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A design reference survey for the Maunakea Spectroscopic Explorer

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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, each studying thousands to millions of astrophysical objects. MSE uses 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 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 plans 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 and identify any performance and functional deficiencies of the MSE Observatory. With this exercise we have begun to lay out a detailed plan of how to schedule and execute observations, including calibration data, in the first five years of the MSE project.

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

1. INTRODUCTION

The Maunakea Spectroscopic Explorer (MSE; MSE Project 2018) 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. 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 arcseconds 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.

MSE is designed to take advantage of the excellent site characteristics of Maunakea, which allows for an extremely sensitive, wide-field, and massively multiplexed facility (see Table 1). The MSE Conceptual Design positions 4,332 input fibers at MSE's prime focus, packed into a hexagonal array. The fibers are precisely positioned to submillimeter accuracy in order to maximize the amount of light injected from science targets into the input fibers, which collect and transmit light

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to banks of spectrographs tens of meters away. The exquisite seeing allows the fiber diameters to be kept small (85 micron diameter, 0.8 arcseconds, for the high resolution “HR” spectrographs and 107 micron diameter, 1.0 arcseconds, for the low and moderate resolution “LMR” spectrographs), thus keeping the size and cost of the spectrographs attainable. One bank of spectrographs receives light from 3,249 fibers from the focal surface and may be used at either low resolution (R~3000) or moderate resolution (R~6000), covering the optical to near-infrared wavelength range of 0.36–1.8 microns. Concurrently, the other bank of spectrographs receives light from 1,083 fibers from the focal surface and is dedicated to collecting the high resolution spectra in three targeted optical wavelength windows within the wavelength range of 0.36–0.5 microns at R~40,000 and 0.5–0.9 microns at R~20,000. All resolutions have simultaneous full field coverage, and the massive multiplexing results in the ability to collect many thousands of spectra per hour and over a million spectra per month, all of which will be made available to the MSE user community. Moreover, an upgrade path to add an Integral Field Unit (IFU) system has been incorporated into the design as a second-generation capability for MSE.

Aside from the physical infrastructure, MSE’s success is enabled by efficiently scheduled and executed surveys, by the quality of the data collected, and by MSE’s ability to make the science products available to survey teams in a timely and efficient manner. MSE will devote 80% of available time to executing large, homogeneous surveys which will typically require several years to complete. More focused programs, which require smaller amounts of observing time and typically lead to more rapid publications, will occupy the remaining 20% of observing time. Proposals for both types of programs will be solicited from the MSE user community at regular intervals. MSE is operated solely in a queue-based mode, requiring sophisticated scheduling software. Data will be made available to the survey team immediately, and to the larger MSE community on a short timescale.

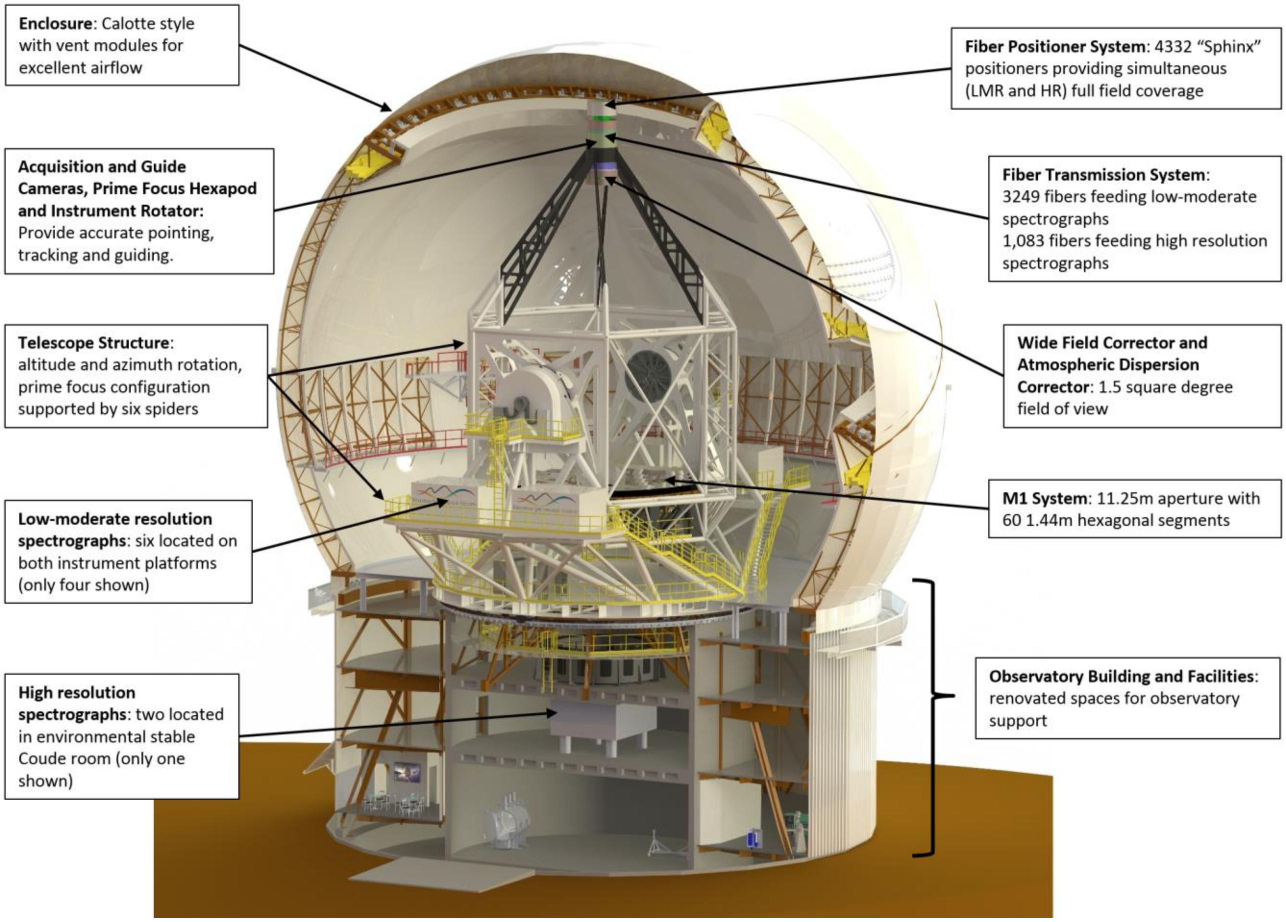
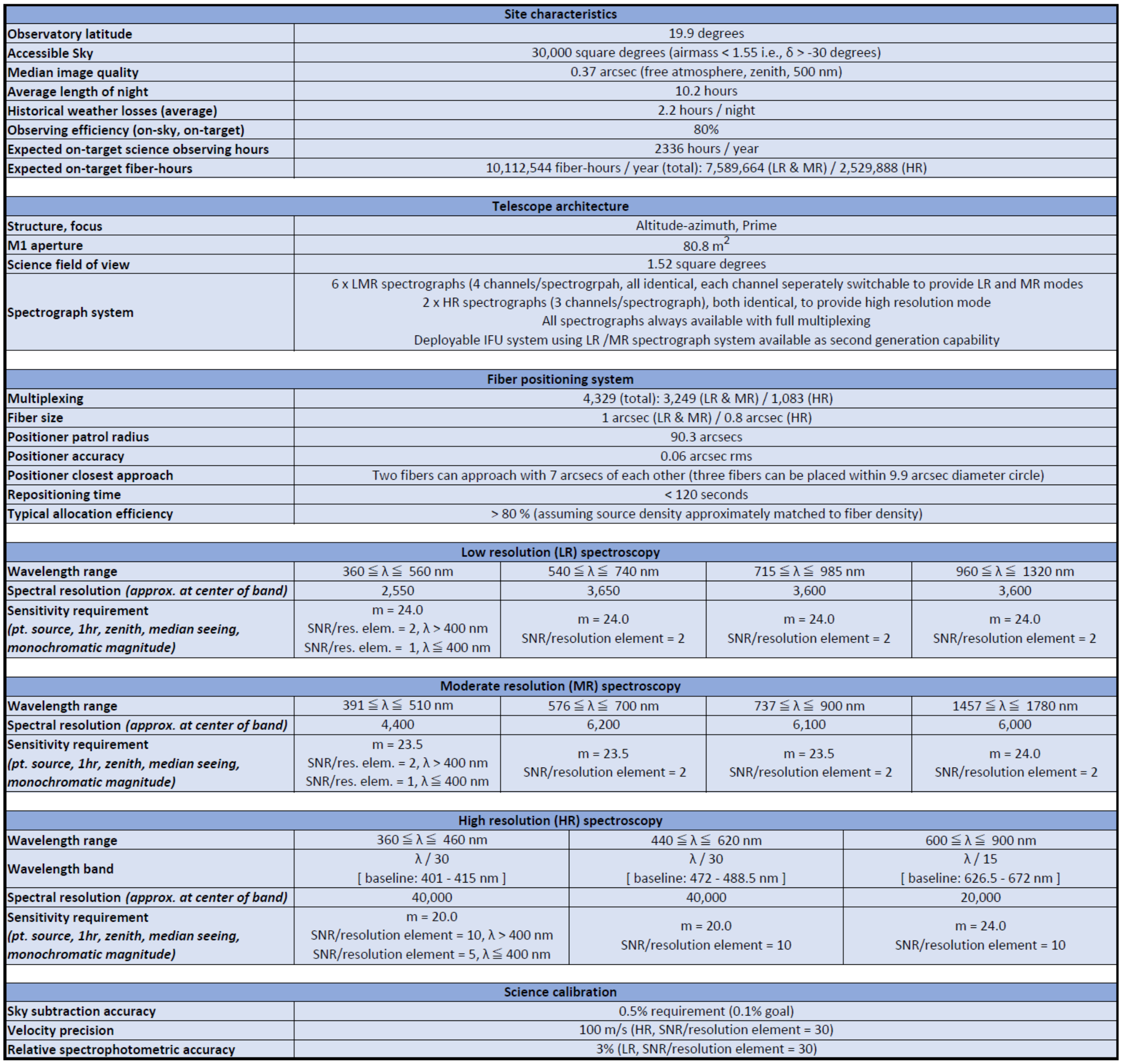


Figure 1: MSE Observatory architecture as described by the 2018 Conceptual Design (MSE Project 2018).

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, the Design Reference Survey (DRS), is described in this document, along with a discussion of the plans for executing the DRS and a summary of progress to date.

Table 1: The detailed science capabilities of MSE.



Site characteristics				
Observatory latitude	19.9 degrees			
Accessible Sky	30,000 square degrees (airmass < 1.55 i.e., $\delta > -30$ degrees)			
Median image quality	0.37 arcsec (free atmosphere, zenith, 500 nm)			
Average length of night	10.2 hours			
Historical weather losses (average)	2.2 hours / night			
Observing efficiency (on-sky, on-target)	80%			
Expected on-target science observing hours	2336 hours / year			
Expected on-target fiber-hours	10,112,544 fiber-hours / year (total): 7,589,664 (LR & MR) / 2,529,888 (HR)			
Telescope architecture				
Structure, focus	Altitude-azimuth, Prime			
M1 aperture	$80.8\ m^2$			
Science field of view	1.52 square degrees			
Spectrograph system	6 x LMR spectrographs (4 channels/spectrogrpah, all identical, each channel seperately switchable to provide LR and MR modes 2 x HR spectrographs (3 channels/spectrograph), both identical, to provide high resolution mode All spectrographs always available with full multiplexing Deployable IFU system using LR /MR spectrograph system available as second generation capability			
Fiber positioning system				
Multiplexing	4,329 (total): 3,249 (LR & MR) / 1,083 (HR)			
Fiber size	1 arcsec (LR & MR) / 0.8 arcsec (HR)			
Positioner patrol radius	90.3 arcsecs			
Positioner accuracy	0.06 arcsec rms			
Positioner closest approach	Two fibers can approach with 7 arcsecs of each other (three fibers can be placed within 9.9 arcsec diameter circle)			
Repositioning time	< 120 seconds			
Typical allocation efficiency	> 80 % (assuming source density approximately matched to fiber density)			
Low resolution (LR) spectroscopy				
Wavelength range	$360 \leqq \lambda \leqq 560$ nm	$540 \leqq \lambda \leqq 740$ nm	$715 \leqq \lambda \leqq 985$ nm	$960 \leqq \lambda \leqq 1320$ nm
Spectral resolution *(approx. at center of band)*	2,550	3,650	3,600	3,600
Sensitivity requirement *(pt. source, 1hr, zenith, median seeing, monochromatic magnitude)*	m = 24.0 SNR/res. elem. = 2, $\lambda > 400$ nm SNR/res. elem. = 1, $\lambda \leqq 400$ nm	m = 24.0 SNR/resolution element = 2	m = 24.0 SNR/resolution element = 2	m = 24.0 SNR/resolution element = 2
Moderate resolution (MR) spectroscopy				
Wavelength range	$391 \leqq \lambda \leqq 510$ nm	$576 \leqq \lambda \leqq 700$ nm	$737 \leqq \lambda \leqq 900$ nm	$1457 \leqq \lambda \leqq 1780$ nm
Spectral resolution *(approx. at center of band)*	4,400	6,200	6,100	6,000
Sensitivity requirement *(pt. source, 1hr, zenith, median seeing, monochromatic magnitude)*	m = 23.5 SNR/res. elem. = 2, $\lambda > 400$ nm SNR/res. elem. = 1, $\lambda \leqq 400$ nm	m = 23.5 SNR/resolution element = 2	m = 23.5 SNR/resolution element = 2	m = 24.0 SNR/resolution element = 2
High resolution (HR) spectroscopy				
Wavelength range	$360 \leqq \lambda \leqq 460$ nm	$440 \leqq \lambda \leqq 620$ nm	$600 \leqq \lambda \leqq 900$ nm	
Wavelength band	$\lambda / 30$ [baseline: 401 - 415 nm]	$\lambda / 30$ [baseline: 472 - 488.5 nm]	$\lambda / 15$ [baseline: 626.5 - 672 nm]	
Spectral resolution *(approx. at center of band)*	40,000	40,000	20,000	
Sensitivity requirement *(pt. source, 1hr, zenith, median seeing, monochromatic magnitude)*	m = 20.0 SNR/resolution element = 10, $\lambda > 400$ nm SNR/resolution element = 5, $\lambda \leqq 400$ nm	m = 20.0 SNR/resolution element = 10	m = 24.0 SNR/resolution element = 10	
Science calibration				
Sky subtraction accuracy	0.5% requirement (0.1% goal)			
Velocity precision	100 m/s (HR, SNR/resolution element = 30)			
Relative spectrophotometric accuracy	3% (LR, SNR/resolution element = 30)			

2. THE MSE DESIGN REFERENCE SURVEY

The MSE DRS is a concept that evolved from the highest priority recommendation of the 2018 CoDR panel report, namely, to execute a "Design Reference Mission" (now referred to as the 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 Science Cases for the MSE DRS

Following on these recommendations, the MSE Project has begun to execute a Design Reference Survey planning exercise, having a goal of planning a complete set of observations that could be executed in the first five years of MSE operations. It should be noted that the surveys described below are not necessarily the actual observations that will be made soon after MSE's first light; rather they represent a selection of surveys that have been chosen to span a range of instrumentation and scheduling requirements. Specifically, they use both the HR and LMR spectrographs, and either contain targets roughly evenly distributed across the entire sky (avoiding the Milky Way disk), as is the case of the MW halo and cosmology cases, or else require denser observations over a narrower field. The reverberation mapping case includes the additional challenge of scheduling synoptic observations.

We have selected the following four key science cases to develop the DRS:

- **Chemistry of Milky Way halo stars:** a chemodynamical study of all stars in the MSE footprint having magnitudes $V<20$ and Galactic latitudes $|b| > 20$ degrees
- **Cosmology:** the primary cosmological survey being planned for MSE, targeting millions of galaxies at redshifts up to $z\sim4$ over 10,000 square degrees
- **Reverberation mapping:** a multi-epoch time-domain study of AGN comprising thousands of robust time lags of the quasar broad-line region over a broad range of galaxy redshifts and luminosities
- **Cosmic noon:** a medium-field survey to study galaxies spanning the epoch of peak cosmic star-formation over three different redshift ranges ($1.5 < z < 2$, $2 < z < 2.5$, $2.5 < z < 3$) having spatial areas of 20, 80, and 80 square degrees respectively

Each of these science cases are described in the 2019 version of the MSE Detailed Science Case (MSE Science Team 2019) in some detail. These cases were chosen to test not only the instrument specifications, answering questions such as whether the LMR spectrographs are fed by a large enough number of fiber optics and whether the HR spectrographs sample a large enough spectral range, but also whether the size of the field of view and the spacing/positionability of the fibers are appropriate for this work. Perhaps most importantly, the exercise of planning the phasing/scheduling of the observations will be enlightening, in particular regarding how the observations for wide field vs. narrow or medium-field surveys will be scheduled when the sky coverage of those surveys overlaps.

2.2 Future science cases to add additional constraints

Once the exercise to study the four initial DRS science cases is complete, we intend to expand the number of science cases to add additional complexity to the exercise. In this next phase of developing the DRS we will be interested in exploring how efficiently MSE will be able to accomplish science cases that have different features than those studied in the first version of the DRS. In particular, we will investigate science cases that include objects with high target densities (e.g. surveys in the Milky Way disk), high cadence observations (e.g. brown dwarfs, LIGO events, and other science cases discussed in MSE's Time Domain science case), radial velocity measurements (including establishing requirements for velocity precision in single observations as well as considerations time series/multi-epoch velocity measurements of single objects as well as for ensembles of objects), and other science cases as they develop.

2.3 Data collection for each science case

Current ongoing work to develop the DRS plan is to assemble required information for each of the science cases. This includes information such as target lists and input catalogs (either real or simulated), required imaging survey data (existing or planned), and calibration requirements. We also collect information regarding the required signal-to-noise of the observations, wavelength coverage of the spectra, and wavelength solution stability as a function of time. Time domain surveys have additional requirements such as cadence and frequency of the observations. In the future, target-ofopportunity observations will be supported; requirements for these programs are specified in terms of elapsed time since event trigger, duration and frequency of data collection, and any other details specific to each science case.

3. SCIENCE INPUT FOR DRS

In preparing to execute the DRS, the MSE "Project Science Team" (i.e., the three authors of this proceeding) have led various levels of investigation and queries to the larger MSE Science Team. The 400+ person Science Team is organized into eight Science Working Groups, each co-led by two scientists. The information gathered to support the DRS, as well as much of the overall organization of the science productivity and planning for the project, is organized according to these working groups. The structure and current co-leads are posted on the MSE website: mse.cfht.hawaii.edu. In this section we describe the work to provide several levels and types of information about the science requirements for the DRS.

3.1 Questionnaire

MSE successfully passed Conceptual Design Review early in 2018. However, the baseline architecture presented at the time did not perfectly meet the science sensitivity requirements over the entire spectral range. As a result, and in preparation for entering the Preliminary Design Phase of the project, the Project Office extensively polled the scientists in the project in Q2 2019 in order to ascertain details of the science requirements for their desired observations to be made with MSE. This survey is referred to as the "Questionnaire", which had a goal to refine and potentially revise some of the Science Requirements presented in the Conceptual Design. The Questionnaire was composed as an extensive Google poll, and requested information from the scientists regarding the detailed science and instrument requirements for a given science case (one science case per response to the poll). The specific questions asked, for each instrument setting (i.e. for both the low-to-moderate LMR and high resolution HR spectrographs, and each arm in both spectrographs) were regarding:

- Minimum required spectral resolution in each spectral region or arm
- Required wavelength coverage in each spectral region or arm
- Surface density of targets at specific benchpoint limiting magnitudes (i.e. at m_{AB} = 16, 17, 18, …)
- Required exposure time for the targets in each magnitude range, according to the MSE Exposure Time Calculator
- Expected impact on the science if any of the above are not met

Respondents were also asked whether they would be willing to devote additional time and effort to developing the DRS. Sixty responses to the Questionnaire were received from 56 individuals after a three week response time. The responses covered a broad range of science themes and instrumentation needs, including representation from all eight of MSE's Science Working Groups. The most represented SWGs are the "Exoplanets and Stellar Astrophysics" (14/60), "Milky Way and Resolved Stellar Populations" (14/60), and the "Galaxy Formation and Evolution" (13/60) SWGs. The least represented SWGS are the "Astrophysical Tests of Dark Matter" (1/60), "Chemical nucleosynthesis" (3/60), and "Cosmology" (3/60) SWGs. The other two SWGs are the "AGN and supermassive black holes" (7/60) and "Time Domain Astronomy and Transients" (5/60) SWGs. This variation in number of responses per Science Working Group is to be expected: some of the groups organize many scientists around one common science theme (the Cosmology and Dark Matter working groups, for example) while others invite every scientist to voice their individual science cases (as in the case of the Exoplanets and Stellar Astrophysics and Milky Way working groups). Although the Questionnaire responses surely do not represent a comprehensive list of MSE science cases, they did sufficiently sample MSE's capabilities as far as the types of science to be executed by the project. The responses ranged from extremely detailed information to a few brief pieces of information regarding the required observations.

3.2 Follow-up queries

Subsequent to the analysis of the Questionnaire, various queries of the Science Team have been executed in order to solidify the findings of the Questionnaire as well as to probe additional detail. In one example, the three Working Groups (Exoplanets and Stellar Astrophysics, Chemical Nucleosynthesis, and Milky Way and Resolved Stellar Populations) that make use of the HR spectrographs' ability to study absorption features from a wide range of chemical species each queried their constituencies to produce an extensive line list containing all of the spectral features required to be studied to enable the planned science programs. In this example multiple entries in the response form counted as "votes", indicating which regions of the optical spectrum were highest priority. Upon inspecting these responses it became clear that the conceptual design of the HR spectrograph did not meet the requirements of a large number of the scientists; plans are underway to modify the HR spectrograph design to include increased wavelength coverage and/or a simpler and faster way to adjust the wavelength range covered by each of the three arms.

In another example, the Cosmology Working Group provided ample detailed information (input catalogs with coordinates, signal-to-noise requirements, etc.) to the Project Science Team early in this process. This information already is sufficient to execute the DRS (indeed, it is likely sufficient to execute the actual MSE observations!) and will be used to evaluate survey strategy and observing efficiencies, as described below.

3.3 Monthly Science Telecon discussions

In addition to the information gathered via surveys and forms, feedback on science planning was gathered from the Science Team verbally as well. The MSE Science Team holds a regular monthly telecon at which a wide range of science topics are discussed. These discussions often focus on updating the Science Team on the progress being made by the instrument design teams as well as welcoming new science working group co-leads and scientists at new and potential MSE partner institutions to present their work to the group. Recently these meetings have focused primarily on gathering additional input from the scientists to support the DRS work, including presenting and discussing the findings of the Questionnaire and Surveys as well as proposed modifications to the spectrograph design for both the LMR and HR instruments. These discussions serve to keep the Science Team informed about the work being done to advance the Project design, but also to allow the design teams to directly ask questions of the scientists to ensure that the design work will be able to execute the required observations. The high level of interaction, discussion, and feedback has greatly benefited the design process and will surely result in a well-considered, capable instrumentation design that will be able to execute all of MSE's varied science goals.

4. ANALYZING THE SCIENCE INPUT

We conducted various levels of analysis of the Questionnaire and subsequent survey responses, documenting the results. These analyses were carried out in two complementary ways. First we conducted a statistical summary of the responses, weighting each response equally. This approach was most useful for assessing the range of feedback received in the responses. Next, we considered the responses from a more science-driven standpoint to form a more subjective, but also more relevant, summary of the responses. In this second analysis it is possible to weight one science case more highly than the others; indeed this was required since the Cosmology Science Working Group co-leads submitted one, very comprehensive, response to the Questionnaire, which clearly deserves more consideration than 1/60th of the total MSE science. However we found it instructive to consider both statistical and science-based analyses in this work, since fully considering the sheer number of potential science cases that MSE will be able to execute is overwhelming, and multiple analyses ensure that individual science cases are not overlooked.

In this second analysis we grouped science cases together according to primary instrument to be used (i.e. the high-resolution HR spectrographs or rather the low-to-moderate resolution LMR spectrograph) and then by science theme. The LMR responses fell into five broad science categories: spectroscopic variability of extragalactic sources, galaxy evolution and dark matter, the Milky Way and the Local Group, cosmology and large-scale structure, and stellar physics and planets. The science cases that use the HR spectrograph were grouped into three categories: general chemical abundances of large numbers of stars, the study of abundances and/or radial velocities of smaller samples of specialized groups of stars, and non-stellar sources (exoplanet or extragalactic studies). Some of the science cases required observations from both LMR and HR spectrographs; these science cases were considered in both groups.

Further analyses and discussions regarding the information gathered from the Science Team subsequent to the Questionnaire responses were similarly documented and discussed with the Science Team for confirmation and clarification.

5. PLANS FOR EXECUTING THE DRS

Now that we have gathered significant input from the Science Team regarding the nature, requirements, and details of many individual science cases, including but not limited to those making up the DRS, we are ready to advance to the next phases of the DRS development.

5.1 Executing the simulated surveys

We plan to fully simulate at least a portion of the planned observations for each of the four DRS science cases. In addition to the input already provided by the Science Team, we will use simulated or template spectra for the types of objects in each survey. This exercise will provide important feedback to the project on the appropriateness and viability of the fiber positioner design, the spectrograph designs, the calibration and scheduling tool plans, and many other aspects of the project planning.

This work will require the following software tools:

- Exposure time calculator (http://etc-dev.cfht.hawaii.edu/mse/index.html; a new version is currently under development)
- Fiber/target allocation simulator (http://etc-dev.cfht.hawaii.edu/mse/index.html)
- Observation scheduler (to be developed)
- Calibration system conceptual design (in progress)

In addition, the DRS will provide feedback on planning and scheduling the observations under a range of weather, seeing, and moon phase conditions. The resulting analysis of the DRS surveys may suggest improvements or modifications to the MSE Conceptual Design (i.e., that presented in Figure 1 and Table 1 above) at all levels of the project.

5.2 Evaluation criteria

Once the DRS has been executed we will analyze the results. Specifically, for each science case we will be able to:

1) Determine whether the conceptual design of MSE will be able to execute the described science programs
    a) If yes, how much time will it take to do so?
    b) If no, what design elements need to be modified to enable the science?
2) Identify synergies and address efficiencies in terms of scheduling or phasing the observations, in particular between science cases and balancing observations to be executed and different moon phases
3) Provide an assessment of the impact of each design capability on the science case (i.e., are there design elements that are underutilized compared to others, that could be deferred to “second-generation”, for example).
4) Provide a summary of the calibration requirements of the science case, including approximate number of fibers to be dedicated to calibration spectra in each pointing for each science case, as well as other calibration needs such as guide stars, additional daytime or nighttime calibration exposures, etc.
5) Identify any additional questions specific to the science case

5.3 DRS milestones

Below we outline the milestones for the work to execute the DRS:

- Compose Science Team Questionnaire
- Solicit responses to Questionnaire from Science Team
- Evaluate Questionnaire responses
    - Statistically
        - HR
        - LMR
    - Scientifically
        - HR
        - LMR
- Select 3-4 science cases for the DRSv0
    - HR: chemical abundances of halo stars
    - LMR: cosmology
    - LMR: cosmic noon
    - LMR: AGN reverberation mapping
- Write “observing proposal” for each science case, summarizing science case, target lists, S/N requirements, calibration needs

- Assemble small working groups to evaluate proposals; iterate with them to reach consensus
- Use/develop software (ETC, allocator, scheduler, etc.) to:
    - Estimate how long it will take to execute the observations
    - Determine whether the required S/N is met at all wavelengths of interest
    - Assess whether the fiber diameter in CoDR is appropriate for the observations (LMR)
    - Assess whether CoDR wavelength windows are appropriate for the observations (HR)
    - Identify difficulties in scheduling the observations, e.g. whether there are significant gaps in the scheduling
    - Assess whether all proposed surveys can be executed simultaneously
- Work with the small working groups and SWG leads to evaluate the proposed surveys, as described above

6. FUTURE WORK REQUIRED TO COMPLETE DRS

The work we have completed to date leaves us yet to complete the final two bullet points in the milestones outlined above. These are arguably the most involved steps of the DRS plan, and also the most important. Fortunately the groundwork we have laid places the Project Science Team on a strong footing to complete this work in the near future.

In particular, the next steps to advance the DRS planning work are to complete the development of the planning software, in particular a fully capable piece of software that can simulate the scheduling of the planned observations. The software will be developed in such a way as to enable upgrades/modifications as necessary, in particular in order to flexibly accept changes to the details of the instrumentation and facility design plans. This work is underway, and several groups within the MSE project have been identified to advance the software concepts, in particular to produce a new version of the exposure time calculator with additional functionality. Development of the "Scheduler", i.e. the software that will enable a full assessment of planning the scheduling of the observations including fiber positions, field pointings on the sky, accounting for weather conditions and moon phase considerations, and many other logistical considerations, is yet to begin and it is a high priority to advance this design work in the near future.

Once we have a complete suite of observation planning software, we will be able to answer questions posed above such as assessing the time, difficulty, and feasibility of scheduling various surveys as well as determining whether the instrumentation is capable to completing the science programs. For example, for the four specific science cases that have been selected for the DRS, we will be able to answer important questions such as: how complicated will it be in practice to schedule all-sky surveys alongside more targeted surveys (e.g. how often and when those areas of the sky with more planned observations than others are revisited); how appropriate are the current plans for time-domain surveys in practice, again alongside all-sky surveys, and in particular when considering the image quality requirements for all surveys; and how observations will be balanced across moon phases and varied weather and image quality conditions. In the future we plan to build upon the DRS by adding additional science cases and other considerations, approaching as close to a full simulation of MSE observational data products as is possible.

In the meantime we will be able to use the software we have already developed to great effect to simulate and study the observation planning of the DRS science cases in a simple way. Throughout this process we plan to continue to work closely with the Science Working Group co-leads and the larger Science Team to ensure that the science requirements are being met. At the same time we will continue to communicate closely with the instrument and facility design teams to ensure that the engineering design work continues to meet the science requirements.

7. CONCLUSION

We have described the plans for and work carried out to date towards executing the MSE Project's Design Reference Survey planning exercise. The considerations, investigations, and analyses conducted thus far have already resulted in continued design evolution of various subsystems within the MSE project, in particular the spectrograph design. This is important work to be done now, as the project prepares to advance to the Preliminary Design Phase. Going forward, completing the DRS planning exercise will be the highest priority for the MSE Project Science Team since the results of this work stand to greatly impact the ongoing design of the project's hardware and software architecture, as well as the high level planning for nearly all aspects of the project.

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