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Science calibration for highly multiplexed fiber-fed optical spectroscopy: update from Maunakea Spectroscopic Explorer

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ABSTRACT

Maunakea Spectroscopic Explorer (MSE) is the only dedicated, >10 m class, multi-object facility under development on the best site in the Northern Hemisphere. MSE is designed to simultaneously obtain 4,332 spectra in three resolution modes in the optical and NIR. The design attributes of a wide field of view, a high multiplex capability, and the use of optical fibers to transport the light from the prime focus to two suites of spectrographs, mandate an efficient and precise science calibration process to account for the throughput and imaging variations between the astronomical targets at the detectors.

To achieve MSE's science goals, the calibration process must enable accurate sky subtraction, wavelength correction, and spectrophotometry. In this paper, we continue our discussion on the science calibration requirements and procedures, and provide an update to the adopted calibration strategy, including likely operational features and hardware.

This paper particularly focuses on two new aspects of MSE analysis, ghost behavior of the wide field corrector and the possible impact of satellite constellations on MSE observations.

Keywords: Massively multiplexed spectroscopic surveys, 10m-class telescopes, spectroscopic facility, survey facility, wide field, multi-object spectrograph, spectroscopy, calibration, satellite constellations, optical ghosts

1. INTRODUCTION

The Maunakea Spectroscopic Explorer (MSE; MSE Science Team 2019) is a next-generation massively multiplexed ground-based spectroscopic survey facility. MSE is designed to enable truly transformative science, being completely dedicated to large-scale multi-object spectroscopic surveys, each studying thousands to millions of astrophysical objects. MSE will use an 11.25 m aperture telescope to feed 4,332 fibers over a 1.5 square degree field of view and has the capability to observe at a range of spectral resolutions, from R~3,000 to R~40,000, with all spectral resolutions available at all times across the entire field. The MSE project completed a Conceptual Design Review of the facility in 2018 (MSE Project 2018); the Conceptual Design of the facility is shown in Figure 1. With these capabilities, MSE will collect more than 10 million fiber-hours of 10m-class spectroscopic observations every year and is designed to excel at precision studies of large samples of faint astrophysical targets.

The scientific impact of MSE will be made possible and attainable by upgrading the existing Canada-France-Hawaii Telescope (CFHT) infrastructure on the Maunakea summit, Hawaii. CFHT is located at a world-class astronomical site with excellent free-atmosphere seeing (0.4 arc-seconds median seeing at 500 nm). The Mauna Kea Science Reserve Comprehensive Management Plan (Ku‘iwalu 2009) for the Astronomy Precinct explicitly recognizes CFHT as one of the sites that can be redeveloped. In order to minimize environmental and cultural impacts to the site, and also to minimize cost, MSE will replace CFHT with an 11.25 m aperture telescope while retaining the current summit facility footprint. MSE will greatly benefit by building on the technical and cultural experience of CFHT throughout the development of the project.

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In order to achieve the science goals of MSE[1] on the faint Universe with a requirement to detect spectral features at m_{AB}=24 magnitude, the calibration process must enable highly accurate sky subtraction and spectrophotometry. In this paper, we discuss the continuing development of the science calibration requirements and procedures, and provide an update to the adopted calibration strategy, including operational features and hardware, that will facilitate successful exploitation of the vast MSE scientific dataset.

From a holistic point of view, there are two classes of calibration necessary for a facility such as MSE. The first is the calibrations required for the various hardware components of MSE, or what we will call Facility Calibration. These are calibrations required to allow and to ensure that a sub-system within the MSE facility will perform at its required and optimal level of performance. The second is the set of calibrations necessary for the science data as required for extraction of the science. This is what is termed as Science Calibration. It is the "frequent" set of calibrations required to ensure that the MSE spectra represent the true spectral characteristics of the scientific target at the level required for optimal MSE science as defined in the MSE Science Requirements Document (SRD).

Errors, misalignments, data biases, etc. can be mitigated by design, by detection and/or calibration, by procedure, and by data processing including modeling.

The vast scientific power of MSE derives from two specific qualities: 1. The large ~81 square meter collection aperture of the telescope that makes MSE unique compared to other spectroscopic facilities currently planned or in existence. 2. The superior conditions offered by the planned site for MSE (replacing the CFHT telescope on Maunakea) compared to other astronomical sites in terms of seeing and atmospheric clarity. Exploitation of this power demands that the MSE calibrations are robust, optimal, and correct at a level unseen with comparable instruments on the smaller telescopes located at lower quality sites.

2. FACILITY CALIBRATION

The MSE Facility Calibrations are those calibrations required for the various subsystems of MSE to operate and perform at their optimum design levels through the lifetime of the MSE facility. Several examples are given here.

2.1 M1 mirror segment calibrations

These are calibrations of the alignment and image quality for the mirror segments when they are either installed or otherwise in need of alignment. During normal operation, mirror segments will be routinely removed for recoating and replaced on a timescale such that the overall reflectivity of the M1 mirror does not degrade below 94%. This requires a 2-year cycle of recoating for each of the 60 mirror segments that translates to 3 segments being recoated approximately every 5 weeks. The reinstalled segments will require realignment, warping, and phasing with the rest of the M1 segments so that the image quality maintains the requisite level of coupling with the fiber optic apertures. Such calibration will make use of the Phasing and Alignment Camera (PAC).

2.2 Telescope pointing/tracking calibration

A pointing model must be produced to enable precise and accurate telescope pointing when it is first commissioned, when major modifications are made, and on an as needed timescale to keep the pointing at optimal levels of performance. Errors in the pointing model will increase the observing overheads resulting in a loss in scientific efficiency. Errors in tracking could result in less than optimal coupling of the images with the fiber optic apertures in a manner similar to degraded seeing.

2.3 Technical camera (AGC and PAC) calibration

Sensor and positional calibration of the Acquisition Guiding Cameras (AGC) and the PAC will be required. This likely includes linearity, dark, and flat field calibration. Most important is a flat field calibration to ensure that there are not any significant pixel to pixel variations in the data that might distort the guiding accuracy or the wavefront determination. Such errors could lead to inaccuracies in the AGC telescope tracking and to degraded image quality of the optical system due to incorrect wavefront corrections being applied to the M1 segment alignment. Positional calibration will be required for the AGC to ensure that the fiber optical system is aligned with the guiding reference frame, otherwise a systematic offset may exist between the target images and their assigned apertures.

These calibrations should be relatively infrequent once they are done after initial installation with repeat calibrations likely required after any reinstallation and maintenance, or to correct for detected drifts in performance over time.

2.4 Astrometric calibration

A calibration is required to ensure that the transformation of the fiber positions precisely and accurately align with the target positions on the sky and to account for telescope orientation, Wide Field Corrector (WFC/ADC) orientation, and environmental conditions. This may need to be repeated to account for changes in the overall facility system behavior.

This calibration will likely involve a complex set of measurements from different sub-systems (metrology of fiber positioner, transformation to sky coordinates). One possible calibration procedure may include configuring the fiber positioner for a target field of relatively bright stars. A set of relatively short exposures would be taken with slight offsets (~0.5 arc-seconds) in the telescope pointing between each exposure such that a small grid of positions (say 3 by 3 or 5 by 5) are observed from which the optimal location of the target object can be determined for each fiber aperture. Perhaps the detectors are used with significant pixel binning for quick readout.

2.5 Spectrograph image calibration (focus and image alignment)

Each spectrograph will need to be focused and aligned such that the spectra are optimally positioned onto each detector. Ideally this will be an infrequent calibration with appropriate stability in the spectrographs, but likely needed on some time cadence and whenever a reconfiguration is applied to the spectrograph.

2.6 Spectrograph shutter calibration

Spectrophotometric precision will require known and stable behavior (exposure uniformity and timing performance) of the spectrograph shutters. Again, this should not be a frequent calibration, only required when something has been modified/maintained or when performance is degrading.

2.7 Responsibilities for facility calibration development

The various sub-system level facility calibrations will be defined and designed by the related MSE work package groups. For example, the metrology calibration will be a responsibility of the fiber positioner group. Another is the spectrograph focus and image alignment which would fall to the spectrograph teams.

System level facility calibrations will be defined and developed through guidance of the MSE Project Office with work allocated to a variety of work packages. An example is the astrometric calibration which will include evaluation of atmospheric effects, telescope behavior, optical performance of the WFC/ADC, functional behavior of the fiber positioner, and capability of the control software.

3. SCIENCE CALIBRATION

The MSE Science Calibrations are those calibrations necessary to ensure that the MSE spectra represent the true spectral characteristics of the science targets as required for the science. Unfortunately, there are many sources of error, biases, and noise that can degrade the quality of the target spectrum which, if uncorrected, could lead to incorrect and invalid scientific interpretation of the data. This section will discuss many of these sources of error, biases, and noise and will suggest approaches for detecting and calibrating them. This will include some discussion on the following:

1. Detection sensitivity calibration
2. Background calibration
3. Wavelength calibration
4. PSF calibration
5. And detection/avoidance of spurious contamination

This discussion is meant to build upon a previous paper[2] that covers the fundamental challenges for the scientific calibration of MSE data. In particular, the exploration of optical ghosts from the WFC/ADC optics and the impact of satellite constellations is presented.

3.1 Detection sensitivity calibration (pixel to pixel, fiber to fiber)

To ensure that the flux of the spectrum is recorded in a consistent and correctable way, it is necessary to determine the relative sensitivities of the instrument from one target spectrum to another and within the spectrum of a target itself. Detector pixel to pixel sensitivity is not likely to be uniform but is typically relatively stable with modern optical detectors. It must be noted that the pixels may themselves have a variation in sensitivity across the pixel that may also vary depending on the illumination angles of the light incident on the pixels. This was particularly true for some earlier generations of CCD sensors where the substrate caused fringes. Although modern detectors do not show significant fringing care should still be taken to ensure that the calibration light used for sensitivity flat fielding illuminates the sensors as similar as possible to the target light.

Target to target sensitivity is also not likely uniform due to various reasons such as:

1. Telescope and fiber alignment on the targets will result in variable and non-optimal aperture coupling that impacts the overall sensitivity and wavelength sensitivity.
2. Varying pupil illumination of the spectrograph optics due to fiber tilt or offset from the assigned target that cause changes in the spectral psf and/or unwanted loss of light due to vignetting.
3. Fiber stresses from fiber cable assembly and motion introducing variable changes in the spectrograph pupil illumination.
4. Contaminants (dirt or other contaminants/blemishes) that impact the efficiency of the optical train.
5. Spectrograph instabilities causing drift of the spectral image on sensor both in position and focus.

Typical sensitivity calibration methodologies include the following:

6. Illuminating the telescope focal surface and apertures with uniform illumination by the use of dome flats, spider flats, deployable screen flats, and/or twilight flats. This approach is used to calibrate the variation in sensitivity amongst the scientific targets and along the spectra.
7. Illuminating the sensor with quasi-uniform illumination (sometimes called pixel or milk flats) with LEDs inside the spectrographs, using leaky fibers along slit, or possibly with a defocused slit. This is to calibrate the detector performance itself (linearity, pixel to pixel sensitivity).
8. Observing calibration target fields of spectrophotometric standards either specific calibration target field or allocating a subset of fibers to calibration stars observed within science target field. This provides calibration of the spectrophotometric sensitivity.

3.2 Background calibration (sky, ghosts, scattered light, bad/hot pixels, dark, thermal, bias, radiation/cosmic rays)

Whereas sensitivity calibration in astronomical spectrographs is fairly well understood, background calibration is potentially much more difficult, especially for a facility like MSE where the observations are required to extract reliably measurable signals that are up to 100 times fainter than the earth based observable sky limit. MSE must be able to calibrate to a source level of m_{AB}=25!

Contributors to the background signal are not just due to the night time sky, but arise from a variety of sources such as: scattered light along the optical train, bad and hot pixels in the detector, thermal background due to sensor thermal emission (dark current) as well as thermal background of the facility structure for the near-IR channel, amplifier bias, radiation and cosmic ray impacts in the detector, ghosting within the optical system, and background sources of light in the sky and surrounding environment.

Sky background

The sky background dominates the faint object optical and non-thermal infrared spectroscopy with faint sky levels nominally swamping the faintest MSE target signals by a factor of 50 to 100 with spectral, temporal and spatial variability across the MSE field. Figure 1 illustrates a range of sky background sources that MSE may have to contend with. The nominal baseline sky background calibration methodology for MSE is to use a subset of fibers (~10%) scattered approximately uniformly across the MSE field of view to directly measure blank sky regions. Parametric or Principal Components Analysis (PCA)[3] modeling of the sky data will likely be used to scale the sky spectra to each observed target spectrum.

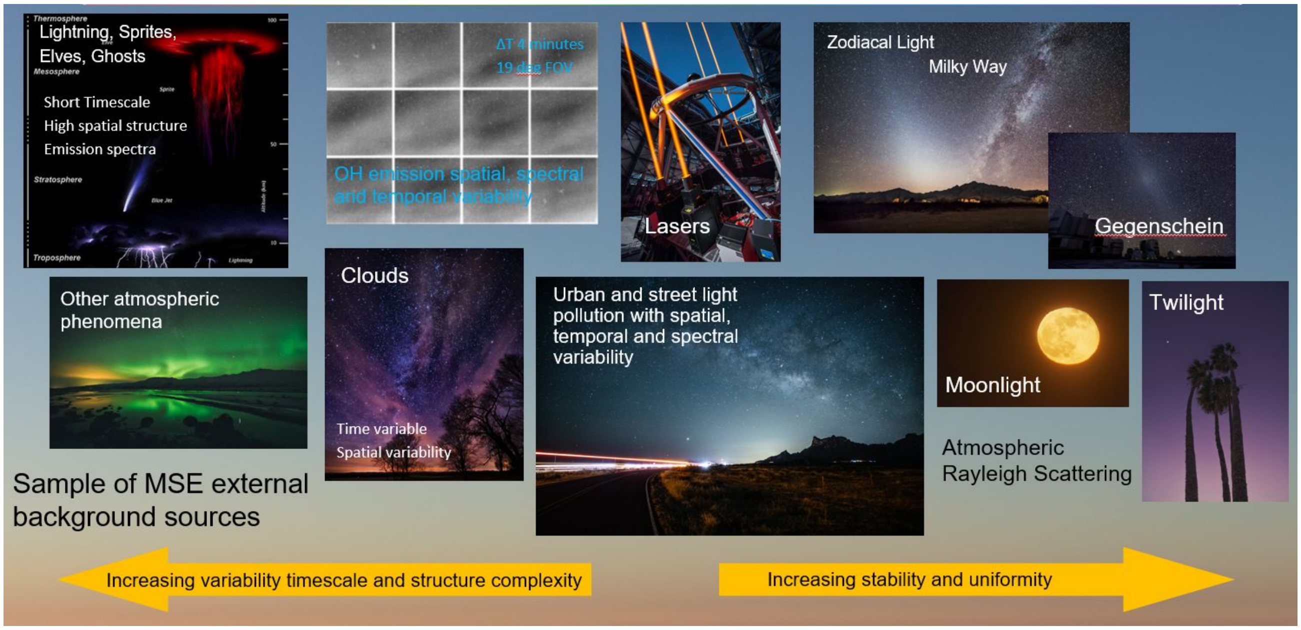

Figure 1: Various sources of sky background. Highly complex sources with rapid time variability are on the left. Sources on the right have a smoother structure and are slowly varying or stable.

Lightning, Sprites, Elves, Green Ghosts, and other phenomena associated with terrestrial thunderstorms are likely to be bright and have significant spatial structure over the 1.5 degree MSE field of view such that a sparse distribution of sky fibers is unlikely to adequately map out the extent of the contamination. Fortunately, the time scale is very short and the contamination is most likely in the form of molecular emission which might make them identifiable in the case that the MSE sky subtraction process does not adequately remove them. Additionally, such storms would typically be far from the observatory with these sources residing near the horizon except for the Sprites and Green Ghosts that extend upwards into the Mesosphere and Thermosphere at altitudes of ~100 km. The ideal mitigation for this type of contamination would be avoiding targets in the direction of such storms. An additional mitigation might be the use of an imaging system viewing the target field with narrow band filters tuned to specific spectral regions for the detection and mapping of this contamination.

Bright aurora should be very low risk given the latitude of the MSE site, however, excitation of the upper atmosphere by solar emission could produce faint emission sources that may be problematic at the 25th magnitude level. The nominal MSE sky subtraction approach may suffice unless the spatial structures are not adequately mapped by the sky fiber distribution. Again, a possible additional calibration tool may be the use of imagers tuned to specific emission wavelengths that monitor the target field during the observation.

OH sky emission is well known but not necessarily well understood. There are likely behavioral aspects at the 25th magnitude level that may prove troublesome. Mitigations planned for MSE include the nominal use of sky fibers plus sky emission modeling along with PCA, though PCA is currently not sufficiently mature for MSE application. Effort is currently under way to study the OH sky behavior at Maunakea and to develop detailed models for this behavior[4]. The use of tuned imagers for the simultaneous monitoring of specific emission bands may provide further mitigation for OH and other sky emission features, especially if the distribution of sky fibers is insufficient to adequately map out the spatial structure of the sky emission.

Clouds present two avenues of bias: increased background contamination due to scattering of light from other sources, such as cities or the moon; and decreased source signal due to attenuation of the target light due to absorption by the cloud. Clouds can be highly variable both timescale and, more importantly, spatially. Again, the distribution of MSE sky fibers may be insufficient to adequately map the spatial structure of the clouds, especially at the 24th magnitude level. Imaging systems could be utilized to detect the presence, attenuation, and spatial structure of the clouds.

Urban and street light pollution will be a source of background, especially in the presence of clouds but also just due to the Rayleigh scattering of the atmosphere. Spatial structure of the contamination should follow that of the clouds so mitigation procedures would be similar.

Laser and other nearby light contamination from the Maunakea facilities will also contribute to the background. The lasers are very limited in wavelength and there are mitigations in place to avoid observing target fields through which the lasers may be crossing. Other light contamination such as from vehicles or other light sources in the domes could be more problematic with a wide array of spectral characteristics, but should have a relatively low spatial frequency such that the MSE sky fibers may prove sufficient for calibration.

Non-terrestrial light sources include the Milky Way, Zodiacal Light, Gegenschein, Moonlight, and Sunlight (or Twilight). Except for the Milky Way, these sources are relatively stable with respect to the typical MSE exposure cadence and should have relatively smooth and low frequency spatial structure. The nominal MSE sky calibration should be adequate along with target avoidance for Moonlight and Twilight.

MSE must be able to sample the collective signal of the background across the field of view with sufficient spatial sampling to capture and correct for the spatial structure at a level that allows the background to be fit or modeled to better than 0.01 of the level of the dark sky contribution.

MSE must be able to sample the collective signal of the background contemporaneously with the science data to capture and correct for the temporal behavior.

MSE must be able to measure the spectral characteristics of the collective background to capture and correct for the spectral structure.

MSE may benefit from specific monitoring via imagers of the spatial structure if adequate sky sampling can not be achieved.

Optical ghosts

Ghosts arise from optical reflections of light from the optical surfaces and dispersing elements. Ghosts from bright objects both in the telescope focal surface and the spectrograph focus may cause spurious signals in fainter target spectra and must be either mitigated by avoidance or appropriately calibrated out.

Focal surface ghosts are generally due to reflections from the optical surfaces of the WFC/ADC. Generally, the ghosts can be mitigated by the use of low reflectivity anti-reflection (AR) coatings. The wide bandpass of MSE, 370 to 1800 nm, along with the large size of the optics (~1 meter apertures) makes the use of multi-layer AR coatings difficult at best. It is currently envisioned that the MSE WFC/ADC AR coatings shall be simple double layer MgF/Solgel coatings, at least for the inner surfaces, and possibly only MgF coating for the external front surface of the WFC/ADC. These coatings typically have reflectivity of 0.5% to 1.5% per surface over the majority of the wavelength range (see Figure 2).

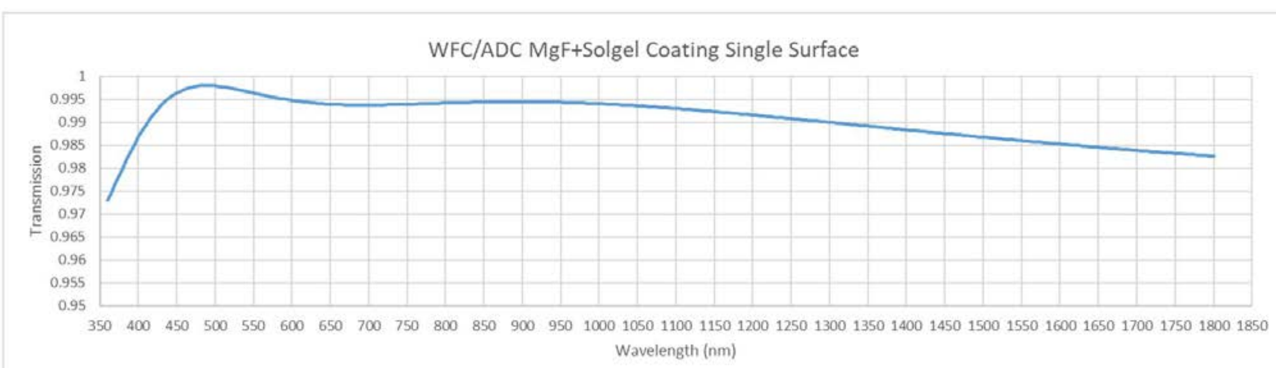

Figure 2: Transmission curve for a single surface MgF+Solgel AR coating.

The focal surface ghosts may introduce background contamination to any fiber apertures residing in the illumination area of the ghost. Fortunately, the Numerical Aperture (NA) of the fiber optics will limit the angles at which the ghost light will be transmitted by the exposed fiber, but this will generally only apply to ghosts that illuminate the focal surface an higher angles than the nominal telescope illumination.

An analysis was done for the current WFC/ADC baseline optical design using the non-sequential (NSQ) modeling available within Zemax/OpticsStudio. A large, plano rectangular detector was placed at the vertex of the MSE focal surface. The detector was set up with a 3386x3386 pixel format with a pixel plate scale of 1.77 arseconds/pixel to cover more than the 1.5 degree field of MSE. Since the MSE focal surface has a convex radius of curvature of 9.8 meters, off-axis images on the detector are slightly out of focus. For this initial ghosting analysis, maintaining the focus was not critical. Figure 3 shows the NSQ model with the rectangular detector visible just to the right of the WFC/ADC optics.

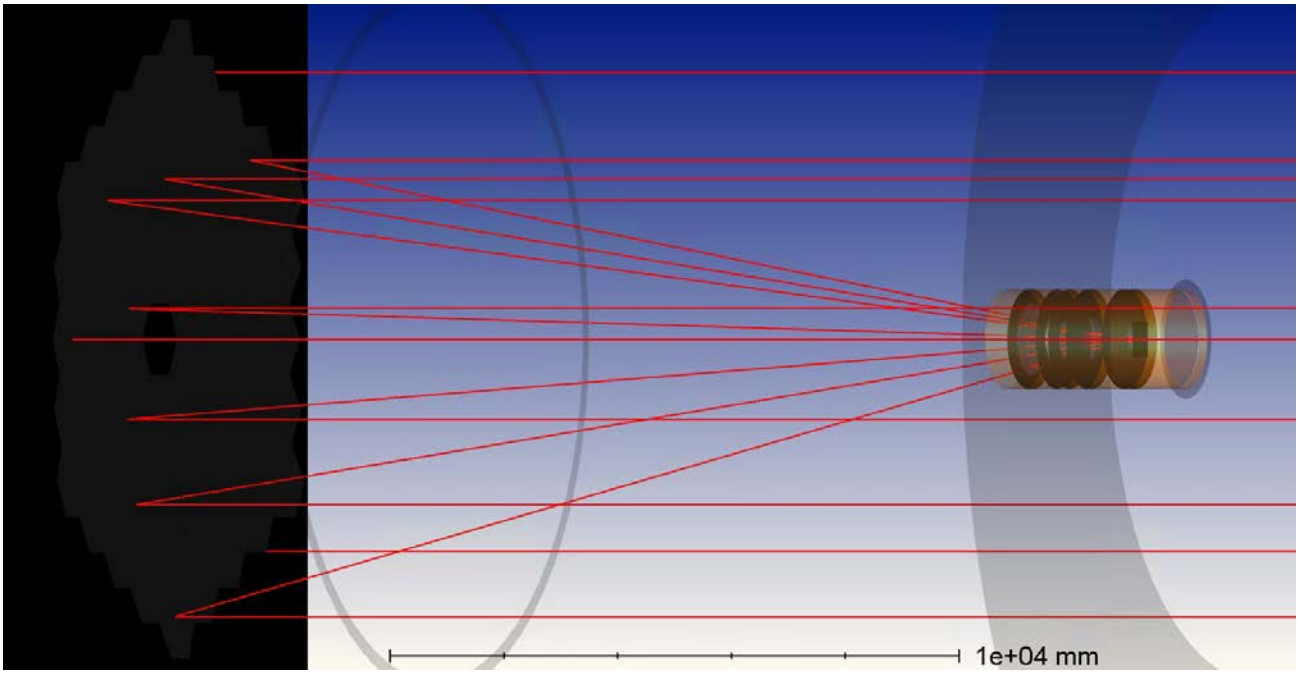

Figure 3: Solid rendering of the MSE NSQ model with WFC/ADC baffles, barrel and other aperture stops.

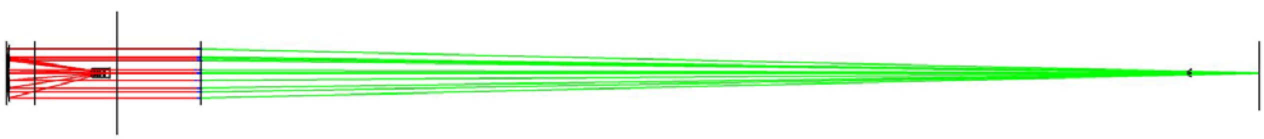

Figure 4: MSE NSQ model showing the point source illumination for the ghost analysis. This is the on-axis configuration.

Three point sources were configured. One was the bright source to generate the ghosts with the flux level set to be 20 magnitudes brighter than the assumed sky level (corresponding to a 0^{th} magnitude star). The other two were set with flux levels to indicate the sky level of 20^{th} magnitude and the level at which the ghost contamination should be fainter than. This threshold level was assumed to be 25^{th} magnitude (a factor of 100 fainter than the sky), but further consideration suggests that MSE should target a threshold at 26^{th} magnitude. The sky and threshold indicators were scaled in flux to account for the pixel size on the detector. The fiber aperture, through with all of the bright source image is assumed to be coupled to, is assumed to be 1 arc-seconds diameter. The detector pixels have an area of 4 times that of the presumed fiber aperture. A paraxial lens is set at the point source location to act as a field lens to concentrate the rays into the MSE collection aperture. An imaging paraxial lens is located near MSE (at the boundary between the green and red rays in Figure 4) with a focal length of 206265 mm so that an offset of the point sources in millimeters correspond directly to arc-seconds.

Image simulations were run at a wavelength of 700 nm with $1x10^8$ rays for the bright source and $1x10^5$ rays for each of the fainter flux indicators. The minimum relative ray intensity for NSQ modeling was set at $1x10^{-20}$. A series of simulations were generated with the bright source at a variety of radial positions in the field to examine the ghost behavior ranging from field center to just outside the MSE field of view. Figure 5 described the data obtained from each ghost simulation.

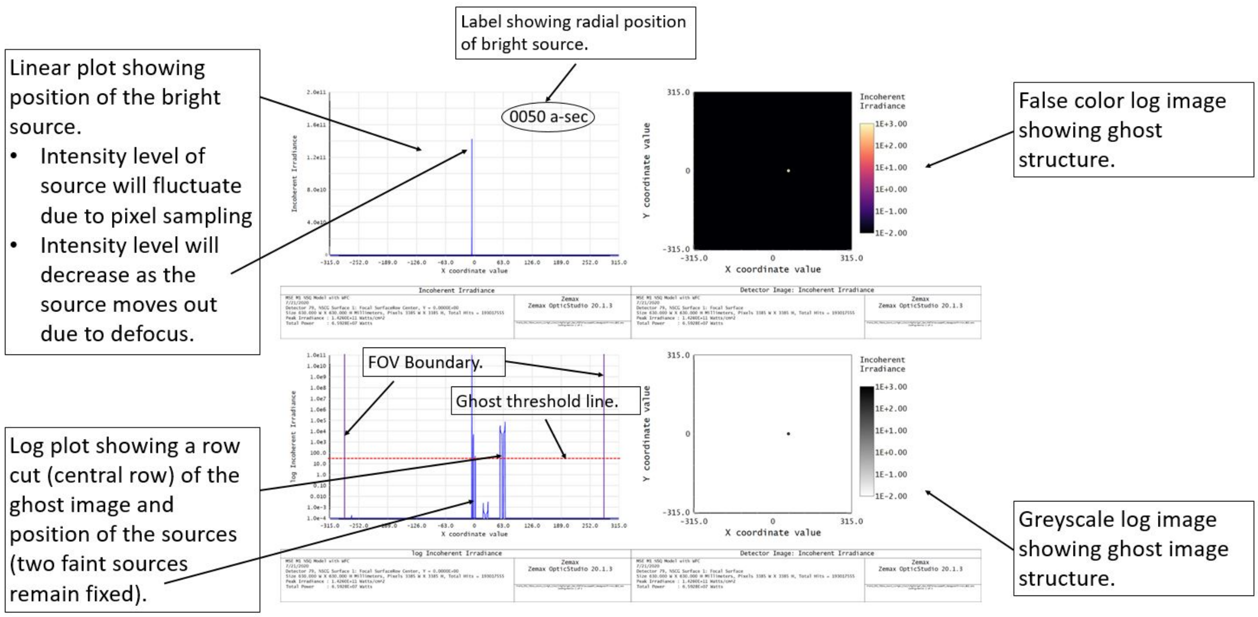

Figure 5: Key of data recorded for each NSQ simulation.

The NSQ analysis revealed three different ghosts of concern for MSE observations. In this discussion, it is assumed that MSE will need to have a much more conservative ghost threshold than that shown in the various analysis figures.

1. A strong "near-image" ghost

    a. This near-image ghost appears when the source is located centrally within the field and exceeds the desired threshold for stars brighter than ~9^{th} magnitude.

    b. The ghost rapidly moves across the field of view as the source star is offset from the center of the field until it is outside the MSE field for source stars offset from the field center by more than about 250 arc-seconds (~4 arcminutes radius).

    c. The ghost is quite bright and illuminates a circular patch with a diameter of roughly 2.2 arcminutes which is roughly comparable to the patrol area for a fiber.

    d. This ghost arises from reflections from the back surface of the last lens in the WFC/ADC (lens 5 surface 2) to the front surface of the first lens (lens 1 surface 1) and then back to the focal surface.

    e. This ghost can be mitigated by avoiding the placement of stars brighter than 9^{th} magnitude within the central 8 to 10 arc-minutes (diameter) of field center. There are approximately 200,000 stars in the sky brighter than 9^{th} magnitude which might make it difficult to completely avoid this ghost. It can also be mitigated by avoiding target assignment to faint targets in the region illuminated by the ghost. This second mitigation will require good modeling of the ghost location and size. Further modeling will be required to understand the behavior of the ghosts as a function of wavelength and ADC orientation.

2. A moderately large "pupil" ghost

a. This pupil ghost appears when the bright source is in an annular zone of 850 to 2300 arc-seconds (14 to 38 arcminutes) from the center of the field and exceeds the threshold for stars brighter than about 4th magnitude.

b. This ghost is persistent and generally contaminates the same region of the MSE field regardless of the radial location of the source. The area of contamination grows asymmetrically as the bright source moves further out in the field.

c. The ghost never disappears, but drops below the threshold when the bright source is near the edge of the field (>2300 arc-seconds).

d. This ghost also arises from a reflection off the back surface of the last lens (lens 5 surface 2) but then reflects off the front surface of the fourth WFC/ADC lens (lens 4 surface 1) and back to the focal surface.

e. This ghost can be mitigated by avoiding the placement of stars brighter than 4th magnitude within the annular zone 14 to 38 arc-minutes from field center. There are approximately 600 stars in the sky brighter than 4th magnitude. It is also possible to mitigate by avoiding target assignment to faint targets in the region illuminated by the ghost, though the extent of this region may be more difficult to model and completely avoid.

3. A strong and sharp image ghost

a. This ghost is another very strong image ghost that is much more in focus than the first ghost and appears when the bright source is located in an annulus 2050 to 2300 arc-seconds (34 to 38 arcminutes) from field center. Stars brighter than 10th magnitude will likely generate ghosts above the desired threshold.

b. This ghost only shows up in the outermost regions of the field and relatively quickly moves beyond the field as the source is moved further from the field center.

c. Given that the MSE field is hexagonal, the field impact of this ghost is much lower than the first two ghosts since this ghost appears in the corners of the hexagon and many of the ghosts would fall outside the hexagon itself. This small size of this ghost also makes it potentially easier to mitigate by avoiding assignment of fibers to the ghost position, although predicting those positions will require excellent understanding of the ghost size and location as a function of wavelength and ADC orientation.

Figure 6 and Figure 7 show the NSQ analysis for the three ghosts as the bright source if moved from field center to just beyond the edge of the field. The specific positions of the source are the following going from the top of Figure 6 to the bottom of Figure 7: 0, 225 (ghost 1 is near the field edge), 850 (ghost 2 is appearing), 1000 (ghost 2 is near maximum impact), 2100 (ghost 3 appears), 2300 (where ghost 3 moves out of the field), 2600 (ghost 2 drops below the threshold), and 2700 arc-seconds (the bright source is out of the field of view).

Other mitigation strategies that MSE is exploring are:

- Can the radii of the lenses be modified to further diffuse the ghosts, particularly the back surface of the last lens? Exploration by the optical designer suggests that no significant gain in ghost reduction can be achieved without starting to degrade the image performance. As such, it is unlikely that the ghosts will be mitigated be design modification.
- Improvement in the AR coating performance will be explored. In particular, if the coating on the second surface of the last lens can be improved, then at least ghost 1 and 2 will decrease in proportion to any reduction in reflectivity across the wavelength band. As that last lens is 650 mm in diameter, this may indeed be an option, assuming that a sufficiently broadband, high performance AR coating can be produced. Likewise, if the Solgel coating is determined to be sufficient robust to be applied to the external surface (front surface) of the first lens, then an immediate reduction in ghost 1 amplitude will be achieved.

Otherwise, it is most likely that MSE will need to mitigate ghost impact through observing procedure. Figure 8 shows the various regions of avoidance for placement of bright sources. Flaring satellites or meteors passing through the field of view will likely impact some targets from ghosts that they generate as they move through the field of view.

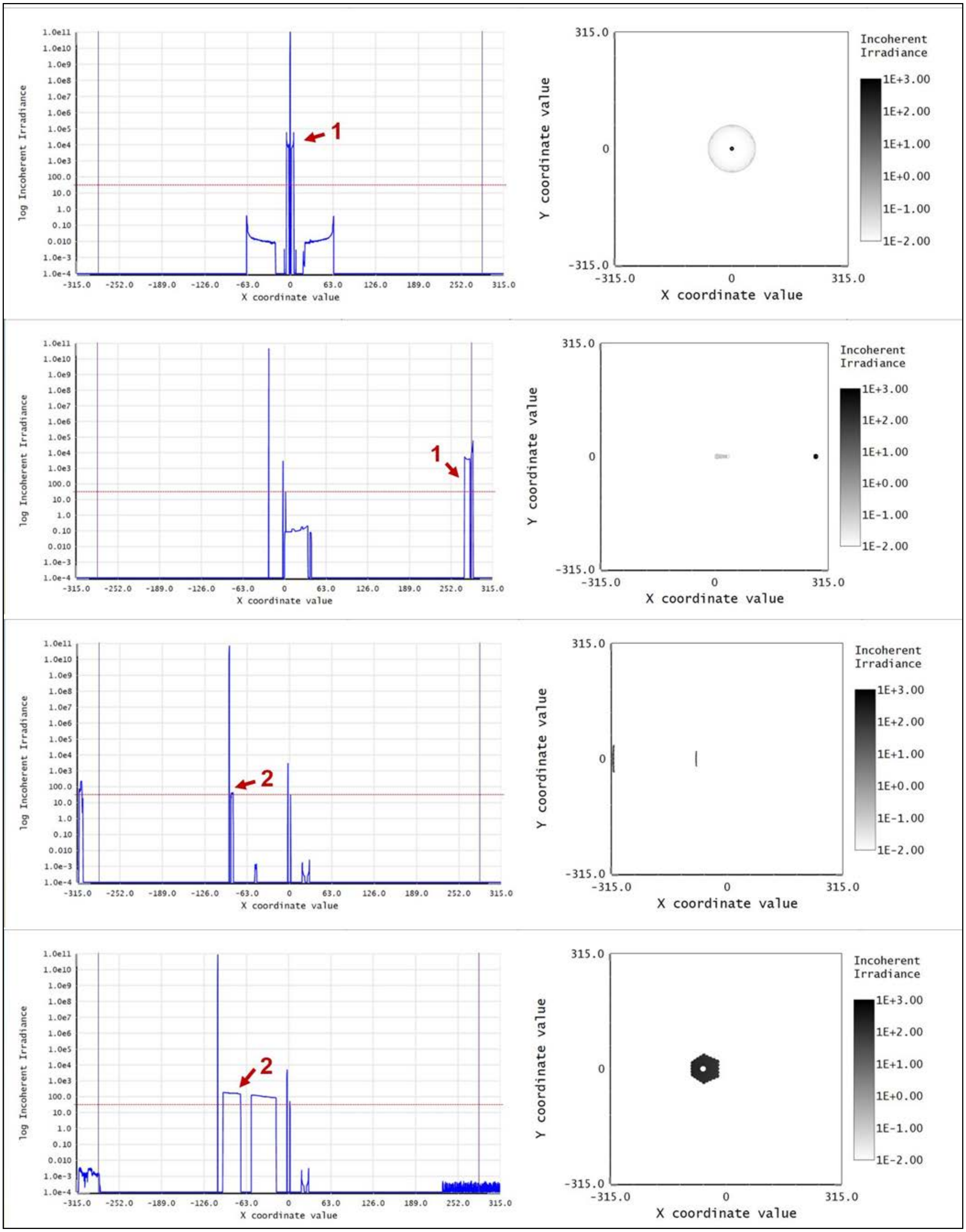

Figure 6: Ghost images for ghost #1 and ghost #2 as the bright source is moved from center outwards.

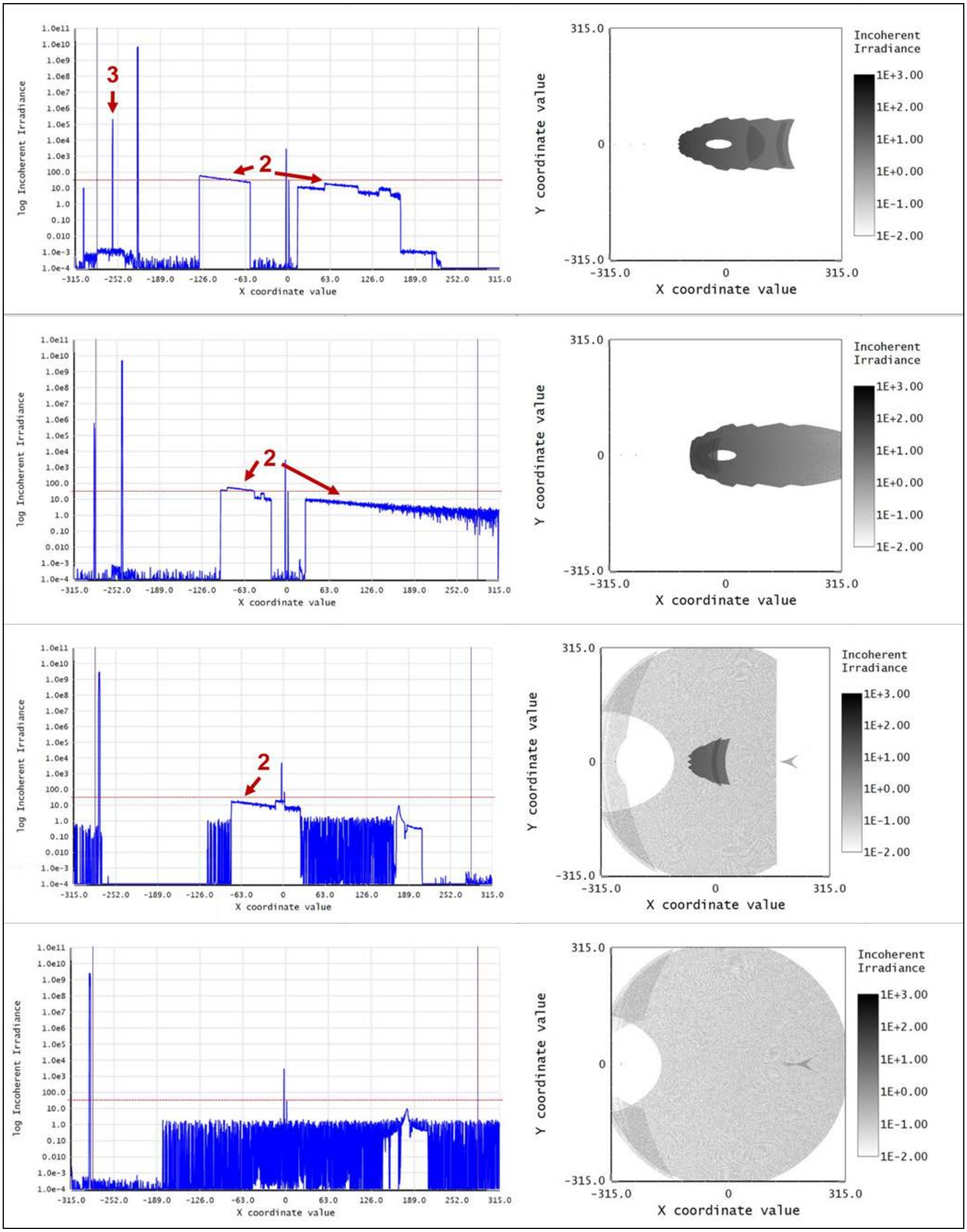

Figure 7: Ghost images for ghost #2 and ghost #3 as bright source is moved further outwards and out of the field.

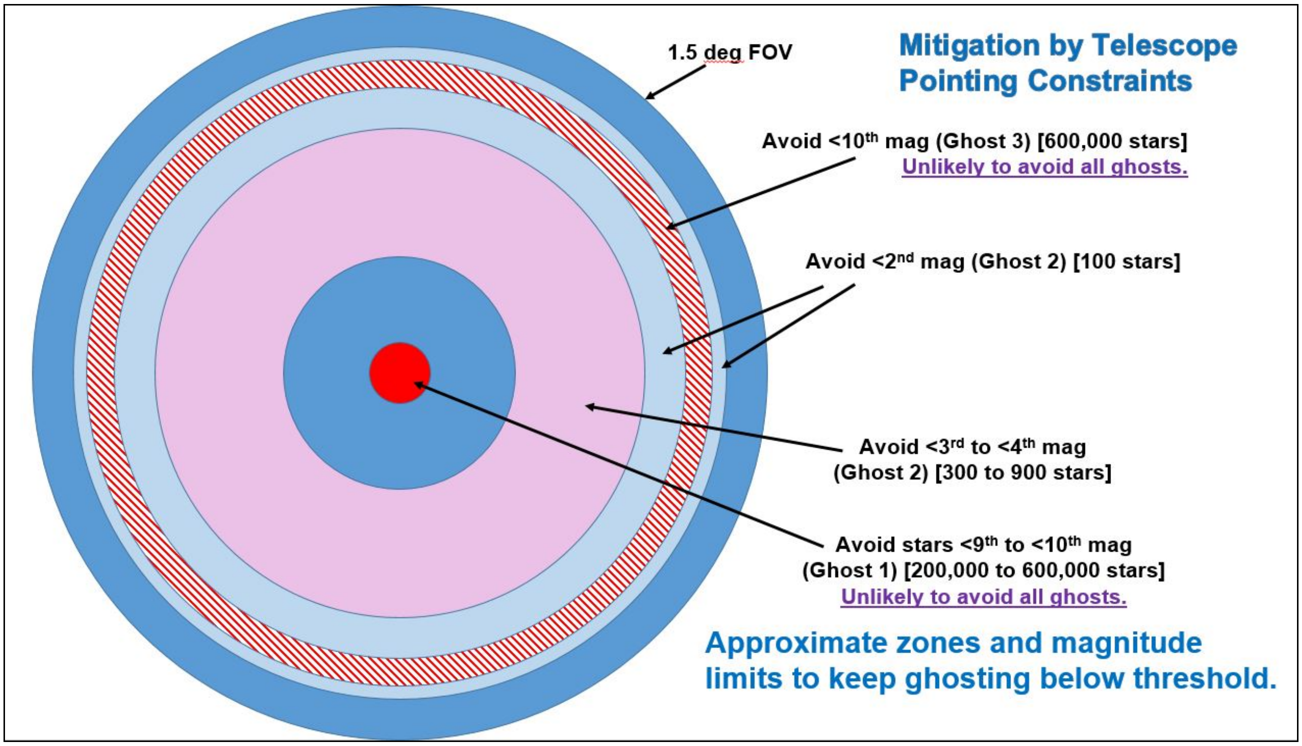

Figure 8: Zones of avoidance for bright sources as indicated in order to mitigate the impact of optical ghosting on faint targets.

Optical ghosts in the spectrographs will also need to be mitigated with excellent AR coatings and may also require predictive modeling of persistent ghosts, such as grating Littrow ghosts. Littrow ghosts can possibly be avoided by utilizing the gratings in a slightly non-Littrow condition such that the ghosts do not fall back onto the detectors. Ruled gratings will have ruling errors that also produce secondary spectra or ghosts.

Scattered light

Scattered light arises from scattering of light by structures and optical surfaces. Roughness in the grating rulings and/or optical surfaces will scatter light.

Best practices in design and production will be required to minimize the presence of scattering. Additionally, gaps should be present between spectra or groups of spectra on the detectors to monitor any remaining scattered light.

Calibration methodologies would benefit from the ability to illuminate spectral apertures (fibers) either individually or in small groups to map out the scattered light and ghosting on the detectors. This could be done either with slit masks, with a deployable projector capable of illuminating single fibers, or by the observation of single bright stars.

Bad/hot pixels, dark, thermal background, bias, and cosmic rays

Bad/Hot Pixels, Dark, Thermal Background, Bias, and Cosmic Rays are detector related with Radiation events possibly arising from slightly radioactive materials near to the detector (e.g. glass in the cryostat window). MSE will follow nominal calibration procedures as previously discussed[2].

3.3 Wavelength calibration (spectral alignment, velocity determination)

The MSE HR spectrograph requires 0.1 km/sec velocity measurements that correspond to 0.01 resolution element, or about 1/30th of a pixel. The LMR spectrograph requirements are relaxed in comparison with about 1/3rd of a pixel measurement.

Instabilities in the pixel illumination will cause instability in the wavelength determination that translates directly to errors in velocity. Such instabilities arise from a variety of sources including the following:

- Seeing variations causes changes in the weighted image profile passed through by the fiber resulting in changes to the imaged resolution profile.
- Spectrograph pupil illumination variations result in changes in the optical aberrations that shape the point spread function (PSF). These are typically caused by – guiding errors, fiber stresses, fiber tilt, thermal and mechanical changes, spectrograph seeing, etc.
- Spectrograph mechanical and thermal instabilities can also cause shifting of images on the detector.
- Imperfect PSF calibration will produce wavelength errors in the extracted spectrum.

Instrumentation that is mechanically and thermally stable will help reduce and mitigate spectral drift on the detector. Likewise, a stable and well calibration wavelength reference source is necessary to map out the wavelength dispersion on the detectors. MSE calibration procedures will likely include the exposure of all fiber apertures to a wavelength reference at least on a daily basis, but preferably for each target configuration; the observation of velocity standard stars either separately or mixed in with the science target field; and possibly require some method for simultaneously tracking wavelength shift on the detector, especially for the HR spectrograph, using either a set of dedicated fibers on the slit that only project wavelength calibrated light and/or through the use of absorption cells. Although the use of absorption cells would allow an imprint of wavelength on each and every spectrum, it is less desirable due to the added loss of light due to such cells.

3.4 PSF calibration

Related to the issue of wavelength stability is the stability and determination of the imaged PSF both spectrally and spatially. The PSF of imaged spectra is likely to be neither uniform across the detector nor stable over time and configuration. Sources of PSF error include:

- Optical aberrations inherent in the design (spot diagrams).
- Optical physics such as that of the disperser causing anamorphic distortions across the field (not necessarily apparent within spot diagrams).
- Alignment and focus errors of the instrument.
- Contamination on the input aperture.
- Varying pupil illumination due to optical contamination, guiding errors, fiber stresses, fiber tilt, thermal and mechanical changes, spectrograph seeing, etc.

Calibration may be possible with the same source as that used for wavelength calibration.

Data reduction pipelines that will utilize PCA methodologies will require excellent models for the spectral and spatial PSF to achieve the best subtraction of sky background and scattered light.

3.5 Spurious contamination

One of the virtues of the sheer number of spectra that MSE will collect over the decades is the ultimate detection of bizarre and previously unknown classes of objects. Unfortunately, spurious contamination can introduce spectral artifacts that would be confusing when the spectra are scientifically analyzed unless it was known that the spectra have been so compromised. Some notable false detections are the infamous potassium flare stars that were ultimately determined to be emission from the astronomers lighting matches as they observed and the more recent microwave outbursts ultimately determined to be from astronomers failing to turn of microwave ovens before opening the doors.

It is likely very difficult or impossible to calibrate out the effects of contamination, but there are ways to mitigate the risk of contamination and detection of such contamination will at least provide a cautionary warning in the analysis of spectra affected by the contamination.

Two key examples of spurious contamination are satellite and meteoric contamination. The issue of satellite contamination has recently come to light as a very serious issue facing large field imaging and spectroscopic facilities given the projected number of satellites being launched now and in the future. These satellite constellations will number in the 10’s of thousands forcing the major observatories to assess the impact on such facilities as the Rubin Observatory, DESI, 4MOST, and the ELT facilities[5,6]. A back of the envelope analysis of the impact on MSE is given here.

Assumptions for probability of satellite impact on MSE spectral observation

The following were assumed:

- MSE Linear field of view = 1.5 degree = 5400 arc-seconds
- Aperture diameter = 1 arc-seconds
- Total number apertures = 4332 (HR apertures 1083) (LMR apertures 3249)
- Ratio of linear aperture coverage to linear field of view = 80% (HR fraction 20%) (LMR fraction 60%)
- Number of satellites in constellation = 50,000
- Distribution of satellites is uniformly distribution across full sky
- Mean orbital period for satellites = 2 hours
- Number of square degrees in the sky = 41252
- Equivalent number of 1.5 square degree MSE fields in total sky = 27500

Impact on MSE targets

Two exposure scenarios are assumed for an MSE observation: 20 minute single exposure and 60 minute single exposure. Each satellite will sweep out a path of 60 degrees in 20 minutes or 180 degrees in 1 hour, hence if a satellite enters the MSE field, it will fully cross the field during either exposure scenario. This makes the probability of the satellite crossing over an MSE target approximately equal to the ratio of target aperture to linear field or 80% for any of the apertures and 20% and 60% for the HR and LMR specific apertures respectively.

With 50,000 satellites uniformly distributed across the sky, the density on the sky is 1.2 satellites per square degree or approximately 1.8 satellites per MSE field. This assumes that the satellites are static (ie. not moving with respect to the MSE field). With the 20 and 60 minutes sweeps of 60 degrees (40 MSE field equivalents) and 180 degrees (120 MSE field equivalents) respectively, the number of target hits in an MSE field will be:

- **Total MSE target hits for a 1 hour exposure** = 120 (sweep rate per MSE field) times 1.8 (static satellite density per MSE field) times 0.8 (probability of hits) = 173 per hour (**4% of the total number of MSE apertures**)
- **Total MSE target hits for a 20 minute exposure** = 40 (sweep rate per MSE field) times 1.8 (static density per MSE field) times 0.8 (probability of hits) = 58 per 20 minute period (**1.3% of the total number of MSE apertures**)

This argues that shorter exposure times are desired for MSE observations. One hour total integrations would allow 2/3rd of the exposures of a compromised target to remain valid rather than losing the full 1 hour integration if the exposure is uninterrupted for the 1 hour. However, this would come at the expense of possibly higher read noise for the faint object spectra.

For the 1 hour case, a 4% hit on MSE efficiency over a decade would correspond to about 100 equivalent lost nights, or equivalently a loss of a few million spectra!

Of course, the satellites might be sufficiently faint if they are in the shadow of the Earth to not introduce significant background when they pass over the target aperture. The dwell time of a 2 hour orbit satellite over an MSE aperture is about 0.006 seconds. For a 20 minute exposure, the satellite would contribute a signal equivalent to a target that is 0.006/1200 times or about 13.3 magnitudes fainter. For a 1 hour integration, the satellite contributes a lower signal, corresponding to a continuously observed target that would be 0.006/3600 or 14.5 magnitudes fainter. If the level of contamination by the satellite is to be fainter than 25th magnitude, then the satellite would need to be fainter than 11.7 magnitude for the 20 minute exposure and fainter than 10.5 magnitude for the 1 hour exposure. These magnitude limits are considerably fainter than what has been computed for the ESO[4] and NOIRLab[5] reports which suggest that imaging surveys only require that the satellites be fainter than about 7th magnitude.

It needs to be noted that the spectral characteristics of the contamination will be dominated by a solar spectral signature.

The impact of meteors will have the same probability of contaminating a target for each meteor that may pass through the field. Fortunately, the density of meteors is significantly lower and the dwell time is considerably shorter than the slower moving satellites. Aircraft could also pose a risk of contamination with the craft having comparable speeds, larger subtended size, and brighter sources of light. However, aircraft avoidance mitigation is well established for the Maunakea observatories.

Mitigation strategies for satellites

It is unlikely that contamination due to satellites can be easily removed by calibration or modeling. Fortunately, there are mitigation strategies to both avoid the contamination and/or to identify which targets have been contaminated.

- Avoid impact by target assignment scheduling procedures that includes consideration of the satellite orbits.
- Monitor the field to image satellites and identify impacts.
- Take multiple exposures in the field to reject compromised spectra.

MSE should avoid flaring satellites within the target field due to ghosting within the WFC. It is unknown if these massive constellations will have flaring predictions available for each and every satellite.

4. SUMMARY AND CONCLUSIONS

4.1 Summary of subsystems required

Given the discussed range of errors, biases, and noise sources for MSE, the following subsystems are likely required.

Telescope flat field lamps and screens

A set of Continuum Lamps with little to no wavelength structure for normalizing the spectral response of the instrument in both wavelength space and from fiber to fiber.

A set of Illumination Optics and/or screens as required to provide stable illumination of the MSE focal surface with either uniform illumination or with a well-behaved and predictable variation across the field of view.

The Continuum Lamps and Illumination Optics may either illuminate a screen mounted to the dome structure and/or illuminate directly the M1 primary mirror in order to fill the telescope pupil with a smooth and flat radial profile. Azimuthally uniform illumination of the telescope pupil is desired, but perhaps may not be required if the fiber optics are determined to adequately scramble any azimuthal structure.

Typically required for each target field configuration.

Telescope wavelength lamps and screens

A set of Wavelength Lamps with sufficient (high wavelength frequency) wavelength structure for linearizing the spectral response of the instrument in wavelength space and from fiber to fiber.

A set of Illumination Optics and/or screens as required to provide stable illumination of the MSE focal surface with either uniform illumination or with a well-behaved and predictable variation across the field of view.

The Wavelength Lamps and Illumination Optics may either illuminate a screen mounted to the dome structure and/or illuminate directly the M1 primary mirror in order to fill the telescope pupil with a smooth and flat radial profile. Azimuthally uniform illumination of the telescope pupil is desired, but perhaps may not be required if the fiber optics are determined to adequately scramble any azimuthal structure.

Typically required for each target field configuration.

Simultaneous wavelength calibration

A system that creates spectra on the science detector providing a high precision wavelength reference during a scientific exposure. Two possible solution examples are:

- Use of a set of dedicated fiber optics distributed along the slit illuminated by a wavelength calibration light source similar or identical to that used for the full field wavelength calibrations to provide wavelength stable spectra at least at the ends of the slits and perhaps distributed at some interval across the slit. The intensity of the wavelength light will require control so that the exposure level is commensurate with the exposure level of the science data.

- Possible use of an absorption cell, such as iodine, to imprint a wavelength signature directly on to each science spectrum. This would probably be deployable and removed in applications not requiring the high precision velocities.

Desired for each and every science observation, particularly for the HR spectrograph. It might not be required for the LMR spectrograph.

Target field imagers

A set of imagers monitoring the target field during the science exposures to provide secondary calibration information on the following:

- Broadband imaging to monitor for satellites and other spurious contaminants such as clouds.
- Narrowband imaging to monitor the spatial and temporal structure of critical sky emission features such as particular OH bands and other bright emitters.

Ideally, the set of imagers would have sufficiently small forms to fit on the MSE telescope structure. The imagers could have shorter exposure time cadences, but they should collect data during the course of each science exposure.

Imaging data would be required for each and every MSE science target exposure.

Detector calibration lamps

A system that allows the direct illumination of the science detectors within the spectrographs to evaluate and monitor detector health and performance (e.g. linearity), pixel to pixel variations, etc.

Possible solutions to consider are LED's located to directly illuminate the detectors; LED's or some other light source (leaky fiber) located near or replaceable with the slit; use of the MSE fiber slit but out of focus (either by displacing the slit or inserting a glass plate).

This is likely not a frequent calibration.

Slit mask for fiber illuminator

A system that illuminates limited areas of the science detectors so that ghosting and scattered light characteristics can be determined, monitored, and calibrated out.

Some example solutions might be:

- A projection source at the telescope focus with the ability to illuminate single fibers, or small groups of fibers, with both continuum and wavelength sources.
- Observation of bright stars down single fibers or bright cluster illuminating groups of fibers.
- A deployable slit mask that can mask off all but one or a few fibers.

This is likely not a frequent calibration.

On-sky calibration targets

Standard stars either observed within an MSE science target field or as a separately exposed target field.

Stars used for velocity calibration, spectrophotometric calibration, telluric line calibration, abundance/metallicity calibration.

This likely doesn't require any special hardware, but is an operational and data analysis procedure.

Procedure

Calibration and/or mitigation by Procedure is the implementation of a set of Rules to be applied to target configurations, telescope pointing, and calibration processes in order to provide robust calibration data or to avoid contamination and/or calibration issues.

WFC/ADC ghosting may require mitigation by Procedure where there may be avoidance zones for faint target assignment due to the presence of a bright object within or near the field of view.

Other Procedural mitigations would be the avoidance of bright targets (planets, Moon, bright stars) within the science target field of view and distance constraints to limit Moonlight, twilight, laser, and thunderstorm related background.

The inherent nature of fiber optics will likely require frequent and careful flat field and wavelength calibrations.

Modeling and calibration data pipelines

Data pipelines/modeling will be required to implement the various calibration strategies and the proposed use of PCA methodologies.

Predictive modeling of the night sky spectrum, ghosting/scattered light behavior, and image profiles should greatly assist in the mitigation of the impact that these sources of errors will have on the final spectrum.

4.2 Concluding comments

With well designed and calibrated MSE system components (Facility Calibration) providing optimal target coupling into the MSE fibers and spectrographs plus a set of robust science calibration hardware, methodologies, and procedures MSE will meet the demands of extracting reliable signals buried in the depths of sky background and cope appropriately with other sources of contamination and bias.

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