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REVEALING THE FAINT UNIVERSE, MILLIONS OF SPECTRA AT A TIME

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Abstract. In this paper we present an overview of the Maunakea Spectroscopic Explorer (MSE) at the end of Conceptual Design Phase. This project aims at transforming the Canada-France-Hawaii Telescope into an large aperture wide-field multi-object fiber-fed dedicated spectroscopic facility. MSE will collect millions of spectra every few weeks, helping astronomers answer questions about the origin of elements, the nature of dark matter, the formation of large scale structures in the Universe, and the mass of neutrinos. The main subsystems for baseline architecture of MSE are described, the concept of operations is summarized, and the overall project cost, partnership, and schedule are outlined.

Keywords: Maunakea Spectroscopic Explorer, Canada-France-Hawaii telescope, spectroscopic survey, wide field, multi object spectrograph, fiber fed

1 Introduction

The Maunakea Spectroscopic Explorer (MSE, Hill et al. 2018) is a project to transform the Canada-France-Hawaii Telescope (CFHT) into an 11.25 m aperture, wide field, highly multiplexed facility dedicated to spectroscopic surveys in the visible and near-infrared. MSE will be the observatory (i.e. the summit facility and the science platform) of the next decades, which will help astronomers answer some of the most exciting questions of modern astronomy. MSE is the answer to a need expressed by the astronomy communities is Europe[*], Canada[†], Australia[‡], and the USA(Council 2015): it is the desired facility of the next decade and beyond to address some of the most pressing and exciting questions in astrophysics.

2 Science

The detailed science case (DSC) for MSE was first release in 2016 (McConnachie et al. 2016) and a second version was released in 2019 after the science team had been reopened and grew from about 100 members to about 400 members (The MSE Science Team et al. 2019). The DSC covers many topics from stars in the Milky Way to nearby galaxies, supermassive black holes, dark matter, cosmology, and time domain astronomy. Reviews on the impact that MSE will have on these topics can be found in these proceedings.

The science cases have been expanded in the form of Science Reference Observations (SROs) which describe in more details the typical observations and samples that MSE surveys will comprise. In turn, these SROs have helped define the top level science requirements for MSE. Figure 1 provides a summary of these requirements.

3 Architecture (Hill et al. 2018)

To answer the scientific requirements, the MSE Project Office (PO) was created in 2014 at the CFHT headquarters. The MSE PO initiated the Conceptual Design Phase (CoDP) of the project which lead to multiple subsystems reviews in 2017 and a system-level review at the beginning of 2018. MSE is still the only dedicated large aperture wide-field MOS facility under development in the world.

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[*] `https://pdfs.semanticscholar.org/dcc0/71607435ee989f05d9396c8ecb2f372da43a.pdf`
[†] `https://www.casca.ca/lrp2010/11093_AstronomyLRP_V16web.pdf`
[‡] `https://www.science.org.au/files/userfiles/support/reports-and-plans/2015/astronomy-decadal-plan-2016-2025.pdf`

Accessible sky	30000 square degrees (airmass<1.55)						
Aperture (M1 in m)	11.25m						
Field of view (square degrees)	1.5						
Etendue = FoV x π (M1 / 2)²	149						
Modes	**Low**		**Moderate**	**High**			**IFU**
Wavelength range	0.36 - 1.8 μm		0.36 - 0.95 μm	0.36 - 0.95 μm ♯			IFU capable; anticipated second generation capability
	0.36 - 0.95 μm	J, H bands		0.36 - 0.45 μm	0.45 - 0.60 μm	0.60 - 0.95 μm	
Spectral resolutions	2500 *(3000)*	3000 *(5000)*	6000	40000	40000	20000	
Multiplexing	>3200		>3200	>1000			
Spectral windows	Full		≈Half	$\lambda_c/30$	$\lambda_c/30$	$\lambda_c/15$	
Sensitivity	m=24 *		m=23.5 *	m=20.0 ♮			
Velocity precision	20 km/s ♪		9 km/s ♪	< 100 m/s ★			
Spectrophotometic accuracy	< 3 % relative		< 3 % relative	N/A			

♯ Dichroic positions are approximate
* SNR/resolution element = 2 ♪ SNR/resolution element = 5
♮ SNR/resolution element = 10 ★ SNR/resolution element = 30

Fig. 1. Summary of the science requirements

The goal of the MSE PO was to maximize the utilization of existing designs and minimize the development of new technologies to minimize the project exposure to technical and programmatic risks while ensuring the project schedule and budget are attainable. In addition, out of environmental and cultural respect, MSE will preserve much of the external appearance of CFHT after the completion of the transformation. In particular, MSE will reuse the CFHT summit building with no additional ground disturbances and the size increase of the summit facility (building and enclosure) will be limited to 10%.

The baseline architecture of MSE at the end of CoDP is shown in Figure 2 and detailed hereafter.

3.1 *Summit building (Bauman et al. 2018)*

MSE will reuse the CFHT building. Both telescope and enclosure piers will be upgraded to meet more recent building regulations. The top floor of the current building will be removed to provide more room to a significantly bigger telescope. In addition, the layout of the building will be modified to adapt to new needs and lessons learned over the past decades. The piers have been shown to be able to support the new enclosure and telescope which, though they are significantly larger, are benefiting from decades of research and development.

3.2 *Enclosure*

During feasibility study, it was shown that a 10 m class telescope could fit in the CFHT dome though the current slit aperture is not large enough to be consistent with the primary mirror aperture. After reviewing the extensive enclosure trade study of the Thirty Meter Telescope, a calotte-style enclosure was selected for MSE. This design is structurally more efficient than conventional designs and allows for a lower mass and size. It also has a similar appearance to that of CFHT. The CoDP design was that of Dynamic Structures Ltd in Canada.

3.3 *Telescope structure (Murga et al. 2018)*

The telescope will use an alt-az mount similar to that of current 8 to 10 m class telescopes. Its design features a "yoke" or "rocking chair" configuration. Its high stiffen-to-mass ratio and open-truss design will promote airflow, which is critical to minimize thermal turbulence and improve the image quality, a key element for fiber-fed instruments. The CoDP design was that of IDOM in Spain. A telescope optical feedback system, a phasing and alignment system, and an acquisition and guiding camera system are located at the top-end and provide pointing and guiding feedback to the telescope structure.

3.4 *Optical design (Saunders & Gillingham 2016)*

The optical design of MSE is a prime focus with a segmented primary mirror and five lenses providing wide-field correction (WFC) and atmospheric dispersion compensation (ADC). The primary mirror is composed of 60 hexagonal segments of 1.44 m corner-to-corner, thus leading to an 11.25 m aperture. The WFC/ADC top-end system is optimized to provide a 1.5 square degree field of view over the 360 nm to 1800 nm spectral range that MSE will have access to. The CoDP optical design was that of the Australian Astronomical Observatory (AAO) while the segments support system has been studied by the Indian Institute of Astrophysics (IIA).

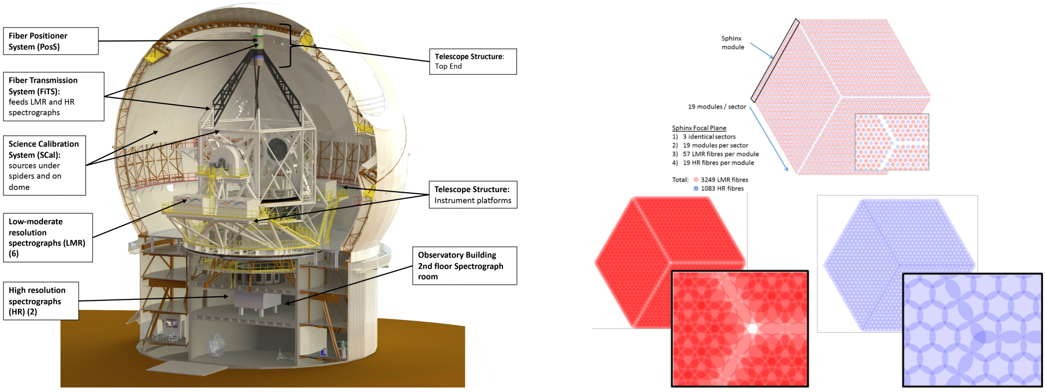

Fig. 2. Left: Schematic of the architecture of MSE with the main subsystems indicated. **Right:** Focal plane arrangement and patrol areas for the fiber positioner system.

3.5 *Fiber system (Monty et al. 2018; Smedley et al. 2018)*

There are 4332 positioners at the focal surface: 3249 carry a 1.0″ diameter fiber leading to low/moderate resolution (LMR) spectrographs and 1083 carry a 0.8″ diameter fiber leading to high resolution (HR) spectrographs (see Figure 2). Each positioner is a tilting spine that can reach any target within a 90″ patrol radius which means that both LMR and HR sets of positioners provide full field coverage. The CoDP design was that of AAO and competed with two other designs based on theta-phi positioners. After careful analysis of the injection efficiency (IE) and target allocation efficiency (AE) of the three designs, the AAO design was selected as its IE was only a fraction of a percent worse than that of the theta-phi designs but its AE was estimated to be about 50% better when considering the system as a whole in operations. This advantage is mainly due to the possibility offered by the AAO design to observe with both HR and LMR positioners at all time. The fibers will be bundled at the top end of the telescope structure, and run along the structure down to the LMR spectrographs located on platforms on each side of the telescope (about 35 m long) and to the HR spectrographs in the Coude room beneath the telescope (about 50 m long). The CoDP design was that of Herzberg Astronomy and Astrophysics (HAA) and Fibertech Optica in Canada.

3.6 *Spectrographs (Caillier et al. 2018; Zhang et al. 2018)*

The LMR spectrographs provide coverage from 360 to 1800 nm at a spectral resolution of about 2000-4000 and visible coverage at a resolution of about 4000-7000 thanks to a 4-arm design with switchable dispersive elements. The CoDP design was that of the Centre de Recherche Astrophysique de Lyon (CRAL) in France. The HR spectrographs provide three spectral windows: one about 50 nm wide in the “red” (600 to 900 nm) at a resolution of 20,000 and two about 15 nm wide in the “blue-green” (360 to 600 nm) at a resolution of 40,000. The CoDP design was that of the Nanjing institute of Astronomical optics & Technology (NIAOT) in China.

3.7 *Performance*

At the end of CoDP, with most of the subsystems designed, the MSE PO estimated the system-level performance and compared it with science requirements. All main science requirements are met except sensitivity at low resolution in the *H*-band (mostly because of the sky brightness) and at high resolution in the “blue” and “green” arms. The science team was then consulted via a Questionnaire to help the MSE PO refine high level requirements for the LMR and HR design ahead of the Preliminary Design Phase (PDP). More than 60 individual answers were received, covering all the science cases for MSE. The MSE PO used these answers to propose refined science requirements to the design teams along with supporting trade-off analyses to be performed before a preferred design solution is selected for PDP. For instance, the *H*-band capability was deemed critical for MSE’s success but with a lower sensitivity. The desired multiplexing at those wavelengths was thus decreased and a solution was proposed for analysis to the design team: the near-IR bands (J and H) would be provided by a different spectrograph unit than that providing the visible bands.

4 Operations (Flagey et al. 2018)

MSE will be a facility 100% dedicated to spectroscopic surveys, in a way similar to the Sloan Digitial Sky Survey (SDSS). It will be remotely operated from the MSE headquarters in Waimea. Most of the operations will be automated with some human supervision to properly handle more than 4,000 spectra being observed at a given time and millions of spectra being collected every few weeks. MSE will automatically schedule observations taking into account, among others, target visibility, targets and programs priority, observing conditions (historical and in real-time), and fiber allocation completeness in a field, so that the observing sequence is optimized to provide for science outcome. MSE will also automatically extract, calibrate, and reduce data to generate a consistent set of science data products based on algorithms and recipes developed in collaboration with the science team. Finally, a science platform will be created to provide access to the data archive and visualization and analysis tools for the scientists. It is currently envisioned that about 80% of the time will be allocated to a few large legacy surveys programs (LPs) and the remaining 20% will be allocated to small strategic observing proposals (SPs). It is expected that the whole MSE partnership will have preferred access to the data with possible differences between LPs and SPs, though this is still under discussion.

5 Partnership, Cost, Schedule

The current partnership for MSE includes the historical partners of CFHT: Canada, France, and the University of Hawai'i. Australia, China, and India are new partners who have been involved in MSE since CoDP. Texas A&M University, the National Optical Astronomy Observatory (NOAO), and a consortium of United Kingdom universities have joined the project since then with the status of observers. This partnership growth is necessary to support the design, construction, and operations of a project like MSE. The estimated construction cost in 2018 US dollars is 424 millions including about 25% risk cost. The most expensive subsystems are the primary mirror (22%), the LMR spectrographs (14%), the enclosure (12%), and the HR spectrographs (8%).

After the CoDP review, the MSE PO successfully increased the partnership and the science team. More recently, the focus was on preparing MSE to enter PDP and secure funding and resources for this next phase while making sure that MSE figures at a top priority in the strategic planning of all partners (e.g. French Prospective, US Decadal Survey, Canada Long Range Plan). PDP will start in 2020 and should last about 2 years. At the end of PDP, the management board of MSE will secure and approve the plan for construction phase which will signal the beginning of the final or detailed design phase. In parallel, MSE will seek to obtain construction permit in the context of what might be a new Master Lease for the astronomy precinct on Maunakea. The MSE PO currently plans to decommission CFHT, manufacture and test subsystems, assemble, integrate, and verify the whole system in the second half of the 2020s with a goal to begin science observations (commissioning, verification, then operations) by 2030.

The MSE collaboration recognize the cultural importance of the summit of Maunakea to a broad cross section of the Native Hawaiian community.

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[§]SPIE = Society of Photo-Optical Instrumentation Engineers