MANIFEST: a many-instrument fiber-positioning system for GMT

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ABSTRACT

MANIFEST (the Many Instrument Fiber System) is a proposed fiber-positioner for the GMT, capable of feeding other instruments as needed. It is a simple, flexible and modular design, based on the AAO's *Starbugs*, the University of Sydney's *Hexabundles*, and extensive use of standard telecommunications fiber technology. Up to 2000 individually deployable fiber units are envisaged, with a wide variety of aperture types (single-aperture, image-slicing, IFU). MANIFEST allows (a) full use of the GMT's 20' field-of-view, (b) a multiplexed IFU capability, (c) greatly increased spectral resolution via image-slicing, (d) efficient detector packing both spectrally and spatially, (e) the possibility of OH-suppression in the near-infrared. Together, these gains make GMT the most powerful of the ELT's for wide-field spectroscopy. It is intended that MANIFEST will form part of the GMT facility itself, available to any instrument able to make use of it.

Keywords: fiber positioners, fiber spectroscopy, Starbugs, extremely large telescopes, OH suppression.

1 INTRODUCTION

As a response to the call for GMT instrument proposals in November 2008, the AAO proposed a concept for the GMT Facility Multi-Object Fiber System (GFFS) called MANIFEST, the Many Instrument Fiber System. MANIFEST accesses the full GMT focal plane and reformats it, filling the detectors of the various GMT spectrographs in a wide variety of modes. Compared with each spectrograph's standalone capabilities, this offers (a) increased fields of view; (b) multiple deployable IFUs; (c) increased resolution via multiplexed image-slicing; (d) efficient detector packing; (e) efficiency gains from working at VPH superblaze angles; (f) simultaneous use of multiple instruments; (g) the possibility of gravity-invariant mounting; and (h) OH suppression in the NIR. Some of these enable entirely new science, while others offer efficiency gains ranging from incremental, through substantial, to transformative.

GMT has several large multi-object spectrographs proposed for it – GMACS[1], NIRMOS[2], and G-CLEF[3]. The huge slit-lengths of these spectrographs mean that very large numbers of fibers are required to fill them. This is difficult to achieve with pick-and-place positioners (such as 2dF[4] or FLAMES/Ozpos[5]), because of (a) fibers crossing the focal plane, (b) the large number of retractors required, and (c) the very long reconfiguration times. All these problems increase as the number of fibers increases. An alternate positioning system based on fixed patrol areas (such as FMOS/Echidna[6] or LAMOST[7]) would not give the desired flexibility to observe clustered targets, or to have a choice of aperture geometries for each target. Therefore, we are proposing an entirely new positioner design which removes the need for retractors, (b) eliminates fiber crossings of the focal plane, (c) allows heavily overlapping patrol areas, and (d) allows parallel reconfiguration.

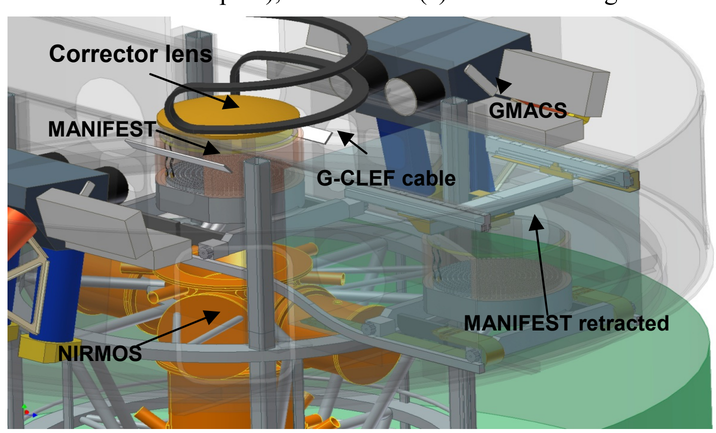

Figure 1. Proposed location for MANIFEST, within a Gregorian Instrument Assembly shared with NIRMOS and GMACS. The available space envelope when retracted is shown.

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It is expected that MANIFEST will share a Gregorian Instrument Assembly with NIRMOS and GMACS (Figure 1). In principle, MANIFEST could live on the Instrument Platform, with a separate large pickoff mirror, field lens, and field rotator. However, this involves additional cost, weight, and throughput losses. Wherever MANIFEST is mounted, it will be designed not to interfere with the normal standalone use of other instruments.

In January 2010, the GMTO Board announced that 'MANIFEST is likely to be a very high priority second generation instrument' and supported a feasibility study, starting in July 2010, to develop MANIFEST as a telescope facility.

2 INSTRUMENT CONCEPT

Overview

MANIFEST provides fiber feeds for GMACS, NIRMOS, and G-CLEF. For each spectrograph, it offers a large number of 'deployable fiber units' (DFU's), in a variety of aperture geometries ('modes'), assembled into a number of separate units ('modules'). The modules are interchangeable, in the senses that (a) each instrument can accept different modules, (b) some modules can feed more than one instrument, and (c) modules can be added, upgraded or replaced as needed. Simultaneous observations of different target sets with different spectrographs are also possible. For each spectrograph it feeds, MANIFEST can make use of the entire available detector width. Most of the modes involve image-slicing, with gains in both spectral and spatial resolution. A schematic view of the MANIFEST system is given in Figure 2.

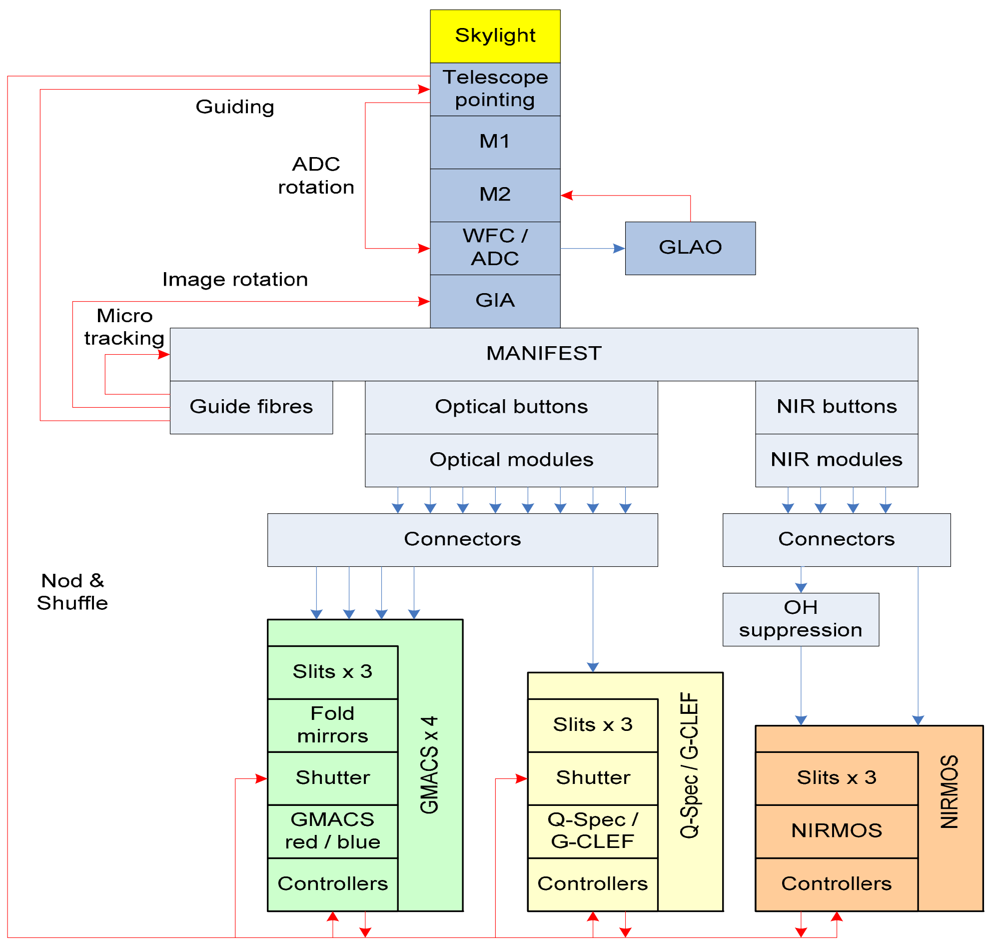

Figure 2: Schematic view of the MANIFEST system

We propose to undertake a full concept design for each of two fundamentally different positioner options. The design presented here is strongly preferred and makes use of *Starbugs*. However, as a backup option, to mitigate the risk involved with this novel technology, we are also designing a 'pick & place' option. This would involve a pick-and-place robot, like 2dF or FLAMES/OzPos. It would have two interchangeable field plates, each with ~600 deployable apertures and associated retractors. The actual robot would be a commercial H-frame gantry with air-bearings, modified only as necessary to allow for the varying gravity vector and the curved field plate. The science specifications for GFFS are still comfortably met by this design.

Fiber positioner

The AAO has successfully used piezo-electric actuators for FMOS/Echidna. These have been developed into *Starbugs*[8], which are small autonomous robots, which simultaneously position themselves on the field plate. They allow great flexibility, short setup times, and allow micro-tracking (e.g. to correct for changing differential refraction, image gyration induced by the Ground Layer Adaptive Optics system, or pupil rotation). The AAO has recently prototyped a new 'lift-and-step' Starbug with a very predictable and repeatable motion; this new version is discussed more fully in an accompanying paper[9]. This new prototype also incorporates the '*hanging Starbug*' concept, whereby the magnetic bugs hang below a thin (few mm) glass plate, with a ring magnet above the plate to provide adhesion (Figure 3). The advantages of this are that there are no retractors, and no fibers crossing the focal plane, so very large numbers of Starbugs can be deployed. Each Starbug has a fixed patrol area to simplify and speed up reconfiguring, but these would heavily overlap and should not significantly limit the available configurations. The required glass dome does not need to be figured to high precision, and can be slumped from commercially available glass sheets. The basic concept is shown in Figure 4, and the layout for the whole instrument in use is shown in Figure 5.

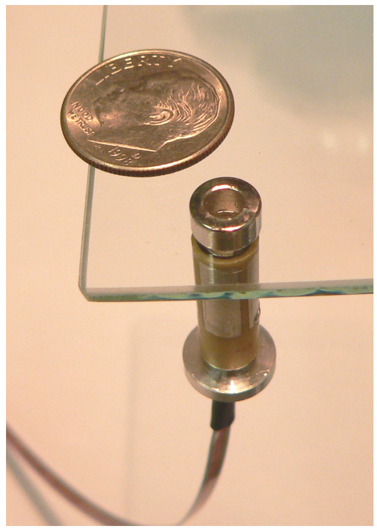

Figure 3. Prototype hanging starbug

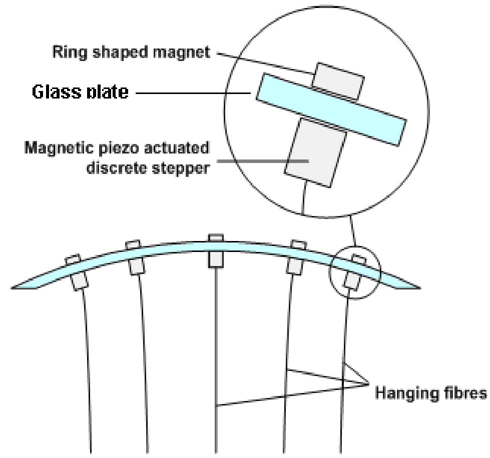

Figure 4. Hanging Starbugs concept

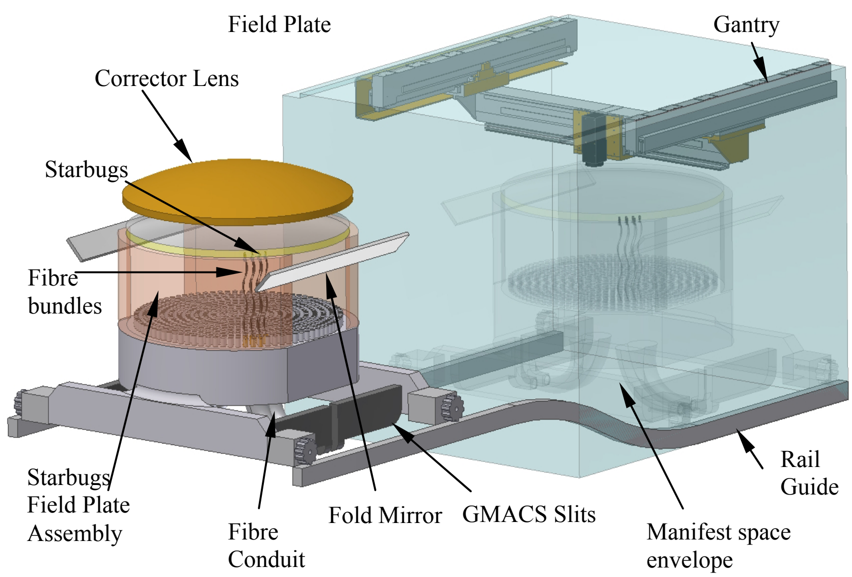

Figure 5. Layout for starbug positioner concept, showing both deployed and retracted positions, and the available space envelope when retracted.

Aperture types and numbers

MANIFEST will provide a wide variety of aperture geometries. The core geometries we are proposing to include are (a) single aperture DFU's, with diameters around 0.75", and (b) image-slicing (or IFU) multiple apertures with individual apertures about 0.25". The proposed geometries and numbers are setout in Table 1. Other modes, e.g. extreme image-slicing, or pupil imaging, are possible and will be considered as part of the feasibility study.

Table 1: Deployable unit numbers. GMACS capacities assume nod & shuffle, G-CLEF capacities assume the use of order-sorting filters.

DFU type	Overall Diameter	Fiber Diameter	# Fibers	GMACS capacity	G-CLEF capacity	NIRMOS capacity	**MANIFEST**
Single aperture	~0.75"	~0.75"	1	1200	50	450	**1200 Vis/NIR**
Image-sliced	~0.75"	~0.25"	7	500	20	150	**500 Vis + 150 NIR**
IFU37	~2"	~0.25"	37	100	4	30	**100 Vis + 30 NIR**
IFU127	~4"	~0.25"	127	25	1	9	**25 Vis + 9 NIR**
IFU 900	~10"	~0.25"	900	4	–	1	**4 Vis + 1 NIR**

Hexabundles

For the input into image-slicing fibers at the focal plane, we propose to use *Hexabundles*[10] (Figure 6). A Hexabundle is a fused set of 7 or more fibers, with very thin cladding between them, which open out after a few mm into separate fibers. We proposed to use them to dissect the images (in either image- or pupil-planes). Filling factors of 85-90% can be achieved (comparable with lenslets), and they are otherwise lossless and achromatic. Prototypes already exist at the University of Sydney, and on-sky tests with the SOAR telescope will take place in 2010. If Hexabundles fail to perform as required, we have a low risk fall-back of using lenslets, as used e.g. for FLAMES/OzPos, or SPIRAL on the AAT[11].

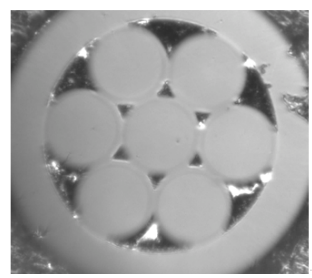

Figure 6. Close-up of a 7-fiber hexabundle aperture

Tapers

The f/8 native speed of GMT is too slow to use directly with fibers, because of Focal Ratio Degradation (FRD). We propose to use fiber tapers[12] (Figure 7) to change the speed of the beam, both on input and output. Fiber tapers have a gradual transition from a larger to smaller diameter, causing an adiabatic change in beam speed. Tests on the throughput and FRD of the tapered fibers will be undertaken by the Astrophysical Institute of Potsdam. Tapers are achromatic and lossless, so they offer great simplicity and efficiency to the design. If thoughput, FRD or cost turn out to be unacceptable, we again have a low-risk fall-back of using lenslets for speed changing, as used (on input) for FLAMES/OzPos, and (on output) for HERMES[13] on the AAT.

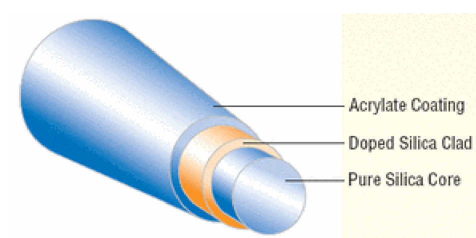

Figure 7. Schematic view of a fiber taper

Fibers and connectorisation

Suitable fibers are already available, such as Polymicro FBP[14], with superb attenuation performance from UV to NIR, and excellent focal ratio degradation (FRD) characteristics. All fibers will be used at fast focal ratios, f/2.4-f/4, to minimize FRD, and all will have 250μm outer diameters (including cladding and buffer), to allow commercial ribboning and connectorisation techniques to be used. Commercial connectors have recently been tested at AAO, as part of the HERMES project, with excellent results for both throughput and FRD. 20-50 (depending on type) of these connectors will be packaged together into a single connectorised 'plug'. The plug, with its associated connectors, ribbons and DFU's, forms a single 'module'. Each module corresponds to a slit length of ~540" (for visible or visible/NIR), or ~330" (for NIR only), as required to fill the largest compatible detector width.

Spectrograph input

Each spectrograph (and counting GMACS as 4) is fed via 1or more separate, parallel, fiber slits, one for each fiber size, and each with its own fiber connector socket. The modules are then interchangeable between the spectrographs, and vice versa.

The output beam from MANIFEST must reproduce the required input beam for each spectrograph. We propose to (a) use tapers to slow the beam down as needed, (b) line up the taper outputs into 'slitlets', with one per connector, and (c) line these slitlets up into a pseudo-slit, optically coupled to an AR-coated cover-slip or field lens. For NIRMOS, the required output beam is non-telecentric (to mimic the bare Gregorian focus); this is straightforwardly achieved by individual polishing and alignment of the slitlets at suitable angles.

The GMACS spectrographs will be fed via fold mirrors. The overall fiber length is only about 2m, allowing excellent UV throughput. For NIRMOS, it is proposed that the fibers will run into the fore-dewar, which will be evacuated and cooled to −50°C, to allow use over the full *H*-band (to 1.81μm). We will prototype this concept as part of the GNOSIS OH-suppression project on the AAT[15]. For G-CLEF, the fibers will run back up to their front ends on the Instrument Platform via a cable wrap (as shown in Figure 1). The additional fiber length over non-MANIFEST use is about 10m.

OH Suppression

Full *J*+*H*-band OH-suppression[16] is a goal for MANIFEST. OH-suppressing fibers have been prototyped successfully on the AAT, and further tests are planned for next year as part of the GNOSIS project. The amount of OH-suppression that can be implemented for MANIFEST depends mostly on the cost, which will become much clearer on the timescale of the feasibility study. We propose to design for both full-OH-suppression, and also a demonstrator capability, with the decision as to which option to pursue being deferred until the end of the feasibility study.

3 WIDE-FIELD CORRECTOR/ATMOSPHERIC DISPERSION CORRECTOR

It is proposed that MANIFEST share the Wife-Field Corrector/Atmospheric Dispersion Corrector (WFC/ADC) system with GMACS. Separate visible and NIR WFC/ADC systems would be very expensive, and would preclude simultaneous visible and NIR observations. However, the current GMT WFC/ADC design[17] was intended only for visible use, and has significant throughput losses in the NIR. We have proposed a revised WFC/ADC design, which (a) uses fused silica instead of BK7 for th first element, (b) has revised ADC glass types, and (c) has a fused silica 'dummy ADC' which can be substituted for the ADC for NIR and UV use. This revision appears to improve the optical image quality and throughput, and allows atmospheric dispersion correction to ZD=60°, as compared with the current 50°.

The all-silica WFC and dummy ADC, and aluminum GMT mirror coatings, would also allow superb UV throughput. This would allow GMACS to be used deep into the UV, either on its own (observing at the parallactic angle) or with MANIFEST (using the deployable IFU's).

The required wavelength range for the WFC/ADC coatings is at least ~370nm-1600nm, with a goal of 320nm-1810nm. The preferred coatings would be Solgel + MgF, which are already in use at Magellan, and offer ~0.5% loss per surface in the visible and 1-2% in the NIR. Hard multilayer coatings would be an acceptable alternative.

4 PERFORMANCE

MANIFEST works in conjunction with one or more spectrographs, so its performance depends as much on them as on our design. However, some generic performance metrics can still be calculated.

Field-of-view: All spectrographs can make use of the full 20' GMT FOV. The WFC/ADC field of view was originally intended to be larger, and if it were increased, MANIFEST could make use of it. MANIFEST can be used with the GLAO system, over the full GLAO field of view.

Multiplex gain: The multiplex factor for each instrument and mode was shown in Table 1.

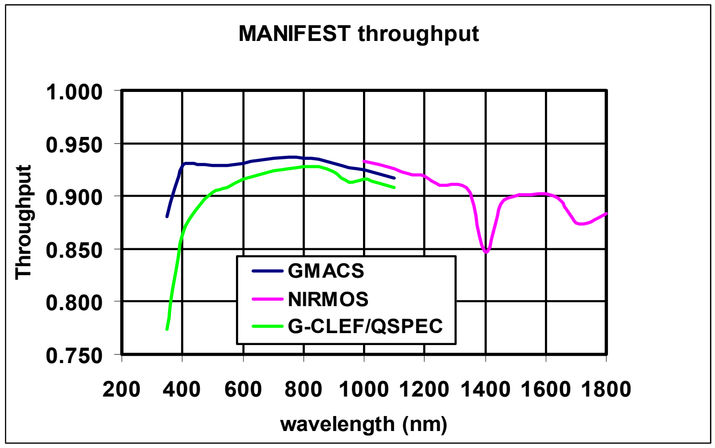

Figure 8. Estimated throughput for single aperture DFU's.

Resolution: Image-slicing improves spectral resolution by a factor ~3 over a seeing-limited slit, for all proposed spectrographs. Larger gains, up to a factor ~7, would be straightforward to achieve for GMACS and G-CLEF.

Efficiency: The proposed design minimises fiber length and fiber fore- and post-optics, with just 4 air/glass surfaces. The estimated MANIFEST throughput, excluding aperture losses is shown in Figure 8. For image-slicing modes, there is an additional loss of 10-15%, from the filling factor of the Hexabundles. These estimates do not include the compensating gain in efficiency, when MANIFEST is used with imaging VPH spectrographs such as NIRMOS or GMACS, that comes from always using VPH gratings at their superblaze angle; this gain is typically 10-20%, depending on wavelength and field position, and this means MANIFEST is effectively 'throughput neutral' for most survey work.

The overall multiplex factor and resolution for the principle science cases is presented in Table 2.

Science goal	Required resolution	Resolution with MANIFEST	Multiplex factor
Star formation & chemical evolution in galaxies	Vis: R~2,000	3Å	1200
	NIR: R~2,000	6Å	450
Massive galaxy assembly	Vis: R~3,000	1Å	500
	NIR: R~3,000	2Å	150
Chemical tagging of Milky Way Substructures	Vis: R~50,000	R=100,000	20
		R=32,000	50
Dark matter distributions	Vis: R~5,000	1Å	500
Evolution of galaxy clustering	Vis: R~2,000	3Å	1200
Tomography of the IGM	Vis: R~2,000	3Å	1200
	Vis: R~10,000	1Å	500

Table 2: Resolution and multiplex for the principle science applications

5 SCIENCE GOALS

The science actually undertaken by new astronomical facilities is rarely that envisaged when they were planned, and GMT is unlikely to be an exception. The best indicator of the scientific productivity and impact of a new telescope is the expansion in the accessible 'discovery space' resulting from new or improved instrumental capabilities. MANIFEST significantly increases the versatility and capability of other GMT instruments, greatly expanding the accessible discovery space. This affects the GMT science cases in three ways: (a) for some cases it provides substantial quantitative gains, allowing programs to be carried out faster or better; (b) in some cases it provides a huge leap in performance, allowing new experiments to be undertaken; (c) for some cases, it provides an entirely new capability, again allowing new experiments to be undertaken.

Quantitative Gains: Systematic surveys of wide areas of sky and/or large numbers of objects are becoming more and more important in astronomy. For such survey (or AΩ) astronomy, the crucial performance criterion is overall survey sensitivity: observing the largest number of targets, with the least background, at the highest throughput and observing efficiency, over the widest FOV. In this context, the gains from MANIFEST are best summarized in terms of the survey speed, Survey speed is given by the inverse of the time taken to survey targets of a given brightness and density on the sky, over a given area, to a given signal-to-noise ratio. Such surveys are either (i) field-limited (if the target density is too sparse to fill all the apertures), or (ii) multiplex-limited (if there are always a larger number of targets than there are apertures). For case (i), MANIFEST allows a larger area to be covered in one observation; while for case (ii), it allows more targets to be observed, because of improved detector packing efficiency. This latter gain is generally a factor of at least two for realistic target densities and clustering. This argument remains true for each of the various sky subtraction techniques envisaged, (dedicated apertures, nod&shuffle, PCA sky subtraction). Table 3 shows the survey speed gains that MANIFEST gives for GMACS, NIRMOS and G-CLEF relative to their native performance. For survey science – the broad swath of astronomy driven by numbers of objects or area of sky – MANIFEST effectively doubles the power of GMT.

Table 3. Gains in survey speed provided by MANIFEST, for single-aperture-per-target surveys

Instrument	Field-limited gain	Multiplex-limited gain
GMACS	~2	~2
NIRMOS	~4	~2
G-CLEF all orders	~10	~10
G-CLEF few orders	~50	~50

Qualitative Gains: There are qualitative gains from MANIFEST in a number of areas, including image-slicing (giving increased resolution), and multi-IFUs (spatially resolved area spectroscopy), and OH suppression. Other future upgrades to MANIFEST offer further qualitative gains such as MOAO (multi-object adaptive optics) for multiplex area spectroscopy at very high spatial resolution.

Image slicing: For realistic slit widths, camera speeds and pixel sizes, any natural-seeing spectrograph on GMT will have a massively oversampled point spread function, typically 10-20 pixels across. Using MANIFEST as an image-slicer allows the resolution to be greatly increased without any loss of wavelength coverage. For sub-apertures sized to sample good seeing, there is a spectral resolution gain of a factor ~3 over single-aperture observations. Larger gains are possible, limited only by the sub-aperture size where the projected full-width-at-half-maximum on the detector drops below 2 pixels. Since AΩ is conserved, any gain in resolution is always accompanied by an equivalent reduction in the number of targets that can be observed (more fibers/target means fewer targets fitted onto the detector).

Multi-IFUs: MANIFEST provides multiple deployable IFUs in a variety of geometries. For extended sources these offer either increased light grasp for integrated spectroscopy, or spatially resolved area spectroscopy. In either case, the spectral resolution is increased, just as above.

OH-suppression: OH-suppression is a goal for MANIFEST. It would allow another order-of-magnitude improvement to the sensitivity of *J* and *H*-band spectral observations[18]; this comes from (a) the dramatic reduction in scattered OH light between OH lines, (b) the greater fraction of the spectrum that can be utilised, and (c) the reduction in read-noise contribution and (d) increased spectral coverage, that come from being able to work at lower dispersions.

The capabilities of MANIFEST and their application to the relevant GMT science cases[19] are summarized in Figure 9, and the achieved resolutions and fiber numbers for each case are listed in Table 2 above.

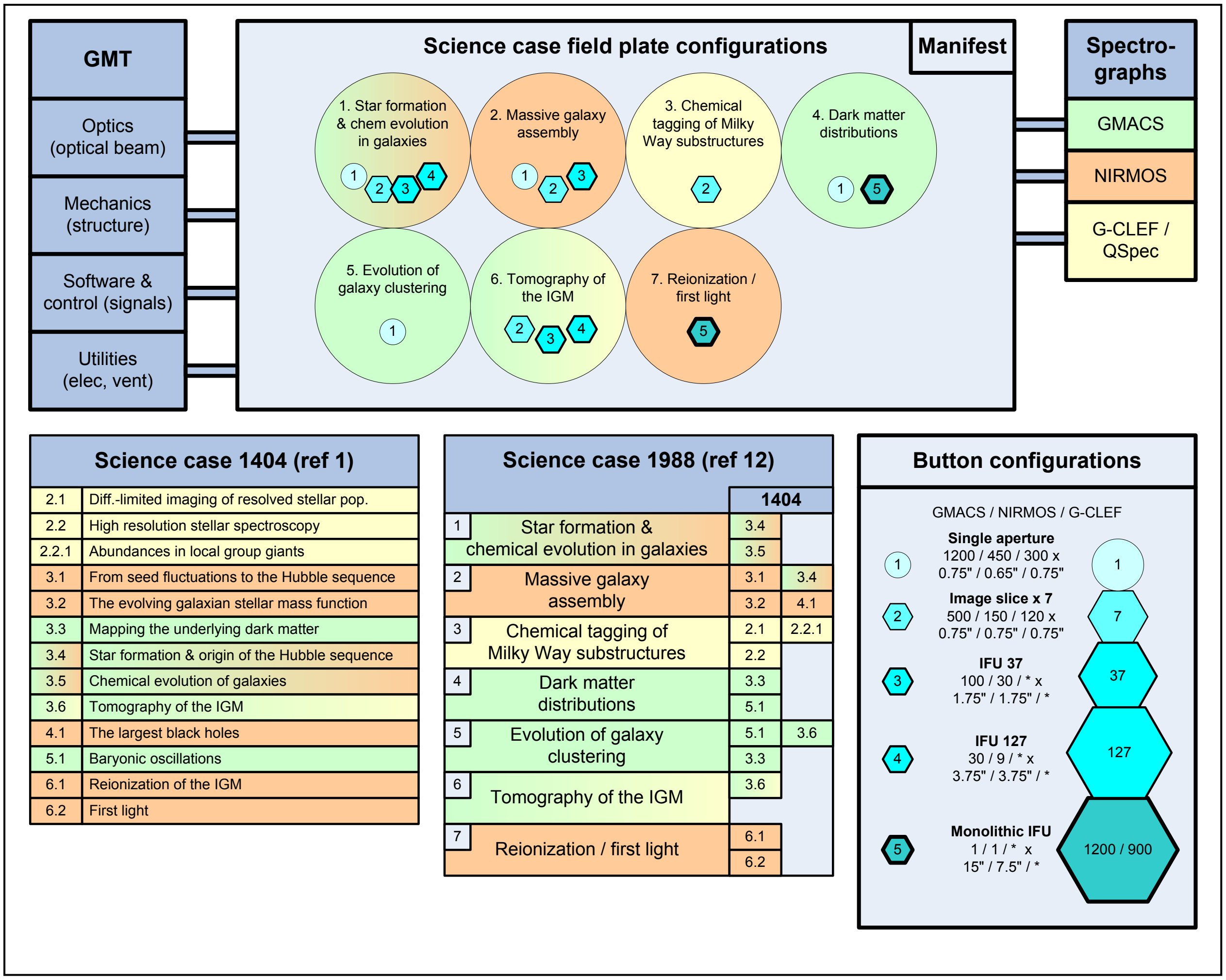

Figure 9: MANIFEST capabilities and GMT science goals. The boxes at lower left list the key programs in the GMT Science Case, as identified in the GFFS Request For Proposals. The box at lower right summarizes the potential DFU configurations offered by MANIFEST for GMACS, NIRMOS and G-CLEF. For each mode, this box gives the multiplex factor and the overall aperture size, for each spectrograph. The top panel of the figure shows how the science cases relate to instruments and MANIFEST configurations: for each of the 7 identified science areas, color coding shows which instruments can contribute, while the small numbered icons show the relevant MANIFEST configurations.

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