PROCEEDINGS OF SPIE

SPIEDigitalLibrary.org/conference-proceedings-of-spie

Maunakea spectroscopic explorer design development from feasibility concept to baseline design

Kei Szeto, Hau Bai, Steven Bauman, David Crampton, Nicolas Flagey, et al.

Kei Szeto, Hau Bai, Steven Bauman, David Crampton, Nicolas Flagey, Mike Gedig, Peter Gillingham, Xuefei Gong, Kevin Ho, Nathan Loewen, Alan McConnachie, Shan Mignot, Richard Murowinski, Derrick Salmon, Will Saunders, Siegfried Stiemer, Tom Vermeulen, Kanoa Withington, Kai Zhang, "Maunakea spectroscopic explorer design development from feasibility concept to baseline design," Proc. SPIE 9906, Ground-based and Airborne Telescopes VI, 99062J (27 July 2016); doi: 10.1117/12.2234213

Event: SPIE Astronomical Telescopes + Instrumentation, 2016, Edinburgh, United Kingdom

Maunakea Spectroscopic Explorer Design Development from Feasibility Concept to Baseline Design

Kei Szeto[1a], Hau Bai[d], Steven Bauman[a], David Crampton[b], Nicolas Flagey[a], Mike Gedig[c], Peter Gillingham[h], Xuefei Gong[d], Kevin Ho[a], Nathan Loewen[g], Alan McConnachie[b], Shan Mignot[e], Richard Murowinski[a], Derrick Salmon[a], Will Saunders[h], Siegfried Stiemer[f], Tom Vermeulen[a], Kanoa Withington[a] and Kai Zhang[d],

[a] CFHT Corporation, 65-1238 Mamalahoa Hwy, Kamuela, Hawaii 96743, USA
[b] National Research Council Canada, Herzberg Astronomy and Astrophysics, 5071 West Saanich Road, Victoria, BC, Canada, V9E 2E7
[c] Dynamic Structures, 1515 Kingsway Avenue, Port Coquitlam , BC, Canada, V3C 1S2
[d] Nanjing Institute of Astronomical Optics & Technology, National Astronomical Observatories, CAS, 188 Bancang Street, Nanjing 210042, People's Republic of China
[e] GEPI, Observatoire de Paris, PSL Research University, CNRS, Univ Paris Diderot, Sorbonne Paris Cité, Place Jules Janssen, 92195 Meudon, France
[f] University of British Columbia, Department of Civil Engineering, 2002-6250 Applied Science Lane, Vancouver, BC, Canada, V6T 1Z4
[g] Sightline Engineering Ltd, 1493 Paisley Road, North Vancouver, BC, Canada, V7R 1C4
[h] Australian Astronomical Observatory, 105 Delhi Road, North Ryde NSW 2113, Australia

ABSTRACT

The Maunakea Spectroscopic Explorer is designed to be the largest non-ELT optical/NIR astronomical telescope, and will be a fully dedicated facility for multi-object spectroscopy over a broad range of spectral resolutions. The MSE design has progressed from feasibility concept into its current baseline design where the system configuration of main systems such as telescope, enclosure, summit facilities and instrument are fully defined. This paper will describe the engineering development of the main systems, and discuss the trade studies to determine the optimal telescope and multiplexing designs and how their findings are incorporated in the current baseline design.

Keywords: Calotte, enclosure, telescope, multi-object spectrograph, wide field corrector, atmospheric dispersion corrector, seismic upgrade, site redevelopment, Maunakea

1. INTRODUCTION

The concept of upgrading the Canada-France-Hawaii Telescope (CFHT) to a dedicated, 10 meter class, wide-field, fiber-fed multi-object spectroscopic facility was first proposed by Côté[1] in 2010 as a white paper entitled *The Next Generation CFHT* submitted to the Canadian Long Range Plan decadal review for astronomy and consequently started the grassroots movement for the next generation CFHT (ngCFHT) project. Following the ngCFHT feasibility study in 2012 led by McConnachie[2] and Szeto[3], their findings unequivocally demonstrated the scientific importance and technical viability of the project. Once completed, the Maunakea Spectroscopic Explorer (MSE), previously known as ngCFHT, will be the largest ground based optical telescope in its class and occupy a unique and critical role in the emerging network of astronomical facilities planned for the coming decade. Essentially, MSE is the only 10 m class spectroscopic facility under development to follow-up current and next generations of multi-

[1] Email: szeto@cfht.hawaii.edu; Telephone: 808-885-3188; Fax 808-885-7288

Ground-based and Airborne Telescopes VI, edited by Helen J. Hall, Roberto Gilmozzi, Heather K. Marshall, Proc. of SPIE Vol. 9906, 99062J · © 2016 SPIE · CCC code: 0277-786X/16/$18 · doi: 10.1117/12.2234213

wavelength imaging surveys, including LSST, Gaia, Euclid, SKA, and WFIRST, and is an ideal feeder facility for extremely large optical telescopes (ELT) under construction including the E-ELT, TMT and GMT.

The next milestone in the growth of the project came in early 2014, when the CFHT Board of Directors approved funding for a dedicated Project Office that would develop the upgrade concept into a full Construction Proposal. From the preceding development, it was clear that the scientific interest in this project was strong in many more communities than just within the Canada, France and Hawaii partnership, and also clear that to proceed into construction the project would need to expand its international partnership. In addition to the engineering progress described in this paper, the critical role of the Project Office to facilitate the partnership development is discussed in a companion paper by Murowinski[4]. To herald this project as a new observatory, reaching into an exciting future with a new partnership, the ngCFHT name was changed and the project christened and announced itself as the Maunakea Spectroscopic Explorer.

In parallel to technical and programmatic development, the driving science case and science requirements for the MSE baseline design are reported in a companion paper by McConnachie[5] and the defining MSE science capabilities are summarized in Table 1.

Table 1 MSE defining science capabilities

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 ★			
Spectrophotometric 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

In the current design phase, there are six participating partners from national institutes in Australia, Canada, China, France, India and Spain. The MSE design team is internationally distributed across these partners and engineering work is organized into work packages by subsystems according to the MSE system decomposition, Figure 1.

The current MSE subsystems include:

- Observatory Building and Facilities
  - Outer building enclosure pier
  - Inner telescope pier
- Calotte Enclosure
- Telescope
  - Telescope Structure
  - M1 System
  - Global Metrology System
- Top end systems
  - Hexapod System
  - Wide Field Corrector/Atmospheric Dispersion Corrector (WFC/ADC)
  - Instrument Rotator
  - Positioner and Metrology System
  - Telescope Optical Feedback System
    - Guide cameras and wavefront sensors
- Fibre Transmission System
- Low/Moderate Resolution Spectrographs
- High Resolution Spectrographs
- Science Calibration System
- Observatory Software and Control System

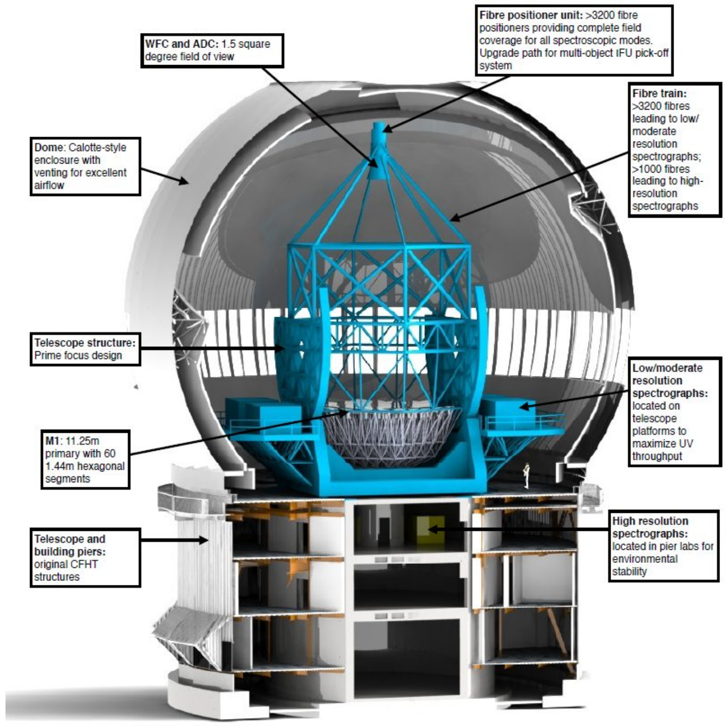

Figure 1 Cross-section of outer building and Calotte enclosure showing the MSE subsystems

2. BASELINE DESIGN DEVELOPMENT

2.1 Design Constraints

The baseline design of MSE follows the Office of Mauna Kea Management Comprehensive Management Plan[6] (CMP) which allows the redevelopment of CFHT provided the new facility does not exceed a 10% increase of the current three dimensional "footprint". Based on considerations for the CMP, we impose a 10% increase limit on the overall building height and enclosure radius while reusing the current telescope and enclosure piers.

Secondly, we do not intend to use connectors in the fiber transmission system between the fiber positioner units and spectrograph inputs in order to maximize throughput and preserve spectrograph stability and repeatability. This imposes additional considerations on placement of structure support and servicing procedures for installation and removal of the fiber positioner system together with the fiber transmission system. The MSE system level requirements and budgets, including throughput, are described in a companion paper by Mignot[7] and throughput optimization is presented in a companion paper by Flagey[8].

2.2 Enclosure Pier Seismic Upgrade

As reported in the previous SPIE proceeding[9], the technical feasibility study found two structural deficiencies in meeting the current seismic load requirements. The outer building enclosure pier steel bracing and, potentially, site soil bearing capacity are insufficient for the new enclosure and telescope. After further discussion with the structural civil engineer who performed the feasibility analysis, the soil capacity was deemed to be sufficient but, as a safeguard, independent geotechnical work is scheduled on-site for summer 2016 to confirm the latest soil capacity assessment.

In 2015, an upgrade plan using buckling restrained braces (BRBs) for seismic reinforcement of the enclosure pier was developed. The operating principle, example of building application and proposed enclosure pier modification are illustrated in Figure 2. The current plan will replace the current chevron braces in the 1^{st}, 2^{nd} and 3^{rd} floor with BRBs along the outer perimeter of the enclosure pier steel frame. However, the BRBs will be designed to operate in their elastic range during extreme earthquake so that there are no future needs for replacement. We believe this is most efficient and least disruptive approach to reinforce the enclosure pier.

Figure 2 Left -Buckling restrained brace provides seismic damping by dissipating energy primarily in yielding of the steel core (in tension and compression) and secondarily by friction between the steel core and fill material. The restraining mechanism is usually a concrete fill hollow structural shell encasing the steel core with an unbonding layer at the interface between them. The unbonding layer allows the steel core to slide over the concrete. Since the steel core is restrained from buckling, its cross section can then be "tuned" to yield plastically at predetermined seismic level to dissipate energy. Middle – Pairs of yellow chevron BRBs are installed in three bays of a steel frame building. Right - Current CFHT enclosure steel frame pier where the chevron braces will be replaced by BRBs in the outside empty bays in the lower floors where there are no chevron braces; however, BRBs are designed to operation in their elastic range as conventional braces, but without buckling limitation.

Additional upgrade to the Observatory Building and Facilities, including the enclosure pier, for MSE are described in a parallel paper by Bauman[10].

2.3 Finalization of Baseline Telescope Optical Configuration

The aperture of the M1 primary mirror is dictated by the etendue requirement, A-Omega $\geq 117 m^2 deg^2$, stated in the MSE Science Requirements Document[11] (SRD). In context of a segmented mirror telescope using 1.44 m ELT-size segments and with a 1.5 deg^2 field of view, the minimum telescope aperture is 11.25 m and comprises of 60 segments, Figure 3. Deducting allowances for top end obscuration, the effective collecting diameter is 10 m, i.e. the largest ground based optical telescope in its class.

Figure 3 also shows a 12.3m telescope aperture which is the next incremental size comprised of 72 segments.

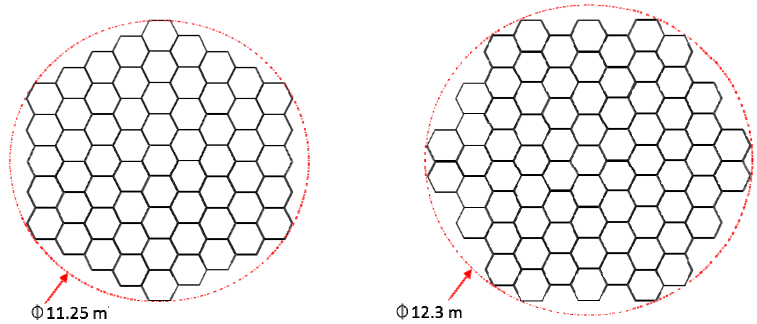

Figure 3 Left - 11.25 m M1, 60 segments not including the central segment. Right - 12.3 m M1, 72 segments not including the central segment.

Given the key design parameters, a system-level trade study was conducted to determine the optimal telescope configuration for the baseline design development process. The international design team was invited to submit alternate telescope optical designs governed by the same set of design requirements and enclosure size constraints. Four optical designs representative of the design space were submitted for evaluation in the trade study, Figure 4:

- National Research Council - Herzberg (NRC) prime-focus (PF) with Φ11.25 m, 60 segment M1
- Nanjing Institute of Astronomical Optics & Technology (NIAOT) Quasi-PF (QPF) with Φ12.3 m, 72 segment M1
- Australian Astronomical Observatory Cassegrain-focus (CF) with Φ12.3 m, 72 segment M1
- Australian Astronomical Observatory (AAO) prime-focus with Φ11.25 m, 60 segment M1

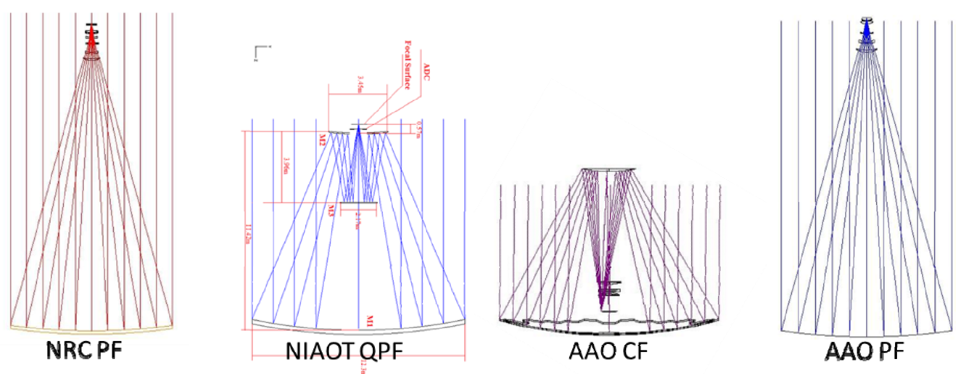

Figure 4 Four candidate optical designs were compared in the trade study – NRC PF has an 11.25 m M1, five element WFC and two element ADC; NIAOT QPF has a 12.3 m M1, 2.17 m M2, 3.45 m M3 and a lens-prism strip ADC; AAO CF has a 12.3 m M1, 2.75 m M2 and three element WFC/ADC; AAO PF has an 11.25 m M1 and five element WFC/ADC.

The trade study was based on comparison of optical performance and non-optical attributes evaluated from a system perspective in order to assess how a telescope based on each optical design would impacts the overall efficiency and operation through the observatory lifetime. CAD models of the MSE observatory are developed for each optical design in order to facilitate evaluation of operation modes, Figure 5.

In general, the PF telescope designs have lower construction costs and programmatic risks due to their simpler optical designs, with M1 and WFC/ADC delivering a focal surface at prime-focus. The PF optical designs provide an open telescope structure which facilitates access and servicing, mirror and dome flushing, and does not impose complex requirements on the observatory building and enclosure-mounted handling equipment. However, the blank size availability for the WFC/ADC leads to vignetting of the focal surface. The open telescope structure is longer therefore more vulnerable to wind-induced vibration and requires the 10% increase in enclosure size.

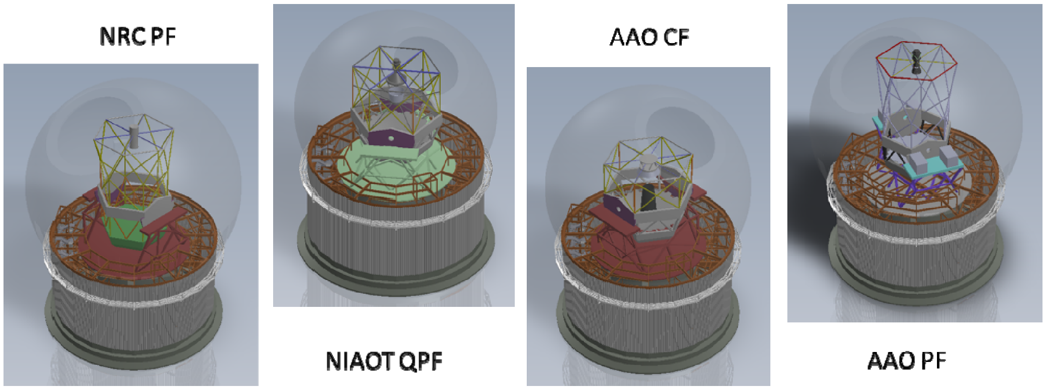

Figure 5 Representative CAD models showing the telescope structure inside the enclosure for each optical design.

The two non-PF telescope designs have extra optic costs over the cost of the WFC/ADC in the PF designs, e.g. 12 more M1 segments, large M3 and/or large M2. Unfortunately, the extra costs do not increase the effective collecting diameter significantly, ~3%, due to the large central obscurations. For the AAO CF design, the M2 light baffle was estimated to be 3.8 m in diameter. For the NIAOT QPF design, M3 has a mirror diameter of 3.45 m not including its cell and support structure. Although the compact telescope structures are less vulnerable to dynamic disturbances such as wind shake due to having top-end far away from external wind at the enclosure aperture opening, compactness does not facilitate access and servicing, mirror and dome flushing, and imposes additional design and operational requirements on the observatory building and enclosure-mounted handling equipment for servicing of instrument system, spectrographs, M3 and/or M2 systems.

By design, the trade study was a quantitative comparison of the four telescope optical designs. A decision matrix was created to facilitate the assessment process which contains eight categories with 45 items. It compares the optical designs performance and analyze their impacts at the observatory system level, Table 2, including:

- Optical performance
- Observatory building design
- Enclosure design
- Telescope structure design
- System performance
- Instrument maintenance
- Observatory operation
- Project programmatic

Table 2 Selected examples of categories and items considered in the decision matrix.

Criterion		Priority	Related Item	NRC Prime-Focus	AAO Cass-Focus	NIAOT Quasi- PF	AAO Prime-Focus
Category	Item	1 to 3*					
				Score 0 to 5, 5 being worst			
Observatory Building	Inner pier foundation load		Mount control: telescope mass				
	Building pier foundation load		Telescope length				
	Observing floor complexity	1		1	2	2	1
Enclosure	Enclosure size		Telescope length				
	Crane and platform complexity	2		1	3	3	1

After examining all four optical designs and their impacts at the observatory system, it revealed the PF configuration as the optimal configuration while meeting the MSE science requirement for etendue. We adopted the AAO PF configuration as the baseline optical design and determined the non-PF designs to have higher costs due to additional optics required which cannot be justified by only a 3% increase in effective collecting area.

2.3.1 External Optical Design Review

To ensure the MSE optical baseline design is suitable, we conducted a design review of the AAO PF configuration with a four member external review panel. The panel members were asked to:

- Provide an assessment on whether the current telescope optical design meets the stated requirements for MSE and if it is a reasonable engineering solution within the available design space and sufficiently mature to be selected as the telescope baseline optical design.
- Assess if there are any specific areas in need of further development prior to becoming the telescope baseline optical design.
- Identify any programmatic, technical and/or manufacturability risks, and provide corresponding mitigation strategies.

The review panel found the optical design to be a reasonable engineering solution that meets the design requirements and commented the biggest risk of the baseline design is the feasibility of manufacturing in the areas of polishing and anti-reflection coating of the WFC/ADC optics, Figure 6. To mitigate the manufacturing risk, the review panel suggested to investigate design variations to ease the polishing challenges and, in parallel, retain the service of an independent consultant to engage potential vendors to explore optimal manufacturing options.

The MSE optical design, including the compensating lateral ADC functionality, is reported in a companion paper by Saunders and Gillingham[12].

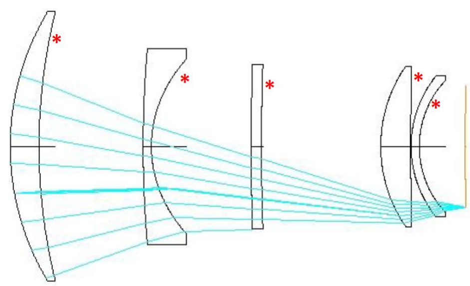

Figure 6 MSE WFC/ADC design. The focal surface is on the right and L1 is on the left, it is the largest lens with clear aperture of 1300 mm. L3 and L5 are PBM2Y; all other lenses are silica. Surfaces marked with a * are aspheric.

2.4 Developing the Baseline Enclosure and Telescope Structure Configuration

Given the following constraints: the Calotte enclosure dimensions; telescope optical layout; telescope-mounted payloads and their locations; access and servicing requirements for instrument and telescope and enclosure components; geometry and load capacities of the enclosure and telescope piers, etc., Dynamic Structure (DS) in Port Coquitlam, BC, Canada was contracted to develop a baseline geometry. The baseline geometry is a coherent Calotte enclosure and Alt-Az telescope structure configuration that is geometrically compatible to form the baseline for conceptual design. In other words, the objectives of the DS work was to provide a structurally credible and geometrically consistent enclosure and telescope structure configuration that enforces operational safety and ensures efficient access for servicing at the observatory level within the stated constraints.

The initial DS telescope structure concept is based on the Keck telescope which is a 10 m segmented mirror telescope of similar to MSE. Recognizing the aforementioned design constraints, DS developed a structural-mechanical solution compatible with the handling procedures envisaged and requires minimal facility modification, e.g. the telescope weight is within the capacity of the inner pier. The baseline configuration established by DS is shown in Figure 7.

The MSE telescope structure is similar to the Keck design but deviates in several key aspects. The deviations are driven by differences in the optical layout, payloads, handling procedures, geometric limitations of the Calotte enclosure. For the telescope elevation structure, the most significant differences are the compression leg top end structure support, larger elevation journals and the replacement of the monocoque elevation ring of Keck with an open space truss to facilitate mirror and dome flushing. The azimuth structure is substantially different from Keck, employing a compact box structure, as opposed to the larger space truss design for Keck, matching the inner pier diameter.

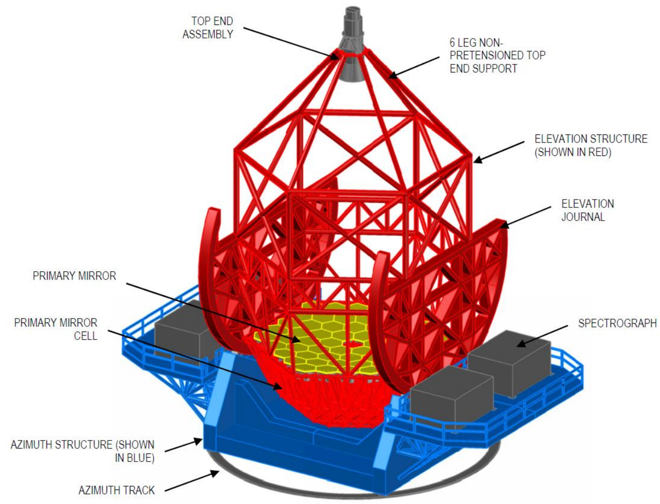

Figure 7 MSE telescope structure baseline design.

The design motivations for the baseline design are as follows:

- Maximize clearance within the enclosure
- Maximize stiffness, while minimizing the overall telescope height, with a low profile azimuth structure
  - Achieve through a direct load path to the pier, and by increasing the diameter of the elevation journals.
- Achieve a direct load path by matching the telescope azimuth track diameter with the inner pier
- Improve prime focus components and handling with non-pretensioned top end support structure
- Achieve a minimum weight design with space-truss structure, rather than monocoque structure
  - Optimize the distribution of structural mass based on stiffness and elevation structure mass balancing
  - The total telescope mass budget is 300 metric tonnes.

A Calotte configuration was selected for the enclosure in earlier design studies due to its compact design and structural efficiency. These features give it the best possibility of closely matching the fundamental requirements for MSE such as the existing CFHT enclosure size and mass but with an aperture opening that is over three times wider. Additional benefits of the Calotte enclosure include balanced rotational mechanisms and a circular aperture opening to provide wind protection of the telescope top-end.

The DS Calotte concept is based on the following requirements:

- Not to exceed combined structure height of 42.0 m, enclosure plus facility building,
- Maximum enclosure radius of 18.4 m
- Aperture opening of 12.5 m and maximum observing zenith angle of 60 degrees
- Total mass limit of 510 tonnes
- Deployable dome crane for instrument handling, capacity 10 tonnes
- Provision for enclosure-mounted mirror segment handling crane, capacity 0.5 tonnes
- Top-end servicing platform to provide access to the top-end with the telescope horizon pointing
- Ventilation modules on the rotating base to facilitate mirror and dome flushing

The most noteworthy design feature is the rotating base fixed shutter which eliminates a separate shutter track and drive system. In operation, the cap rotates over the shutter to close the enclosure aperture. Structurally, the shutter is supplementally supported by the cap via a pintle bearing and hard-stop assembly which limits the bending force at base attachment points under survival wind and seismic conditions by load sharing with the cap structure, Figure 8.

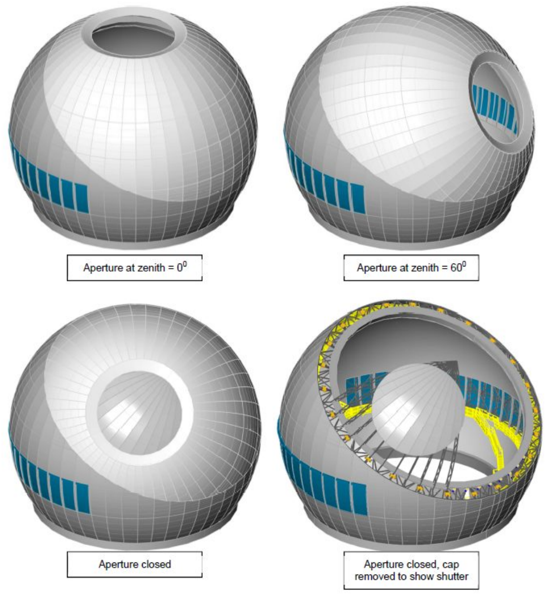

Figure 8 MSE Calotte enclosure concept with fixed shutter structure.

2.4.1 Safety Clearance Zone between Enclosure and Telescope Structure

Since the geometric relationship between telescope and enclosure is tightly coupled, a safety clearance zone of 0.3 m is enforced for collision avoidance between the enclosure stay-out envelope and telescope stay-in envelope, Figure 9. To maintain optimal clearance, the enclosure spherical center is coincident with the telescope center, i.e. the intersection point between the azimuth and elevation axes.

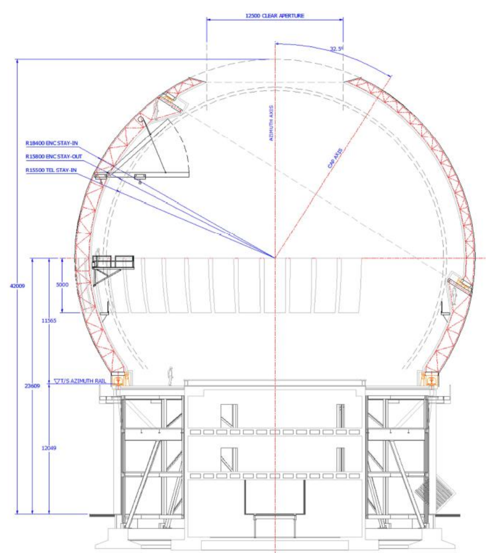

Figure 9 Dimensions of the enclosure geometry, safety stay-in and stay-out zones. The dome crane for instrument handling stows within the enclosure stay-out radius and the top end servicing platform in deployed position.

2.4.2 Handling and Access Features for Instrument, Enclosure and Telescope Components

Using the maintenance and servicing procedures envisaged for the instrument, enclosure and telescope components, an enclosure-mounted dome crane and top end servicing platform are incorporated in the design. The dome crane can safety handle the top end systems and spectrographs located on the telescope structure, Figure 10.

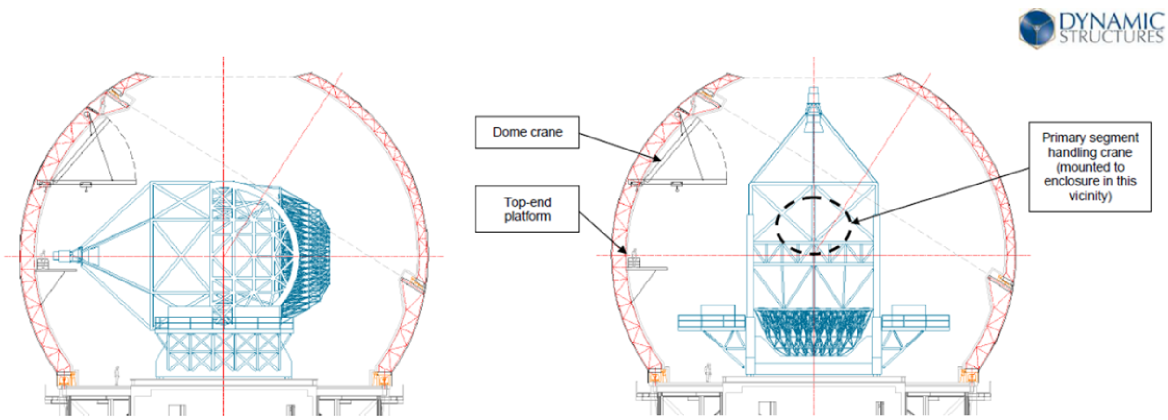

Figure 10 Instrument servicing scenarios: top end components access via top end servicing platform with telescope horizon pointing and dome crane overhead (left); dome crane above the spectrograph platfrom (right). Note: the top end servicing platform can be fixed in its deployed position permanently without colliding with the telescope structure.

In addition, an enclosure-mounted segment handling system similar to the Keck telescopes using a customized crane and lifting talon is envisaged, Figure 11. Figure 12 shows the access walkways to service the vent level, top end servicing platform and cap-base interface mechanical system.

Figure 11 Keck telescope style enclosure-mounted segment handling crane.

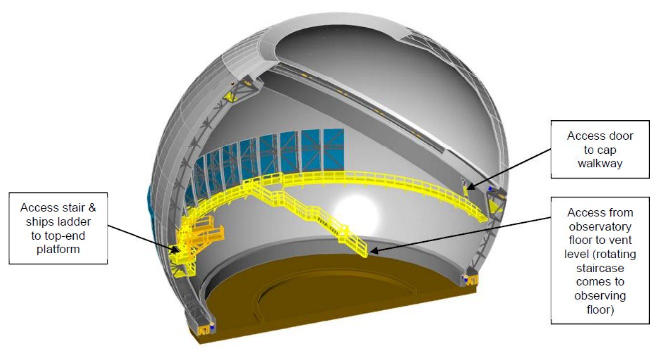

Figure 12 Enclosure system access walkways.

2.5 Developing the Optimal Multiplexing Configuration

The SRD specifies the multiplexing levels at the three designated spectrograph resolutions:

- ≥3,200 spectra at R3,000 (low) and ~R6,000 (moderate) at full field coverage
- ≥1,000 spectra at high resolution ~R40K (high) at full field coverage

The block diagram of MSE is illustrated in Figure 13. The systems that directly affect the multiplexing capabilities are the Positioner System (PoS), Fibre Transmission System (FiTS) and spectrograph resolutions. The MSE system architecture divides the spectrographs into two groups: low and moderation resolution (LMR) and high resolution (HR). The spectrographs can be “fed” by one of the two positioner technologies, Echidna or Phi-Theta, Figure 14, with either two sets of dedicated fibre bundles or a single set of fibre bundles that are shared among the LMR and HR spectrograph systems by reconfiguring their slit inputs. The slit options are manual switching, optical relay, image slicers or remote fibre switches. To achieve full field coverage at all resolutions, only every one of three Echidna positioners is required to carry separate LMR and HR fibres whereas every Phi-Theta positioner needs to carry two fibres each and must depend on fibre switching technology to operate successfully.

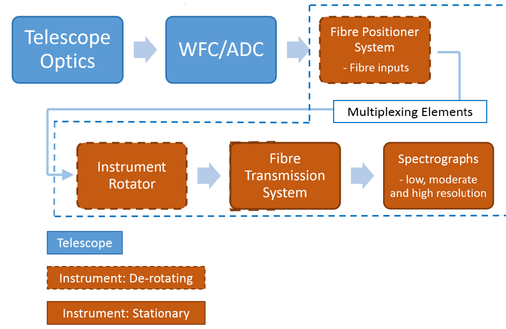

Figure 13 MSE system level block diagram.

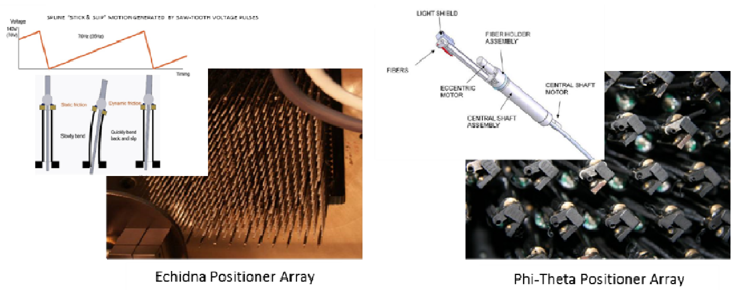

Figure 14 Positioner technologies - Echidna and phi-theta.

After considering 15 possible combinations of multiplexing configurations with different positioner technologies, fibre bundle and slit input options with or without fibre switches to deliver the required number of science targets to the LMR and HR spectrographs, the 12 most viable options were included in a trade study to determine the optimal configurations. Like the telescope optical configuration trade study, it was conducted at the same level of quantitative details with ten categories and 25 items ranging from performance comparisons such as throughput, positioner accuracy and configuration time, operation considerations such as reliability, interface requirements and versatility, and programmatic appraisals such as technical readiness level, schedule and cost, Table 3.

Table 3 Portion of the multiplexing trade matrix showing quantitative details

1	Expectations				Score 1 (poor) to 5 (good)			Score 1 (poor) to 5 (good)			Score 1 (poor) to 5 (good)
2	Category	Criterion									
3			Score	Value	Phi-Theta 3200/4000 fiber	Score	Value	Phi-Theta 3200/4800 fiber	Score	Value	Phi-Theta 3200/6400 fiber
4	Performance	Optical throughput - end to end	2	10	Ref 3: PFS maximum optical tilt at fibre tip = 0.6 deg, ref 4: LAMOST maximum tilt = 0.5 deg. Improved HR SNR possible with custom HR fibre diameter.	5	25	Ref 3: PFS maximum optical tilt at fibre tip = 0.6 deg, ref 4: LAMOST maximum tilt = 0.5 deg. Improved HR SNR possible with custom HR fibre diameter.	5	25	Ref 3: PFS maximum optical tilt at fibre tip = 0.6 deg, ref 4: maximum tilt = 0.5 deg. Improved HR SNR possible with custom HR fibre diameter.
5		Positioning Placement Accuracy	3	15	Ref 3: PFS = 10um, ref 4: LAMOST = 40um, new UTSC design = 5um	3	15	Ref 3: PFS = 10um, ref 4: LAMOST = 40um, new UTSC design = 5um	3	15	Ref 3: PFS = 10um, ref 4: LAMOST = 40um, new UTS = 5um
6		Fiber position stability		0			0			0	
7		FRD	2	6		4	12		4	12	
8		Fringing of optical path		0			0			0	
9		Reconfiguration speed			Ref 3: PFS shall be capable of completing fiber configuration in 105 seconds [TBC] or less for 95% [TBC] of the 2394 fibers after the telecope and instrument rotator are settled at the target positions. Ref 4: LAMOST reconfig time < 5min. New UTSC design is expected to reconfigure in 33s, not including metrology time.			Ref 3: PFS shall be capable of completing fiber configuration in 105 seconds [TBC] or less for 95% [TBC] of the 2394 fibers after the telecope and instrument rotator are settled at the target positions. Ref 4: LAMOST reconfig time < 5min. New UTSC design is expected to reconfigure in 33s, not including metrology time.			Ref 3: PFS shall be capable of completing fiber configurati seconds [TBC] or less for 95% [TBC] of the 2394 fibers afte telecope and instrument rotator are settled at the target posi Ref 4: LAMOST reconfig time < 5min. New UTSC design i to reconfigure in 33s, not including metrology time.
10		Target Allocation Yield - LR	4	12		4	12		4	12	
11		Target Allocation Yield - HR	3	12		3	12		3	12	
12		Capability for accurate short open-loop movement	0	0	40um	0	0	40um	0	0	40um
13		Cross-talk		0			0			0	
14		Cost	2	8	PFS: 21.66m, USTC: 15.5m	3	12	PFS: 22.8m, USTC: 16.4m	3	12	PFS: 25.2m, USTC: 18.7m

After examining all feasible combinations, six conceptual design studies including one for each different positioner technology are selected for conceptual design development and the work was divided among the international design team:

- Phi-Theta positioner system design
  - Dedicated 3468 fiber bundles feeding the LR/MR and HR spectrograph system separately
  - Additional Theta stage option to feed the HR spectrograph system with 1156 fiber bundle without requiring fibre switches
- Echidna positioner system design
  - One 3468 fiber bundle feeding the LR/MR spectrograph system
  - One 1156 fiber bundle feeding the HR spectrograph system
- Low and moderate resolution spectrograph design
  - Modular design with a total of 3468 spectra capacity
- High resolution spectrograph design
  - Modular design with a total of 1156 spectra capacity
- Optical switch study (feasibility study only)
  - Ability to switch from 3468 fiber inputs to 1156 fiber outputs
- Fiber transmission system design

We believe at the completion of these design studies an optimal multiplex configuration fully meeting the SRD requirements will be identified as the multiplexing baseline design.

2.6 Additional Design Development

2.6.1 Science Calibration System

A companion paper by Flagey[13] describes the current status of the science calibration development and the associated challenges and proposed solutions in meeting the calibration requirements as dictated by the SRD. Once this work is complete, the calibration solutions will be implemented by incorporating them in the telescope structure design.

2.6.2 System Budgets

A companion paper by Mignot[7] describes the current status of the system budgets development using the bottom-up approach to understand and capture the "complex" relationships between requirements and maintain traceability to Level 0 requirements from the SRD, Figure 15. Once this work is complete, the system budgets will be incorporated in the Observatory Requirements Document (ORD) and then flow down to the level 2 system design requirements documents, Figure 16.

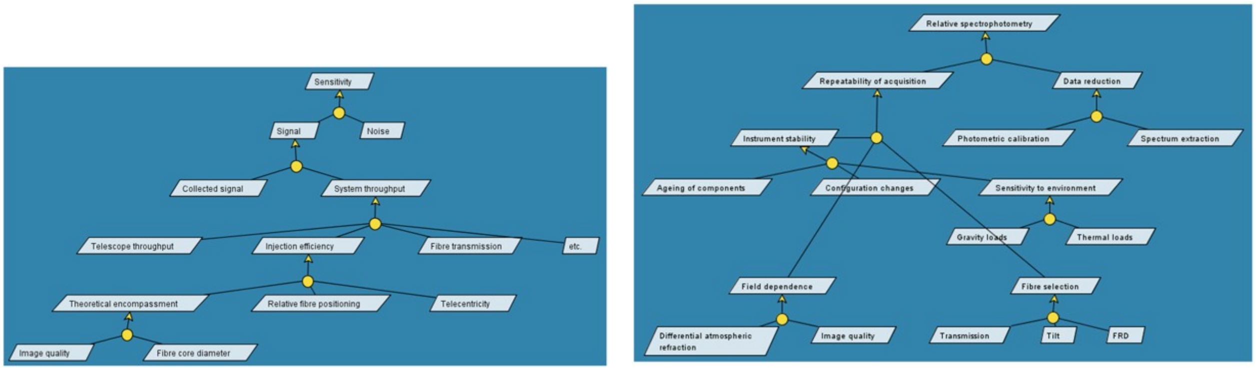

Figure 15 KAOS semantics to illustrate pictorially the inter-relationships among the different system budget items. Left - Requirement flow-down from Sensitivity to IQ (partial diagram). The refinement links indicate that the target requirement is only met if all the source requirements are satisfied. Right - Requirement flow-down from Relative spectrophotometry to IQ (partial diagram).

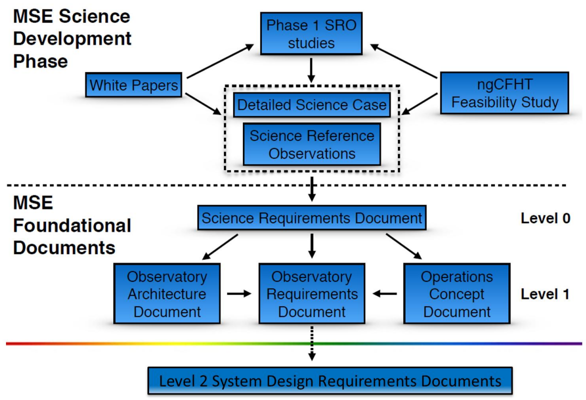

Figure 16 Requirements flow down for level 2 system design requirements.

2.6.3 Observatory Software Architecture

A companion paper by Vermeulen[14] describes the current status of the observatory software design development. The MSE software design will be led by the Project Office and partitioned among the international design team with a goal to build on the success of the existing remote observing software from CFHT and other observatories with large survey programs, by reusing and redeployment where appropriate.

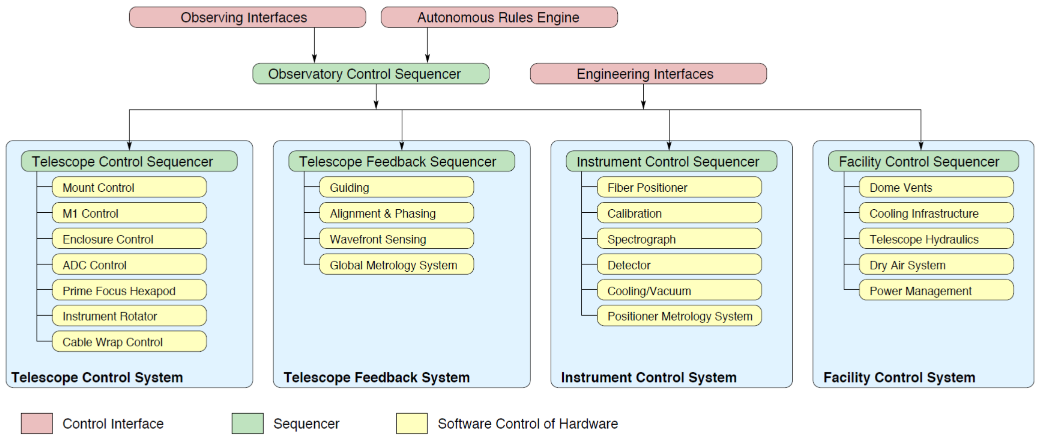

Figure 17 MSE software control architecture diagram

3. SUMMARY

With the system decomposition of the observatory fully described and the baseline design of the major systems defined the MSE project is progressing into the conceptual design phase. We plan to complete the enclosure and telescope structure conceptual design in early 2017. The multiplexing baseline development is underway supported by three competing positioner systems designs, LMR and HR spectrograph designs, and fibre switch and transmission system designs. We will finalize the multiplexing baseline design by the end of 2016 after down-selecting to one positioner technology.

Parallel design development of science calibration, system budgets, level 2 system requirements and observatory software are also underway with a goal to complete a system level conceptual design review in 2017.

REFERENCES

1. Côté P., et al., "The Next Generation CFHT", white paper submitted to the Canadian Long Range Plan decadal review, (2010).
2. http://mse.cfht.hawaii.edu/observatory/Feasibility_Science_Final.pdf (2012)
3. http://mse.cfht.hawaii.edu/observatory/Feasibility_Technical_Final.pdf (2012)
4. Murowinski, R., McConnachie, A. W., Simons, D., and Szeto, K., "Maunakea Spectroscopic Explorer: the status and progress of a major site redevelopment project", *Ground-based and Airborne Telescopes*, Proc. SPIE 9906 (July 2016, this conference).
5. McConnachie, A., "Science-based requirement and operations development for the Maunakea Spectro- scopic Explorer", *Ground-based and Airborne Telescopes*, Proc. SPIE 9906 (July 2016, this conference).
6. http://www.malamamaunakea.org/?p=323
7. Mignot, S. B., Flagey, N., Szeto, K., Murowinski, R., and McConnachie, A. W., "Systems budgets architecture and development for the Maunakea Spectroscopic Explorer", *Modeling, Systems Engineering, and Project Management for Astronomy*, Proc. SPIE 9911 (July 2016).
8. Flagey, N., Mignot, S. B., Szeto, K., McConnachie, A. W., and Murowinski, R., "The Maunakea Spectroscopic Explorer: throughput optimization", Ground-based and Airborne Instrumentation for Astronomy, Proc. SPIE 9908 (July 2016).
9. Szeto K., Angers M., Breckenridge C., Bauman S., Loewen N., Loop D., McConnachie A., Pazder J., Salmon D., Spano P., Stiemer S., Veillet C., "Feasibility studies to upgrade the Canada-France-Hawaii Telescope site for

the next generation Canada-France-Hawaii Telescope", *Ground-based and Airborne Telescopes*, Proc. SPIE. 8444, (September, 2012)

10. Bauman, S. E., Green, G., and Szeto, K., "Maunakea Spectroscopic Explorer observatory upgrade: a revised and optimized astronomical facility", *Ground-based and Airborne Telescopes*, Proc. SPIE 9906 (July 2016, this conference).
11. http://mse.cfht.hawaii.edu/docs/mse-science-docs/DSC/SRD_2015Nov04%20v2.pdf
12. Saunders, W. and Gillingham, P. R., "Optical designs for the Maunakea Spectroscopic Explorer telescope", *Ground-based and Airborne Telescopes*, Proc. SPIE 9906 (July 2016, this conference).
13. Flagey, N., McConnachie, A. W., Murowinski, R., Szeto, K., and Mignot, S. B., "Spectral calibration for the Maunakea Spectroscopic Explorer: challenges and solutions", *Observatory Operations: Strategies, Processes, and Systems*, Proc. SPIE 9910 (July 2016).
14. Vermeulen, T. A., Isani, S., Withington, K. K., Ho, K. K. Y., Szeto, K., and Murowinski, R., "Observatory software for the Maunakea Spectroscopic Explorer", *Software and Cyberinfrastructure for Astronomy*, Proc. SPIE 9913 (July 2016).