Planning scientific operations for the Maunakea Spectroscopic Explorer

Jennifer L. Marshall*[a,b], Jennifer Sobeck[a], Andreea O. Petric[a,c], Nicolas Flagey[c]

[a]The Maunakea Spectroscopic Explorer Project Office, 65-1238 Mamalahoa Hwy Kamuela, HI 96743 USA
[b]Mitchell Institute for Fundamental Physics and Astronomy and Department of Physics and Astronomy, Texas A&M University, College Station, TX 77843-4242 USA
[c]Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218 USA

*marshall@mse.cfht.hawaii.edu; mse.cfht.hawaii.edu

ABSTRACT

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. MSE's conceptual design includes an 11.25 m aperture telescope which feeds 4,332 fibers over a wide 1.52 square degree field of view. Its spectrographs will have the capabilities to observe at a range of spectral resolutions, from R~3,000 to R~40,000, with all spectral resolutions available at all times and across the entire field. As a dedicated survey facility, MSE must be able to efficiently execute a wide variety of scientific programs at the same time. Here we describe continued planning to execute MSE's Design Reference Survey, an exercise to plan for and simulate a sample of potential first-generation science programs that exercise the design parameters of the spectroscopic facility.

Keywords: Massively multiplexed spectroscopic surveys, 10m-class telescopes, design reference mission, survey planning, observation scheduling

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. At a minimum, 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~40,000, with all spectral resolutions available at all times across the entire field. Alternate facility architectures are under evaluation with insight from participants' national strategic planning priorities along with technical feasibility. Engineering development is supported by a culturally and geographically diverse design team that is centrally coordinated and managed by the Project Office (PO). The Maunakea Spectroscopic Explorer Project deeply respects its cultural importance and storied past. We are cognizant that the decisions we make today are intertwined with the future of Maunakea and its cherished summit.

The MSE project completed a Conceptual Design Review in 2018 (MSE Project 2018); the Conceptual Design of the facility is shown in Figure 1. The project is now preparing to advance to the Preliminary Design Phase of the project, engaging with both the instrument design teams as well as with the 400+ scientists that comprise MSE's "Science Team" to ensure the next design phase is successful. One of the major activities envisioned to ensure the success of MSE's science program is the Design Reference Survey (DRS); an update on progress on the DRS and other aspects of the scientific planning process for MSE are described in this document.

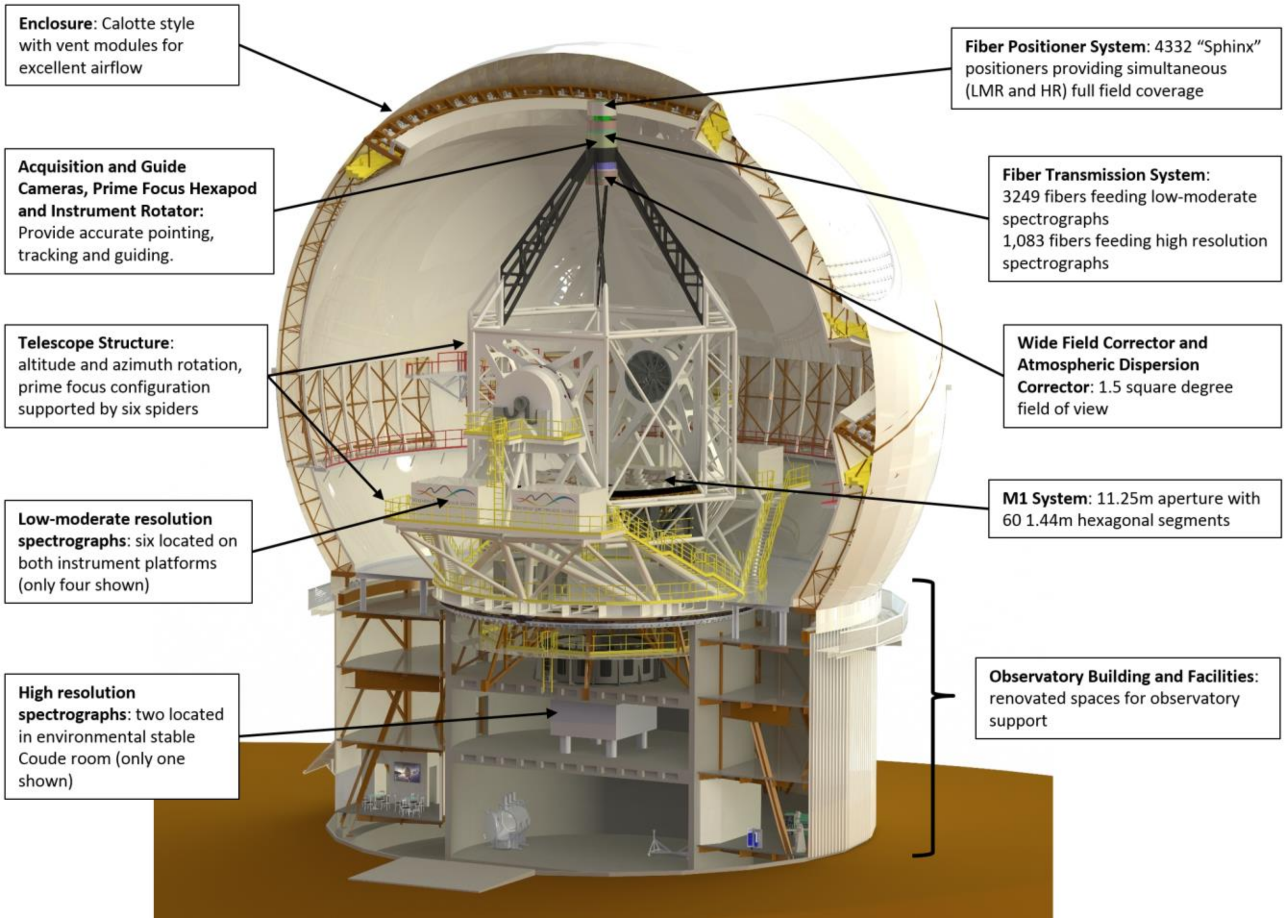

Figure 1: MSE Observatory architecture as described by the 2018 Conceptual Design (MSE Project 2018).

2. DRS PROGRESS

In recent years the MSE Science Team worked to publish an updated Detailed Science Case (MSE Project 2019), which includes several new science cases as compared to the original Detailed Science Case (McConnachie et al. 2016). In response to these new and expanded science requirements for the MSE project, over the past two years significant advancement of MSE's scientific planning has occurred in the form of further fleshing out the science case as well as revisiting the instrument designs to ensure that they address the new science needs that have been identified in the DSC Science planning has also evolved in light of recently published decadal reviews from MSE partner countries around the world.

In 2018 MSE carried out a successful Conceptual Design Review (CoDR). In their report, the CoDR panel had one main recommendation regarding the science planning for the project: the execution of a "Design Reference Mission" (now referred to as the Design Reference Survey, or DRS) to best ensure scientific and mission design success as the project advances through the Preliminary and subsequent Design phases. The CoDR panel describe the DRS as *"the 'narrative' document that distills the science requirements and science case into an executable survey plan, taking into account both external constraints (weather, lunar cycle, sky availability as a function of time of the year), as well as the observatory, instrument, and calibration constraints."* Other suggested goals are to define requirements on preparatory photometric and astrometric datasets, inform observatory scheduling software requirements, and formalize sky coverage and wavelength coverage requirements. According to the panel, the DRS should be an evolving document and one that forms a strategic plan for observations, thereby summarizing and informing the three key Level 1 requirement documents, the Observatory Architecture Document, Observatory Requirements Document, and Operations Concept Document (OAD, ORD, OCD; available at mse.cfht.hawaii.edu).

2.1 Advancing the DRS

Following on these recommendations, the MSE science team has continued to make progress towards executing the DRS. Having selected four disparate, compelling science cases (Marshall et al. 2020); we are now beginning to build the infrastructure necessary to plan for the appropriate observations.

MSE has been upgrading the software tools necessary for the execution of the DRS, including the Exposure Time Calculator (ETC) and the Fiber to Target Allocator (FTA) and were originally developed for the MSE Conceptual Design. We are now scaling up these software tools so that they can be used for comprehensive MSE survey planning and the development of the associated targeting strategy. Further details regarding these tools are given below.

In addition, we have incorporated a variety of existing observational catalogs, which consist of photometric, astrometric, and spectroscopic data sets. The ingestion of these target catalogs is critical to the generation of robust target lists and the target selection process, as well as essential to the execution of the DRS. Eventually we will include a wide variety of target catalogs from which targets for all MSE science cases may be selected and will incorporate mock data catalogs as well. These efforts lay the groundwork for a targeting database and prepare for the ingestion of future data sets such as those from the Rubin Observatory/LSST Project.

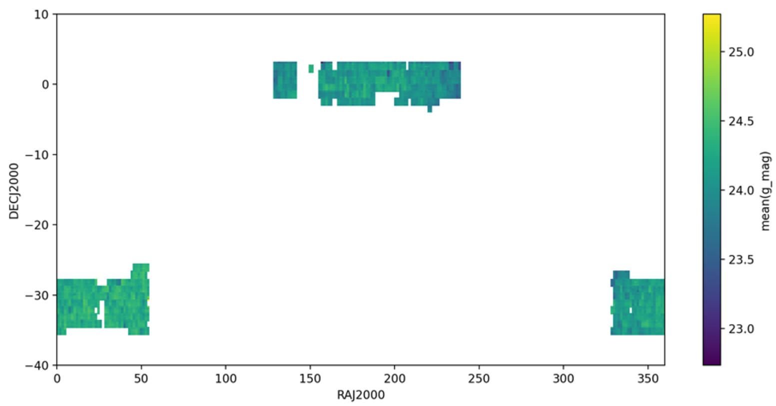

Figure 2: A heatmap visualization of the most recent Kilodegree Survey data release (KiDS DR4). The catalog was downloaded and reformatted extensively for MSE target selection purposes associated with the MSE cosmology science case.

2.2 Software development

Science planning for MSE will eventually rely on development of the Program Execution Software Architecture (PESA), and significant advancement has been made toward planning the PESA software over the past two years. Progress on the overall PESA design and execution is described in more detail by Surace et al. (2022) in these proceedings; progress on the aspects of PESA that are most tightly coupled to scientific planning for MSE are described below.

2.2.1 FTA

The execution of the DRS necessitated the development of various software tools including a Fiber to Target Allocation Simulator (hereafter referred to as the FTA). In brief, a nearest neighbor methodology is employed to assign instrument fibers to targets with a predetermined prioritization. The stable version of the FTA code is Python-based and open-source, made available through Github: https://github.com/mse-cfht/flagey/tree/main/mse_alloc. Additionally, a Web API exists for users (a java wrapper of the Python source code) and is accessed as follows: https://etc-dev.cfht.hawaii.edu/mse/alloc.html.

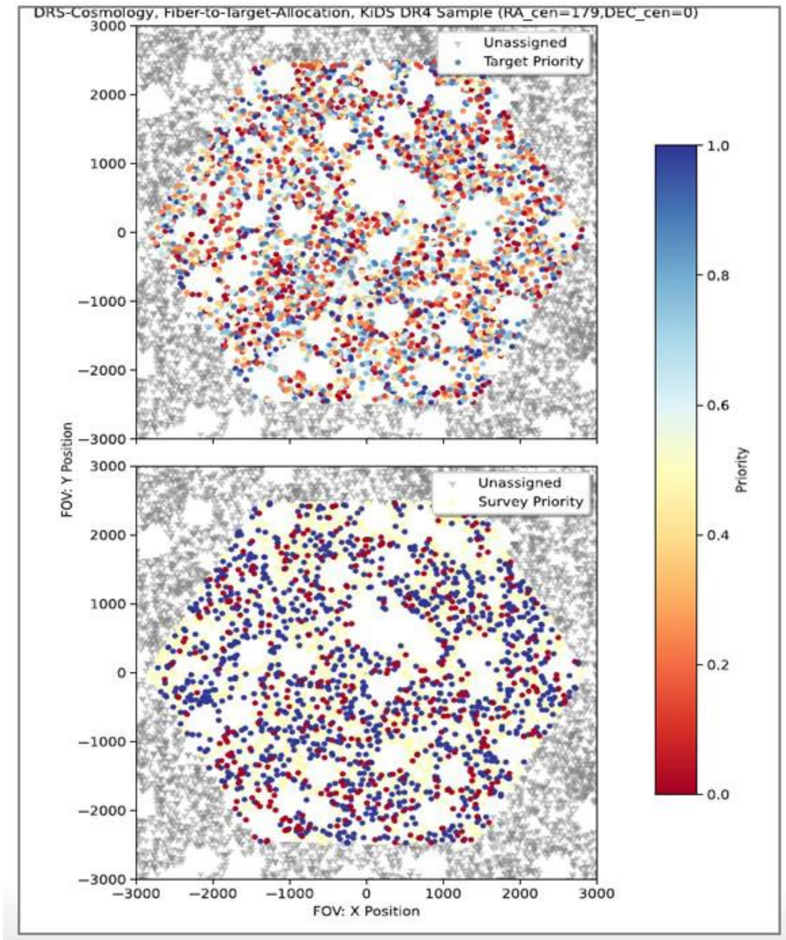

Figure 3: Visualization of the original FTA tool. The figure shows a potential allocation of fibers for MSE Cosmology Science Case targets drawn from the KiDS DR4 (modified) Catalog (for 3 specific target classes). In this visualization, target priorities are assigned randomly while survey priorities are purposefully assigned according to target type.

The overarching goal of the FTA code is to establish a set of score metrics for a particular field location (i.e., a location on the sky with a defined RA and DEC center and a total area of 1.5 square degrees). The code considers 3 score metrics: a field score, a fiber score, and a target priority score. The allocation of fibers to targets occurs through the minimization of the total score of a field, the *field score*, which is the sum of all scores from individual fibers. The *fiber score* metric is the distance between the fiber's rest position (no tilt) and the position of the target to which it is allocated, divided by the priority score of the target. Finally, the *target priority score* is derived from a combination of the MSE Science Working Group established priority as well as a global priority as set by the MSE Survey. Note that fiber reach limitations as well as other factors are considered.

For optimization of the allocation process, the FTA code relies on the assumption that, in most cases, the density of targets is either significantly larger than that of the fibers or significantly lower. Consequently, each fiber can simply be allocated to its nearest target (in the case of a target rich field) or each target can be allocated to its nearest fiber (in the case of a target poor field). The code achieves an allocation solution very quickly if there are no conflicts, which is assumed to occur most of the time, given the positioner system architecture for MSE. This major underlying assumption is being vetted by applying it to various fields of view for different science cases.

After the initial fiber allocation, the code checks for conflicts: either a fiber is allocated to two targets (only possible in the case of a target poor field) or a target is allocated to two fibers (only possible in the case of a target rich field). If conflicts do arise, the FTA code then randomly goes through all fibers (in the case of a target rich field) or all targets (in the case of a target poor field) and re-allocates them to their nearest target or fiber. The allocated target or fiber is then flagged as unreachable by other fibers or targets and a fiber-target pair is established. Once the code has gone through all fiber-target pairs, the total "energy" is computed as the sum of all normalized distances. The FTA code initiates a few random allocation sequences. Finally, it retains the lowest "energy" solution, and the allocation process is complete.

2.2.2 ETC

The Exposure Time Calculator (ETC) has been developed in concert with the PESA effort, so that it may be incorporated into both the front end science planning needs for MSE, but also may be incorporated into the larger PESA effort to be used to control and monitor MSE observations at the telescope in real time. For the ETC, two major development efforts have occurred over the past few years: an initial effort by the MSE Project Office over the 2017-2020 period and then, a current effort from a group spearheaded by S. Pak at Kyung Hee University (KHU; Ji et al. 2022). Both codes are Python-based and open source, made available through MSE Github site: https://github.com/mse-cfht/flagey/tree/main/mse_etc and https://github.com/mse-cfht/etc_khu_group, respectively. Also, a Web API exists for the original (i.e. that developed by N. Flagey for the MSE PO) ETC code and is accessed as follows: https://etc-dev.cfht.hawaii.edu/mse/index.html. The two codes share many commonalities, yet the text below will focus on the current ETC development effort of the KHU Group.

The ETC relies upon previously generated ETC software by the KHU Group (e.g., Le et al. 2015, the IGRINS ETC). The ETC code incorporates the most recent MSE instrument configurations (and allows for any future modifications to these instrument parameters via built-in flexibility). In general, the code takes into account the telluric background emission and absorption, the reflectivity and transmission of the telescope and instrument optics, and the dark current and read noise of the detector arrays. For the telluric absorption spectra, data from the ESO SKYCALC are used, which are based on the Cerro Paranal Advanced Sky Model. The telluric emission line spectra are from Rousselot et al. (2000) and these data are convolved to the MSE instrument resolutions via a Gaussian 1D kernel data convolution. The throughput calculation considers numerous components of the MSE light path: Enclosure, Telescope Mount Structure, Primary Mirror Optics System, Wide Field Corrector, Atmospheric Dispersion Corrector, Prime Focus Hexapod, Positioner System, Fiber Transmission System, Spectrographs, and Detectors.

The KHU ETC code provides users with four calculation modes: signal-to-noise (SNR), exposure time, SNR as a function of magnitude, and SNR as a function of wavelength. For point source objects, ETC users provide target and background magnitudes as well as airmass and water vapor. The ETC generates plots for the SNR vs. wavelength and SNR vs. Magnitude calculation modes and the associated output associated can be written to file.

2.2.3 Future work

In the near term, software development will be pushed forward for both the FTA and the ETC. Alternate approaches to fiber allocation, such as simulated annealing and genetic algorithms, have been and will continue to be explored. These approaches have the potential to increase fiber-fill factors as well as highly optimize the fiber assignment process. Future versions of the FTA will consider additional impacts associated with focal plane sharing between the two instruments, calibration schemes and assigned calibration fibers, and other restrictions on targeting (such as bright nearby neighbors). The KHU Group will continue the development of the ETC via the incorporation of new functionality (e.g., calculations for extended source objects, user-specified spectral types, predetermine spectral and galaxy templates). In addition, a Web API will be created for the code and Sphinx-based documentation will be generated.

3. MSE SCIENCE PLANNING

In this section we highlight various efforts to advance MSE scientific planning and preparations over the past few years.

3.1 Science leadership

A key to planning science operations for MSE is active participation from the Science Working Group co-leads. MSE has enjoyed excellent scientific leadership via the co-leads throughout its past; that strength has continued as some of the co-leads have recently transitioned to other projects while new co-leads have stepped up to take their place. In this way MSE is able to keep the Science Team enthusiastic and engaged with planning for observations with MSE in the future, and continues to enjoy scientific input from a continually growing international group of 400+ scientists.

3.2 Talks

The MSE "Project Science Team" (i.e., currently the first three authors of this proceeding) continue to present talks about MSE to international audiences. This was in some ways simpler, and certainly less expensive, during the pandemic, when most talks were delivered over zoom. If anything, the number of presentations promoting MSE science increased over the past two years, increasing interest and membership in the project.

3.3 Synergies

In light of developments over the past few years, in particular the advancement of scientific planning for observing facilities that have capabilities quite complementary to MSE's, it has become clear that science planning for MSE should expand to more fully flesh out and document the synergies between MSE and these other facilities as they advance toward first light. This was quite evident at the recent "SKA-MSE" conference organized by MSE science team member Mamta Pommier and others (https://skamse2020.sciencesconf.org/).

The MSE Science Team is now embarking on an effort to produce a white paper outlining synergies between MSE and other facilities operating at other wavelengths, sensitivities, and observational modes, both on the ground and in space. The white paper will highlight scientific synergies and opportunities between MSE and other facilities in terms of wavelength coverage, sensitivity, and imaging vs. spectroscopic observations, while considering both ground- and space-based facilities.

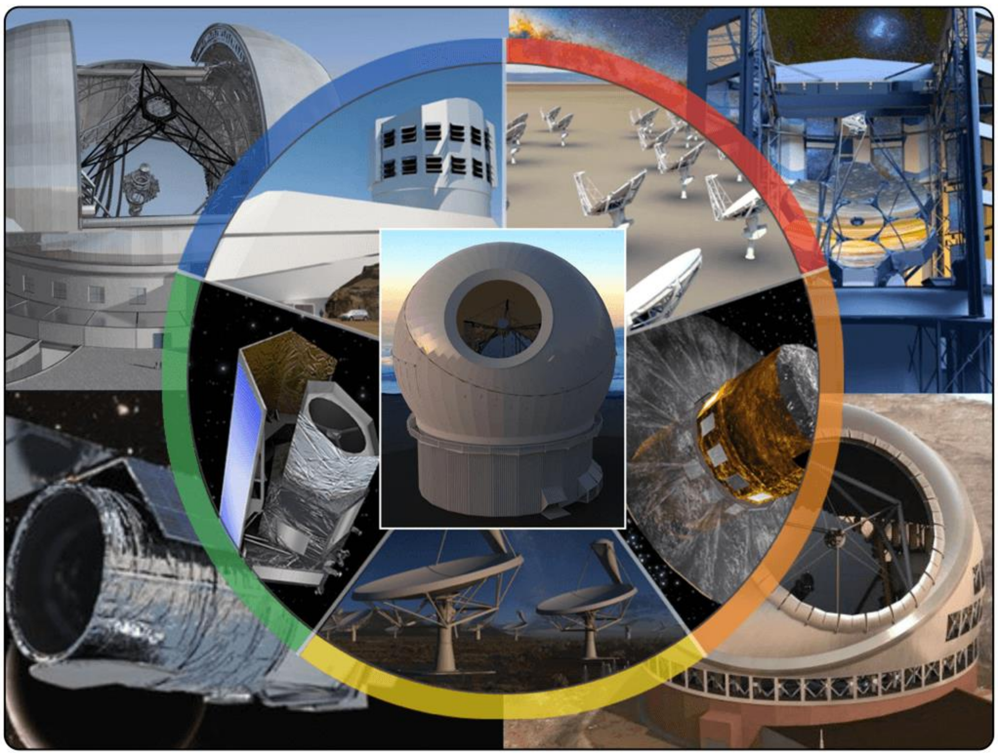

Fig 4: From its inception, MSE has considered synergies with other observing facilities as a high priority. In the near future we plan to expand on these considerations, as new facilities begin to come online and MSE's future contemporaries advance their plans.

3.4 MSE in programmatic reviews

The past few years have seen multiple international programmatic reviews of astronomy in many of MSE's partner institutions. MSE's response to these reviews is summarized elsewhere in these proceedings (Szeto et al. 2022); here we highlight the scientific contributions and input to the reviews.

3.4.1 Astro2020

MSE scientists actively participated in the white paper submission for the Astro2020 decadal survey in early 2019, submitting dozens of white papers that highlight the scientific need for a facility like MSE across a vast range of scientific topics. In addition, MSE was asked to produce a TRACE analysis for the decadal committee in late 2019.

MSE was very pleased to review the final decadal survey report; we completely agree with the committee that massively multiplexed spectroscopic surveys should be a high priority for the astronomical community in the next decade. Furthermore, most of Astro2020's scientific priorities align well with MSE's capabilities. In particular, its prioritization of transient science, in response to Rubin Observatory's upcoming first light, is well aligned with MSE's transient science case; the extragalactic and many other science cases also overlap significantly with MSE's planned science program.

3.4.2 Snowmass

MSE was invited to participate in the Snowmass process, the US astroparticle physics community's roughly decadal facility planning process. MSE Science Working Group co-leads of the Astrophysical Tests of Dark Matter (Li and Kaplinghat) and Cosmology (Yeche and Percival) working groups provided significant input to this planning process at many levels. The Snowmass process included multiple opportunities to discuss the MSE project with the US astroparticle physics community, beginning with a broad solicitation of Letters of Interest and ending with the production of a set of contributed white papers which will serve as summary input from the process to the next planning phase. Overall the Snowmass community showed interest in the MSE project, even more so once MSE introduced its new concept for a quad mirror telescope which enables a much larger field of view and consequently many more fibers in the focal plane (Barden et al. 2022a in these proceedings), since cosmological science requires observations of a large number of faint galaxies, densely packed and spread over the entire sky.

3.4.3 Other reviews: LRP, Australia Mid-Range Plan, French Prospective

In 2020, the Canadian astronomical community published the Long Range Plan. The review stated their top priorities: *"a very large optical telescope (ranked first), and SKA1 (ranked second). We make additional unranked recommendations for **MSE** and the ngVLA: these two projects represent compelling future opportunities for Canada, which should be explicitly ranked once they have been fully developed."* Realization of MSE continues to be a high priority for the Canadian astronomical community.

Around the same time, the Australian astronomy community produced a mid-term review of their decadal plan, which stated *"One of Australia's traditional strengths has been large-scale spectroscopic surveys. Australian engagement with a multiplexed spectroscopic capability on a very large telescope is important to build on this strength, but the optimum path remains unclear."* It goes on to highlight the importance of engaging with ESO, and suggests that engagement with MSE would require additional funding sources.

Finally, the regular French astronomy programmatic review, the "Prospective," named "*maintaining access to the CFHT site in the long term*" as the highest priority. As can be seen, MSE and CFHT continue to be highly ranked in reviews around the world, most importantly in our participant institutions.

3.5 Remote meetings

As a large, international collaboration, MSE was accustomed to meeting remotely even before the pandemic. However, the lack of large, in-person conferences has somewhat impacted the opportunities for promoting the project throughout the astronomical community. Nonetheless, there continues to be strong interest in MSE by astronomers worldwide, and the Science Team grew by ~10% in the past two years. This has been in part due to strong efforts by MSE science leadership to continue to advertise MSE's capabilities via remote participation in conferences and colloquia at potential future partner institutes.

These efforts have served to increase interest in the MSE project as well as to expand the science case and encourage continued design evolution of MSE's observational capabilities and instrument design.

4. SCIENTIFIC INPUT INTO INSTRUMENT DESIGN ADVANCES

4.1 Instrument design advances

Over the past two years, significant advances have been made on both of MSE's instruments, the Low-to-Moderate Resolution (LMR) spectrographs and the High Resolution (HR) spectrographs. In these proceedings, Hill et al. (2022) describes recent instrument development activities at a high level, while Jeanneau et al. (2022) describe in more detail the LMR design advances and Zhang et al. (2022) describes the new HR design. Throughout the design evolution, significant input was sought from the Science Team and MSE science leadership. The close interaction between scientists and the engineering team will ensure that the final instrument design will be capable of efficiently realizing the science goals of the project.

4.2 Developing MSE calibration techniques

Over the past year, MSE's Science Calibration (SCal) system has been more fully fleshed out, with various design and hardware alternatives explored. These efforts culminated in a Conceptual Design Review of SCal in early 202s. Scientific oversight and input was an important piece of this development effort. See Schmidt et al. (2022) in these proceedings for more details.

In addition, recent progress has been made to advance plans for developing sky subtraction techniques for MSE's challenging science observations. In light of the fact that the majority of MSE's targets will have brightnesses at or near the sky background level, careful thought must be put into how to appropriately remove the sky background from the science data, in particular since the fibers may pose additional challenges. Elsewhere in these proceedings we describe progress on developing machine learning techniques to remove telluric features from astronomical observations (Dauphin et al. 2022).

4.3 Instrument and design documentation

Throughout the process of advancing the instrument designs, the MSE Project Office has actively managed the project and documented the instrument design evolution from both an engineering and scientific perspective. We have developed an approach for managing project deliverables, described in these proceedings by Small et al. (2022). This process has led to a more effective and efficient communication between the Project Office and the engineering teams, while allowing for scientific input from the Science Team as well. In addition, we have continued to apply standard project management techniques to check all MSE systems' compliance against the high level science requirements. Progress on this effort is presented in these proceedings by Barden et al. (2022b).

5. FUTURE WORK

Going forward, the MSE Project will continue to carefully consider the scientific planning process alongside the technical advances in the project development. In particular, we will continue to advance the DRS and further refine the software required for the development, commissioning, and science operations of a successful observatory, while soliciting input and advice from the large and diverse Science Team.

In the meantime, we continue to consider further refinements to the Conceptual Design of MSE. As one example, over the past year more detailed investigations of the MSE telescope optical performance have inspired the consideration of alternative optical designs for the telescope. Barden et al. (2022a) describe this work in more detail in these proceedings. As mentioned previously, one significant scientific advantage of this approach would be to greatly expand the area covered by the focal plane, thus enabling many more fibers and associated spectrographs. This would obviously have significant impact on the Science Case (and also the cost to the project) as it would enable many more observations to be obtained contemporaneously.

In planning the details of the future development of MSE, a new concept for the transition has emerged, opening up a new range of scientific possibilities for the CFHT facility. In these proceedings, Sheinis et al. (2022) describe the MSE Pathfinder, which would facilitate the transition between the existing CFHT facility to MSE. The Pathfinder would enable the project to retire some key technical, software, and calibration risks to the MSE Project, and would also enable early MSE-style science for brighter targets.

With all of this technical development ongoing, and as new scientific discoveries and revelations are had thanks to ongoing and near future imaging surveys and other projects, eventually the MSE Science Case will need to be refreshed again. We look forward to reconsidering the plethora of scientific opportunities that a project like MSE will enable.

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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