GMOS Operational Concepts Definition Document (2.0)

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APPENDIX (separate) contains detailed observing scenarios:

1 [A.1] Dark matter in dwarf spheroidal galaxies

2 [A.2] Brightest cluster galaxies at z=0.2

3 [A.3] Multiobject spectroscopy of faint galaxies

1. Introduction

The OCDD is intended to provide a single authoritative source of information on how the GEMINI multiobject spectrographs (GMOS) will be operated in order to provide the required scientific function. It is required as an aid for the designers of both the instruments and the observatories. Clearly, the way in which the instrument will be used has an impact on the design of the instrument, for instance the requirement to switch between a grating and a plane mirror during target acquisition means that each station of the turret must be equipped with separate motors so that the tilt of each grating can be accurately maintained even when it is out of the beam. Furthermore the design of the observatory must take account of the way the instrument will be operated, for instance, the wide field of the instrument means that telescope control system (TCS) must be able to accurately compute refraction corrections as a function of position within that field.

This document is not intended to provide a definition of the *capabilities* of the instrument or to lay down specifications for its *performance*. That is the purpose of the Functional and Performance Requirements Document (FPRD). Both the FPRD and OCDD are, to some extent, living documents, although it is expected that they will be frozen at CDR. Although the FPRD is the primary source of information on the instrument capabilities, information needs to flow in both directions as the documents are finalised.

The main part of this document contains a description of the instrument, its interfaces to the telescope, the main instrumental modes, operational issues common to all modes and, finally, generic observing scenarios. More detailed observing scenarios aimed at particular observations are included in a separate appendix.

Outstanding issues, especially those where action may be required in external work packages are highlighted like this.

2. Instrument description

2.1 Overview

The capabilities of the *baseline system* (based on that defined in the FPRD) are summarised below.

Wavelength range	0.4-1.1 µm
Field of view	Unvignetted: 7 arcmin diameter Mask: 5.5 x 5 arcmin Maximum slit length: 5.5 arcmin
Image scale	0.08 arcsec/pixel
Spectral resolution	Up to R=10,000 with 0.25 arcsec slits
Minimum slit width	0.2 arcsec
Detector	3 x (4096 x 2048) CCD with 15 µm pixels
Integral field unit	Element size: 0.2 arcsec Object field area: 50 $arcsec^2$ Separate background field
Filters	2 wheels each with space for 10 filters
Gratings	Mounted in a turret with space for 3 demountable gratings plus a plane mirror

In addition to this the GSC has defined (resolution 8.5, April 1996) two `desirable options':

- An integral field unit with finer sampling for wavelengths longer than 0.7 µm.
- Extensions to the wavelength range to 0.36–1.8 µm.

This document deals only with the baseline version.

2.2 Pre-slit optics

2.2.1 Atmospheric dispersion compensator and corrector

Light from the telescope will be corrected for atmospheric dispersion and the telescope focal surface (TFS) flattened by an Atmospheric Dispersion Compensator and Corrector (ADC-C).

If uncorrected, atmospheric dispersion causes a misalignment between the image of the target and the entrance aperture at wavelengths different from that at which the target is acquired and guided, resulting in wavelength-dependent reduction in throughput. Over the full wavelength range of the instrument this can easily amount to more than 1 arcsec and is likely to be a problem even when observing over restricted wavelength ranges. The ADC attempts to correct for this by introducing an equal and opposite dispersion at the expense of a small reduction in throughput.

Although removable, the ADC is not deployable: it cannot be inserted into or removed from the light-path as a remote operation.

The corrector is required to partially flatten the TFS which would otherwise have a radius of curvature ~2m. This gives two main benefits: (a) defocus over the field with respect to the mask plane is reduced leading to smaller and more uniform slit losses, (b) the optical system can be simultaneously optimised for spectroscopy, where the flat mask plane must be focused on the detector, and for direct imaging, where the sky must be focused onto the detector. This leads to more uniform images across the field and improves the quality of spatial information along the slit.

The current design consists of a pair of null-deviation prisms, whose relative orientation (in azimuth around the optical axis) can be altered to provide the required compensating dispersion, and another element which acts with the curvature of the final element of the ADC to provide partial field flattening. The system is designed to provide atmospheric dispersion correction for airmasses less than 2 .The system may inevitably produce some distortion in the field (Section 5.4).

2.2.2 On-instrument wavefront sensor

An on-instrument wavefront sensor (OIWFS) will be deployed in front of the TFS so as to pickoff a small region (a few arcsec) within a patrol field which covers much of the science field as well as a limited region outside it. The fraction of the sky field which is covered can be increased by rotating the instrument. The central part is accessible at all instrument orientations. The patrol field is sized to give a high probability of finding a star which is sufficiently bright for the order of correction required.

Although part of the instrument, the positioning of the OIWFS is controlled by the TCS and the WFS itself is the responsibility of a separate GEMINI work package.

2.3 Post-slit optical system

2.3.1 Overview

The main body of the optics consists of a *collimator* and *camera* which together produce images of both the sky and mask apertures at the telescope focal surface (TFS) on a detector located at the camera focal surface (CFS). A dispersing element is positioned in the collimated beam so as to produce images of the spectra at the CFS. The grating can be replaced by a flat mirror to produce a direct image of the sky. Optionally filters will be placed in the optical train. It will be possible to refocus to account for chromatic focus shifts by moving the detector. An integral field unit (IFU; see below) will be deployable at the TFS for two-dimensional (integral field) spectroscopy. The optical components that can be adjusted or interchanged are listed below.

2.3.2 Aperture masks

These are sheets of opaque material covering the full field of view and located at the TFS. They have one or more apertures (usually rectangular slits) cut in them to admit light to the spectrograph. They also contain holes to facilitate target acquisition. Although the corrected TFS is slightly curved, the masks will be planar. There are two types of mask.

- *Generic* masks which are applicable to more that one target field
- *Specific* masks which are made specially for a given field and instrument configuration

They are removed from the beam for direct imaging.

2.3.3 Integral field unit

The IFU provides two-dimensional spectroscopy by reformatting a two-dimensional field of view into one or more longslits which are positioned at the TFS. The *baseline system* is decribed here, but other IFUs can be added. The input field is made up of a regular array of elements of size ~ 0.2 arcsec covering a field of view with an area of 50 $arcsec^2$. The elements are contiguous so that the field has a filling factor near unity. Both the entrance field and the reformatted slits are located at the TFS so that no focal shift is introduced when the IFU is deployed. In addition to the main *object field*, the IFU will include a *background field* positioned at least 1 arcmin from the object field. This will be optically identical to the object field so that estimates of the sky background can be obtained in cases where the target object completely filled the object field. The background field will be smaller than the object field. The output of the IFU will be one or more longslits divided into a number of slitlets which correspond to a full row or column of the input field.

2.3.4 Dispersion elements

These are classically-ruled planar diffraction gratings used in reflection. In general they will be blazed to optimise the throughput over a specific wavelength interval. Different gratings will provide different dispersions and blaze wavelengths and the accessible wavelength range will be altered by tilting the gratings. The *dispersion configuration* is determined by the grating used and its tilt.

2.3.5 Filters

In imaging mode, standard broadband filters are required for photometry over the full instrument field. In spectroscopic modes, other filters are required to avoid overlaps between spectra by limiting the wavelength range.

2.4 Mechanical system

2.4.1 Support Structure

This is used to attach the instrument to the GEMINI instrument support structure (ISS) and to hold the optical components fixed with respect to each other. It is divided into a Fore Optical Support Structure (FOSS) which supports the focal-plane assembly and a Main Optical Support Structure (MOSS) which supports the rest of the instrument.

Flexure of this system is partially compensated by the Flexure Compensation System (FCS).

2.4.2 Enclosure

This prevents stray light from reaching the detector and provides thermal conditioning of the instrument components.

2.4.3 The ADC-C assembly

This consists of a mechanism to rotate the two prisms independently around the optical axis so as to alter the amount of correcting dispersion and its orientation.

2.4.4 OIWFS assembly

This positions the OIWFS probe at desired locations within the field of view close to the TFS.

2.4.5 Focal plane assembly

This consists of a system to put masks or IFUs into the lightpath at the TFS. The masks and IFUs are held in a cassette.

2.4.6 Grating turret

This places a grating or flat mirror in the collimated beam. Each grating will be permanently mounted within its cell and each such unit can be loaded into any one of the three available stations in the grating turret as a manual operation. One station will be permanently reserved for the imaging mirror. Facilities for setting the tilt of each grating, so as to alter the wavelength range falling on the detector, will be provided in the turret. Each station of the turret will include a separate tilt system so that the tilt can be maintained even if the grating is not in the light path so as to eliminate wavelength errors while changing between imaging and spectroscopic modes during target acquisition.

2.4.7 Filter wheels

This places filters in the collimated beam. A clear aperture is also provided. Focusing aids, such as Hartmann masks, may also be mounted here. Two identical filter wheels will be provided so as to increase the number of filters that can be accommodated within a limited space and to allow combinations of filters to be used. Different filters can be installed manually in the wheels via hatches in the instrument enclosure.

2.4.8 Detector focus and translation stage

Focusing is achieved by moving the detector along the optical axis within the cryostat. Flexure compensation is effected by moving the detector in all three axes using information from a look-up table that will be created during instrument testing.

2.4.9 Exposure shutter

This prevents light from reaching the detector except during an exposure. It is fast enough in operation to avoid timing errors for very short exposures, such as might be required for calibration and to ensure that the detector field is uniformly illuminated.

2.5 Mask maker

This consists of the hardware to manufacture the masks from a file of instructions. The masks contain apertures which may be rectangular (slits) or curved. Other types of aperture may also be provided to aid target acquisition. The system will include software to interpret and carry out the instructions fed to it. The system would normally be operated by observatory staff.

2.6 Instrument control system

The instrument control system (ICS) has three main subsystems:

- Instrument sequencer
- Instrument component controller
- Instrument detector controller

Software that simulates the operation of the instrument may be available to help plan observations.

2.7 Data analysis system

This is used to reduce and analyse the data (obtained via the data handling system; DHS). The main purpose is to provide enough information to allow the observer to assess the quality of observational data and to acquire the target fields. The end product will not necessarily be suitable for final scientific analysis, as many applications will require special processing and possibly calibrations that can only be performed after the observing run (e.g. construction of sky flats using all data from a run, etc.). Data analysis operations are divided into the following catagories of processing.

- *Synchronous* - must be executed before the nest step in the observing sequence.
- *On-line* - provides basic data quality assurance
- *Off-line* - provides improved data quality assurance and final reduction

The main functions are:

1. Archiving of the instrument and associated house-keeping data
2. To facilitate target acquisition by providing (synchronous) functions:
   a) For aperture spectroscopy, to generate the telescope offset required for fine positioning of the targets on the slits.
   b) For integral field spectroscopy, to reconstruct an image of the field from the integral field data to aid fine positioning.

3. Quick-look (on-line) data reduction to allow the observer and/or investigator to assess the data quality in near real-time by carrying out a subset of the full data reduction with default calibration obtained from incomplete calibration data or from the instrument database.
4. Data reduction (off-line). Generally this involves background subtraction and spectrum extraction with an absolute wavelength and flux scale derived from calibration data.
5. To facilitate mask design by providing (off-line) functions to:
   a) Generate coordinates from direct images taken with GMOS including functions to perform star-galaxy separation and to measure the brightness of all detected sources.
   b) Design the masks and produce a file containing the manufacturing instructions to be passed to the mask maker.
6. Displaying data interactively

The GMOS team is responsible for defining the functionality of the data analysis system but not for writing the programs or scripts.

3. Interface to the telescope

3.1 Physical interface

The instrument will be attached to the ISS, usually at one of the side ports reserved for heavy instruments. Facilities will be provided to enable the instrument to be mounted and demounted from the ISS. The instrument is also interfaced to the telescope via cables which carry commands, data and status, coolant for temperature conditioning and compressed air for pneumatically operated systems.

The orientation of the instrument field can be altered by changing the zero-point of the instrument rotator.

3.2 Optical interface

3.2.1 Telescope optics

The telescope optics have the following optical characteristics.

1 Curvature of the telescope focal surface. The uncorrected TFS is curved rather than flat (radius of curvature 1.9m) as would ideally be required to allow flat masks to be used. This is partially flattened by the corrector optics in the ADC-C.

2 Image scale. The image scale delivered by the telescope alters as the separation between the primary and secondary mirrors is adjusted to compensate for focus changes induced by temperature variations.

The change in telescope image scale could have an effect on the alignment between targets and the slits assigned to them leading to flux calibration errors, reduction in signal/noise and velocity errors which vary over the field.

3.2.2 Science fold mirror

Light will be directed to reach the instrument via the science fold mirror mounted within the ISS. The folded field is 7 arcmin in diameter.

It is possible that this system will introduce low-level field distortions that may affect the accuracy with which accurate radial velocities can be measured. If so, the distortion needs to be mapped as a function of telescope attitude and the information used in much the same way as the distortion from the ADC (Section 5.4).

3.3 Control interface

There are three major external control systems which interface with GMOS.

3.3.1 Observatory Control System (OCS)

The OCS provides the overall control of the various sub-systems and is the primary route by which the observer interacts with the instrument.

3.3.2 Data handling system (DHS)

Data produced by the instrument is routed through this system. Its main functions, as relating to GMOS, are outlined in Section 2.7.

3.3.3 Telescope control system (TCS)

This system moves the telescope mount and controls the position of the various wavefront sensors including the OIWFS and the ADC. Close interaction with the ICS is required to carry out important functions such as telescope focusing and guiding in the presence of variable atmospheric refraction over the field and/or variable distortion from the ADC.

4. Instrument operation modes

4.1 Multiaperture spectroscopy

4.1.1 Optical configuration

In this mode, the instrument views the sky through a multiaperture mask positioned at the TFS. Usually, the mask consists of a number of rectangular slits (perhaps several hundred) including a number of holes with which to positional reference stars as an aid to target acquisition. Generally, a separate mask is required for each combination of target field and dispersion configuration. In some critical cases, different masks will be required to carry out the same observation at different elevations because of atmospheric distortion and ADC distortions (Section 5.4). In addition to these *specific* masks, a number of *generic* masks will be required for standard instrument setups, usually for spectroscopy of single objects or for calibration.

Because the apertures in the mask can be positioned anywhere within the field of view, the accessible wavelength range in each spectrum varies due to the finite size of the detector. Overlaps between spectral orders may often be avoided by employing filters to limit the wavelength range present in the spectra. It is the responsibility of the investigator to design the mask and choose the filter and dispersion configurations so as to minimise these effects and to ensure that the desired wavelength range is present in each spectrum. Software tools may be provided to assist with the design process.

All the multiaperture masks required for a particular observing sequence should be designed and made in advance of the observation so that they can be loaded into the mask changer before the start of the sequence. Each mask will be uniquely identified.

The masks are made at the observatory by the mask maker which is operated by observatory staff. Because of the great accuracy required in the positioning of the apertures, it will usually be necessary to obtain direct images of the target field in order to design the masks. This can be done conveniently by GMOS in imaging mode in advance of the spectroscopic observations.

4.1.2 Target acquisition

The target is acquired by determining the offset needed to position the slit mask apertures on the target objects (after blind positioning at the field). This is done by comparing a direct image of the field with an image of the mask. Although various methods may be employed, a simple and reliable technique is to view relatively bright stars through holes cut in the mask. Whichever method is used to obtain the necessary offset, the grating must be moved out of the light path while the image is taken. Therefore, to avoid non-repeatability in the dispersion configuration, the dispersion assembly must preserve the grating tilt even when it is not in the light path.

4.1.3 Distortions

When working over a wide field, it is very important that the images formed at the mask do not move relative to each other (or to the OIWFS). If they were to do so, this would lead to loss of throughput and, more importantly, errors in radial velocities depending on position on the field.

The main sources of distortion are the atmosphere and the ADC optics, as discussed in Section 5.4 and modelled for a specific observing scenario in Appendix A.1

4.1.4 Science data

The goal is for most calibration exposures to be taken during the setup process, generally in the daytime. However, wavelength calibration and exposures necessary to remove detector fringing may have to be taken when the telescope has acquired the target, depending on factors such as instrument flexure and the degree of stability required.

The final data consists of a number of spectra laid out one above each other with variable shifts in the dispersion direction. Data reduction consists of geometrical rectification, flat-fielding, wavelength calibration, sky subtraction, spectrum extraction and flux calibration using suitable calibration observations. Each spectrum will be identifiable by reference to the mask design and each mask will be identified by a suitable label added during manufacture.

4.2 Single-aperture spectroscopy

4.2.1 Optical configuration

This mode resembles multiaperture spectroscopy except that a generic mask is used rather than one designed for a particular observation and target. Usually the mask contains a single slit of length up to the full width of the field of view (a longslit), but with different widths to match different seeing. These generic masks differ from multiaperture masks, not only in that they are reusable, but also, in having no holes for target acquisition.

4.2.2 Target acquisition

Because the generic masks have no holes, target acquisition can only be done either by removing the mask while a direct image of the sky is taken and re-inserting it for the spectroscopic exposure or via the OIWFS/PWFS or A&G acquisition camera. The requirement to move the mask out of the light-path and back in again places greater constraints on the repositioning accuracy than if acquisition holes were used. The investigator still has the option of making specific masks for the field consisting of a simple aperture with acquisition holes customised for that specific observation.

4.2.3 Distortions

The effect of field distortion is generally less than for multiaperture spectroscopy because it is less likely that the full extent of the field will be used and because there is greater freedom to orient the slit to minimise distortion. However there will be cases, when using the maximum slit length, that the sources of distortion discussed in Section 5.4 will have to be taken into account. In principle, these effects can be removed altogether when observing a single object. In practice this depends on the ability of the TCS to calculate the size of the atmospheric dispersion and field distortions.

4.2.4 Science data

Calibration and data reduction is similar to that for multiaperture spectroscopy but with some simplifications.

4.3 Integral field spectroscopy

4.3.1 Optical configuration

In this mode the spectrograph admits light into a number of elements which form a contiguous two-dimensional field of view and reformats them into one of more longslits which are then dispersed in the same way as for the other spectroscopic modes. Compared with the aperture spectroscopy modes the only difference is in how the sky is sampled.

4.3.2 Target acquisition

Target acquisition is different from that of the aperture spectroscopy modes. Although it might be argued that stringent target acquisition specifications are not required, as a map of the entire field can be reconstructed in the processing stage, for some applications it might be necessary to re-acquire a particular target with great accuracy or judiciously place two or more objects on the lenslet array. This would require that the IFU be used in an imaging mode in which an image of the field could be reconstructed in real-time from images of the undispersed subapertures using appropriate software. This mode is insensitive to atmospheric dispersion providing that it does not change appreciably during the observation since this effect can also be reconstructed from the spectroscopic data.

4.3.3 Distortions

Because of the small size of the field, this is much less of a problem than for the multiaperture spectroscopy mode. Atmospheric dispersion, too, is less of a problem since its effects can be removed in the data reduction by rectifying the 3-D data cube in a way already familiar to users of scanning Fabry-Perot data.

4.3.4 Background subtraction

The method of background subtraction needs careful consideration. Slit spectroscopy has the advantage that a sample of sky close to the object and obtained through the same physical aperture is generally available. For integral field spectroscopy this is not the case. Often it will be possible to estimate the background from elements at the edge of the IFU field but in some cases the target will completely fill the field. In either case the, different physical elements sample the target and background leading to the possibility of errors in background cancellation.

For this reason, in addition to the main *object field* the IFU includes a second *background field* separate from the object field by at least 1 arcmin. The two fields are designed to have identical optical characteristics. This two-channel configuration can be used in a number of ways to match the type of observation and to cope with varying degrees of non-uniformity between IFU elements.

This arrangement easily solves the problem of the size of the target but also allows element non-uniformity to be tackled effectively. Accurate background subtraction requires that the recorded shape of the profiles of night-sky emission lines are identical in both the object and background spectra. To first order this can be ensured by using the same optical design for each IFU elements, whether in the object or background field. However it is possible that there will second-order differences in line profiles due to unavoidable variations between elements arising during manufacture of the device.

If this turns out to be a problem (the answer will not be known until the device is built and tested and the result will in any case depend on the application), the investigator has the option to beam-switch between the two fields by offsetting the telescope so that the two fields alternately sample the target and a blank region of sky nearby. This will provide the optimum background subtraction accuracy since the same physical elements will be used to sample both the object and background, albeit only over a limited field determined by the size of the smaller background field. However even over the remainder of the field, significant benefits in terms of subtraction accuracy may still be possible and temporal variations in the background on timescale longer that the beam-switch period will certainly result. The time period for the beam-switching and its duty cycle will depend on the frequency of variations in the background and the specific requirements of the observation. For example, working in a region dominated by OH emission lines, which can be variable, may require relatively rapid switching although this must be balanced against the increase in effective detector noise from multiple readouts. The minimum period is unlikely to be shorter than a minute. If the background is constant, only one beam-switch cycle is required.

The observer therefore has a number of options for background-subtraction depending on whether the dominant error source is background photon statistics or uncertainty in the cancellation and whether or not these second order effects turn out to be important.

	Second-order effects:	
	important	***unimportant***
Target faint and compact *(background-limited)*	use object field edge	use object field edge
Target faint and large *(background-limited)*	use background field	use background field
Target bright and compact *(subtraction-limited)*	beam switch	use object field edge
Target bright and large *(subtraction-limited)*	beam switch	use background field

4.3.5 Science data

The format of the data will resemble that from one or more longslits displaced from each other in the dispersion direction. If more than one longslit is used, it will be necessary to employ a passband filter to cleanly separate the ends of the spectra. In fact each longslit will be made up of separate slitlets, each corresponding to a single row or column in the rectangular input field. Some of these slitlets will be dedicated to the background field. Slitlets from the background and object fields will probably be interleaved. The image formed at the slit from each element may overlap with its neighbour but this does not matter because the elements were also neighbours on the sky. However the slitlets will be isolated from each other by an intervening blank region from which the instrumental background (e.g. scattered light in the spectrograph optics or a variable detector bias) may conveniently be estimated.

On this basis it is expected that data reduction will proceed using standard multiaperture spectroscopy techniques by treating each slitlet as if it were a true multislit. Each slitlet produces a spectrum for one slice of the object field. It is not yet certain how the variation along each slitlet due to the sampling by discrete elements would be dealt with. The main difference from slit spectroscopy would be in the method of background estimation, the signal for which would which would generally come from other slitlets. In some cases, it may be acceptable to form simple average of the background spectra and subtract it from all the object spectra. In other cases it might be necessary to model the variation of the background over the field.

4.4 Imaging

4.4.1 Overview

This mode is required to support the spectroscopic modes. The instrument can be rapidly converted into an imager by selecting a clear aperture using the mask changer and selecting a plane mirror (with fixed tilt) rather than a grating. All imaging observations will require a filter to be selected to optimise the image quality by limiting the passband in the presence of chromatic aberrations. The spectroscopy support functions are listed below.

4.4.2 Mask preparation

In most cases, suitably accurate astrometry of the target field will not be available. This would be provided by taking direct images of the field with the instrument some time ahead of the spectroscopic observations. Software will be provided to extract the necessary astrometric information and convert to coordinates in the mask frame. These data will then be passed to the mask maker.

4.4.3 Target acquisition

It will usually be necessary to acquire the field by taking an image with the instrument in imaging mode. For slit spectroscopy, a direct image of the sky will be compared with an image of the mask to generate the offset required to map the targets onto the slits. Software will be provided to do these calculations.

5. General operational issues

Operational issues which are common to the main observing modes of the instrument are discussed below.

5.1 Telescope observing mode

The instruments can be used in *Classical*, *Remote* or *Queue* observing modes since they will be fully automated. This document assumes that the instrument is used in queue mode since this is considered to be the most challenging. Consequently, each observing scenario assumes that the *investigator* pre-plans the observations, so that an *observer* at the telescope (who is not necessarily the investigator) can carry out the observations with a high degree of success. The investigator will be aided by appropriate software tools to provide them with information on the capabilities of the instrument and, if appropriate, to design the masks with the aid of direct images taken with the instrument ahead of time. The observer will have access to the same information and will be equipped with other software tools to allow them to execute the queue and to assess the data quality in real-time.

5.2 Instrument focus and image scale

The focus of the optical system can be altered by moving the detector along the optical axis via the detector focus and translation stage.

The surface to which the instrument is internally focused is termed the Instrument Focal Surface (IFS). The collimator and camera will be set so that the IFS is focused on the detector. Strictly the IFS is the surface over which an image of the detector (formed in reverse by the camera and collimator via the imaging mirror) is in focus. In general this will not be completely flat. The ADC-C will be set so that the telescope produces sharp images of the sky at the IFS when the telescope focus is within a specified range. The surface over which the telescope give sharp images of the sky is termed the Telescope Focal Surface (TFS). When discussed in the context of GMOS, the TFS is defined by the combination of the telescope and the ADC-C. When the TFS and IFS coincide, sharp images of the sky will be produced on the detector.

Normally the IFS is defined to be coincident with the mask plane. However, because the IFS may be curved (and because the TFS is also curved), it is necessary to define the location within the field where the TFS and IFS must coincide. Normally this would be the centre of the field. However, for some types of observation, it will be necessary for the TFS and IFS to coincide at some other place. For example, wide field applications would benefit if the focus was optimised half way out to the field edge so that the TFS/IFS intersection is a ring with radius roughly half that of the full field. In contrast the IFU will require the focus to be optimised for the central region of the field although it is possible to build in a physical focus offset so as to match that for the wide-field focus. Changes in the intersection of the IFS and TFS can only be effected by moving the TFS since there is no provision for changing the position of the IFS. This means that, when considering the internal focus of the instrument, it is only necessary to ensure that images of objects on a *plane* surface (normally the mask plane) intersecting the IFS at some fixed, specified location with the field, form sharp images on the detector.

The instrument focus can be determined using *Hartmann masks* installed in the filter wheels and a mask containing pinholes installed at the nominal instrument input focus, defined by the mask plane. Each one of a pair of Hartmann masks has opposing halves of its aperture blocked off. Exposures are recorded with each of the Hartmann masks in the lightpath in turn. If the instrument is out of focus, there will be a shift between each pair of images of the same pinhole. The tests can be done in imaging or spectroscopic modes with appropriate choices of light source (e.g. arc lamps for spectroscopy) and filters/gratings.

The focus may need to be altered in operation for a number of reasons.

(a) To optimise the focus for the desired wavelength and position within the field. This is simply because of the intrinsic characteristics of the optics which produce variations in image quality as a function of wavelength and position within the field.

(b) To allow for temperature changes which affect the focus position due to:

(i) the change in refractive index of the glass
(ii) changes in the spacing between optical elements

(c) To compensate for flexure as part of the Flexure Compensation System.

Note that a change in focus may also alter the *image scale* on the detector since the camera is non-telecentric. This is unlikely to be a problem for effect (a) since the distortions will be accounted for by separate distortion maps made for each wavelength of interest (for direct imaging) and by the extraction software (for spectroscopy). However the thermal effect (b) will be more of a problem since it requires knowledge of the variation of the distortion with temperature and, if the temperature changes significantly during the course of an observation, it will result in smearing of the image (i.e. an effective degradation of image quality) at the edge of the field and possible errors in measurements of radial velocity. For this reason, it is desirable to allow the observer to specify one of two modes:

IFOC-1 Hold the focus constant during an observation (or sequence of observations). This will reduce changes in the image scale at the expense of a possible degradation in image quality as the optical system becomes defocused. Although the defocus will be the same throughput the field, the effect on image quality may vary over the field because of e.g. the curvature of the detector field.

IFOC-2 Allow the focus to be updated as rapidly as required to optimise the image quality at the expense of a greater change in image scale resulting from temperature changes. This could lead to image smearing at the edge of the field during an exposure.

The OCS/DHS must record in the image headers, the temperature at which the observation was made, the focus value used and the focus compensation mode (IFOC-n). It may be necessary for temperature information from temperature sensors outside the instrument to be recorded as well.

5.3 Flexure compensation

Flexure compensation is necessary because of the large size of the instrument, in particular the long light path, and the tight tolerance on flexure imposed by the requirement to measure radial velocities to high accuracy. The philosophy adopted is that the optical components will be constrained to move in such a way that the only effect of flexure will be a translation of the image of the slit on the detector. Most of this can be removed by translating the detector orthogonal to the optical axis using a look-up table to calculate the repeatable parts of this motion.

The way in which the FCS works depends on the accuracy to which the centroid of a given spectral feature needs to be measured. We can define two regimes:

High-accuracy For observations requiring high velocity accuracy (e.g. 1-2km/s), wavelength-calibration observations will be recorded bracketing the science exposures as the telescope tracks the field. In this case, the FCS must ensure that the image of a spectral feature does not move (by more than a specified small amount) during an exposure, i.e. between that the time of one calibration observation and the next. The motion of the image must be controlled to be high accuracy (typically 0.2 pixel). Shifts between different science exposures taken in a sequence will not matter since they can be accounted for in the data reduction and the size of the shift will be known precisely from the interleaved calibration observations. Therefore it is only necessary for the FCS to compensate for flexure *differentially* over the maximum period envisaged between successive calibration exposures, 1 hour.

Low-accuracy For observations where great velocity accuracy is not required, wavelength-calibration observations may be taken when the telescope is not tracking the target often at some other time of the night, or, most conveniently, during the day while parked. In this case, the FCS must correctly account for the full range of flexure between the calibration and science exposures, which could be several hours, and allowing for widely different telescope attitude. However the required accuracy of the compensation will not be as great as for high-accuracy work (typically 0.5 pixel). For this type of observation, the FCS must be able to compensate in an *absolute* sense for the full amount of flexure expected within its operation limits (ZD ≤ 75 deg).

The FCS will support both types of observation: it will provide full compensation over the entire operational attitude range of the instrument. Therefore we may define a single operational mode as follows.

FLEX-1 Compensate for flexure at all times while the instrument is used within its operational attitude limits. This will give sufficiently accurate registration between the science exposure and wavelength-calibration exposures taken at a different time and/or a different telescope attitude and provide accurate compensation over the timescale of single exposures..

The OCS/DHS must record in the image headers the data necessary to fully describe the correction that has been applied.

5.4 Atmospheric dispersion compensation

The ADC may introduce field distortion which varies as the ADC is reconfigured when tracking a target. This is clearly undesirable but is inevitable given the externally-imposed requirement that the ADC be placed close to the instrument. This means that the vertex angles of the prisms are inconveniently large, leading to a relatively large distortion that varies as the prisms rotate.

There is another effect which has the same qualitative effect: the distortion caused by the dependence of atmospheric refraction on zenith distance (this should not be confused with atmospheric dispersion, which the ADC is designed to eliminate). The distortion, which is largely independent of wavelength, is caused by the fact that the refraction is slightly different at the top of the field compared with that at the bottom.

An analysis of the distortion from both atmosphere (ATM) and ADC is contained in *The effect of ADC and atmospheric distortion, Jeremy Allington-Smith, 21 Oct 1996*. Possible strategies include the following.

a) Reduce the field over which radial velocity measurements of the required relative accuracy are to be obtained. This is because both ATM and ADC distortion scales with radius within the field.

b) Observe the field only close to the zenith with the mask designed to take into account the ADC distortion at the zenith (the ATM distortion will be small).

c) Work close to a designated zenith distance (e.g. at transit), making sure that the mask is designed to take into account the correct ADC+ATM distortion at that ZD. The range of ZD for which the mask can be used, and therefore the time at night during which the observation can be made, will necessarily be limited.

d) Turn the ADC off (null the prisms) so that the ADC distortion is fixed to that at the zenith. This removes the variable distortion but introduces wavelength-dependent errors because of the uncorrected dispersion. These errors will be both in the recorded flux (leading to errors in relative flux calibration with wavelength and a reduction in signal/noise at the ends of the spectrum) and in the wavelength of spectral features (leading to velocity errors for lines at the ends of the spectrum). The slit position angle can be chosen to minimise atmospheric dispersion. However the relative velocities will still be correct since the same ensemble of features will be used in each spectrum to determine the object's overall radial velocity.

e) Configure the ADC to give optimal dispersion correction at a designated ZD (typically at transit) and then maintain it in that same configuration. The mask design should take into account the ADC+ATM distortion at that ZD. Dispersion effects will only be fully corrected at one particular instant during the observation but the residual effect will be relatively small, especially if the slits are aligned at the parallactic angle. As with (c), there will be a limited window over which the observation can be done. *This option assumes that the ADC distortion is accurately known at all ZD, or that the images used to design the mask were taken at the same setting of the ADC.*

For fields which can only be observed at large airmass, the only strategy available will be (a) since the atmospheric distortion will always be the limiting factor, even if the ADC is turned off. In extreme cases, high accuracy radial velocities will only be available for single objects.

For these reasons, it is likely that there will be three different modes of operation for the ADC.

ADC-1 Null the ADC so that that no dispersion correction is provided but so that the distortion is always the same.

ADC-2 Put the ADC at a particular setting (optimised for a particular observation) and keep it fixed..

ADC-3 Continuously reconfigure the ADC (with an update rate that is short compared with the duration of a typical exposure) so that it always provides the best correction, at the expense of variations in the distortion.

The best strategy to adopt will depend critically on the requirements of the particular observation. The investigator will need the aid of a software tool that simulates both the dispersion and distortion effects.

The TCS must:

- *include a satisfactory model of the atmosphere (and have access to adequate information which affects the model, such as the temperature and pressure) so that the telescope can, by calculation, guide at a specified reference wavelength which may be different from that at which the WFS operates. The reference wavelength will normally be that of the middle of the spectrum or of a particular feature in the spectrum. Unless this is so, systematic flux and velocity errors will be introduced into the data.*
- *work with the GMOS ICS to correctly account for distortion caused by the atmosphere and ADC when calculating the position offset between the science targets and the reference star observed by the WFS. The scheme adopted is that the TCS will work in a coordinate system from which the ADC distortions have been removed and the GMOS ICS will then apply the necessary distortion correction.*

The OCS/DHS must record in the image headers:

- *The zenith distance, field orientation and other pointing information*
- *The ADC mode used (ADC-n) and the chosen ADC setting if ADC-2.*
- *Details of the atmospheric model used by the TCS (perhaps a unique identifier for the model plus the current values of the input parameters — e.g. temperature and pressure).*

Information on the distortion information used to design the mask is implicit in the mask design itself. The mask used will also be identified in the header.

5.5 Wavefront correction

There are two types of wavefront sensor (WFS): the On-instrument WFS (OIWFS) which is closely integrated within the instrument and one or more Peripheral WFS (PWFS) incorporated in the telescope A&G unit. The PWFSs patrol a field extending to ~ 14 arcmin diameter — outside the field passed to the instrument by the science fold mirror. The information from these various WFSs is used to correct the telescope mount (i.e. guiding) and to correct the telescope optics as follows:

a) The telescope primary mirror figure and other active optics (aO) functions are controlled by means of the PWFS which views a suitable reference star. This star may be chosen in real-time by the observer from an on-line catalogue or be pre-selected by the investigator when the observations are being planned (using the same catalogue). It is assumed that the operation of the aO system is a background task that does not interfere with the main scientific observations.

b) Fast guiding (to control the articulated secondary mirror) is preferably done by means of the OIWFS. Its probe will be positioned so that it samples an appropriate reference star within the OIWFS patrol field (different from that used by the PWFS). It is assumed that the TCS will automatically offset the probes (peripheral or on-instrument) as required during the acquisition sequence, so that they remain in lock throughout, and take into account such effects as differential atmospheric refraction, both chromatic and non-chromatic and (if required) to compensate for variable distortion in the ADC. It is possible that the other PWFS could be used to provide guide signals if it was not possible to use the OIWFS. In this case, the OIWFS could still provide some (slow) information on differential flexure between the PWFS and the instrument if it was able to lock onto a faint star which was too faint to provide full wavefront correction.

Control of the OIWFS requires integration between the TCS and ICS.

The TCS must correctly calculate the position to which the OIWFS should be moved, allowing for:

- *atmospheric refraction (both dispersion and distortion) and ADC distortion.*
- *the difference between the wavelengths at which the OIWFS operates and that required for the science observation (usually within the wavelength range projected onto the detector).*

It should be possible for both the PWFS and OIWFS to be used together in cases where the OIWFS can only provide slow correction signals to correct for differential flexure between the instrument and PWFS.

5.6 Telescope focus

An essential prerequisite for all observing modes is that the telescope is correctly focused on the instrument. What this actually means depends somewhat on the observing mode. For aperture and integral field spectroscopy, the telescope must produce sharp images over the surface defined by the masks or the IFU fields (both object and background). For imaging, all that matters is that sharp images are produced on the detector. However the requirement that the filters be illuminated only by parallel light (to avoid focus shifts when changing filter) also means that the telescope should be correctly focused on the instrument.

The Instrument Focal Surface (IFS) and Telescope Focal Surface (TFS) are defined in Section 5.2. The action of focusing the telescope means making these surfaces intersect at some specified location within the field. This can only be done by changing the spacing between the primary and secondary mirror so as to change the position of the TFS since there is no facility to change the position of the IFS.

However changing the TFS will, in general, result in a change of image scale at the IFS leading to the possibility of misalignment between targets and slits at the edge of the field. However the change of scale should be calculable so that it can be incorporated in the mask design. It is therefore essential that the mask is designed with a particular *focus strategy* in mind. Note that the temperature of the telescope will also affect the image scale as the primary/secondary distance is changed to maintain the same location of the TFS.

Because of the image scale changes that may result from the requirement that the telescope remains correctly focussed as the temperature changes, it may be necessary to consider the following operational modes for the telescope:

TFOC-1 *Hold the telescope focus constant during an observation (or sequence of observations). This will reduce changes in the image scale at the expense of a possible degradation in image quality as the telescope becomes defocused. Although the defocus will be the same throughput the field, the effect on image quality may vary over the field because of e.g. the curvature of the TFS..*

TFOC-2 *Allow the focus to be updated as rapidly as required to optimise the image quality at the expense of a greater change in image scale resulting from temperature changes. This could lead to image smearing at the edge of the field during an exposure.*

The OCS/DHS must record in the image headers, the temperature at which the observation was made, the focus value used and the focus compensation mode (TFOC-n).

The best way to assess the telescope focus is to examine the output from the OIWFS. The signal processing should result in an output that records the focus independently of other wavefront parameters. This requires that the instrument is set up during commissioning so that the OIWFS is confocal with the IFS. An offset between the OIWFS and IFS is allowable provided that the offset is well calibrated and within the range over which the WFS is sensitive to focus. The ability to work with a calibrated focus offset is required in any case to allow the focus to be optimised for some other location in the field or if the focus was to be assessed at some location in the field away from the centre.

The procedure during normal operations is therefore to acquire a bright star,1 known to have a single point-like image, and to examine the OIWFS focus output while varying the telescope focus. Other methods can be devised which are independent of the OIWFS but these should only be needed for commissioning.

The telescope focus should be within a specified range otherwise this would indicate that the instrument was incorrectly mounted. Even if the telescope focus could be altered to accommodate an error in the instrument mounting, this might still lead to a significant error in the image scale (see above). It will also be necessary to ensure that the PWFSs and OIWFS are confocal within a specified tolerance.

As a final check that both the telescope and instrument are both correct, direct images of reference stars can be examined with GMOS in imaging mode. However their sharpness does not necessarily indicate that both the instrument and telescope focus are separately correct. An error here might indicate that the OIWFS and input spectrograph focus were not confocal.

5.7 Instrument database

During commissioning the following data will need to be recorded so that it can be retrieved automatically by the ICS during operation as an aid to the observer and (optionally) be made available to the investigator when planning the observation.

a) Optimum camera focus as a function of wavelength/passband (at a defined reference temperature)

Optimum camera focus as a function of temperature (at a defined reference wavelength and field location).

a) Image quality as a function of instrument configuration and wavelength
b) Dispersion configuration required to select a given wavelength range and throughput
c) Mask-detector distortion maps at each wavelength/passband
d) Sky-mask distortion maps at each wavelength for each ADC configuration (depending on which ADC modes are used)
e) Default wavelength calibration for generic masks used with standard dispersion configurations
f) Information required for the flexure correction system (a look-up table). This also includes (a) and (b).

The DHS must record the version of the database which has been used for the observation. This could be done either by recording the entire database in the headers or a title which uniquely identifies the database, provided that the necessary different versions of database were also recorded in the data archive.

5.8 Calibration

The calibration of data will be done using measurements obtained from the sky and from the GEMINI Facility Calibration Unit (GFCU). In the latter case the instrument will be fed light from the GFCU mounted on another port of the Instrument Support Structure (ISS) via a particular orientation of the science fold mirror. This will preclude light from the sky reaching the TFS at the same time with the result that the OIWFS will not function during calibration exposures. Calibration light will reach the instrument through the ADC (unless removed).

The GFCU will provide wavelength calibration and flat-field illumination that has appropriate spatial, temporal and spectral uniformity (as outlined below) to mimic the illumination through the telescope. This will ensure that that the calibration obtained via the GFCU is directly applicable to sky data.

The main types of calibration that the instrument require are listed below.

5.8.1 Wavelength calibration

This can be obtained from a lamp which provide sufficient bright emission lines within the spectral band under consideration. This will be difficult to achieve at the highest dispersions where the simultaneous wavelength range on the detector is very small. In such cases it may be necessary for the investigator to procure a special lamp. An alternative would be to use a calibration source for which specific lines could be selected (perhaps a Fabry-Perot system). In some cases, additional wavelength calibration may be obtained from measurements of night-sky emission lines — but these are not always suitable due to blending.

5.8.2 Flat-fielding

To remove short-scale variations in the response of the detector requires the instrument to be supplied with illumination that is uniform over the field and smooth with wavelength and generate sufficient counts at all wavelengths without saturating messily (e.g. charge bleeding) at other wavelengths. The GFCU will provide this source of illumination via a variety of lamps and (optionally) with colour-balance filters. Additional flatfield information may be obtained from observations of the twilight sky to give a source of illumination that can (if the field is carefully chosen) provide high levels of spatial uniformity at the expense of smoothness with wavelength.

5.8.3 Flux calibration

This is required to correct an observed spectrum to a scale of flux density. The only way to provide this information is to observe spectrophotometric standard stars of which many have published spectra given in absolute flux density units. Observations which require absolute flux calibration will need to be done in such a way that *all* the light from both the standard star and target is recorded. For aperture spectroscopy this requires the use of a slit which is wider than the image profile. Otherwise the flux calibration is only relative. Special consideration needs to be given to the effects of atmospheric dispersion which can cause error in the relative flux scale as a function of wavelength.

5.8.4 Geometrical calibration

Depending on the main operational mode of the instrument, various types of geometrical calibration may be required. These are discussed separately in the Sections dealing with each mode. In general, these require light from the GFCU employing either the flat-field or wavelength calibration light sources.

6. Generic observing scenarios

In this section, we present generic observing scenarios which should be applicable to a broad range of observations. Specific observing scenarios, based on real projects, are presented in the appendix.

6.1 Multiaperture spectroscopy

Where necessary, the instrument configuration is described using the following notation *(focal plane, filter, disperser) + cal(lamp)* where *cal* refers to the configuration of the calibration unit. 'lamp' is either white-light (*white*) or wavelength-calibrator (*arc*). Filters are described either as *i-filter* for imaging (usually a standard bandpass filter) or *s-filter* for spectroscopy (order sorting and non-standard passband filters).

6.1.1 Assumptions and requirements

In this example of a generic observation using multiaperture masks, it is assumed that:

1 The operational mode is queue observing and the observations are undertaken by an *observer* who is not necessarily the *investigator* (i.e. the person responsible for the scientific investigation). This is the most difficult case: the procedure for other observing modes can be derived trivially from this case.

2 Astrometry of the required precision does not already exist but must be obtained from the instrument used in imaging mode and that there is no need to design and manufacture the masks very close to the time of the spectroscopic observations.

3 Wavelength calibration is required while the telescope is *on target* rather than at any other position. This is appropriate for observations requiring accurate wavelength determination.

4 One particular target acquisition method is used which makes the least possible demands on the repositioning accuracy of the mask mechanism. Many others may be devised but the one described has been used successfully with existing multiaperture spectrographs.

5 For instrument calibration, the following *setup* masks are required

i-focus-masks: a mask suitable for use with Hartmann masks installed in the filter wheels for focus checks in a specified passband in imaging mode *and/or*

s-focus-mask: a mask for focus checks in spectroscopic mode

matrix-mask: a mask consisting of an array of tiny holes to measure the distortion between the IFS and detector at different wavelengths.

6.1.2 Planning the observations

Before the spectroscopic observations can be made, images of the fields are required to obtain the necessary astrometry and to select suitable targets. Queue or remote observing allows this to be done conveniently by scheduling a short imaging run before the spectroscopic observations. In most cases the imaging would probably be done at least a week before the spectroscopy, to give time for detailed photometric analysis for target selection.

1 The investigator plans the imaging observations required to obtain the astrometry and sends the plans electronically to the observatory in the form of an *observing file*.

2 Each field is imaged in the specified passbands and standard stars observed for photometric calibration. The data are then sent to the investigator.

3 The investigator carries out the following functions:

a) obtains local astrometry for each candidate target in the coordinate frame of the detector
b) determines which stars are to be used for acquisition (generally a set of > 2 positional reference stars to be observed through holes in the mask plus a local reference star to locally recalibrate the telescope pointing model)
c) determines the 'guiding' strategy required to produce the desired image quality (given the seeing) and the positions of suitable reference stars for the OIWFS if required (we assume that the reference stars for the PWFS are selected at the telescope by software linked to, for example, a guide star database).
d) designs the masks by allocating apertures to each object of interest and adding the acquisition holes. This information is recorded in an *Object Definition File* (ODF).
e) determines which other *generic* masks are required (e.g. a longslit mask)
f) selects the required instrument configurations in concert with the mask design: the choice of grating, the diffraction order, the grating tilt and the s-filter to be used.
g) determines the strategy to be used for atmospheric dispersion depending on the balance between chromatic errors and field distortion.
h) determine where the telescope should be focused within the field, depending on the field to be used
i) determines the strategy to be used for focus compensation, depending on the requirements for stability of the image scale
j) determines the required observing conditions for each observation, generally:
- the seeing and/or
- the required performance of the telescope systems in obtaining the required image quality (depends on the chosen guiding strategy and the azimuth with respect to the prevailing wind direction)
- photometric stability and absolute transparency
- water vapour (for wavelengths longer than 0.7 μm)
- the range of altitude when the observation may take place for cases where ADC or atmospheric distortion limits the use of a particular mask

All this information is sent to the observatory. The investigator may be assisted by:
- a software tool containing all the necessary information about the instrument and the telescope (including the ability to simulate the image quality to be obtained for a given 'guiding' configuration)
- a software tool to assist with the mask design
- a catalogue of suitable reference stars

4 The masks are made at the observatory by technical staff .They first generate *Mask Definition Files* (MDFs) from the ODFs. There may be more than one MDF for each ODF if it is necessary to make different masks for the same field for use at different elevations Each mask is checked for quality and labelled..

6.1.3 Day-time setup

Once the data has been received by the observatory and the masks made, the spectroscopic run can be scheduled. This deals with the preparations that are needed during the day before the spectroscopic observations are carried out.

1 The specified masks, gratings and filters are loaded into the instrument and their location within each changer determined (by reading their bar-codes automatically). In addition the setup masks must be loaded.

2 The general health of the instrument is checked and the focus checked (probably just the focus zeropoint; see Section 5.2).

(i-focus-masks, i-filter, mirror) + cal(white)
and/or
(s-focus-masks, s-filter, grating) + cal(arc)

3 The focus settings for any new filters (because of chromatic effects) are determined and entered into the filter database.

4 Detector bias exposures are taken.

5 Optionally, geometric calibration exposures could be taken to determine the orientation and position of each mask within the focal plane assembly.

(mask, i-filter, mirror) + cal(white)

6 For each combination of mask and dispersion configuration, dispersed flatfield exposures are taken to provide a spectroscopic flat field. Note that, once set, it is desirable not to change the grating tilt unless another tilt-value is required for a different dispersion configuration.

(specific-mask, s-filter, grating) + cal(white, colour balance filter)

7 Optionally, for each combination of mask and grating configuration, wavelength calibration exposures are taken to obtain a default wavelength calibration.

(specific-mask, s-filter, grating) + cal(arc)

6.1.4 Procedure at the start of an observing sequence

At the start of an observing sequence involving GMOS, the internal instrument focus and that of the telescope can be checked. This is an optional step as the focus control loop should maintain the focus at the correct value at all times.

1 The internal instrument focus is checked. This would have been done in detail during the daytime instrument setup but it might be desirable to check that images of generic masks (particularly the matrix mask which has very small holes) appear sharp when back-illuminated by the sky or by a calibration lamp.

(matrix-mask, i-filter, mirror) + cal(white)

2 The best telescope focus is now determined as described in Section 5.6. Since this only involves the OIWFS, the instrument configuration does not matter.

3 As a final check that both the telescope and instrument are both correct, direct images of reference stars can be examined. However their sharpness does not necessarily indicate that both the instrument and telescope focus are separately correct.

(no mask, i-filter, mirror)

6.1.5 Procedure for each new target field

This section details the procedure required for each observation of a new field.

1 Point the telescope to a bright position reference star close to the target field for local recalibration of the telescope pointing. The position of this star must be tied to the target coordinate frame by an amount much less than the size of the acquisition holes. This setup may be unnecessary if the global pointing model is good enough.

2 Point the telescope to the field centre and set the instrument rotator to the required position angle.

3 The PWFS is locked onto a pre-selected reference stars for the purpose of (slow) guiding and correction of the primary figure (aO) as follows:

a) the probe is moved so that the star fall within the imaging area;
b) if necessary, offset the telescope to refine the position of the star within the field.
c) the star position within the probe field is recorded by the TCS or ICS (the *probe reference position*)
d) when the signal is stable, guide signals are sent to the TCS so as to keep the star fixed at the same location within the fixed probe fields without dragging the telescope.

4 The OIWFS is locked onto a pre-selected reference star in the same way as for the PWFS (above). The probe is allowed to vignette the science field as viewed as a direct image (provided that the reference stars are not obstructed) but the mask will have been designed so that the probe does not vignette any of the slits or holes in the mask.

5 The field is imaged through the mask (with fast windowed readout as appropriate)

(specific-mask, i-filter, mirror)

6 The image data are displayed and analysed to determine the best-fitting mask-field offset from vectors joining the geometric centres of the holes with the image centroids. If a number of acquisition holes have been used, stars with poor positions can be edited out to refine the fit.

7 The telescope is offset by the calculated amount. The probe reference positions should move in concert with the telescope offset so that the offset is performed under *closed-loop control* (this may also require a physical movement of the probe).

This tracking must be done by at least one of the probes (normally the OIWFS since it will have a fast update rate).

8 Optionally, a further direct (acquisition-check) image is taken for later analysis.

(specific-mask, i-filter, mirror)

9 The dispersion configuration for the spectroscopic observation is selected by putting the desired grating in the light path (the tilt would normally have been set earlier) and selecting the appropriate spectroscopic filter.

(specific-mask, s-filter, grating)

10 Wavelength calibration exposures are taken if required, unless the stability of the instrument and the nature of the observations make this unnecessary. The science fold mirror will be reconfigured to allow light from the calibration system to enter the instrument. This step may also be desirable if the grating tilt had to be altered since the last wavelength calibration for this configuration was taken, unless the repositioning accuracy is very good. This will probably not interrupt guiding by the PWFS but will cause the OIWFS to lose lock.

(specific-mask, s-filter, grating) + cal(arc)

11 Remove the calibration light by reconfiguring the science fold mirror so that the instrument views the sky. The OIWFS must now regain lock on its reference star using the same probe reference position as before. This should ensure that the telescope pointing will be exactly the same as before the calibration exposure was taken. Note that the PWFS will not have lost lock so the catch-up motion of the telescope should be very small. This step is only necessary if step 10 was also followed.

12 Start the science exposure.

13 While the spectroscopic exposure is proceeding, analyse the acquisition-check image to check that the acquisition was successful. If it was not, terminate the spectroscopic observation and return to step 5.

14 Upon termination of the spectroscopic observation, check the data using the quick-look system and proceed depending on its quality. Return to step 1 for each new field or to 12 for each observation using the same mask or to 10 if a fresh wavelength calibration is required, for example if the dispersion configuration is changed.

6.1.6 Calibration

The various types of calibration required are summarised below.

1 Geometric calibration. For multiaperture spectroscopy in particular, it is important to determine the coordinate transformations between the sky, IFS, detector and each mask. These transformations are required for a number of reasons including: (a) the determination of slit positions from image data to facilitate mask design; (b) the correct calculation of telescope offsets from displacements measured at the detector to facilitate acquisition and (c) to ensure that the acquisition stars appear within the holes in the mask during the initial telescope pointing. In general, these transformations will have a chromatic component. The mask-detector transformation can be deduced by taking images through each mask loaded in the mask changer and comparing the expected positions of the apertures with those predicted if the mask and its mounting were perfect. For example, this may account for shifts in the way that the mask is mounted in its holder. This may need to be re-determined every time a new mask is introduced into the instrument and would normally be a daytime operation. The IFS-detector transformation is determined by taking images through a matrix mask in different passbands. The sky-detector transformation is determined by taking images of fields with very accurate pre-existing astrometry. Both the IFS-detector and sky-detector transformations would normally be determined during commissioning and periodically re-checked.

2 **Flatfield and bias calibration**. These determine the relative response of the each pixel of the detector. The *bias* is taken with no light incident on the detector to determine the electronic bias level. This might also provide some check on the CCD gain. For spectroscopy, it will be necessary to determine the flatfield correction with dispersed white light for each combination of mask and dispersion configuration. This is so that each pixel receives light of the correct wavelength as it experiences in the on-target exposures. In this way, fringing effects can be removed (in the absence of instrument flexure). It also provides a more accurate calibration of the vignetting function since this depends on the dispersion configuration. In most cases, the flat-field exposures would be done during the daytime setup. In exceptional cases, where fringing was a problem, it might be necessary to repeat them while tracking the target field to eliminate flexure problems. If the spatial uniformity of the calibration light is not sufficient to measure large-scale non-uniformity (due to e.g. vignetting) this information could be obtained from observations of blank regions of sky.

3 **Wavelength calibration**. For observations requiring accurate wavelength determination, it may be necessary to take calibration exposures while tracking the target field so as to eliminate the effect of instrument flexure. In the most demanding cases, it will be necessary to interleave these exposures with exposures of the target field so that effect of the flexure can be measured and accounted for in the data reduction. In cases where accurate wavelengths are not required, it may be sufficient to carry out the calibration at the start of the night (perhaps during the day) or at intervals while the telescope is parked. The best strategy for a given observation depends critically on the amount of instrument flexure. Note that this calibration will not remove wavelength errors caused by tracking (which causes the target to move with respect to the slit) since the calibration system will not be able to reproduce this effect. In all cases, the calibration observation would be done with the same mask and dispersion configuration used for the observations of the target field. Supplemental wavelength calibration may also be available. For example, at wavelengths longwards of 0.7 μm there are a large number of telluric emission lines while, at least for some programmes,

the internal wavelength calibration could be checked using observations of radial velocity standards.

4 **Flux calibration**. This is needed to reduce spectra to a *relative* or *absolute* scale of flux density. For *relative* flux calibration, it is necessary to observe a spectrophotometric standard star. This should be observed at the same airmass to avoid errors due to differential extinction. (If the ADC were not used, this would also be important to ensure that wavelength-dependent slit losses were the same for the standard and target observations.) For *absolute* flux calibration, it would be necessary to observe both the target and standard with a very wide slit so as to admit all the light. Again, it would be necessary to observe them at the same airmass so that the atmospheric extinction was the same. Generally, the standards would be observed after a complete sequence of observations of the same field, perhaps just once or twice per night. Usually, it would be sufficient to observe the standard star with a generic single-aperture mask. Any systematic difference in flux calibration over the field, because of vignetting, for example, would be accounted for in the flat-field calibration.

6.2 Integral Field Spectroscopy

Although some of the procedures are similar to those for multiaperture spectroscopy, many others are quite different.

The IFU is deployable at the TFS in the same way as for a slit mask. In addition to its main *object field*, each IFU will include a smaller *background field* which is optically identical to the object field, except for its field size. The displacement between the fields will be ≥1 arcmin. See Section 4.3.4 for a description of the available methods of background subtraction.

The number of output slits will probably be two, but it may be possible to operate with a single output slit with some compromise in field size. There is no mechanism to switch between one-slit and two-slit remotely modes but it is expected that some form of manual changeover will be possible. If two output slits are used, the spectra from each slit may overlap in the dispersion direction in which case a passband filter will generally be required to eliminate or minimise the overlap.

6.2.1 Assumptions and requirements

These are mostly the same as for aperture spectroscopy (Section 6.1.1) except that:

- Astrometry of the same accuracy is not generally required (item 2) since the pointing of the telescope can be determined from the data.
- On-target wavelength calibration (item 3) is less likely to be necessary since it is not expected that observations which require the ultimate in velocity accuracy will use this mode.

We further make the following assumptions.

- Only one IFU is to be used

- The IFU is configured with two output slits
- Background subtraction is done by beam-switching

In addition, data reduction software tailored to the needs of integral field spectroscopy is needed.

- To produce a pseudo-image of the sky by reformatting an exposure taken through the IFU. There are two variations: (a) starting from an undispersed exposure in which case the images of the output elements are simply relocated in the right order in which they appear on the sky, (b) starting from a dispersed exposure in which case the spectra must also be summed over wavelength for a specified bandwidth.
- To reduce beam-switched data. This takes a sequence of pairs of observations taken with the telescope pointing either at the target or at the background region and processes them to produce the final exposure. This procedure allows the intrinsic variations of each IFU element to be removed.
- To inspect the (x,y,λ) data cube by stepping through in wavelength (for example).

6.2.2 Planning the observations

Because this observing mode is not generally concerned with multiple objects and because the positioning of the telescope can be recreated from the data after the observation, it will not usually be necessary to obtain very accurate absolute astrometry. In most cases, an accuracy of some fraction of the size of the IFU field (typically an accuracy of 0.5-1 arcsec) will be sufficient. There is no particular need to observe the field first with GMOS in imaging mode. Such images can be obtained from any other suitable source.

One complication is that, for background-subtraction modes which make use of the separate background field, it will be necessary to identify clean regions of sky from which the background may be estimated. If beam-switching is to be used, two such regions, symmetrically disposed around the target will be required. Therefore the investigator will need to plan the observations with the aid of an image that covers both the object and background field locations (i.e. a diameter of 1-4 arcmin depending on the finally selected displacement between the fields and the selected subtraction mode).

The configuration of the instrument will need to be pre-planned in much the same way as for aperture spectroscopy. The main difference is that there is no need to design masks. The investigator must still perform the following functions identified under item (3) in Section 6.1.2

- selection of the instrument configuration (3f) regarding the grating choice/tilt and s-filters and any i-filters for imaging. Note that the choice of s-filter is especially important to reduce overlaps between the two banks of spectra. In some cases a custom filter may be required.
- determine the guiding strategy (3c)
- determine the required observing conditions (3j)

As before, the observer will be aided by software tools that contain all the necessary information about the instrument and catalogues of reference stars.

6.2.3 Day-time setup

This follows the procedure for multiaperture spectroscopy closely except that the variety of *specific masks* is replaced by a single *IFU*.

1. The IFU, gratings and filters are loaded into the instrument and their location within each changer recorded (entered into the instrument database).
2. The general health of the instrument is checked and the focus checked (probably just the focus zeropoint).

   (I-focus-masks, i-filter, mirror) + cal(white)

   and/or

   (s-focus-masks, s-filter, grating) + cal(arc)
3. The focus settings for any new filters are determined and entered into the filter database
4. Detector calibration exposures are taken. These consist of bias exposures and white-light flatfields

   (no mask, no filter, mirror)+ cal(white)
5. If necessary, geometric calibration exposures are taken to determine the orientation and position of the IFU within the focal plane assembly and to determine the location on the detector of the output of each element.

   (IFU, i-filter, mirror) + cal(white)
6. Take flatfield exposures with the IFU in place to provide a dispersed flat field.

   (IFU, s-filter, grating) + cal(white, colour balance filter)
7. Take wavelength calibration exposures. These may also be taken at other times for observations requiring high accuracy,

   (IFU, s-filter, grating) + cal(arc)

6.2.4 Procedure at the start of an observing sequence

At the start of an observing sequence involving GMOS, it will be necessary to check the focus of the instrument, telescope and OIWFS as described in Section 5.

6.2.5 Procedure for each new target field

This section details the procedure required for each observation of a new field.

1. If necessary, point the telescope to a bright position reference star close to the target field for local recalibration of the telescope pointing.

2 Point the telescope to the field centre and set the instrument rotator to the correct position angle.

3 The PWFS is locked onto a pre-selected reference stars for the purpose of (slow) guiding and correction of the primary figure (Section 6.1.5).

4 The OIWFS is locked onto a pre-selected reference star in the same way (Section 6.1.5). This must not vignette either of the IFU fields.

5 Optionally, take a direct image of the field

(no mask, i-filter, mirror)

6 Optionally verify the field and the location of the areas for background estimation. This exposure could be used to generate any required offset since the location on the detector surface that corresponds to the position of the IFU fields will be known.

7 Optionally, deploy the IFU and take an undispersed exposure.

(IFU, i-filter, mirror)

8 Optionally, create a pseudo-image of the field using appropriate on-line software. The image is used to verify the field and (further) adjust the pointing as required.

9 The telescope is offset by the calculated amount if required. It is probably not necessary for the offset to be done with the WFS probes in closed-loop but this will be possible for very precise adjustments.

10 The dispersion configuration for the spectroscopic observation is selected by putting the desired grating in the light path (the tilt would normally have been set earlier) and selecting the appropriate spectroscopic filter.

(IFU, s-filter, grating)

11 Wavelength calibration exposures can be taken now if high wavelength accuracy is required, by reconfiguring the science fold mirror and turning on the appropriate lamp in the calibration unit. Note that the OIWFS will lose lock while this is done.

(IFU, s-filter, grating) + cal(arc)

12 Remove the calibration light and return to viewing the sky. The OIWFS must now regain lock on its reference star using the same probe reference position as before. This is only necessary if step 11 was followed.

13 Setup for beam-switching. Having verified that the background-subtraction fields (on either side of the target) are in the expected position, setup the duty-cycle for beam switching. The science observation will consist of a number of pairs (a+b) of observations with the telescope pointed so that: (a) the object field samples the object, (b) the background field samples the object. The size of the offset can be adjusted slightly about the nominal object-background field displacement to allow the location of the optimum beam-switch to be adjusted slightly within the object field.

14 Start the beam-switch science exposure. This should be an automatic procedure in which the operation of the instrument is synchronised with the telescope pointing. The observer should have the ability to examine any one of the individual exposures of which the sequence is comprised, for example to verify that the background-estimation region is indeed empty.

(IFU, s-filter, grating)

15 Upon termination of the science observation, check the data using the data analysis system and proceed depending on its quality. Return to step 1 for each new field or to 11 or 13 to make a further observation of this field.

6.2.6 Calibration

In general the procedure for calibration will the same as for multiaperture spectroscopy (Section 6.1.6).

1 **Geometric calibration**. As for Multiaperture spectroscopy, the coordinate transformations between the sky, IFS, detector and the IFU output slit must be known. In this sense the IFU is treated as if it were a mask with the location of each element as it appears on the detector being measured and recorded. However it is hoped that, aside from the fore-optics, the IFU will be built so that the input and output elements are on a strictly regular grid. If so, it will only be necessary to account for geometric distortion within the main optics — which will be the same as for multiaperture spectroscopy — and to measure the average element spacing at the output. It will also be necessary to map the layout of the spectra as function of wavelength. Operationally this could be done with a dispersed white-light exposure, such as is required for dispersed flat-fielding or with a wavelength calibration lamp to provide additional information in the dispersion direction. This may be need to be backed up by exposures taken with a regular grid or grating at the input end (e.g. a Ronchi grating) to provide highly-accurate measurements of the geometry. However, this would normally be confined to commissioning and maintenance. Geometric effects will be expected to vary slightly depending on the wavelength range selected.

2 **Flatfield and bias calibration**. The bias calibration relates only to the detector and so are the same as for other observing modes. Dispersed flatfield exposures are also required and would be done in exactly the same way as for multiaperture exposures. They will also provide geometric information (see above). Note that additional, second-order, flatfield effects may be removed if beam-switching is used for background estimation.

3 **Wavelength calibration**. The requirements for this are the same as for multiaperture spectroscopy. These exposures may also provide geometric information (see above).

4 **Flux calibration**. This is the same as for multiaperture spectroscopy except that careful account must be made of the flatfield calibration (i.e. relative throughput) of the IFU elements on which the light from the flux standard falls. One way to obtain the relative throughput of elements as a function of wavelength (but not absolutely) would be to

observe a standard star and raster the telescope pointing so that the star is scanned over the entire IFU field during the course of a single exposure. The variation of the velocity of the star over the field does not matter since we are seeking only to measure the relative throughput as a function of wavelength.