MSE: Instrumentation for a massively multiplexed spectroscopic survey facility

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ABSTRACT

MSE is a massively multiplexed spectroscopic survey facility that will replace the Canada-France-Hawaii-Telescope. This 11.25-m telescope, with its 1.5 square degrees field-of-view, will observe 4,332 astronomical targets in every pointing by using fibers to pick up the light at the prime focus w and transmitting it to banks of low/moderate (R=3,000/6,000) and high (R=30,000) resolution spectrographs. Piezo actuators position individual fibers in the field of view to enable simultaneous full field coverage for both resolution modes. A Calibration system ensures good quality and reliable raw data. This instrument suite, dedicated to large scale surveys, will enable MSE to collect a massive amount of data: equivalent to a full SDSS Legacy Survey every 7 weeks.

Since 2018, MSE has made progress by refining the science cases, exploring design space for the instrumentation and understanding the limits of chosen telescope and instrument architecture to achieve the science cases. To improve performance and reduce risk, challenging conceptual designs for spectrographs have been reconsidered. As well, the science calibration plan and associated technical hardware system have been developed to a conceptual design level. This paper includes a discussion of the trades, design decisions and outstanding risks for the entire instrument suite with a focus on recent developments for the spectrographs and calibration system.

1. INTRODUCTION

Maunakea Spectroscopic Explorer (MSE) is the first of the future generation of massively multiplexed spectroscopic facilities. MSE is designed to enable 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 wide 1.52 square degree field of view. It will have the capabilities to observe at a range of spectral resolutions, from R~3,000 to R~30,000, with all spectral resolutions available at all times across the entire field.

MSE is an upgrade of the 3.6-meter Canada France Hawaii Telescope (CFHT) on Maunakea, with the MSE Project Office located and supported within the CFHT organization, with its 40-year history of scientific outreach and leadership in the local and astronomical communities. MSE deeply respects the cultural importance and storied past of Maunakea and is cognizant that the decisions made today are intertwined with the future of Maunakea and its cherished summit. Engineering development is supported by a culturally and geographically diverse design team that is centrally coordinated and managed by the MSE Project Office in Hawaii, USA.

MSE completed a Conceptual Design Phase (CoDP) in 2018, as described in submissions to previous SPIE conferences [1], [2], [3] and a comprehensive MSE Project Book [4].

MSE is an altitude-azimuth prime focus telescope with corresponding structures to support the telescope optics and hardware. The overall layout of the baseline design of the observatory is shown in Figure 1.

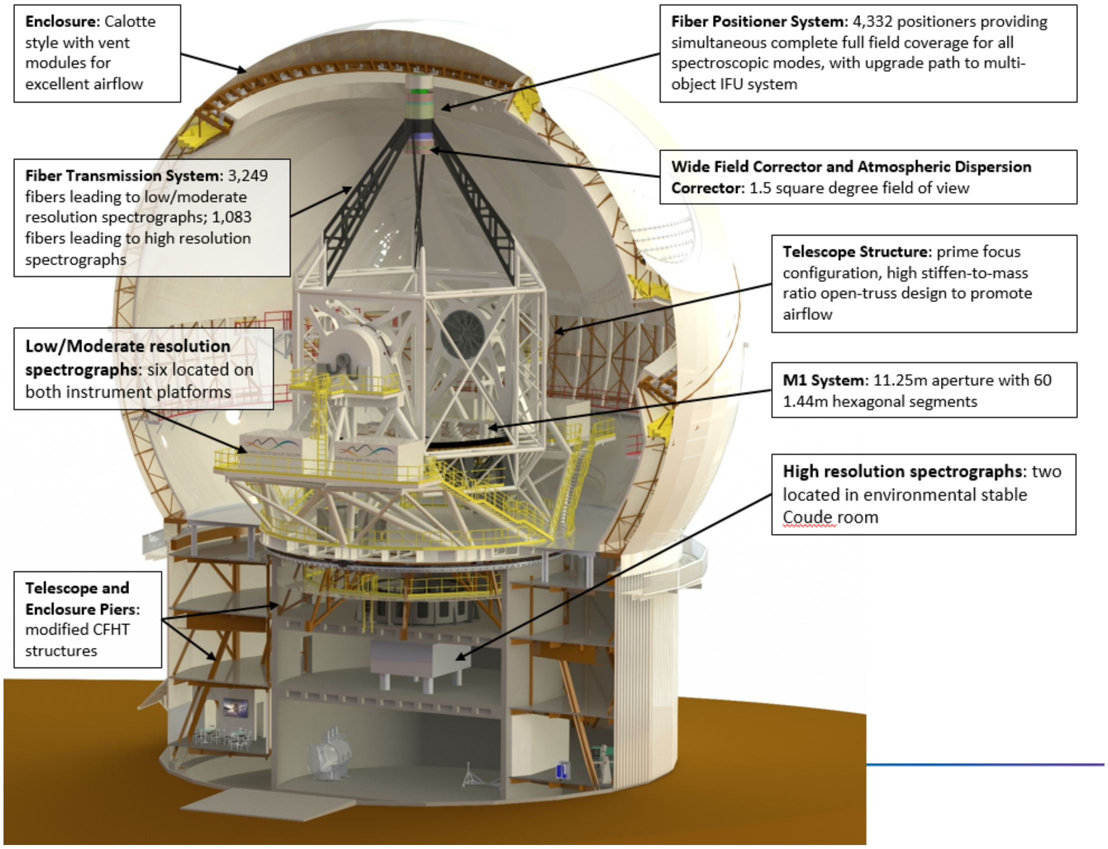


Figure 1. Overall layout after Conceptual Design Phase.

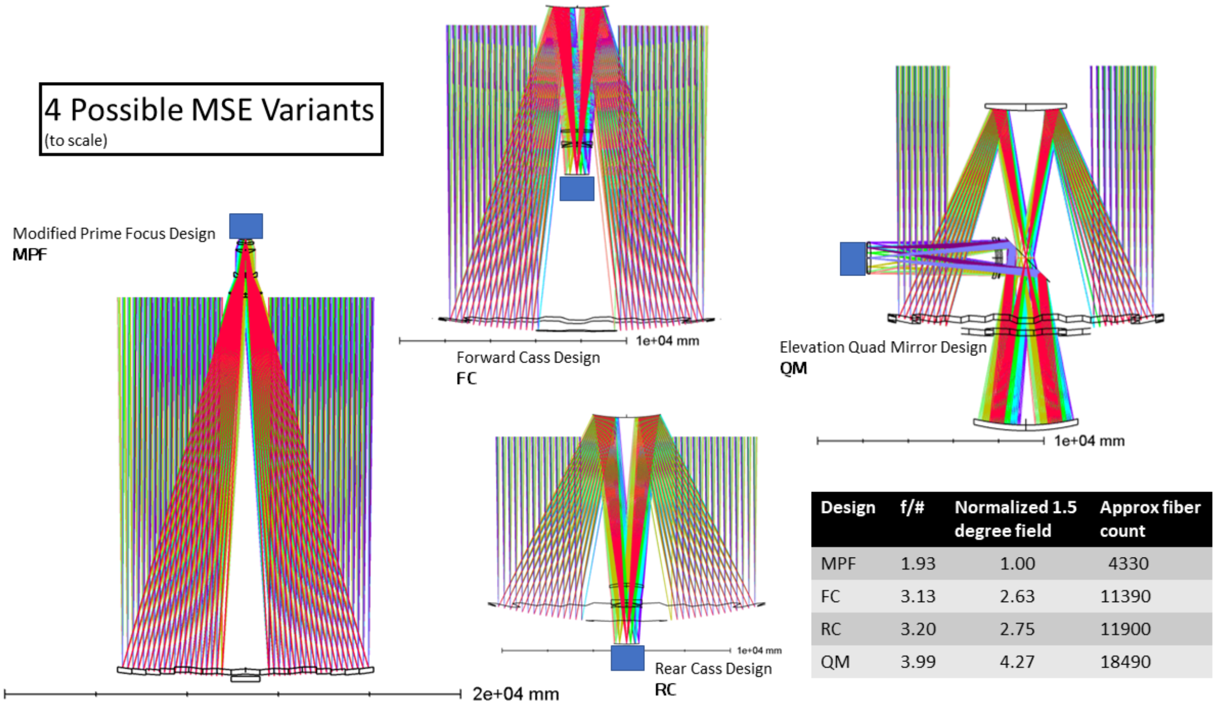
After CoDR, MSE began preparations for the coming future phases of development, including reviewing science goals in consultation with the MSE Science Team (> 400 members) and exploring the impact on resulting design requirements. In particular, instrument design concepts and trades have been undertaken with the goals of reducing risk, reacting to the updated science goals and ensuring requirements can be met with the 2018 Baseline design [5].

In addition, recent major developments in the astronomy community have an impact on MSE. This is discussed in more detail in a paper by Laychak/Szeto in this conference [6]. Specifically,

- Maunakea will come under a newly establish Mauna Kea Stewardship and Oversight Authority (MKSOA) as a result of the State of Hawai'i's House Bill 2024 / Act 255 (2022) and
- Several of MSE's partner countries have recently completed national strategic reviews, including completion of the USA's Astro 2020 Decadal Survey, Canada's Astronomy Long Range Plan 2021 and France's Prospective Astronomie-Astrophysique 2020-2025.

The funding timelines that are recommended in the Astro 2020 Survey in particular provide an interesting opportunity to ensure the MSE Observatory will have the best possible science impact, aligned with the science interests of all project partners. This aligns well with the timelines established in the MKSOA.

Specifically, MSE is exploring alternative telescope designs and methods of reducing risk by building a prototype of MSE at CFHT. A system-level trade study to understand the viability, technical and programmatic, of three alternate telescope concepts: two with a two-mirror telescope concept and one with a quad-mirror telescope concept [7] (see Figure 2). If proven, the expanded capabilities is will enable thousands of additional fibers and substantially increase MSE's degree of multiplexing and its survey speed. An MSE Pathfinder is being proposed and is in the early stages of development as an additional instrument at CFHT [8].



Design	f/#	Normalized 1.5 degree field	Approx fiber count
MPF	1.93	1.00	4330
FC	3.13	2.63	11390
RC	3.20	2.75	11900
QM	3.99	4.27	18490

Figure 2. Alternative design concepts.

This paper highlights the current state of development of MSE's Instrument Suite, including a discussion of the trades, design decisions and outstanding risks for the entire instrument suite with a focus on recent developments for the spectrographs and calibration system.

2. ARCHITECTURAL OVERVIEW

As shown in Figure 1, the altitude-azimuth telescope supports the primary mirror (M1) and Wide Field Corrector/Atmosphric Dispersion Corrector (WFC/ADC) (at the prime focus) points through 0° to 60° Zenith motion in altitude via an elevation structure. An azimuth structure rotates over ±270° and supports the elevation structure as well as instrument platforms on both sides of the structure.

M1 is a 60-segment primary mirror with an 11.25-m entrance pupil (10-m effective diameter) and a five-element Wide Field Corrector/Atmospheric Dispersion Corrector (WFC/ADC). M1 has 18.81 m focal length and radius of curvature is 37.698 m. This optical configuration delivers f/1.9 at a convex focal surface (Figure 3) with a radius of curvature of 11.33 m and a 1.52 degrees^2 field of view (584 mm diameter).

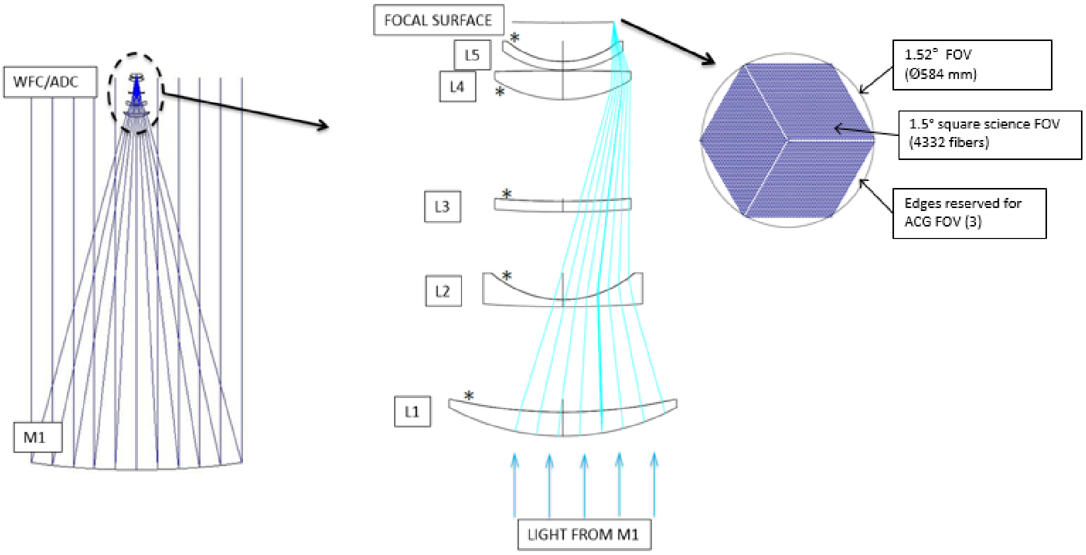


Figure 3. M1 and WFC/ADC (left, middle) and field of view at prime focus (right).

The WFC/ADC is located at the top end of the telescope, supported by a Prime Focus Hexapod (PFHS) that provides positional correction for focus, decenter and tip/tilt, to compensate for dimensional changes of the telescope structure due to environmental and gravity orientation effects. By making these moves, PFHS maintains the alignment of the WFC barrel to M1, ensures the fibers and the guide cameras (also mounted on the top end) are positioned at the focal surface and provides a small offset as part of the ADC control action to allow for atmospheric dispersion correction.

For survey efficiency, the science field must be suitable for tiling so MSE has chosen to define the science field of view as a hexagon, taking up 1.5 degrees^2 (Figure 3). The hexagon is packed with 4,332 fibers to collect light from targets and transmit them to the spectrographs. The remaining edges of the field of view are reserved for three off-axis guide cameras (not shown). Science targets in the field of view rotate as the telescope follows the sky, so the instrumentation and the guide cameras also ride on a large-bearing instrument rotator (InRo) mechanism. Details of the top end assembly and prime focus mechanisms and guide cameras were previously reported in [9].

MSE's instrumentation suite includes all hardware needed to collect the light at the prime focus, transmit it through the observatory to spectrographs throughout the observatory and calibrate it so that raw data from millions of targets per year can be collected and distributed.

3. INSTRUMENTATION

MSE's instrumentation (Figure 4) includes several subsystems, each designed by a partner institution.

As mentioned previously, a hexagonal array of fibers is packed into the focal surface to accept the light from the M1-WFC/ADC optical system. Each fiber is simultaneously positioned to maximize the amount of light entering them based on individual sky targets. This positioning is performed by piezo actuators in the Fiber Positioner System (PosS). The Fiber Transmission System (FTS) then transmits the light from the focal surface at the top end of the telescope, through the observatory to banks of spectrographs several tens of meters away. Two sets of spectrographs are planned, the Low-Moderate Resolution (LMR) and High Resolution (HR) Spectrographs.

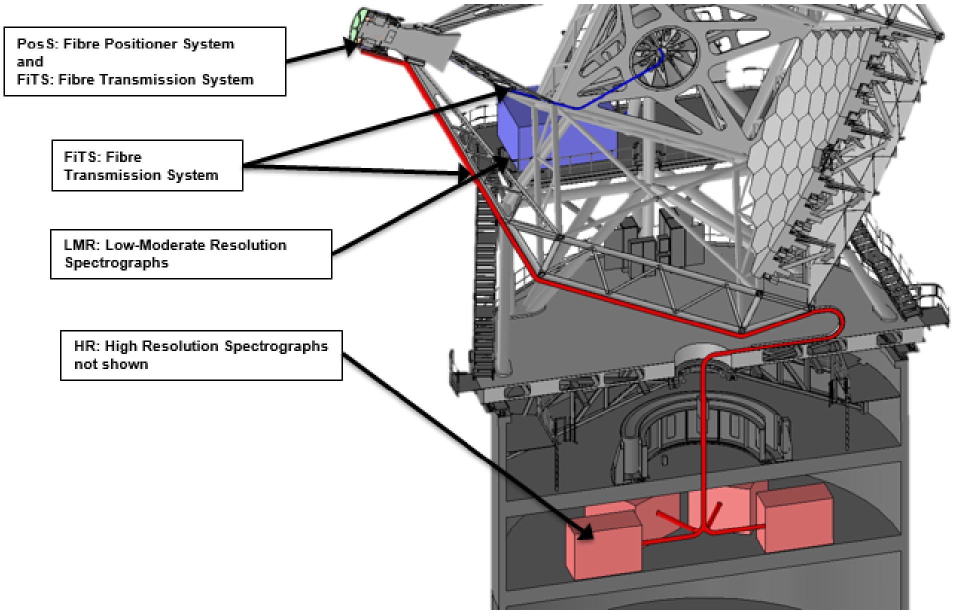


Figure 4: MSE instrumentation.

3.1 Positioner System (PosS)

The Fiber Positioner System (PosS) (concept named the Sphinx system by Australian Astronomical Observatory, AAO MacQuarie) is an array of identical actuators, which carries and positions each fiber to a unique lateral position on the focal surface. Sphinx is based on the successful FMOS/Echidna positioning system and incorporates a piezo-actuated tilting spine to position the fibers (Figure 5). This was previously reported in [2], [10] and has not changed substantially since a down-select of the technology in 2018. A summary is given here for reference.

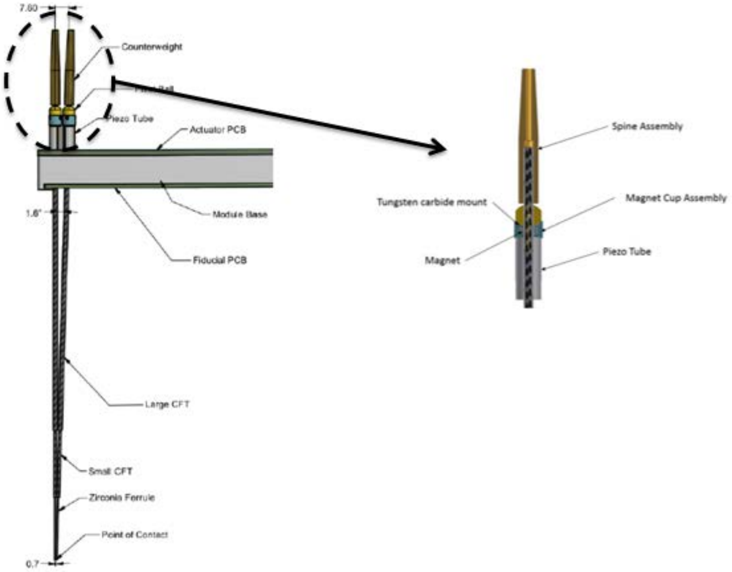


Figure 5: PosS tilting spine assembly.

For a given image quality delivered to the focal surface, injection efficiency (the amount of light that enters a fiber vs. light lost) is dependent on the accuracy of the positioners (both laterally and in the focus direction) and tilt angles of the positioners (which affects defocus). Each Sphinx actuator is closely integrated with a fiber from the FTS system and is able to attain a position of 0.06 arcsec RMS on-sky within a patrol radius of 90 arcsec. When the spine is tilted to its full patrol range, the defocus of the fiber tip versus the fiber tip at vertical is 80 um (max). Since the amount of defocus will vary from positioner to positioner, PFHS will provide a correction to position the entire top end assembly to correspond to the median of all of the spine tilts. The pitch of the actuators is 7.7 mm, with each actuator capable of moving the tip of each spine within a field patrol radius of 1.24 times the pitch (9.63 mm). The patrol areas overlap, allowing 1,083 HR and 3,249 LMR fibers to maintain full field coverage, with 97% of field positions accessible by 3 or more LMR fibers and 58% of field positions accessible by 2 or more HR fibers. A metrology system images the full array of positioner fibers and iteratively works in closed loop with the positioner system to achieve its accuracy during configuration.

This technology has many advantages. One of the critical factors was the flexibility and multiplexing that is enabled by having simultaneously HR and LMR full field coverage. Fiber to fiber collisions are low risk as any contact will not cause damage to the fibers or actuators. Finally, the choice of tilting spine actuators is thought to induce minimal stress as fibers are moved to position, which minimize transmission losses and throughput variations due to bends in the fibers. Stress can be a source of changes in Focal Ratio Degradation (FRD) and undesirable near-field and far-field effects, affecting wavelength resolution. This will be tested in future work.

The Sphinx design is an evolution of the piezo-actuated technology, first designed and implemented in FMOS-Echidna (Subaru), and later refined and simplified through design studies and prototypes for various other systems. Sphinx represents a mature and low risk solution to the MSE's positioner requirements.

3.2 Fiber Transmission System (FTS)

The Fiber Transmission System (FTS) (concept provided by Herzberg Astronomy and Astrophysics, HAA in Canada) includes more than 4,332 fibers that collect the light at the focal surface and deliver it to the spectrographs. This was previously reported in [2], [11] and has not changed substantially since a down-select of the technology in 2018 but a summary is given here for reference.

Along with providing the fiber bundles, FTS subsystem also includes a fiber management system at the top end to accommodate field rotation during observations (Figure 6). FTS also routes and protects the fibers through all motions of the telescope in all environmental conditions, as shown in Figure 4.

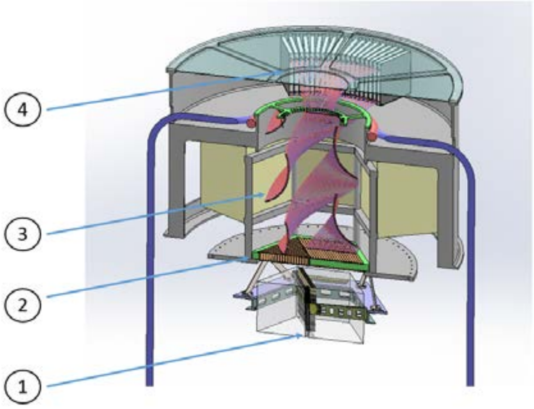


Figure 6. FTS. 1) PosS (simplified), 2) fiber combiner, 3) helical tubes, 4) loop boxes

Fiber bundles terminate at slit input units that provide the interface from the fibers to the spectrograph. The interface to the spectrographs is required to have a spherical shape or "smile" due to the off-axis collimators in both spectrograph designs. The shape of the slit compensates for the optical distortion such that spectra are "flat" (or straight line) when delivered to the spectrograph detectors. It is expected that these will look something like the slit input unit from Hermes (Figure 7, left) but with the design features, such as V-grooves and strain-relief proposed by HAA (Figure 7, right).

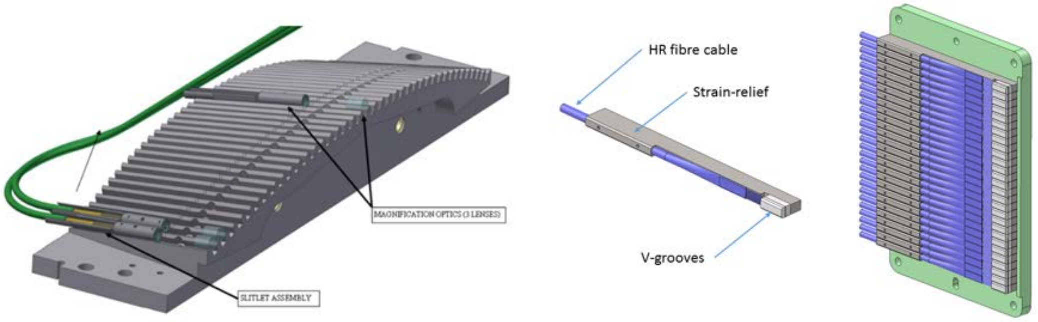


Figure 7. Left: Curved slit input unit from AAT-HERMES (shows magnification optics that will not be included in MSE). Right: Straight slit input unit proposed by HAA.

The design of FTS is primarily driven by throughput (FRD and near- and far-field) requirements and the need to have stable and repeatable calibration over 24 hours over the full range of pointing motion of the telescope. This includes throughput due to transmission losses (mostly based on fiber length and use of continuous fibers), Fresnel (input and output) losses and focal ratio degradation (FRD). To provide the highest possible throughput, fibers are provided in a continuous link, using no connectors, all of the way from the focal surface to the spectrograph inputs.

High (0.26 – 0.28) numerical aperture fibers capable of accepting f/1.9 have been selected to avoid adding additional input optics at the fiber input and the resulting throughput losses. During CoDP, it was found that FRD in this type of fiber is relatively small. Future work includes testing based on the stability of FRD which will affect the calibration of the system.

Throughput is also affected by the length of the fibers, particularly at the blue end of the wavelength spectrum. The current baseline of having the HR spectrographs in the inner pier (< 50 m fiber length) and the LMR spectrographs on instrument platforms (< 35 m fiber length) is the subject of a trade study for MSE as it has been determined that the HR spectrograph has the potential to benefit much more from the shorter fiber length in the blue wavelengths than the

The integration of a long continuous fiber length, creates integration, maintenance and presents repair risks. Fibers cannot break and must be robust and field repairable. Current thinking is to employ fusion bonding for this purpose. The FTS team determined that it is possible to achieve good performance and consistency using fusion bonds in controlled conditions. Whether this can be adapted to an in situ repair process is a subject for future work.

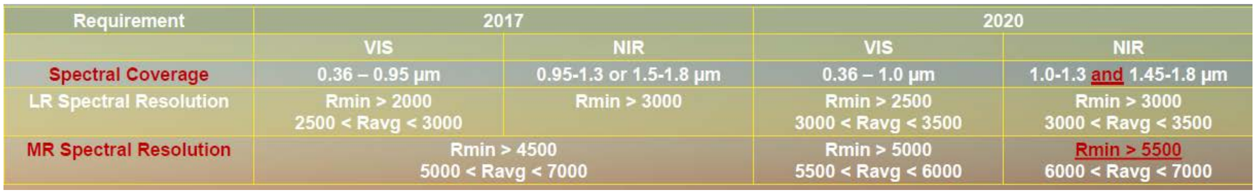
3.3 Low Moderate Resolution Spectrograph System (LMR)

In the 2018 baseline, the Low Moderate Resolution Spectrograph [12] (concept provided by Centre de Recherche Astrophysique de Lyon (CRAL), France) included six identical spectrographs, with three arms in the visible (VIS) and one in the near-infrared (NIR) arm each, and an ability to switch between the low resolution (R=3,000) and moderate resolution (R=6,000) modes. The low resolution mode covered optical plus J-band while the moderate resolution mode covered optical plus H-band (at R=3,000 only) (see Table 1). This configuration included strong aspherical optics and tight space constraints. As well, the combination of H-band into the optical spectrograph necessitated cooling all arms to approximately 200K, complicating the design and integration process for the spectrographs and MSE overall.

After review, it was decided to explore alternative low-risk designs and review scientific priorities. Through consultation with the science team, it was found possible to modify the architectural and design requirements. First it was found that the number of targets per pointing in the NIR could be reduced by a factor of 3 (based on target densities in the field) to approximately 1,000 targets per pointing. In the VIS, there is still a strong desire to observe as many targets as possible in each pointing (i.e. 3,000 or more). This led to the conclusion that combining the VIS and NIR arms into the same spectrograph (and the unnecessary cryo-cooling of a large and complex spectrograph) could be reconsidered. Second, it was recognized that sensitivity needed in H-band could lowered by a full magnitude in low spectral resolution and the requirement for that was reduced. Third, it was found that spectral coverage at low resolution need not be contiguous in the visible plus NIR, leaving some options for building different spectrographs for each wavelength range. It was also found that the resolution requirement for NIR is required to be higher than previously anticipated.

This change in requirements prompted a design study by Labortoire d'Astrophysique de Marseilles (LAM), Centre de Recherche Astrophysique de Lyon CRAL and other organizations in France to explore alternative concepts. The concept was presented in 2021 and includes splitting the overall concept from 2018 into two different flavours of spectrograph: VIS and NIR, with the >3,000 dedicated LMR fibers from the field of view divided between the two types of spectrographs (2166 for the VIS and 1083 for the NIR). This implies a decrease in multiplexing in VIS from > 3,000 to > 2,000 and note that observing any given target in VIS and NIR is no longer possible. The resolution and wavelength coverage changes from 2017 to this design are shown in Table 1. This was reported previously at SPIE in 2020 [13].

Table 1. Comparison of 2017 (Baseline) and 2020 (Current) requirements.



Requirement	2017		2020	
	VIS	NIR	VIS	NIR
Spectral Coverage	0.36 – 0.95 µm	0.95-1.3 or 1.5-1.8 µm	0.36 – 1.0 µm	1.0-1.3 and 1.45-1.8 µm
LR Spectral Resolution	Rmin > 2000 2500 < Ravg < 3000	Rmin > 3000	Rmin > 2500 3000 < Ravg < 3500	Rmin > 3000 3000 < Ravg < 3500
MR Spectral Resolution	Rmin > 4500 5000 < Ravg < 7000		Rmin > 5000 5500 < Ravg < 6000	Rmin > 5500 6000 < Ravg < 7000

The NIR design was developed first, as it was more challenging. At the same time, it was decided to abandon switching between LR and MR modes and design the design the spectrograph to collect photons at MR and then recover LR data via binning spectra after the fact.

The LMR design team developed a NIR design [14] (see Figure 8), inspired by ELT MOONS "WonderCamera". There are two NIR spectrographs that accept 1/3 of the >3000 LMR fibers, via the curved slit discussed previously. The catadioptric layout includes two arms, H- and J-, an f/0.95 camera, beam sizes approx. 265 mm and a Mangin mirror. The field lens is embedded in L2 as can be seen in the figure. The detectors are 4k x 4K – 15 um Detectors (H4RG). The two NIR units will be in a cryo-cooled environment at 200-220K to reduce thermal background.

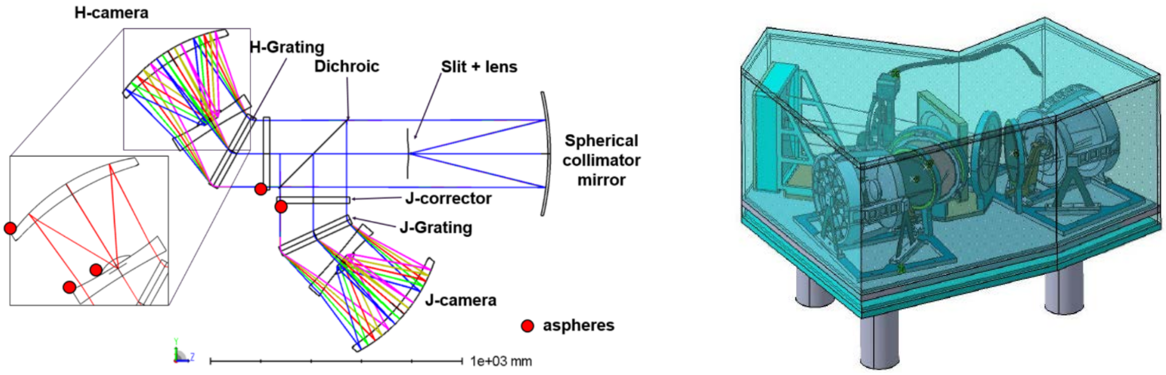


Figure 8. LMR NIR optical layout (left). Optomechanical layout (right)

In addition, an optical design for the VIS spectrographs has been proposed by Winlight [15], in collaboration from LAM, France. The design includes four VIS spectrographs that accept > 2,000 dedicated fibers also with a curved slit input. Winlight also adopted a design similar to MOONS. A 4-arm vs. 5-arm architecture with different cameras were compared and it was found that 5-arms is not physically realistic. The chosen design (Figure 9) is a 4-arms with a VPHG and max beam diameter 270 mm. The camera is f/0.9 camera with L1 acting as a cryostat window. This design also incorporates 4k x 4K – 15 um Detectors (H4RG).

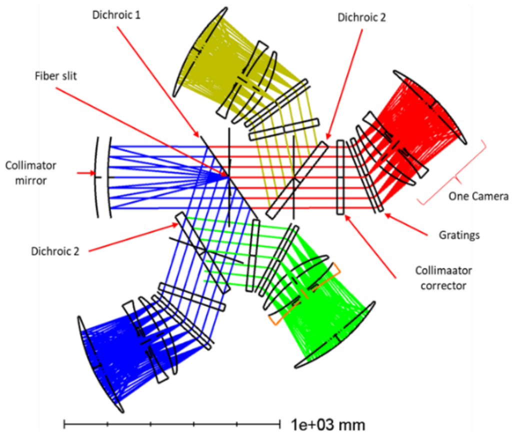


Figure 9. LMR VIS optical layout.

Both designs significantly reduce risk in optical fabrication and are much simpler in that there are fewer components and mechanisms, fewer aspheres and fewer cryo-cooled components. The design has lower throughput compared to CoDR 2018, approx. 40% vs. 50% and the impact of this on sensitivity is still being assessed. The designs meet the majority of other requirements except cross-talk between the fibers is high and will need to be addressed. Again, the reduced multiplexing in VIS needs to be reviewed with respect to survey efficiency overall.

These designs concept stage at this time and will be developed further, along with other studies ongoing at MSE.

3.4 High Resolution Spectrograph System (HR)

In the 2018 baseline, the High Resolution Spectrograph [16] (concept provided by designed by Nanjing Institute of Astronomical Optics & Technology, NAIOT in China) included two identical spectrographs with three optical arms each, blue (R=40,000), green (R=40,000) and red (R=20,000). Each arm covered a small bandpass that could be changed with a changed grating. This configuration included a grating with ultra-high line density (5,800 lines/mm) on a 700 mm x 400 mm substrate, as well as a challenging f/2 off-axis collimator. This design would require the project to take on significant risk and cost, particularly in the ultra-high line density grating, strong aspheres and some significant space constraints for opto-mechanical packaging.

In an effort to ease constraints, it was determined through discussions with the science team that the resolution may be relaxed in the green arm (now R=30,000), the red end of the accessible wavelength range may be reduced to 700 nm, multiplexing may be significantly lowered from 1,083 by a factor of 2 or 3 and the sensitivity in the green and blue may be relaxed to mag=19.5. The changes over time are summarized in Table 2.

Table 2. Change of HR requirements in the past years.

Year	Multiplexing (fibers)	Spectral Arms	Resolution	Window Bandpass	Instrument Sensitivity (EXPT = 1hr)
2017	1084 fibers (Φ0.7”-0.8”)	B: 360 nm - 450 nm G: 450 nm - 610 nm R: 610 nm - 900 nm	R_B=40K R_G=40K R_R=20K	B: λ/30 G: λ/30 R: λ/15	mag = 20 SNR=5@<400nm SNR=10@>400nm
2018		B: 360 nm - 430 nm G: 430 nm - 510 nm R: 510 nm - 900 nm			
2019	*500 - 1084 fibers (Φ0.75”-0.8”)*	B: 360 nm - 500 nm G: 500 nm - 600 nm R: 600 nm - 700 nm	R_B=40K R_G=30K R_R=20K	B: λ/30 G: λ/22 R: λ/15	*mag = 19 - 19.5 SNR=5@<400nm SNR=10@>400nm*
2020		*B: 360 nm - 420 nm G: 420 nm - 580 nm R: 580 nm - 900 nm*	R_B=30K-40K R_G=20K-30K R_R=30K-40K	*λ/30 @ R30K*	

After some design iterations and explorations, in 2021, an optical design by NIAOT (Nanjing Institute of Astronomical Optics & Technology) has been proposed. The details for this design are presented in this conference [17]. The design features a bank of 11 spectrographs, each with ~100 fibers per spectrograph. Each spectrograph has 3 channels (B, G, R) with the wavelength splitting in a “pre-optics” unit as shown in Figure 10.

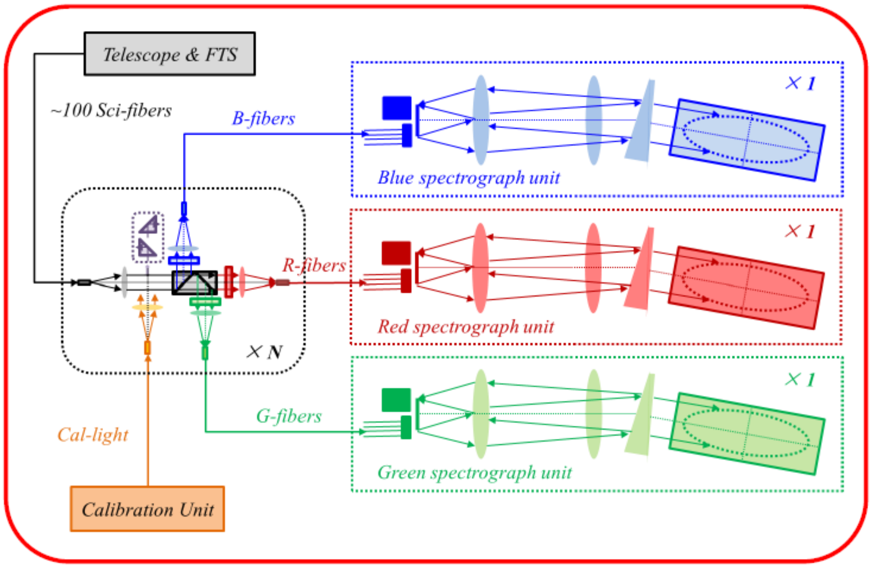
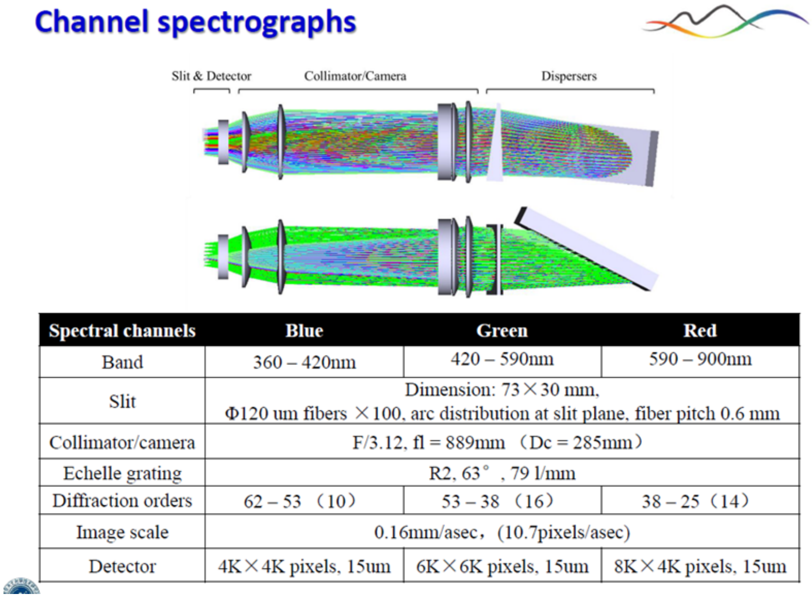


Figure 10. HR 2021 proposed architecture.

Each preoptics unit includes an 80 um input fiber from FTS and a 120 um output fiber to each channel. Between the input and output fibers, light is split into the blue, green and red channels using dichroics and window bandpasses (wavelength windows) are controlled using filters. These filters are selectable on a filter changing mechanism. As well, the preoptics unit incorporates injection of a calibration light for wavelength calibration and back-illumination of the fibers.

Each spectrograph channel incorporates a double-pass design with an f/3.12 camera (diameter 285 mm), Echelle grating and three detector sizes, depending on the arm. For the red arm, the detector will likely have to be a mosaic of two 4k x 4k detectors.



Channel spectrographs

Spectral channels	Blue	Green	Red
Band	360 – 420nm	420 – 590nm	590 – 900nm
Slit	Dimension: 73×30 mm, Φ120 um fibers ×100, arc distribution at slit plane, fiber pitch 0.6 mm		
Collimator/camera	F/3.12, fl = 889mm （Dc = 285mm）		
Echelle grating	R2, 63° , 79 l/mm		
Diffraction orders	62 – 53 （10）	53 – 38 （16）	38 – 25（14）
Image scale	0.16mm/asec，(10.7pixels/asec)		
Detector	4K×4K pixels, 15um	6K×6K pixels, 15um	8K×4K pixels, 15um

Figure 11. HR 2021 spectrograph optical design.

The HR concept reduces some of the previous risks in fabrication and procurement, especially by using conventional Echelle gratings instead of high density gratings. It will be necessary to investigate the cost implications of the many optical elements in the system and large number of spectrographs as well as the feasibility within the space available in the MSE observatory. As well, there are some areas to explore in the optical design, including ghosts in the double-pass arrangement, straylight due to the filters and crosstalk between adjacent fibers on the detector.

The wavelength splitting concept is presented at a time when MSE has an opportunity to explore its design space, as mentioned in the Introduction. This is being contemplated as a path forward also for the LMR Spectrographs and both HR and LMR by and investigation into some technology options for reducing pupil size, which MSE plans to pursue.

3.5 Science Calibration System (SCal)

The Science Calibration System (SCal) is comprised of light sources, fiber bundles, projectors, and optical systems required to focus, collimate, or otherwise modify the calibration light to maximize system efficiency. This system also includes means of detecting spurious contamination, such as low-earth-orbit satellites crossing an individual fiber.

A concept for the SCal has been developed by Texas A&M University (TAMU) and is presented in this conference [18].

- Light sources – Broadband and line sources projected onto the primary mirror or reflected by a dome screen. May include internal optics for collimation, focal ratio matching, filtering, etc. Light sources on the dome (for daytime) and spider-mounted lamps.
- Relay Optics – Optics for coupling light sources into fiber optics, fiber optics to transport light from the light sources to the projection optics located on the telescope, or directly into the spectrographs.
- Projection System – Optics, diffusers, or other optomechanical devices used to project calibration light into the telescope.
- Spurious Contamination Detection – A system that monitors the MSE field of view for transient signal sources (satellites, airplanes, etc.).
- Supplemental Calibration – Any additional calibration sources as deemed necessary (e.g. internal spectrograph light source).

Overall the concept is sound, however the MSE Science Calibration Plan is needed to fully complete the concept. The calibration strategy will be used to develop a more complete set of requirements. This calibration strategy will be developed by the stakeholders in the calibration plan for MSE including, but not limited to, the Science Team, calibration scientists, and the data reduction team with input from the SCal project team at TAMU, the spectrograph design teams, and the telescope optical and mechanical design teams.

Because of the overlapping domains incorporated under the umbrella of the science calibration, the discussions held to come up with the calibration strategy should also be used to make initial guesses at the interfaces between various subprojects within MSE and the SCal subproject so that the scope of the SCal subproject is better defined.

4. FUTURE WORK

As discussed, each of the instrumentation subsystems will be exploring various aspects of their design. The MSE Project Office will be responsible for leading various studies and explorations as well.

First and foremost will be the alternative telescope design study, with a close look at the quad-mirror concept. A shift to that design will mean major changes to all subsystems. For example, there is potential for a 4-fold increase in multiplexing which will mean the PosS and FTS will be asked to consider the feasibility of those changes. The focal ratio entering the telescope will change, probably easing the design of the spectrographs and causing redesign efforts. The increase in the number of spectrographs will also have to be accommodated both in cost estimates and in space available in the observatory. Industrialization and economies of scale will have a positive impact but a quantitative assessment is needed.

In the current design of LMR, the multiplexing in the VIS is lower than ever and the combination of the alternative telescope structure and potential for regaining multiplexing through wavelength splitting is attractive. This has opened up a related line of exploration for reducing the size of the individual spectrographs and creating large numbers of small spectrographs via some technology explorations. This will be explored going forward.

As well, some known studies regardless of telescope design are needed. FTS has a continuous length of fiber through the system and careful thought must be given to how to install that through the observatory and whether fusion bonding can be performed reliably in situ and over the > 4,000 fiber units.

Spectrograph locations will need to be considered with a goal of improving throughput which declines quickly over long fiber lengths. The concept of "banks" of small spectrographs that incorporate wavelength splitting is exciting in this context because the "blue" channels may have the potential to be closer to the focal surface while "redder" channels are further away.

The current designs for both spectrographs are struggling to meet crosstalk requirements and this is a serious concern that will need to be both analyzed and addressed in future work.

Finally, as mentions, the Calibration Plan overall will be fleshed out in future work, with input from the SCal, data reduction and spectrograph teams.

5. CONCLUSION

Since the baseline was developed in 2018, MSE has been working on several fronts. While consulting with MSE's science team to understand and verify the operational goals of MSE, design teams in China, France and Texas have progressed on investigating several alternative design architectures.

In addition, MSE has an opportunity to ensure this massively multiplexed observatory will be a powerhouse of scientific productivity. Recent developments in the management of Maunakea and national strategic objectives are allowing MSE the time and opportunity to ensure MSE's plans are aligned with Hawai'i cultural and environmental concerns, explore ways to expand MSE's science capabilities and improve performance and reduce risk overall. By expanding the architectures and instrument designs as currently proposed in the context of the science needs in the next decades, MSE will be well positioned to produce excellent survey science.

To this end, MSE has chosen to investigate some alternate facility architectures to facilitate some major improvements that may be gained in performance overall when compared with the baseline design from 2018 and make the observatory more scientifically competitive. During this process, spectrograph designs and their fiber inputs will be explored and will surely lead to a significantly more productive, reliable and easy to build observatory.

ACKNOWLEDGEMENTS

The mission of the Maunakea Spectroscopic Explorer Project is to realize a dedicated facility that enables a diverse suite of large-scale spectroscopic surveys of millions of astrophysical objects at a range of wavelengths, spectral resolutions, redshifts, and spatial scales.

The MSE Project is hosted by the Canada-France- Hawaii Telescope Corporation, and supported by contributing organizations in Canada, France, Hawaii, Australia, China, India, South Korea, Texas, the UK, and the US. The MSE collaboration recognizes the cultural importance of the Maunakea summit to a broad cross-section of the Native Hawaiian community, and is committed to equity, diversity and inclusion.

Statements of MSE's mission, cultural respect, and equity, diversity and inclusion are available on https://mse.cfht.hawaii.edu.

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