, and

one devoted to the definition and design of an instrument suite covering the prime wavelength range (1-5 microns) and a possible extension to the domain up to about 20 microns;

- a study of a complete deployable telescope which should also concentrate on those areas of particular European expertise such that Europe could make valuable contributions to NGST. It is proposed that the study of the complete instrument suite and the telescope study are combined in a single study which will then encompass the complete NGST optical configuration.

The results of these studies should be used in future discussions with NASA to further refine ESA's contributions to NGST and to define the follow-on activities in Europe, compatible with the NASA schedule.

The three studies recommended above should also identify the key technologies which need to be developed for a successful contribution to NGST. They could eventually be used in future ESA space missions, such as the interferometry cornerstone.

Furthermore, and in parallel with the implementation of the above recommendations, ESA should promote European participation in the further developments of the case of NGST through:

1. support of European scientists to enable them to participate in NASA's scientific working groups;

2. sponsorship of an NGST worskhop to be organized in Europe en 1998.

A. Appendix : Integral Field Spectrographs in Europe

Integral Field Spectroscopy has seen a serious boost in use as larger detector arrays have become available. It is now a major part of most new designs on large telescope spectrographs. Europe is playing a leading role in this technology. The following table presents a compilation of all the various projects in Europe - instruments already in operation as well as future instruments with significant development work already underway. A brief description of some of the instruments follows the table.

A.1 CFHT

A.1.1 TIGER

TIGER was one of the first instruments for integral field spectroscopy in the world. It made use of a microlens array inserted in a classical focal reducer, using a grism as the dispersing element. The microlens elements were 0".3 to 0".7 on the sky. This has allowed the spectacular results on e.g. the core of M31 (Bacon et al. 1995). The device produced more than 600 simultaneous spectra for a contiguous sampling of a sky area up to 7x7 arcsec^2.

Figure 4.4 presents an overview of Tiger and results (from Bacon).

A.1.2 MOS-ARGUS

A simple, yet powerful, device has been installed on the Multi Object Spectrograph at the CFHT. It is made of re-imaging optics feeding a fibre bundle, with the output fibres end arranged into a makeshift longslit illuminating the spectrograph.

The geometry at the entrance side is a hexagonal arrangement of the fibres within an almost complete hexagonal area with a total of 594 active fibres. The useful field of view is 12.8" x 7.8" and the sampling 0".40 per fibre (fibre core).

At the “slit" end, successive rows are simply aligned one after another, while keeping the internal order within each row, to form a ``long slit". The geometry is similar to an image slicer.

A.1.3 OASIS

OASIS is being put into operation at CFHT. It is the successor of TIGER, and is based on the same optical principle. The instrument is installed behind the adaptive optics bonnette at the Cassegrain focus for diffraction limited spectroscopy.

OASIS is a multi-mode spectro-imager, working in the 0.4 μm to 1 μm range and using a 2048x2048 15μm pixels CCD. OASIS will normally observe the corrected 90 arcsec diameter F/20 field given by the CFHT Adaptive Optics Bonnette, but may also work at the direct F/8 Cassegrain focus, as a backup mode.

Table A. 1: *Summary of selected integral field spectroscopy projects with a European connection:*

	Type	Wavelength range (micron)	Field area (arcsec^2)	Spatial resolution (arcsec)	Resolution elements spatial	Resolution elements spectral[d]	Ref
GEMINI							
GMOS-IFU	L+F	0.36–1	70	0.17×0.20	2006	930	1
GNIRS-IFU[a,b]	?	1–5	?	0.05			13
AIS+GMOS[c]	IS	0.36–1	49	0.09×0.16	3400	3000	2
	IS	0.36–1	200	0.09×0.16	13000	600	2
VLT							
VIRMOS[b]	L+F	0.37–2	3600	0.7	6000		
	L+F	0.37–2	576	0.3	6000		
SINFONI[a,b]	L+F	1.1–2.5	64	0.06–0.25	1024	1024	15
CFHT							
MOS+ARGUS	F	0.4–1	96	0.4	594		3
TIGER	L	0.37–1	49	0.3	600	~150	4
	L	0.37–1	100	0.7	600	~150	4
OASIS(ARGUS)?	F	0.37–1	27	0.23	635	300–500	5
OASIS(TIGER)	L	0.37–1	4	0.1	400	400	5
	L	0.37–1	25	0.25	400	400	5
WHT							
2D-FIS/ISIS	F	0.4–1	115	0.9	125	~1000	6
INTEGRAL/WYFFOS	F	0.4–1	49	0.45	175	~1000	12
	F	0.4–1	985	2.7	115	~1000	12
ELECTRA/WYFFOS-IFU	0.5–1	1	197	0.5	905	~1000	7
	L+F	0.5–1	8	0.13	905	~1000	7
SAURON	L	0.48–0.54	950	1.0	1170	1000	14
AAT							
SPIRAL (Phase A)	L+F	1.1–1.8	8	0.13	905	~1000	10
Calar Alto/AAT							
MPE 3D[b]	IS	1.4–2.5	64	0.3–0.5	256	256	8
UKIRT							
SMIRFS/CGS4-IFU[b]	L+F	1.1–1.8	23	0.6	72	128	9
UIST-IFU[a,b]	IS	1–5	25	0.24	400	512	11
AIS/CGS4-IFU[a,b]	IS	1–5	54	0.6	150	128	
LBT							
SPIFFI[a,b]	L+F	1.1–2.5	64	0.06–0.25	1024	1024	15

Notes:		
	F	fibres only (sparse sampling)
	L	lenslets only
	F+L	fibres plus lenslets
	IS	image slicer
	a	projected
	b	Infrared optimised
	c	design exercise
	d	assuming critical sampling where only the spectrum length is known

See next table for references

Table A 2 :

References for previous table

1	Allington-Smith *et al.*1997b
2	Content 1997
3	Crampton *et al.*1995, Vanderriest et al. 1994
4	Bacon et al. 1995
5	This document. Le Fevre (priv. com.)
6	Garcia *et al.*1994
7	Content (priv. com.)
8	Weitzel *et al* 1996
9	Haynes (priv. com.)
10	Parry (private communcation)
11	Ramsay-Howatt & Content (priv. com.)
12	Arribas (priv. com.)
13	GNIRS PDR documentation (GEMINI)
14	de Zeeuw and Bacon (priv. com.)
15	Genzel *et al.*1997

OASIS can be operated in the following modes:

•Imaging mode: Image quality has been optimized so that high spatial resolution (0.1 sec) images will be available for scientific use. Furthermore, it will offer the flexibility of combining imaging and spectrographic programs during a single night.

•TIGER mode: it offers a 2D spectrographic capability (using a micro-lens array) with a large range of spatial samplings, and low-to-medium spectral resolutions. The field is 2" to 5" , with 0".10 to 0".25 sky sampling and about 400 resolved spectral elements with R < 1400 (spectral resolution).

•ARGUS mode: it gives a smaller maximum field of view than the TIGER mode, but with a larger spectral range, as well as a more classical data reduction software.

•The long-slit mode: full coverage of the AO bonnette field with down to 0".1 spatial sampling and R < 1400.

•Scanning Fabry-Perot mode: covers the whole AO bonnette field, with spectral resolutions up to 16000.

A.2 WHT

A.2.1 TEIFU

A fibre/microlens IFU is under construction for the 4.2 m Herschel Telescope by the Durham University Astronomical Instrumentation Group (AIG). It is designed to exploit adaptively-corrected images produced by Durham's ELECTRA adaptive optics system and has two image scales: 0.13 and 0.25 arcsec/element. It contains ~ 1000 elements giving a field of 13 and 54 arcsec^2 respectively. It feeds fibres into the WYFFOS fibre spectrograph. The system is optimized for visible wavelengths up to 1µm. The fibres are coupled to microlens arrays at the input and output to provide optimum coupling to the telescope and spectrograph. A fore-optics module contains an interchangeable enlarger and pickoff mirror. A separate object and background field are provided whose separation may be varied. Commissioning is expected in early 1998.

A.2.2 2D-FIS

This is a fibre system without lenslets built by the Instituto Astrofisicas Canarias (IAC). The field of view is 115 arcsec^2 with 0.9 arcsec sampling. The fibre bundle feeds the ISIS long slit spectrograph.

A.2.3 INTEGRAL

This comprises three unlensed fibre bundles built by the IAC. The image scales are 0.45, 0.9 and 2.7 arcsec with fields of view of 16x12.1, 33.5x29.4 and 7.8x6.3 arcsec^2 respectively. The fibres are fed into the WYFFOS fibre spectrograph mounted on one of the Nasmyth platforms.

A.2.4 SAURON

A wide-field IFU to study internal galaxy kinematics in the optical is being built by the Observatoire de Lyon for a European consortium. The instrument, which will resemble OASIS will be used on the WHT. The field of view is 28x34 arcsec^2 with 1.0 arcsec sampling. With a 2048x2048 CCD, the system will provide up to 1170 spectra over spectral ranges of 460-550 and 640-700nm with ~300 resolution elements per spectrum.

A.3 Calar Alto

A.3.1 3D

The MPE 3D spectrograph uses an image slicer (Weitzel et al. 1996) to simultaneously provide 256 spectra of a field of view 8"x8" in size, with 100% spatial filling factor. Spectral resolutions of 1000 to 2000 are available, covering the near infrared H and K bands. The spatial pixel scale can be varied from 0".3 to 0".5 per pixel, depending on the seeing. 3D pioneered the use of an image slicer for an IFS, and has been yielding spectacular results (e.g. Krabbe et al. 1995, Genzel et al. 1996) over the last 4 years. The slicer design is fully reflective and consequently achromatic.

3D underwent an engineering run together with ALFA, the Calar Alto LGS assisted adaptive optics system, in July 1997. In this mode, it provides a spatial sampling of 0".07 - 0".25 per pixel to provide spatially diffraction limited spectra with almost complete sky coverage. The first science run is planned for early 1998.

A.4 Gemini

A. 4.1 GMOS-IFU

A fibre/microlens IFU is under development for the GEMINI multiobject spectrographs (GMOS) which are being built by a UK-Canadian consortium. Durham is developing a system similar to that for the WHT (above) but with an image scale of 0.2 arcsec and a field area of 50 arcsec^2. Separate object and background fields are provided. This IFU must operate confocally with the multiaperture and imaging modes of GMOS and is packaged into a small unit which can be slid into the lightpath at the telescope focus in the same way a multiaperture mask. The 2000 elements are reformatted into two output slits which are dispersed onto a CCD array containing 4608x6144 pixels. There is the option of blocking off one slit so as to increase the spectrum length to the maximum 6144 pixels. A separate offset field for background estimation is also provided. The two GMOS instruments are scheduled for completion in 1999 and 2000.

A.4.2 GNIRS-IFU

An IFU is being designed for the GEMINI Near-IR spectrograph (1-5μm), being constructed by NOAO. The choice of technology has not yet been made. The sampling increment is likely to be

0.05 arcsec.

A.5 VLT

A.5.1 VIRMOS

VIRMOS is an on-going Franco-Italian project to build 2 spectro-imagers for the VLT, covering together the wavelength range 0.37-2 µm. The long slit length (~110 arcmin) allows to design an IFU with more than 6000 spatially resolved elements, 6000 microlenses coupled to fibres. The field of 1x1 arcmin^2 is sampled by a microlens array with a sampling of 0.7 arcsecond per fibre (a mode with 0.3 arcsec/fibre and 24 x24 arcsec^2 field, is also available).

The infrared instrument, NIRMOS, will work up to the thermal regime, in the 0.8-2 µm range, and use 4 2kx2k HgCdTe detectors. The visible instrument, VIRMOS, is to see first light in 2000, NIRMOS in 2001.

A. 5.2 SINFONI

SINFONI is a joint ESO--MPE project to provide an integral field spectrograph for the VLT. It incorporates a curvature sensor based adaptive optics system which feeds the IFS with diffraction limited images. SINFONI provides 1024 spectra with spectral resolutions of 2000 to 5000 in the near infrared J, H and K bands. The 1024 spatial pixels are arranged in a hexagonal pattern to provide ~100% fill factor in the image plane. SINFONI uses ``flared fibres", where the tip of a silica-silica fibre is flared to ~10 times its original diameter, and a hexagonal lenslet is post-polished onto the flared tip. The hexagonal lenslets are then close-packed to cover the image plane. A schematic of the SINFONI fibre unit is shown in figure A.1, while figure A.2 shows an image of an actual flared fibre.

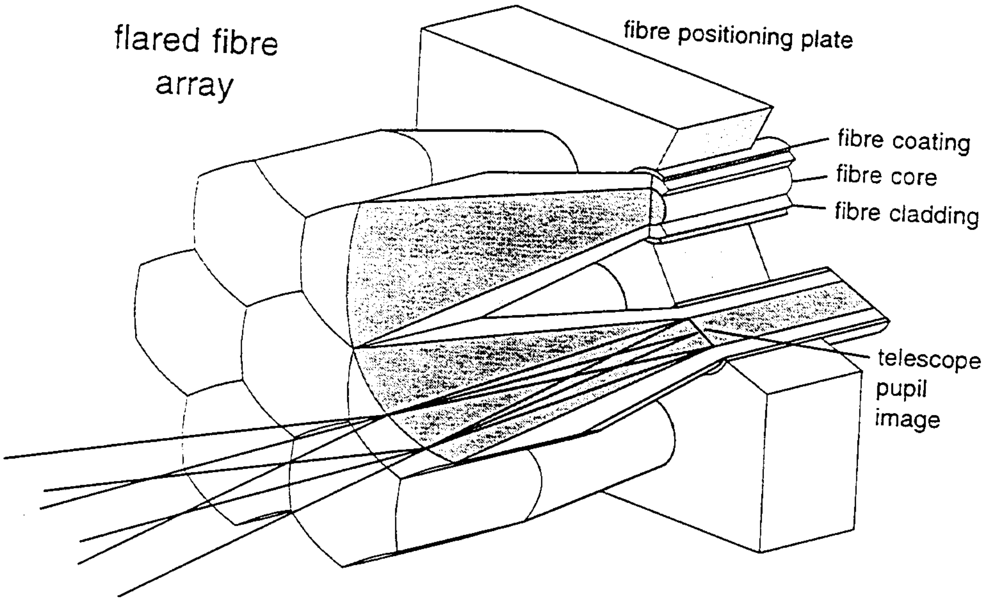


Figure A.1– *Illustration showing the concept of the SINFONI slicer design, which integrates the fibre and microlens into a single unit.*

SINFONI provides pixel scales ranging from 0".06 to 0".25 with a field of view upto 19" in diameter, so as to provide both seeing and diffraction limited scales at the VLT. If approved by the ESO--STC, it will see first light in early 2001.

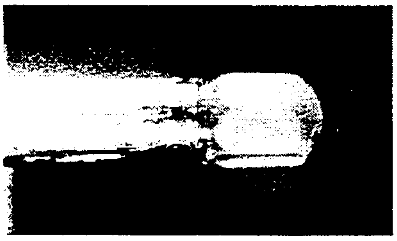


Figure A.2 – *Photograph of an actual flared fibre tip. The front is polished to a microlens , while the sides are ground to form a regular hexagon.*

A.6 UKIRT

A.6.1. SMIRFS-IFU

A prototype near-infrared IFU has recently been built in Durham for UKIRT. It works with the CGS4 cryogenic 1-5 μm spectrograph. The system has a field of view of 6x4 arcsec^2 with each element covering 0.6 arcsec. It uses (warm) fused silica fibres, coupled to microlens arrays at the input and output. An optical relay, originally developed for the SMIRFS IR multi-fibre system (Haynes et al. 1995). reimages the fibre slit onto the slit within the spectrograph cryostat. The input microlens array (72 x 0.4mm hexagonal elements) couples the slow telescope beam to the fibres with a ~100% filling factor. The output microlenses convert the beam back to the telescope focal ratio required by the spectrograph. Technical commissioning in June 1997 was successful and data were obtained on Seyfert-2 galaxies. Figure A.3 shows data for NGC7469.

A.6.2 AIS prototype

Durham has received funding approval to develop a prototype IFU to work with the CGS4 spectrograph at UKIRT. This uses an image slicing approach based on the Advanced Image Slicer of Content (1997). The system has a field of view of 6x9 arcsec with a sampling increment of 0.6 arcsec (dictated by the image scale of the spectrograph)

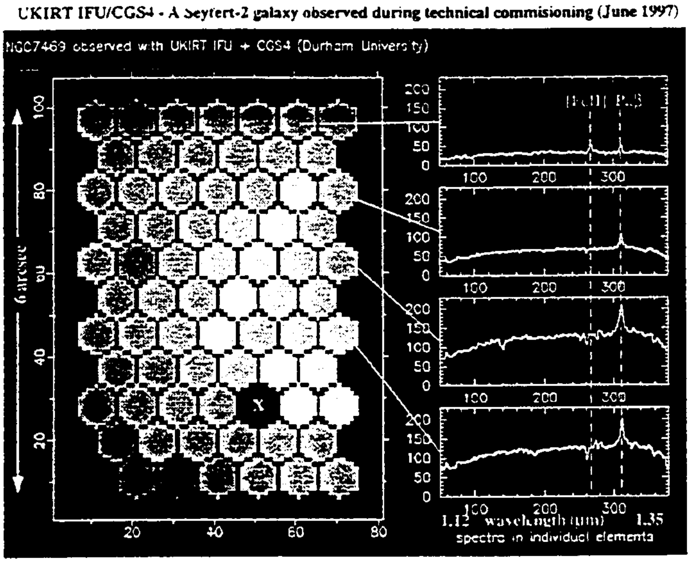


Figure A3 – *Commissioning results for a Seyfert-2 galaxy observed with the prototype UKIRT SMIRFS-IFU system with CGS-4. The image on the left is a reconstructed white-light J-band image. Spectra from individual elements are shown on the right.*

A.6.3 UIST-IFU

The UK Infared Spectrograph (UIST), planned for completion in ~2002 will include an IFU. The required spatial sampling is 0.24 arcsec with a field of view of ~5x5 arcsec^2. It is likely to be based on the AIS design (Content 1997)

A.7 AAT

A.7.1 SPIRAL

A prototype spectrograph with an integral field mode has been built for the AAT by Cambridge IoA and the AAO. The prototype contains 36 fibres coupled at the input to a close-packed array of hexagonal macrolenses. It was recently commissioned at the AAT. A 100-element version is under development.

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