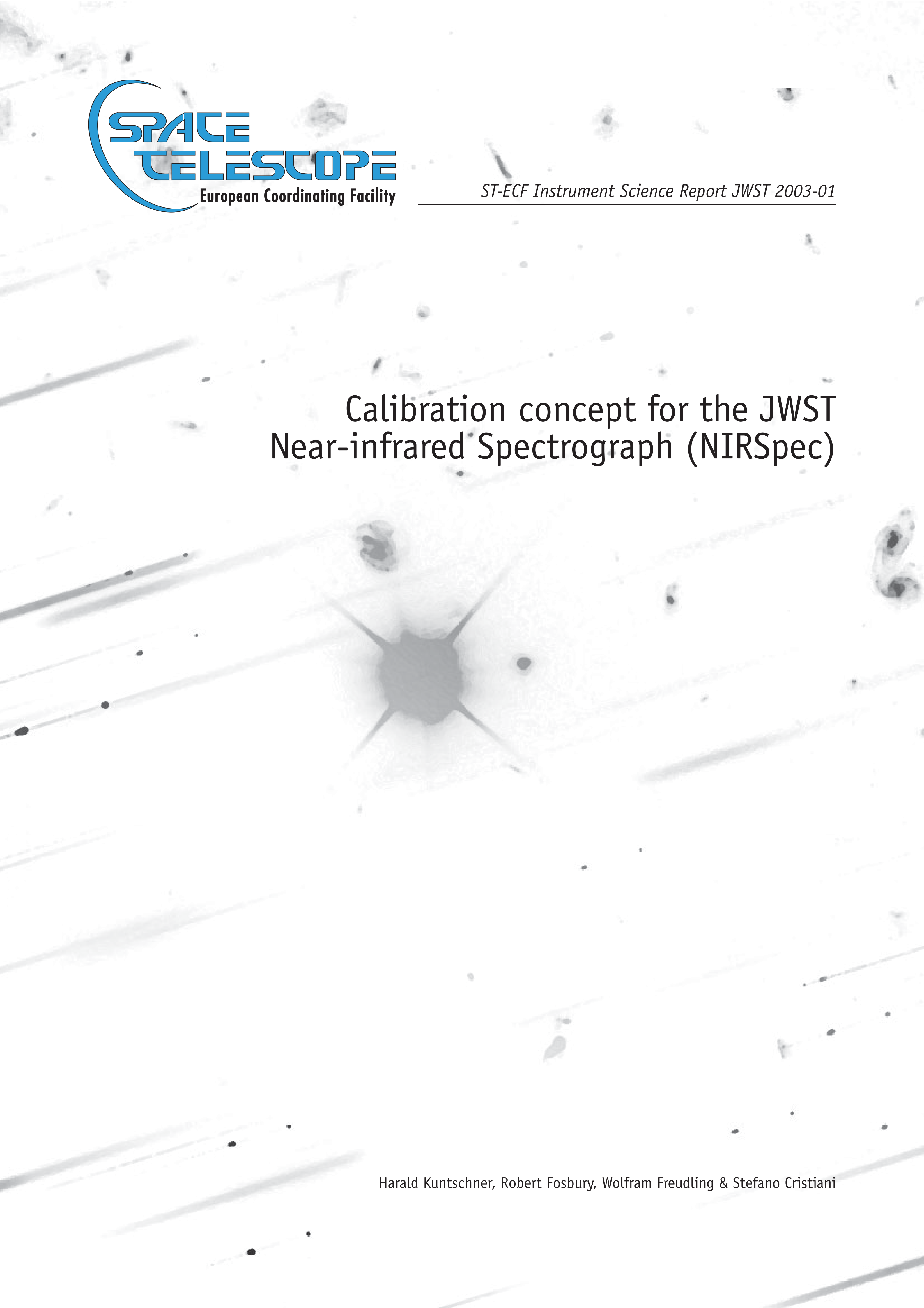

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ABSTRACT

This document provides a discussion of the basic calibration needs and calibration time consumption for the Near Infrared Spectrograph (NIRSpec) on JWST. The current version assumes that slits for multi object spectroscopy will be formed via a micro-electromechanical system and that NIRSpec will carry internal continuum and line lamps.

1. Introduction

The James Webb Space Telescope (hereafter JWST) has been conceived to carry out break-through observations in the infrared ($0.6 - 28\,\mu$m) bringing major progress in areas such as:

- Cosmology and the Structure of the Universe
- The Origin and Evolution of Galaxies
- The History of the Milky Way and its Neighbours
- The Birth and Formation of Stars
- The Origin and Evolution of Planetary Systems

In particular these themes have been expanded by the JWST Ad Hoc Science Working Group (ASWG) into a set of potential scientific observations comprising the JWST Design Reference Mission (DRM; `http://www.ngst.nasa.gov/science/drm.html`), that is a representative science program elaborated in sufficient detail to aid in the development of functional requirements for the JWST mission. In its revised version (`http://www.ngst.stsci.edu/studies/drmv2.3/`) the

DRM is made up of 18 programs, requiring approximately half of the nominal JWST 5-year mission life to complete.

In order to carry out the DRM, a complex range of instrumentation is required with imaging and spectroscopic capabilities over a large wavelength range ($0.6 - 28\,\mu$m). The JWST instrument suite will consist of three science instruments: a Near Infrared Camera (NIRCam), a Near Infrared Spectrograph (NIRSpec) and a Mid Infrared Instrument (MIRI). Unlike the Hubble Space Telescope, the JWST will be in a second Lagrange point orbit and will not be serviceable. Therefore, these will be the only instruments JWST will ever have.

This document focuses on the basic outline of tasks needed to provide the calibration for the NIRSpec; emphasis is given to the astrophysical requirements, the time consumption of the calibrations and the general feasibility of the strategy. The calibration requirements derived here are based on the current status of the instrument design and will need to be refined when more details of the instrument and its operation concept become available.

2. Baseline of the Near Infrared Spectrograph

The Near Infrared Spectrograph (NIRSpec) will be the spectrograph in the wavelength range of 0.6 to 5 μm. The study of galaxy formation, clustering, chemical abundances, star formation, and kinematics, as well as active galactic nuclei, gamma-ray-bursters, supernovae, young stellar clusters, and measurements of the initial mass function of stars (IMF) require a near-infrared spectrograph.

NIRSpec in its current design provides users of JWST with the ability to obtain simultaneous spectra of more than 100 objects in a $\approx$9 ($3\farcm4 \times 3\farcm4$) square arc-minute field of view. The spectra cover the 0.6 to $5\,\mu$m wavelength range with a resolving power of $\sim$100, and 1 to $5\,\mu$m with $\Re \simeq 1000$. The baseline spectrograph will probably take advantage of a micro-electromechanical system to provide dynamic aperture shutter masks on a fixed grid. The micro shutter array (MSA) will feature approximately 800×400 shutters, with each 200×450 mas (TBC) slit width and slit length respectively (see also Figure 1). Observations will be performed with 200 mas wide slits while the slit length is variable and will be constructed by opening several adjacent shutters. The $\Re \simeq 100$ mode will be covered by one prism (0.6 to 5 μm). For $\Re \simeq 1000$ the observations are separated in three wavelength ranges ($1.0 - 1.8\,\mu$m, $1.7 - 3.0\,\mu$m, $2.9 - 5.0\,\mu$m) where long pass filters are used to avoid order overlapping.

The aperture focal plane (AFP) will also carry a small number of fixed, conventional slits (200 mas slit width, slit length $\approx 4''$). In combination with the fixed slits there will be an additional $\Re \simeq 3000$ mode covering the 1.7 to $5\,\mu$m range in two steps[1]. Furthermore an optional IFU, (3×3 arcsec FOV) to be used with $\Re \simeq 3000$, may be incorporated into the aperture focal plane.

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[1] Note, that the wavelength range below $2\,\mu$m is thought to be covered by ground based instruments with $\Re \geq 3000$.

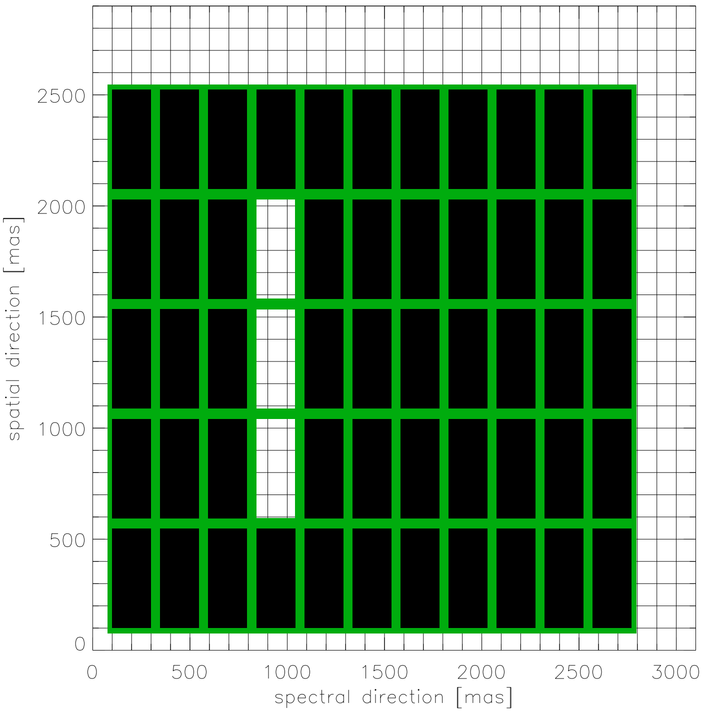

Fig. 1.— Schematic view of MSA shutters (shaded regions) configured with a 1×3 slit projected onto the detector (fine grid). The dispersion direction is along the x-axis. The effective shutter width and height is 200 mas and 447 mas respectively, while the pitch size is 247 mas and 494 mas, respectively. The detector is sampled at 100 mas per pixel.

The schematic layout of the spectrograph showing the sequence of the basic spectral components is presented in Figure 2. Current designs forsee eight filter wheel positions: three order sorting filters for $\Re \simeq 1000$ & 3000, one transparent position for $\Re \simeq 100$, one closed position with a reflective diffuser for internal calibration lamps, and three broad band filters (JKL). The grating wheel will carry one $\Re \simeq 100$ prism covering the full wavelength range, three $\Re \simeq 1000$ gratings & two $\Re \simeq 3000$ gratings. Additionally there is one mirror for direct imaging (for target acquisition, and calibration purposes). Thus there are 14 spectral elements in total provided. Not all of the elements will be used independently. Most importantly there are ten standard grating/prism and order blocking filter combinations to calibrate (see Table 1). If the IFU is implemented then there are two more modes to be considered in the calibration concept. Additionally at least four imaging modes (for target acquisition, hereafter TA) need to be calibrated. This assumes that the same filters are used for TA as for the spectroscopic modes. The use of the broad band filters will add another three imaging modes (TBC). The $\Re \simeq 100, 1000$ modes can be used with the MSA and with the conventional slits. The $\Re \simeq 3000$ mode will be only used with the conventional slits and the IFU. Non-standard combinations such as the $\Re \simeq 100$ prism with a $\Re \simeq 1000$ order sorting filter are possible but not considered in this document. We note that there is a potentially large number of non-standard dispersing element and filter combinations to be calibrated if they are being offered to the general user.

Not all modes listed in Table 1 need a full set of individual calibrations. For example, all internal lamp calibrations carried out for the MOS modes will deliver a signal for the conventional slits as well. It is assumed that the IFU needs individual calibrations. In summary, for the internal lamp calibrations we consider eight different spectroscopic operational modes and four imaging modes. For pointed observations we assume that each mode has to be calibrated individually (12 spectroscopic modes and four imaging modes).

In order to allow for an efficient calibration strategy we assume that the NIRSpec can be built in such a way that every combination of the filter and grating wheel positions share the same focus.

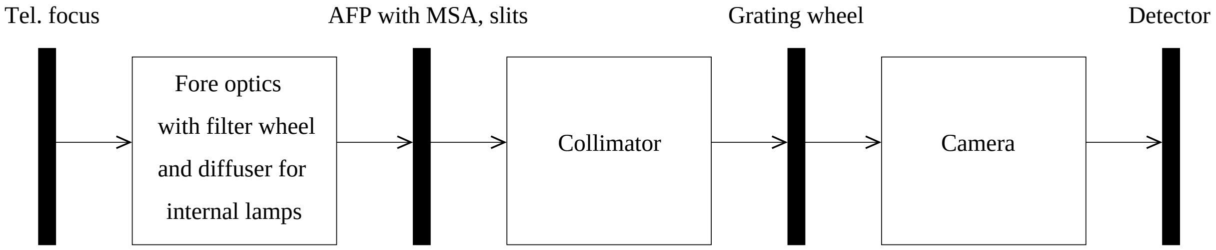

Fig. 2.— Schematic layout of spectrograph

We assume that the MSA position is fixed with respect to the detectors. Therefore the detectors cannot be illuminated directly but all light has to go through the MSA. To optimise sensitivity, detector pixels with a relatively large projected size on the sky will be used (100 mas, see also Arribas et al. 2002). The focal plane assembly will be covered by a mosaic of detectors (TBD). Detectors will be either InSb or HgCdTe; both technologies are actively under study.

3. The Scientific Needs

The DRM observations which involve the NIRSpec instrument are summarised in Table 3 (adapted from ASCII text form, version 2.4; August 6, 2001). The S/N requested for all observations is equal 10 or lower. More details (including texts of the proposals) can be found at `http://www.stsci.edu/jwst/science/drm/programs.html`.

From a scientific point of view the following items need to be addressed in the calibration of the NIRSpec.

1. Knowledge of wavelength calibration
2. Knowledge of spectrophotometric calibration

Table 1: Main operational science modes

Mode	wavelength	Filter wheel	AFP	Grating wheel
Imaging	$0.6 - 5\,\mu$m	transparent	TA configuration	mirror
Imaging	$> 1.0\,\mu$m	long pass I	TA configuration	mirror
Imaging	$> 1.7\,\mu$m	long pass II	TA configuration	mirror
Imaging	$> 2.9\,\mu$m	long pass III	TA configuration	mirror
Imaging	$\sim 1.2\,\mu$m	J	TA configuration	mirror
Imaging	$\sim 2.2\,\mu$m	K	TA configuration	mirror
Imaging	$\sim 3.8\,\mu$m	L	TA configuration	mirror
Spectroscopy	$0.6 - 5\,\mu$m	transparent	200 mas MOS	R=100
Spectroscopy	$0.6 - 5\,\mu$m	transparent	200 mas slit	R=100
Spectroscopy	$1.0 - 1.8\,\mu$m	long pass I	200 mas MOS	R=1000
Spectroscopy	$1.7 - 3\,\mu$m	long pass II	200 mas MOS	R=1000
Spectroscopy	$2.9 - 5\,\mu$m	long pass III	200 mas MOS	R=1000
Spectroscopy	$1.0 - 1.8\,\mu$m	long pass I	200 mas slit	R=1000
Spectroscopy	$1.7 - 3\,\mu$m	long pass II	200 mas slit	R=1000
Spectroscopy	$2.9 - 5\,\mu$m	long pass III	200 mas slit	R=1000
Spectroscopy	$1.7 - 3\,\mu$m	long pass II	200 mas slit	R=3000
Spectroscopy	$2.9 - 5\,\mu$m	long pass III	200 mas slit	R=3000
Spectroscopy	$1.7 - 3\,\mu$m	long pass II	IFU	R=3000
Spectroscopy	$2.9 - 5\,\mu$m	long pass III	IFU	R=3000

Table 2: Summary of DRM NIRSpec observations (version 2.4)

Proposal	Title	λ μm	S/N	mag (AB)	diam (“)	# per sq.arcm.
		Low Resolution (100)				
P004	IGM	1.26	10	29	-	-
P015	Form. & Evol. Galaxies II	3.5	10	29.4	0.5	112
P018	GRB	2.1	7	27.5	0.2	-
P026	SN	3.5	10	28	0.005	-
		Low Resolution (300)				
P008	Kuiper Belt	3	10	26.4	-	-
P013	Sub-stellar Mass Objects	3	10	27.5	-	100
P020	Circumstellar Disks	3	10	26.5	-	-
P026	SN	1.6	10	27	0.005	-
		Moderate Resolution (1000)				
P015	Form. & Evol. Galaxies II	3.5	10	25.4	0.5	112
P015	Form. & Evol. Galaxies II	3.5	10	23.8	2	-
P016	Form. & Evol. Galaxies III	3.5	10	25.4	0.5	13
P017	Form. & Evol. Galaxies IV	3.5	10	25.45	0.5	110
		High Resolution (3000)				
P013	Sub-stellar Mass Objects	3	10	25.3	-	12
P018	GRB	2.1	10	25	-	-
P017	Form. & Evol. Galaxies IV	3.5	5	24.45	0.5	110

3. Knowledge of astrometric position along spatial extent of slit, or IFU
4. Knowledge of spatial and spectral PSF

In order to quantify the scientific requirements for spectroscopy it is useful to classify the spectroscopic observations in three broad categories:

1. Redshifts
2. Line Diagnostics
3. Dynamics

3.1. Redshifts

The determination of redshifts for galaxies, SNe, gamma-ray bursters at the faintest magnitudes is a major part of the DRM. Typically it will be carried out at a resolution of $\Re \simeq 100$. Not all the astrophysical applications require an extremely accurate absolute wavelength calibration (for example when the emphasis is on line ratios). There are however cases in which an accurate absolute calibration is mandatory. Requirements on the wavelength accuracy, absolute and relative, are derived from studies of large scale structure (clustering) and of the correlations between luminous matter (for example galaxies) and gas in the intergalactic medium (IGM, see, for example Steidel et al. 2002; Adelberger et al. 2002). A plausible upper limit can be set by the dispersion of the systemic velocities observed in Lyman-break galaxies, that show pronounced differences depending on the lines used to determine the redshift: nebular emission from gas around stars as opposed to absorption of stellar continua by outflowing interstellar gas or multiply-scattered Lyman-α emission. A typical value is $\sigma_v = 300$ km/s. Another important case to be envisaged is the comparison of the systemic velocities of line-systems observed with NIRSpec with respect to other instruments (e.g. ALMA). In such cases it is required that the wavelength determination is limited by the photon noise of the astrophysical source rather than by systematics in the zero point determination.

Therefore, in the following we will assume as a goal for the accuracy of the wavelength calibration (combined effects of systematic and relative errors) in the $\Re \simeq 100$ mode 1/10 (rms) of a resolution element (FWHM; e.g., FWHM sampled by 2.3 pixels, i.e. 0.23 detector pixel accuracy or $\Delta\mathrm{v} \simeq 300\,\mathrm{km/s}$).

The wavelength calibration accuracy sets a lower limit on the redshift accuracy. The final accuracy which can be achieved for a given object critically depends on the number and type of spectroscopic features which can be used for the redshift determination. Therefore, in practice the redshift error can be significantly larger than that given by the wavelength calibration accuracy.

Spectrophotometric calibration is not a critical issue for the above mentioned observations. In general it can be assumed that in many cases, when required, the SED will be re-calibrated *post-facto* on the basis of broad-band photometry. Exceptions are provided by the DRM proposals “Probing the IGM out to the re-ionisation epoch” and “Measuring Cosmological Parameters with High-z Supernovae and the Evolution of the Cosmic Supernova Rate”. In the former program an accurate measure of the damping wing of the IGM absorption marking the transition to a neutral IGM requires at least a relative accuracy of 10% in order to determine reliable optical depths. The relative spectrophotometric accuracy for SN observations needs to be of the order of 5% while the absolute accuracy can be relaxed to 15% (B. Leibundgut, private conversation).

For $\Re \simeq 100$ we are not aware of any stringent requirements on the spatial information in the spectra. The overall goal is to observe sources as faint as possible which naturally requires the collection and extraction of as much of the available flux as possible. A basic requirement for the spatial information is that the spectra of neighbouring slits, separated by two closed shutters in spacial direction, do not overlap on the detectors. In order to minimize detector read-noise contributions the signal should be concentrated on as few detector pixels as possible. We assume that diffraction limited spatial imaging quality at $3\,\mu$m (Strehl ratio > 0.8) and longer wavelength can be achieved at the detector level. A reasonable knowledge of the *spatial* PSF shape (at all wavelengths) will be needed to facilitate an optimal data extraction. The spatial PSF shape is defined as the relative intensity distribution of a point source observed with NIRSpec along the spatial direction of the slit at the detector level. The FWHM of the spatial PSF will be known and mappable with a low order polynomial over at least 95% of the FOV to better than 5% (rms) at all wavelengths.

A good knowledge of the *spectral* PSF shape as a function of wavelength (i.e. line spread function) is needed to minimize systematic shifts introduced by template mismatch in e.g., cross correlation techniques used for redshift determinations. The spectral PSF shape is defined as the relative intensity distribution of a delta function observed with NIRSpec along the dispersion direction at detector level. We assume that the knowledge of the first moments of the spectral shape (i.e. FWHM + asymmetry modelled by e.g., a Gauss-Hermite series) to better than 5% (rms) will be sufficient.

In order to compare NIRSpec observations to other data sources such as radio maps it is important to have a good knowledge of the astrometric position of the observed spectra (i.e. along the spatial extent of the slit). This should be limited by the detector pixel sampling only. Thus we assume that an astrometric accuracy of 1/5 of a detector pixel (i.e. 20 mas, rms) or better can be achieved. The astrometric position accuracy is defined with respect to the coordinate frame given by the target acquisition reference objects.

3.2. Line Diagnostics

The $\Re \simeq 1000$ mode will be customarily used for astrophysical diagnostics such as determination of stellar ages, metallicities, temperatures, densities, stellar surface gravity, and classification of objects. A typical example is shown in Figure 3, illustrating a diagram to discriminate AGN from Liners and Starburst galaxies.

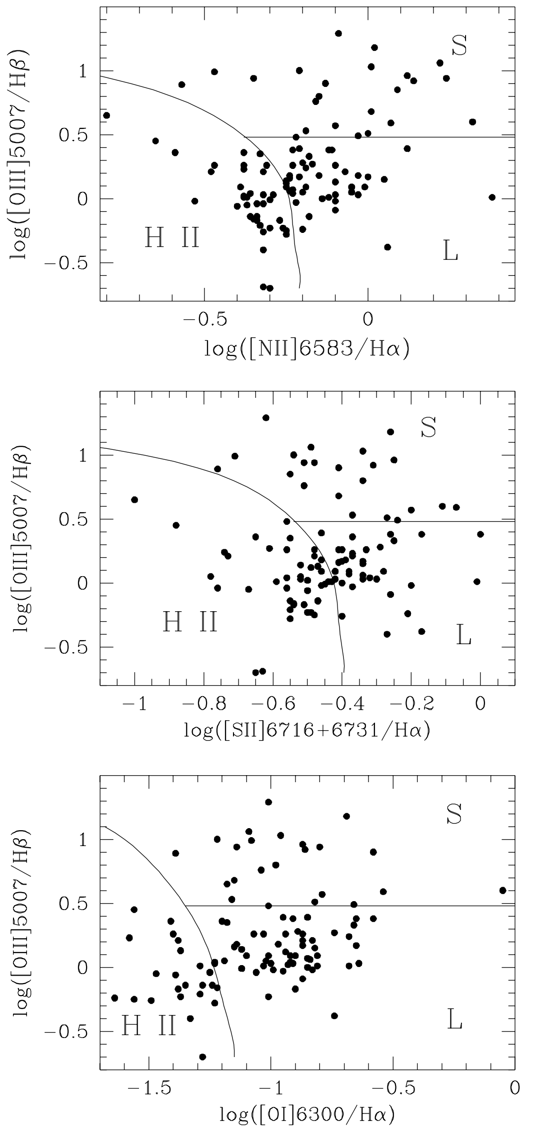

Fig. 3.— Examples of line ratio diagrams used for the classification of ultra-luminous infrared galaxies. From Veilleux et al. (1999).

Typical lines used in this type of study will be: Hα, Hβ, [OII]λ3727, [OIII]$\lambda 4363, 4959 + 5007$, [NII]$6548, 6583$. As can be inferred from Figure 3, an accuracy better than 10%, absolute, over possibly large spectral ranges will be required for a correct application of the diagnostic tests. This sets tight constraints on the absolute spectrophotometric calibration.

The measurement of characteristic continuum shapes (e.g., 4000 Å break) can be used to constrain the star-formation history of stellar populations in galaxies through spectral synthesis models. Particularly interesting are diagnostics which can probe the first Gyr after a star-burst. For example, in order to determine the difference between a 0.9 and 0.7 Gyr old stellar population with the 4000 Å break, we require a relative spectrophotometric accuracy of the order of 5% (see Figure 4).

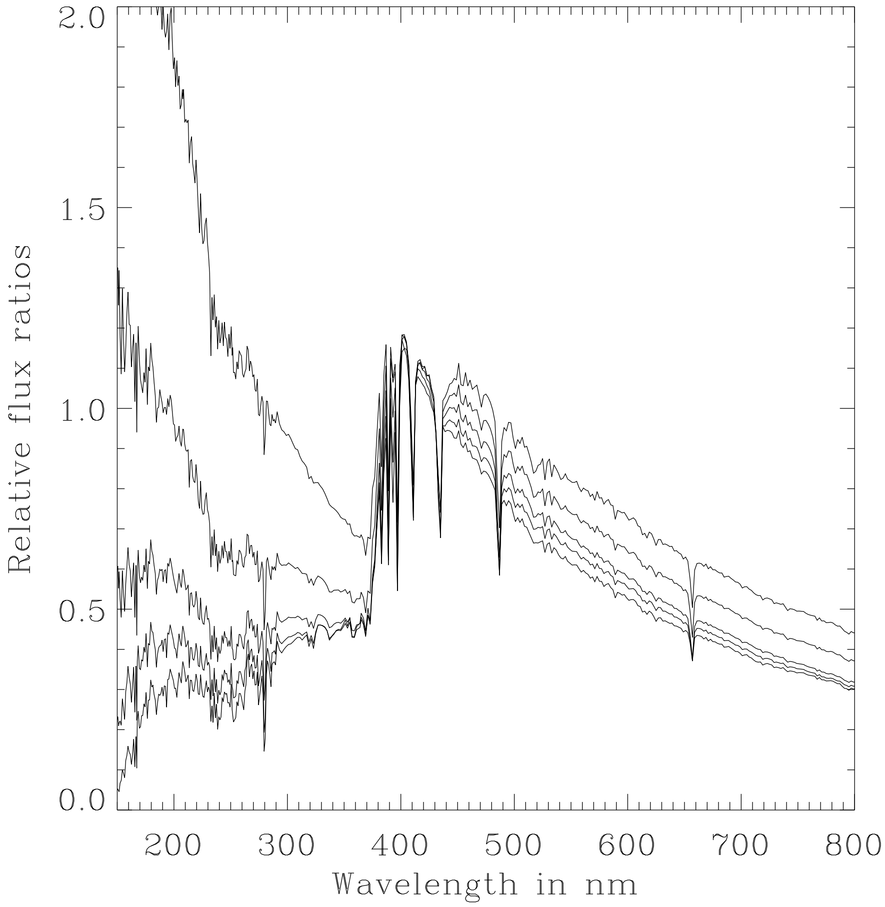

Fig. 4.— Stellar population models of an instantaneous starburst of age = 0.1, 0.3, 0.5, 0.7, 0.9 Gyr (from top to bottom) and a constant metallicity of Z=0.008 are shown (models from STARBURST99). The models are normalized around ∼4000 Å.

Requirements on the stability of the wavelength scale can be derived from the ability to clearly separate and analyse neighbouring emission lines such as Hα and [NII] ($\Delta\lambda \simeq$15 Å). A combined absolute and relative wavelength scale accuracy of 1/5 (rms) of a resolution element (FWHM) appears sufficient.

For the $\Re \simeq 1000$ mode spatial information will be of scientific interest since diagnostic properties are likely to change with position in extended objects. Since the objects are typically small we require diffraction limited spatial imaging quality at $3\,\mu$m (Strehl ratio > 0.8) and longer wavelength.

In order to investigate for example winds in star-formation regions the stability and repeatability of the line-spread function is of scientific interest. In order to detect the expected asymmetric line profiles (e.g., a outflow from a few 10 km/s to ∼1000 km/s) we estimate that the knowledge of the spectral and spatial PSF shape (defined in Section 3.1) to better than 5% (rms) is sufficient. However, a more detailed knowledge of the spatial PSF shape will be useful in the data-reduction of bright sources. It is to be expected that some observations in the $\Re \simeq 1000$ mode are carried out at a higher S/N than the standard DRM observations.

The astrometric requirements are similar to the ones given in Section 3.1.

3.3. Dynamics

Studies of the dynamics of clusters of galaxies and individual galaxies at high redshift are another major component of the DRM, aiming at the determination of masses and the relation between visible and dark matter.

A typical observation of cluster galaxies will require multi-object spectroscopy (MOS) of about 100 objects per cluster with the $\Re \simeq 1000$ mode. An absolute and relative precision for the wavelength calibration of $\simeq 1/10$ (rms) of a resolution element is sufficient for the determination of velocity dispersions and substructure of clusters ($\Delta v \simeq 30\,$km/s). The value of Δv $\simeq 30\,$km/s is to be interpreted as a minimum characteristic since in reality all gratings/prisms will show a wavelength dependent spectral resolution.

Internal dynamics of individual galaxies require a higher resolution mode, $\Re \simeq 3000$, to be implemented in the form of an Integral Field Unit (IFU) or with a set of gratings in combination with the fixed slits. The observations are likely to be carried out at a higher S/N (e.g., ≥ 30). Features like the Mg5177 line, the CaII triplet at 8500 Å or the CO bands at 2.3 μm will be observed. The requested accuracy of the wavelength calibration (relative + absolute) is of the order of 1/10 of a resolution element (i.e. $\Delta v \simeq 10$km/s). Since this mode will predominantly be used to determine internal galaxy dynamics the absolute spectrophotometric accuracy can be relaxed to ∼15%, while the relative spectrophotometric accuracy should be on the same level as for the $\Re \simeq 1000$ grating (i.e. better than 5% rms). For high S/N observations the line spread function needs to be very well determined and reproducable in order to measure accurate line-of-sight velocity distributions (LOSVD). The LOSVDs can be used together with models to investigate the dynamical state of the target. The knowledge of the spectral and spatial PSF shape (defined in Section 3.1) to better than 5% (rms) is sufficient for the successful operation of this spectroscopic mode.

For the $\Re \simeq 1000, 3000$ mode spatial information will be of scientific interest since dynamics are likely to change with position in extended objects. Since the objects are typically small we require diffraction limited (at $3\,\mu$m and longer wavelength, Strehl ratio > 0.8) spatial imaging quality.

The astrometric requirements are similar to the ones given in Section 3.1.

3.4. Summary of the scientific requirements

Almost all DRM observations with $\Re \simeq 100$ or 1000 require a S/N of 10. The GRB observations are an exception with a requested S/N $= 7$. The $\Re \simeq 3000$ mode is likely to be used with higher S/N ratios (S/N ≥ 25). The core calibration requirements derived from the major science areas are listed below. Individual observations may need a less accurate calibration, while some observers may also desire a more accurate calibration for specific programs. Where a requirement is given as a function of wavelength, the relevant sampling is assumed to be the size of one resolution element (FWHM) of the dispersive element. For imaging it is the band-width of the filters. For spatial requirements the sampling is assumed to be the pixel size at the detector level. All requirements are applicable to fully reduced and calibrated data, i.e. the end-product of a data reduction pipeline. We note, that in order to meet the following requirements, a typical, fully calibrated spectrum of a given target may need to be built up of multiple exposures. For example, in order to meet the spectrophotometric throughput one may need to dither individual exposures.

Requirements for $\Re \simeq 100, 1000, 3000$

- The combination of absolute and relative wavelength calibration errors will be smaller than 1/8 (rms, goal 1/10) of the resolution element (FWHM) of a given dispersive element at all wavelengths and over at least 95% of the FOV.
- Assuming no Poisson noise in the signal, multiple observations of the same target with different MSA or single slit configurations will provide a repeatability for the overall throughput (with respect to a given standard source[2]) of better than 5% (rms) for the full FOV. The throughput uncertainty as a function of wavelength will be below 5% (rms).
- The imaging quality at the focal plane assembly will be diffraction limited for $3\,\mu$m and longer wavelengths (Strehl ratio > 0.8). The width (FWHM) of the *spatial* PSF at detector level will be known and mappable with a low order polynomial to better than 5% (rms) over at least 95% of the FOV and at all wavelengths.

  The first moments of the *spectral* PSF shape (i.e. FWHM + deviations from a Gaussian modelled by e.g., a Gauss-Hermite series) will known and mappable with a low order polynomial over at least 95% of the FOV to better than 5% (rms) at all wavelengths.

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[2] We assume that suitable standard stars calibrated in absolute terms will be available for the wavelength range of NIRSpec.

- The astrometric position along the spatial extent of the slit will be known and mappable over at least 95% of the FOV to better than 20 mas (rms) with respect to the coordinate frame defined by the target acquisition reference objects for all wavelengths.

We require that the fixed slits and the IFU are placed in a region of the FOV where the knowledge of the parameters stated above is not degraded by vignetting or similar effects.

4. Calibration Procedures

We follow largely the general overview of calibration procedures given by Casertano (2001) and Henry & Casertano (2002), having in mind the specific needs of the NIR-spectrograph. We also make use of the "JWST-NIRSpec Operations Concept Document" (Regan et al. 2003) which describes the overall operations concept.

A number of uncertainties affect the design of the JWST NIRSpec calibration strategy. Major ones are the level of stability and predictability of the optical train of the telescope and the detectors, the detailed consequences of the diffraction properties of the MSA, and the availability of internal calibration sources in spite of the tight limits on power dissipation. Furthermore, the effects and the frequency of the re-phasing of the primary mirrors is currently not well established. We assume that monthly re-phasing will be carried out. It is likely that the re-phasing will change not only the focus of the instrument but also the PSF and the overall distortion model. Therefore the calibration unit and the calibration concept have to provide for efficient and accurate re-calibrations of focus, PSF and distortion model.

Continuum micro-lamps which reach temperatures of ~1000 K have been reported by the GSFC group (Moseley, private communication). A useful calibration lamp for JWST should probably achieve somewhat higher temperatures (~1300 K, see Figure 5). Proper emission line sources have not yet been investigated. If no cold line sources are available at the wavelength of interest for NIRSpec, an alternative possibility is filtering the continuum source using a Fabry-Perot etalon or similar for the internal wavelength calibration. For the determination of the zero point this procedure should provide a few emission lines in the wavelength range of each of the gratings. In order to determine the dispersion function more lines are necessary. Typically > 10 unambiguously identifiable lines (line/continuum contrast $> 80\%$) covering the wavelength range of each dispersive element uniformly are sufficient to meet the requirements stated in Section 3.4. This assumes that the true dispersion function of the spectrograph can be described by a simple function derived from the spectrograph optical model (detailed ground based measurements with >100 lines per spectral band are needed). The line-spread function of the lines produced by the lamp (e.g., via Fabry-Perot etalon) should be such that one can easily determine the central wavelength of the lines. This sets tight constraints on the stability of the lamp itself and the line-shapes of individual lines. We estimate that the lamps need to be stable to better than < 0.025 FWHM (rms) of spectral element for at least a month (goal one year) in order to allow for efficient operations.

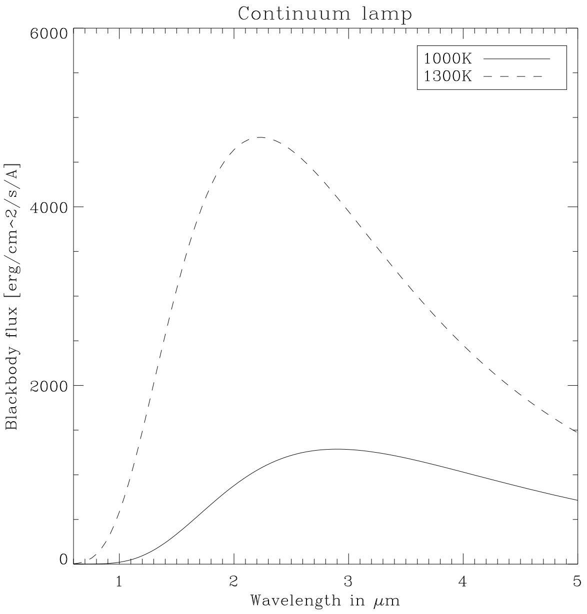

Fig. 5.— Black body curves for T=1000 K and T=1300 K. The flux is given in ergs/s/cm^2/Å. Specifically note the low flux at wavelengths $< 1.3\,\mu$m.

In the following analysis we assume that good internal line lamps are available. The line calibration lamp exposure time is assumed to be 60 sec. For this exposure time we expect a S/N of > 30 (per detector pixel) at the peaks of the lines. In order to achieve a pixel-to-pixel flat-field accuracy of better than 1-2% (rms) the continuum lamps need to produce a S/N > 100. We assume that this signal can be achieved within 1000 sec. We note, that accurate flat-fields particularly at wavelength below $1.3\,\mu$m are probably very challenging (see also Figure 5). The details depend on the actual temperature achieved by the lamp which is TBC. We note that the internal lamps are not required to cover the wavelength range $0.6 - 1\,\mu m$, but it should be a goal. Furthermore, we assume that the calibration lamps are adequately redundant systems.

For on sky calibrations we assume generic exposure times of 100 sec for bright sources and 500 or 1000 sec for faint sources. We give only the on-source exposure times and do not include overheads for read-out time, telescope slews etc.

A further critical point of uncertainty are the diffraction properties of the MSA and their implications for the spectroscopic observations. The introduction of the MSA is driven by the requirement to observe ~100 objects simultaneously. However, its properties are quite different from conventional multi-slit observations for two main reasons: (a) The individual slits will be constructed by opening adjacent shutters which leads to diffraction effects by the MSA support structure in the spatial direction; (b) Due to the random distribution of targets on the sky, only one science target per mask can be placed at an optimal position within its slit. All other objects within the same MSA mask will be slightly misplaced by up to half the shutter size in spectral direction.

The final calibration strategy for many NIRSpec components may depend on these diffraction properties. Therefore detailed instrument modelling is needed. First results have been obtained (see Freudling 2002) on which this document is based. We further note that the MSA properties, particularly the influences on the spectrophotometric accuracy, may determine the overall observing strategy (e.g., dithering, see Section 4.1.3) which in turn has an impact on the calibration needs.

Overall the on board calibration concept should provide for some redundancy. For example it should be still possible to acquire a target with the fixed slits if the MSA or one detector fails.

4.1. Characteristics of the Calibrations

The goal of this section is to establish the need for and approximate time consumption of calibrations to ensure the successful operation of NIRSpec.

The type and frequency of calibrations is determined by the scientific requirements, the instrument design, performance & stability and the observing strategy. All of these items are not finalized yet, hence this document can only describe the calibration needs with respect to our current knowledge. It is expected that some of the requirements will change when the final instrument design is known.

It is useful to separate calibrations by themes such as detector, optics, sensitivity, geometric and spectroscopic calibrations. Furthermore the calibrations can be classified into three broad time categories: pre-flight, beginning of mission and regular calibrations during science operations. In this document we concentrate on the regular calibrations during mission. Pre-flight and beginning of mission calibrations are referred to where deemed necessary, but are not described in detail. Throughout this document it is assumed that calibrations taken in orbit can built on extensive ground-based calibrations and an accurate instrument model. Therefore the character of the in-orbit calibrations is one of "verification" rather than "determination". However, the instrument and in particular the calibration unit design should provide the means to determine the individual calibrations without the input of the ground based model wherever this is possible.

The tables in the following sub-sections summarize the routine calibrations needed during a typical year of observations. We follow the nomenclature of Henry & Casertano (2002). Specifically the "Type" of calibration is defined as:

- **Pointed** calibrations. These require dedicated pointings.
- **Sky** calibrations. Here the objective is to observe the sky background; the pointing generally doesn't matter, although crowded fields or bright objects need to be avoided.
- **Lamp** calibrations. These observations make use of internal (continuum and line) lamps.

- **Dark** calibrations. Observations with the shutter closed.
- **Auto** calibrations. Here the calibration information is extracted via iterative methods directly for the science data. Although no spacecraft time will be necessary some methods will require substantial analysis in order to provide the required information.
- **Opportunistic** calibrations. Here calibration information is extracted from a set of suitable science exposures (separate from the observation being calibrated).

The third table column gives the frequency of the calibration per year. This depends on the stability of the quantity being measured. For auto calibrations and opportunistic calibrations this is given as 0.

The fourth column shows the number of separate calibrations needed to perform the measurement. An individual calibration is defined as a set of exposures that generates a particular piece of information or reference file. The number of calibrations depends on how the measurement must be iterated over parameters such as readout pattern, filters etc. to produce a complete set of data.

The number of separate exposures is given in the 5th column. Often this number is one but some calibrations need dithering or summing to produce an adequate signal.

The last column of each table gives the effective cost in % of available NIRSpec time, assuming that NIRSpec will be used 1/3 of the time during one year.

4.1.1. Detector characteristics calibrations

A thorough ground based characterisation will be needed for the whole set of detector calibrations summarised in Table 3. In orbit, only verification and monitoring of potential changes should be required. The frequency of these checks depends strongly on the stability of the detectors and their aging properties (e.g., increase in number of hot pixels). The detector type and its properties are TBC, so only general calibration procedures and time estimates can be described at the moment. Detector characteristics have also significant implications on the flat-field determination which will be discussed in Section 4.1.3.

Current designs of NIRSpec foresee one detector readout mode (MULTIACCUM) with user selectable exposure times ranging from 50 to 20000 sec in steps of 50 sec and a single gain setting ($\approx$ 1.5 e^-/ADU). The 50 sec intervals are determined by the maximum available bandwidth to down-link the data. The exposure times are given for full frame modes. There is likely to be a sub-array mode for bright object observations with much shorter exposure times (minimum 40 ms). These bright-source modes need to be considered in the calibration strategy but are not expected to significantly contribute to the overall calibration time consumption. Furthermore, specific readout-patterns may be used for frequent calibrations such as the target acquisition image, the mirror

Table 3: Detector characteristics calibrations

Measurement	Type	Frequency per year	# Calibrations	# Exposure (exp. time)	Total time ksec/year	Eff. cost % time
Bias drift	auto	0	1	- (-)	0.0	0.00
Dark current	dark	2	8	20 (1000)	320.0	**3.04**
RN determination	dark	2	1	10 (1000)	20.0	0.00[a]
RN verification	dark	52	1	1 (500)	26.0	0.00[a]
Gain	c. lamp	2	3	5 (60)	1.8	0.02
Linearity	pointed	1	10	1 (500)	5.0	0.05
Bad pixels	opp.	0	1	- (-)	0.0	0.00
Hot pixels	dark	120	1	1 (1000)	120.0	0.00[a]
Image persistence	pointed	6	10	1 (1000)	60.0	0.57
Sum						3.68

[a] It is assumed that the dark observations can be shared with the main dark current determination program.

position calibration, the through-slit image and the wavelength zero-point (see Sections 4.1.4 & 4.1.5 for details).

Casertano (2002) recommends auto calibration for the bias drift. The NIRSpec detectors are likely to carry reference pixels which can be used to track effects such as bias drifts.

The dark current can be calibrated with long exposures taken with the external light path blocked (diffuser selected in filter wheel). In order to achieve accurate dark subtraction (dark noise $\leq 0.7\,e^{-}$/frame) a total exposure time of $\sim$20 ksec is estimated per exposure time setting (assuming a detector noise of $3\,\mathrm{e}^{-}$ rms per frame). Since most of the JWST science targets are very faint sources it is essential to minimise the noise contributions from bias and dark subtractions. Therefore we see the estimated dark exposure time (20 ksec) listed in Table 3 as minimum requirement. Casertano (2002) recommends calibrations twice a year. However, dark calibrations will probably be run on a daily basis to track short term changes. It is envisaged that a super dark for the most important exposure time settings (we assume 8 different ones) is determined at the beginning of mission and then adjusted accordingly with the daily dark calibrations. Dark calibrations for intermediate exposure times can be extracted from the long dark exposures since all science exposures will have the same sampling, i.e. every 50 sec one full frame will be send down to the ground station. Since the dark calibrations will take up a significant amount of time ($> 3\%$), this calibration would greatly benefit from a parallel capability of NIRSpec, i.e. obtaining darks while another instrument on JWST is observing astrophysical targets.

The read noise (RN) can be obtained from a series of short darks and should be determined twice a year, while RN verifications should be run on a weekly basis. We expect that these observations can be shared with the dark calibrations proper.

For the gain calibration Casertano (2002) suggests examination of the noise statistics of high illumination images. This calibration can be performed most efficiently with a bright internal continuum lamp and the mirror selected in the grating wheel.

Casertano (2002) points out that the effective gain may be wavelength dependent if each photon can produce multiple electrons. This will impact the noise model. Careful ground testing of this effect is mandatory since in orbit an illumination of the detector in different wavelength bandpasses with internal lamps is difficult. Depending on the design, the internal calibration lamps may carry filters which can be used to calibrate the wavelength dependence in orbit. Extended astronomical sources (nearby galaxies, nebulae) are also viable gain calibration targets but their use makes the procedure longer and more complex. Currently we assume that the gain calibration will be performed with internal continuum lamps in three filters twice a year and that 5 exposures of 60 sec are sufficient to determine the gain.

The linearity of the detectors will be determined on the ground and the resulting model can be checked by pointed observations of bright astronomical targets on a yearly basis. Nearby elliptical galaxies may be good targets to probe a large dynamic range with one object. We assume that 10 exposures are sufficient to validate the ground based model. If the internal calibration lamp output does show a high degree of stability then the calibration may be performed with the continuum lamp.

The position of bad pixels can be frequently monitored by making use of suitable science exposures. The monitoring of hot pixels probably requires frequent (e.g., daily) darks which accounts for a significant amount of exposure time, however, it is envisaged that observations can be shared with the dark calibration proper.

A thorough ground characterisation of latent images (persistence) is essential, since precise verification from space can be time-consuming. The in orbit calibration strategy requires observations of bright targets followed by a series of darks. Latent images from cosmic rays can be verified from darks and do not require dedicated observations. However, the behaviour during solar events producing a rise in cosmic ray frequency needs to be carefully calibrated at the beginning of mission, if possible. Major solar events ($\sim$6 per year) will require image persistence calibrations.

Another important issue in connection with image persistence are observations of bright objects or highly illuminated calibration frames (e.g., bright emission lines). Current (conservative) estimates are of the order of 0.3% image persistence in the next exposure. For example, an emission line with a S/N of 100 will produce a latent image of $\sim$30 electrons on the next exposure. The data-reduction pipeline may be able to remove the remaining signal if one can predict the exact time dependence of the remaining latent image. This demands careful ground based testing and calibration of the detector system. Additionally, in orbit verification is necessary to monitor changes. We estimate that a half yearly verification is adequate.

4.1.2. Optics calibrations

The optics calibrations are summarised in Table 4 and involve most importantly the focus of the instrument and the determination of the PSF. In order to allow for an efficient calibration strategy we require that NIRSpec can be built in such a way that every combination of the filter & grating wheel positions with the MSA, the conventional slits and the IFU share the same focus. Due to the frequent (monthly, TBC) re-phasing of the primary mirror segments we expect that the basic focus and PSF determinations have to be carried out on a monthly basis.

Table 4: Optics calibrations

Measurement	Type	Frequency per year	# Calibrations	# Exposure (exp. time)	Total time ksec/year	Eff. cost % time
Focus	pointed	12	1	7 (100)	8.4	0.08
F. field dependence	pointed	2	1	25 (100)	5.0	0.05
PSF	pointed	2	16	16 (100)	51.2	0.49
PSF verification	pointed	12	1	16 (100)	19.2	0.18
PSF field dependence	pointed	2	16	16 (100)	51.2	0.49
Image anomalies	pointed	1	16	5 (500)	40.0	0.38
Sum						1.66

The determination of the focus in orbit requires a good, a priori, knowledge of the PSF shape as function of focus position. Therefore extensive ground based calibrations and instrument modelling is required. At the beginning of mission a possible dependence of the focus on orbital conditions needs to be established. Having NIRSpec in focus requires two steps: a) focusing of the instrument from the MSA to the detector; b) focusing of the telescope on the MSA. Whether both foci are actively controlled in orbit is TBC. The first step can be accomplished with internal continuum and line sources. The second focus step requires the observation of astronomical point-sources placing a mirror in the grating wheel.

The best focus needs to optimise the PSF in the spatial as well as in the spectral direction (i.e. line-spread function, see Section 4.1.5). We note that due to the diffraction effects on the MSA support structure the PSF shape variations may not be trivial. Therefore, an instrument mode which would allow access to a clear aperture would be very useful to establish the best focus. The aperture size should be such that the full PSF of the telescope is sampled (e.g., 3 arcsec diameter). Such a clear aperture could be incorporated in the aperture focal plane next to the conventional slits. There should be at least two clear apertures (one on each detector) in order to allow for some redundancy. The clear apertures can also be used for target acquisition if the MSA should fail. We assume that 7 images of a bright source (100 sec exposure time) will be sufficient to determine the best instrument focus after each re-phasing of the primary mirrors. The accuracy of the focus adjustment should be such that the requirements on the knowledge of the PSF shape listed in Section 3.4 can be easily achieved.

Focus field dependence can be investigated by observing, for example, a star cluster with all shutters open and the mirror selected in the grating wheel. At the beginning of mission extensive, dedicated observations of astronomical targets are necessary. We assume that the routine focus field dependence calibration need to be carried out only twice a year and that five pointings with five dither positions of each 100 sec exposure time are sufficient. If the re-phasing procedure changes the focus field dependence, this calibration step has to be carried out after each re-phasing.

Much of the monitoring and control of the PSF produced by the telescope itself will be carried out by the Wavefront Sensing and Control (WSC) subsystem. The stability requirement is 2% (rms, 24h). Although the exact description of the PSF shape produced by the combination of telescope and NIRSpec may be complex, we expect a high stability. We assume currently that the PSF has to be re-calibrated after each re-phasing, while the PSF field dependence will need to be re-calibrated only twice a year. The PSF calibration can be performed with observations of astronomical point sources. For a full calibration, the spatial PSF has to be determined as a function of wavelength for at least 12 spectroscopic instrument configurations and four imaging modes (see Table 1). It is assumed that a full calibration is only needed twice a year while the PSF after re-phasing will be determined for only one dispersive element (PSF verification). The observations should deliver at least a S/N of 200 (peak) for the combined images. The calibration of the PSF in the wavelength direction (line-spread function) is described in Section 4.1.5. Each individual calibration may require dithers in order to account for sub-pixel accuracy and diffraction effects of the MSA. The number of dithers could be large (e.g., 16; see Section 4.1.3 for details). However, we expect that bright targets can be used with exposure times of 100 sec. The requirements on the knowledge of the PSF shape are listed in Section 3.4.

FOV variations of the PSF can be determined by observations of e.g., a star cluster while it is important to avoid crowding and therefore overlapping of PSFs.

Stray light, ghost images, images of stars outside FOV can be largely predicted on the basis of the instrument model but are typically identified on the basis of science data. The expected calibration time required for these image anomalies is limited to short (e.g., 500 sec) observations of appropriate astronomical fields on a yearly basis. We assume that 5 exposures per calibration will be sufficient to determine the signal.

4.1.3. Sensitivity Calibrations

Sensitivity calibrations are a complex issue and need to be performed in principle for a prohibitively large set of instrument configurations (e.g., 800 × 400 shutters in MSA, and 12 spectral modes). Key to an efficient calibration strategy is a well behaved spectrograph where sensitivity parameters change only smoothly across the FOV and thus a rather coarse sampling is sufficient to calibrate the full system. We require that the overall system sensitivity (excluding MSA diffraction effects) does not change more than 10% (TBC) over the full FOV. The changes should be known and mappable to an accuracy of better than 2% (rms) with a low order polynomial.

A precise determination of the system parameters on the ground and at the beginning of mission are required. We assume that the photometric response of the optical elements (excluding the MSA) is stable so a yearly re-calibration will be sufficient to characterise the system (stability better than 1% per year). The necessary sensitivity calibrations are summarised in Table 5.

Table 5: Sensitivity calibrations

Measurement	Type	Frequency per year	# Calibrations	# Exposure (exp. time)	Total time ksec/year	Eff. cost % time
Shutter throughput	c. lamp	12	1	10 (60)	7.2	0.07
Slit throughput	c. lamp	2	1	10 (60)	1.2	0.00[a]
IFU throughput	c. lamp	2	1	10 (60)	1.2	0.01
Phot. resp. MSA	pointed	1	4	256 (100)	102.4	0.97
Phot. resp. slit	pointed	2	6	2 (100)	2.4	0.02
Phot. resp. IFU	pointed	2	2	1 (100)	0.4	0.00
Phot. resp. filters	pointed	1	6	16 (100)	9.6	0.09
Background	opp.	0	0	0	0.0	0.00
Small scale FF[b]	c. lamp	12	5	10 (60)	36.0	0.34
Large scale FF	sky	2	9	10 (1000)	180.0	1.71
Sum						3.23

[a] It is assumed that the throughput calibrations of the MSA shutters and the conventional slits can be shared.

[b] A complete determination of the small scale MSA related flat field (FF) in orbit seems not feasible at the moment. The FF will heavily rely on a ground based model and occasional verifications in orbit.

The spectroscopic throughput is a product of a) throughput for each aperture (slit made of several shutters), b) throughput of the dispersive element, and c) the sensitivity of the detector. We assume that an overall sensitivity model can be constructed by determining the individual components:

a) **Aperture throughput:** The variations in principle optics and shutter throughput (i.e. exact size on the sky) should be measured on the ground to a high precision (knowledge <1% rms over full FOV) and can be verified in orbit with exposures of an internal continuum lamp with the mirror selected in the grating wheel. We assume that the illumination of the internal lamp is uniform (deviations <1% rms) over scales of $5''$. This allows for illumination calibrations of the fixed slits and the IFU without the need for external, pointed observations of background sources. For the conventional slits and the IFU a half-yearly verification seems adequate. We assume that ten exposures of 60 sec are sufficient to deliver the information. For the MSA, ten exposures are sufficient to map the entire array if the MSA mask is configured with a specific pattern; for example opening one micro-shutter every ten in the x direction and shifting the x position of the opened micro-shutters by three units for each increment in y direction. With this procedure one can also monitor MSA failures and partial openings which can severely affect the throughput. We recommend monthly checks.

However, depending on the exact position (sub-shutter accuracy) of a point source within the slit the throughput can vary significantly. For example, at $1.4\,\mu$m we estimate slit efficiencies between 55 and 65% within the nominal acceptance zone of one shutter (see W. Freudling 2002, for details). Therefore it is quite challenging to meet the scientific requirements in spectrophotometric throughput accuracy (see Section 3.4). Two themes may be envisaged:

(i) The actual throughput correction for each spectrum can be modelled theoretically if the exact object position, characteristics of shutters and the incoming effective PSF is known for each object [*active calibration*].

(ii) The throughput variations are smoothed out by an appropriate dither pattern which ensures a semi-uniform illumination of the slit in the dispersion direction [*passive calibration*].

The first option implies an accurate knowledge of the objects parameters which may be difficult or even impossible to obtain. For example, the emission line emitting regions for a given target may not be at the same location as the target position seen in the broad-band acquisition image. The second (passive) strategy will partly smooth out these effects. Preliminary simulations show that reasonable dither patterns can deliver a mean absolute and relative throughput accuracy of $\leq 2\%$ (e.g., 16 dither positions with 4 MSA re-configurations). Dithering is also necessary to achieve a full wavelength coverage, because there will be substantial gaps between the detectors in wavelength direction (see Section 4.1.4). An optimal dither pattern, which possibly depends on the wavelength band is TBD.

We note that almost all pointed calibration observations may have to be dithered in order to eliminate the MSA diffraction effects. This will impose a significant overhead in configuration and read-out time particularly if exposure times are short.

b) **Dispersive element throughput:** At least 12 dispersive elements and order blocking filter combinations need to be calibrated as a function of wavelength and position within the FOV. For the MSA modes the photometric response can be determined by observations of a spectrophotometric standard star placed at e.g., a 4x4 grid on the array (16 dithers of 16 positions gives 256 observations in total). By interpolating between grid positions one can determine a model for the entire area. The behaviour of the dispersive element and the required accuracy determine the number of grid points needed to achieve a successful calibration. We estimate that a 2% (rms) accuracy is needed. For the IFU and the conventional slits we assume that the photometric response can be determined from one-point spatial sampling (spatial information can be derived from continuum lamp exposures). We assume a bright source can be used (exposure time 100 sec). The MSA mode calibrations will be performed on a yearly time scale, while the conventional slits and the IFU will be repeated every half year. We expect to achieve a higher quality for the fixed slits and the IFU calibrations.

We note that the currently available spectrophotometric standard stars in the wavelength range

1-5 μm are probably not suitable for NIRSpec calibrations since they are very bright. Ground based observations need to provide "secondary standards" by the time JWST will take up its operations.

It would be desirable to calibrate individual filter throughput changes as well. For this the mirror needs to be selected in the grating wheel. We assume that the observation of one standard star field with 16 dithers in each of the filters is sufficient to calibrate the system. We assume high stability of the throughput so only yearly dedicated observations are necessary.

Variations in the sky background as a function of wavelength and orbital conditions will be determined at the beginning of mission. Further determinations can probably be extracted from science data.

c) **Detector sensitivity:** The determination of the flat fields is the last and possibly most challenging step in this sequence. There are two fundamental strategies to obtain the flat-fields: (i) Individual calibration of each instrument set-up (grating+MSA configuration) with an internal calibration lamp. This obviously carries a heavy load on the calibration time needed (∼1000s) for each MSA reconfiguration but will deliver accurate flat-fields; (ii) Alternatively, one can aim to built up a global model of the detector flat-field where the wavelength dependent response for each pixel is known. Assuming a stable detector this model should be verified only once a year.

We expect that the first method may be used for some individual high S/N observations while the second method will be used for the DRM programs. The two conventional slits and the IFU, which are presumably used for high S/N observations, can be calibrated every other month with dedicated lamp observations. The information from the MSA observations can be used as a guideline.

The second method will minimise the calibration needs during normal observations. In order to evaluate the feasibility of such a global model a detailed knowledge of the detector is needed. For example, information on the following aspects would be useful: wavelength variation of small & large scale flat-field, spatial scale variation, temporal stability and perhaps most critically, fringing.

Assuming favourable detector characteristics, a possible calibration strategy, following largely the ACS slitless grism mode (Pirzkal, Pasquali & Walsh 2002), is outlined in the following: On the ground the wavelength dependence of pixel-to-pixel variations can be calibrated with narrow-band filters (a possible temperature dependence needs to be investigated). Here the detectors need to be illuminated directly (MSA removed). Possible fringing needs to be investigated. Fringing effects may require a monochromatic illumination of the detector. Medium-scale (∼20 pixel) flat-field variations introduced by the detector should also be established on the ground. In orbit regular flat-field calibrations will be performed with a subset of the possible MSA configurations. These in orbit calibrations can be used to validate the ground based model. The stability of the detector flat-field determines the frequency of these in orbit calibrations. We estimate, that monthly checks of 5 configurations with 10 times 100s exposures are sufficient to validate the ground based model. We note, that unstable detector flat-fields can demand much more time intensive calibrations. A complete re-calibration of the wavelength dependent pixel-to-pixel variations in orbit appears with the current design very difficult (800 shutter columns, each 1000s exposure for all dispersing elements).

The large scale flat-field will be thoroughly calibrated at beginning of mission with exposures of astronomical targets and sky observations. Regular in-orbit calibrations (half-yearly frequency) will be used to verify the validity of the large scale flat-field.

As described in Section 3 the requested total spectrophotometric accuracy needs to be as good as $< 5\%$ for some observing modes, based on astrophysical considerations (e.g. line diagnostics) which sets tight constraints on the overall flat field accuracy of the order of 1-2% (rms). In order to achieve this accuracy we require that the large scale flat-field variations are $<15\%$ over the full FOV and that the variations can be mapped with a low order polynomial to better than 2% (rms).

4.1.4. Geometric calibrations

The astrometric calibration includes the overall telescope plate scale solution, the position of NIRSpec in the focal plane, and the small scale distortions within NIRSpec. The general shape and amount of geometric distortion within NIRSpec will be largely known from the instrument model. However, precise in orbit validation of the model is necessary. The initial characterisation must be carried out as a function of Fast Steering Mirror and any other parameters that may affect the geometric solution, such as wavelength, temperature, orientation, focus etc. See Table 6 for a summary of the geometric calibrations.

The accuracy of the geometric calibration is driven by the target acquisition procedure demands. Here a knowledge of the image distortions (sky to detector and MSA to detector) of better than 5 mas (rms) is required at all times. In order to allow for efficient operations a high stability of the distortion mapping is needed. Frequent (monthly, TBC) re-phasing of the telescope mirrors may have an effect on the distortion model. At the moment it is assumed that the distortion model will need to be re-calibrated after each re-phasing procedure. In order to meet the stringent demands of the target acquisition we estimate that the distortion maps need to be determined to an accuracy better than 4.5 mas (rms) while the stability of the distortion model in between re-phasings is assumed to be better than 2 mas (rms).

The geometric distortion calibration of the NIRSpec is a two-step process, requiring (i) measurements of the mapping of the aperture focal plane (carrying the MSA, fixed slits & IFU) onto the detector grid and (ii) of the telescope focal plane on the MSA.

The first step can be accomplished with exposures of an internal continuum lamp with the mirror selected in the grating wheel and configuring the MSA mask with a specific pattern. For example, a pin hole mask. In order to allow for efficient calibrations in orbit the distortions within the spectrographic stage of the NIRSpec should be smaller than 5% over the full FOV. The distortions should be known and easily mappable (i.e. low order polynomial) to an accuracy of

Table 6: Geometric calibrations

Measurement	Type	Frequency per year	# Calibrations	# Exposure (exp. time)	Total time ksec/year	Eff. cost % time
Geometric dist.	pointed	1	3	25(100)	7.5	0.07
Geometric dist. verf.	pointed	12	1	25(100)	30.0	0.29
Geometric dist.	c. lamp	2	3	5(60)	1.8	0.02
Mirror position	c. lamp	1000	1	5(12)	60.0	0.57
TA image	pointed	1000	1	5(24)	120.0	1.14
Focal plane pos.	pointed	2	1	5(100)	1.0	0.00[a]
Detector gaps	pointed	2	1	5(100)	1.0	0.00[a]
AFP rel. position	pointed	2	1	5(100)	1.0	0.00[a]
Sum						2.09

[a] It is assumed that theses calibrations can be derived from the geometric calibrations.

better than 4.5 mas (rms) over the full FOV. For these measurements we expect a S/N > 50 (per pixel) to be necessary which can be achieved with the internal continuum lamp within 60s. In order to check for chromatic trends at least three different filters should be used, where we assume that 5 MSA configurations per filter are sufficient. Since the re-phasing of the primary mirrors will have little affect on this calibration step we estimate that calibrations will be carried out only twice a year.

The second step requires the observation of astrometric fields. For example, a star-cluster where the exact positions of individual stars are known. Note that a relative astrometric accuracy of < 5 mas is required (ACS images will be able to provide this accuracy). Here the "imaging" characteristics of the MSA array can play an important role. First simulations show that the diffraction on the MSA support structure and the exact position of a point source within the slit can result in small systematic displacements ($\sim$1/7 detector pixel, i.e. $\sim$15 mas). Dithering of the astrometric target will be needed to deliver a better accuracy on the position. Since individual star positions will not be known accurately enough we assume that $\sim$10 stars can be combined to deliver one independent point in the distortion map fit. We assume that 5 pointings, with 5 dither steps of each 100 sec in three filters will be sufficient to meet the requirements. While the full calibration is carried out once a year, we currently assume that after re-phasing distortion calibrations in one filter will be needed. Similar observations can also be used to determine the exact focal plane position of NIRSpec and the monitor the gaps between detectors.

The distortion model which describes the optical path from the MSA to the sky can be determined from the two steps described above. We assume that an accuracy of better than $\sqrt{5.0^2 + 5.0^2}\,\mathrm{mas} \simeq 7.1\,\mathrm{mas}$ (rms) can be achieved.

Current instrument designs show that the repeatability of the grating wheel (carrying the mirror for direct imaging) is a critical issue. Should the designs not produce a repeatability of the wheel position to better than 5 mas (rms) at the detector level then a contemporaneous "zero-point" calibration is necessary. In order to avoid that the whole distortion model is affected, we require that the wheel moves to better than one detector pixel accuracy (i.e. < 100 mas rms). Once at a a given position we assume that the dispersive elements or the mirror do not move by more than 1/60 (rms) of a resolution element. If a "zero-point" calibration of the grating wheel should be necessary this will be achieved with special "L-shaped" slits in the aperture focal plane. Exposure times of 5×12 sec (5 exposures for cosmic ray rejection) seem sufficient since the light is not dispersed. However, this calibration is needed for each target acquisition. The special slits should be designed such that neither a MSA failure nor a failure of one detector impacts on the grating wheel calibration.

With the help of these calibrations one can also track relative motions of components in the aperture focal plane (e.g., MSA unit with respect to fixed slits) or drifts of the detector positions. Overall, we expect these motions to be small and the aperture focal plane and the focal plane assembly to be highly stable (i.e. $< 1\%$ change per year over full FOV). Accurate ground based measurements are needed to characterize the aperture focal plane and focal plane assembly geometry.

In order to perform the target acquisition (TA), i.e. the exact alignment of the AFP with the science targets, images (mirror selected in grating wheel) of the target field will be taken. We assume that relatively bright reference targets can be used thus total exposure times of $\sim$120 sec will be sufficient. We recommend to take 5 individual images of 24 sec in order to allow for cosmic ray removal. We assume in this document 1000 TAs per year (TBC).

4.1.5. Spectroscopic calibrations

In this section we discuss the spectroscopic calibrations which ensure that the observations meet the scientific requirements. Table 7 summarises the calibrations. An important assumption for this section is that not all possible MSA configurations need to be calibrated independently, but a coarse sampling is sufficient to built up a global model. Furthermore we assume that the information on spectral trace, dispersion solution and zero points derived from the internal lamps can be directly applied to observations of astronomical objects. Note, that the light of the calibration lamps does not go through the filters used for external sources. However, the internal lamps may carry their own filters to avoid e.g., second order contamination.

Typical targets for NIRSpec are going to be faint and not clearly visible on individual exposures. Furthermore, the spectra of emission line objects with no detectable continuum flux will be difficult to trace on the detector. In order to determine the position of the spectrum from each slit element a priori, an exposure with an internal continuum source is required ("trace" calibration). The instrument stability should be such that one can built up a global model of the spectral trace and re-calibrate it on a yearly basis (deviations from the model < 0.1 pixel/year rms at detector

Table 7: Spectroscopic calibrations

Measurement	Type	Frequency per year	# Calibrations	# Exposure (exp. time)	Total time ksec/year	Eff. cost % time
Spectral trace	c. lamp	1	9	5 (60)	2.7	0.03
Dispersion sol.	line lamp	6	9	5 (60)	16.2	0.15
Zero points	line lamp	2600	1	1 (12)	31.2	0.30
Through slit image	pointed	1000	1	1 (300)	300.0	**2.85**
Internal line lamp	pointed	1	8	1 (1000)	8.0	0.08
Line spread func.	pointed	1	4	7 (1000)	28.0	0.27
Shutter contrast	pointed	1	1	10 (60)	0.6	0.01
Sum						3.69

level). The distortion mapping requirements described in Section 4.1.4 are sufficient to meet this criterium. For $\Re \simeq 100$ one can calibrate the spectral trace with columns of small slits separated by ∼300 shutters in spectral direction and by a few shutters in spatial direction. A few of these masks should be sufficient to calibrate the full system. For $\Re \simeq 1000$ the calibrations need more individual exposures since only one column of slits can be observed at the same time (otherwise spectra will overlap). We assume that 5 exposures of 60s per dispersing element are sufficient to perform the calibration. In order to allow for a optimal extraction we estimate that a knowledge of the trace of ∼1/10 (rms) of a detector pixel is necessary. We note that an instability of the grating wheel will result in bulk shifts of the trace. If the stability of the grating wheel cannot deliver a high accuracy one can use the contemporaneous wavelength-zero-point calibrations (described below) to adjust the trace model after each grating wheel move.

The calibration of the dispersion solution can be performed in a similar way as the spectral trace calibration with the line-lamp switched on. In order to achieve an overall wavelength calibration accuracy of 1/10 (rms) of a resolution element, the dispersion solution has to be known very accurately (<1/20 FWHM, rms). This knowledge can be achieved by building on an accurate ground based model of the dispersion solution. Here measurements with a fine wavelength grid are required (>100 lines per spectral band). In orbit this model will only be adjusted on wavelength scales determined by the line sampling of the internal lamps (∼ 10 lines per band). The stability of this solution should be such that bi-monthly calibrations are sufficient.

While we expect the spectral trace model and the dispersion solution to be very stable with time, the wavelength zero point calibrations will need to be performed more frequently. In this document we take a conservative approach and assume that a calibration is necessary after each prism/grating wheel move. We estimate ∼2600 grating wheel moves per year. We assume that the normal line lamps used for the dispersion solution can also be used for the zero point. By averaging the measurements of several (≥3) lines one can reduce the exposure time to about 12 sec which corresponds to the minimal readout time for a full frame. It is envisaged that by fitting a low order polynomial to the peaks of the lines one can adjust the global trace model in the data-reduction pipeline.

The zero-point wavelength calibration obtained with an internal lamp is in principle only valid for a science object which fills the slit uniformly. However, typical JWST targets may be better described by a point source which will lead to wavelength shifts if the target is not in the middle of the slit. If the exact position within the slit is known the effect can be modelled or alternatively one can use a dither strategy to smoothly illuminate the slit (see also Section 4.1.3). As detailed in Section 3.4, the goal is to ensure an absolute accuracy of the wavelength calibration of 1/10 of a resolution element. The size of the wavelength shifts for point sources should be minimised by the design of the spectrograph. In order to aid the data reduction pipeline we recommend to obtain after each successful target acquisition a "through slit" image of the science targets. In this way the actual positions of targets within the slits can be determined. We estimate exposures times of 300s. The exposure time should be user selectable.

The use of internal line sources is mandatory for the spectroscopic calibrations since a completely external calibration is virtually impossible with an unstable grating wheel.

If the line lamps are realized via a Fabry-Perot etalon or similar, the lamps themselves need to be calibrated on a regular basis with external line sources (see Castertano & Holfeltz 2003, STScI-JWST-R-2002-0005). We assume that the lamps are stable on a yearly timescale and that eight different calibration channels need to be calibrated.

The knowledge of the line spread function is important for astrophysical diagnostics and for the deconvolution of complex spectral features ($\Re \simeq 1000,\ 3000$). The detailed diffraction properties of the MSA play an important role here and need to be modelled in the future. Extensive ground based testing is needed to confirm the model. We require that the line-spread function is mapped out with ground based testing at least to 10^{-3} (TBC) of the line peak. The in orbit calibration requires observations of astronomical narrow-line sources observed at several positions over the field of view (FOV) and as a function of target position within the slit. These calibrations are expected to be carried out in detail at the beginning of the mission and then verified on a yearly basis. Currently we estimate 5 exposures are needed to calibrate the line-spread function for each dispersing element as a function of wavelength. If no suitable line sources can be found the number of observations may increase significantly.

The contrast, i.e. the ratio between transmitted light with a micro-shutter on and off, is a driving factor in the design of NIRSpec as it ultimately determines the faintness of the sources observable with the instrument and the fraction of the spectra "spoiled" by the un-suppressed light of bright sources in the field of view. Contrast issues and confusion limits for the JWST NIRSpec have been discussed in detail by Freudling et al. (2002). The determination of the contrast is essential for observation planning and will be extensively carried out on the ground. Orbital verification will take place at the beginning of the mission and will continue on a yearly basis by comparing observations of bright astronomical sources with the mirror selected in the grating wheel and with the MSA elements on and off. We estimate ten exposures are sufficient to achieve the calibration.

4.2. Conclusions

This document gives an overview of the basic calibration strategy and time consumption for the NIRSpec on board of JWST. The description of the calibration strategy is presented only in general terms since many details of the spectrograph and its detectors are not determined at this point. Naturally this document will evolve when more information becomes available.

Typical basic calibrations, including detector, optics, sensitivity, geometric and spectroscopic calibrations, which are needed during one year of operation, are summarised in Tables 1–6. The total amount of calibration time is estimated to be 14.5%. Using parallel observations for darks one can free up $\geq 3\%$.

Critical calibration issues which are identified in this document are listed below:

- Extensive instrument modelling, including the effects of all major components of the spectrograph, is required to design an efficient calibration strategy in orbit. The resulting spectrograph model needs to be confirmed with detailed pre-flight observations and a thorough beginning of mission verification.

  The Flat-Field (FF) determined by the detectors requires a particularly complex pre-flight calibration. We note that the determination of the full pixel-to-pixel FF as a function of wavelength is extremely difficult, if not impossible, to obtain in orbit. In the current strategy the FF calibration will largely rely on a ground based model with occasional up-dates from data obtained in orbit.

- The provision of internal lamps (continuum and line sources) is mandatory since the full calibration with astronomical targets would take up a significant amount of additional exposure time (>>5%) and put strict limits on the target sample construction. In the case of an unstable grating wheel, the zero point calibrations cannot be carried out without internal lamps.

- The scientific requirement for the spectrophotometric accuracy is as stringent as 5% (rms) for some observations. In order to meet this criterium with the current design of NIRSpec, a well defined dithering technique seems necessary. The dithering needs to deliver a semi-uniform illumination of the slit in order to remove throughput variations introduced by diffraction on the MSA support structure and science target misplacement introduced by the fixed nature of the MSA grid. The optimal dither pattern is probably dependent on the detailed diffraction properties of the MSA and therefore needs to be determined with future accurate instrument modelling.

- In order to perform the target acquisition a very accurate knowledge of the distortion model is needed ($\leq$4.5 mas rms). Furthermore, the distortion map must be very stable (drift $\leq$2 mas rms) in between calibrations. It is also essential that the prism/grating wheel shows a high repeatability ($<$ 1 pix) even if contemporaneous offset calibrations will be carried out.

- The influence of regular telescope mirror re-phasing on the focus adjustment of NIRSpec and potentially the overall calibration concept is unclear at this point. Currently it is assumed that the re-phasing (monthly, TBC) will demand re-calibrations of the focus, the PSF and the distortion model. Therefore, it is important to provide efficient means to carry out these calibrations. For this purpose the AFP should carry a set of clear focus apertures.

- Key to an efficient calibration strategy is a well behaved spectrograph where sensitivity parameters change only smoothly across the FOV and thus a rather coarse sampling of the parameter space is sufficient to calibrate the full system.

- The currently available standard stars for spectrophotometric calibrations are probably not suitable for NIRSpec. Extensive ground based preparation work will be needed to establish a useful list of secondary standards.

- At this point there is little information on the expected temperature changes on JWST during the observations. Future studies will have to consider potential influences on the calibration concept in more detail (e.g., temperature sensitivity of detector flat-field).

Table 8: Acronym description

Acronym	Description
AFP	Aperture Focal Plane
DRM	Design Reference Mission
FF	Flat Field
FGS	Fine Guidance Sensor
FOV	Field of View
FPA	Focal Plane Array
IFU	Integral Field Unit
JWST	James Webb Space Telescope
MSA	Micro-Shutter Array
NIRCam	Near-Infrared Camera
NIRSpec	Near-Infrared Spectrograph
POM	Pick-off Mirror
SI	Science Instrument
TA	Target Acquisition

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