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The science calibration challenges of next generation highly multiplexed optical spectroscopy: the case of the Maunakea Spectroscopic Explorer

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ABSTRACT

MSE is an 11.25m telescope with a 1.5 sq.deg. field of view. It can simultaneously obtain 3249 spectra at $R = 3000$ from $360-1800$nm, and 1083 spectra at $R = 40000$ in the optical. The large field of view, large number of targets, as well as the use of more than 4000 optical fibres to transport the light from the focal plane to the spectrographs, means that precise and accurate science calibration is difficult but essential to obtaining the science goals. As a large aperture telescope focusing on the faint Universe, precision sky subtraction and spectrophotometry are especially important. Here, we discuss the science calibration requirements, and the adopted calibration strategy, including operational features and hardware, that will enable the successful scientific exploitation of the vast MSE dataset.

Keywords: Manuscript format, template, SPIE Proceedings, LaTeX

1. INTRODUCTION

The Maunakea Spectroscopic Explorer (MSE) is the only dedicated, optical and near-infrared, large aperture (> 10 m), multi-object spectroscopic facility being designed for first light in the mid-2020s. It is a re-purposing of the Canada-France-Hawaii Telescope, within an expanded international partnership and upgraded to a larger aperture.

MSE will obtain more than 4000 spectra per observation. Specifically, photons will be collected by the 11.25m aperture M1, reflected to the prime focus where a Wide Field Corrector will provide a 1.5 square degree field of view. An Atmospheric Dispersion Corrector will correct for some effects from the atmosphere, and at the focal plane more than 4000 fiber positioners will move fibers to the expected locations of the astronomical targets, including science objects, calibration sources, and sky positions. Those photons within the entrance aperture of the fibers will pass down tens of meters of fiberoptic cable to one of two different suites of spectrographs. There, the photons will pass through numerous optics, including dispersive elements, before being registered on the CCD or H4RG detectors.

Astronomers using MSE will only obtain an improved understanding of the wonders of the Universe by successfully relating the counts on detectors (the end result of the journey of the photons through the atmosphere and the MSE system) to the physical properties of the astrophysical objects that the photons left some large

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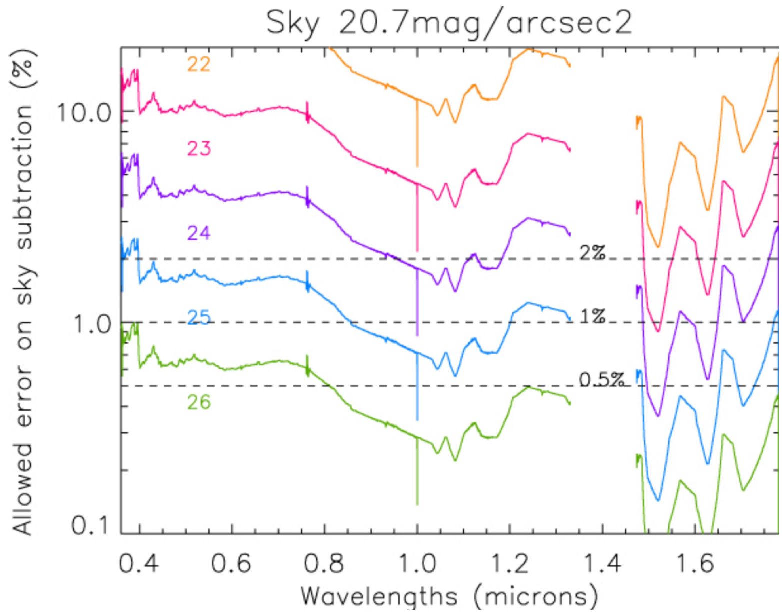

Figure 1. For dark sky conditions, each line shows the required sky subtraction accuracy as a function of wavelength for sources with different (monochromatic) magnitudes, to ensure that a majority of the flux is the subtracted spectrum is from the target object, rather than residual sky flux.

number of years ago. Calibration is therefore central to all aspects of MSE. By its nature, accurate and precise calibration is challenging, and it is made doubly so for MSE which has as its driving goals the study of exceptionally faint astrophysical sources, including spectrophotometric studies and time-domain (long baseline) observations.

At the previous SPIE Astronomical Telescopes and Instrumentation meeting, the status and progress of the project were detailed in Ref. 1 while an overview of the project design was given in Ref. 2 and the science based requirements were explained in Ref. 3. An update of the project at the end of conceptual design phase is presented this year in Ref. 4 with a review of the instrumentation suite in Ref. 5. Other papers related to MSE are focusing on: the summit facility upgrade (Ref. 6,7), the telescope optical designs for MSE (Ref. 8), the telescope structure design (Ref. 9), the design for the high-resolution (Ref. 10, 11) and the low/moderate-resolution spectrograph (Ref. 12, the top end assembly (Ref. 13, 14), the fiber bundle system (Ref. 15, 16), the fiber positioners system (Ref. 17), the systems budgets architecture and development (Ref. 18,19), the observatory software (Ref. 20), the spectral calibration (Ref. 21, 22), the throughput optimization (Ref. 23, 24), the observing efficiency (Ref. 25), and the overall operations of the facility (Ref. 26).

This paper is structured as follows. Section 2 describes some of the key science capabilities of MSE and their consequences for the calibration requirements. Section 3 outlines the technical considerations for sky subtraction and spectrophotometry , both in a general sense and specific to MSE observations. Operational considerations that affect calibration strategies are described in Section 4. In Section 5, we present an overview of the baseline calibration procedures for MSE, and in Section 6 we describe the initial concept for the science calibration hardware. Section 7 discusses future development plans and summarises.

2. SCIENCE CAPABILITIES AND CONSEQUENCES FOR CALIBRATION

As a large aperture, dedicated, spectroscopic facility, MSE is designed to obtain spectra of faint targets that cannot be observed with smaller facilities. A multitude of possible science programs for MSE are outlined in the Detailed Science Case.[27] Extragalactic targets are typically 24th magnitude or even fainter; it is already expected that MSE will obtain spectra on galaxies fainter than 25th magnitude. Dark skies in Maunakea correspond to around 20.7mags/sq.arcsec in the V-band. Thus, for unresolved or partially resolved sources, we will routinely be targeting galaxies that are more than 20 or even 50 times fainter than the sky.

Figure 1 shows the challenge for accurate sky subtraction as a function of wavelength. Here, we consider astronomical targets with a range of (monchromatic) intrinsic magnitudes, as indicated by the text in the figure. Given dark time sky conditions ($V = 20.7$mags/sq.arcsec), the diffferent lines correspond to the accuracy on the sky subtraction required at any wavelength in order to ensure that the subtracted spectrum is dominated by target flux, not residual sky flux. In almost all science cases, it will be necessary to require a significantly higher fraction of science photons that this (at least 10 times more). For discussion purposes, however, we can consider it an absolute lower limit to what might be useful for science. For example, a target at 25th magnitude at 850nm requires better than 1% sky subtraction in order to ensure a majority of the photons in the subtracted science spectrum are actually science photons, not residual sky photons. Clearly, to push to 25th magnitude or better requires sky subtraction accuracies much better than 1% at all wavelengths, and the requirements are even more stringent in the H-band.

It is not just sky subtraction that will be challenging. A driving science goal of MSE is reverberation mapping of Active Galactic Nuclei. This necessitates accurate ($< 3\%$) relative spectrophotometry i.e., the integrated flux is a given wavelength interval compared to that in a different wavelength interval should be able to be measured to $< 3\%$ accuracy. This necessitates extremely accurate knowledge of the transmission function of the system as a function of wavelength at all times. Enabling this specific goal for reverberation mapping enables many other science goals, especially in relation to the stellar population modeling of galaxies and measurements of their star formation histories.

Reverberation mapping also requires repeat observations with multiple cadences, spread over a period of many years. Indeed, time-domain science is expected to feature heavily in the science program of MSE. Accurate calibration over timescales of years, to enable observations taken at widely seperated times to be directly compared to one another, is a challenging but scientifically compelling capability for which MSE is being designed.

There are 6 high level MSE Science Requirements that explicitly focus on calibration, specifically velocity accuracy, spectrophotometric accuracy, and sky subtraction. The calibration requirements, like all science requirements, have been derived from consideration of the science described in the Detailed Science Case, and in particular the Science Reference Observations. The SROs describe, in considerable detail, specific and transformational science programs that are uniquely possible with MSE. Science requirements are defined as the core set of science capabilities that MSE must have in order to enable the science described by the SROs.

The Science Requirements relating to calibration are the following:

- REQ-SRD-041/042/043 Velocities at low/moderate/high resolution: For any object with a known velocity, observed at multiple epochs by MSE with up to a 5 year cadence with a signal to noise ratio per resolution element of 5/5/30 at low/moderate/high spectral resolution, the contribution from MSE to the rms difference between the known velocity of the object and the measured velocity of the object shall be less than or equal to 20/10/0.1 km/s

- REQ-SRD-044 Relative spectrophotometry: For a spectrophotometric standard star, observed in the low resolution mode at multiple epochs by MSE with up to a 5 year cadence with a signal to noise ratio per resolution element of 30, the rms variation in the ratio of fluxes measured in any two wavelength intervals shall be less than 3% of the mean measured value.

- REQ-SRD-045 Sky subtraction, continuum: In wavelength intervals free from airglow emission-line contamination and strong telluric absorption, MSE shall allow for removal of the sky flux with a root-mean-square error of less than 0.5% of the sky flux, at all wavelengths (TBC).

- REQ-SRD-046 Sky subtraction, emission lines: MSE shall achieve a sky subtraction accuracy for atmospheric airglow emission-lines such that the mean residual error for spectral pixels, within 1 resolution element of known atmospheric emission-lines, is < 1.5 times (TBC) the Poisson limit indicated by the propagated variance spectrum for each resolution element.

In what follows, we develop a calibration procedure based on three principles:

1. Calibration exposures shall not introduce any significant sources of noise into the observations (either directly such as a spectral flat or indirectly such as through a model of the flux response across the focal plane)
    - The number of counts in a calibration exposure at any wavelength that is combined with the science data should greatly exceed that of the typical counts in the data (targets+sky combined).
2. Calibration exposures shall not add significant overheads to science observations
    - Any (standard) nighttime calibration observations will be quick, and any necessary time-consuming calibration should ideally be done during the day. It is a high level science requirement (see next section) that the nighttime science observing efficiency (i.e., open shutter time on science targets, excluding weather) should exceed 80%.
3. Calibration exposures shall be obtained in a configuration and under circumstances that are as close as possible to that of the science observations
    - To reproduce as closely as possible the system-wide behavior at the time of the science observation

3. TECHNICAL CONSIDERATIONS

3.1 General considerations

In order to provide high quality science calibration, it is essential to understand the wavelength-dependent transmission of MSE (the transfer function) and the behaviour of the point-spread function for astronomical targets positioned anywhere in the sky, in addition to the wavelength solution. Thus, for every target, we want to know the throughput, wavelength solution (mapping detector pixels into wavelength), and the behaviour of the point spread function, as a function of

- Wavelength (λ)
- Telescope pointing [Azimuth (a), Altitude (A)]
- Position in field (on focal plane) $[X, Y]$
- Position of fiber in its patrol region $[x, y]$
- Time (t)
- Environmental conditions (temperature, humidity, etc.)

In practice, this means understanding the performance of various MSE subsystems as a function of all these variables. Relevant subsystems include (considering successive "Product Breakdown Structure" elements along the optical path):

1. MSE.ENCL: the enclosure
2. MSE.TEL.STR: the telescope structure
3. MSE.TEL.M1: the primary mirror
4. MSE.TEL.PFHS: the prime focus hexapod system
5. MSE.TEL.WFC/ADC: the wide field corrector and atmospheric dispersion corrector
6. MSE.TEL.InRo: the instrument rotator

7. MSE.SIP.PosS: the fibre positioner system
8. MSE.SIP.FiTS: the fibre transmission system
9. MSE.SIP.LMR or MSE.SIP.HR: the spectrographs, either low/moderate (these two modes are realised in a single spectrograph system) or high resolution
10. MSE.SIP.SCal: the science calibration hardware, specifically the calibration lamps and associated infrastructure
11. MSE.SIP.PESA: the program execution software architecture, including the data reduction and processing software and pipelines

Our focus in this contribution is the strategy, operational considerations and hardware that will allow us to obtain the best empirical measurements of the PSF, throughput and wavelength solutions. We do not discuss the data processing techniques by which the calibration and science data will be combined ("PESA"), and leave this as the subject of a future contribution.

A major calibration concern is is with respect to the behavior of the fibers, and related components (e.g., positioners), in particular our ability to map measurements made in one fiber at one time (with a particular pointing and at a particular position in the field, where the system, especially the fibers, are experiencing a specific flexure, twist, etc.), to any other fiber (including the same fiber) with a different pointing and/or at a different position in the field. Consider two extreme scenarios:

- In an idealized perfect case, each fiber would be identical and have identical characteristics regardless of the details of the observation. Thus, it would be trivial to relate observations taken in one fiber (say, a spectrophotometric calibration star) to calibration information for another fiber. It would also be trivial to apply the wavelength solution derived for a fiber at one time to the same fiber at any future point in its usage.
- In an idealized terrible case, each fiber would be very different, and would behave very differently depending on the details of the observation. Worse, this behavior would be non-repeatable. In such a situation, calibration observations such as arcs and flats would ideally be taken simultaneously (although in practice they would be taken immediately after or before the science observation) in order to estimate the behavior of the fiber at the particular moment of the observation.

We expect MSE and most other fiber MOS systems to be somewhere between these two extremes, and the requirements of the system should seek to make MSE as close as possible to the idealized perfect case. However, each fiber will be intrinsically slightly different. We expect that the behavior of MSE as a system (and the fiber system in particular) will vary as a function of telescope pointing and target position within the field, but we expect/require that this behavior will be repeatable. Given the need to calibrate MSE to a very high level of precision, we are cognizant that these effects may force us to consider the MSE system hardware as closer to terrible than perfect, and allowance must be made to accommodate for this possibility.

3.2 Considerations for sky subtraction

Sky subtraction with fiber-fed spectrographs is usually performed by allocating some number of fibers to measure the sky background spectrum in blank locations across the field of view. These 1-D sky spectra are then combined, scaled to match the expected sky spectrum in each target fiber, and subtracted from the 1-D target spectra.

The sky background consists of a smooth continuum plus airglow emission lines, mostly from OH and mostly at wavelengths > 0.6 microns. The emission lines can vary on timescales of minutes (Section 2.1.2 of Ref. 28) and on spatial scales of arcminutes.[29] It is therefore necessary to obtain sky spectra at the same time as the target spectra.

The sky background entering the fibers will vary depending on the fiber's position in the field of view. The sky background recorded for each fiber on the detector will also depend on the wavelength-dependent throughput of the fiber + instrument + detector system for that fiber. A wavelength-dependent scaling will be applied to each spectrum to bring them to a common background level and a common throughput. Sky subtraction is limited by the accuracy of such scaling, which will be limited by the accuracy of our measurements of fiber positioner characteristics, of radial plate scale changes, and of the wavelength-dependent system throughput for each fiber.

To help measure the rapidly changing sky background, one of two varieties of "beam-switching" is sometimes used, at the cost of observing efficiency.

- In telescope-based beam-switching, the telescope is offset between exposures so as to place each target fiber on a blank sky position. By assigning half the fibers to targets in each exposure, half the fibers measure sky in each exposure, and each target has blank sky measurements through the same fiber (at somewhat different times), removing the need for spatial interpolation of the sky spectrum across the field of view (FOV). The disadvantage of this approach is that exposure times per field become twice as long.
- In fiber-based beam-switching, each target has two fibers assigned to it. One is placed on the target and the other is placed on a blank sky location as close by as possible (and certainly within 60 arcseconds). The allocation of one sky fiber to each target removes the need for spatial interpolation of the sky spectrum across the FOV. The fibers assigned to each location can be swapped between exposures, so that the target and sky fluxes are measured through both fibers, to help with scaling sky spectra before subtraction. The disadvantage of this approach is that the number of fibers available per field for science targets is cut in half.

Beam-switching is not planned to be the default MSE operational mode. Nonetheless, to test the improvement (if any) obtained by fiber-based beam-switching, it is recommended that MSE have the capability to assign sky and object fiber pairs which could be alternated between observations.

We now consider some more detailed specifics relating to sky subtraction. We require calibration data that can provide wavelength solutions and line spread function information for all fibers during the observation. Thus, arc spectra and lamp flats taken close to the science observation are useful.

The night sky background flux is uniform over the input face of a fiber. Thus, the PSFs of spectrally unresolved sky lines (in both the spatial and spectral directions) will be determined by the exit beam from the fibers and the spectrograph optics.

The spatial component of the PSF on the detector will affect sky subtraction in 1-D spectra because spectrograph distortions cause the spatial and spectral directions in a given 2-D spectrum to deviate from lying exactly along detector rows or columns.

To correctly estimate the sky spectrum in one fiber from sky spectra measured in other fibers requires knowledge of both the relative wavelength-dependent sensitivities of the fibers and how the PSF changes across each detector, in each spectrograph, with temperature and mechanical changes, and with fiber illumination and focal ratio degradation (see appendix A1 of Ref. 30).

The PSF can in principle be affected by:

1. Fiber tilt: For MSE, tilting spine positioners - "Sphinx" - are being used after an extensive trade-study comparing the anticipated performance of these compared to phi-theta positioners. Tilted spine positioners have been used by Subaru/FMOS ("Echidnas"), and are to be used in 4MOST ("Aesop").

   Tilted spines hold the fibers very gently in comparison to ph-theta positioners, and no twisting of the fiber occurs. However, for most configurations the light enters the fiber at an angle. Light entering a tilted fiber has a different angular distribution relative to the fiber normal than light entering a face-on fiber. That different angular distribution yields a different far-field radiation pattern emerging from the fiber into the spectrograph. This effect is known as geometrical focal ratio degradation (FRD). The emerging radiation pattern will propagate through the spectrograph optics to yield a different PSF (e.g., the PSF may have a tilt-dependent centroid shift in the wavelength direction).

2. Focal ratio degradation (FRD) in the fibers: light exits an optical fiber with a slightly wider angular distribution (a faster beam) relative to the fiber axis than it had upon entering the fiber. This form of FRD depends on the stress on the fiber due to its routing from the focal plane to the spectrograph. In MSE, FRD could decrease the focal ratio capturing 95% of the light by $3 - 6\%$, placing some light at a given wavelength outside of the acceptance speeds of the collimator and altering the PSF of the accepted light. The effect of a FRD-dependent PSF on the sky lines is in principle removable through a principal component analysis.

   FRD effects can also be minimised at the design stage of the SIP.FiTS subsystem. Fibers leading to the high resolution spectrograph are approximately 50m long, and fibers leading to the low/moderate resolution spectrographs are approximately 30m long. Careful fiber-routing and strain-relief are therefore essential to reduce any twisting effects or any other action that stresses the fibers.

3. Spectrograph optics: MSE requirements impose a minimum resolution and an acceptable range for the average resolution. However, no requirement is placed on resolution variations at the same wavelength for fibers imaged by the spectrographs at different locations on the detectors. Such variations have been reported in the conceptual design report for the low/moderate resolution spectrograph. We note that such variations in PSF spectral *width* can be accounted for more easily than variations in PSF spectral *shape*.

4. Detector effects (including pixel-to-pixel sensitivity variations, and charge diffusion): To achieve continuum sky subtraction accurate to 0.5% at any wavelength, pixel-to-pixel sensitivity variations on the detectors will have to be calibrated so as to contribute $< 0.5\%$ uncertainty to the sky per extracted 1-D pixel. For example, if a spectral trace is three pixels across in the spatial direction, the response of each pixel must be calibrated to $< 0.87\%$ each to yield a combined $< 0.5\%$ in the corresponding 1-D spectral pixel.

5. Fiber-to-fiber wavelength calibration errors. The wavelength calibration will depend on fitting numerous individual lines. Shifts in the wavelength centroid due to fiber tilt affecting the PSF are estimated to be very small.

6. Spectrograph thermal or mechanical changes. Neither the LMR or HR spectrographs will be located on the telescope elevation structure, so spectrograph flexure during exposures is not an issue. However, mechanical stability in the LMR spectrograph due to grating changes between the LR and MR modes is a potential issue.

Also required is knowledge of the properties of any significant spectrograph stray light or ghost image across each detector in each spectrograph. Such light could mimic sky background light but with different wavelength and spatial variations; such light would have to be modeled and removed.

3.3 Considerations for spectrophotometry

Absolute spectrophotometry is the conversion of recorded photon counts at each wavelength in a spectrum to an objects total flux density (traditionally in ergs per cm^2 per Angstrom). Relative spectrophotometry is the reconstruction of an objects relative flux density at each wavelength, yielding accurate spectral shapes but not photometry (i.e., with an unknown normalization factor). Relative spectrophotometry is desired for low and medium resolution spectra. For high-resolution spectra, there is no spectrophotometry requirement, but calibration stars can be observed when a correction for telluric absorption.

Flatfield calibrations (pixel flats and spectral flats) provide the relative throughput as a function of wavelength for all fibers in a given observing setup, enabling conversion from recorded counts (photoelectrons) in a fiber to recorded counts normalized relative to a reference fiber (or fibers, or other reference value).

However, flatfield calibrations do not correct for the injection efficiency (IE). The IE is the fraction of light from an astrophysical object incident at the focal plane that enters the fiber, and it depends on the distribution of object light at the focal plane and the relative positioning accuracy of the fibers. The former depends on all terms that contribute to the image quality - including the polychromatic seeing of the free atmosphere, thermal and airflow effects in the enclosure (dome seeing), the residual effects of atmospheric dispersion not corrected for by the ADC, atmospheric refraction, and all optical effects in the M1 system and WFC/ADC - and is potentially able to be modeled given excellent knowledge of the system. The latter depends upon numerous hardware performance issues, especially the fiber positioners but other effects as well. IE is discussed at length in Ref 31.

Converting flatfielded counts to relative flux densities requires observing targets with a known spectral energy distribution (SED. In practice, for a fiber-fed multi object spectrograph, this requires observing many (~ 20 or more) relatively bright, hot stars of known, constant magnitude whose spectra can be modeled to high accuracy. Such spectrophotometric calibration stars are spread over the field of view and are observed simultaneously with science targets. Each model spectrum, normalized to the stars known magnitude, is divided by the counts at each wavelength to compute a "fluxing vector" i.e., the transformation between the flatfielded calibration star counts and the physical SED. These fluxing vectors are typically averaged to produce a final fluxing vector which is multiplied by the flatfielded counts of all targets in the exposure to yield final flux-calibrated spectra.

In the SDSS-I/II survey, which used 3" diameter fibers and no ADC, an RMS spectrophotometric accuracy for calibration stars of 4% at a given wavelength was achieved on average. In the SDSS-III/BOSS survey, which used 2" diameter fibers and the same site and telescope as SDSS-I/II, the corresponding number was 6%. For comparison with the MSE relative spectrophotometry requirement, note that the uncertainties on the $g - r$ and $r - i$ colors [equivalent to flux ratios] in BOSS were 5.7% and 3.2%, respectively, or 4.5% on average. In the SDSS-RM campaign (part of SDSS-III), the corresponding number was 5%. SDSS-RM observed its targets twice as long as normal SDSS-III targets and was thus somewhat more susceptible to the effects of atmospheric dispersion, but was able to compensate for that effect and even improve the calibration slightly by using 70 spectrophotometric standards instead of 20.

Maximizing the number of fibers on science targets makes it practical to observe only enough calibration stars to calculate a single fluxing vector per exposure. Therefore, known systematic effects on the wavelength-dependent injection efficiency of different fibers across the field of view should be accounted for by removing those effects before calculation of the fluxing vectors. If all known systematic effects have been removed, then the scatter in the fluxing vectors will be minimized and the accuracy of the spectrophotometry maximized. It is worth emphasizing that effects which vary across the field of view must be corrected before calculation of the fluxing vector, but that effects which are uniform across the field of view can be incorporated in the fluxing vector.

If only random uncertainties remain to limit the spectrophotometric accuracy, then the spectral shape of a target will be as accurately characterized as possible even when it is observed repeatedly with the telescope at different elevations and azimuths, using different fibers at different locations in the focal plane, at different fiber tilts, and recorded on different detectors in different spectrographs.

Finally, we note that the approach used to meet MSE's relative spectrophotometry requirement will also yield absolute spectrophotometry of comparable accuracy for point sources. Our first step toward relative spectrophotometry is a correction for flux not intercepted by each fiber as a function of wavelength. We only require that step to be accurate in a relative sense. In the next step, the fluxing vector incorporates whatever correction factor is needed to match the absolute fluxes of the spectrophotometric calibration stars, with an accuracy determined by the known photometry and the modeled spectral shape of those stars. The result is spectrophotometry which is accurate in both a relative and an absolute sense, though we do not consider here any additional uniformity considerations relevant to absolute spectrophotometry.

4. OPERATIONAL CONSIDERATIONS

We now discuss (nighttime) operational considerations that impact the calibration of the data.

4.1 Observing efficiency requirement and definition

MSE is a survey facility, whose success will be primarily related to the quantity and quality of data obtained every night. There is a high level science requirement that states that the "observing efficiency" of MSE will be 80%. Specifically, observing efficiency is defined as the fraction of time the observatory is collecting photons divided by the time the observatory could have been collecting photons, which is all the time available for observations except that lost to weather. We refer the reader to Ref. 25 for a detailed discussion of observing efficiency in the context of MSE.

The observing efficiency is defined in steady state operations for MSE, i.e. after commissioning of the observatory. In addition, we assume it is averaged at least over a year, given the nature of the typical events occurring at a ground based astronomical facility.

The intent of this requirement is to ensure the efficient acquisition of quality data. Some calibration observations will be required during the nighttime, and while these officially count "against" the observing efficiency, it is not deemed acceptable by the Project to have a high acquisition rate of data that cannot be used for science. The challenge is therefore to minimise nighttime calibration time, while ensuring an efficient acquisition rate of science-quality data.

4.2 On-sky calibration time

The "worst-case scenario" for nighttime lamp calibrations with MSE is that they are expected before and after each science observation (which we term an "Observing Matrix", OM, in what follows). In order to mesh with other aspects of night-time operations and the overall observing efficiency budget, we aim for a nighttime calibration sequence to last no more than 4 minutes, broken down as two blocks. We assign the timing of these blocks as follows:

- 95 seconds for collecting photons (TBC)
- 18 seconds for all readouts (TBC)
- 3.5 seconds to turn on the system (TBC)
- 3.5 seconds to turn off the system (TBC)

The justification for this break-down is as follows:

- A nighttime calibration sequence will use the exact same configuration of the telescope as during the corresponding OM. No additional time will be required to configure the system, apart from turning on the calibration unit. The "calibration time" is the sum of the time spent collecting photons, reading out the detectors, and turning the calibration system on/off.
- There will be two different sets of calibration exposures to obtain at night: flat and arcs. There will possibly also be a set of calibrations for low/moderate resolution, and another for high resolution, given that both modes operate continuously. We baseline multiple exposures for both flats and arcs, to mitigate issues that could occur on a single exposure (e.g. cosmic rays), although we ultimately aim to only require a single exposure. With a baseline of 3 arcs and 3 flats for each set of calibrations, we need to allocate time for a total of 12 calibration exposures.
- Detectors read-out with low noise (a few electrons) can occur at a frequency of about 1 MHz (e2v 231 series, 6k by 6k, 3 MHz max, 5e- at 1 MHz, 2e- at 50 kHz). For calibration exposures, low read-out noise is not be necessary and the fastest read-out rate will be used (12 seconds). Binning (2x2 for HR, 2x1 for LMR) will shorten the readout time to 6 seconds, and using all 4 outputs will decrease it to 1.5 second. The total allocated time for all readouts is thus 18 seconds.
- We allocate 7 seconds to switching the system on/off (3.5 seconds each). This includes moving any mechanical part of the calibration system (e.g. deploying a screen). Some of this time will be spent in parallel with other processes.
- Each nighttime calibration block is limited to a reasonable allocation (2 minutes). We therefore have 95 seconds left to allocate to the time spent collecting calibration photons.

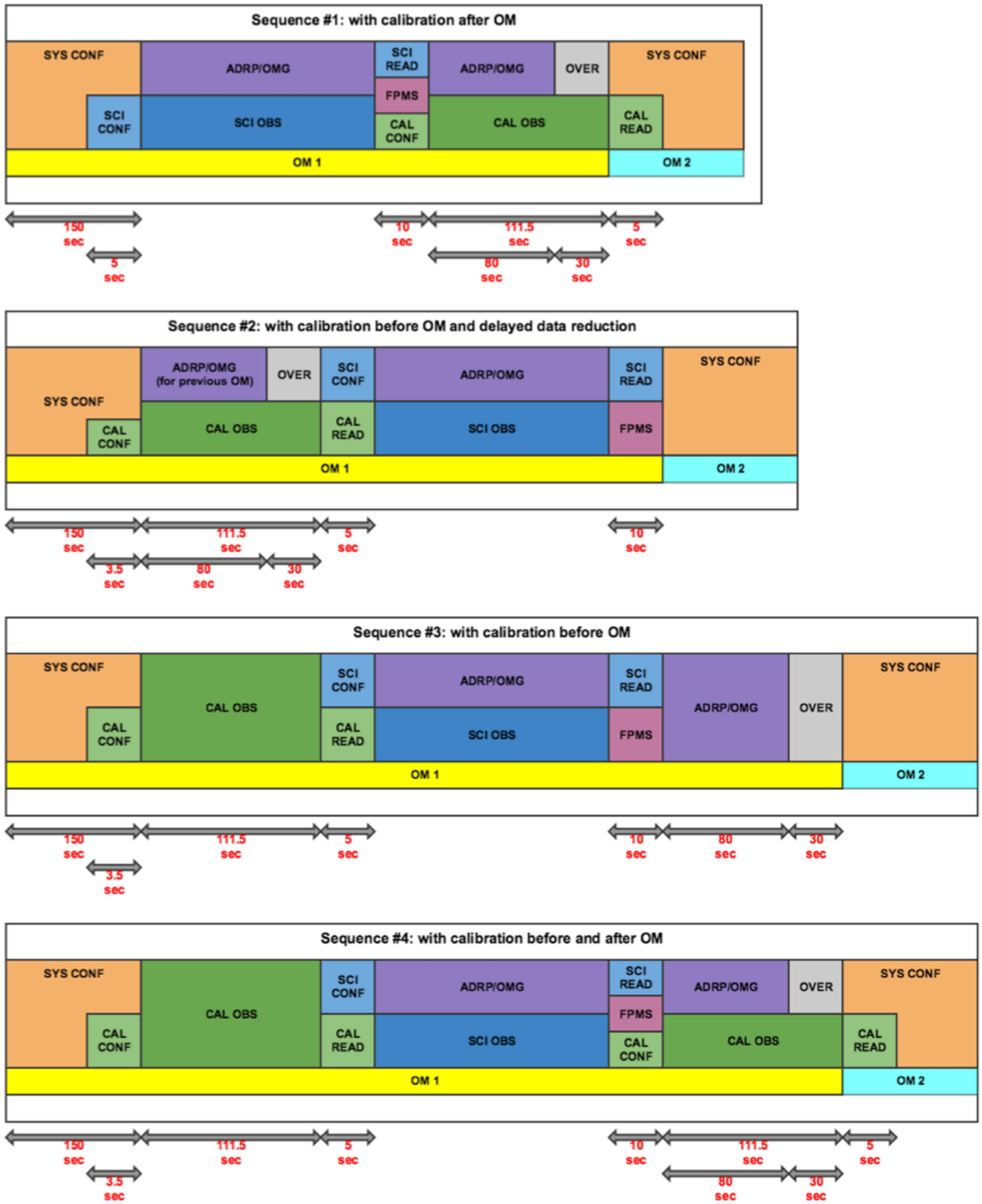

Figure 2. Typical nighttime sequences, baseline at bottom (calibration exposures both before and after the science exposure). See text for details.

4.3 Night-time observing sequence

Given the time spent on calibrations, we now illustrate how we can reconcile our calibration needs with the observing efficiency requirements. We assume a typical science observation of 1 hour in what follows.

Figure 2 shows typical nighttime sequences, with the following definitions for the blocks:

- SYS CONF: system configuration (telescope, enclosure, positioners,)
- SCI OBS: science observations (collecting photons from science targets, not including last readout)
- SCI READ: science readout (last readout of the SCI OBS)
- FPMS: measuring positions of fibers after SCI OBS
- CAL CONF: calibration configuration (turning on calibration unit)
- CAL OBS: calibration observations (collecting photons from calibration unit, not including turning it on/off and last readout)
- CAL READ: calibration readout (last readout of the CAL OBS, turning off the calibration unit)
- SCI CONF: science configuration (usually after a CAL OBS to make sure the guiding is still good for science observations)
- ADRP/OMG: automatic data reduction pipeline and updating schedule
- OVER: MSE Staff override of the schedule update

In all sequences, we assume the following processes can occur in parallel:

- SCI CONF, SYS CONF, CAL CONF: the elements in SCI CONF (guiding check) and CAL CONF (turning calibration unit on) are part of SYS CONF when this block is followed by a SCI OBS and CAL OBS, respectively.
- SCI READ, CAL CONF, FPMS: while the last science exposure is readout, the calibration system is turned on, and the FPMS accurately measures the positions of the fibers at the end of the OM.
- CAL OBS, ADRP/OMG, OVER: while the calibration exposures are being obtained and readout, the real-time feedback to the scheduler as well as the scheduling will occur. In addition, we allocate some time for the MSE Staff to override the decision of the scheduler.
- SYS CONF, CAL READ: while the last calibration exposure is readout and the calibration system is turned off, the system will configure for the next OM.
- SCI CONF, CAL READ: while the last calibration exposure is readout and the calibration system is turned off, the system will verify guiding is still active.

The sequences in Figure 2 differ by the order in which the CAL OBS and ADRP/OMG are executed. The baseline for MSE is to use the sequence at the bottom (Sequence 4) with calibration exposures obtained right before and right after the OM, for improved data reduction and calibration. The other three sequences each only obtain a single calibration observation (before or after the science observation); other differences between these sequences relate to when certain events occur relative to others, and is outside the immediate scope of this paper.

Figure 2 indicates the time allocated to each block and we use it to derive the total amount of overhead per OM in each sequence. For the baseline sequence (Sequence 4), overheads sum to 388 seconds. Given an average OM duration of 60 minutes, these overheads lead to a total time per OM of 3988 seconds.

Given the average time available per night, we then derive the average number of OM per night. Combining with other elements of the Observing Efficiency calculation, such as mean failure rates, engineering time, etc, leads to an estimated observing efficency of 82%. Details can be found in Ref. 25. Thus, even with calibration exposures occuring before and after each science exposure, we still expect to meet the (demanding) observing efficiency requirement.

5. OVERVIEW OF CALIBRATION PROCEDURE

This section describes the entire suite of observations - both daytime and nighttime calibrations, lamps and contemporaneous targets - that are envisioned as being required to provide suitable calibration for MSE.

5.1 Biases and Darks

Biases should be obtained at the start and/or end of every night, and scripts set up to take bias frames when the telescope is not otherwise in use. Ideal bias frames are the median of a very large number of bias frames all taken close in time to the science observations to which they are applied. This follows best-practice techniques for calibration exposures, but we clearly hope that the bias frames do not change significantly with time.

Dark frames are, ideally, not necessary, since modern optical detectors generally do not have a large dark current. However, they may be necessary for NIR channels. If they are required for either the optical and/or the NIR they should be obtained as part of a daytime procedure (likely taken the day after the nighttime science, in order to match the actual exposure times used).

Even in the case of dark frames proving to be unnecessary, it is good practice to take occasional dark frames (weekly or monthly) to monitor the detectors and ensure that their characteristics have not changed unexpectedly (which would indicate an issue for trouble-shooting).

5.2 Continuum flats

5.2.1 Lamp flats

The adopted baseline for MSE for flat-fields will require a sequence of high SNR lamp flats to be observed immediately before and immediately after the science exposure. This will ensure that the flats are obtained with the entire system in the same setup as used during the science exposure, in environmental conditions as close as possible to the science exposure.

It is essential that these lamp flats illuminate the focal surface with a repeatable illumination pattern and Spectral Energy Distribution which is the same for every fiber, at a level not compromising either spectrophotometric or sky-subtraction-precision requirements.

It is very desirable that the far-field light arriving into the spectrographs from these lamp flats reproduce the beam arriving from the sky as closely as possible. This is because small errors in the modeled spatial PSF translate into significant errors in correcting for cross-talk.

Obtaining calibration exposures at the beginning and end of the science exposures ensures that any differential changes in the system and/or environment occurring during the science exposure (e.g., due to the InRo) will be captured by the calibration exposures.

Since these exposures are being taken during the night, appropriate hardware is required in order to ensure the observations can be done quickly and so not impact the observing efficiency of MSE more than is already discussed in the previous section. We discuss this possible hardware configuration in Section 6.

5.2.2 Twilight flats

The adopted baseline for MSE for flat fields will additionally require obtaining as many twilight flats at the beginning and end of the night as is possible. These flats are used specifically to ensure that all fibers have an even illumination to a high level. This will be accomplished by taking the median of numerous twilight flats, and if needed correcting for intrinsic non-uniformity in the twilight sky across the field.

Lamp flats, or even dome flats, do not provide the level of uniformity that is possible via a twilight flat.

5.2.3 Combining twilight and lamp flats to obtain the transfer function

At the beginning of the night, and again at the end of the night, a sequence of twilight flats are obtained with the entire MSE system (including telescope, PFHS, InRo, fiber positioners, etc.) in some reference position. The median of these flats provides a reference frame with even illumination across all fibers (hereafter, the master twilight flat).

Immediately at the end of twilight, a series of lamp flats are taken with the telescope and system in exactly the same configuration as for the twilight flats. The median of these frames (hereafter, the reference lamp flat) provides a suitable reference to connect the lamp flats to the twilight flats.

At the beginning and end of every science exposure, a series of lamp flats are taken with the telescope and system in the same configuration as will be used (or, will have been used) for the science exposures. For long exposure sequences in which fiber allocations do not change, the option will be available to reduce the number of lamp flats taken during the sequence. including taking just one lamp flat in between exposures, instead of two. Each individual calibration lamp flat exposure obtained in this way is hereafter referred to as a science lamp flat.

The Master Science flat field, that defines the transfer function to be applied to the data, is then given by:

$$Master\ Science\ Flat = Median\left[science\ lamp\ flat \times \left(\frac{master\ twilight\ flat}{reference\ lamp\ flat}\right)\right] \tag{1}$$

Based on experience with other fiber spectrographs, we do not anticipate using dome flats as part of the standard MSE calibrations. However, a flat-field screen will exist for use with dome arcs, and so the possibility exists of designing an illumination system to provide dome flats.

5.3 Arc calibration exposures

5.3.1 Lamp arcs

Lamp arcs are obtained in exactly the same fashion as lamp flats. Specifically, the adopted baseline for MSE for arc calibration will require a sequence of high SNR lamp arcs to be observed immediately before and immediately after the science exposure. There is no requirement for a uniform intensity of arc illumination across the focal surface, provided that the signal is strong enough everywhere that good wavelength solutions can be derived for all fibers. However, It is essential that both the near-field and far-field light arriving into the spectrographs from these lamp arcs reproduce the light arriving from the sky, at a level that does not compromise the required velocity precision or sky-subtraction precision (via errors in knowledge of the PSF). All other considerations are the same as for lamp flats.

5.3.2 Dome arcs

The adopted baseline for MSE for arc calibration additionally requires sequences of high SNR dome arcs. We baseline these as daytime observations to be taken daily. Dome arcs are required in order to illuminate the system with arc light with a similar far field pattern as the science light, which will affect the PSF. Lamp arcs may not fulfill this requirement, and comparison of lamp arcs to dome arcs will provide the information necessary to make any required corrections to the lamp arcs.

5.3.3 Combining dome and lamp arcs to obtain precise wavelength calibration

During the day, a sequence of dome arcs will be obtained with the entire MSE system (including telescope, PFHS, InRo, fiber positioners, etc.) in some reference position. The median of these arcs provides a reference frame with a far field illumination that matches the science observations (hereafter, the master dome arc).

Immediately before and after these dome arcs, a sequence of lamp arcs are taken with the telescope and system in exactly the same configuration as for the dome arcs. The median of these frames (hereafter, the reference lamp arc) provides a suitable reference to connect lamp arcs to dome arcs.

At the beginning and end of every science exposure, a series of lamp arcs are taken with the telescope and system in the same configuration as will be used (or, will have been used) for the science exposures. Each individual calibration lamp arc exposure obtained in this way is hereafter referred to as a science lamp arc.

Different far field illumination patterns can yield different wavelength solutions (via different line spread functions, for example). If the dome arcs and the science exposures have identical far field illumination, then dome arcs taken in the same configuration as the science lamp arcs would provide the most accurate wavelength solution. Because such arcs will not be available for MSE, the following approach is used to account for the possibility of wavelength solution differences between lamp arcs and dome arcs, and between lamp arcs obtained in science configurations and in the reference configuration in which dome arcs are obtained.

The science lamp arc wavelength solution is compared to the reference lamp arc wavelength solution to derive a transformation between solutions in the different system configurations. The final adopted wavelength solution is the master dome arc wavelength solution corrected by this transformation. For example, in a simple case in which different PSFs produce wavelength solutions which differ only in their zeropoints, the adopted wavelength solution is the master dome arc wavelength solution corrected by the zeropoint offset between the reference lamp arc and science lamp arc wavelength solutions.)

Ideally, dome arcs should use the same sources as the lamp arcs, and certainly the same type of sources, to ensure there are no additional, unnecessary, systematic differences between the two sets of arcs.

5.4 Additional considerations regarding procedures for calibration lamps

Since both high resolution and low resolution spectrographs are used simultaneously by MSE, the lamp calibrations must be useful for both modes. It is a goal that this can be obtained in a single set of flats and a single set of arcs, but we note it is possible that the lamp arc calibration procedures will need to be repeated for both the low resolution and high resolution modes, and this is what is currently budgeted in the observing efficiency budget described in Section 4.

As more data is obtained by MSE, and as we obtain more and more calibration exposures, new opportunities might become available to improve the efficiency of lamp calibration observations (flats and arcs):

- We should be able to determine the feasibility or otherwise of obtaining calibrations at the start or end of science exposures, instead of both at the start and at the end;
- Comparisons of twilight flats and master twilights taken as a function of time should reveal the need, or otherwise, to obtain these at the start and end of every night (potentially, the frequency with which they are obtained could decrease);
- Similarly, comparison of reference lamp flats with time will reveal the frequency with which these need to be obtained;
- Comparison of nighttime science lamp calibrations (flats and arcs) between exposures taken as a function of system set-up (including InRo position, fiber positions, time, etc.) should reveal the need or otherwise to obtain science lamp flats for every individual science set up, versus some other frequency based on the observed behaviour;
- The frequency of dome arcs may be able to be decreased, if it is clear that the daily dome arcs do not vary significantly with time.

Additionally, during the day, some calibration exposures (lamp flats and arcs) should be repeated. That is, the system should repeat the sequence of moves that it went through the previous night, and lamp exposures should be repeated as they were during the night:

- Over time, the comparison of daytime lamp calibration exposures versus the corresponding night time exposures will inform us on whether there is a way to utilize daytime science lamp exposures in place of some or all nighttime science lamp exposures;
- It is a goal of MSE to be able to reduce or remove the need for nighttime science lamp exposures to improve observing efficiency, so long as the science utility of the calibrated science data are not affected detrimentally.

5.5 Pixel flats

The detector introduces an additional dependency of throughput, response (etc.) on the pixels (spectral flats and arcs measure the system response as a function of wavelength, including but not limited to the detector). Thus, to remove this pixel dependency requires creating a flat field that measures primarily the response on the detector, not the fibers or the rest of the system.

A direct way of making this measurement is to put a lamp inside the spectrograph, that illuminates the collimator, and hence detectors, uniformly. It can prove tricky to get the desired level of uniformity. For SDSS, pixel flats are taken rarely (every 6 months or so), since the procedure involves changing the entire slit-head with a leaky fiber, that evenly illuminates the slit.

An alternative to putting lamps inside the spectrographs is to create a pseudo-pixel flat by taking a large number of (possibly defocused) spectral flats (the defocus might be necessary to put light between the spectral traces). These flats would be median-combined. The resulting frame would then be divided by a 2D model of itself (i.e. a smooth spectrum multiplied by the fitted spatial profiles). This would then be divided by a locally median-filtered version of itself, to remove residuals from the imperfect 2D model and give a pixel flat. In principal defocusing is not needed, since the raw frames are much brighter than the data frames in every pixel, and there are many of them. This procedure is an elaboration on that successfully used for AAOmega, which adopted this process after unsuccessful use of lamps inside the spectrographs, and is the adopted baseline for MSE.

5.6 Diffuse light

The diffuse light background from spectrograph stray light must be modeled at a level so as to not compromise the spectrophotometric and sky-subtraction accuracy. Sufficient space at the edges of the detectors and gaps between selected spectra on the detectors must be allocated to measure the spectrograph stray light to a precision better than 1% of the sky flux in neighboring spectra and to fit a plausible model to the two-dimensional distribution of such light on the detector. Such edge and gap locations are needed so that the contribution of the wings of the PSF from the neighboring spectra is minimized. While the wings of the PSF are a type of diffuse light by some definitions, they are a very local source and our intent here is to measure the overall background due to spectrograph and telescope structure stray light.

5.7 Contemporaneous observations: sky spectra and spectrophotometric calibration stars

Spectrophotometric calibration stars will need to be observed contemporaneously to science targets. The number of these per field will be defined primarily via the spectrophotometry requirements, and further analysis is required to determine this number. We note that, given the expected limited number, spectrophotometric calibration stars will likely need to be assigned in a given field with the highest priorities (i.e., before most science fibers have been assigned to fibers). Ideally, these will be distributed across the field and will be distributed between the banks of spectrographs.

The number of fibers assigned to sky is expected to be around 10%, and these should likely be distributed evenly across the field and will be distributed between the banks of spectrographs. It is expected that subject to a minimum sampling of the slit for every spectrograph, the sky fibers can be assigned with the lowest priority; that is, that any fibers not able to be allocated to science targets will instead be allocated to sky.

6. SCIENCE CALIBRATION HARDWARE REQUIREMENTS

6.1 General considerations

Consideration of the calibration procedure described above suggests the following:

- Lamp flats/arcs must provide enough photons, for all modes, fibers and wavelengths in a matter of seconds, allowing them be obtained at a high SNR in a reasonable amount of time. Since this must be done without saturating the detectors (except perhaps for a known subset of arc lines), there are stringent constraints on the allowed variation in flux with wavelength or spectral line. Calibration read-out times need to be as short as possible. Ideally, fast read-out options should be available, and the SNR of the calibration exposures will be high enough such that these can be used without affecting the overall SNR of the exposures;

- To minimize overheads, solutions that close the dome or deploy a screen onto which the lamps are shone during the night, are not feasible for standard operations;
- As the concept below is developed further, we need to investigate the consequences of having lamps illuminated in the dome with the shutter open for the other telescopes on the mountain. If the lamps are "faint", then this shouldn't be an issue but will be seriously investigated;
- We do not want to spend a significant time per nighttime calibration observation waiting for the lamps to switch on and warm up. Either the lamps will have to warm up and stabilize in less than the science exposure readout time, or they must be used with a shutter, and be capable of continuous use without compromising heat or light leakage requirements;
- During the night, the dome aperture will be aligned with the telescope. Therefore, when calibration exposures are being executed, photons from the sky will also be collected (as well as the targets). All arc-line or continuum fitting, flat-fielding, etc., will have to allow for this effect. Several options exist to remove this effect:
  - The severity of the effect will be reduced with reduced exposure times (i.e., brighter calibration lamps are preferred);
  - Calibration arc or flat exposures can be accompanied by a "calibration sky" exposure, ideally of identical exposure time and with a fast readout time. The "calibration sky" exposure would be subtracted from the calibration exposures themselves, after scaling for exposure time differences if needed, to remove the object and sky flux from each fiber.
  - We could scale the data frames according to time (and change in gain) and subtract them from the calibration exposures, potentially removing both the object and sky signatures simultaneously;
  - We also considered offsetting the telescope a few arcsecs in azimuth, to avoid changes in airmass or gravity vectors, and to place the fibers on empty sky, particularly for calibration exposures at the end of a science exposure. Guiding would continue with the same guide stars, by switching the guide stars between two different sub-rasters on the guide cameras. Guiding contributes only 2 microns RMS to the fiber positioning uncertainty; the uncertainty in returning to the same position after offsetting away and back would be of the same magnitude. However, calibration exposures taken at this position still contain sky light, and so this is an incomplete solution.

6.2 Lamp flats and arcs

The baseline calibration lamp concept for MSE has the calibration lamps (flats, arcs, appropriate for all spectral resolution settings of MSE) distributed along the underside of each strut of the telescope structure (or fiber outputs distributed along the underside of each strut, where the fibers are fed by the appropriate calibration lamps) and which point down onto M1. The distribution of the lights along the struts of the telescope will be such that the radial light distribution mimics that of the telescope as closely as possible. When these lamps are switched on, the light is incident on M1 and sent to the focal plane of the telescope. There, we rely on the azimuthal scrambling properties of the fibers to ensure that the azimuthal light output from the fibers has a uniform intensity and does not possess a memory of the initial light distribution on the struts.

We note that the distribution of lights (either in radius or in function, e.g., arcs, flats) can be staged for each strut, since what matters is the overall radial distribution.

It is TBD whether fixed sources on the underside of the struts will be sufficient, or whether these sources need to be on movable stages. Movable stages will almost certainly produce a smoother light distribution than is possible with discrete, fixed, locations, but will increase the complexity of the system significantly. However, it is expected to be more likely that the lamps at largest radius have to be on movable stages, to avoid discrete jumps in the illumination of the focal surface due to WFC vignetting.

It is TBD whether we can use the limited radial scrambling properties of fibers to help smooth the radial distribution of light, to ease the issue of discretization due to multiple sources.

The precise nature of the lamps is open, as is the question as to whether single sets of lamps will suffice, or if different configurations will be needed for different arms or resolutions. The lamp flats would ideally provide useable photon fluxes at all wavelengths and spectral resolutions simultaneously (albeit with curtailed exposure times in some arms/resolutions). The lamp arcs must provide useable densities and fluxes of spectral lines at all wavelengths and resolutions, preferably simultaneously, and again with curtailed exposure times as needed.

6.3 Dome arcs

Ideally, the dome arcs should use the same sources (and certainly the same type of sources) as the lamp arcs to ease all comparisons between dome arcs and lamp arcs.

Hollow cathode arc lamps are intrinsically very faint, and so a large number of lamps and/or long exposures would likely be required to obtain arcs with sufficient SNR to be useful.

There must be an area on the interior of the dome that the telescope can point to for science observations, that is white and to which the telescope can point to obtain dome arcs. This could take the form of a deployable or fixed screen.

7. CONCLUSIONS AND FUTURE WORK

In this paper, we have discussed the operational and subsystem issues pertaining to accurate scientific calibration of science spectra obtained with MSE. The operational strategies and proposed observations are designed to provide the user with sufficient empirical information on the performance of MSE to enable estimation of the differential throughput, PSF behavior and wavelength solutions for all the objects observed in each observation. This information is necessary to allow accurate sky subtraction, spectrophotometry and velocity estimation. We note that we have not discussed the analysis methods by which we use this information to do precise sky subtraction; this is an extensive subject by itself that will be discussed in future contributions.

MSE will shortly undertake a conceptual design of the SCal subsystem during which the detailed requirements of this unit and the calibration strategy in general will be refined. In addition, MSE has formed a Calibration Working Group. This group consists of three people from Europe, the US and Australia that have extensive practical experience in wide field fiber MOS. They will advise the Project on all matters relating to calibration, including reviewing all relevant material and offering solicited and unsolicited feedback on any aspects of MSE that they deem relevant to the goal of obtaining high quality calibrated science data. Finally, MSE is starting to develop a Design Reference Survey, that is a detailed simulation of an actual 2 year observing program conducted with MSE, and which will include calibration observations, both contemporaneous on-sky calibrators and nighttime lamp calibration exposures. Updates on all aspects of these developments will be provided in future SPIE contributions.

ACKNOWLEDGMENTS

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