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Spectral calibration for the Maunakea Spectroscopic Explorer: challenges and solutions

Nicolas Flagey[a], Alan McConnachie[a], Kei Szeto[a], Rick Murowinski[a], and Shan Mignot[b]

[a]Canada-France-Hawaii Telescope Corporation, 65-1238 Mamalahoa Hwy, Kamuela HI 96743, USA

[b]GEPI, Observatoire de Paris, PSL Research University, CNRS, Univ. Paris Diderot, Sorbonne Paris Cité, Place Jules Janssen, 92195 Meudon, FRANCE

ABSTRACT

The Maunakea Spectroscopic Explorer (MSE) will each year obtain millions of spectra in the optical to near-infrared, at low ($R \simeq 2,500$) to high ($R \simeq 40,000$) spectral resolution by observing >3000 spectra per pointing via a highly multiplexed fiber-fed system. Key science programs for MSE include black hole reverberation mapping, stellar population analysis of faint galaxies at high redshift, and sub-km/s velocity accuracy for stellar astrophysics. This requires highly precise, repeatable and stable spectral calibration over long timescales. To meet these demanding science goals and to allow MSE to deliver data of very high quality to the broad community of astronomers involved in the project, a comprehensive and efficient calibration strategy is being developed. In this paper, we present the different challenges we face to properly calibrate the MSE spectra and the solutions we are considering to address these challenges.

Keywords: wavelength calibration, sky subtraction, fiber fed spectrograph

1. INTRODUCTION

The Maunakea Spectroscopic Explorer (MSE) is a project to upgrade the 3.6-meter telescope and instrumentation of the Canada-France-Hawaii Telescope (CFHT) into a 10-meter class telescope equipped with fiber-fed spectrographs dedicated to optical and near-infrared (NIR) spectroscopic surveys. The current baseline for MSE is that of a prime focus, 10-meter effective aperture telescope feeding a bank of low and moderate spectral resolution spectrographs (LR, R∼2000-3500 and MR, R∼6000) located on pseudo-Nasmyth platforms, as well as high spectral resolution spectrographs (HR, R∼20000-40000) located in the more stable pier of the telescope. The 1.5 square degree field of view of MSE will be populated with more than 3200 fibers of about 1″ diameter allocated to the LMR spectrographs, and at least 1000 fibers for the HR spectrographs.

The status and progress of the project are detailed in Ref. 1 while an overview of the project design is given in Ref. 2, the science based requirements are explained in Ref. 3, and details about the summit facility upgrade are presented in Ref. 4. Other papers in this year SPIE Volumes present optical designs for MSE,[5] a conceptual design of the High-Resolution Spectrograph,[6] systems budgets architecture and development,[7] observatory software,[8] and throughput optimization.[9]

This paper presents the challenges that MSE will face in terms of spectral calibrations to fulfill its science requirements, and the solutions that are currently being considered to address those challenges both from a technical and operational perspective. Section 2 describes the context of the science requirements and the challenges that they represent. In Section 3 we give the general considerations that we follow to define the science calibration requirements. Section 4 details two specific calibration requirements relative to the sky background subtraction and wavelength calibration. Finally in Section 5 we summarize our conclusions.

Further author information: (Send correspondence to N.F.)
N.F.: E-mail: flagey@cfht.hawaii.edu

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2. CHALLENGES FROM THE SCIENCE REQUIREMENTS

MSE will be the ultimate facility to study the composition and dynamics of the faint Universe. It will be the largest ground based optical telescope aside from the extremely large telescopes (E-ELT, TMT, GMT) and a critical follow-up observatory in the current and next generations of imaging surveys (LSST, Gaia, SKA, Euclid, WFIRST). MSE will enable transformational science in the fields of tomographic mapping of the interstellar and intergalactic media, chemical tagging of the disk and halo stars, large scale structure, dark matter, reverberation mapping, and cosmological surveys.

The typical faint end magnitudes of the targets that MSE will observe with the HR spectrograph is about 20, and about 24 with the LR spectrograph. The LMR spectrograph will be preferentially used during "dark time", near the New Moon, when the sky background is fainter than about 20.5 mag/arcsec^2, while the HR spectrograph will be mostly used during "bright time", near the Full Moon, when the sky background is brighter than about 19.5 mag/arcsec^2. The spectrophotometry with the LMR spectrographs shall be exquisite, and the HR spectrograph will be used to obtain highly accurate velocity measurements ($\sim$100 m/s).

The Science Requirements for MSE are ambitious, and to meet them means to retrieve the largest signal-to-noise ratio on the spectrum of each target across the field of view. This necessarily implies that calibrations of the highest quality will be required.

3. GENERAL CONSIDERATIONS

The calibration exposures that are envisioned for MSE are those usually obtained for spectroscopic observations. The spectrum of the sky and those of telluric and (spectro-)photometric standard stars, as well as wavelength calibration exposures will be acquired to correct for the atmospheric absorption and calibrate the flux and wavelengths observed in the science observations. Flat fields, dark current, and bias exposures will be recorded to remove the signatures of the observatory in the data. The specifics about these exposures (e.g. frequency and duration) however highly depends on the science requirements.

The Science Calibration Requirements are derived from the Science Requirements, and define the exposures that need to be recorded, in addition to the observations of the science targets, to meet the Science Requirements. These calibration exposures, obtained either independently of the science exposures (i.e. off-sky), or simultaneously (i.e. on-sky), will be used to extract from the observations the spectra of the highest quality possible. These calibration exposures will also help to monitor the observatory throughout its lifetime. The Science Calibration Requirements are incorporated into the Operations Concept Document and they follow some general guidelines that are listed hereafter.

1. **The calibration exposures shall not introduce any significant sources of noise into the observations.**
   The goal of the calibration exposures is to get the best information possible out of a science observation and they should therefore not significantly degrade its quality. Since in most cases, the observations performed with MSE will be sky limited, flat field calibration exposures shall have more counts that the sky component in the corresponding science exposure. It is, in fact, part of the calibrations' objectives to *make* the observations sky limited. Similarly, the wavelength solution shall lead to a velocity accuracy significantly better than that derived from the science spectra alone.

2. **The calibration exposures shall not add significant overheads to science observations or significantly reduce the effective multiplexing.**
   The most time-consuming or fiber-consuming calibration exposures shall be obtained during the day (e.g. flat field which needs to go through all fibers), to avoid losing the most precious nighttime. For those on-sky calibration exposures, which needs to be obtained at night (e.g. sky, standard stars), the fraction of required fibers shall be as small as possible. Over the life of MSE, the amount of calibration exposures required during the night will significantly decrease, thanks to an increased accuracy of our understanding of the telescope's throughput and subsystems stability.

3. **The calibration exposures shall allow the accurate modeling of the observatory's transfer function for all the fibers in the field of view during science observations.**
The calibration exposures should characterize with great accuracy the spectroscopic transfer function that is applied to the photons coming from any target during science observations. The calibrations exposures could for instance be obtained in a configuration (e.g. telescope pointing, fibers positions) that is as close as possible to that of the science observations and very close in time too. The photons from the calibration sources (e.g. standard stars, sky, arc lamps) shall thus see the same optical path and therefore be affected the same way as the photons from the science sources. Alternatively, the transfer function of the observatory shall be sufficiently well known to be accurately characterized with a limited amount of dedicated time and fibers.

These are general guidelines that are meant to evolve during the lifetime of MSE. At first light, the observatory and its subsystems will still need to be fully characterized and hence extra care (i.e. time) will be required to obtain the necessary calibration exposures. The goal however is to limit the impact of the calibration requirements on the science requirements by developing an accurate model of the observatory and thus reduce the amount of time and the number of fibers dedicated to calibration.

4. SPECIFIC CALIBRATIONS

In this section we detail our analysis of two particular calibrations: the subtraction of the sky emission and the calibration of the wavelength. While the sky subtraction can be improved mostly through optimized operations, strategies, and data reduction techniques, the wavelength calibration will require additional hardware.

4.1 Sky emission subtraction

One of the major challenges for large aperture fiber-fed spectrographs is that of subtracting the emission from the sky - lines and continuum - down to a precision significantly smaller than 1%. Unlike slit spectrographs which measure the sky's spectrum near the target and simultaneously to the target's, fiber-fed spectrographs only measure spectra at one position at a time. Multiplexed fiber-fed spectrographs can mitigate this effect by dedicating some fibers to the observation of the sky within the field of view, the fraction of which shall be minimized while the accuracy on the subtraction is maximized.

4.1.1 Sensitivity science requirements

The Science Calibration Requirements on the sky subtraction flow down directly from the Science Requirements on the sensitivity.

> [REQ-SRD-034] In the low resolution mode, an extracted spectrum from MSE taken in the observing conditions described below shall have a signal to noise ratio per resolution element at a given wavelength that is greater than or equal to two for a 1 hour observation of a point source with a flux density of 9.1×10^{-30} ergs/sec/cm^2/Hz at that wavelength, for all wavelengths longer than 400 nm. Between 370-400 nm, the SNR shall not be less than one at any wavelength. The observing conditions in which this requirement shall be met correspond to a sky brightness of 20.7mags/sq.arcsec in the V-band and a natural seeing condition of $0.8''$ in the r band, at an airmass of 1.2.

> [REQ-SRD-035] In the moderate resolution mode, an extracted spectrum from MSE taken in the observing conditions described below shall have a signal to noise ratio per resolution element at a given wavelength that is greater than or equal to two for a 1 hour observation of a point source with a flux density of 1.4×10^{-29} ergs/sec/cm2/Hz at that wavelength, for all wavelengths longer than 400 nm. Between 370-400 nm, the SNR shall not be less than one at any wavelength in the relevant window. The observing conditions in which this requirement shall be met correspond to a sky brightness of 20.7 mags/sq.arcsec in the V-band and a natural seeing condition of $0.8''$ in the r band, at an airmass of 1.2.

[REQ-SRD-014] In the high resolution mode in any wavelength window observed over the lifetime of MSE, an extracted spectrum from MSE taken in the observing conditions described below shall have a signal to noise ratio per resolution element at a given wavelength that is greater than or equal to ten for a 1 hour observation of a point source with a flux density of 3.6×10^{-28} ergs/sec/cm^2/Hz at that wavelength, for all wavelengths in the relevant window longer than 400 nm. Between 370-400 nm, the SNR shall not be less than five at any wavelength in the relevant window. The observing conditions in which this requirement shall be met correspond to a sky brightness of 19.5 mags/sq.arcsec in the V-band and a natural seeing condition of $0.8''$ in the r band, at an airmass of 1.2.

There is an additional science requirement on the subtraction of the sky emission lines. The exact requirement still needs to be refined but the ambition is to do at least as good as what can currently be achieved. It is also worth noting that observations that rely on the target's line emission will avoid focusing on wavelengths that can potentially be contaminated by sky lines.

The requirements on sensitivity correspond to sources of magnitude 24, 23.5, and 20, for the LR, MR, and HR spectrographs, respectively. These are typical magnitudes that MSE will observe though a wide range of magnitudes will actually be observed at each resolution. The sky surface brightness of 20.7 and 19.5 mag/arcsec^2 correspond to typical "dark" and "bright" time on Maunakea. Given the typical image quality expected and the size of the fibers, the observations will mostly be sky-limited, at all resolutions. The most demanding requirement is that for the LR spectrograph, and hereafter we focus on the calibration requirement for sky subtraction at low resolution.

4.1.2 Sky emission variations

The emission from the night sky is composed of multiple components. The Moon light and the light from stars is being scattered by the atmosphere. The Sun light is being scattered by particles in the ecliptic plane and forms a band of zodiacal light. The atmosphere also emits light at peculiar frequencies associated with OH radicals and other molecules and in the form of a continuum (airglow).

Variations of the sky emission is significant in both space and time. Studies have revealed that spatial variability on scales of about 2 degrees and larger is about 3-4%, and that over the course of a night, temporal variability could reach a factor 2, and 15% within less than an hour.[10,11] Emission lines fluxes also vary significantly on time scales of the order of a few minutes, both as a whole, and relative to each other.[12–14]

4.1.3 Sky subtraction requirements

In order to observe very faint targets with the LR spectrograph of MSE, the sky subtraction shall be accurate to sub-1% levels. This results from the following analysis.

The spectrum of the sky is computed using the SkyCalc tool of the European Southern Observatory* and scaled to the sky background surface brightness usually observed at Maunakea in dark condition (20.7 mag/arcsec^2 in V band. The number of counts per resolution element measured on the detector are then computed with the MSE Instrument Time Calculator†. In this analysis, the sky lines have been removed from the sky spectrum thanks to a median filter, leaving only the continuum component. A separate analysis will be required to deal with the sky emission lines. The sky spectrum on the detector is then converted into a required accuracy on the sky subtraction to observe a target at a given AB magnitude and at a given wavelength. The results are shown in Figure 1.

Assuming the sky subtraction is accurate at the 1% level, the noise equivalent magnitude (i.e. the magnitude of a target that would be equal to the noise) that can be reached with MSE under "dark" conditions varies from ∼24.5 to ∼26 in the optical and J band, and from ∼23 to ∼25 in H band. The noise equivalent magnitudes averaged over typical bands in the optical and near-infrared are given in Table 1 for a sky subtraction accuracy of 1% or 0.5%.

*https://www.eso.org/observing/etc/bin/gen/form?INS.MODE=swspectr+INS.NAME=SKYCALC
†http://etc-dev.cfht.hawaii.edu/mse

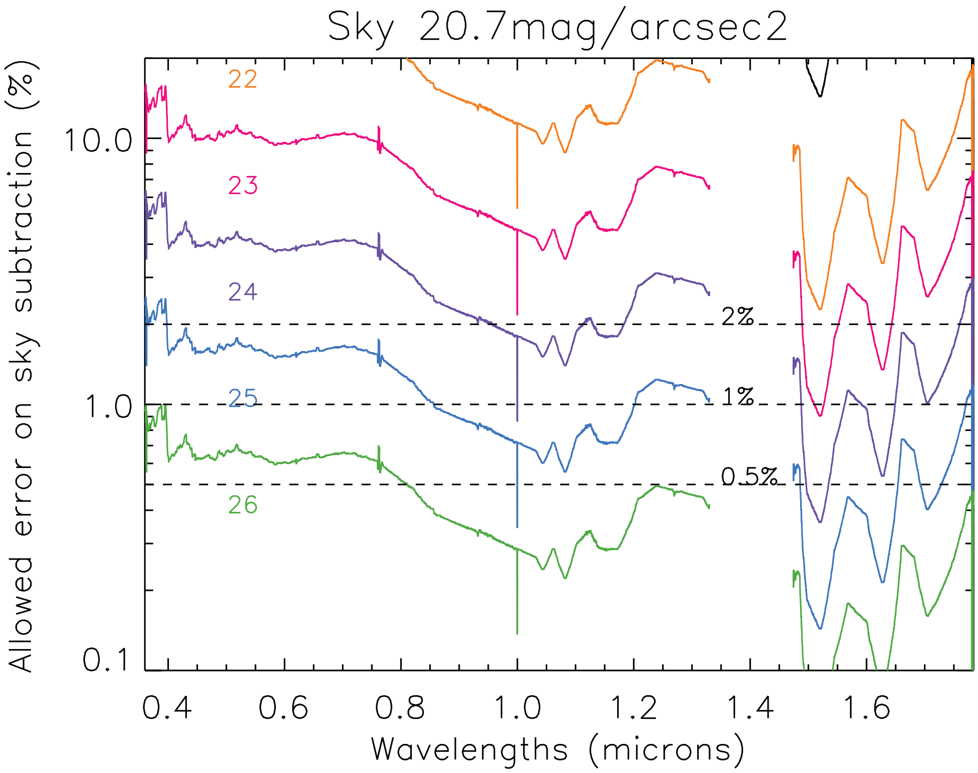

Figure 1. Maximum allowed error on the subtraction of the sky continuum as a function of wavelength to reach the noise equivalent magnitudes indicated on the curves.

This analysis shows that to observe with a decent signal-to-noise ratio targets of magnitude 24 and fainter in the LR spectrograph of MSE, the accuracy on the sky subtraction shall be at the very worst 1% in the optical, and significantly better in the near-infrared.

These results do not take into account the possibly many other intervening elements that will decrease the magnitude of a target that can actually be observed with a decent signal to noise. For instance, the throughput of the fiber observing the sky and the response of the detector at the location of the sky spectrum may differ from those of the target. Calibration exposures will be used at different steps in the data reduction process, and errors will propagate to increase the noise above this theoretical limit. Additionally, the sky background emission shall be estimated at the position of the target and at the time the target is being observed, either through direct measurement or modeling. This may be challenging and solutions are discussed hereafter.

Table 1. Noise equivalent magnitudes that can be reached with MSE in various optical and near-infrared bands assuming a 1% and 0.5% sky subtraction accuracy.

Band	Noise Equivalent Magnitude	
	(accuracy 1%)	(accuracy 0.5%)
u (340-410nm)	25.7	26.4
g (420-560nm)	25.4	26.2
r (570-690nm)	25.4	26.2
i (680-840nm)	25.3	26.1
z (850-1000nm)	24.7	25.5
Y (950-1050nm)	24.5	25.3
J (1175-1325nm)	25.0	25.8
H (1480-1780nm)	23.9	24.7

4.1.4 Sky subtraction solutions

Different methods can be used to best estimate the spectrum of the sky at the position of each target and at the time of the target observation. These methods do not require any specific hardware and solely rely on optimized operations, strategy, and data reduction procedures, which are facilitated by MSE being a facility dedicated to spectroscopy.

Methods that use dedicated fibers or similar approaches. Relying on the observational experience acquired on slit spectrograph for decades, several methods of observations have been suggested and used to improve the sky subtraction on fiber fed spectrographs. In the dual fiber strategy, one half of the fibers is allocated to targets while the other half is dedicated to simultaneously observe sky positions near each of these targets. This strategy basically mimics a slit, at the cost of 50% of the multiplexing. It also requires fibers positioners that can allocate fibers to a sky position as close as possible to the target of interest, anywhere in the field of view. In the beam switching or cross beam switching strategies, the telescope or each fiber is switched between two positions, essentially moving all fibers between a sky and a target position. In the beam switching strategy, the advantage is that the sky is observed with the same fiber used to observe the target, though 50% of the time is lost to sky sampling. In the cross beam switching strategy, two fibers are allocated to a target, thus reducing the multiplexing by 50%, and while one is observing the target, the other is observing the sky, alternatively. Those methods have been studied and compared to others in, for instance, Ref.15–17 for the fiber-fed spectrograph planned for the E-ELT. It was found that the dual fiber and beam switching method were leading to a more accurate sky subtraction, down to a fraction of 1%, than using the mean sky spectrum or the closest sky spectrum over the field of view.

Nevertheless, these strategies are not favored by MSE, as the high multiplexing is an important science requirement. However, the use of a fiber dedicated to the sky may be required in some specific conditions. For instance, observing a very faint target in the H band corresponds to a more stringent requirement on the accuracy of the sky subtraction (see Figure 1) and could require the allocation of a fiber to a sky position near such target. This does not mean all the fibers in the entire field of view would follow such a strategy, and a dedicated, very high multiplexed observatory like MSE is expected to be extremely flexible when it comes to operations. Besides, in the early life of MSE, while it is being commissioned or during science verification, additional care and time may be required when obtaining calibration exposures, and strategies like dual fiber or (cross) beam switching may thus be favored during these phases.

Methods that attempt to model the sky with a small number of fibers. Other strategies that do not impact the multiplexing or observing time of the observatory to the same extent include, e.g. $\lambda-\lambda$ reconstruction, principal component analysis (PCA). These methods rely more importantly on the understanding of the sky variations than on a large number of fibers allocated to sky positions. Their goal is to model the sky at the position of any fiber allocated to a target using a minimum number of fibers.

The Sloan Digital Sky Survey (SDSS) dedicates 80 fibers out of 1000 to sky positions for the BOSS survey in the optical[18] and 35 out of 300 for the APOGEE survey in the near-infrared.[19] The 2dF/HERMES experiment suggests to allocate 20-30 fibers out of 392 to sky positions. The Dark Energy Spectroscopic Instrument (DESI) guarantees 40 sky spectra per spectrograph (10 total) per exposure out of a total of 5000 fibers. On average, only 10-15% of the fibers are allocated to sky positions in those surveys. In those conditions, the sky subtraction has been as good as 1% in the SDSS/APOGEE data[20] and, in the SDSS/BOSS survey, at the positions of bright OH air-glow lines, the systematic residuals are generally at or below 1% of the sky flux.[21] The method used for APOGEE corresponds to a weighted average of the four sky spectra closest to each target spectrum and a scaling of the sky emission lines.

Ref. 15 has shown thanks to simulations that to subtract the sky continuum to 1% accuracy, using a $\lambda-\lambda$ reconstruction method with linear triangulation interpolation, the number of required fibers within a $5'$ by $5'$ field of view is 30-40 in the optical and 80 in the near-infrared. For MSE, the density of sky fibers required for a $\lambda-\lambda$ reconstruction with a simple interpolation is too large: 30-40 fibers over a $5'$ by $5'$ field of view corresponds to more than 4000 fibers over a 1 square degree field of view. The use of a better interpolation method relying on our understanding on the sky variations may help lower such requirement.

The OH lines have been accurately removed from the target spectrum by scaling their intensities to those observed in a sky spectrum for each group of vibrational transitions then rotational groups.[12] This has been shown to allow the use of a sky spectrum taken hours before/after the target spectrum without significant loss of accuracy compared to a sky spectrum obtained right before/after the science observation.

The application of a PCA with the use of 20-25 sky fibers for 400 science fibers (5%) has shown that it is possible to reach the Poisson limit, especially near bright emission lines. It has also revealed that the error on sky subtraction continues to decrease down to 0.3-0.4% for long exposure times (several hours or longer), contrary to the method using a dedicated sky fiber, which reaches a plateau at about 1% after about 1h integration time. Furthermore, the PCA method is more efficient that nodding-shuffling, with or without cross beam switching, for exposure times at least up to 7h, and likely beyond too.[22]

The use of dedicated fibers to subtract the sky will not be the baseline for MSE, but it may be required, either in the form of dual fiber or cross beam switching strategy, for the very faint targets. The goal will be to obtain an accurate representation of the sky over the entire field of view with a limited number of dedicated fibers (<10%), the use of physical models of the sky emission, and modern analytic techniques.

4.2 Wavelength calibration

The wavelength calibration is critical to obtain accurate velocity measurements. The usual method to calibrate the wavelength of a spectrograph in the visible and near-infrared, i.e. to determine the relation between wavelength and pixel on the detector, is to use a combination of spectral lamps and atmospheric lines. The questions that need to be answered relate mostly to hardware: how many lamps are required and of what type? Hereafter we describe the science requirements for MSE in terms of velocity accuracy and translate them into calibration requirements in terms of density of bright lines provided by arc lamps.

4.2.1 Velocity accuracy requirements

The Science Requirements on wavelength accuracy are as follows:

> [REQ-SRD-041] 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 at low 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 km/s*, and shall have no systematic dependence on the wavelength region of the spectrum that is used to the level of *5 km/s* (provided suitable features exist, i.e., any strong absorption or emission lines).

> [REQ-SRD-042] 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 at moderate 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 *9 km/s*, and shall have no systematic dependence on the wavelength region of the spectrum that is used to a level of *1 km/s* (providing suitable features exist, i.e., any strong absorption or emission line).

> [REQ-SRD-043] For a radial velocity standard star, observed at multiple epochs by MSE with up to a 5 year cadence with a *signal to noise ratio per resolution element of 30 at 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 *0.1 km/s*.

At a spectral resolution R$\sim$3000 (LR), a feature (emission or absorption line) with a signal-to-noise ratio per resolution element of 5 leads to a velocity accuracy of $(c/3000)/5 = 20$ km/s. At a spectral resolution R$\sim$6000 (MR), a feature (emission or absorption line) with a signal-to-noise ratio per resolution element of 5 leads to a velocity accuracy of $(c/6000)/5 = 10$ km/s. At a spectral resolution R$\sim$30000 (HR), a feature

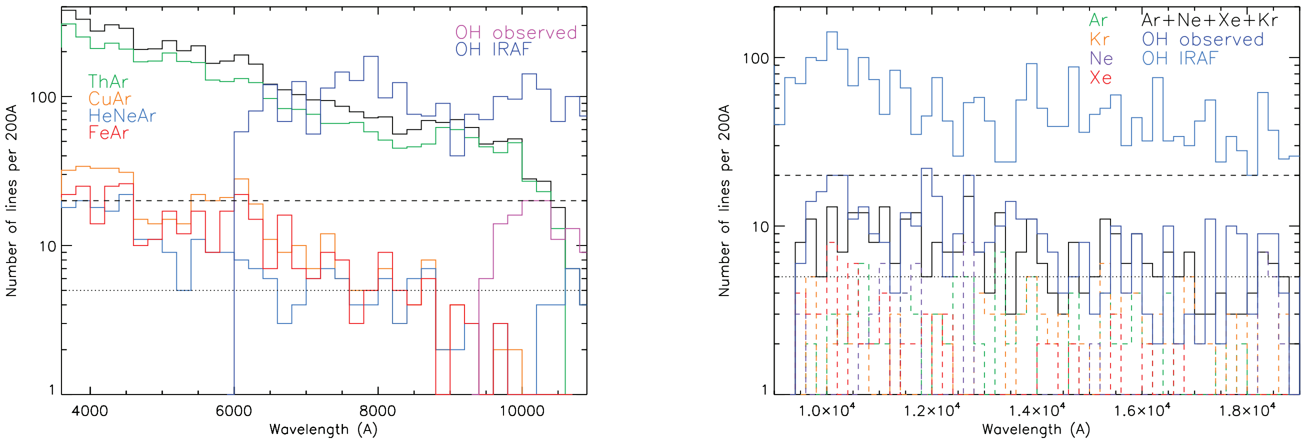

Figure 2. Emission line density for various arc lamps and for atmospheric OH lines derived from NOAO's spectral atlas, between 360 nm and 1055 nm on the left, and from Keck/NIRSPEC database, above 950 nm. The horizontal dashed and dotted lines indicate line densities of one line per nm and one line per 4 nm, respectively.

(emission or absorption line) with a signal-to-noise ratio per resolution element of 30 leads to a velocity accuracy of $(c/30000)/30 = 333$ m/s. We can assume that multiple features exist in the spectrum of the target in the LR and MR spectrographs, given the expected spectral coverage. At high spectral resolution however, the wavelength range will be limited, therefore several features or a larger signal-to-noise ratio than 30 will therefore be required in the target's spectrum. Additionally, the velocity error introduced by the wavelength solution shall remain significantly smaller than 20 km/s, 9 km/s, and 100 m/s at low, moderate, and high resolution, respectively. Assuming the uncertainty associated with the wavelength solution adds in quadrature with that from the target's spectrum, and that the contribution of the wavelength calibration to the final velocity accuracy shall not be larger than 10%, then the wavelength solution shall lead to typical accuracy of 9 km/s, 4 km/s, and 45 m/s at most in the LR, MR, and HR spectrographs, respectively. Additionally, the wavelength solution should not introduce any systematic dependence on the wavelength range that is used for velocity measurement to a level of 5 and 1 km/s in the LR and MR spectrographs, respectively.

4.2.2 Spectral lamps

The spectral lamps that are typically used in astronomical observatories for wavelength calibration are Argon based lamps (e.g. ThAr, FeAr, CdAr). Atmospheric lines are also often used in the near-infrared.

The positions of the emission lines in these arc lamps can be found, e.g., on NOAO's website[‡]. The emission line density is shown in Figure 2 for several types of arc lamps or species and for atmospheric OH lines, using Keck/NIRSPEC database[§]. The ThAr arc lamp appears to provide, by far, more lines than any other arc lamps, and always more than one line per nm up to about 1 μm. Beyond 1 μm, most arc lamps species provide less than one line per nm.

In addition to providing enough lines in a given spectral window, the arc lamps shall also be bright enough so that the signal-to-noise ratio of the emission lines is large and the error on the wavelength solution small even with short calibration exposures. We obtained the spectra of several arc lamps at the DAO 1.2 m telescope with a calibrated photodiode: a Westinghouse FeAr operating at 20 mA, a Westinghouse CdAr operating at 4 mA, and a Heraus ThAr operating at 9.5 mA. To convert the measured line flux in the lab into the integrated photon counts per second as measured on the detector of MSE, we assume that the entire flux from the spectral lamp can be delivered to a 2 square degree field of view, that the fraction representing a 1.2″ diameter section of that field of view is injected into each fiber, and that the efficiency of transmission along the fiber and in the spectrograph is 25%.

[‡]http://iraf.noao.edu/specatlas/
[§]http://www2.keck.hawaii.edu/inst/nirspec/lines.html

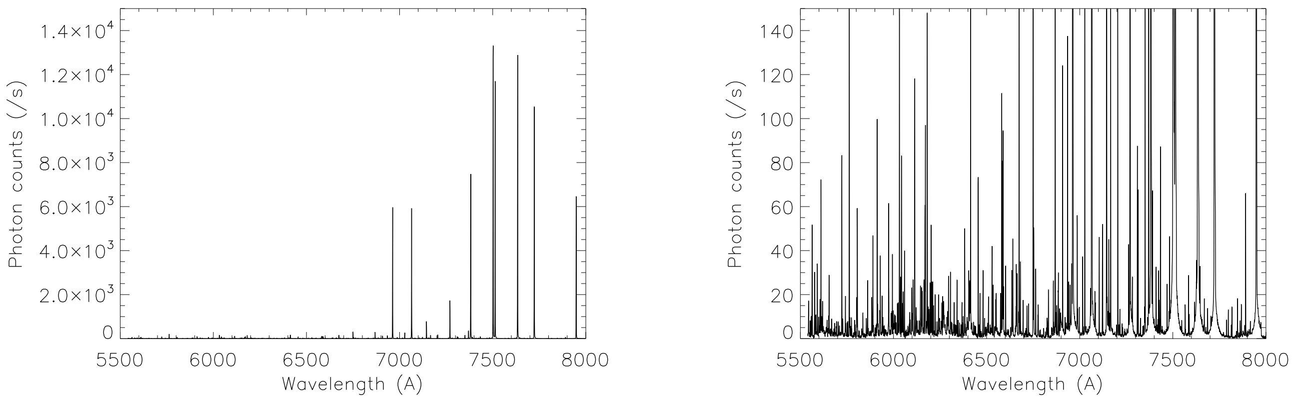

Figure 3. Spectrum of the ThAr arc lamp obtained at the DAO 1.2m telescope between 550 and 800 nm. The intensity is that of the integrated lines on the detector, derived as explained in the text. *Left:* the "red" end of the spectrum is dominated by intense Ar transitions. *Right:* the "blue" end of the spectrum is rich in Th lines.

The spectrum obtained at the DAO telescope for the ThAr arc lamp is shown in Figure 3. Hereafter we only discuss the use of this lamp for wavelength calibration purposes.

4.2.3 Wavelength solution

The ThAr arc lamp spectrum is used to simulate the wavelength calibration process. We assume that the wavelength solution is a one dimensional polynomial of order three. We can imagine, for instance, that we are dealing with an extracted and resampled spectrum. We then assume that the position of each line can only be measured with an accuracy σ_i, in pixel, proportional to the size of a resolution element divided by the signal-to-noise ratio of that line. The signal-to-noise ratio of a line, assuming Poisson noise, is given by the square root of the product between the exposure time used for the wavelength calibration exposure and the integrated photon counts per second for that line. The actual error on a given line's position is normally distributed within a standard deviation σ_i, while the assumed error for that line, when the actual wavelength solution is derived thanks to a third order polynomial fit, is σ_i.

Any pixel on the detector can then be related to a wavelength within the spectral range explored. Given the true wavelength solution, we can assess the typical error made on each wavelength because of the imperfect wavelength calibration, and then convert it into a velocity error. For a given wavelength range and spectrograph, we repeat the test 100 times to obtain a statistical representation of what would happen in reality. The difference between each test lies only in the random distribution of the error on the emission lines positions.

Figure 4 shows the typical velocity error made using the ThAr arc lamp, three-second exposures, and a detector that mimics the one in the LR spectrograph of MSE. The size of the detector is however limited to about 6300 pixels (instead of the 9000 expected) to match the wavelength range of the spectrum obtained at DAO (550 to 800 nm) with a resolution element of 6.4 pixels. On the "red" end of the spectrum, intense Ar lines are present and help secure a precise wavelength solution, while on the "blue" end of the spectrum, i.e. below about 650 nm, only weaker, though more numerous, transitions are available, and lead to less stringent constraints on the wavelength solution. In this particular example, typical errors reach 2 km/s in the "blue" and 1 km/s in the "red". These values are significantly smaller than the requirement of 9 km/s for the LR spectrograph (see Section 4.2.1). For a given wavelength calibration, there can be a non-negligible systematic effect on the velocity error depending on the wavelength that is used for the measurement. This can be seen on the right panel in Figure 4, which shows a distribution of the dispersion (i.e. standard deviation) of the velocity error across the whole wavelength range. In this particular example, the worst systematic effect is 1.5 km/s, which is again significantly lower than the requirement of 5 km/s.

For the MR spectrograph, we consider two wavelengths windows: a "blue" one between 550 and 680 nm, and a "red" one between 660 and 810 nm. With a ThAr arc lamps, 3 seconds exposures in the "red" and 10 seconds exposures in the "blue" are sufficient to meet both requirements (rms and systematic, see Figure 5). This difference is obviously related to the lack of intense emission line below 690 nm in the ThAr arc lamp. In these conditions, the typical velocity errors are about 1.5 km/s while the systematic effect remain below 0.8 km/s.

For the HR spectrograph, we also considered two wavelengths windows: 600 to 625 nm and 711 to 740 nm, each covering 18000 pixels with a resolution element of 11.5 pixels. The ThAr arc lamp has stronger emission lines in the "red" window (32 lines, almost half with a SNR greater than 10 with 1 second exposures) but a higher line density in the "blue" window (49 lines, though 80% with SNR below 10 with 1 second exposures). In order to achieve a wavelength calibration precision of 45 m/s with a single ThAr arc lamp, an exposure time of at least 300 seconds is required in the "red" and 600 seconds in the "blue" (see Figure 6). We assume that the requirement will remain within a factor two at most of these values over the entire optical range, though additional analysis would be required at shorter wavelengths to confirm this. Naturally, using several arc lamps will reduce the required integration times.

In order to obtain the wavelength calibration exposures necessary to meet the velocity accuracy requirements at high resolution, several options are available depending on how well the stability of the spectrographs and the effect of other sub-systems on the wavelengths have been characterized. At first light, a calibration exposure may be obtained at night, right before or after each science exposure, with the telescope and fibers in the same position as they were during the on sky observation (i.e. for targets, sky, and standard stars). However, assuming typical exposure times of 15 minutes for the on sky observations, we may want to limit to about 1 minute the time spent on off-sky calibration exposures, including all overheads associated to the procedure (e.g. warming up lamps and waiting for them to cool down), and thus use at the very minimum ten ThAr arc lamps. On the longer term, our goal is to have a good enough understanding of the spectrograph stability and telescope effect on the wavelength solution to remove the wavelength calibration exposures from the night plan completely. Some monitoring may however still be required at night but could benefit from the use of *simultaneous* fibers, in a way similar to VLT/FLAMES. This solution would then only minimally impact the observing efficiency of MSE. Given the ten ThAr lamps required for the HR spectrograph, the precision of the wavelength solution will be significantly better than that required for the LR and MR spectrographs. Given the wavelength coverage of these two spectrographs, we expect that many lines in the target's spectrum will be used to derive a velocity with an accuracy that is significantly better than the science requirement. This will increase the flexibility on the operations as long as the effect of other parts of the telescope on the velocity accuracy remain sufficiently small. In this situation, one set of day time or twilight exposures may be sufficient to meet the science requirements on velocity precision at low and moderate resolutions.

It is important to keep in mind that we here focus on the strength and density of lines provided by arc lamps only, and they should be considered lower limits on the requirements. Several other aspects have to be considered (not in this paper) to derive the true requirements. For instance, if simultaneous fibers are used, soem uncertainty will result from deriving the wavelength solution of all spectra on the detector from the few simultaneous fibers.

In addition, it is worth mentioning that other light sources are being investigated. Fabry-Perot or laser frequency combs for instance could provide a high density of bright lines at any wavelengths, while gas cells would allow simultaneous calibration of all the fibers without any loss of time or fibers, though the throughput would be affected.[23]

5. CONCLUSIONS

The Maunakea Spectroscopic Explorer will reveal the composition and dynamics of the faint Universe, like no other current or projected facility. MSE will revolutionize our understanding of the interstellar and intergalactic media, the chemistry and dynamics of stars in the distant Galaxy, the connections between galaxies and large scale structure of the Universe, cold dark matter sub-halos, and reverberation mapping of super-massive black holes in quasars. The success of MSE will depend on the quality of the data that it will observe at the dark end of the observable Universe. This critically relies on obtaining exquisite calibrations that shall provide an accurate model of the complete transfer function from the observed targets to the spectrographs' detectors.

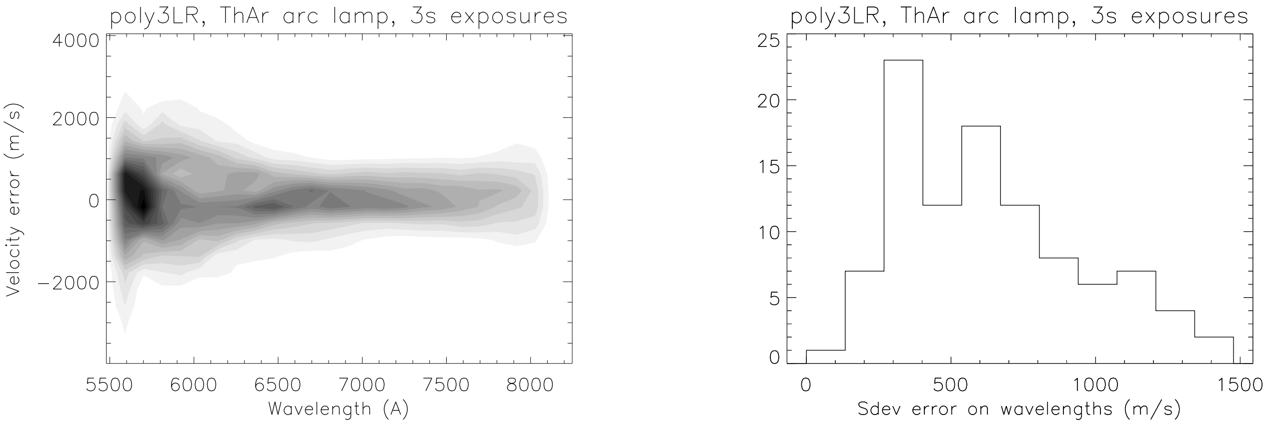

Figure 4. *Left:* density plot of the velocity error across the entire spectral range, for the ThAr lamp, assuming a third order polynomial wavelength solution in the LR spectrograph covering the 550 to 800 nm range and 3-second exposures, obtained after 100 simulations. *Right:* histogram of the dispersion of the velocity error across the entire spectral range.

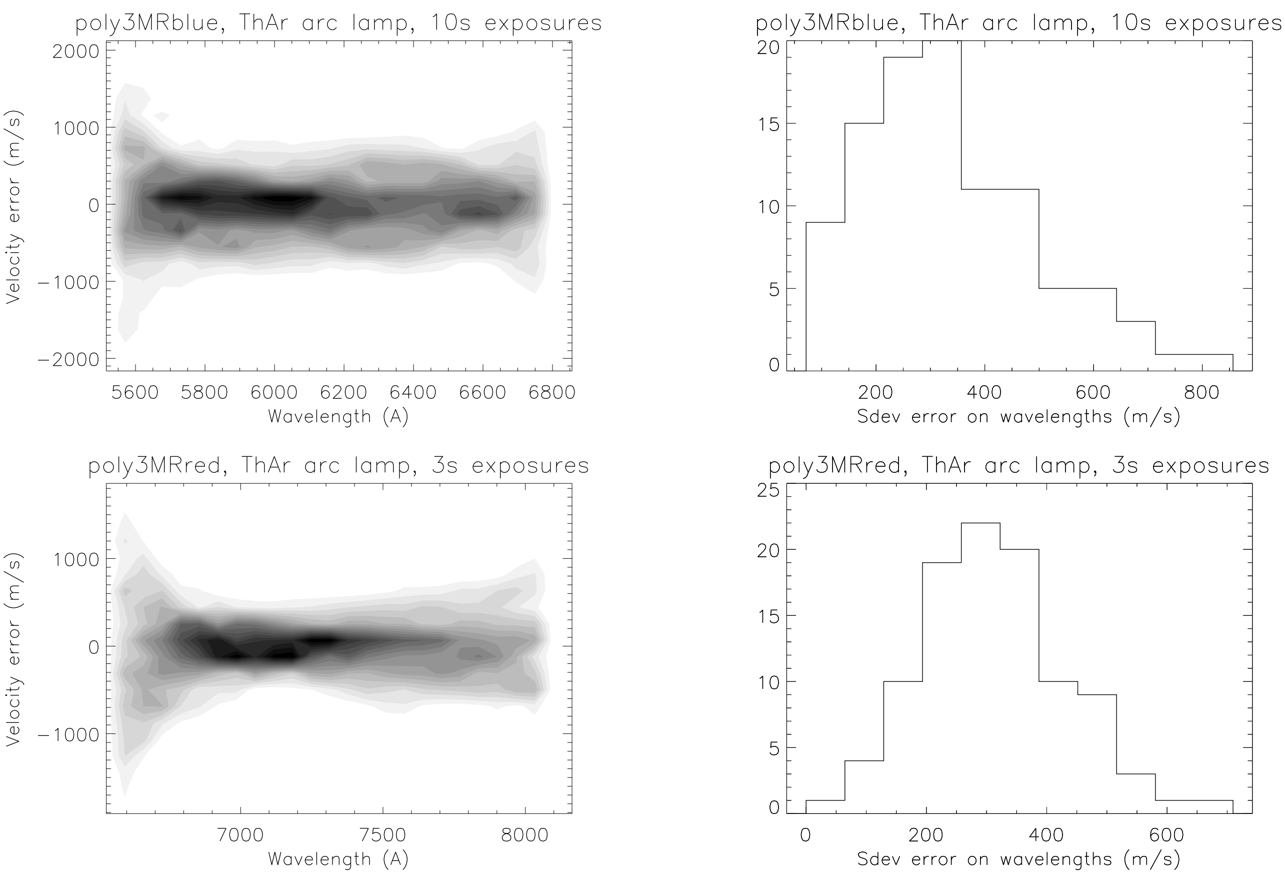

Figure 5. *Left:* density plots of the velocity error across the entire spectral range, for the ThAr lamp, assuming a third order polynomial wavelength solution in the MR spectrograph covering the 550 to 680 nm range (*top*) or 660 to 800 nm range (*bottom*)and 10-second exposures, obtained after 100 simulations. *Right:* histograms of the dispersion of the velocity error across the entire spectral range.

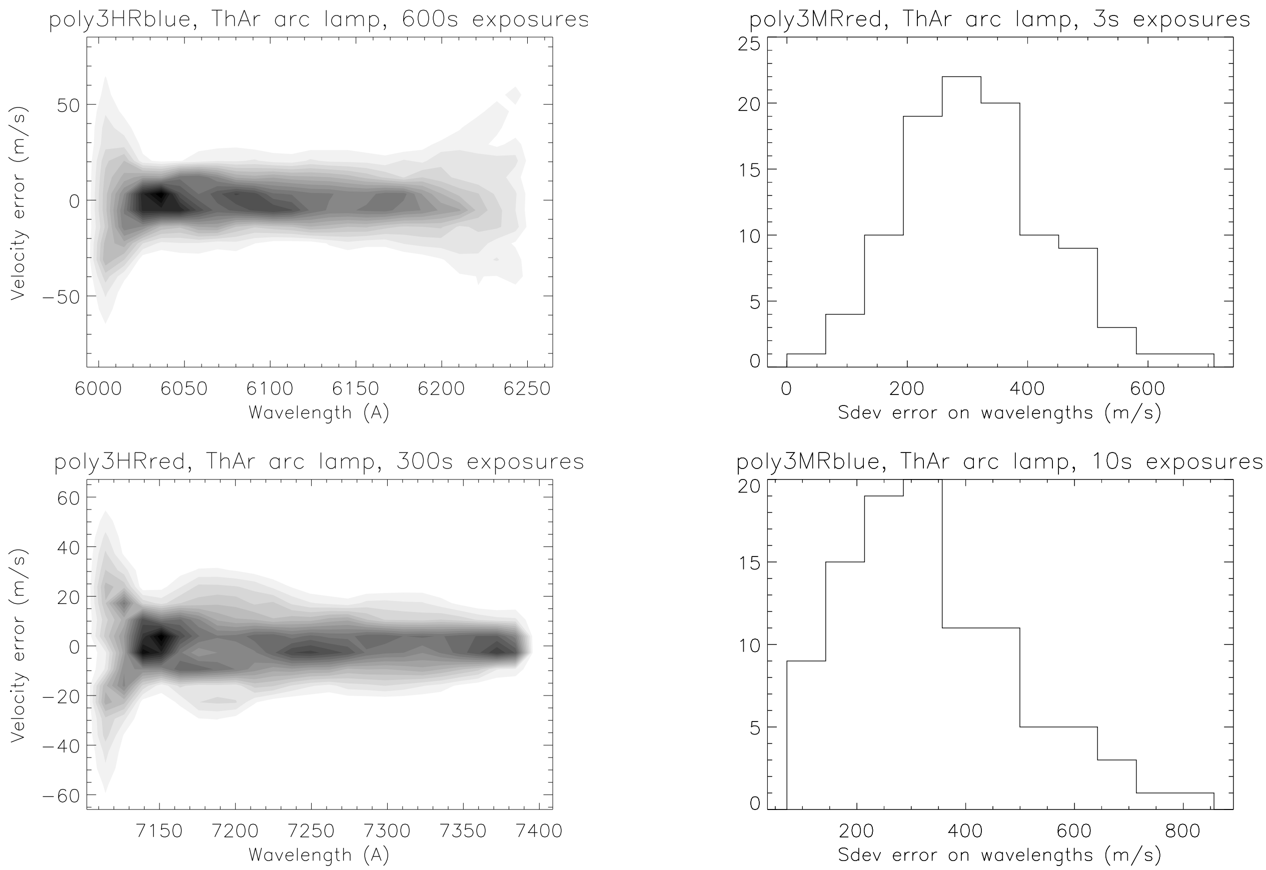

Figure 6. *Left:* density plot of the velocity error across the entire spectral range, for the ThAr lamp, assuming a third order polynomial wavelength solution in the HR spectrograph covering the 600 to 625 nm range (*top*) or 711 to 740 nm range (*bottom*) and 600-second exposures, obtained after 100 simulations. *Right:* histogram of the dispersion of the velocity error across the entire spectral range.

In this paper we have presented the approach that is currently being favored for the calibration strategy with MSE at first light, and that is envisioned over the lifetime of the observatory. The calibration procedures with MSE will rely on decades of experience with standard techniques at CFHT and other observatories on Maunakea and in the world, while exploring how novel methods in operations, data reduction, and hardware, will help MSE fulfill its ambitions.

The subtraction of the sky has to be accurate down to a fraction of 1%, especially in H band. Rather than relying on the allocation of every other fiber to the sky, we will generate a model of the background emission across the whole field of view, using our understanding of the sky emission variations and promising analytical method. The wavelength precision at high resolution will be challenging because the spectral windows will be narrow. While the use of usual arc lamps may provide enough photons in a reasonable time, other sources of light and methods of calibration remain under investigation.

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