Crosschecking the Maunakea Spectroscopic Explorer performance budgets and science requirements compliance

Samuel C. Barden[*a]

[a]CFHT Corporation, 65-1238 Mamalahoa Hwy, Kamuela, Hawaii 96743, USA;

ABSTRACT

Maunakea Spectroscopic Explorer (MSE) is a massively multiplexed spectroscopic survey facility that will replace the Canada-France-Hawaii-Telescope. This 11.25-m telescope, with its 1.5 square degrees field-of-view, will observe 4,332 astronomical targets in every pointing. Fibers at the prime focus will pick up the light and transmit it to banks of low/moderate (R=3,000/6,000) and high (R=40,000) resolution spectrographs. Actuators position individual fibers in the field of view to enable simultaneous full field coverage for both resolution modes. This instrument suite, dedicated to large scale surveys, will enable MSE to collect a massive amount of data: equivalent to a full SDSS Legacy Survey every 7 weeks.

A conceptual design was developed in recent years and the project is preparing for the preliminary design phase. Now is the time to do a thorough cross check of the system level performance budgets against the predicted performance of the conceptualized systems and to check their compliance against the high level science requirements. This is particularly important in light of changes in scope due to scientific revisions and to technical challenges encountered during the conceptual design phase. Areas of non-compliance will require review as to how best to mitigate the non-compliance.

The results of this analysis led to issues being identified with the telescope and spectrograph concepts. This paper will summarize progress on this analysis, redesign, and trade study.

Keywords: Massively multiplexed spectroscopic surveys, 10m-class telescopes, telescope design, spectrograph design, systems engineering, trade studies

1. INTRODUCTION

Maunakea Spectroscopic Explorer (MSE) is the first planned project among 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. We are cognizant that the decisions we make today are intertwined with the future of Maunakea and its cherished summit. The MSE Project deeply respects its cultural importance and storied past.

Massively multiplexed spectroscopic facilities have recently been or will soon be implemented on a variety of 4-meter class telescopes (e.g., WEAVE[1], DESI[2], 4MOST[3]). Although these facilities will enable extensive scientific surveys exploring such questions as the nature of Dark Energy and the structure of the Milky Way galaxy, they will remain somewhat limited in the depth of those surveys due to the aperture of the telescopes. Imaging surveys already produce targets fainter than what these spectroscopic facilities can observe. The 8-meter class Simonyi Survey Telescope (LSST) of the Vera C Rubin Observatory[4] and the James Webb Space Telescope will also soon flood the field with targets 6 to 7 magnitudes fainter than the background sky. As such, there remains a need for larger aperture facilities for proper spectroscopic follow-up of the targets coming from these facilities and their related surveys.

[*] barden@cfht.hawaii.edu; phone 1 808 885-3174; cfht.hawaii.edu

MSE will be a premier facility for spectroscopy of the faintest targets (S/N = 2 in 1 hour for 24th magnitude objects at a spectral $\lambda/\Delta\lambda$ resolution of 3000) in the optical and near-IR bands from a ground-based observatory. As the project moves forward from concept to preliminary design, now is the time to do a thorough crosscheck of system level performance budgets against the predicted performance of the conceptualized systems and to check their compliance against high level science requirements. This is particularly important due to changes in scope from scientific revisions and to technical challenges encountered during the conceptual design phase. Areas of non-compliance require review as to how best to mitigate the non-compliance. This paper presents some of the progress in this process.

2. AREAS OF CHALLENGE

TELESCOPE DESIGN: As reported previously[5], an optical ghost issue was uncovered with the baseline conceptual MSE telescope design. This ghosting manifested itself in the production of ~0.6 arc-minute sized image ghosts. Two such ghosts were generated per 13th magnitude or brighter source at a signal level that would impact observations of 24th magnitude targets if the ghost were to fall within the target's fiber aperture. Although such ghosts could, in theory, be avoided through fiber assignment algorithms, the larger number of ghosts within each MSE field of view is significant. Target assignment mitigation would be complex and would be an unnecessary observational constraint if the ghosts could be diffused or removed by design.

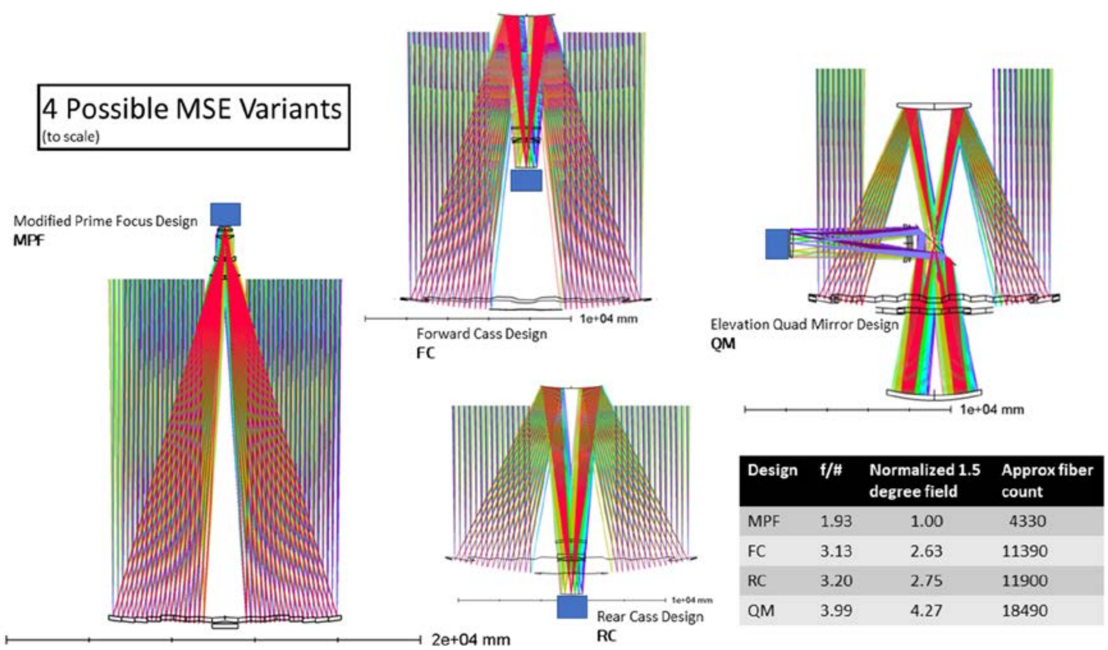
Several telescope design options have been explored to reduce optical ghosting[6] with four likely viable solutions of which two are considerably more advantageous to the existing baseline concept.

SPECTROGRAPH DESIGN: The conceptual design reviews flagged both the optical high resolution (HR) and optical/near-IR low resolution (LMR) spectrographs as very challenging.

Both spectrograph designs are undergoing significant redesign to reduce these technical risks, but remain quite challenging. Continued monitoring of progress and design exploration remains.

3. TELESCOPE OPTION TRADESTUDY

Significant effort has been undertaken to re-examine the telescope design options to reduce the optical ghosting. This has led to the production of the four viable solutions displayed in Figure 1.



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

Figure 1. Raytrace schematic of the four telescope concepts under review. These figures are to the same scale. The table shows the focal ratio, the normalized ratio of the 1.5-degree field of view physical area, and an approximate scaling of the fiber count based upon that change in physical size of the field assuming the same fiber physical spacing.

1. The Modified Prime Focus (MPF) design is very similar to the MSE baseline concept but with larger optical elements that relax the design to reduce the optical ghosting. The fast focal ratio is required to fit a prime focus into a dome that doesn't exceed 10% larger volume than the existing CFHT dome. The fast focus requires high NA fibers and limits the number of fibers while making spectrograph design somewhat challenging due to the fast focal ratio.

   Notable advantages:

   + Minimum number of mirrors (only one) and minimum central obstruction providing highest efficiency concept.

   + Most similar design to current baseline MSE concept therefor least disruptive for other MSE subsystem design development.

   Notable disadvantages:

   - Very fast focal ratio to fit the telescope into space constraints that likely impacts on fiber and spectrograph design/performance.

   - Design has more lenses, hence optical ghosts that need to be constrained to remain diffuse.

   - Abberation correction requires strong power within the WFC lenses plus glasses other than fused silica that are not readily available in the large volume required.

   - Field of view is the smallest which limits the density of fiber probes for a given field size.

   - Requires significant mass ballast due to dome size and location constraints.

   - Prime focus requires the longest fiber runs which impact blue efficiency performance and makes instrument access and exchange potentially difficult.

   - Instrumentation and WFC/ADC move fully with the telescope and have 3-dimensional gravitational variations.

   - Only one focal port limiting instrumentation options.

2. The Forward Cassegrain (FC) design is a design that preserves a long radius of curvature for primary mirror segment fabrication (RoC > ~30 meters). Although image performance and ghost behavior are good, the forward and embedded nature of the focus is deemed likely difficult and undesirable.

   Notable advantages:

   + Only two mirrors and 3 Fused Silica lenses required.

   + Optical ghost issue significantly reduced.

   + Slower focal ratio relaxes fiber cable requirements and possibly relieves spectrograph design parameters somewhat.

   + Larger physical field of view allows considerably more fiber probes enhancing survey capabilities.

   + More compact than current MSE concept allowing smaller dome volume.

   Notable disadvantages:

   - Focal station is embedded within the telescope between the primary and secondary making access likely difficult as well as fiber routing.

   - WFC optics still require considerable power for aberration correction with high order aspheric surfaces on most optical surfaces.

   - Instrumentation and WFC/ADC move fully with the telescope and have 3-dimensional gravitational variations.

- Only one focal port limiting instrumentation options.

3. The Rear Cassegrain (RC) design is a design with the focus located on the backside of the primary mirror. This design requires a shorter radius of curvature for the primary mirror segments. Production of such segments appear to be viable with modest retooling of existing segment production test facilities. The 3-meter secondary mirror is of an acceptable size. This design does require a considerable number of high order aspheric surfaces as do the MPF and FC designs. The WFC/ADC elements have half of their surfaces with 4th through 10th order aspheres. Image quality is excellent, and the potential fiber count is quite good with ~12,000 fiber probes possible within the 1.5 square degree field of view. Given that the focus is also concave, the fiber count is likely higher, and it may be possible to fit upwards of 15,000 fibers within the field of view.

   Notable advantages:

   + Only two mirrors and 3 Fused Silica lenses required.
   + Optical ghost issue significantly reduced.
   + Slower focal ratio relaxes fiber cable requirements and possibly relieves spectrograph design parameters somewhat.
   + Larger physical field of view allows considerably more fiber probes enhancing survey capabilities.
   + Most compact of all concepts allowing smallest dome volume.

   Notable disadvantages:

   - WFC optics still require considerable power for aberration correction with high order aspheric surfaces on most optical surfaces.
   - Instrumentation and WFC/ADC move fully with the telescope and have 3-dimensional gravitational variations.
   - Only one focal port limiting instrumentation options.

4. The Elevation Quad Mirror (QM) design is a radically different approach initially explored to minimize the number of lenses for a drastic reduction in optical ghost contamination. A strength of the QM design is the location of the focus at Nasmyth coincident with the elevation axis of the telescope. The f/4 focus allows ~19,000 fiber probes in a nearly gravitationally fixed orientation. The large lenses for the ADC are oriented vertically with respect to gravity likely making it more viable for implementing the ~1.8-meter diameter optics. The internal focus provides an intermediate location for alignment and test facilities. The flat fourth mirror is at a pupil image of M1 and could, in principle, be upgraded as an adaptable mirror for GLAO. The mirrors are conics and lenses are spherical.

   Notable advantages:

   + Mirrors do the aberration correction allowing simplification of 3 Fused Silica lenses required.
   + Mirrors are pure conics; all lens surfaces are spherical.
   + Fourth mirror located at pupil image and may provide best option for possible ground layer adaptive optics correction.
   + Optical ghost issue most significantly reduced of all concepts.
   + Slower focal ratio relaxes fiber cable requirements and possibly relieves spectrograph design parameters somewhat.
   + Largest physical field of view allows considerably more fiber probes than other concepts further enhancing some survey capabilities.
   + Compact configuration allowing smaller dome volume.
   + Focus at Nasmyth reducing gravitational variations to 2-d radial as instrument rotates.

+ Large fused silica optics feeding Nasmyth rotate with rotational variation only and could include an axial support.

+ Nasmyth foci allow option for multiple instruments being accessed by rotating the fourth mirror.

+ Nasmyth focus provides shortest fiber length and provides option for blue sensitive spectrographs being very close to the focal surface.

Notable disadvantages:

- Four mirrors reduce efficiency.
- Large central obstruction from the field of view increases vignetting.
- Nonstandard telescope concept.

The RC and QM designs both offer unique capability compared to the previous prime focus concept. Both would likely fit into a dome volume equal to that of the current CFHT. Both provide comparable image quality with >80% encircled polychromatic energy within 0.25 arc-seconds at 30 degrees ZD.

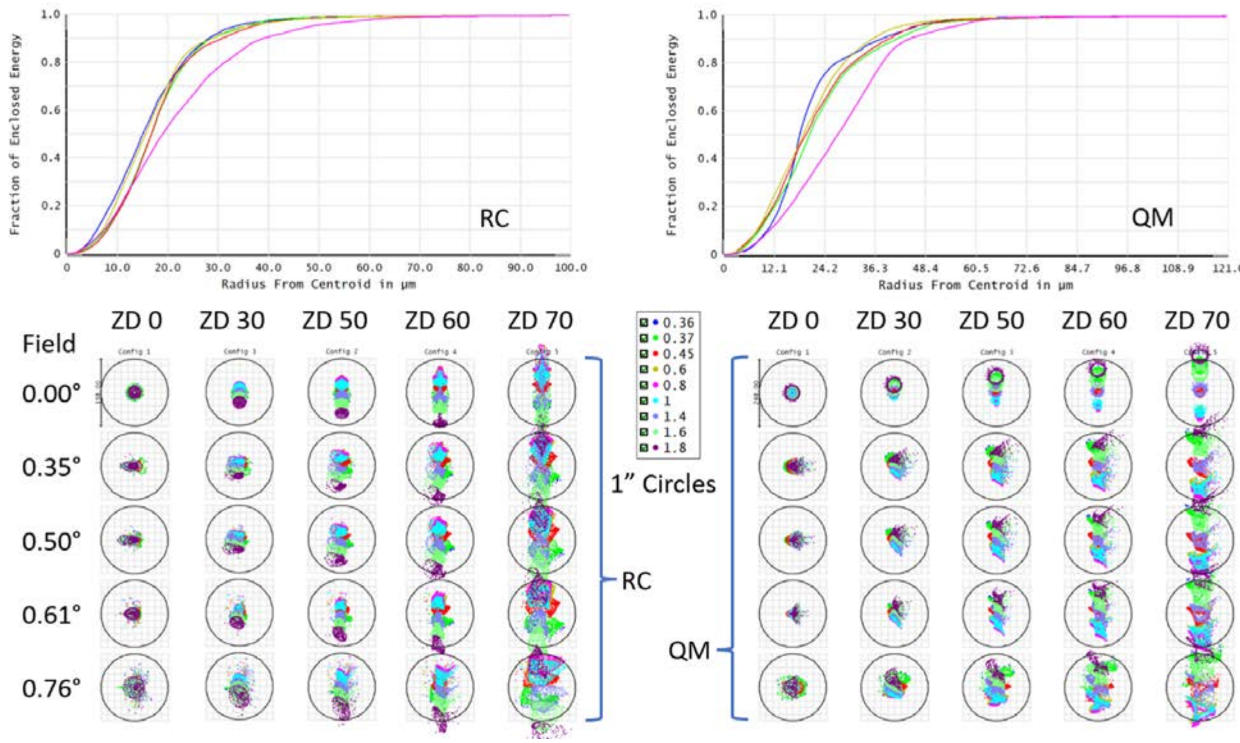


Figure 2. Image performance comparison of the RC (left) and QM (right) concepts. The top figures display the polychromatic (0.36 to 1.8 microns) encircled energy of a point source as a function of field angle (0 to 0.76 degrees) with the maximum radius of 0.5 arc-seconds. The 0.125 arc-second radius point (25 microns for the RC and 30.25 microns for the QM) show that 80% encircled energy is achieved for all but the outermost field angle. The bottom figures show the spot diagrams as a function of field angle and zenith distance. The circles are each 1 arc-second in diameter.

There are numerous other aspects of each design that need to be contrasted and evaluated before MSE can decide on the path forward. These will include analysis of the telescope structures required, the ease of implementation and maintenance (e.g., mirror coating effort, etc.), impact on scientific capabilities and performance, as well as cost among other aspects.

A formal review will be conducted to evaluate this trade study and that an incremental concept study of the selected design be conducted prior to the project advancing into the preliminary design phase of the MSE project.

4. ONGOING SPECTROGRAPH STUDIES

Continued explorations in spectrograph design are being pursued along with a proposal for a Pathfinder[7] instrument to solidify the designs. The Pathfinder will be proposed to evaluate key MSE related technologies for the evaluation of sky subtraction, component performance, and spectrograph performance. Many MSE components will likely utilize new or emerging technologies that have not yet been proven. The Pathfinder will provide that proof of concept.

The critical technologies that will likely be explored are those that enable the spectrographs to meet the demands of the MSE requirements. This may include methods for doing the wavelength splitting within the fiber assembly rather than the spectrographs and may explore options for image/pupil slicing. The intent is to enable the following:

- Reduction in spectrograph volume to allow more spectrographs to fit within the facility.
- Easing of spectrograph design to allow off-axis and transmissive optics.
- Reduction in spectrograph beam diameter to ease grating requirements.

As with the telescope design, the spectrograph designs will likely require further conceptual design phase effort before the project can fully move into the preliminary design phase.

5. CONCLUDING COMMENTS

The various studies described herein are intended to enhance the viability of the MSE project and to take advantage of slippages in project timeline stemming from the Maunakea lease process. The end result will be development of a facility worthy of the investment, worthy of the site, and worthy of a long lifetime of science productivity in the realm of the new generation of other telescope facilities such as Rubin, TMT, E-ELT, and GMT.

6. ACKNOWLEDGEMENTS

The mission of the MSE 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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