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Current status and future plans for the Maunakea Spectroscopic Explorer (MSE)

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ABSTRACT

The Maunakea Spectroscopic Explorer (MSE; formerly ngCFHT) will be a large format wide field spectroscopic facility that replaces the existing 3.6 m Canada-France-Hawaii Telescope. Capable of recording tens of thousands of spectra on faint targets each night, and sustain that pace for years, MSE will be an ideal complement to emerging space- and ground-based imaging survey facilities. The combination of aperture, spectral resolution, and dedicated access to support large surveys makes MSE distinct from any other facilities under development or being planned. We provide an overview of the MSE technical design, organization of the project office, and the core science goals that will help drive MSE for decades.

Keywords: spectroscopy, fiber, survey, optical, ngCFHT, wide-field

1. CONTEXT – NEW INSTRUMENTS & UPGRADES AT CFHT

Throughout its 35 year history, CFHT has provided forefront research capabilities from its remarkable site on Maunakea. To maintain CFHT's competitive edge several strategies will be used to build upon CFHT's strengths that ultimately lead to the Observatory being transformed into a new facility within a decade. Near-term, through upgrades to existing instruments and the delivery of new instruments, CFHT's community will continue to take advantage of Maunakea's unique characteristics including enhanced sensitivity at ultraviolet and infrared wavelengths (exploiting the dry atmosphere with limited aerosols above Maunakea), deep, high-resolution panoramic imaging (due to the stable atmosphere which yields good seeing), and dedication of large amounts of observing time to surveys (thanks in part to the large fraction of clear time available from the summit of Maunakea). To date the vast majority of the research publications produced over CFHT's history have been with its 1 degree panoramic imager MegaCam[1], which will be upgraded over the next year with more efficient filters and faster detector readout electronics to enable a new generation of imaging surveys. In addition an imaging Fourier Transform Spectrometer SITELLE[2] will be delivered to CFHT in 2014 which will be capable of generating spectra at visual wavelengths at each point in its ~10 arc minute field – much wider than conventional integral field spectrographs. This instrument will be the first facility-class imaging FTS used in astronomy and relies upon an extremely stiff carbon fiber support structure to house its Michelson interferometer. Precise laser metrology is used to maintain control of its scanning mirror system. This instrument will be particularly effective at mapping the motions and dissecting the chemical contents of stellar nurseries across entire galaxies. SITELLE is being built by ABB in Quebec under the leadership of the University of Laval and in collaboration with CFHT. In a few years SPIRou[3] will be delivered from a large international team with partners in France (Toulouse IRAP/OMP/UPS, Grenoble IPAG/OSUG/UJF, Marseille LAM/OHP/Pythéas/AMU, Paris IAP-IdF), Canada (NRC-H, UdeM, UL), Switzerland (Geneva Observatory), Taiwan (ASIAA), Brazil (LNA/UFRN/UFMG), Portugal (CAUP) and Hawaii (CFHT). SPIRou will be a unique fiber-fed near-infrared spectropolarimeter designed to detect terrestrial class exoplanets orbiting low mass stars in their habitable zones through precise radial velocity measurements. SPIRou relies upon ultra-stable thermal control of its optical bench, a sophisticated calibration system, and custom fluoride fibers that transmit through 2.5 μm. The lead team at Toulouse is starting the process of organizing an enormous survey that, if approved, will start in a few years and require ~500 nights of time at CFHT to complete, likely leading to the detection of hundreds of new exoplanets in the process. Overall this combination of upgrades and new capabilities will propel CFHT forward for the better part of a decade and will help bridge CFHT to its transformation into a new facility in the future.

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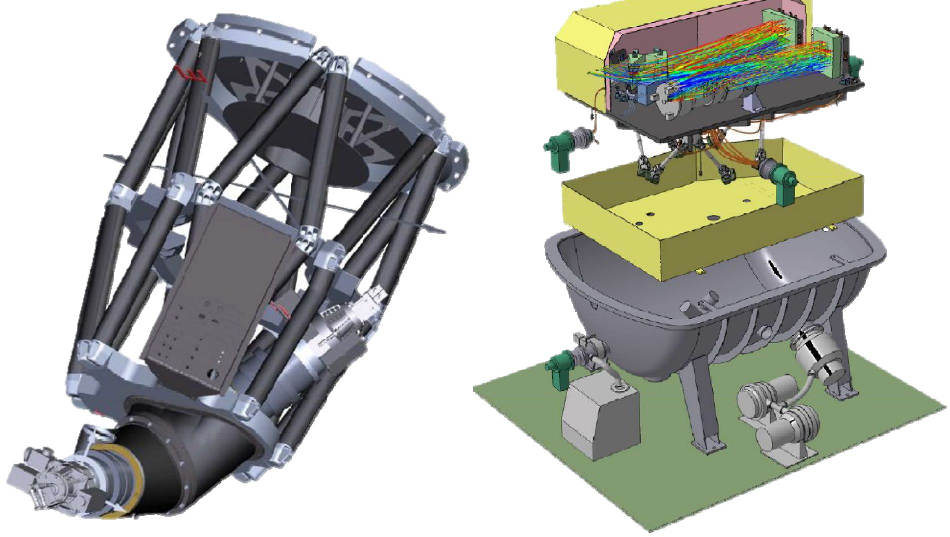

Figure 1 – Left: A CAD rendering of SITELLE is shown, which will be delivered to CFHT in 2014 and is the first facility-class imaging Fourier Transform Spectrometer used in astronomy. Right: The spectrograph portion of SPIRou is shown in this illustration, which yields R ~70K spectra across the YJHK bands in a single integration.

To shed light upon the biggest questions confronting 21st century astrophysics, CFHT is launching a project to explore its renewal. Recently completed feasibility studies have demonstrated the opportunity to achieve compelling and dramatic science through upgrading CFHT into an advanced, modern and unique facility. When completed, the "next generation CFHT" – now named the Maunakea Spectroscopic Explorer (MSE) – will yield stunning new research capabilities to tackle problems ranging from dark matter, dark energy and cosmology, to galaxy evolution and structure, the archaeology of the Milky Way, stars and stellar systems, exoplanets, and much more. The MSE project will upgrade the current 3.6 m telescope to a 10 m dedicated wide field spectroscopic telescope. With a field of view of ~1.5 degrees in which up to ~3000 separate objects could be observed simultaneously at spectral resolutions ranging from ~2000 – 20,000, MSE will be capable of delivering an exceptional quantity and quality of scientific data. Intended to support both individual programs and large scale surveys of unprecedented scale, MSE will enable new and richly diverse astrophysical research, complementing the other Maunakea observatories as well as those planned for deployment worldwide and in space. Near term the MSE Project Office, which was recently formed in CFHT's headquarters in Waimea, Hawaii, will take the lead on coordinating the design of MSE and developing the resource base needed to construct and operate it.

A cornerstone of this renaissance will be the expansion of CFHT's current partnership, making Maunakea accessible to an even broader international research community. Beyond the founding partners representing the astronomical communities in Canada, France, and Hawaii, CFHT also has Associate Partner agreements in place that provide opportunities for scientific and technical collaboration for the astronomical communities of Brazil, China, S. Korea, and Taiwan. Such international partnerships provide the foundation for developing revolutionary facilities like MSE. Accordingly the focus of the MSE Project Office for the next 3-4 years will be on developing a MSE construction proposal and cultivating support for this project within CFHT's existing and prospective new partners. All of this activity is described below in the following sections.

2. BUILDING UPON CFHT'S LEGACY OF INNOVATION – MAUNAKEA SPECTROSCOPIC EXPLORER (MSE)

For centuries observatories have expanded their research horizons by building new instrumentation using the latest technologies. For example CFHT was the first Maunakea observatory to develop a facility class multi-object spectrometer, integral field spectrometer, and adaptive optics system. When deployed nearly a decade ago CFHT's MegaCam was the largest digital focal plane in astronomy. This strategy served CFHT well over its history but in an age

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when 8 – 10 m telescopes are almost common and ELT's are being developed at several sites worldwide, a bolder approach is needed that builds upon CFHT's legacy and takes advantage of its exceptional site characteristics. MSE represents a complete facility upgrade and involves not just deploying a new instrument at CFHT, but replacing CFHT with a much larger telescope and dedicating a wide field multi-object spectrometer to its prime focus, all while remaining within essentially the same space envelope of CFHT's enclosure. The nominal top-level design parameters of MSE include –

- Ability to record efficiently very large numbers ($>10^6$) of low (R ~ 2000), moderate (R~ 6500), and high (R ~ 20,000) spectra of objects
- Faint science targets brightness range: $10 < g$ (mag) < 24
- Large areal coverage (1000 – 10,000 deg^2)
- Wavelength coverage from blue to NIR (~0.4 – 1.3 μm)
- Velocity accuracy of <<1 km/s in high-resolution mode
- Complete wavelength coverage in a single exposure at low resolution

MSE as currently envisioned is a powerful facility at the intersection a number of design and scientific goals. With several 4 m class facilities also planning to use wide field optical multi-object spectroscopy (e.g., 4MOST, WEAVE, DESI, HERMES, MOONS) and Subaru planning to deploy its Prime Focus Spectrograph[4] (PFS), it is important to point out the distinctions which make MSE not a competitor but a successor to these current-generation facilities. The combination of aperture, spectral resolution, and multiplex advantage already make MSE unique among these other facilities but it is the dedication of the entire MSE *system* to this single mode of operation that sustainably enables its remarkable scientific grasp. Because the MSE opto-mechanical configuration will be stable over the lifetime of the facility, i.e., the fiber positioner assembly and spectrographs will always be coupled, the wide field corrector and atmospheric dispersion compensator will always remain at the telescope top-end, subtle metrology shifts that might arise due to the repeated removal of the fiber positioner assembly are avoided, etc., the MSE data products are expected to be highly repeatable and well characterized. As SLOAN demonstrated, such large, well calibrated homogenous data sets are powerful tools for archival research on the universe. The difference is that programs that took SLOAN years to complete, MSE could complete in months.

3. KEY SCIENTIFIC OBJECTIVES

A comprehensive analysis of the broad range of science applications possible with MSE can be found in the ngCFHT feasibility study[5-7], a portion of which is summarized in the accompanying paper by McConnachie[8]. A common theme behind these science use cases is the need for enormous (often millions) of spectra of stars and galaxies at depths and spectral resolutions that are not accessible with any facility currently on the ground or in space. The wealth of objects identified through panoramic imaging surveys in recent years, and about to be uncovered through additional large scale surveys, is generating a critical need for spectroscopic follow-up to fully exploit these databases. While MSE is a successor to other highly multiplexed spectrometers under development now, it is likely that once demonstrated similar or even more powerful spectroscopic facilities will be developed through the next several decades as astronomy relies more on large scale statistical analyses of the universe to gain key insight into the structure, origin, and evolution of the universe. The revolution that MSE represents is due to a combination of advancements in computing, global information storage and

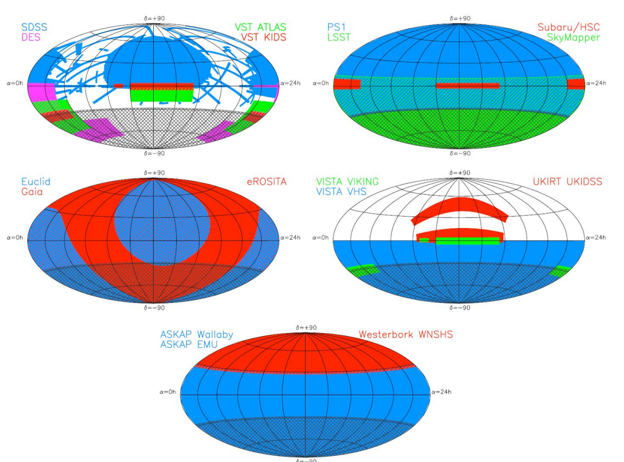

Figure 2 – The sky coverage associated with various wide field surveys from X-ray to radio wavelengths is shown. The ~3π steradian sky coverage possible from Maunakea using MSE leads to enormous overlap with these various surveys. Image credits: ngCFHT Feasibility Study.

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Figure 3 – Left, the Kepler field is shown superimposed on the night sky. Right, a rendering of the Kepler field with dots representing planets of varying mass discovered across the field. A comprehensive spectroscopic survey of this field which includes $>10^5$ stars is feasible with MSE. Image credits: NASA

sharing, and the replication of thousands of parts using advanced technologies. These same advancements have underpinned high energy physics through projects like the Large Hadron Collider, so in a sense astronomy projects that generate vast stores of data suitable for "mining" by astronomers are following the same path of high energy physics.

Just one example of how a spectroscopy facility like MSE could be used in a contemporary sense is to monitor the Kepler field (Figure 3), taking advantage of the faint object sensitivity and multi-object gain of MSE. Given its ~1.5° field of view, MSE will be able to survey the entire Kepler field with ~80 pointings, leading to spectroscopy of >100,000 stars. While MSE is not envisioned as a high precision velocimeter, surveying this field in which thousands of planets have already been found will be extremely useful to better link planet formation with stellar environment. More specifically, to determine the link between stellar metal content and planet formation. Furthermore, the sizes of transiting planets are derived from orbital transit times and assume a particular stellar diameter. Having high resolution spectra of all such stars to better determine their spectral types would significantly improve the characterization of the planets detected by Kepler. Finally, the high resolution mode of MSE would be enough to detect most of the brown dwarfs and closely separated hot Jupiters orbiting stars in this field and, combined with Kepler data, serve to better characterize the entire field's planetary component. This sample science case is linked to Kepler but could be extrapolated to other future exoplanet missions that involve staring at large numbers of stars in search of transiting planets.

A subset of other research applications explained in detail in the aforementioned feasibility study include –

- Generating a 3D map of the interstellar medium including flow dynamics, composition, and density measurements
- Studying quasar fields that would allow much better understanding of the interrelationships between galaxies and the inter-galactic medium through observations of thousands of Lyman-alpha absorbers
- Pursuing time-domain spectroscopy in a manner akin to time domain imaging using various panoramic facilities in place now or planned (e.g., LSST), opening new perspectives on high energy phenomena in the universe (e.g., novae).

4. TECHNICAL OVERVIEW

MSE will be a major upgrade to CFHT and, as such, some design constraints are fundamentally linked to the existing CFHT facility design. Central to these is the reuse of CFHT's existing telescope pier. One of the important products of the previous feasibility study for ngCFHT is that CFHT's existing pier is strong enough to accept the weight of a ~10 m segmented mirror telescope, similar to Keck. Some pier modifications would be needed to bring the current pier into conformance with modern building codes (for earthquake protection), but importantly the pier is already strong enough to support a modern large format telescope. The implied large mass of CFHT stems from its relatively slow focal ratio and large capacity top-end assembly, originally designed to support large wide field correctors, photographic plates, and astronomers in a prime focus "cage". The large prime focus instrument loads, and requisite dome crane and clearances needed to safely remove and install various top-end assemblies on CFHT, led to a dome diameter that is comparable to

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that used to enclose modern 8 – 10 m telescopes. Finally, the CFHT telescope assembly rests atop a large support building which provides ample space for housing the spectrographs envisioned for MSE, as well as all of the plant equipment (pumps, compressors, etc.), computer room, laboratory, and living space needed for MSE. Existing power and a 10 GB fiber link to CFHT provide a support backbone that is easily capable of supporting electrical loads and data rates envisioned for MSE. Given the costs of building such a large facility on the summit of Maunakea, and all of the connectivity needed to make it operational, the implied savings of reusing this infrastructure for MSE are substantial. The reuse of so much established infrastructure also accelerates the construction time needed to enable MSE and minimizes the downtime when CFHT is deconstructed in advance of the installation of the new MSE telescope and spectrographs.

Less obvious but equally important in the overarching goal of building MSE in a rapid and cost-effective manner is the anticipated simpler site permitting requirements associated with upgrading the facility compared to razing CFHT to ground level and starting from grade. By avoiding significant new concrete pours, preserving the existing footprint on the ground, and planned replacement of the CFHT enclosure with a similar size enclosure (albeit with a large aperture shutter), from the exterior MSE will ostensibly look similar to CFHT. This is important since Maunakea summit development is overseen by the Office of Mauna Kea Management (OMKM) and the process used to modify existing facilities, yet alone build new ones, involves considerable review, with consideration from environmental, cultural, and technical perspectives. This process is derived from the Mauna Kea Comprehensive Management Plan[9] (CMP) set in place several years ago to help ensure that this precious resource is preserved for future generations to enjoy. The CMP defines the sites available for astronomical facilities, protects native Hawaiian cultural sites on the summit, and establishes procedures to preserve the delicate Maunakea ecology. The MSE project is committed to not only working within the CMP throughout its development and operation but to promote its spirit through the responsible reuse of CFHT's site.

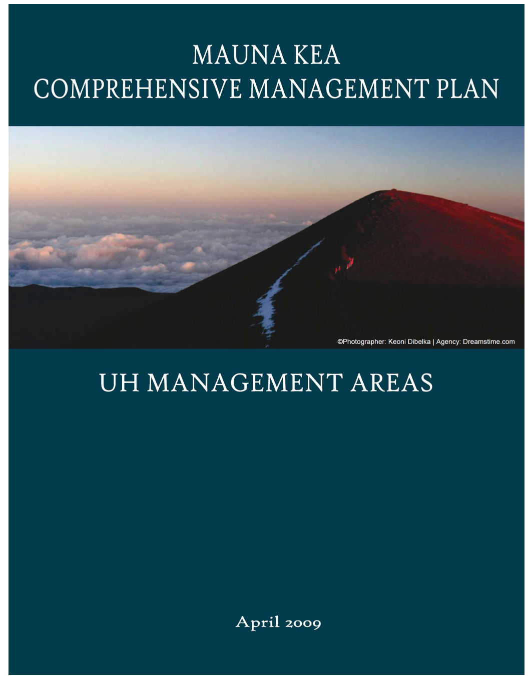

Figure 4 – Recycling CFHT will be done in the context of the Maunakea CMP to ensure that all requirements are met and the project is conducted in an environmentally and culturally sensitive manner.

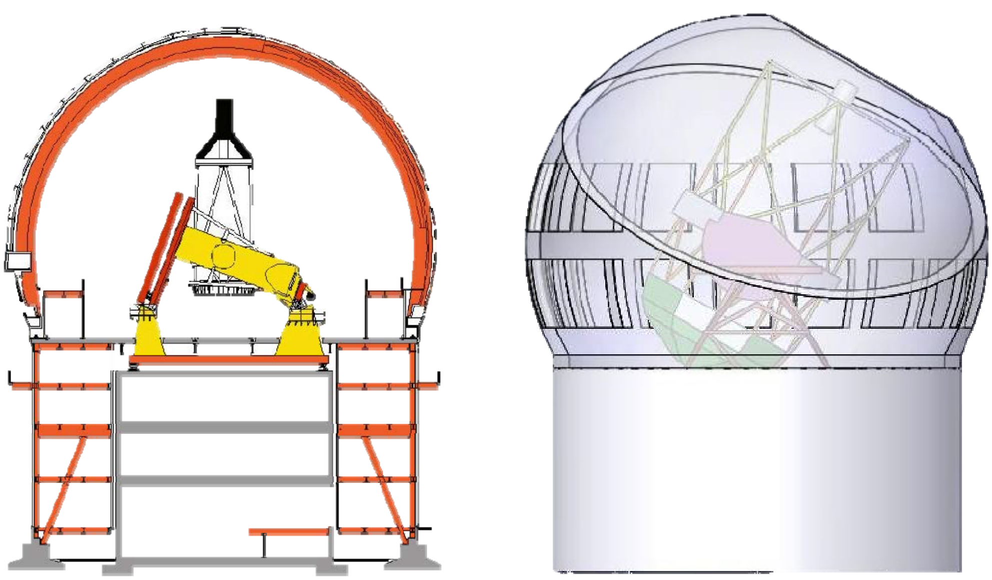

Figure 5 – On the left CFHT is shown while, on the right, a concept for MSE is shown that includes replacing the telescope and dome while preserving the underlying support structures.

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Another dimension in MSE's development schedule is the expiration of CFHT's existing sublease with the University of Hawaii for its site on the summit of Maunakea. CFHT's sublease, like all of those in place now for other Maunakea observatories, expires in 2033 together with the Master Lease issued by the Hawaii State Department of Land and Natural Resources. The University of Hawaii is currently seeking an Environmental Impact Statement as part of the approval process for a new Master Lease, effective through 2078. Though many of the new Master Lease terms are unchanged from previous terms, an important new term is the provision for funding to be provided by observatories in exchange for site access. The bulk of this funding will be used for the support of initiatives described in the CMP, including road maintenance, rangers, site preservation, and helping provide OMKM funding to support overall summit management in the face of a multitude of public and state interests. The finite duration of the Maunakea observatories' subleases will tend to drive significant change in Hawaii astronomy as the question of supporting aging facilities, with reduced competitiveness, is considered by funding agencies in the future. MSE is not only a fantastic research facility that will enable panoramic spectroscopy in an unprecedented manner, but MSE is also CFHT's response to the need to ensure that its site is used for advanced astronomical research well beyond the expiration of its current sublease. With >2200 scientific publications to date based upon CFHT data, and as one the most prolific sources of scientific publications of any ground-based observatory today, MSE is building upon an impressive body of work that stems from a large international community that has made significant contributions to modern astronomy. With this history and foundation it is expected that the scientific promise of MSE will be large enough to motivate a new sublease between CFHT Corporation and the University of Hawaii, under the terms of the new Master Lease.

The aforementioned top-level design parameters in section 2, combined with the goal of making this an upgrade to an existing telescope, and the various constraints summarized above lead to certain baseline design choices for MSE. Considerable latitude remains in defining the final MSE design, as an array of technical solutions remain to be evaluated, consistent with a design philosophy that makes use of demonstrated design solutions to reduce costs and accelerate MSE's operational phase. These parameters lead to the following top-level design aspects –

- 10 m segmented primary mirror
- Lightweight telescope structure that can be supported by existing pier
- Compact, efficient enclosure that can use the existing fixed base
- Wide field corrector (~1.5° field of view)
- Rapid, precise, ~3000 element fiber positioner
- Efficient fiber relay system
- High performance spectrographs with R = 2,000, 6,500, and 20,000
- Operations concept and control system supporting a cost-effective operations phase

The general design solution of the MSE performance parameter space outlined above provides for a major increase in capability over all other existing and planned facilities, while taking advantage of cost, schedule, and permitting benefits of reusing the existing CFHT facility. To be clear, performance gains are of course possible with even larger apertures,

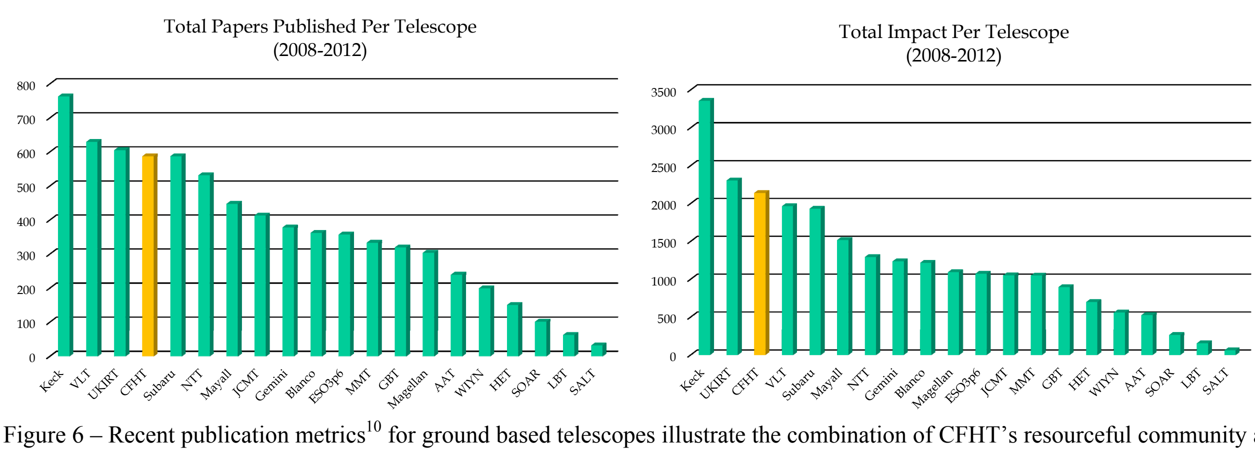

Figure 6 – Recent publication metrics[10] for ground based telescopes illustrate the combination of CFHT's resourceful community and capabilities which continue to keep CFHT competitive worldwide. An observatory like MSE will surely continue this trend which is probably not sustainable for CFHT in an era of 8-10 m telescopes and ELTs on the horizon.

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more fibers, or more exotic technologies (e.g., GLAO) but the broad-brush optimization process used to converge upon these design parameters also factors in practical considerations and is intended to accelerate MSE's deployment to realize the incredible power of this facility by the middle of the next decade.

5. BUILDING THE MSE PARTNERSHIP THROUGH THE PROJECT OFFICE

With a nominal cost of $200M to $250M, split roughly 50/50 between the telescope and instrument, MSE is a major undertaking by modern ground based astronomy standards and necessarily requires an expansion of the existing CFHT Corporate partners to provide the necessary funding. Beyond CFHT's founding agencies in Canada (National Research Council - NRC), France (Centre National de la Recherche Scientifique - CNRS), and Hawaii (University of Hawaii - UH), CFHT currently has collaborative agreements with agencies in Brazil (Brazilian Ministry of Science and Technology - MCT), China (National Astronomical Observatory of China - NAOC), Taiwan (Academia Sinica Institute of Astronomy and Astrophysics - ASIAA), and South Korea (Korea Astronomy and Space Science Institute - KASI). These renewable agreements with CFHT's Associate Partners in Brazil, China, Taiwan, and S. Korea serve as the basis for these communities to gain access to CFHT's resources in Waimea and Maunakea, as well as participate in CFHT's development program. They are natural conduits for their possible future direct involvement of these communities in the burgeoning MSE consortium. *In addition to CFHT's Associate Partners, the MSE Project Office is coordinating interest in other entities worldwide in this project.*

The MSE Project Office, which is located in CFHT's corporate headquarters in Waimea, Hawaii, is intended to be a nexus of scientific and technical collaboration needed not only to build MSE but to build the international partnership that must ultimately ground MSE. During its first year, the Project Office is focused mostly on developing in-house infrastructure, recruiting key staff, exploring permitting issues, consulting with the Hawaii island community, and most importantly disseminating information globally as new partners are sought. The bulk of the Project Office costs are associated with labor expenses and can therefore be provided through external in-kind collaboration (which is preferred), CFHT staff, or through dedicated Project Office staff funded directly by CFHT. The cost of developing the Construction Proposal is estimated to be ~$4M. This is less than the canonical 10% construction cost associated with major projects but the Project Office is building off of the aforementioned extensive feasibility studies already completed at NRC-

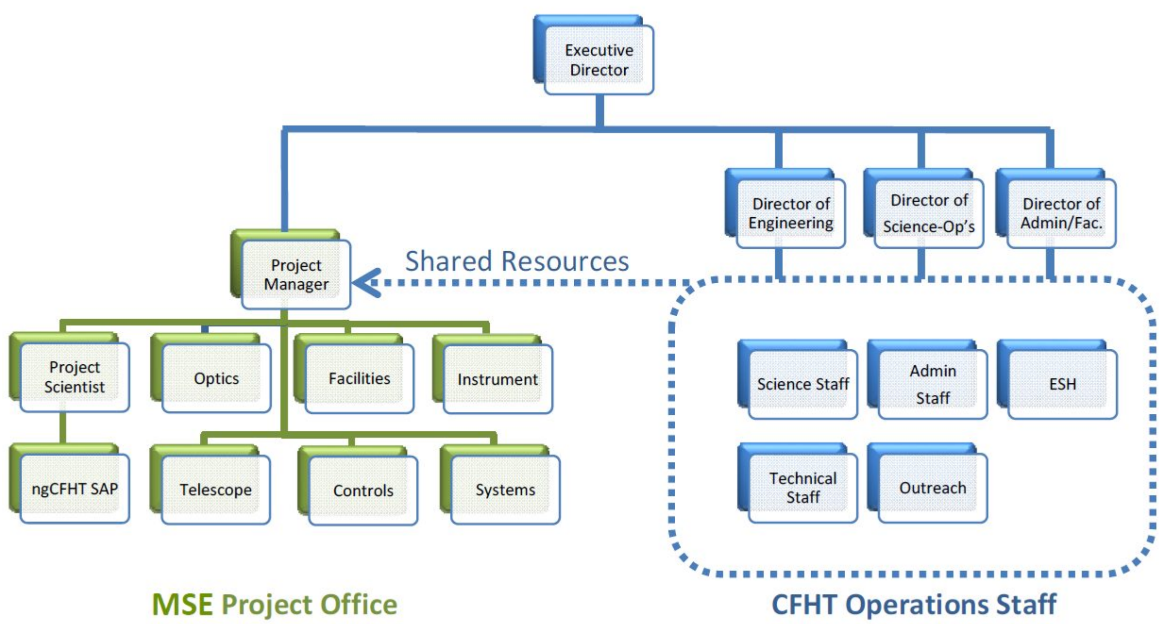

Figure 7 – Various MSE Project Office functions are shown on the left while existing CFHT functions relevant to supporting the Project Office are shown on the right. The Project would be structured as a standalone unit within CFHT, reporting to the Executive Director. Support from CFHT would come in various forms, including administrative, outreach, etc. Resource conflicts would ultimately be resolved by the Executive Director who would be accountable to the CFHT Board to deliver the Project Office products while sustaining CFHT operations.

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Herzberg, designs of similar segmented telescopes, and will tap existing expertise in fiber positioners, spectrographs, data pipelines, etc.

Locating the Project Office in Waimea, like the planned summit facility, takes advantage of existing office, administrative, procurement, and management infrastructure at CFHT. It provides a natural mechanism for staff dedicated to MSE to interact with CFHT's operations staff and archives which can provide a wealth of information needed to build MSE upon a CFHT foundation. It also makes it possible for CFHT to directly inject, to the extent practical, effort from CFHT's support and operations staff into the MSE Project Office as a form of in-kind effort. Some of the administrative support the existing CFHT office will contribute to the MSE Project Office includes –

- Human Resources (including staffing, safety procedures, etc.)
- General administration including accounting, payroll, etc.
- Financial reporting
- Procurement and contracting
- Travel support
- Support for meetings
- Communications and IT support

Beyond that, resources for the MSE Project Office come from CFHT development funds and in-kind engineering and scientific effort provided by MSE's international partners. CFHT has long benefited from an extensive network of laboratories and research facilities across its partner countries and it is anticipated that this existing network will provide extensive support of MSE's development.

The primary objective of the MSE Project Office is the generation of a construction proposal which, in summary, contains all of the information necessary for the agencies funding MSE to make the necessary commitments when a formal request for funding is made. The construction proposal is expected to contain the following elements –

1. Science Capability
    a. Top level Science Requirements
    b. Operations Concept
    c. Data products
    d. Compliance matrix and technical risks in meeting the top level requirements
2. Technical Description
    a. Brief description of design for each major element of the WBS
    b. Development status and completion plan for each major element of the WBS
3. Management Plan
    a. Relationship of Project Office with CFHT, with partner regional offices, and with organizations performing work
    b. Schedule to completion
    c. Listing of work packages, to whom allocated, value, and status of defining documents
        i. Statement Of Work
        ii. Requirements
        iii. Interface Control Documents
    d. Configuration control, performance contingency, and document management
    e. Product Assurance and Safety
    f. Risk Ledger
4. Budget
    a. Summary of the construction budget including completeness, amount of budget contingency, confidence level in each estimate
    b. Budget contingency management process
    c. Summary of the operations budget

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While the Construction Proposal is being generated the Project Office will take the lead, working closely with the CFHT Board and funding agencies, to identify additional partners in MSE. Both efforts (Construction Proposal generation and partner building) are expected to take ~3.5 years to complete, meaning the decision to proceed with constructing MSE can be made as soon as 2017. Roughly 3 months of schedule contingency have been built into this plan to help address various uncertainties in its execution. The generation of the Construction Proposal will be pursued as fast as resources permit at any given time. The self-contained nature of the Project Office makes it relatively detached from CFHT operations activity, hence the effort is not pinned to any other major projects occurring at CFHT.

This Construction Proposal design phase of MSE culminates with an independent design review of the various project deliverables. Several months of effort are loaded into the plan after the design review to enable design changes/feedback stemming from the review and to streamline future Project Office work (e.g., PDR/CDR-level design work, letting contracts for detailed design and/or construction, etc.). Additional outcomes are of course possible with the anticipated formal review and adoption of the Construction Proposal, including the pursuit of additional studies, resolving remaining permitting challenges, securing additional funds, etc. At this point the intent is to synchronize resolution of partner and funding challenges in parallel with the final definition of MSE's technical design and science requirements, recognizing that phasing of these sorts of international consortia are notoriously challenging but also rewarding, once achieved.

6. MSE AND THE FUTURE OF THE MAUNAKEA OBSERVATORIES

A number of important trends have emerged in recent decades with the globalization of economies, societies, and scientific research. These include the emergence of large science teams to conduct cutting-edge research, the assemblage of major research facilities through international collaboration, and the unprecedented scales (in terms of cost and complexity) of research being conducted by these large teams at these large facilities. This trend will doubtless continue well into the next century, as the information exchange infrastructure needed to sustain it grows rapidly and the need to make meaningful progress in basic research drives collaboration and defies the borders of the past. No single country will have the means to build the mega-facilities for research in the future. In that sense, projects like MSE are a spearhead in forging, within the astronomical community, the types of international working relationships that will help foster the research of tomorrow. It is in this vision – *that the future of astronomy relies critically upon international collaboration* – that MSE is grounded. A basic objective of this vision is to enable research opportunities that would otherwise be impossible, for sociological, technical or financial reasons. On Maunakea a combination of strategic coordination of developing new capabilities at various facilities and time-exchange programs designed to open access to facilities that have historically been inaccessible, are the building blocks for our vision.

Currently there are 13 telescopes operating on Maunakea that collectively make observations of the universe from radio to ultraviolet wavelengths of light. The fact that over a billion dollars has been invested in building and operating the Maunakea observatories to date is a testament to the superb properties of this site and the opportunities it represents. The exceptionally dry conditions at this high altitude site are particularly well-suited for sub-millimeter and infrared observations. Each night, observations ranging from high resolution interferometry of compact astronomical objects to wide-field panoramic imaging of the sky might be performed. In many cases objects first discovered at one Maunakea telescope are then subsequently examined in greater detail or with different instrumentation at another telescope, consistent with the spirit of collaboration that makes optimal use of these remarkable facilities.

Using this foundation, a number of important initiatives have been launched in recent years which serve as pathfinders for more extensive forms of collaboration in the future. A good example is the Keck/Subaru/Gemini time exchange program. Already nearly a decade old, this informal program provides access to these large format telescopes across distinct communities. The time exchange program has been an excellent success and has recently expanded considerably. A more recent and remarkable example of inter-observatory collaboration is the GRACES[11] project. This project is designed to fiber feed the CFHT high resolution optical spectrometer ESPaDOnS from Gemini-N. A deployable fiber feed module has been built into GMOS-N, feeding a ~300 m run of high performance optical fiber that is coupled to the ESPaDOnS entrance image slicer. The first implementation of this hybrid telescope/instrument system will be used to demonstrate the anticipated performance of the system (which is expected to be comparable Keck's HIRES at red wavelengths) before it is further developed into a full facility class system. While Gemini is funding this new capability, the cost for GRACES is an order of magnitude below what it would cost to develop a comparable system in-house, from scratch. Furthermore, since CFHT spends the bulk of its time using instruments to perform panoramic observations, access to ESPaDOnS by the Gemini community should meet demand.

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As indicated above, the future of Maunakea astronomy is crucially linked to the renewal of existing facilities and this renewal timeline is paced by the expiration in 2033 of the current Master Lease the University of Hawaii holds on the site. In the near future and as a result of terms in all existing observatory subleases, the University of Hawaii is gaining title to two observatories for which operations funding is ending from their founding agencies, namely UKIRT and JCMT. New funding is being sought for both observatories and the prospects for that funding, at least near-term, is encouraging. The termination of subleases will lead to either new operators, deconstruction of facilities, or the University of Hawaii retaining title to these facilities and gaining an impressive foothold in global astronomy through the ownership of roughly half the telescopes on Maunakea. In any case significant changes are occurring in the extent of inter-observatory collaborative development and operations, driven by common funding challenges and the need to restructure on the expectation of eventual sublease expirations and the arrival of TMT. East Asia's investment is also on the rise on Maunakea, with significant new investments in SMA, CSO, and JCMT. Under the East Asia Observatory (EAO), these facilities and Subaru are drawing closer and most of the partners in EAO are already Associate Partners in CFHT. While many details remain to be resolved, the general trend is one of increased collaboration among the Maunakea observatories – a significant departure from the relatively independent nature in which these same observatories came into being. In this environment, in which telescope time exchanges are more common and coordination of new capabilities better organized, projects like MSE thrive. Though specialized as a wide field multi-object spectrograph, when cast against a background of other capabilities including wide field imaging from U to K-band, high strehl laser adaptive optics, integral field spectrographs, high resolution spectropolarimeters, submillimeter interferometers, and much more, the ensemble of capabilities across the Maunakea observatories is unmatched if optimally coordinated and operated across its international constituency. For that reason CFHT is continually exploring opportunities for collaboration consistent with this vision for Maunakea astronomy. While it is impossible to say which of the current Maunakea observatories will exist in 20-30 years, economies of scale, global internationalization of research, the need to develop ever more capable research tools, and the establishment of a network of specialized facilities networked to provide a comprehensive suite of capabilities to astronomers worldwide seem on the horizon for Maunakea astronomy. It is an exciting future and MSE will be an important part of it.

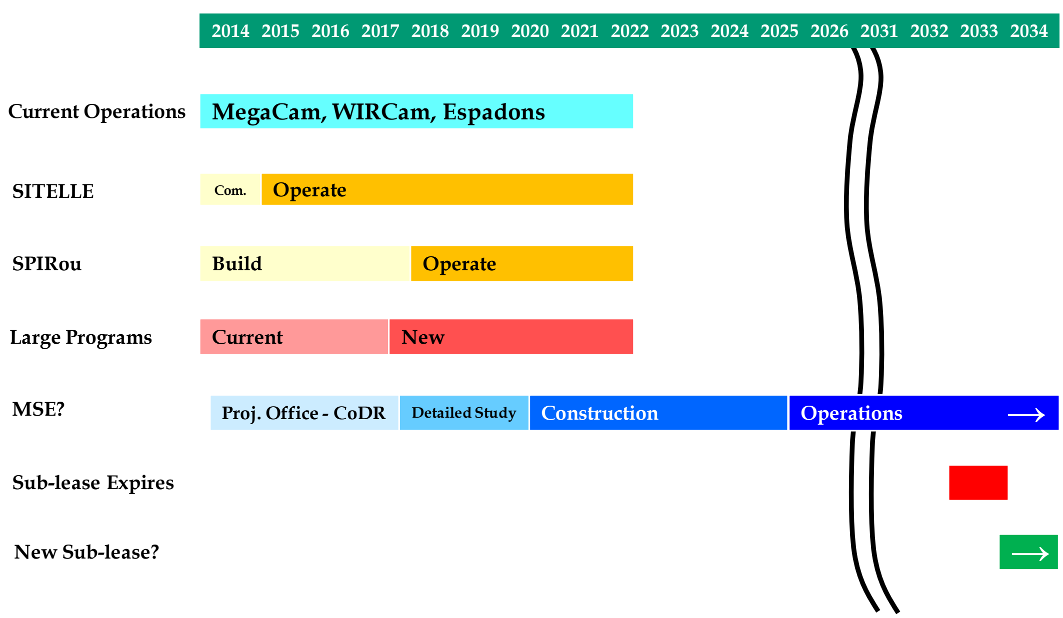

Figure 8 – A timeline illustrating various parts of CFHT's strategic plans is shown. This notional plan only shows basic feasibility of meshing on-going activity at CFHT with future installation and operation of MSE, with 2022 identified as a logical time to make the transition. A much more detailed plan will be developed through the MSE Project Office as part of the Construction Proposal.

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