NRC·CNRC

The Montréal-Ohio-Victoria Échelle Spectrograph (MOVIES)

Feasibility Study Final Report

Submitted to the Gemini Observatories by the MOVIES team

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Contents

1 Executive Summary

We present Gemini/MOVIES (the Montréal-Ohio-VIctoria Échelle Spectrograph). MOVIES is a broad bandwidth, moderate resolution (R3 – 10K) dual arm optical and near infrared (NIR) échelle spectrograph that simultaneously covers 0.36 – 2.45μm. It is supported by a rapid acquisition camera operating simultaneously in two optical and one NIR bands. MOVIES is designed for obtaining spectra of the faint Universe with high throughput, high efficiency and high reliability. MOVIES uses an optimized, low-risk, design with a minimum number of elements and mechanisms to ensure ease of calibration and high stability on long and short timescales. It will be the "go-to" long slit spectrograph for the follow-up of faint objects from future facilities such as LSST, WFIRST and DESI, and will be a valuable feeder instrument for the ELTs. MOVIES is fundamentally a time-domain spectrograph, a precision spectrophotometer, and a workhorse instrument for the Gemini community.

MOVIES has been developed with reference to several key science cases. The driving, defining science goals for MOVIES are those that take advantage of its ability for time domain science and for precision spectrophotometry. In particular, new science will be enabled through the discovery space that it opens up in the early-stage physics of explosive astrophysical phenomena. The optional inclusion of EMCCDs expands the potential of MOVIES in the time-domain by enabling unprecedented high-cadence spectroscopy of rapidly varying astrophysical targets. The ability of MOVIES to perform highly accurate spectrophotometry means that MOVIES will also be the premier facility for transit spectroscopy and the study of exoplanetary atmospheres at moderate resolutions, without some of the restrictions in target selection that frequently limit this science.

In addition to these defining science goals, reference was made throughout the MOVIES design to a large number of science themes, in particular:

- Transients and the time-variable Universe
- The Outer Solar System
- Low mass stars
- Stellar populations
- Galaxies and massive black holes
- The high redshift Universe
- Exoplanet atmospheres

MOVIES is conceived to address these cases by building on the intrinsic strengths of Gemini. An essential and defining characteristic of MOVIES is that it will capitalize on Gemini's "target of opportunity" mode. MOVIES will acquire targets (including starting the acquisition exposure, reading out the images, identifying the target, centering and verifying the object in the slit, switching to guiding mode and starting the science exposure) within 90 seconds. The acquisition and guiding cameras have large fields of view (3 x 3 arcmins) to ensure good sky coverage, to facilitate precise astrometry, and to enable blind acquisition when necessary. Two optical and one near-infrared acquisition images are obtained simultaneously, to easily acquire targets with an unknown spectral distribution. Further, they are designed to be used as simultaneous multi-band imagers to obtain “one-shot color-color diagrams”, and they are an important science imaging capability in their own right. We anticipate that the spectrophotometric accuracy of MOVIES enabled by these cameras will be unparalleled among 8-m spectrographs in the 2020s.

MOVIES will be the premier spectrograph on 8 – 10m class facilities for observations of faint objects in the Universe. High throughput is achieved by the dual-arm design, where optimized optics in each arm and high efficiency gratings minimize light loss. The design has been developed to allow for a minimum number of optical elements per arm. Detectors optimized for broad wavelength ranges in the optical and NIR are used with coatings that further enhance their efficiency. For the optical arm, we further present an option of using a large format electron multiplying CCD as the primary science detector; when used in EM-mode (large gain), these detectors allow for a very significant increase in observing efficiency obtained relative to normal CCDs for faint targets. Further, zero-read noise in these detectors gives the option of temporal and spectral binning post-processing at potentially extremely high (hertz) cadence, opening up a new domain of high cadence optical spectroscopy for energetic, variable and/or transient observations.

MOVIES will capitalize on the NIR optimization of the Gemini telescopes. In addition to throughput, low emissivity and excellent sky subtraction are critically important for observing faint targets in the red. The latter is achieved by mounting at Cass and using a 10 arcsec slit (greatly preferred to fibre-fed designs). The former is achieved by careful design choices and benefits from Gemini’s low-emissivity design. The NIR will assume new importance in the 2020s with the advent of the ELTs, JWST, Euclid and WFIRST, all requiring support from existing facilities. Here, MOVIES will occupy a critical role.

Our team is a collaboration of three Gemini-partner institutes with extensive experience in the design, build and integration of complex astronomical instruments, including near infrared and cryogenic system. The resulting collaboration has depth and strength in all necessary disciplines required to deliver a premier spectrograph to the community, from the science, to optics, mechanics, electrical, software, detectors, to the systems engineering and project management. MOVIES is a low risk instrument building on an extensive “tried-and-tested” design heritage. We have developed the science cases in tandem with the opto-mechanical, electrical, software and operational concepts, producing a clear flowdown from science requirements. This has allowed us to develop an understanding of the cost-complexity-science-schedule trade-offs, ensuring adoption of suitable risk-mitigation strategies where necessary.

The international suite of premier astronomical facilities is changing rapidly with the advent of many new and large facilities. Gemini can occupy a unique position within this new paradigm as the preferred follow-up telescope for faint targets at optical and NIR wavelengths. MOVIES is positioned to be a critical component of the future Gemini instrumentation suite, by providing a unique set of capabilities that enables a vast range of science, extends existing Gemini capabilities, and complements future astronomical facilities.

2 Science Objectives, Science Case and Science Requirements

We begin by describing the scientific considerations that have informed the development of MOVIES. We first provide an overview of MOVIES from the science-user perspective, highlighting its “science-enabling” functionality. We then describe the science context of MOVIES. In particular, we describe how it plays to the strengths of the Gemini Observatories by building on their unique capabilities and heritage, and we describe how MOVIES helps place Gemini in a strategic position in the future network of astronomical facilities.

After reviewing the general context of MOVIES, we describe the primary science cases used to guide its development. We then use these science cases to derive high level science requirements for the instrument. We discuss these requirements for MOVIES in considerable detail to highlight key aspects of its functionality. We go on to discuss key operational aspects of MOVIES, including sensitivity, acquisition, calibration, and the option of high cadence observing. We finish with a description of the concept of operations through several “science-use scenarios” that cover the range of MOVIES capabilities. Throughout, we illustrate how MOVIES will be used to advance these fields while providing workhorse capabilities.

2.1 Functional Overview of MOVIES

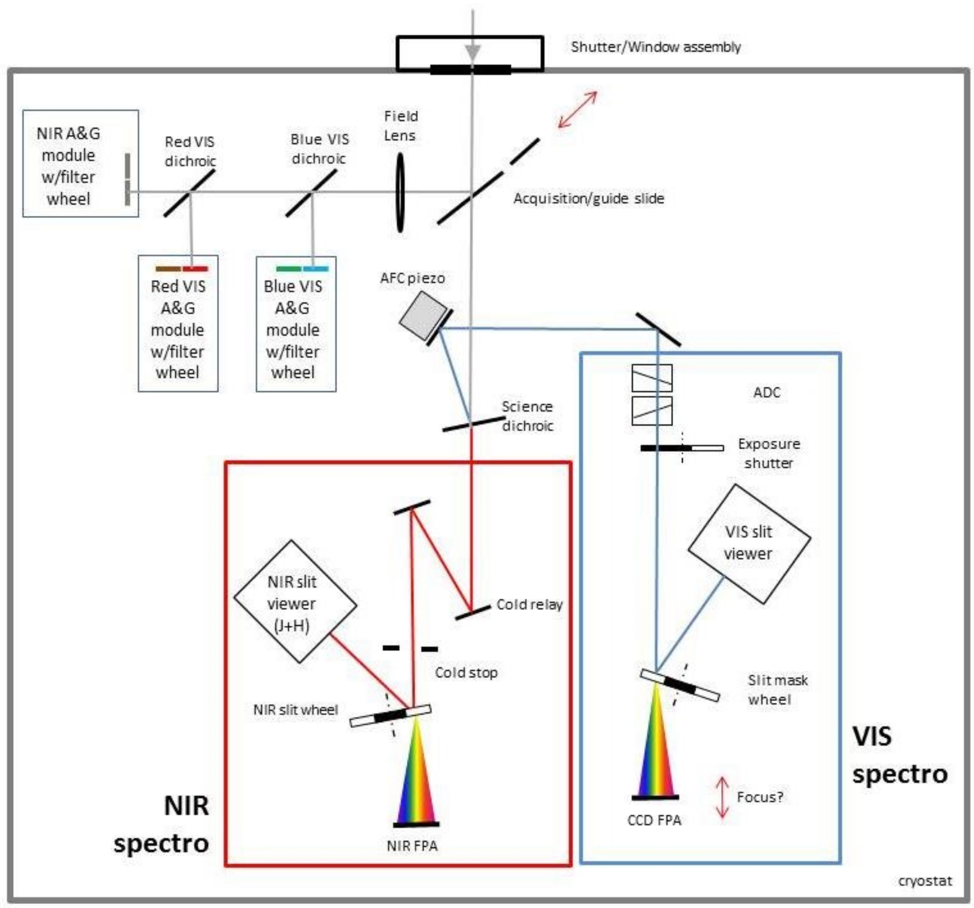

Figure 1: MOVIES design schematic.

MOVIES is a broad bandwidth, moderate resolution optical and near infrared spectrograph, supported by a multi-channel, rapid acquisition camera operating simultaneously in optical and NIR wavelengths. MOVIES is optimized for obtaining spectra of the faint Universe with high throughput, high efficiency and high reliability. A schematic of the MOVIES layout is shown in Figure 1.

Science-defining capabilities include:

- Rapid configuration and acquisition time of < 90 seconds (excluding telescope and dome slew), minimizing overheads, maximizing efficiency and making MOVIES the spectrograph of choice for time-critical phenomena;
- Three acquisition cameras operating in two optical bands and one NIR band. NIR sensitivity allows for easy and robust direct acquisition of targets that are faint in the optical. Each acquisition channel is critically sampled and each have a 3 x 3 arcminutes field of view. These cameras are a powerful imaging capability in their own right, and are essential for spectrophotometric calibration;
- Full and complete spectral coverage in a single pointing from 0.36 – 2.45μm;
- Cass-mounted long-slit system, to provide high throughput compared to fiber-fed systems and to ensure superior sky subtraction, particularly in the NIR, to push to the faintest targets;
- Dual-arm design with specialized optics, coatings and detectors, and a minimum number of optics, giving high throughput at all wavelengths. Low emissivity design – including fully cryogenic and benign environment – enabling extreme sensitivity in the K-band;
- Spectral resolution from R = 3K – 10K in both the optical and NIR arms, well matched to the intrinsic velocities of AGN and galaxies, and enabling observation between the sky lines. Detector binning gives lower resolution when required;
- A selection of multiple, fixed, slits, including a large "pseudo-slitless" setting for exoplanetary transit spectroscopy. Fixed slits can be used to modify the resolution settings and match to the seeing conditions (especially to maximize throughput in poor conditions);
- Highly stable spectrograph system to allow robust daytime calibration procedure using facility calibration system. Overall design produces long-term stability enabling multi-epoch science. Fixed slits ensure robustness in comparison to more complex slit-mechanisms (essential for time-variable phenomena and other observations where knowledge of the slit-profile is important).
- Potential use of large format electron-multiplying CCDs in the optical arm of the spectrograph providing enhanced sensitivity to faint targets and enabling a new field of high cadence time domain optical spectroscopy by allowing post-processing to determine the optical cadence and spectral resolution with no read-noise penalties.

Table 1 provides a summary of the relation between the major science cases discussed later in this document, and the major instrument capabilities of MOVIES. Green boxes indicate an essential requirement for that science case; yellow indicates a useful capability. Note that all of the science requirements/capabilities listed in Table 1 are required by the driving science goal of transients, and nearly of the capabilities are required by the driving science goal of exoplanet atmospheres.

Table 1: Summary of the connection between the major science cases and major requirements for MOVIES. Green indicates a driving requirement; yellow indicates a useful science-enabling capability. The two major, driving science cases of transients and exoplanet atmospheres make full use of the capabilities of MOVIES.

	Broad Wavelength Range	Simultaneous bandwidth	Moderate Resolution	Faint targets	Rapid acquisition	Multi-band acquisition		High cadence read-out
Transients (Major science driver)	✔	✔	✔	✔	✔	✔		✔
Solar System	✔	✔	✔	✔	✔	✔		✔
Stellar populations	✔	✔	✔	✔		✔		
Low mass stars	✔		✔	✔				
Massive Black Holes	✔	✔	✔	✔	✔			✔
High redshift Universe	✔	✔	✔	✔		✔		
Exoplanet atmospheres (Major science driver)	✔	✔	✔	✔		✔		✔

2.2 Science Context

2.2.1 Overview

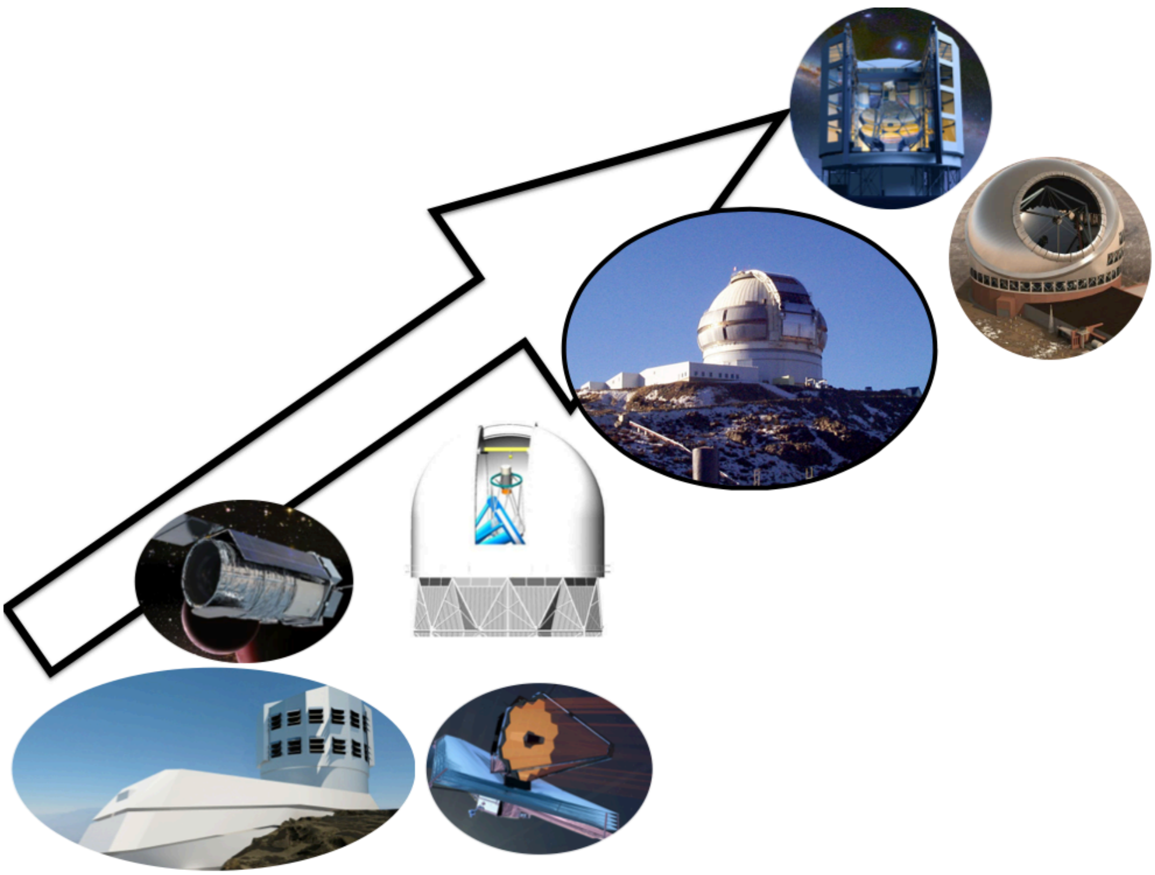

Figure 2 The role of Gemini in the future suite of astronomical facilities if it is equipped with MOVIES. Wide field optical imaging with LSST, perhaps supported by, or independent from, space-based NIR capabilities such as WFIRST and JWST, can provide billions of targets for observations with future MOS instruments such as the Mayall/DESI. Key targets identified from MOS observations, or directly with LSST and other imagers, will feed Gemini/MOVIES to provide high SNR, moderate resolution, broad wavelength spectra. The most interesting targets can then be fed to the ELT facilities for their definitive characterization.

The Gemini Observatories are prominent members of the international suite of 6 – 10m class optical and near-infrared (OIR) astronomical observatories. They are among the forefront ground-based facilities for providing the highest quality view of the Universe at these wavelengths. However, changes are occurring to the roles these facilities occupy, and these facilities must change their operational models to adapt to this new reality.

Increasingly, OIR observations are used in conjunction with other wavelengths, and many peer-reviewed publications often use data from multiple facilities. Analysis of the

Gemini publication record for 2010 – 2012 shows that ~75% of all Gemini publications use data from additional facilities, and that these publications have a higher impact factor than publications using Gemini alone[1]. This trend will continue; ALMA is now providing exquisite images at a remarkable resolution in the sub-millimeter, and the SKA will provide a similar, if not greater, paradigm shift at radio wavelengths. LSST and the ELTs will soon change the focus of OIR astronomy with their arrival early next decade. The former will provide an unprecedented wide and deep perspective of the Universe (including of the variable and transient sky) and the latter will herald a new frontier for OIR capabilities, in terms of spatial resolution and depth.

The 6 – 10m class telescopes will increasingly occupy new roles; as follow-up facilities to discoveries in LSST (and elsewhere), as feeder facilities for ELT observations, and as the OIR component in multi-wavelength analyses spanning the electromagnetic spectrum. We believe the Gemini Observatories can use their extensive heritage and unique capabilities to occupy a strategic and scientifically compelling position within this new paradigm, that we have attempted to illustrate in broad terms in Figure 2. Our team has paid careful consideration to these issues during the development of MOVIES.

MOVIES capitalizes upon two defining capabilities of Gemini:

1. **Rapid-response**
   The Gemini Observatories successfully operate arguably the most successful queue-observing system in the world. As a result, the Gemini Observatories have become the premier 8m telescopes for rapid response observing and "Target of Opportunity" (ToO) capabilities. Indeed, the design of Gemini naturally enables such a capability, since instruments are continually mounted on the telescopes and in a state of constant readiness. The scientific need for this capability is already acute and getting sharper, for example, with the advent of LSST and the SKA. Gemini can position itself to be the go-to facility for time-critical observing programs.

   The success of Gemini within the world of ToO observing is well recognized within the international community; the recent report entitled "Optimizing the US ground based optical and infrared astronomy system" (Elmegreen et al. 2015) made the following prescient recommendation:

   "The National Science Foundation should work with its partners in Gemini to ensure that Gemini South is well positioned for faint-object spectroscopy early in the era of Large Synoptic Survey Telescope operations, for example, by supporting the construction of a rapidly configurable, high-throughput, moderate-resolution spectrograph with broad wavelength coverage."

2. **NIR optimization**

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[1] Based on bibliometric analysis by Dennis Crabtree, private communication

> The Gemini Observatories are designed to be the premier facilities for NIR observations, with a low emissivity design utilizing an undersized secondary, and silver coatings to provide high throughput at red wavelengths. Ground-based 8m facilities will soon have a new importance with the launch of JWST, Euclid, WFIRST, and the first-light of the ELTs, all optimized for the NIR and requiring support from existing facilities. There is a clear opportunity for Gemini to occupy a key role as the astronomical community turns increasing attention to NIR wavelengths.

MOVIES is conceived to build on these intrinsic strengths of Gemini, to become the premier follow-up (and "feeder") single-object spectrograph for the 2020s and beyond. MOVIES maintains the 8-m aperture advantage, by following up faint sources beyond the grasp of 4m facilities, and by providing the initial data required to select targets for the ELTs. MOVIES observes efficiently faint targets by having high throughput, low emissivity and allowing excellent sky subtraction.

We now discuss particular examples of these synergies in more detail.

2.2.2 Gemini/MOVIES as follow-up to LSST, SKA and future facilities

LSST and the SKA will open up time-domain astronomy to the Gemini and international communities, and build upon many successful time domain programs such as the Palomar Transient Factory, Catalina Real-Time Transient Survey, PANSTARRS, La Sill-QUEST, ASAS-SN and SkyMapper. Central to probing these phenomena is the ability to acquire targets rapidly.

The importance, and difficulty, of rapid follow-up to LSST cannot be overstated. The problem was highlighted at the recent workshop "Spectroscopy in the Era of LSST", hosted by the National Optical Astronomy Observatory (NOAO) on April 11 – 12, 2013 (summary available in Matheson et al. 2013, arXiv:1311.2496). The underlying issue is data rate: LSST is predicted to issue 10^6 transient alerts per night. To cope with this, time domain astronomers are actively pursing the development of a time domain "ecosystem" using existing telescopes of all apertures to identify and characterize all known transient events. This ecosystem must eventually allow for the accurate identification of "normal" transients, so that software can be developed to automatically filter these alerts. This automatic filter is termed an event broker. The small number of most interesting events that the broker identifies must be followed up immediately to probe new physics and enable discoveries. With this time domain ecosystem, Gemini must aim to be the ultimate observatory for follow up.

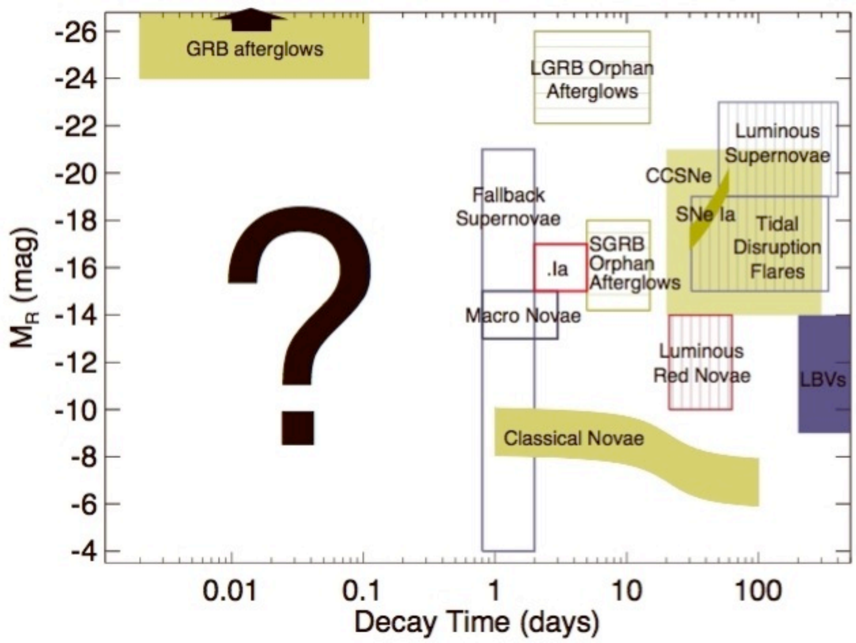

Figure 3: Decay time versus magnitude for known explosive transient phenomena, emphasizing the need to quickly identify these sources (as will be done with LSST), and to quickly observe these targets with follow up spectrographs, for which MOVIES will be a premier instrument. Figure taken from the LSST Science Book v2.0 (arXiV:0912.0201).

Most of the interesting new astrophysics likely occurs within the first few minutes of the life of transients: Figure 3 beautifully illustrates our dearth of knowledge of transients caused by current inabilities to follow-up targets rapidly. The Swift satellite is responsible for issuing many of these alerts, and this highlights an additional difficulty to be navigated with rapid follow-up; depending on the source of the alert, the optical and NIR luminosity of the object may be unknown, and the astrometry may be imprecise (the Swift satellite initially estimates the position to within a few arcminutes, which gets quickly refined to within 5 arcseconds – too imprecise to automatically position a slit at the estimated position without additional data[2]). Multi-band acquisition using a relatively large field is therefore key. A broad coverage, moderate resolution spectrograph is an essential capability for these sources given their unknown nature. Clearly, MOVIES is well suited to this task.

2.2.3 Gemini/MOVIES as complement to JWST, Euclid and WFIRST

MOVIES will become a mature facility after the nominal lifetime of JWST, although some overlap might occur if the mission proceeds beyond its nominal 5 year lifetime (the lifetime of JWST could exceed 10 years). JWST will have exceptional sensitivity relative to any other NIR facility. Its instrumentation payload includes: NIRCAM (an imager

[2] http://swift.gsfc.nasa.gov/swift.html

operating at 0.6-5um); NIRSpec (a multi-object spectrograph operating up to R~1000 from 0.6 – 5um); MIRI (an imager and spectrograph operating longward of 5um); NIRISS (a wide field grism spectrograph at R~150 and single object grism at R~700 operating shortward of 2.5/3um, as well as an imager between 1 – 5 um). JWST will be transformational; however, there will still be an important role for spectroscopy at resolutions of more than a few thousand from the ground, since this capability is lacking in JWST. The NIR sensitivity of MOVIES and its moderate resolution settings will make it the spectrograph of choice to complement JWST in this capacity.

Wide field, space based NIR imaging capabilities are in active development with Euclid (launch date ~2018) and WFIRST (launch date ~mid 2020s). Both will therefore be in operation during the early life of MOVIES. Both facilities provide imaging up to 2um; both WFIRST and Euclid also have some spectroscopic capabilities, with resolutions of a few hundred at most. While the science goals of Euclid and WFIRST are directed heavily towards Dark Energy (and Exoplanets, in the case of WFIRST), the impact of these facilities will be immense given the vast number of sources that will be identified through deep imaging. Again, MOVIES will be able to provide excellent synergies with these facilities due to the moderate spectral resolutions that it provides and its K-band sensitivity, both of which are absent from these space-based facilities.

2.2.4 Gemini/MOVIES as a follow-up to DESI and future MOS

With the large number of dedicated imaging surveys online and in development, spectroscopic survey capabilities to try to keep pace are in development. Most notably, Mayall/DESI, WHT/WEAVE, Subaru/PFS and VLT/MOONS are all extremely multiplexed spectrographs due to come online between 2017 – 2020. VISTA/4MOST and MSE are both dedicated facilities in development that may see first light later in the 2020s. These MOS capabilities are natural follow-up facilities for the plethora of wide field imaging surveys. Through this route, particularly interesting and compelling objects will be identified based on the moderate or low resolution spectra that these surveys provide (with most objects observed at generally low SNR). The wavelength range that these surveys operate at are all optical or optical/NIR, and the red end cut-off is always shortward of K band due to the unavailability of glasses that can provide wide-field corrections through to the K band. Thus, follow-up spectroscopy of targets already observed with MOS survey facilities will ideally have extensive wavelength coverage, at moderate-to-high resolution, on a large aperture facility, and will involve observations at high SNR. MOVIES provides the increased sensitivity, wavelength coverage and resolution that makes it ideal to act in this capacity.

2.2.5 Gemini/MOVIES as a science feeder for the ELTs

TMT, GMT and E-ELT will create a paradigm shift for OIR astronomy. These billion-dollar investments will provide unprecedented datasets on the faint and high-resolution Universe. These facilities offer the greatest gains in the NIR due to the D^4 advantage offered by adaptive optics. Spatial resolution is therefore a key parameter in addition to their increased light gathering ability relative to 8m class facilities.

Gemini/MOVIES can provide a critical step to observations with the ELTs. For example, faint galaxies at moderate redshift identified by other surveys (e.g. DESI MOS observations following up an LSST field) can be observed with MOVIES at moderate resolution. The most interesting of these can then be observed with complementary spectral resolution but higher spatial resolution and higher SNR using integral field units on the ELTs. MOVIES will therefore be part of a system of facilities connecting wide field imaging to the ELTs, described in Figure 2. To fulfill this role, it is essential that MOVIES has high efficiency and NIR sensitivity.

2.3 Science Case Descriptions

To demonstrate the science capabilities that inform the MOVIES instrument concept, we have identified the following science cases that span a broad range of astronomical topics. By addressing these science topics, we ensure that MOVIES will provide a workhorse suite of capabilities:

1. Driving science: The Transient Universe
2. Outer Solar System Science
3. Stellar populations of nearby galaxies
4. Low-Mass Stars
5. Galaxies and Massive Black Holes
6. The High Redshift Universe
7. Driving science: Exoplanet Atmospheres

Of these seven science themes, two highlighted areas are the Transient Universe and Exoplanetary Atmospheres. These two science areas are drivers for MOVIES: they represent areas in which we expect MOVIES will have a transformational impact and which will become defining science areas for the instrument. For the former, this is ensured due to our focus on rapid acquisition being able to probe the early stages of explosive astrophysical phenomena; for the latter, this is due to MOVIES ability to provide exquisite spectrophotometric calibration. We return to these issues more later.

2.3.1 The Transient Universe

2.3.1.1 Overview

When it becomes fully operational in the early 2020s, LSST will give us an unprecedented view of the transient universe. At the projected survey depth (r=24 to 17 mag) and rapid cadence, LSST will produce orders of magnitude more transient optics than all of our ground-based spectroscopic assets can hope to follow-up. However, they don't need to: most classes of transients may be readily classified from their light curves, even most of the common types of Supernovae. While supernova follow-up is an obvious application of Gemini/MOVIES in service of well-established cosmological programs, a particularly exciting area for LSST is to follow-up the rare and the unexpected that will give us new insights into physical processes in the Universe.

We already have a foretaste of the riches LSST promises in recent wide-field transient studies that work to shallower depths (e.g., brighter than 16-17 mag) such as Pan-

STARRs (led by the University of Hawaii), the All-Sky Automated Survey for Supernovae (ASAS-SN led by K. Stanek at Ohio State), Intermediate Palomar Transient Factory (iPTF led by S. Kulkarni at Caltech), and the Catalina Real-Time Transient Survey (CRTS, led by A. Drake at Caltech). Essential to understanding the events discovered by LSST and on-going all-sky transient surveys is spectroscopic follow-up, especially in the cases of rare or previously unknown transients. A strong science driver of MOVIES is rapid and sustained spectrophotometric follow-up of transient sources using Gemini

We present three representative science cases that provide operational characteristics that inform the MOVIES spectrograph concept.

2.3.1.2 Supermassive Black Hole Tidal Disruption Events

All massive galaxies harbor supermassive (10^{5-10} M_{sun}) black holes in their nuclei. Bright Active Galactic Nuclei (AGN) are the few percent of these black holes that are actively accreting material and radiating at a substantial fraction of the Eddington Luminosity at nearly steady-state luminosities of 10^{39-46} erg s^{-1} with few percent variability on timescales ranging from days to months that scale with square-root of luminosity (larger mass active black holes have larger luminosities and vary more slowly). The majority of such supermassive black holes, however, are quiescent. If a star or gas cloud passes close to the black hole it can be tidally disrupted and partially accreted, resulting in a powerful transient outburst that could last many months. Models of such Tidal Disruption Events (TDEs; e.g., Roos 1992) predict peak luminosities of 10^{43-45} erg s^{-1}, comparable to a fully-lit AGN. These events are relatively rare, with rates down to r=24 at a median redshift of z=0.3 of ~10^4 $M_7^{3/2}$ yr^{-1}, where M_7 is the central black hole mass in units of 10^7 M_{sun}. Gezari et al. (2008, 2009) estimate that LSST should detect of order 100 TDEs per year within the LSST survey limits (r = 17 – 24 mag). A conservative estimate on the small number of TDEs identified by ASAS-SN, PTF, PANSTARRS, and SDSS we estimate we could detect 1 – 3 TDEs per year brighter than r=17 mag (Holoien et al. 2014, 2015; Arcavi et al. 2014; Chornock et al. 2014). TDEs are not just curiosities: models of nuclear black hole growth suggest that such tidal accretion is the primary growth pathway at low masses (e.g., Volonteri 2011), so understanding the physics and rate of occurrence of TDEs is essential for constraining models of galaxy/black hole co-evolution.

Rapid spectroscopic follow-up of a TDE candidate after outburst detection, and then follow-up over the course of many months to a year is crucial to understanding these events. Most TDEs found to date have been recognized long after the main event is over, primarily in archival UV and X-ray data (e.g., Grupe et al. 1995, Gezari et al. 2008), and detailed spectroscopic follow-up is available for two recent bright TDE candidates: ASASSN-14ae (Holoien et al. 2014a) and ASASSN-14li (Holoien et al. 2015; arXiv:1507.01598). Detected in the ASAS-SN survey at near their lower detection limits (r=17 mag), these events are relatively nearby (z~0.04 and 0.026, respectively) than the typical redshift of predicted LSST TDEs (z~0.3). Rapid and sustained spectroscopic follow-up from LBT and APO of ASASSN-14ae (Figure 4) shows dramatic spectral evolution over a course of months with the appearance of broad hydrogen and helium emission lines, but no narrow line components, and then steady fading away of the continuum and broad lines. ASASSN-14li showed similar behaviour.

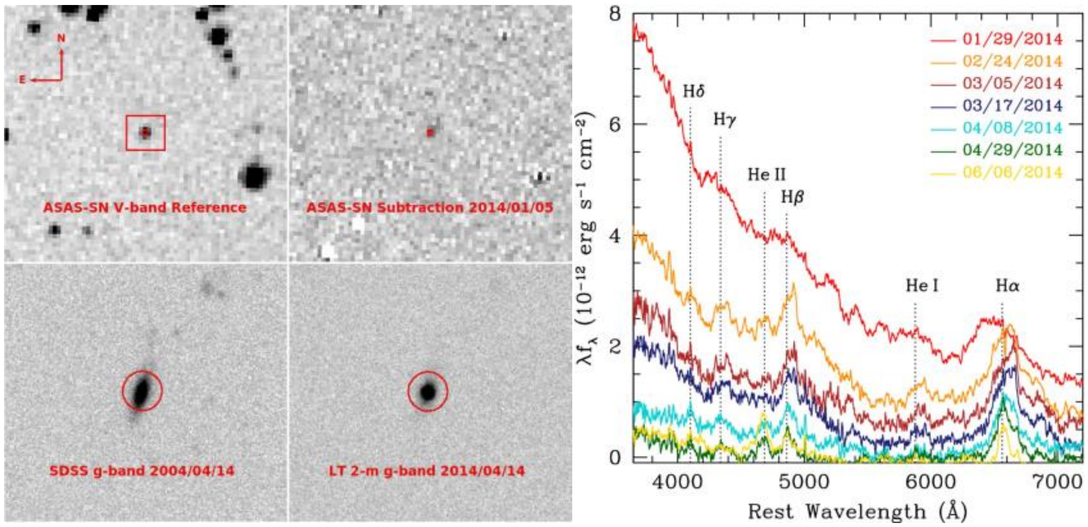

Figure 4: Discovery images (left) and spectral evolution (right) of Tidal Disruption Event ASASSN-14ae over a 150 day period (Holoien et al. 2014a, Figures 1 and 5).

The implied rate of the two ASAS-SN events is 5.4×10^{-5} per year per galaxy, with a 90% confidence interval of (2.2–17.0) $\times10^{-5}$ per year per galaxy, which corresponds to a rate of roughly 1 TDE event for every 70 SNeIa found in ASAS-SN.

Thorough spectroscopic follow-up of TDE candidates requires a medium (R~5000) spectrograph with broad wavelength coverage from UV to near IR. Rapid response requires a spectrograph that can be quickly brought on-target after the alert of the outburst, and long-term stability is required to be able to compare spectra taken many months apart with confidence that changes in the spectral details are not a consequence of changing spectrograph performance. The combination of Gemini and MOVIES, following up candidate TDEs from LSST and shallow surveys like ASAS-SN will give us many dozens of examples, opening up this window on black hole growth and evolution to detailed study.

With MOVIES on Gemini, a science program based on just ASAS-SN follow-up would be a ToO program triggered by detection of a TDE candidate. Initial follow-up spectroscopy could be done with 20-30 minutes of integration time at the typical ASAS-SN trigger magnitude of r~16 mag. If confirmed TDE, the rapid evolution of these events indicates following the event spectroscopically on a weekly cadence (~4 visits per month) for 4 to 5 months for a cost of ~1 hour per visit. We expect 1 to 2 such events per year, and a 5-year program would net 10-12 such events at a cost of about 20 hours of Gemini time per event, so 200-300 hours total over 5 years. Time coverage is guaranteed by the flexible queue scheduling capability of Gemini, and the rapid target acquisition and calibration stability of MOVIES would allow collection of a homogeneous data set with broad wavelength coverage to study the event evolution in detail.

2.3.1.3 "Changing Look" Active Galaxies

The traditional division of AGN to Type 1 (broad- and narrowl-line spectrum) and Type 2 (narrow-line only spectrum) is well-known and broadly understood in the context of so-called Unified Models of AGN (e.g., Antonucci 1993). However, it has become clear that these spectral types may be mutable at some level – Type 1 AGN having their broad lines face until they look like Type 2 narrow-line AGN, and Type 2s that suddenly "grow" broad Balmer emission lines.

Two recent examples of such "changing look" AGN are NGC2617 (Shappee et al. 2014) and Mrk 590 (Denney et al. 2014). NGC2617 was a non-descript, low-luminosity z=0.014 Type 2 AGN that in early 2013 triggered as a transient in the ASAS-SN survey. Subsequent rapid-response (few day) ground-based spectroscopic follow-up augmented by visible and SWIFT X-ray and UV photometric observations found the appearance of a previously unseen broad emission-line component led by a bright X-ray outburst (Shappee 2014). Subsequent monitoring shows that unlike a Tidal Disruption Event, NGC2617 is still a Type 1 AGN nearly 1.5 years after the initial ASAS-SN alert. Mrk590 was for decades a classic Type 1 AGN, but serendipitously was found to have faded by nearly a factor of 100 in the continuum and spectroscopic follow-up at visible wavelengths from the ground (LBT, Lick, and MDM), and ToO Chandra and HST X-ray and UV spectroscopy. By late 2013 this object hat little or no detectable broad line emission (Denney et al. 2014; see Figure 5) and this galaxy showed dramatic changes in the X-ray and UV spectral characteristics. However dramatic, because it was caught by chance, we do not know when the fade-out event began or the timescale upon which it occurred.

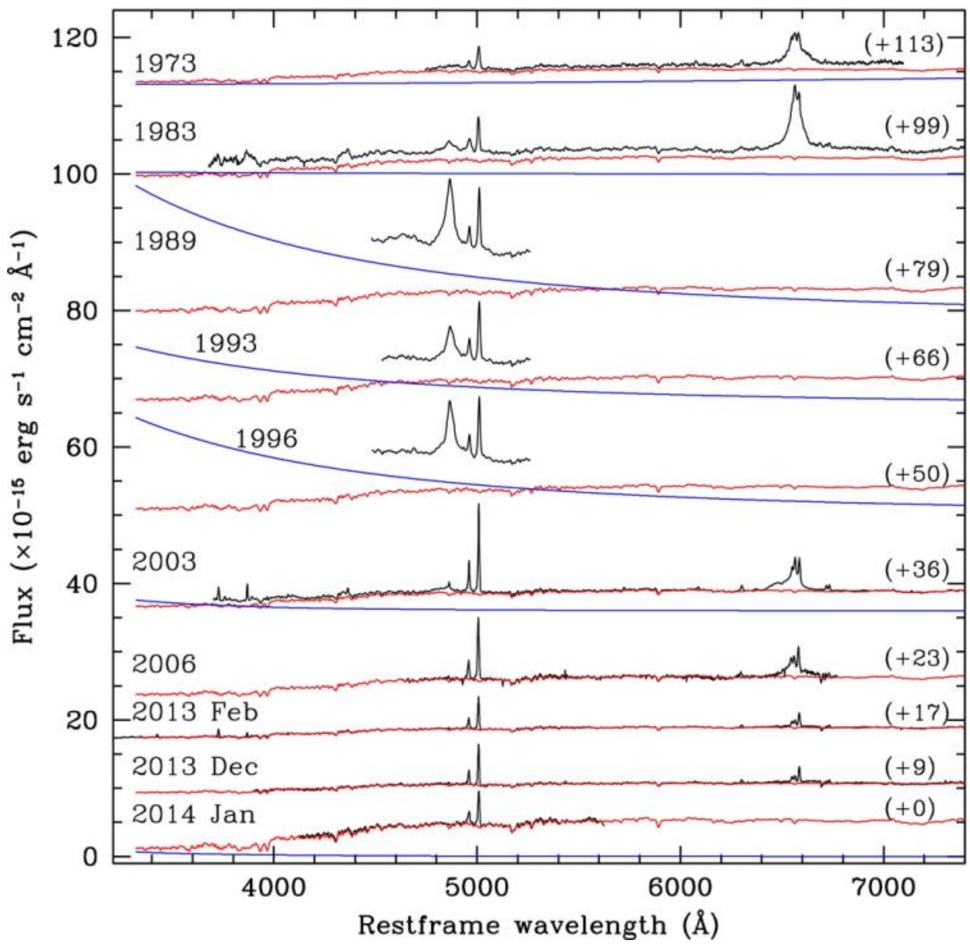

Figure 5: Rest-frame optical spectra of Mrk 590 spanning more than 40 years from Denney et al. (2014, Fig 1). The black curves show the observed spectra, the red curves show a host galaxy starlight template that was fit to the 2013 LBT+MODS1 spectrum and has been scaled to all other spectra, and the blue curves show power-law continuum fits for the epochs in which the stellar component could not account for all of the observed continuum flux. All spectra are on the same flux scale.

With LSST complemented by shallower all-sky monitoring surveys like ASAS-SN, we can expect to be able to catch ~100 of these changing-look AGN events per year (extrapolating from the rates inferred from the few events noted in the literature – which may be significant underestimates as nobody to date is monitoring such "boring" AGN, though the ASAS-SN team at OSU is gearing to initiate such a study starting in 2015). Events like Mrk590 suggest we should augment the usual "outburst" triggers to include "downburst" triggers for when known AGN fade out.

Key to understanding the physics of these transient events and their importance to the AGN phenomenon requires a medium (R~5000) spectrograph with broad wavelength coverage from UV to near IR, and the ability to get onto the source upon alert and stay on the source at a slower (monthly) cadence following the initial outburst with high calibration stability. The proposed Gemini/MOVIES combination is ideal for this type of study. A typical program would use surveys like ASAS-SN or LSST to trigger the start of a brightening event in a known AGN. Initial response is to rapidly acquire a MOVIES spectrum requiring a ~30 minute visit (most of these AGN will be bright, catalogued objects of known type, e.g., by SDSS or other archival surveys). If the AGN type has changed, follow up observations on a 1-month cadence would be taken to follow the event for up to 1 year after the initial trigger. The broad wavelength coverage and moderate resolution of MOVIES enables modeling of the underlying stellar continuum from 400 to 2400 nm, allowing detailed measurement of changes in the shape of the underlying power-law continuum as well as measurement of changes in the broad emission line characteristics. Rates of such events are difficult to estimate because large-scale monitoring of AGN is not undertaken by anyone in a systematic way, but the advent of short-cadence, all-sky imaging surveys like LSST and ASAS-SN make it possible to catch such events and determine the rate.

2.3.1.4 Spectroscopic Follow-up of Rare Transient Events

Transient surveys (like ASAS-SN) are dominated by cataclysmic variables, M-dwarf and T Tauri flares, AGNs, QSOs, Blazars, and many Supernovae of all types. These are all expected. Truly exciting science return will come from very rare or totally unprecedented transients.

An example of particular relevance to the MOVIES design is ASASSN-13db, an unusual Galactic transient triggered by a $\Delta V \sim 5.4^{mag}$ brightening in a red SDSS star (Holoien et al. 2014b). Initial follow-up spectra at low resolution (R = 1000 – 2000) were confounding – an undifferentiated mass of lumps with no distinguishable emission or absorption lines beyond Hα (which was later plausibly from the foreground). Higher resolution (R~4000) spectra with the Magellan MagE spectrograph (Marshall et al. 2008), showed the "lumps" in the spectra were dense forests of narrow emission lines. This led to the recognition that ASASSN-13db is an EX Lupi-type accretion event on a low-mass T Tauri star (a so-called "Exor" event; e.g., Herbig 2007). The match between ASASSN-13db and EX Lupi could only be made at medium resolution (see Figure 6).

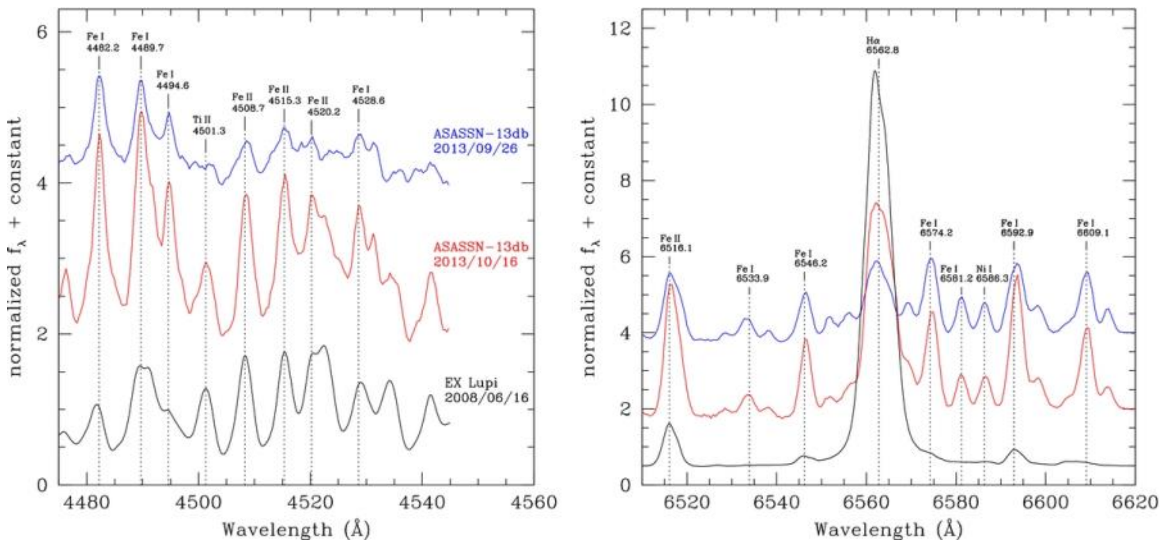

Figure 6: Normalized Magellan MagE spectra of ASASSN-13db plotting with spectra of EX Lupi, showing the similarities between the two (Holoien et al. 2014b, Figure 4)

The correct identification and subsequent follow-up science was enabled by the higher resolution of MagE combined with wide wavelength coverage as these lines blanket the spectra from 3500 to 10000Å. Long-term study requires a spectrograph with high calibration stability, and since the target is bright and requires relatively short exposures, rapid target acquisition to maximize overall on-the-clock efficiency is essential to reducing the opportunity costs of observing sources like this.

2.3.2 Outer Solar System Science

2.3.2.1 Background

Very little is known about the compositions of the outer Solar System's planetesimals (OSSPs). Beyond the orbit of Jupiter, only a handful of materials have been clearly identified in the reflectance spectra of OSSPs. The largest, and therefore brightest, few Kuiper Belt Objects and Centaurs have received considerable attention. Spectroscopy has revealed the existence of volatile ices on the surface of objects such as Pluto and Eris, including methane and N_2 (Owen et al. 1993, Brown et al. 2005). Of the smaller, volatile poor objects, very little compositional information is known. Water ice is the only reliable spectroscopic material identified on volatile-poor OSSPs (Barkume et al. 2008).

Other than for water ice, only indirect compositional information is available. It is generally accepted that the outer Solar System's planetesimals must consist in large part of silicate materials, as many objects exhibit densities higher than that of perfectly compacted water ice (see Brown, 2013 for an up to date list). Additionally, OSSPs are known to exhibit red to very red optical colours (see for example, Fraser and Brown 2012, Peixinho et al. 2012) and low albedos (eg. Vilenius et al. 2014) which is interpreted as evidence of complex organic materials on the surfaces of those objects (eg. Cruikshank et al., 1991).

The main identifying feature of most organics found in the Solar System is the so-called optical gap feature. Reminiscent of the behaviour of semiconductors, this feature is due to the liberation by an incoming photon of the outermost valence electron in a π-π bond. Centred in the UV at ~0.39 μm, the red wing of the optical gap is responsible for the red optical colours and low albedos of most complex hydrocarbons including polyaromatic hydrocarbons (PAH's; Izawa et al. 2014) and solid bitumens (Moroz et al., 1998). Importantly, this feature is also found in the spectra of the materials produced during irradiation-induced chemistry of simple organic ices such as methane and water (Brunetto et al. 2006, Callahan et al. 2013). The location and profile of the optical gap absorption depends critically on the structure of the hydrocarbon chain (see Figure 7, panel b). Roughly speaking, the longer and more disordered the chain, and the more complex the non-carbon based side groups, the wider the optical gap. Recently, laboratory work on PAHs however, has revealed small absorption bands in the ~0.35-0.4 μm range. These features have been tentatively associated with the vibration mode splitting of the optical gap centre. While the nature of these structures is still under scrutiny in the lab, the shape and structure of these small UV features clearly holds structural and compositional information about the molecules producing them.

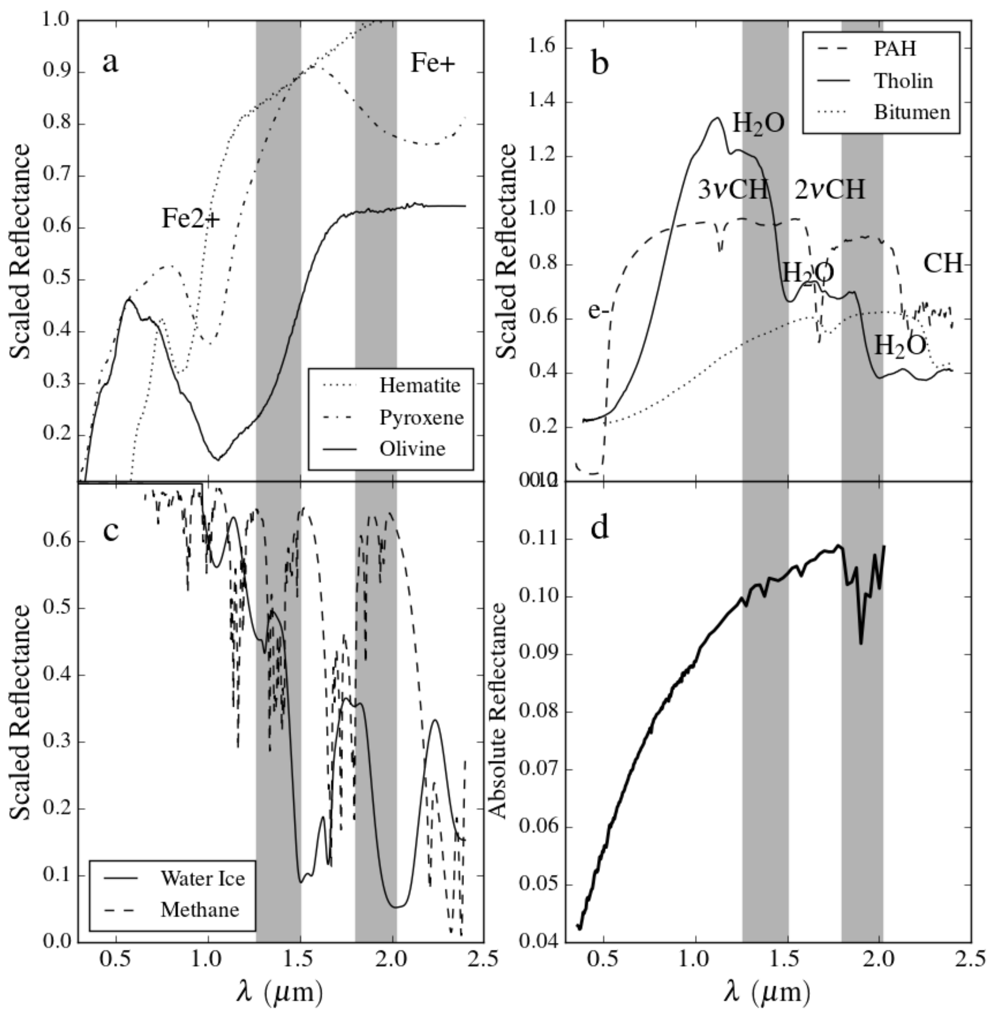

Figure 7: Spectra of example silicate (a), organic (b), and icy (c) materials expected to be found on the surfaces of outer Solar System planetesimals. Relevant absorption features discussed in the text are marked, including the Fe2+ iron feature and the valence electron optical gap. Grey regions mark wavelengths strongly affected by telluric lines. Panel d shows a high quality spectrum of a centaur which exhibits 1% deviations away from linearity at ~0.39 and ~0.6 μm.

Longward of the UV-optical range, other sharper organic features in the red optical and NIR may be apparent depending on the specific organic materials the OSSPs posses. These include vibrational features such as the 3 and 2νCH overtones (e.g., Izawa et al. 2014), and the equivalent CN features at 1.1 and 1.7, and 2.2 μm, and H_2O in clathrate form or as part of the organic molecular structure. While detection of any single organic feature will be provide a massive jump in our understanding of the true nature of the organic material, only detection of multiple features in an OSSP spectrum will allow the true characterization of that object's surface.

While organic materials appear to dominate the spectra of OSSPs, their bulk composition clearly must consist in part as silicate. The most basic silicates identified as potential candidates are olivines and silicates. These materials possess strong ferric and ferrous iron features near 0.9, 1.5 and 2.2 μm (Figure 7, panel a). Such features are obvious in the spectra of most asteroids. To date however, no published spectra bear hints of these absorptions requiring that the silicates on OSSPs must not be in pure form, but thoroughly mixed with low albedo organic material that would dramatically diminish the depth of those features. Only with extremely high SNR spectra will these silicate features be detected.

2.3.2.2 Absence of Detection

Detection of organics and silicates has been entirely elusive primarily due to sensitivity and incomplete wavelength coverage across the UV-NIR range. The nature of the anticipated absorption features requires high SNR spectra, broad wavelength coverage, and accurate telluric line removal. MOVIES can meet all of these conditions.

The most challenging to detect features are those that fall across the regions most heavily contaminated by telluric lines, the removal of which practically sets two requirements for the instrument. The first requirement, resolution, must be high enough such that the major telluric lines are resolved and isolated, requiring resolution R>2000 longward of 0.9μm (see arXiv:1405.3679v1).

The second requirement is the ability to rapidly acquire targets. Under all but the most stable conditions, ambient humidity and temperature can vary on minute timescales. As such, the strength of the telluric lines also varies dramatically on multi-minute timescales. The ability to rapidly switch between target and stellar calibrator under everything but perfect conditions is absolutely critical to decontaminate the regions between the J, H, and K bands, wavelength regions that are critical for organic and silicate detection. MOVIES will be the first instrument on an 8 – 10m class telescope with sufficiently short acquisition times to meet this requirement.

Characterization of the anticipated organic features, including the splitting of the optical gap centre, and the CN and H_2O combination bands requires spectra of resolution only R~100 across the full spectral range. Hints of these features have appeared in the highest SNR spectra available (Fraser et al., in prep, see Figure 7, panel d). Available data suggest that feature detection requires extremely high quality spectra. At least SNR~50 per binned spectral resolution element, or SNR~8 in the native instrument resolution is required before these features can be identified. In a ~1 hour exposure, this SNR can be achieved for an r'~21.5 magnitude source in the UV where OSSPs are faintest. Scaling from the absolute magnitude distribution of Kuiper Belt Objects (Fraser et al. 2014) this translates to roughly 150 targets in the outer Solar System bright enough for spectral characterization with MOVIES.

Gathering reliable moderate SNR spectra is complicated by the requirement of spectral order combination, which when performed using only the observed spectrum, can often result in wildly incorrect results. With spectral photometry from the acquisition camera, the difficulty of arm and order combination will be greatly alleviated, allowing reliable spectra to be gathered with native SNR as low as ~2. While insufficient for full characterization, such low SNR spectra can still provide a spectral classification that is based broadly on a target's colours (and maybe water-ice depth; Fraser and Brown 2012). Classification is possible on objects roughly a half magnitude fainter, affording an additional ~300 observable targets. Any further sensitivity gains over the nominal camera design – especially in the UV and long NIR ranges – will bring massive increases in the number of observable targets.

2.3.3 Stellar Populations in Nearby Galaxies

The study of the stellar content in galaxies is directed at constraining their star formation histories, metallicities, and dust content – all required to better understand the physics of galaxy formation and evolution. This topic provides a number of examples of the workhorse capabilities of MOVIES.

2.3.3.1 The colour-metallicity relation of extragalactic globular clusters

The optical color distributions of extragalactic globular cluster (GC) systems in massive galaxies generally exhibit a bimodal shape (Zepf & Ashman 1993, Peng et al. 2006). Based on an assumed linear relationship between GC colors and their metallicities, this bimodality has usually been interpreted as evidence for two distinct GC metallicity populations differing by roughly a factor ten in metal abundance. This fundamental piece of evidence has led to the argument that massive galaxies assemble via two distinct formation mechanisms and/or epochs (Forbes et al. 1997, Cote et al. 1998).

However, this simple picture has been recently challenged by the finding that a non-linear color-metallicity relation (arising due to horizontal branch morphology variations as a function of metallicity) can artificially introduce multiple peaks in the GC color distribution function even when starting from a single-peak metallicity distribution (Yoon et al. 2006, 2011a; see Figure 8). The situation seems to be even more complicated: recent investigations have found evidence both for and against metallicity bimodality in the individual GCSs of a few nearby galaxies (Blakeslee et al. 2012, Brodie et al. 2012). The systematic study of Usher et al. (2015) on a homogeneous sample of ten early-type galaxies presents strong evidence for variations in the GC colour–metallicity relation. They suggest that two possible explanations for the colour–metallicity relation variations are that the average ages of globular clusters vary from galaxy to galaxy, or that the average abundances of light elements (He, C, N and O) differ between galaxies.

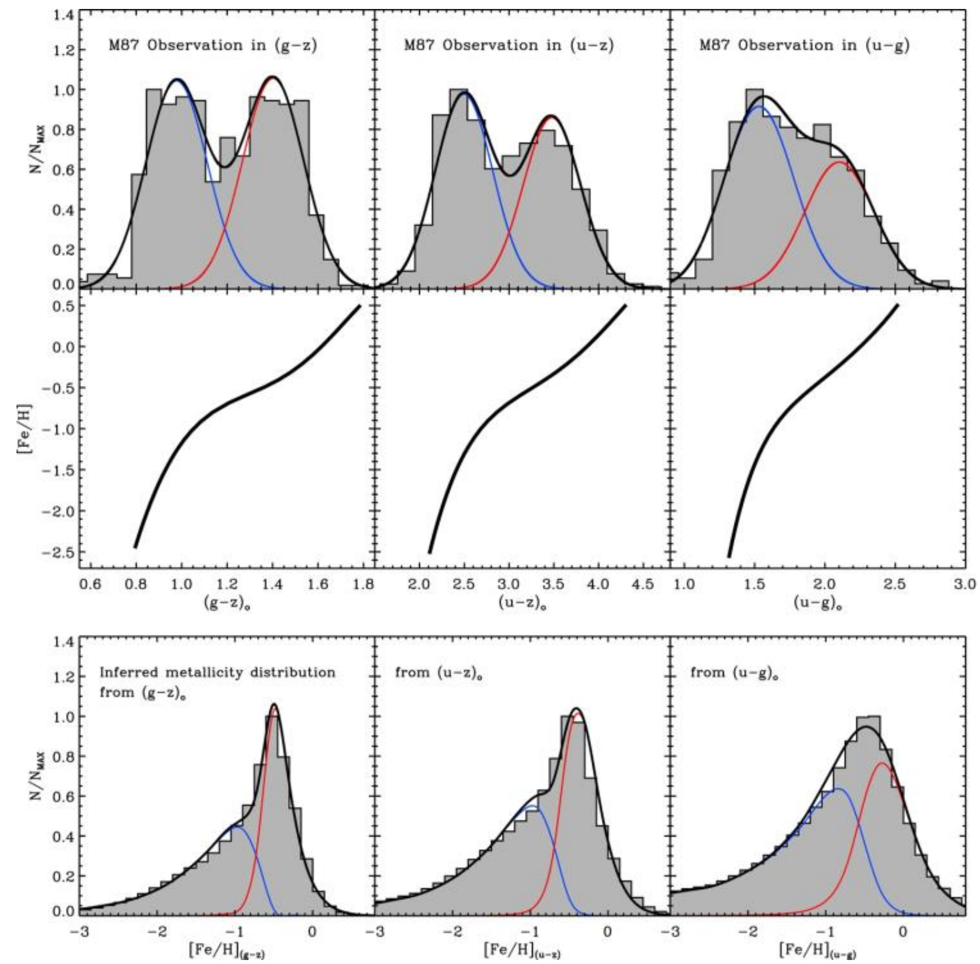

Figure 8: (top row) observed GC colour distributions in the central Virgo galaxy M87; (middle row) non-linear colour-metallicity relations derived from synthesis models; (bottom row) single-peaked metallicity distibutions arise as a result of the strong non-linearity (from Yoon et al. 2011, Fig. 5).

Knowledge of the precise colour-metallicity relation over the entire metallicity range, and its dependence on host galaxy properties will have profound implications in the area of galaxy formation, assembly, and evolution. For this, it is absolutely crucial to i) homogeneously sample the GC color distributions in a statistically significant sample of nearby galaxies, and ii) at the same time, obtain high-enough metallicity resolution in the non-linear part of the color-metallicity relation at ~ 0.05 dex or better.

Recently, Muñoz et al. (2014) showed that the *uiK* colour–colour diagram allows a very clean selection of GCs, virtually free of contamination from foreground stars and background galaxies (Figure 9). Other filter combinations with narrower baselines (e.g., the well-known BzK) perform comparably much worse. As a result, this near-ultraviolet, optical and near-infrared diagnostic diagram is a unique tool that shall guide future searches for globular clusters in extragalactic systems. Additionally, it is well known (Cantiello & Blakeslee 2007, Chies-Santos et al. 2012) that optical/near-infrared colours are a better metallicity proxy than purely optical colour distributions. Therefore, an observed bimodal distribution in such former colours is more likely to indicate a true underlying bimodal metallicity distribution.

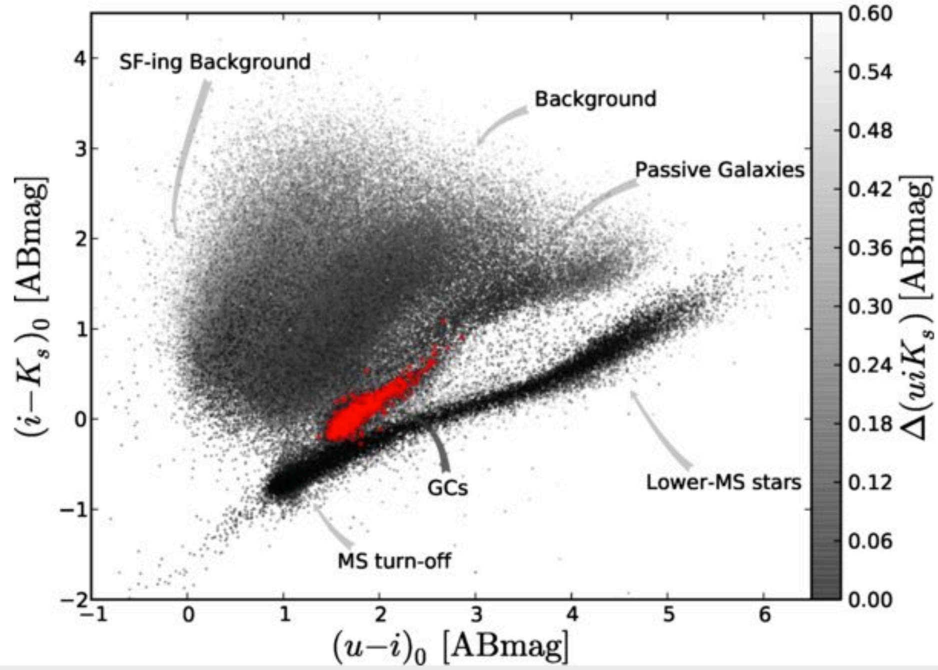

Figure 9: Diagnostic *uiK* colour-colour diagram for objects in the surroundings of M87. The characteristic sequences for several types of objects are indicated. Red symbols represent spectroscopically-confirmed GCs in the Virgo cluster. The GC sequence is cleanly separated from the locii of both MW stars, and background galaxies (from Muñoz et al. 2014).

An instrument capable of performing simultaneous NUV, optical, and NIR imaging (e.g., *uiK*) down to faint levels will become the primary workhorse in the field of extragalactic globular clusters detection and characterization. The GC luminosity function peaks at a turnover magnitude M_V = -7.5 mag, which corresponds to V<24 mag for objects with distances D<20 Mpc. According to the 2MASS Redshift Survey (Huchra et al. 2012), there are >350 galaxies with $M_{star}>10^{10}$ M_{sun} in the 5<D<20 Mpc volume centred on the Milky Way. They span a wide range of environments, from isolation to the cores of the Virgo and Fornax clusters, and therefore are excellent targets for a systematic study of GCSs in the nearby Universe. With typical apparent sizes $1.5<R_{26}<2.5$ arcmin, a camera with FOV=3 arcmin would only need between one to four pointings to image the bulk of their GCS. According to the MOVIES ITC, a S/N=20 integrated over the PSF area in the V-band can be obtained with integrations of only 900s.

In order to achieve ~0.05 dex metallicity accuracy, it is necessary to simultaneously access multiple line features that are sensitive to metal and molecular abundances (Mg, Fe, Ca, C, N, CH, NH, CN, CO). This requires at least moderate resolution spectroscopy (R>5000) across the full 350-2500 nm spectral range with S/N≥10 per spectral bin. For bright GCs (V<20), this can be achieved with 900s on-target integration time. The derived absorption indices will allow the determination of the overall chemical composition as well as various abundance ratios (e.g. α/Fe, C/Fe, C/N, O/Fe). Balmer lines can be used to derive relative GC ages with enough accuracy to classify them into young (t<2 Gyr), intermediate-age (2<t<8 Gyr), and old objects (t>8 Gyr). This, in turn, will be a definitive step toward establishing the color-metallicity relation for old and younger stellar population ages in compact stellar systems.

2.3.3.2 Resolving the galaxy-star cluster divide

The traditional dichotomy between galaxies and star clusters at the low-mass end of stellar systems has been erased in recent years by the discovery of new classes of stellar groupings with masses and sizes intermediate between these two families. In particular, ultra-compact dwarfs (UCDs) are generally old stellar systems defined to be brighter and larger than massive globular clusters (GCs), but fainter and smaller than prototypical compact elliptical galaxies like M32 (see Figure 10).

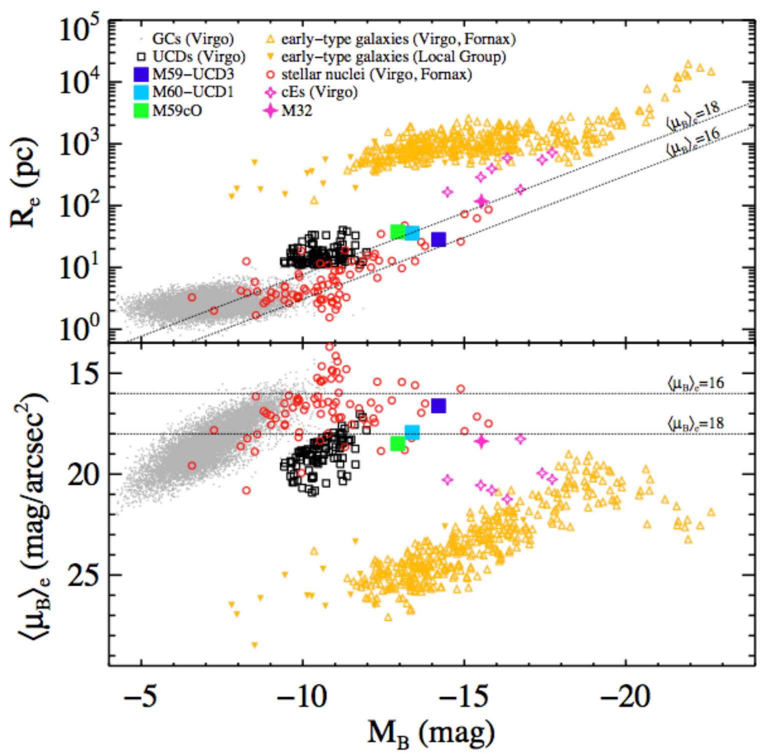

Figure 10: Structural scaling relations of low-mass stellar systems in nearby galaxy clusters (from Liu et al. 2015). It is clear that UCDs and nuclei exhibit some overlap, and that the galaxy-star cluster divide is bridged by these extremely dense stellar systems

Given the intermediate nature of UCDs, there has been ongoing debate about their origin since their discovery (Hilker et al. 1999, Drinkwater et al. 2000). Formation mechanisms are divided between those that consider them stellar clusters (e.g., the end-products of mergers of young massive clusters, or simply being the most massive GCs); and those that ascribe them a galactic origin (e.g., the remains of tidally-stripped nucleated galaxies, or the remnants of primordial compact galaxies). There is a growing body of evidence that suggests many UCDs, especially at the high-mass end, are the remains of nucleated galaxies that have suffered significant tidal "threshing" (Pfeffer & Baumgardt 2013; Zhang et al. 2015); thus, these systems represent an important new diagnostic of stripping processes within massive haloes. Perhaps the most compelling one is the recent discovery of a ~20 M_{sun} black hole in M60-UCD1 (Seth et al. 2014, Nature), since it strongly points out to a galactic origin for these objects. Even if a fraction of UCDs are remnants of stripped low-mass galaxies, the origin of stellar nuclei themselves is unclear, with scenarios ranging from dynamical friction-driven mergers of GCs (Oh & Lin 2000), to a dissipational origin as a result of gas inflows and confinement aided by an enhanced environmental pressure (Babul & Rees 1992).

What is needed now is a high precision, comparative chemodynamical study of low-mass compact stellar systems using homogeneous and well-characterized samples. To date, this has been a fundamental obstacle in these studies, with existing samples assembled from heterogeneous data collected in a range of environments, and with very different selection functions and observational biases (e.g., Norris et al. 2014). Using data from the Next Generation Virgo Cluster Survey, Liu et al. (2015) have assembled a homogeneous catalogue of hundreds of UCDs in Virgo. Of particular interest are ~35 objects with absolute magnitudes $M_V<-11.5$ (masses $M_{star}>5\times10^6$ M_{sun}). This is a critical mass scale, because systems above this value tend to have elevated dynamical mass-to-light ratios (more than a factor two compared to GCs; Mieske et al. 2008), which can be interpreted as marking the onset of dark matter domination at these mass scales. Additionally, one can build a similarly-sized sample of low-mass galaxies with stellar nuclei sharing the same photometric properties as the UCDs (Liu et al. 2015).

For these samples of UCDs and stellar nuclei we propose to i) resolve the velocity dispersion of the system and derive its dynamical mass (including any possible dark mass components); and ii) characterize with unprecedented detail their stellar population properties. We will not only measure all the important absorption features (e.g. via standard line index systems) but also obtain their chemical fingerprint via the comparison of absorption features in the near-UV to near-IR using the latest generation of population synthesis models (e.g., Conroy & van Dokkum 2012). These model spectra extend from 0.35 to 2.5μm with a resolving power R~2000, and combine blue spectral features with surface gravity-sensitive NIR features to simultaneously constrain the stellar population age, metallicity, and abundance pattern–as well as the low-mass IMF–from integrated light measurements.

This study has two main requirements: i) accurate kinematic measurements down to σ~20 km/s, sufficient to resolve the internal velocity dispersion of compact stellar systems of these luminosities (e.g., Mieske et al. 2008, Norris et al. 2014); and ii) high-enough metallicity resolution at the level of ~0.05 dex or better. The former can be achieved with a resolving power R=10,000, corresponding to σ=13 km/s. Toloba et al. (2011) show that SNR≥15 are needed to obtain unbiased σ measurements. The latter requires SNR~40 per spectral bin in the optical (e.g., Paudel et al. 2011) at R~1000, typical of line index systems (Burstein et al. 1984, Vazdekis et al. 2010). This particular case would benefit greatly from the EMCCD technology: because they are not limited by readout noise, these detectors allow observations at very high spectral resolution–so the OH sky emission lines can be resolved. Once the lines are suppressed during the post-processing stage, the original R~10K spectrum can be rebinned down to R~1K to achieve the required SNR=15×√10=50 with no read noise penalty.

Using our MOVIES ITC with a 0.5-arcsec wide slit, and assuming a G2V spectral template, airmass=1.4, seeing FWHM=0.8", 7-day old moon, and targeting magnitudes of V~19 (M_V~−12 in Virgo) for a point source, we require an on-target integration time of 2200 sec to reach the required SNR=15. This exposure time will also provide low-SNR spectra for the stellar field in the close vicinity to the stellar nuclei, and a 900 sec off-target exposure can be used to subtract the sky contribution. Another important characteristic of MOVIES are its reduced overheads, which we estimate at ~300 sec per exposure. We thus estimate a grand total 35×(2200+300)+35×(2200+900+300) sec = 57 hours of MOVIES Gemini observing time to complete such a program.

2.3.3.3 Mass-to-light ratios and stellar population properties of dwarf galaxies from pixel-by-pixel SED fitting

Spectroscopic observations provide the strongest constraints on the stellar population properties of unresolved galaxies. However, spectroscopic galaxy surveys are always built upon a delicate balance between sample size, spatial and spectral coverage, and signal to noise. This is even more important in the case of nearby galaxies and/or intrinsically faint systems, where large apparent sizes and/or low surface brightness seriously impact the fraction of galaxy body that can be studied. On the other hand, broadband imaging is capable of providing high S/N photometry across a wide range of surface brightness (or equivalently, area) – at the expense, of course, of spectral resolution.

The proliferation in recent years of large-area, multiwavelength imaging surveys has been accompanied by a significant effort to model the spectral energy distributions (SEDs) of galaxies, with a particular emphasis in exploring a wide range of physical properties – e.g., star formation histories, ages, metallicities, initial mass functions, dust reddening and reddening law (e.g., Salim et al. 2007, da Cunha et al. 2008, Pforr et al. 2012). Gil de Paz & Madore (2002) computed the uncertainties associated to the derivation of galaxy physical properties when comparing UV-to-NIR broadband photometry to the predictions of evolutionary synthesis models (see Figure 11). They show that, as expected, the best results are obtained when the SEDs are frequently sampled across the entire wavelength range, but also point out that the availability of wider wavelength baselines results in lower uncertainties (for a fixed number of observing bands). In particular, they identify the use of the *U*-band as fundamental to derive the star formation history, age, and dust extinction in nearby galaxies. NIR photometry further constrains age and metallicity, and is instrumental to derive accurate M/L ratios.

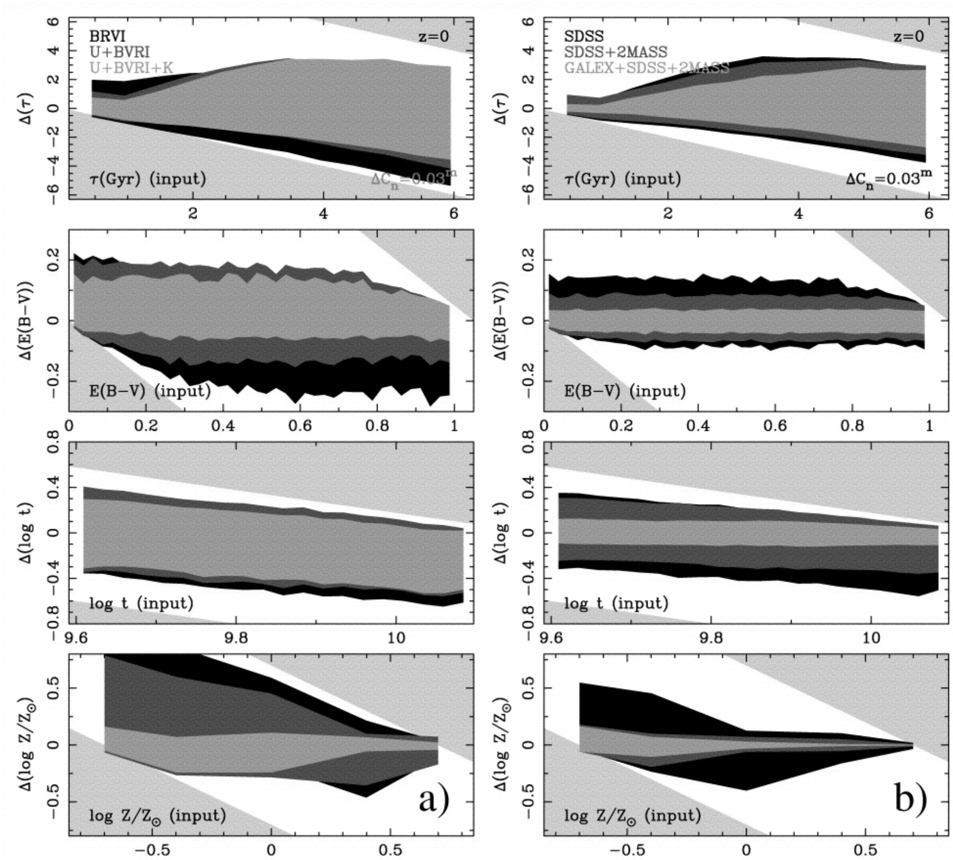

Figure 11: Uncertainties in derived galaxy stellar population properties from SED fitting. From top to bottom, the panels correspond to formation timescale, extinction, age, and metallicity. The shaded regions in each plot show the corresponding uncertainties for different filter combinations. Note how the addition of the U- and K-band photometry greatly reduces the uncertainties in derived extinction and metallicity (from Gil de Paz & Madore 2002).

A similar conclusion was reached by Zibetti et al. (2009) in their derivation of stellar mass maps from optical/NIR colours (e.g., *giH*). While most previous works had focused on integrated (or area-averaged) SEDs, Zibetti et al. (2009) developed a novel method to derive two-dimensional stellar mass maps with accuracies <30% from sets of optical plus NIR galaxy images. More importantly, they show that unresolved stellar mass estimates for galaxies with prominent dust lanes can miss up to 40% of the total stellar mass because dusty regions are strongly under-represented in the luminous fluxes.

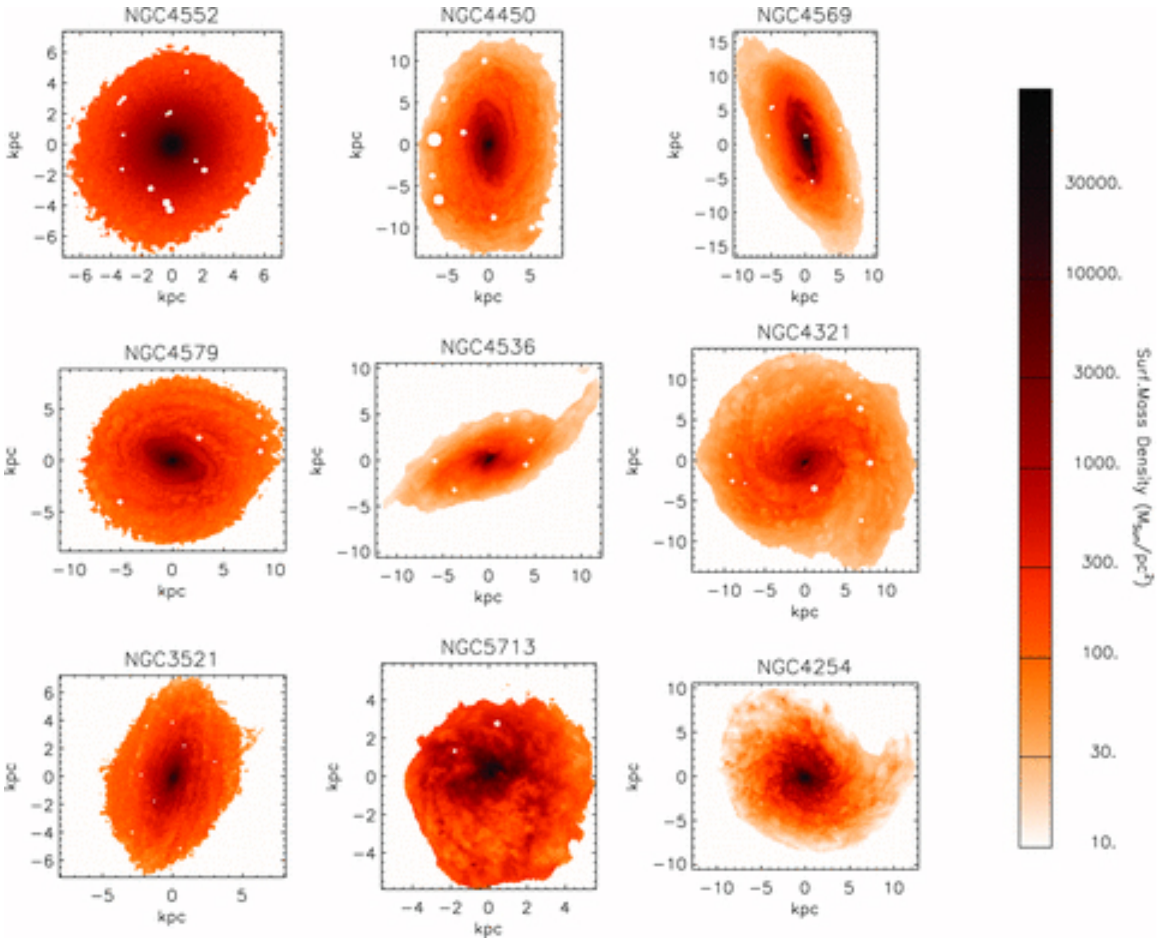

Figure 12: Pixel-by-pixel stellar mass maps for luminous nearby galaxies derived from optical/NIR colours (from Zibetti et al. 2009).

While this approach has been applied successfully to derive the stellar masses of intrinsically luminous galaxies, little has been done in the realm of dwarf galaxies. These faint, low surface brightness objects are the most abundant galaxy type in the Universe. As a population, they are suspected to be extremely inefficient at retaining baryons, as well as in converting them into stars -- as evidenced by their high total-to-stellar and gas-to-stellar mass fractions (Strigari et al. 2008, Geha et al. 2006). In general, the stellar masses used in these computations are simply derived by using the M/L-optical colour relations derived for more massive galaxies, and can therefore be highly uncertain. Moreover, in the case of strongly star-forming galaxies, where the bulk of the light is dominated by (a few) very luminous young stars, the area-averaged M/L ratios will be biased low.

As has been done for luminous galaxies, it is desirable to firmly establish spatially-resolved M/L-colour relations for a statistically significant sample of dwarf galaxies spanning a range of masses, morphological types and environments. The Karachentsev et al. 2013 all-sky catalog of nearby galaxies contains >450 dwarf galaxies (M_B>–16), all with apparent diameters D_{26}<5 arcmin, and with distances <10 Mpc. Given the considerations above, NUV-to-NIR colours are required to avoid significant biases and uncertainties as a function of the local physical properties of a galaxy. A large-baseline *uiK* deep imaging survey of a large sample of dwarfs in the Local Universe would become a unique diagnostic tool to investigate the star formation efficiency within these small haloes. According to the MOVIES ITC, S/N=6 per resolution element at μ_i~26 mag/arcsec^2 can be obtained in only 1800s integration time. Moreover, the method can be easily generalized to include additional bands, and thus carry out pixel-by-pixel SED fitting to derive two-dimensional maps of other stellar population properties beyond M/L ratios. This would be highly informative on where and how star formation takes place in these inefficient systems, and would further provide unique information on the occurrence and properties of stellar haloes at the low end of the galaxy mass function.

2.3.3.4 Stellar populations properties, and the low-mass stellar initial mass function in nearby galaxies from integrated spectra

The single largest source of uncertainty in the study of nearby stellar populations is the shape of the stellar initial mass function (IMF). Historically, it has been usually assumed that the IMF is universal, and hence similar to the one measured in the solar neighbourhood: a power-law with slope $x = -\text{dlog(N)/dlog(M)} \sim 2.35$ (Salpeter 1955) above a few solar masses, that transitions to shallower slopes (x~1) for lower mass stars. This assumption was justified in the light of existing observational evidence from field stars, young clusters and associations, and old globular clusters in the MW, as well as from resolved stellar populations and the integrated properties of other galaxies (see the review by Bastian et al. 2010).

This scenario has drastically changed in the last few years with the realization that the IMF in massive elliptical galaxies is much more bottom-heavy (i.e., a larger ratio of low to solar mass stars) compared to the IMF in the Galaxy (van Dokkum & Conroy 2010). This result was recently extended by Cappellari et al. (2012), who used detailed dynamical models of early-type galaxies spanning two decades in stellar mass to uncover a systematic variation of their IMF as a function of their stellar mass-to-light ratios.

Even though these low-mass stars ($M<0.4\ M_{sun}$) comprise the bulk of the stellar mass in galaxies, they only contribute of order one percent of the luminosity of old stellar populations. As a result, determining their abundance from integrated light measurements is extremely challenging. Recently, Conroy & van Dokkum (2012) have developed new population synthesis models tailored at measuring the low-mass IMF down to 0.1 M_{sun} for metal-rich populations with ages 3<t<13.5 Gyrs. With these new models they specifically address the importance of individual elemental abundances, including C, N, Na, Mg, Si, Ca, Ti, Fe. They find that the low-mass IMF of old populations can be inferred directly from red or NIR spectral features (e.g., the Wing-Ford FeH molecular band at ~1000 nm). But perhaps even more importantly, they show that by combining blue spectral features with surface gravity-sensitive NIR features it is possible to simultaneously constrain the stellar population age, metallicity, and abundance pattern – as well as the low-mass IMF – from integrated light measurements.

Their model spectra cover the $350<\lambda<2400$ nm wavelength range with a resolving power R=2000, and would therefore allow for a direct comparison with observations covering the entire NUV-to-NIR spectra of massive (metal-rich) galaxies. Because the expected differences are usually at the level of a few percent (see Figure 13), the spectra need to have high signal-to-noise, ranging from 20 to 200 per Å depending on the specific indices under study. While absolute flux calibration is not necessary, it is important to have a good handle of sky emission and absorption, with overall uncertainties at the <1% level—and instrument stability is definitely a requirement.

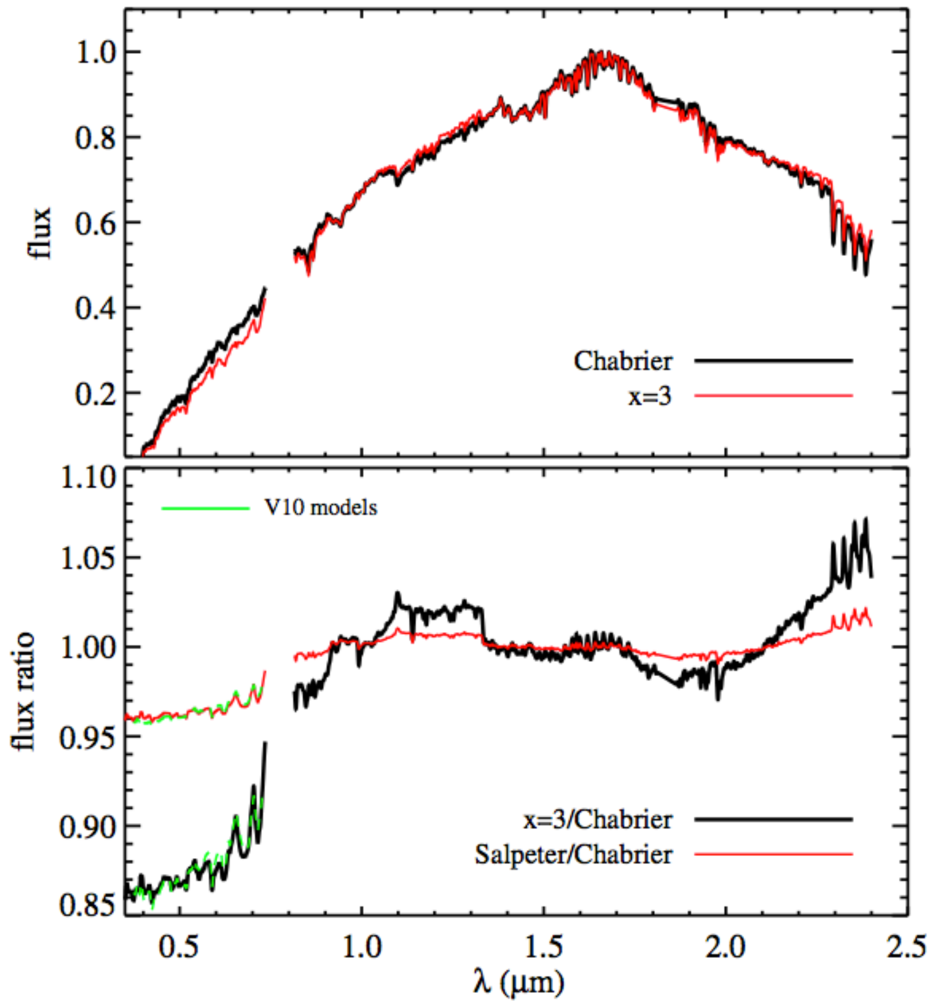

Figure 13: (top) optical-to-NIR model spectra for solar metallicity and 13.5 Gyr populations with different IMFs; (bottom) flux ratio between models having different IMFs. The bottom-light Chabrier IMF is used as a normalization for both a Salpeter, and a bottom-heavy x=3 IMF. The broadband differences for the x=3 model are significant, whereas Salpeter and Charbrier IMFs only differ at a few percent level (from Conroy & van Dokkum 2012).

This approach offers the exciting possibility of carrying out a systematic study of the stellar population properties in a large sample of galaxies spanning a wide range of masses and in a variety of environments – therefore probing the physics of star formation and metal production throughout cosmic history. For example, one can envision a programme targeting the 260 early-type, nearby galaxies in the ATLAS3D sample

(Cappellari et al. 2011). With only 900s on-source integration time per galaxy (plus another 900s for sky) one can achieve S/N = 100-400 spectra (depending on the galaxy surface brigthness) at a resolving power R = 2000

2.3.4 Low-mass Stars

2.3.4.1 Probing the Bulk composition of rocky material with white dwarf stars

It has recently been realized that the presence of heavy elements at the photosphere of cool white dwarfs is most probably due to contamination by rocky remains of terrestrial planetary systems (planetesimals, asteroids, small planets). There is growing evidence that cool metal-polluted white dwarfs have acquired their heavy material from an orbiting debris disk reservoir whose origin is explained by the tidal disruption of one or many large rocky bodies that ventured too close to the star (Debes & Sigurdsson 2002; Jura 2003, 2006, 2008; Jura et al. 2007; Farihi et al. 2010a, 2010b). The heavy elements observed in the spectra of these otherwise pure hydrogen or helium atmosphere white dwarfs thus represent a unique fingerprint that contains information about the detailed Bulk composition of rocky material that once orbited the star. As such, the most metal-polluted white dwarfs represent perfect test beds to discriminate between various planet formation scenarios, allowing the first empirical verification of extrasolar terrestrial planet formation simulations.

As the sample of well-studied metal-contaminated white dwarfs increases, a more comprehensive picture should emerge, leading to a better understanding of how, both individually and statistically, these planetary systems form and evolve. Thanks to the Sloan Digital Sky Survey, the number of white dwarfs polluted with heavy elements has dramatically increased in recent years. From only a few dozen exceptional objects known in the late '90s, the sample has now grown to more than 400 stars in the latest spectroscopically-confirmed white dwarf catalog (DR7, Kleinman et al., 2012). However, the low-resolution spectroscopic observations from the SDSS allows only the detection of one or two elements in most cases, hardly enough to infer the detailed composition of an object.

Follow-up high resolution optical spectroscopy (mostly with Keck) of the brightest candidates with strong H & K lines revealed more than 8 elements in about a dozen objects and even as many as 15 distinct elements in one case (Zuckerman et al. 2007, 2011, Klein et al. 2010, 2011, Dufour et al. 2012). Since the low-hanging fruit have already been picked, it is now necessary to go after fainter object to increase the sample of objects with 8 or more elements. We estimate that spectroscopy at R = 10000 of a highly polluted white dwarf should easily reveal close to a dozen distinct elements between 350 – 800nm given 6-8 hours of observations on a g=18.5 object. The SDSS DR7 spectroscopic sample already contains more than 20 such candidates and many more will certainly be identified soon in the subsequent data releases. We should thus soon enter an era where a large enough sample of highly polluted white dwarfs analysed in detailed will be available to make meaningful statistics on these planetary systems.

To achieve these science goals with MOVIES, the following capabilities are required:

1. High sensitivity to efficiently observe very faint targets
2. Low overheads to acquire efficiently large samples
3. Moderate resolution (R~10000) to resolve key elements
4. Broad wavelength coverage in the optical

2.3.4.2 Ultra-cool dwarfs and planetary mass objects

Since the discovery of the first brown dwarf and exoplanet in 20 years ago, the study of these objects has blossomed into one of the most active fields in astronomy. Most early observational efforts in both brown dwarf and exoplanet studies concentrated on the gathering of large samples of objects. More than 1000 L and T dwarfs are now known and tens of planetary mass objects have been imaged around young stars.

While the search for ever cooler brown dwarfs, some even below room temperature, is ongoing, much of the observational effort is now shifting toward understanding the diversity of known brown dwarfs. The diversity of physical properties emerging from recent studies is impressive; some L dwarfs turned out to be planetary-mass objects, while others represent Gyr-old stars at the very bottom of the main sequence. Most of the characterization of ultracool dwarfs to date has been performed at low (R< 500) or low/intermediate (R = 500 − 2000) resolution, sampling the overall shape of deep molecular bands. While this approach has allowed the classification of ultracool dwarfs into high and low-gravity objects and identifying substellar members of nearby moving groups (e.g., Gagné et al. 2014ab), these observations only sample a handful of chemical species. Temperature is probed mostly through the depth water bands, and gravity sensitive features (e.g., Allers & Liu 2013) sample a handful of species (FeH, VO, K, Na and molecular hydrogen). While these species already provide some insight into the chemistry of ultracool dwarfs atmospheres, they fall short from sampling the entire suite of chemical species present.

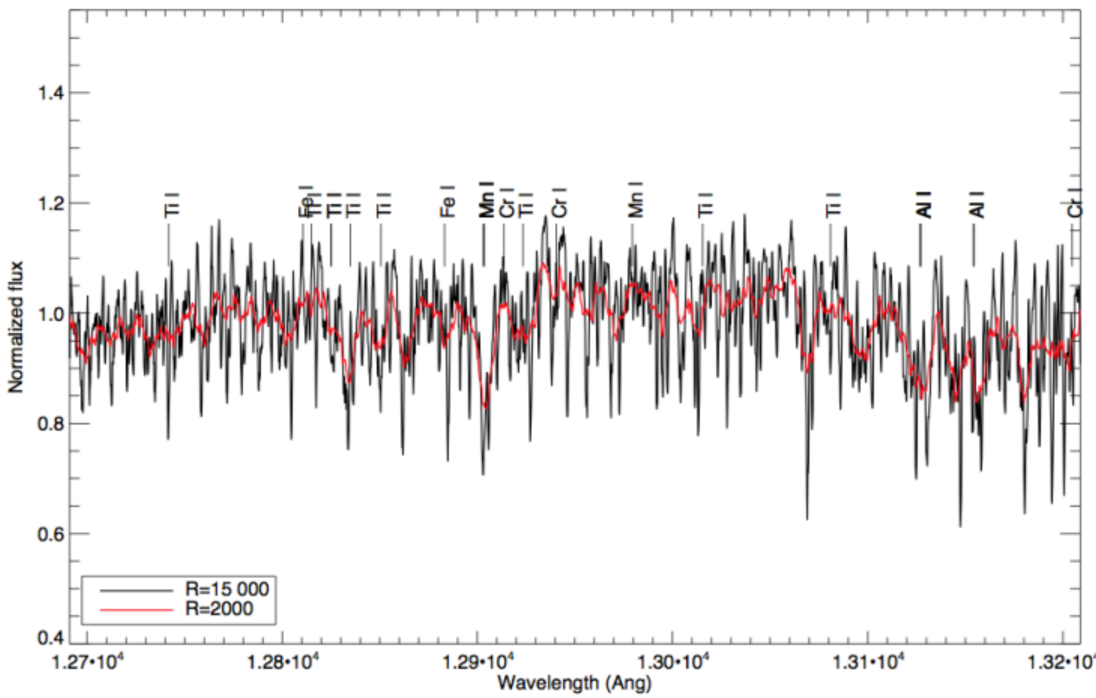

Figure 14: Atmosphere model spectrum for a Teff = 1700K ultracool dwarf over a sample region of the J band. Many trace chemical species have spectroscopic signatures in this domain, but can only be reliably identified at high-resolution. Observations at R = 2000 (e.g., GNIRS, F2) cannot reliably constrain the abundance of most trace chemical species

High-resolution spectroscopy (R ~10 000) provides access to a large number of minor chemical species that have yet to be studied in detail and compared between objects. The study of trace elements in ultracool dwarfs and its relation to the overall properties of the object (metallicity, presence of planets or disk, formation mechanism) is still largely terra incognita. Figure 13 illustrates the large number of chemical species that can be probed in a sample part of the near-infrared domain. These features are well resolved at R ~10 000, but are largely blended at the GNIRS or F2 resolutions. An homogenous study of a large sample of ultracool dwarfs at high-resolution could solve outstanding problems in our understanding of these objects; what are the physical processes leading to the diversity of near-infrared colors among field L dwarfs; how, if at all, do directly imaged exoplanets differ from free-floating L and T dwarfs, etc.

Young moving groups (YMGs) in the solar neighbourhood are the remnants of individual star-forming regions, meaning that their members formed at the same time and in the same environment. These groups are natural laboratories for the study of young population of stars due to their common age and proximity. Until a decade ago, our knowledge of YMGs was limited to bright and relatively massive members, roughly M0V and earlier, for which HIPPARCOS astrometry and parallaxes were available. Much work has been done in the past few years to identify the lower-mass stars of YMGs (e.g., Malo et al. (2013); Shkolnik et al. (2009)) through a combination of methods based on the kinematics and gravity measurements. More recently, these searches have been extended successfully to the brown dwarf and planetary-mass regime. The lowest mass candidate members to YNGs have masses well below the deuterium burning limit. While the membership of these planetary mass objects (PMOs) at the very low end of the IMF has been established through statistical means, they will ultimately require a complete measurement of their kinematics to unambiguously establish their memberships. The typical velocity dispersion within a kinematic group is on the order of 1km/s. At a typical distance of a few tens of pc, astrometric measurements, especially with GAIA, readily reach this accuracy, but obtaining a radial velocity measurement of a faint L-type object requires a resolution of a few tens of km/s. The combined resolution and low-flux sensitivity of MOVIES will enable RV measurements at the 3-5 km/s accuracy level, allowing a confirmation of the kinematic membership of planetary-mass objects in young moving groups.

Flaring and activity in general are hallmark features of M dwarfs, which have long been called flaring stars. It is well established that activity extends into the L dwarf regime, but as temperature drops, the atmosphere of ultracool dwarfs become increasingly neutral, leading to a decoupling of the atmosphere from the magnetic field and a rapid decline in activity. This decrease in activity does not necessarily imply that magnetic fields weaken in the late-L and T dwarf regime; only that the canonical magnetic field signatures used for earlier-type objects weaken. The strength of magnetic fields in L and T dwarf remain largely unconstrained. In a few very young brown dwarfs, strong magnetic fields have been shown to significantly impact the evolution of radii and temperature with time, but it is yet unknown whether magnetic field have a significant impact of the bulk properties of brown dwarfs older than a few Myr. Malo et al. (2014) has shown that the isochronal age measurements of the β Pictoris moving group had been underestimated significantly due to the impact of magnetic fields on the evolution of M dwarfs, and are most likely to affect the evolution of lighter objects, though this has yet to be demonstrated. High-resolution spectroscopy has been used to directly measure the magnetic field of M dwarfs through the Zeeman spitting of various magnetically sensitive molecules (e.g., FeH; Reiners & Basri (2010). This has the advantage of not depending on the interaction of magnetic field with a conductive atmosphere and could be extended into the L and T dwarf regime. Establishing the magnetic field strength of a large sample of L and T dwarfs will measure the impact on the bulk properties of these objects. This technique requires R>~10000 to measure individual line profiles in ultracool dwarfs.

M dwarfs flaring as seen in transient surveys likely represent the tail of the distribution of much more common small amplitude events. Very high cadence (>Hz) spectroscopy of M dwarfs has never been obtained, and it may provide a unique tool to characterize chromospheric heating of these objects. With a ~1 minute time-sampling, Crespo-Chacón (2006) has demonstrated that a bright, nearby, M dwarf displays numerous short flares (~10 minutes), hinting toward a large number of shorter, smaller amplitude, flares. Correlating flaring activity on various time scales with the bulk properties of M dwarfs derived by Zeeman splitting and line profile fitting will lead to new insights into the evolution of magnetic fields in the coolest stars and their coronal heating. MOVIES will open a unique window on M dwarfs, as it will provide an unparalleled combination of spectral and temporal resolutions. These studies will be possible for nearby field Gyr-old M dwarfs, members of YMGs, but also, thanks to MOVIES low-flux sensitivity, for the very young Ms in the Scorpius-Centaurus complex (~12 Mry) at 120 pc, allowing a better understanding of the evolution of M dwarf corona as a function of age.

In summary, to achieve these science goals places the following requirements on MOVIES:

1. A resolution of R>10000, to resolve a large number of chemical species and resolve line profiles for analysis of the magnetic field strengths;
2. Efficient observing is paramount to obtain the large samples that are essential to develop a clear physical understanding of the diversity of brown dwarf systems;
3. Good velocity accuracy of a few km/s to measure the dispersions of low mass moving groups.

2.3.5 Galaxies and Massive Black Holes

Massive black holes ($M_{BH} > 10^6$ M_{sun}) play an important role in the formation of galaxies by likely modulating the growth of the stellar component. The observed correlation between the bulge stellar velocity dispersion (σ) and the mass of the central black hole (M_{BH}), the so-called M_{BH}–σ relation (Begelman et al. 1980), is testimony to this coupling. Yet, our understanding of black holes and the mechanisms by which they impact their surrounding medium through feedback processes, is far from complete. MOVIES will provide a unique view into the physics of black holes, as well as the physics of AGN feedback in galaxies.

2.3.5.1 Brightest Cluster Galaxies

Some of the strongest cases for AGN feedback are seen in clusters of galaxies, where the central AGN hosted by the brightest cluster galaxy (BCG) is capable of driving large jetted outflows that propagate through the intracluster medium, pushing aside the hot X-ray gas and creating structures known as X-ray cavities (see Figure **15** and e.g. Birzan et al. 2004). These X-ray cavities are extremely important because they provide a unique opportunity to directly measure the work done by the AGN on the surrounding medium. AGN feedback can therefore be studied in great detail though BCGs with X-ray cavities.

At optical wavelengths, high-resolution images of nearby BCGs show that the hot X-ray gas is embedded in a web of optical Hα emitting filaments (Figure **15**) that generally trail behind the X-ray cavities. The origin of these filaments remains however, a controversial topic. Some filaments have line ratios consistent with gas that has cooled from the hot intracluster gas (e.g. McDonald et al. 2011), while others are more consistent with particle heating mechanisms, where the filaments been dragged out by the buoyantly rising radio bubbles en-training both gas and dust our to large radii (Fabian et al. 2003, Hatch et al. 2006). Determining the leading excitation mechanism is therefore challenging. This is further complicated by the fact that several lines used to map the line ratios are scattered between the near-UV (e.g. [O II]λλ3726, 3729, [Ne III]λ3869) up to optical (Hα) and beyond, requiring that the spectra be taken with several different instruments. MOVIES will simultaneously cover the near-UV to near infrared range, allowing us to compute reliable line ratios across the entire spectrum to study BCGs with medium resolution (R=5000).

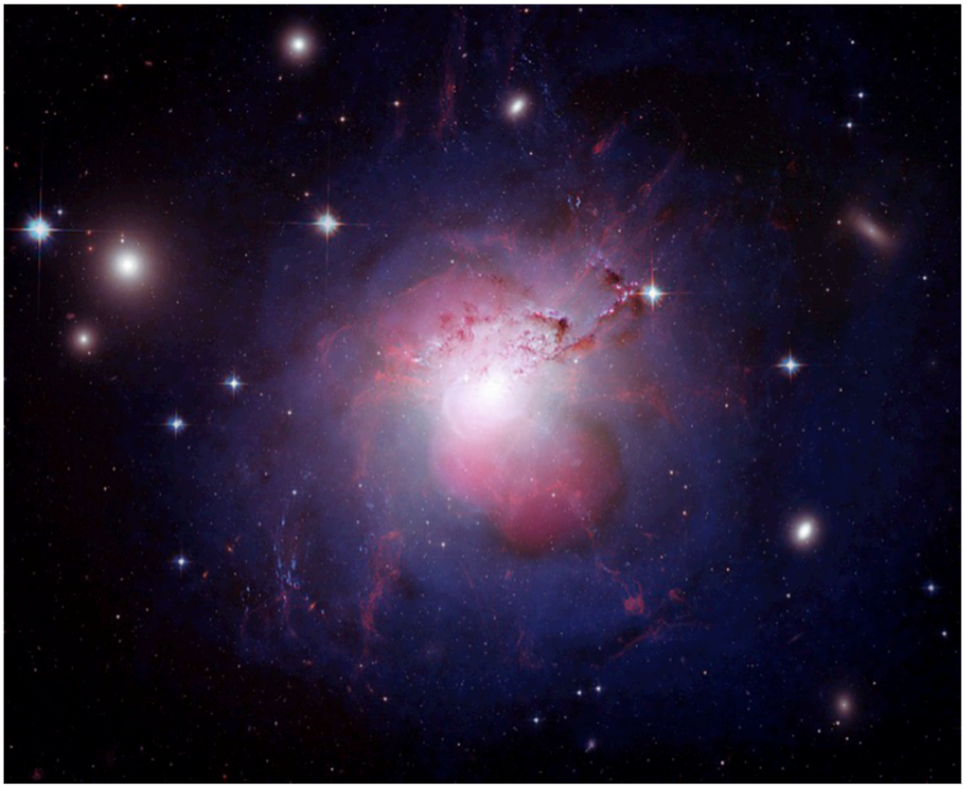

Figure 15: The BCG in the Perseus cluster of galaxies (z=0.018): the hot intracluster medium (hot X-ray gas) is shown in blue (Fabian et al. 2006); the radio jets are shown with the pink blobs; the optical emitting filaments are shown in pink.

*2.3.5.2 Galactic massive black hole: Sgr A**

The massive black hole at the center of our Galaxy, known as Sgr A∗, provides a rich laboratory for studying the physics of black holes, as well as the physics of accretion phenomena. Recently, an in-falling object onto Sgr A*, named G2, was discovered (Gillessen et al. 2012). Several monitoring campaigns were launched in response to this discovery, over a wide range of wavelengths. This lead to the discovery of pulsar PSR J1745-2900 near Sgr A* (e.g. Degenaar et al. 2013), but no significant variations were detected in Sgr A* in response to G2. The Galactic Center is therefore a topical and extremely interesting science case for transient phenomena.

Interestingly, studies have shown that the Galactic center is highly variably and that there are approximately four times more flares in the near-infrared (NIR) band than in X-rays originating from the Galactic center (e.g. Genzel et al. 2003). These NIR flares occur about 4 times a day and can last dozens of minutes. While the X-ray flares are usually accompanied by a simultaneous NIR flare, not all NIR flares are accompanied by an X-ray counterpart (e.g. Hornstein et al. 2007). Sgr A* is therefore are extremely interesting target in the transient Universe, yet the origin of the flares remains poorly understood.

MOVIES will not only provide a simultaneous broad band coverage, but – with the possible inclusion of a large format EMCCD – we will also have the capability of exploring the variability down to a second and even less from near-UV to red-optical wavelengths.

To study SgrA* with MOVIES, we require:

1. A spectrograph with broad band coverage.
2. A spectrograph that can be quickly brought on target after the alert.
3. Long-term stability to compare spectra taken months apart (or years).

2.3.6 The High-Redshift Universe

2.3.6.1 High-redshift Quasars

Quasars and other types of active galactic nuclei (AGN) are interesting phenomena that influence the evolution of galaxies and their environments. The high luminosities of quasars make them excellent probes of the distant universe, both within galaxies and in the intergalactic medium (IGM). Moderate resolution spectroscopy of these sources enables measurement of their continua, broad emission lines, narrow emission lines, broad absorption lines, narrow associated absorption lines and narrow IGM absorption lines. These many types of measurement make for a wide range of science applications of which a few are mentioned further below. Large multi-object spectroscopy quasar surveys (SDSS, BOSS, DESI, MSE) find many interesting, rare classes of quasars that will require single-slit spectroscopy with a wider wavelength range, higher resolution and/or further epochs.

Outflowing gas from galactic nuclei appear as broad absorption lines and inform on the quasar energetics and the feedback effect on the host galaxy. Studies of different ions tell us about the ionization state of the gas. Some broad absorption lines vary with time due to either ionization changes or motion across our line-of-sight.

Studies of the Lyman forest and metal absorption lines in the IGM are one of the few probes of the ionization state, temperature and metal enrichment of diffuse intergalactic gas. Such observations help us answer questions such as how and when did cosmic reionization of helium and hydrogen take place, how do metals escape from galactic potentials and how pristine gas is distributed in the cosmic web.

Very high-redshift ($z>6$) quasars are so rare that there is little multiplex advantage from most MOS spectrographs, so such surveys tend to be done in long-slit mode. Studying these quasars provides information on the early build-up of black holes in galaxy nuclei and the hydrogen reionization process.

These studies benefit from MOVIES as follows:

1. Wide, contiguous wavelength range in order to obtain many spectral lines in individual quasars and/or to measure the same lines at a large range in redshift.

2. Good UV response important for Lyman alpha forest at $z<2.2$.
3. K-band required for black hole mass measurements from MgII (279.9nm rest-frame) broad emission line in $5.5 < z < 7.5$ quasars.
4. Spectral resolution: R~2000 for emission lines and broad absorption lines. $2000 < R < 10000$ for narrow absorption lines. Near-IR resolution high enough to work between OH lines.
5. High-sensitivity for spectra of faint quasars, e.g. L* quasars at $z > 6$ (AB~22) .
6. Low overheads including acquisition – some studies require a large sample of relatively bright quasars (e.g. 5 to 15 minutes integration), these would be inefficient if overheads are high.

2.3.6.2 High-redshift Galaxies

Despite considerable progress there are still large uncertainties in our picture of the cosmic evolution of galaxies. The complex interplay of baryonic and radiative processes makes simulating realistic galaxies difficult. Observations of galaxies in various phases of their evolution and across a wide range of mass and activity are crucial to constrain the models. Moderate resolution spectroscopy is used to study the emission lines (tracers of star formation, AGN activity, non-thermal shocks) and absorption lines (stellar and interstellar lines that are star formation history, metallicity and IMF sensitive). In addition, spectroscopy over a wide wavelength range can be used to fit population synthesis models to measure ages and dust extinction or the extinction law.

For sources too faint or small to resolve with an IFU, emission or absorption line kinematics provides information on the dynamical mass and in some cases mass-to-light ratio. Further, these data can be used as precursor observations for TMT or GMT observing programs using IFUs.

With the advent of MOS spectrographs and IFUs on large ground-based telescopes and the forthcoming *JWST*, much of this work would not be done by a long-slit spectrograph. Examples of science that would likely be done by this instrument are studies of rare types of galaxies where there is little multiplex advantage, for example gravitational lenses, high-mass galaxies, rare star-forming galaxies. Additionally JWST will have a maximum spectral resolution of R=2700 so higher resolution work must be done from the ground.

MOVIES is an ideal instrument for the study of high-redshift galaxies. Specifically, MOVIES provides the following important capabilities:

1. Wide, contiguous wavelength range in order to obtain many spectral lines in individual galaxies and/or to measure the same lines at a large range in redshift. Multiple lines important for metallicities.
2. Near-IR required for rest-frame optical emission lines and continuum in $z>1.5$ galaxies. Important for most types of galaxy, especially those at high-redshift and/or old.
3. K-band important for highest rest-frame wavelength features, but should be comparable sensitivity to J and H to be of most use.

4. Spectral resolution: R~2000 for emission lines. 2000<R<10000 for narrow absorption lines. Near-IR resolution high enough to work between OH lines.
5. Throughput very important as many high-z galaxies are very faint (AB~22) and require long integration times. Need to outperform fibre-fed MOS spectrographs in optical and near-IR by slit width matching the conditions and galaxy size.
6. Good background subtraction by nodding along the slit, particularly the NIR.
7. Low noise detectors (optical and near-IR) so that can observe at high spectral resolution if required without inferring a high penalty compared to the background-limited case.
8. Photometric calibration will be achieved in most cases by using imaging in standard broad-band filters, so availability of standard filters for acquisition are important.

2.3.6.3 High-redshift Gamma–Ray/Optical Bursts

Gamma-ray bursts have been found up to at least redshift 8.2 and possibly 9.4. They provide an alternative background light source for IGM spectroscopy in a much lower bias environment than that of luminous quasars. In the near-future optical transient surveys will be providing optical transients, some of which will be *orphan* afterglows. Rapid follow-up spectroscopy of such sources is crucial as they often fade quickly.

MOVIES brings the following capabilities to enable these studies:

1. High-quality data over 0.8 to 1.5 microns to fit continuum and break in the highest-redshift sources;
2. Low noise detectors (optical and near-IR) so that can observe at high spectral resolution if required without inferring a high penalty compared to the background-limited case. Important as flux often not known accurately when observations planned;
3. Spectral resolution: R~5000 for metal lines, Lyman alpha forest peaks. Near-IR resolution high enough to work between OH lines;
4. Fast slewing and acquisition to be on-source as soon as possible after trigger.

2.3.7 Exoplanet Atmospheres

Hot Jupiter planets, gas giant orbiting within a few stellar radii of their parent star, offer unique laboratories for the study of planetary atmospheres. One application is to study the composition of these planets' atmospheres through transmission spectroscopy by comparing the spectrum of the star+planet in and out of primary transit. Such differential spectroscopy techniques require broad spectral coverage and superb control of systematic variations in transparency and observing conditions (e.g., seeing, telescope tracking jitter, etc.) between the many hours that can elapse between the planet in and out of transit.

Another application is to study spectroscopic variability in and out of secondary eclipse, when it is possible to fully distinguish stellar and planetary atmosphere contributions to the spectrum. Typical hot Jupiter planet atmospheres have temperatures in excess of 1000K, and secondary transit spectroscopy can be used to study such atmospheres under conditions of extreme irradiation by the parent star. Such experiments also require exquisite characterization of time-dependent systematics in transparency and observing conditions.

The conventional way to do time-dependent transit spectroscopy from the ground is with a multi-object spectrograph. A custom slit mask is cut with one slit for the exoplanet transit target, and then one or more auxiliary slits are devoted to nearby (<few arcminute distant) reference stars of hopefully comparable brightness. These serve as real-time photometric references to measure variations in transparency along the common path through the telescope and instrument. Not all transiting planet systems are so accommodating as to have conveniently located reference stars of sufficient brightness, and so this technique has only been done for a relatively small number of the many transiting exoplanet systems. In addition, very few (no) multi-object spectrographs can cover wavelengths from the UV to the near-IR, encompassing a range of spectral features of interest. Combinations of different instruments on different telescopes are very difficult to schedule, and are subject to essentially irreducible non-common path differences between the two observing sites. The queue-scheduling of the Gemini Observatories means that they are operationally well suited to this type of science program.

An example of one attempt to perform this type of experiment on an isolated transiting hot Jupiter system using a hybrid instrument at the same observing site was recently presented by von Essen et al. (2015, arXiv:1507.05963) for the WASP-33B system. They used the Large Binocular Telescope in a parallel ("pseudo-binocular") configuration with the LUCI near-infrared spectrograph on one telescope and the LBC-Red prime focus camera on the other. LBC-R was used to take real-time photometric data of WASP-33b in the V-band (0.55μm) while the LUCI spectrometer was collecting spectral data in and out of a secondary eclipse at 1.1μm. Figure 16 shows the raw and detrended V-band and 1.1μm light curves resulting from their analysis. This illustrates the considerable difficulty of performing this type of analysis, and the promise of this technique.

MOVIES can employ this technique routinely and to great effect to advance the study of exoplanet atmospheres, and we discuss a detailed operational case of this type of program in Section 2.6. In brief, the three science-grade acquisition detectors provide the photometric monitoring of the stars in the transiting system field in three bands, all of which are both *contemporaneous* and *co-wavelength* with the two spectroscopic channels. This avoids problems of non-common path systematics because at least to the GEMINI focal plane, both imaging and spectral channels share the same atmospheric and telescope path.

The baseline design of MOVIES uses standard CCDs in the optical arm of the spectrograph. However, if the option of using large format EMCCDs is implemented (see discussion in Sections 2.5.6 and 0), in addition to Hybrid IR arrays for the NIR arm, we can read out rapidly to maintain high observing cadence. The EMCCD channels have the additional considerable benefit of excellent noise performance, essentially photon-counting, and the ability to time sample *after the fact* to optimize the analysis. While not essential to the basic science program (relatively short exposures can still be obtained at moderate resolutions using the default design), the large format EMCCDs clearly provide compelling value-added science goals for this observing program.

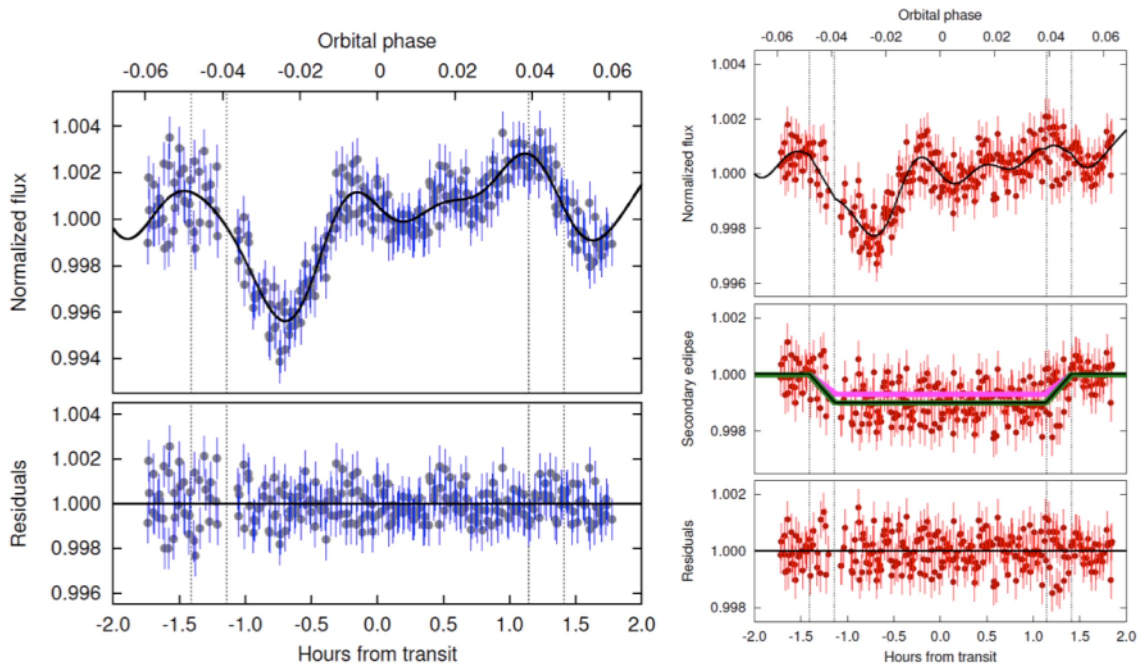

Figure 16: Left: V-band light reference light curve before and after detrending, Right: raw, detrended, and best fit IR secondary transit light curve corrected using the V-band model from the left plane. From von Essen et al. 2015 (Fig 1 and 3).

An additional operational strength of this observing program for Gemini is the fact that the Observatories have very flexibly queue schedules. This scheduling system enables this science in ways that conventional block-scheduled telescopes do not. A huge problem doing experiments like von Essens and ones by members of this instrument team on LBT is the problem of scheduling observing blocks during critical transit timing, and nervously waiting go/no-go on weather conditions that must prevail for many hours (we have done 4 to 6 hour visits at LBT on such transits; historically of the nearly dozen or so programs attempted over the past three years, only 3 were successful). Flexible queue scheduling, a large aperture, and a good site, combined with MOVIES that offers UV to Near-IR spectral coverage and simultaneous UV to Near-IR time-series photometry (with the potential inclusion of time-series capable detectors) is almost the ideal combination to enable these kinds of studies of exoplanet atmospheres. Gemini/MOVIES could become the ultimate instrument for spectroscopy from the UV to the Near-IR of exoplanet atmospheres.

2.4 Science Requirements

2.4.1 Derivation

The development of MOVIES is built upon a direct connection and understanding between the key science objectives previously described in Section 2.3 and the flow-down requirements for the instrument performance. Through this understanding, we have determined how any change in a requirement will affect the scientific capabilities of the instrument, and we have further determined science-enabling requirements that the instrument design must satisfy.

Two major considerations dictate the methodology we have used to identify the top-level science requirements of MOVIES:

1. MOVIES is designed as a work-horse spectrograph with a very broad scientific appeal. All of the science cases described in the previous section detail science areas in which the impact of MOVIES will be particularly profound, and these have been used to derive the key science and operational requirements for MOVIES. These topics were selected as a representative sample of the diverse science that MOVIES is expected to undertake based on their perceived need for rapid acquisition procedures and/or broad spectral coverage at OIR wavelengths and/or moderate spectral resolutions. We stress that the requirements that were developed based on consideration of these science cases have resulted in an instrument with broad scientific appeal beyond these specific cases.

2. Workhorse science is clearly essential for an instrument on a telescope with a broad user community. However, it is equally important that the instrument is recognized as excellent, which means there must be areas in which it clearly excels. With respect to all other spectrographs on 8m-class telescopes, MOVIES will be uniquely powerful as a time domain spectrograph and as a precision spectrophotometer. As such, the areas of transient (time-domain) science and exoplanet atmospheres are considered especially important in the derivation of the science requirements, and will be especially important to consider in the future as design trades are made that may affect the scientific performance of MOVIES in these two key areas.

Table 2 makes explicit connections between the science cases described previously and instrument capabilities. The first column details the science area; the second column lists the key science considerations for each case as justified in Section 2.3; the third column links these considerations to high-level functionality for MOVIES.

Table 2: Summary of impact of MOVIES science cases on capabilities for the instrument

Science case	Science considerations	Impact on Requirements
Transients (Major science driver)	Unknown astrophysical phenomena	Moderate spectral resolution that can be modified; Broad wavelength coverage
	Variable on short timescales (seconds, minutes, hours)	Rapid acquisition; Simultaneous wavelength coverage
	Variable on long timescales (weeks and months)	Stable spectrograph system and robust calibration
Solar System	Ability to work between telluric lines in the red and NIR	Moderate spectral resolution
	Obtain science spectrum and stellar calibrator in very similar conditions that change on rapid timescales	Rapid acquisition
	Source spectral variability on ~hour timescales	Simultaneous wavelength coverage
	Very broad spectral features from silicates and organics	Broad wavelength coverage; Spectrophotometric calibration
	Steep power law luminosity function	Sensitivity
Stellar populations	Detection of small relative differences from model spectra requiring high SNR	Sensitivity
	Weak absorption features of scientific interest	Excellent sky subtraction
	Efficient identification of targets through color-color diagrams	Multi-color imaging
	Derivation of accurate metallicities through access to multiple features sensitive to	Broad and simultaneous wavelength coverage

	metal and molecular abundance	
Low mass stars	Access to a large number of chemical species; magnetic field analysis through Zeeman splitting requiring resolved line profiles	Moderate/high spectral resolution (R>10000)
	Cool targets with temperatures of only a few hundred Kelvin	NIR sensitivity essential
	Large samples for homogeneous analysis	Efficient observing
	Velocity accuracy of a few tenths of a km/s	Moderate resolution; excellent calibration; stability
	Faint targets	Sensitivity
Massive black holes	Important spectral features spread across full OIR range	Broad wavelength coverage
	Measure strengths of OII, NeIII, Ha, etc	Moderate resolution
	Observing flares in Sgr A*	Rapid acquisition
	Flares in Sgr A* more common at longer wavelengths	NIR sensitivity
High redshift Universe	Measure spectral features over wide range in redshift; multiple lines for metallicity measurements	Broad wavelength coverage
	Measure MgII (279.9nm rest-frame) broad emission line in $5.5<z<7.5$ quasars;	K-band sensitivity
	Narrow absorption line measurements; work between OH lines	Moderate spectral resolution
	Large samples for statistical analyses	Efficient observing
	Faint targets at high redshift	Sensitivity
	Weak features in areas affected by sky	Excellent sky subtraction
	Gamma-ray and optical bursts highly variable	Rapid target acquisition

Exoplanet atmospheres (Major science driver)	Large number of spectral features of interest to be observed simultaneously	Broad wavelength coverage
	Contemporaneous monitoring of transparency and observing conditions along sight line	Simultaneous imaging of field
	Observing over entire period of ingress/egress	Highly stable system
	Small changes in spectral features due to planet transit	Sensitivity / SNR

Table 3 presents a summary of the science requirements for MOVIES by synthesizing results from Table 2 in addition to operational considerations discussed later. The first columm gives the Requirement ID number, the second column gives the name of the requirement, and the third column gives the text of the requirement. The requirements are derived from consideration of all the necessary capabilities highlighted in Table 2 that enable each of the science cases described previously. However, **it is worth highlighting that every single requirement is absolutely necessary for the major driving science case of Transients. Further, almost all requirements are necessary for the major driving science case of Exoplanet Atmospheres.**

Table 3: Summary of science requirements for MOVIES

ID	Name	Requirement
REQ-SCI-001	Wavelength range	Gemini/MOVIES will obtain complete spectral coverage from 360nm to 2.45um in a single exposure for all spectra.
REQ-SCI-002	Spectral resolution	Gemini/MOVIES will be able to operate at a range of spectral resolutions between R~2000 and R~10000
REQ-SCI-003	Sensitivity	At a spectral resolution of R=5000, an extracted spectrum from Gemini/MOVIES will have a signal to noise per resolution element at a given wavelength that is greater than or equal to one for a 1 hour observation of a point source with a flux density of 3.6 x 10^-29 ergs/sec/cm2/Hz at that wavelength, for all wavelengths intervals between 0.36 - 2.45um free from airglow emission-line

		contamination and strong telluric absorption.
REQ-SCI-004	Acquisition time	Gemini/MOVIES will be able to acquire any target and begin taking a scientific spectral observation within 90 seconds
REQ-SCI-005	Sky coverage	Gemini/MOVIES will be able to identify suitable guide stars over at least 90% of the sky
REQ-SCI-006	Sky subtraction	(i) Gemini/MOVIES must allow for removal of (100 +/- 0.2)% of the sky flux, as estimated for sky-subtracted sky spectra. (ii) Gemini/MOVIES shall achieve a sky subtraction accuracy for atmospheric airglow emission-lines such that the mean residual error for spectral pixels, within 1 resolution element of known atmospheric emission-lines, is <N.n (TBD) times the Poisson limit indicated by the propagated variance spectrum for each resolution element.
REQ-SCI-007	Velocity accuracy	For any object with a known velocity, observed at multiple epochs by Gemini/MOVIES with a signal to noise ratio per resolution element of 5 at R=5000, the contribution from Gemini/MOVIES to the rms difference between the known velocity of the object and the measured velocity of the object will be less than or equal to 12km/s, and will have no systematic dependence on the wavelength region of the spectrum that is used (providing suitable features exist, i.e., any strong absorption or emission lines)
REQ-SCI-008	Spectrophotometry	For a spectrophotometric standard star, observed at multiple epochs by Gemini/MOVIES with a signal to noise ratio per resolution element of 5, the rms variation in the ratio of fluxes measured in any two wavelength intervals will be less than 1% (TBC) of the mean measured value.

REQ-SCI-009	Quick look data tools	Gemini/MOVIES will allow for initial inspection of science spectra within 60 seconds of completion of the observation, including the detrended detector image, extracted and sky-subtracted 2D and 1D spectra.

2.4.2 Detailed Science Requirements

This section provides the details of the science requirements that are summarized in Section 2.4.1. Sections 2.4.2.1 – 2.4.2.9 present, for each science requirement summarized in Table 3, a full description of the requirement, including supporting text detailing its derivation, linkage to specific science cases, and notes regarding any important additional information to fully understand the intent of the requirement, including miscellaneous notes for future reference.

In all, we have identified 9 high level science requirements that together define the essential capabilities of the MOVIES systems:

- The first three requirements – wavelength range, spectral resolution and sensitivity – define the essential characteristics of the main spectrograph system;
- The fourth requirement – acquisition time – is a crucial requirement for a spectrograph designed to operate in the time domain ecosystem of LSST;
- The fifth requirement – sky coverage – represents the need to be a flexible workhorse instrument and observe targets at a wide range of galactic latitudes;
- The next three requirements – sky subtraction, velocity accuracy, sky subtraction - relate directly to calibration issues and reflect the need for MOVIES to be a robust and stable system capable of precision measurements;
- The final requirement relates to data analysis, and in addition to being a generally useful capability for astronomers to check their data, it is specifically needed in the case of ToO observations to ensure that the observations are optimal given the unknown nature of the sources.

More details on how the science requirements are used to define the technical requirements of MOVIES are given in Section 3.1.

ID	REQ-SCI-001
Name	Wavelength range
Requirement	Gemini/MOVIES will obtain complete spectral coverage from 360nm to 2.45um in a single exposure for all spectra.

2.4.2.1 Wavelength range

Derivation	Blue wavelength cut-off: Large number of features in 360-400nm wavelength window that are critical for low-redshift stellar populations (resolved stars and unresolved galaxies). Further, analysis of SEDs of Solar System objects requires going shortward of 400nm due to very broad spectral features extending into the UV. While throughput blueward of 360nm is desirable from a science perspective, cost and technical risk outway diminishing science gains when considering practical limitations set by optical coatings and the atmosphere. Red wavelength cut-off: High redshift science and SED determination require as red a wavelength as is possible. In reality, red end cutoff is set by cost and technical risk, in addition to consideration of the sky absorption windows in the IR Complete spectral coverage: Unknown SEDs of (unknown) transient phenomena requires broad wavelength coverage to give best chance of chracterising its SED. High redshift observations require broad wavelength coverage to identify similar tracers over a broad range in wavelength
Science Cases	Transients; Solar System; Low mass stars; Stellar populations; Black holes; High redshift; Exoplanet atmospheres
Notes	See "Blue Throughput" trade-study

2.4.2.2 Spectral Resolution

ID	REQ-SCI-002
Name	Spectral resolution
Requirement	Gemini/MOVIES will be able to operate at a range of spectral resolutions between R~2000 and R~10000
Derivation	Moderate resolutions matched to the intrinsic velocity dispersions of galaxies and AGN; moderate resolution of R>3000 needed to work between sky emission lines; range of resolutions required to optimise SNR for specific science cases; range of resolutions also required so that sources with variable luminosity (e.g., transients) can be monitored at different epochs with a spectral resolution chosen to suit the luminosity
Science Cases	Transients; Low mass stars; Stellar populations; Black holes; High

	redshift; Exoplanet atmospheres
Notes	Spectral resolution is defined as lambda/d(lambda). d(lambda) is the full width at half maximum of a Gaussian fitted to an unresolved spectral line on the extracted spectrum that has a wavelength of lambda

2.4.2.3 Sensitivity

ID	REQ-SCI-003
Name	Sensitivity
Requirement	At a spectral resolution of R=6000, an extracted spectrum from Gemini/MOVIES will have a signal to noise per resolution element at a given wavelength that is greater than or equal to one for a 1 hour observation of a point source with a flux density of 3.6 x 10^-29 ergs/sec/cm2/Hz at that wavelength, for all wavelengths intervals between 0.36 - 2.45um free from airglow emission-line contamination and strong telluric absorption.
Derivation	Many of the anticipated science targets of MOVIES are intrinsically faint e.g., PMOs, brown and white dwarfs, high redshift galaxies and AGN. Efficient spectroscopy of faint sources is required to access targets beyond the light grasp of current 4m facilities.
Science Cases	Transients; Solar System; Low mass stars; Stellar populations; Black holes; High redshift; Exoplanet atmospheres
Notes	This requirement corresponds to an observation of an astrophysical source with a monochromatic AB magnitude of m=22.5, with a sky brightness of 20.7mags/sq.arcsec in the V-band and a natural seeing condition of 0.8 arcseconds in the r band, and an airmass of 1.2. It assumes that the throughput of the atmosphere is well modelled by https://www.gemini.edu/node/10781?q=node/10790#MK%20near-infrared%20extinction It further assumes that the throughput of the Gemini telescope (all optical elements prior to entering MOVIES) is well modelled by the reflectivity data at http://www.gemini.edu/sciops/instruments/optics/Gemini_Optics_Reflectivity_Data.xlsx Specifically, the "GS M1 Ag Sample 10-8-2010" (three reflections)

2.4.2.4 Acquisition Time

ID	REQ-SCI-004
Name	Acquisition time
Requirement	Gemini/MOVIES will be able to acquire any target and begin taking a scientific spectral observation within 90 seconds
Derivation	Rapid acquisition is necessary for observations of transient phenomena and for observations of solar system objects that require accurate removal of telluric features that change on short timescales.
Science Cases	Driving requirement for Transients. Also Solar System; Black holes
Notes	The acquisition time does not include the telescope or dome slew times, but includes all other processes i.e., changing the position of the science fold mirror if necessary, instrument configuration, initial acquisition exposures, identification of guide stars, initiating tip-tilt guiding, identifying the target, centering and verifying the target in the slit, and starting the science exposure

2.4.2.5 Sky Coverage

ID	REQ-SCI-005
Name	Sky coverage
Requirement	Gemini/MOVIES will be able to rapidly acquire targets over at least 90% of the sky
Derivation	MOVIES must be able to efficiently acquire Target of Opportunity objects located anywhere in the sky
Science Cases	Transients; Solar System; Low mass stars; Stellar populations; Black holes; High redshift; Exoplanet atmospheres
Notes	This sky coverage applies only to when using the MOVIES A&G system for tip-tilt guiding, that allows for extremely rapid acquisition. MOVIES can optionally use the PWFS for guiding, for which sky coverage will be higher.

2.4.2.6 Sky Subtraction

ID	REQ-SCI-006
Name	Sky subtraction
Requirement	(i) Gemini/MOVIES must allow for removal of (100 +/- 0.2)% of the sky flux, as estimated for sky-subtracted sky spectra. (ii) Gemini/MOVIES shall achieve a sky subtraction accuracy for atmospheric airglow emission-lines such that the mean residual error for spectral pixels, within 1 resolution element of known atmospheric emission-lines, is <N.n (TBD) times the Poisson limit indicated by the propagated variance spectrum for each resolution element.
Derivation	MOVIES is designed for observations of very faint targets. In a one hour exposure, MOVIES can obtain a SNR per resolution element of 5 for a soure with a monochromatic AB magnitude of m=24 in median dark sky conditions. This corresponds to an object that is roughly 30 times fainter than the sky (20.7mags/arcsec). To do science on such a target requires sky subtraction much better than 1%. In the region of sky lines, it does not make sense to define the sky subtraction accuracy in the same way as for regions dominated by the sky continuum, hence this requirement is in two parts.
Science Cases	Transients; Low mass stars; Black holes; High redshift; Exoplanet atmospheres
Notes	For sky subtraction in the region of bright sky lines, we follow the definitions of the mean residual error as discussed in Sharp & Parkinson (2010, MNRAS,408, 2495)

2.4.2.7 Velocity Accuracy

ID	REQ-SCI-007
Name	Velocity accuracy
Requirement	For any object with a known velocity, observed at multiple epochs by Gemini/MOVIES with a signal to noise ratio per resolution element of 5 at R=5000, the contribution from Gemini/MOVIES to the rms difference between the known velocity of the object and the measured velocity of the object will be less than or equal to 12km/s, and will

	have no systematic dependence on the wavelength region of the spectrum that is used (providing suitable features exist, i.e., any strong absorption or emission lines)
Derivation	Accurate wavelength and velocity calibration is essential to all science cases. The velocity accuracy of this requirement is the intrinsic velocity accuracy for this SNR and resolution.
Science Cases	Transients; Solar System; Low mass stars; Stellar populations; Black holes; High redshift; Exoplanet atmospheres
Notes	

2.4.2.8 Spectrophotometry

ID	REQ-SCI-008
Name	Spectrophotometry
Requirement	For a spectrophotometric standard star, observed at multiple epochs by Gemini/MOVIES with a signal to noise ratio per resolution element of 5, the rms variation in the ratio of fluxes measured in any two wavelength intervals will be less than 1% of the mean measured value.
Derivation	Precision (relative) spectrophotometry is required in order to characterise the SEDs of known and unknown objects.
Science Cases	Driving requirement for Exoplanet atmospheres. Also important for Transients; Solar System; Stellar populations
Notes	

2.4.2.9 Quick Look Data Tools

ID	REQ-SCI-009
Name	Quick look data tools
Requirement	Gemini/MOVIES will allow for initial inspection of science spectra within 60 seconds of completion of the observation, including the detrended detector image, extracted and sky-subtracted 2D and 1D

	spectra.
Derivation	Observations of transient phenomena require rapid access to data to ensure successful observations and allow dynamic observing
Science Cases	Transients; Solar system; Black holes
Notes	The purpose of this software is to deliver to the queue observer an image and spectra for inspection shortly after the next spectrum in sequence has begun integrating. This greatly accelerates making decisions about how to tailor exposures times for rapidly-evolving transient sources whose brightness can be assumed to be unknown to a factor of a few, as well as providing crucial data for informed continue/abort decisions during marginal observing conditions.

2.5 Operational Performance

2.5.1 MOVIES and the Gemini instrumentation suite

Table 4: MOVIES in comparison to other spectrographs in the Gemini instrumentation suite.

	GMOS (long slit only)			GNIRS (spectroscopy only)			FLAMINGOS-2 (long slit only)		GHOST (2018)		**MOVIES**
Acquisition time	~16mins * + redo every 3hrs			~12mins * +6mins reacq. every 45mins			~20mins * + redo every 2 hrs		TBD / unknown		**5mins max (goal < 2mins)**
Spectral coverage	0.36 – 0.94μm			0.85 – 2.5μm			0.95 – 2.4μm		0.36 - 0.95μm		**0.36 – 2.35μm**
Spectral resolution	600	–	4500	1700	5000	18000	1300	3000	50000	75000	**3500 – 10000**
Simultaneous bandwidth	Full	–	~0.2μm	Full	~0.2μm	~0.05μm	JH or HK	Y, J, H, or K	Full	Full	**Full: 0.36 – 2.45μm**

***** *includes telescope slew time (maximum of 3 minutes)*

MOVIES extends the science capabilities of Gemini with respect to its current instrumentation suite. Table 4 lists some of the relevant spectroscopic capabilities of MOVIES with respect to GMOS, GNIRS, and FLAMINGOS-2. We have also included in this table the Gemini High Resolution Optical Spectrograph currently under construction with first light planned for around 2018. In addition to the defining characteristics listed in Table 4, MOVIES takes advantage of the Gemini environment by using GCAL to meet its primary calibration needs, as discussed in detail in Section 2.5.4 and Section 3.3.2. Crucially, MOVIES will be a highly stable spectroscopic system, which will greatly facilitate operations, enable science, and reduce overheads.

MOVIES enables new science and provides Gemini with broad workhorse capabilities that builds on the interests of the Gemini User Community. This can be illustrated by examining the usage of GNIRS. Since its arrival on Gemini-N in 2010B, our team has identified 159 GNIRS proposals ranked in Bands 1 or 2 prior to the end of 2013B. The approximate break down of these proposals by subject area is:

- ~17 Solar System proposals
- ~65 stars proposals [~24 low mass stars, ~14 star formation, ~11 stellar pops., ~16 misc.]
- ~19 quasar and AGN proposals
- ~26 galaxies proposals
- ~13 miscellaneous proposals (SNe progenitors, DIBs, X-ray variables, Galactic center, etc.)

Several of these areas are key science drivers for MOVIES. Informal discussion with PIs on these proposals (who have also been involved with proposals on VLT/XShooter) reveals an interesting consideration for MOVIES; for galaxies, XShooter is preferred over GNIRS because the resolution setting on GNIRS that allows the most extensive wavelength coverage is too low a resolution when compared to the intrinsic velocities of most galaxies i.e., a higher resolution, broad-wavelength coverage instrument is of particular interest to this community.

Interestingly, 46 distinct GNIRS proposals in the sample of 159 used GNIRS in combination with at least one other instrument (not including ALTAIR). Three requested GNIRS+NIFS, and the remainder required NIRI and/or GMOS. NIRI has only been available in imaging mode since GNIRS has been on Gemini-N, and so these proposals are seeking NIR imaging and spectroscopy. *MOVIES provides these capabilities in a complete package, with a much larger imaging field of view than NIRI.* The GNIRS+GMOS proposals are mostly the follow-up of high redshift gamma ray bursts and quasars, and the characterization of Solar System objects i.e., these proposals require the very broad optical+NIR coverage of these instruments in combination. *MOVIES provides these capabilities as a package, without the associated difficulties of combining spectra taken on different instruments at different times.*

2.5.2 Sensitivity

2.5.2.1 Exposure time calculator

MOVIES is designed to be the premier 8m class spectrograph for observations of the faint Universe. To assist in the development of MOVIES science cases and to perform design trades relating to the optimsation of MOVIES, an exposure time calculator has been developed that is able to determine the anticipated sensitivity of MOVIES in both imaging and spectroscopic modes. Briefly, the design criteria for this tool were the following:

1. The calculator must be easily distributed and utilized among the MOVIES team. This motivated the use of Python due to its extensive standard library and widespread adoption.
2. It must function for both imaging and spectrographic exposures. This was accomplished by splitting development into two parallel branches.

3. The calculator must be simple to maintain and update due to foreseen shifts in the primary developer. This requirement also motivated the use of Python, due to its accessibility.
4. Calculation characteristics must be easily set to account for different component selections, science cases, and differences between acquisition and spectrographic arms. This was facilitated by storing all transmission and efficiency data in clearly marked text files that can be modified or replaced as the user requires.
5. An option should exist for inclusion of EMCCDs.

Source spectra complete from 1150Å to 25000Å were selected from the Pickles Atlas. The sky background[3][4] and transmission[5] were modeled using sample spectra provided by the Gemini science pages, with the near-infrared spliced to the visible band at 9200Å. Extinction coefficients[6] for the sky came from the Gemini science pages. The filters chosen as standards were the SDSS set in the visible band, and Bessel J and H for the near-infrared.

Aperture and slit losses were calculated assuming that target flux is distributed according to a Moffat distribution for point sources, i.e.,

$$I(r) = I_0\left[1 + \left(\frac{r}{\alpha}\right)^2\right]^{-\beta}$$

where

$$\beta = 3, \alpha = \frac{FWHM}{2\left(\sqrt{2^{1/\beta} - 1}\right)}$$

and FWHM is the full-width-at-half-maximum of the PSF (i.e. equivalent to the seeing/IQ.

Mirror reflectivity data was taken from the Gemini science pages, using M1 data as representative of all mirrors within MOVIES. Dichroics were assumed to have a flat 98%

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[3]https://www.gemini.edu/sciops/telescopes-and-sites/observing-condition-constraints/optical-sky-background

[4] https://www.gemini.edu/sciops/telescopes-and-sites/observing-condition-constraints/ir-background-spectra

[5] https://www.gemini.edu/sciops/telescopes-and-sites/observing-condition-constraints/ir-transmission-spectra

[6] https://www.gemini.edu/sciops/telescopes-and-sites/observing-condition-constraints/extinction

reflection or transmission in the relevant band. The detector characteristics were taken from manufacturer data sheets of candidate components (see Section 3.7).

Input parameters are stored in a Python file that is imported into the main program. All parameters are modifiable with any text editor. Parameters with unclear naming are annotated with clarifying description.

Calculations were performed by interpolating all input spectrum and curves onto a linear grid with one angstrom spacing. Input spectra were normalized according to user-input source magnitude and sky brightness. Source and background count rates are calculated based on the total throughput of the instrument. Following this calculation, the signal-to-noise ratio or required exposure time is calculated in the usual way.

2.5.2.2 Imaging sensitivity

Figure 17 shows the SNR as a function of magnitude for a 300s exposure in each of the three imaging cameras, assuming the presence of a g, I and J filter, in dark conditions at an airmass of 1.2 and a seeing of 0.7 arcsecs. Here, the SNR is calculated within an aperture equal to the FWHM.

For comparison, in the optical at m=25, MOVIES obtains a SNR=9.4 in 300s in the g band, 10% higher than GMOS according to its ETC[7]. In the NIR, MOVIES obtains a SNR=15 in 300s in the J band for a target that is m = 23. This is 40% higher than for NIRI for a similar set-up[8]. We conclude that the MOVIES imaging cameras are a very powerful and efficient system in their own right.

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[7] http://www.gemini.edu/sciops/instruments/integration-time-calculators/gmosn-itc

[8] http://www.gemini.edu/sciops/instruments/integration-time-calculators/niri-itc

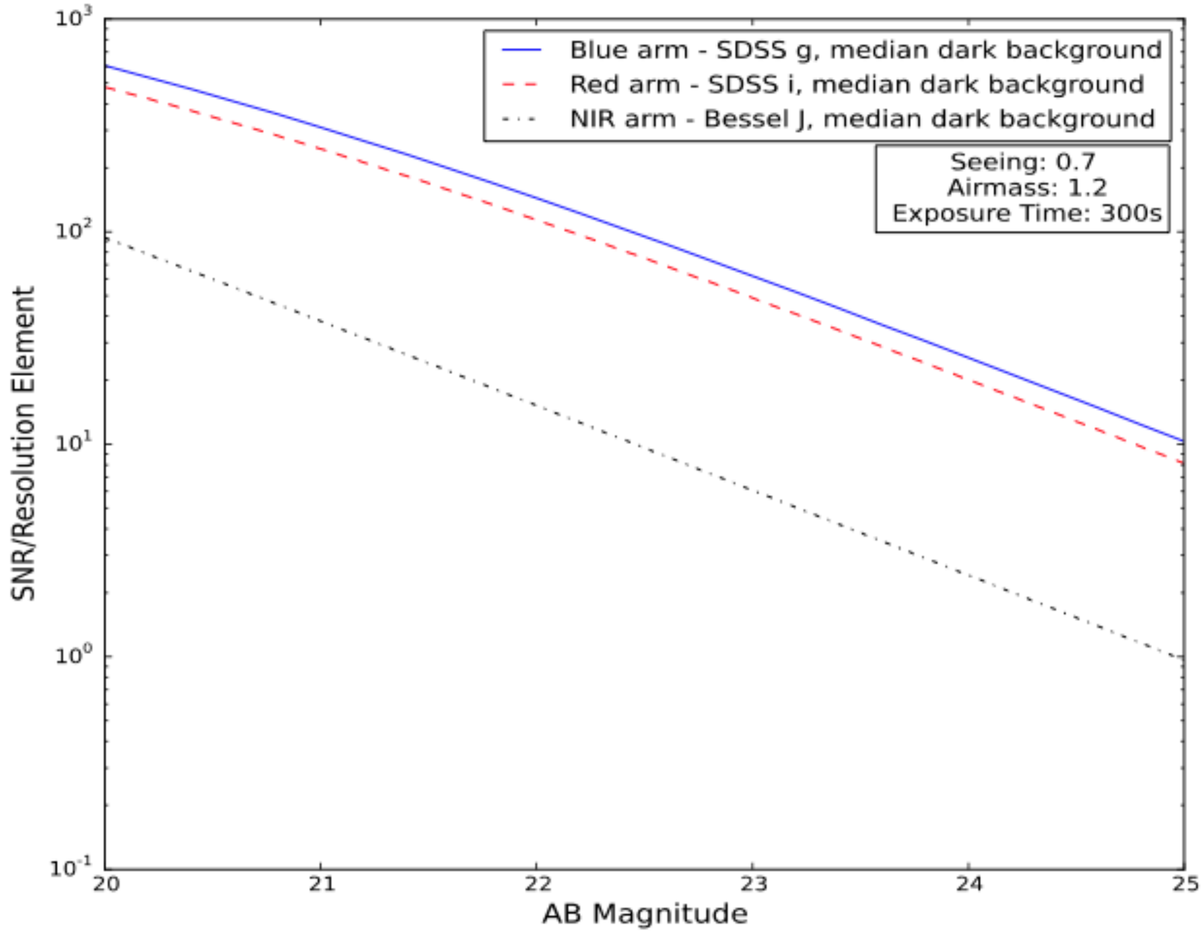

Figure 17: SNR as a function of magnitude for the three imaging (acquisition) cameras, obtained in a 300s exposure at an airmass of 1.2 in dark conditions with a seeing of 0.7 arcsecs

2.5.2.3 Spectrograph sensitivity

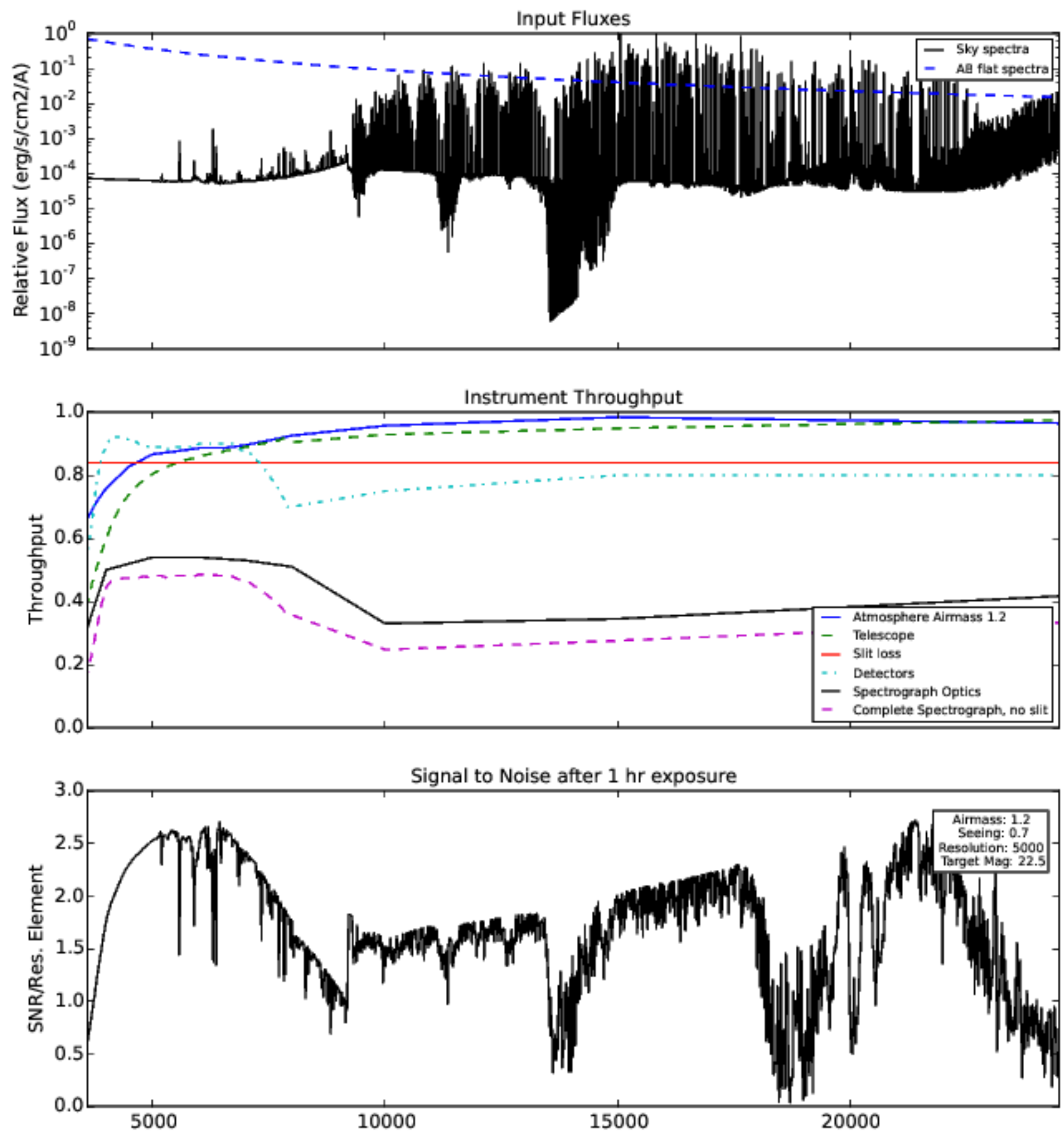

Figure 18: The throughput and sensitivity of MOVIES

Figure 18 summarises the throughput and resulting sensitivity of MOVIES from a science user perspective.

- The top panel shows the input object spectrum (blue dashed line) and the input sky spectrum (black solid line). Here, the flux units are arbitrary. The input "object" in this specific calculation corresponds to an object that has a monochromatic AB magnitude at every wavelength of m = 22.5 (as per science requirement REQ-SCI-003);
- The second panel shows the various contributions to the overall efficiency of an observation with the MOVIES spectrograph. The blue line corresponds to atmospheric extinction at a typical airmass of 1.2. The green line corresponds to

the throughput of the Gemini telescope, here modelled as three silver reflections (primary, secondary, science-fold). The horizontal red line corresponds to the slit losses for a 1 arcsecond slit assuming a point source target with a FWHM corresponding to 70%-ile conditions. The black line is the overall throughput of all the optics of the spectrograph. The cyan line is the quantum efficiency of the detectors. The purple line gives the overall efficiency of the spectrograph (optics x detectors), excluding slit-losses.

- The third panel shows the SNR obtained as a function of wavelength for a point source target with an AB magnitude everywhere of m=22.5, observed at an airmass of 1.2 with 0.7arcsec seeing for a period of 1 hour. The spectral resolution corresponds to R~5000. The curve has been smoothed slightly to remove the strongest NIR sky lines for clarity. In the optical and NIR transmission windows, the SNR is approximately 1.5 – 2.5 everywhere.

In Section 3, we discuss in considerably more detail the design of MOVIES to optimize the spectrograph for faint objects. From a science user perspective, the ultimate test of sensitivity is the overall throughput of the entire system i.e., including the atmosphere, the telescope, slit losses and the spectrograph. As such, Figure 19 shows the overall throughput of MOVIES in the above set-up, in comparison to XShooter using an equivalent set-up, as given by their ETC[9]. *We stress that this comparison includes the atmosphere, the telescopes, the slit losses and the spectrograph optics/detectors.* Gemini/MOVIES is everywhere more efficient than VLT/XShooter, except at the very bluest wavelengths (where XShooter has a dedicated arm, and the Gemini coatings have decreasing reflectivity).

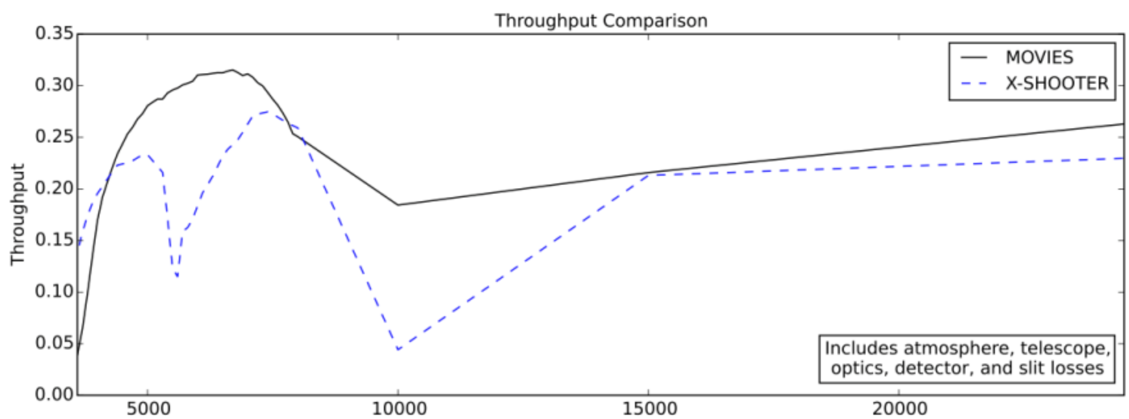

Figure 19: The overall throughput of Gemini/MOVIES in comparison to VLT/XShooter, including atmospheric extinction, the telescopes, slit losses and the spectrographs.

[9] https://www.eso.org/observing/etc/bin/gen/form?INS.NAME=X-SHOOTER+INS.MODE=spectro

2.5.3 Target Acquisition and Guiding

Robust and repeatable target acquisition is essential for efficient observing of many targets. Further, it is an absolutely essential science enabling capability in the case of target of opportunity follow-up and other time-variable phenomena. For MOVIES, the importance of this capability is captured in the high-level science requirement *REQ-SCI-004: Acquisition time – "Gemini/MOVIES will be able to acquire any target and begin taking a scientific spectral observation within 90 seconds"*. To meet this requirement, MOVIES has an on-board Acquisition and Guiding system that is capable of tip-tilt guiding by sending commands to M2.

A detailed examination and optimization of the acquisition process for spectroscopic observations with MOVIES has been conducted as part of this Feasibility Study. There are multiple acquisition/guiding modes that are possible:

- A&G for a bright target for spectroscopic observations ("Direct" acquisition)

  See Section 2.5.3.1

- A&G for a faint target for spectroscopic observations ("WCS" acquisition)

  See Section 2.5.3.2

- A&G for imaging

  If all of the imaging cameras are being used for obtain deep imaging (i.e., long exposures), then there are no MOVIES imaging cameras available for guiding. In this case, guiding is done using the Gemini guide system (PWFS). If only one or two of the cameras are required for imaging, then the third can be used for tip-tilt guiding, particularly if rapid acquisition is necessary where use of the Gemini guide system would introduce unacceptable delays. Alternatively, the Gemini PWFS can be used if rapid acquisition is not necessary

Examples of situations where all three of these modes are required are given in the Concept of Operations in Section 2.6. The first two of the modes – Direct and WCS (World Coordinate System) – are particularly important with respect to the science requirements, and are specialized to the MOVIES instrument. As such, we now describe them in detail.

2.5.3.1 Direct Acquisition

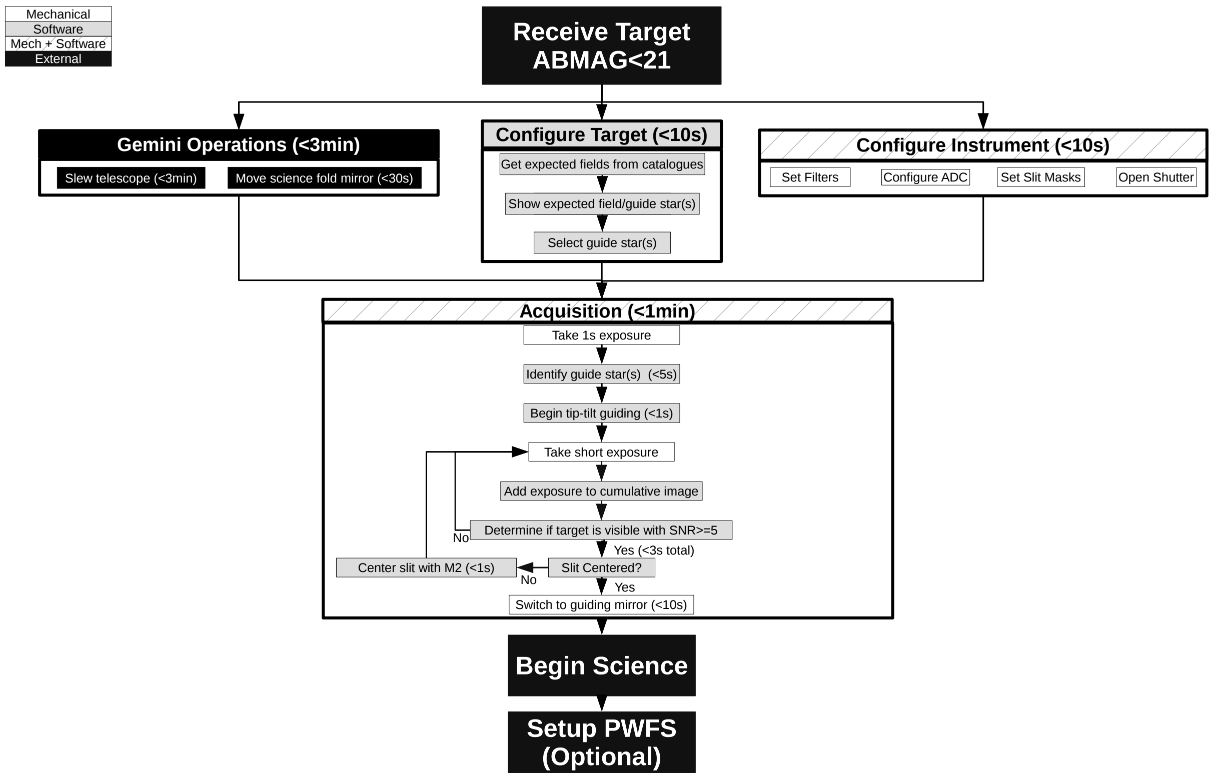

Figure 20: Acquisition procedure for MOVIES in the case of Direct Acquisition (i.e., a reasonably bright target that can be observed directly in the acquisition image.

Figure 20 is a flow chart of the acquisition process for the spectroscopic mode of MOVIES, where the target is identified in the acquisition cameras prior to switching to spectroscopic science observations. This mode is anticipated to be used either for the observations of bright targets (which we define here as brighter than r=21), or for observations of objects with imprecise astrometry (e.g. SWIFT GRB alerts), where confirmation of the position of the source is required.

Black boxes indicate processes that are outside the control of MOVIES (e.g., dome and telescope slew). All the remaining processes are internal to MOVIES: grey boxes are primarily software processes; white boxes are primarily mechanical processes; hatched boxes are processes requiring both software and mechanics. Total time budgets for each process are indicated; excluding the slew and movement of the science fold mirror, MOVIES is anticipated to take 70 seconds to acquire a target and begin a science exposure; this increases to 90 seconds if the science fold mirror must be moved. Both of these meet or exceed the 90 second requirement described in REQ-SCI-004. We describe the salient features of this flow chart below.

Receive Target

The process of receiving target coordinates (either scheduled observations or target of opportunity, ToO) is separate from operation of the MOVIES instrument. For ToO observations, prioritization of new targets in relation to scheduled observations will be in accordance with policies and procedures defined by the Gemini Observatories. This process is not budgeted within the procedure outlined here, but it is clearly advantageous to ensure the process is efficient and at least partially automated.

Gemini Operations

Gemini operations are essential processes which are not directly under the control of MOVIES. This includes slewing to the ToO, and switching between instruments on the ISS. Due to the inability of MOVIES to affect these procedures, the acquisition time requirement is defined independent of these procedures.

Clearly, the slew rate of the Gemini telescope and dome is a potential bottleneck in the acquisition procedure. For the dome, the slew rate is one degree per second. This results in the worst-case slew rate of three minutes for a source that is on the opposite side of the sky to the target observed immediately before the new observation. For the telescope, the slew rate is 2.2 degrees per second in azimuth and 0.75 degrees per second in elevation.

In cases where MOVIES is not the instrument currently in use, the science fold mirror will need to be repositioned to send the light to MOVIES. According to Gemini staff, this process takes less than 30 seconds.

All of these processes (dome slew, telescope slew, science fold mirror repositioning) can occur in parallel. For favorable circumstances, when MOVIES is the instrument in use, and observations are well planned to ensure large slews are not required, we adopt 10 seconds as a reasonable lower limit to the time required to perform these tasks (during which time the dome can move up to 10 degrees, the telescope can move up to 22 degrees in azimuth and nearly 8 degrees in elevation).

We note that these overheads are the single greatest limitation to the efficient use of Gemini as a “Target of Opportunity” telescope. Clearly, careful planning of observing strategies (e.g., observing in the same region of sky as LSST on a given night) can help minimize these overhead, and it may be worth the Gemini Observatories investigating operational and infrastructure developments to best utilize the MOVIES system.

Configure Target

This box refers to all aspects of preparing the instrument to identify guide stars and the primary target; essentially, the preparation of an automated “finding chart”. This process should be quick and automated since ToOs are by nature not defined ahead of time and so these charts must be prepared on the spot. This is unlikely to prove a significant issue, due to the existence of tools such as the Aladin sky atlas, astrometry.net, and the Vizier catalogue access tool.

Software specific to MOVIES will search local guide star databases to identify all bright stars that will be present in the acquisition camera once the Gemini Telescope comes to rest very near to the target coordinates. Given the known WCS solution for the acquisition cameras, estimates of their expected positions on each of the acquisition cameras can be made.

Configure Instrument

The time estimate for instrument configuration (inserting acquisition mirror, ADC calibration, slit mask selection, opening shutters, moving filter wheels) is based on previous experience from the MOVIES team. Each of these tasks can be performed in parallel.

Acquisition Image

Once the telescope comes to rest at the nominal target location, the acquisition cameras initially takes a 1 second exposure (long enough to average out the effects of wind-shake and other vibrations). An automatic search is then run on each of the acquisition images to identify the guide star(s). At this point, tip-tilt guiding begins by MOVIES sending updates to M2 based on the locations of these stars in the acquisition cameras (which now operate as guiding cameras being read out at ~20Hz, although updates can be sent to M2 at a higher rate if required).

Each of the short guide frames is stored and each output is coadded to the previous exposure in each camera to build up a deeper image of the target region. Once the target becomes identifiable in any of the three cameras at a reasonable SNR (nominally taken to be SNR~5, allowing for the centroid to be known to <0.15' in median seeing conditions assuming a point source), the software determines if the target is at the required location to center it in the slit. If it is not, an offset is applied to M2 to center the object in the slit. At this point, the acquisition mirror is replaced by the guiding mirror (which has a hole in the center to allow the science light to pass through to the spectrograph).

Note that, if the NIR A&G arm is required to directly image the target, an additional overhead may be required in order to apply an appropriate correction for the sky background.

Begin Science/Guiding

This completes the direct spectroscopic acquisition process for MOVIES and the science exposure can now start. If desired, the Gemini peripheral wavefront sensors (PWFS) can now be set up for high order image corrections.

2.5.3.2 WCS Acquistion

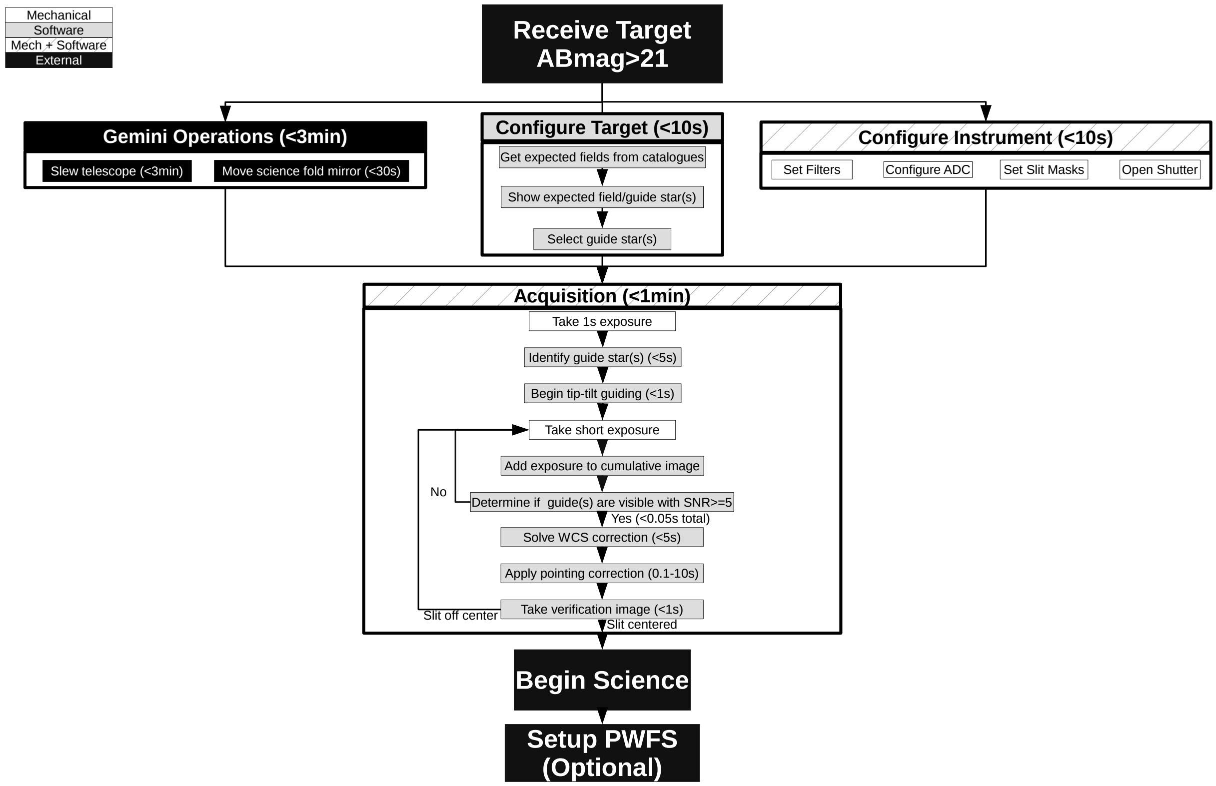

Figure 21: Acquistion procedure for MOVIES in the case of a faint target that cannot be directly imaged by the acquisition cameras

WCS acquisition is anticipated to be used in all scenarios in which direct imaging of the target is unnecessary or impractical (e.g., extremely faint targets, emission line objects, etc.). The flowchart for WCS acquisition is shown in Figure 15. Unlike for the case of direct imaging, the coordinates of the target must be well known (to within small fractions of the width of the slit).

The acquisition procedure for the WCS mode proceeds as for Direct Acquisition. The only difference, however, is that once the guide stars are identified on the acquisition camera and guiding begins, a sequence of offsets are applied to M2 to force the guide stars to be at the predicted location on the acquisition camera under the WCS transformation that would place the target location at the center of the slit. Once the guide stars are at their predicted positions, it is then taken for granted that this means the target is in the center of the field. Spectroscopic observations can then begin.

Since direct imaging of the target is not required in this mode, the guiding mirror (with the hole in the center) can be used for acquisition, removing the need to switch mirrors (in contrast to the Direct Acquisition procedure).

2.5.3.3 Guiding

In the majority of cases (i.e., those science programs not requiring simultaneous three band deep imaging), guiding and tip-tilt corrections will be applied direct to M2 via some combination of the three MOVIES acquisition cameras. Due to the size of the field, it is possible to combine the signals from multiple objects, and even from multiple cameras. These will nominally be read at a rate of 20Hz, which we feel should be sufficient for T/T guiding. If required, predictive, filtered control algorithms can be implemented to produce a command stream at 200Hz if the M2 system is more efficient at this rate.

To monitor the focus of the instrument, we propose utilizing a simplified, degenerate form of "phase diversity". For this, the Red VIS acquisition camera will be set confocal to the spectrographs. The Blue VIS acquisition camera will be set inside of focus, at a distance that leaves it within the depth of field so that image quality is insignificantly affected. The NIR acquisition camera will be likewise set outside of focus within its depth of field. Under normal circumstances when MOVIES is in focus, all three cameras will have similar image quality that is repeatable from observation to observation (once changes in atmospheric conditions, wavelength dependence etc are taken into account). However, if MOVIES is not in focus, then the three images delivered by the acquisition cameras will be discrepant. The direction of this discrepancy (ie which of the NIR or Blue VIS acquisition camera displays the largest image size) will inform the system of the appropriate correction that needs to be applied, and offsets to M2 focus will be applied.

As a contingency, the Gemini PWFS can be deployed after the science observations have begun, so that its deployment does not affect the acquisition time budget and hinder the science (of course it could be moved during the telescope slew to be closer if required). As it patrols a large annulus outside the MOVIES FoV, and incorporates a higher-order capability, it can provide additional guiding information simultaneously with the MOVIES guiding.

2.5.4 Calibration Procedures

Here we describe the basic calibrations procedures needed for a typical night of observing with MOVIES. We expect that calibrations will be valid on multi-week to month timescales under normal operating conditions provided MOVIES is not removed from the telescope or allowed to warm up or exceed normal operating parameters.

In many ways, MOVIES is a very conventional spectrograph by design, and no particularly novel calibrations are required. Similarly, MOVIES is designed for high operational stability, so it does not require intensive calibrations. Overall, MOVIES calibration is straightforward to implement in the Gemini observing queue system and does not present any particular operational challenges.

2.5.5 Observing Block Calibrations

These calibrations refer to those that must be performed at the start of an operational block with MOVIES after it is installed on the telescope and at operating temperature. These provide basic operating parameters that should not change (geometric mapping of spectra, detector gain and readout noise) during normal operations, and are not expected to change over a typical operational block of, for example, and entire semester.

1. Pinhole slit spectra with a white-light continuum source to provide the spectral trace functions with slit position.
2. Pinhole slit spectra of calibration lamps to provide the 2D spatial/spectral mapping parameters used for quick-look spectral reduction and the zero-points for the 2D extraction maps used by the spectral extraction pipeline.
3. Conversion gain and readout noise measurements for all science detectors.

While not expected to change, prudence dictates that they should be repeated every month or two to monitor instrument performance, as substantial changes could indicate incipient problems (e.g., problems with the detector or its electronics).

2.5.5.1 Routine Daytime Calibrations

Routine daytime calibrations are those that provide basic calibrations needed for regular science operations: biases and darks, flat fields, and wavelength calibration spectra. Because of the long-term stability design of MOVIES, these calibrations do not need to be done every night. Rather, they can be scheduled on a rolling basis since when operating normally the mean time between repeated calibrations (e.g., imaging flats in a given detector+filter combination) is expected to be roughly 2 weeks.

1. 2D bias frames for all acquisition and spectroscopic detectors
2. 2D flat fields for the three acquisition cameras through each filter
3. Spectral white-light flat fields
4. Wavelength calibration comparison lamp spectra.

While "daytime," they may be performed at night as part of a bad-weather program executed when the telescope dome cannot be opened because of inclement weather conditions. Standard scripts would be run that execute these observations on a regular basis.

2.5.5.2 Night-time On-Sky Calibrations

Night-time on-sky calibrations are performed either as part of a running observatory calibration program or as part of a scheduled PI science program. Standard flux ("response") calibrations are effectively common to most spectroscopic science programs and are thus a "common" calibration unless the PI program is doing something (justifiably) unique. Some calibrations, however, must be matched to the science target airmass, for example, telluric absorption correction spectra or observation of solar analog stars for solar system object spectroscopy. In general, the design stability of MOVIES eliminates the need for on-position wavelength or flat field calibrations.

The most basic routine night-time on-sky calibration is spectral flux calibration of the spectroscopic channels using observations of the Hubble Space Telescope CALSPEC library primary and secondary calibrators, which are well-characterized from the UV to near-infrared. These are observed using s 5-arcsecond wide flux calibration slit. Ideally a number of these observations should occur during photometric conditions to monitor instrument plus telescope throughput, but for basic "response" calibration, observations during periods of modest transparency or degraded seeing are useful. This makes they readily queue scheduled, especially during "Band 3" conditions. Standard scripts would be run to acquire CALSPEC standards.

Imaging of standard calibration fields in the acquisition camera filter bands should be done on a monthly basis during photometric conditions to measure basic photometric calibration parameters, and to monitor the long-term photometric performance of the acquisition channels plus telescope. These would be short exposures and readily queue scheduled as they need short exposure times and do not require good seeing conditions. Non-photometric observation of standard photometric fields is not indicated. Again, standard scripts would be provided to acquire photometric calibration fields with MOVIES.

Telluric standards, particularly in the near-infrared (700 to 2400nm), are used to explicitly correct for telluric absorption features, many of which are time variable (depending, for example, on the precipitable water column above the observatory at the time of observation). A library of suitable telluric standard stars with associated observing scripts would be provided to enable efficient observation of telluric standards time to match the airmass of the science target as part of the instrument target acquisition system. However, advances in atmospheric transmission forward modeling (e.g., the atmospheric modeling program at ESO: www.eso.org/sci/software/pipelines/skytools/; Smette et al. 2015, A&A, 576, A77 & Kausch et al. 2015, A&A, 576, A78) may reduce the need for extensive use of telluric standards for routine observing in the future.

Spectrophotometry of solar system targets requires contemporaneous observations of a suitable Solar Analog star. Because these are often also called into service as telluric standards, they will generally be taken at comparable airmass, and so would be performed as part of a specific PI program, rather than as a routine calibration as it cannot generally be used by an unrelated program (unlike the case of flux standard star spectra). A library of suitable solar analogs that are readily observable with MOVIES will be identified and standard scripts would be run to acquire and observe solar analogs distributed across the sky for use in the Gemini queue.

2.5.6 High Cadence Observing: the benefits of large format EMCCDs

The inclusion of an EMCCD in MOVIES enables various science cases by providing a significant improvement to the parameter space explored. The key advantages of the EMCCD are extremely low read noise and a very high frame rate. The unique science capabilities that these enable from an operational perspective are described below. A more detailed performance comparison is in section **Error! Reference source not found.**.

2.5.6.1 Near Zero Readout Noise ->Variable spectral resolution

One significant complexity in most spectrographs that attempt a certain level of polyvalence comes from the inclusion of a set of gratings and the accompanying mechanisms for grating changes. Using multiple gratings also requires more complex calibrations and requires that the optimum resolution is known in advance of the observation. However, conceptually, provided that the wavelength coverage is sufficient, one could simply observe at the highest dispersion and during the post processing smooth the data to the desired resolution. For the sake of the argument, imagine an R~10 000 spectrum degraded to an R~40 resolution to sample the shape of the continuum of a very faint object. It is well known that this approach doesn't work in practice because readout noise in the high-resolution spectrum will completely overwhelm the down-resolved spectrum. A smoothing of ~250 will lead to an increase by a factor 16 in the per-element readout noise (e.g. from 5e-/pixel to the equivalent of 80e-/pixel).

The inclusion of an EMCCD, with an effective readout noise of ~0.001 e-/pixel/frame, removes this noise problem. The effective amplification of noise when smoothing the spectrum remains, but because it is extremely low initially, the resulting noise remains small compared to other contributions (e.g., sky background, shot noise from target), even when degrading the resolution by factors of >100.

The ability to adjust the resolution in post-processing also means that the resolution does not need to be constant in the final product. If one observes a very faint target with a set of strong emission lines, both the line profile and continuum measurements can be obtained. For example, if one observes an active young low-mass star, a data set obtained at R~10 000 can be used to derive an Hα line profile to determine the relative contribution from the chromosphere and accretion while retrieving the SED at low-resolution in the blue end of the spectrum. This brings a major benefit for transient follow-ups: one does not need to know in advance if emission lines will be present and at which wavelength. The dataset will allow proper analysis of line profiles without sacrificing sensitivity of the overall SED.

2.5.6.2 Reduced sky contribution in the far-red

There is another advantage that arises from this posteriori determination of resolution: one can mask sky lines before degrading resolution. This reduces significantly the sky shot noise, leaving only the continuum contribution. Of course this comes at a cost as photons from the object at the wavelengths of strong OH lines are also rejected, but the overall impact on the low-resolution spectrum obtained is positive. Figure 22 illustrates the benefit of OH line masking when binning a spectrum from R=10 000 to R=40. Overall, in *i* and *z* band (>700 nm), there is a gain in observing efficiency of ~2 and larger.

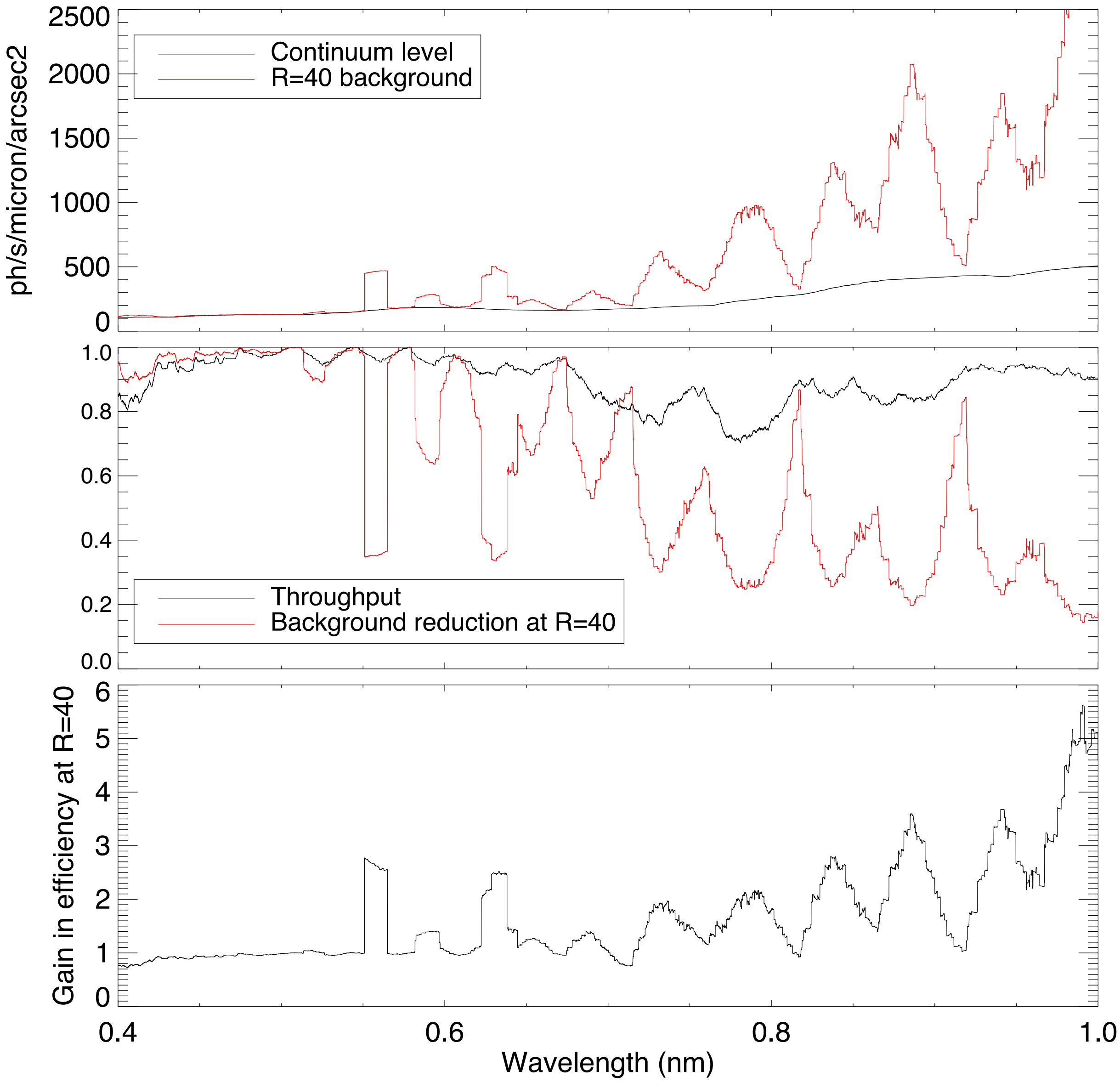

Figure 22: Upper panel : Sky spectrum at R=40. The red line denotes the sky contribution without masking strong OH lines, while the black line illustrates the continuum contribution. In the blue domain (<500nm), the noise background contribution is dominated by continuum, while in the far-red (>700nm), OH line emission dominates. Middle panel : Effective throughput for a white source when masking OH lines at R=10 000 and smoothing to R=40. Overall, regions with strong OH lines all have throughputs >70% after masking, but this masking leads to a 3-5 fold decrease in background. Lower panel : Telescope efficiency gain for very faint targets. Beyond 700nm, a spectrograph with pre-smoothing rejection of OH background would reach a given SNR on a faint target >2 times faster than the equivalent low-resolution spectrograph.

2.5.6.3 Data filtering

An EMCCD can be read at very high rates (up to 30 Mpx/s) without degrading the read noise, which opens the possibility of sub-second time resolution in the dataset. For the majority of targets, for which one expects no intrinsic variability, the dataset will simply be combined into a single spectrum. However, even in these cases the rapid time resolution provides advantages due to time-varying observing conditions. For example, frames affected by cosmic ray events can be discarded and only a tiny fraction of the effective exposure is lost. The fast frame rate also creates the possibility of weighting frames in poor weather conditions, such as passing clouds. A classical integration would have to be paused should the cloud cover thicken, while the observer hopes for an improvement in conditions before cosmic ray hits affect the quality of the data. With a very rapid frame rate, exposures can simply continue regardless of conditions and poor quality frames discarded at the time of post-processing. This also allows the optimal weighting of spectra obtained under varying seeing and/or atmospheric transmission.

2.5.6.4 Time resolved spectroscopy

The ability to noiselessly combine high frame rate data sets also enables some unique science with time-varying targets. Because one does not need to know on which timescales the target varies prior to observations, significant serendipitous discoveries can be made. For example, observation of an M dwarf may display a short-lived flaring event that can be identified only upon analysis. The EMCCD dataset will allow a recovery of the time-resolved flare's spectrum. When observing a transient of unknown nature, one will have the latitude to bin the data at any time-resolution for any spectral element. This opens an entire parameter space for the discovery of short bursts, especially if they are at a monochromatic wavelength. For example, a compact object with 1s bursts in Hα every ~1000s would see its burst flux deeply buried in the time-averaged continuum flux in a sequence of 60s exposures, but sub-second time sampling would provide a much more significant detection. An EMCCD-equipped high-resolution spectrograph would open an entirely new window on accretion processes on compact objects and provide access in the optical to processes normally studied with high-energy observatories.

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2.6 Concept of Operations

MOVIES enables a large variety of observing modes and is very flexible in its operation. In particular, it nominally requires very little in the way of other Gemini sub-systems, but does not preclude their use (eg see Section 2.5.3.3). In general, all of them possess the same underlying structure from an operational perspective, namely:

- Slew to target and Configure Instrument (parallel processes)
    - Set acquisition filters
    - Set acquisition mirror
    - Set ADC
    - Set slit masks
    - Lookup guide stars and prepare guide boxes
- Identify guide stars, offset through M2 and then begin guiding
    - One of the acquisition cameras becomes guide camera, being read at a frame rate of ~20Hz. Note that with the default VIS guide cameras, the full frame will be read out at 20Hz and can be 'stacked' to retain the equivalent full exposure time
    - Updates set to M2 for tip/tilt and guiding. Updates can be send at rate higher than 20Hz if required, as noted in Section 2.5.3.3.
    - If three-band deep imaging is required, Gemini PWFS will be deployed for guiding (see Section 2.6.5)
- Acquire target
    - Direct or WCS (see Section 2.5.3)
- Select imaging or spectroscopy mode (via acquisition mirror)
- Begin science observations
- Set Gemini PWFS for higher order image corrections (if required and not previously deployed)

We now proceed to describe a number of specific MOVIES science operations modes, using examples of typical and atypical observations that MOVIES makes possible. Some are so simple as to require only brief description, others are potentially unique and powerful modes enabled by MOVIES. They include:

1. A simple spectroscopic target
2. Spectroscopy of a Z=6 quasar candidate
3. Spectroscopy of a very faint target
4. Time resolved spectroscopy with simultaneous photometric monitoring
5. Deep multiband imaging
6. Target of Opportunity

2.6.1 A Simple Spectroscopic Target

Likely the most common operational mode of MOVIES will be to acquire spectra of a single target visible at all wavelengths by the acquisition and slit-viewing cameras.

The target is acquired by the acquisition cameras and verified following the procedures described in Section 2.5.3.1. Once slit centration is verified, science integration begins.

This mode should have minimal operational overhead because the target should be readily identified and easily verified when it is on-slit.

The PI receives copies of all acquisition and slit-viewing camera images taken as part of the target acquisition procedure along with the science data. For targets in crowded fields, the slit-viewing camera images provide the PIs with a definitive record of the target that was placed on the slit.

2.6.2 Spectroscopy of a z=6 quasar candidate

In this case, we consider a target that is not visible in all acquisition and slit-viewing cameras. A good working example is a candidate Z>6 quasar that is only visible in the z-band in the red acquisition camera and in the NIR acquisition camera. For example, if Z~6.5, the Gunn-Peterson trough blueward of Lyman-α will make this an i-band dropout target. For this target, the blue acquisition camera is will not be able to identify the target, and guiding/tip-tilt imaging will use the red acquisition camera. The quasar field would be acquired simultaneously with the red camera with the z filter and in the NIR camera with the J or H filter, then positioned onto the slit. Science integrations commence once slit centration is verified.

2.6.3 Spectroscopy of a very faint target

In this case, the science target is too faint for direct acquisition in a reasonable integration time in any of the acquisition cameras, and so a "WCS acquisition" is required. The target acquisition script calculates the expected positions in the acquisition camera field of view of nearby bright guide stars (here used as reference objects) assuming the science object is in the center of the field of view. Once guiding begins (using these same stars), a series of offsets are applied to M2 to force these stars into their "correct" position in the field of view. Once at these positions, it is taken for granted that the science object is in the center of the slit.

Since no exchange of the acquisition and guiding mirrors are required, operationally the WCS acquisition is at least as rapid as the direct acquisition procedure.

During the first spectroscopic science integrations, the slit viewing camera(s) are used to accumulate a series of long exposures of the slit comparable to the unit science integration time. These images are combined automatically and available to the queue observer to provide confirmation by the time the first deep spectrum is completed and readout that the faint target really was properly centered in the spectrograph slit. Blind acquisitions such as this always provide some level of risk, regardless of the supposed robustness of the procedure, and so these images provide a way for the queue observer to make any small corrections to the slit centering if the blind offset was incomplete, or to provide the direct confirmation that the procedure was successful. It allows for the observation to be "tweaked" and salvaged in the case of serious error. This lowers the risk of this type of acquisition to targets that may require an hour or two of deep spectroscopy before you know if you have anything, and allows confidence that very long super-faint target spectra (integration times of ~4 hours for very high-z galaxies) will be executed correctly.

2.6.4 Time-Resolved Spectroscopy with simultaneous photometric monitoring

A particular challenge of time-resolved spectroscopy is that, in the absence of a non-variable reference target on the spectrograph slit, it is nearly impossible to remove variations in atmospheric transmission or monitor changes in seeing that can introduce false variability in the science target. For example, for studies of transiting exoplanet atmospheres, the conventional way to do this from the ground is using a multi-object spectrograph where by a nearby star (or stars) of comparable brightness are available and observed with the same slit on the mask with the science target. This is not always possible, making some transiting planet targets effectively unobservable from the ground to the precision required (fraction of a percent variation – especially critical if targeting a secondary eclipse). Attempts to use simultaneous photometry presents numerous practical issues, the greatest of which is non-common path variations because the imaging and spectral observations use different optics (e.g., at LBT spectroscopy on one telescope, imaging on the other) or two separate telescopes (e.g., imaging from a smaller auxiliary telescope).

The baseline acquisition camera detectors for MOVIES will be high candence devices, EMCCDs (1k x 1k format) or CMOS detectors. Therefore, because MOVIES can simultaneously image the acquisition field with science-grade high cadence detectors in multiple bands, we eliminate the limitation described above, and our photometric monitoring channel is a true common-path channel.

We illustrate this observing problem with the extremely challenging example of acquiring time-series spectra of a transiting exoplanet for about 30 minutes pre-transit, through ingress, transit, and egress lasting approximately 6 hours. The science case for this type of program was presented in Section 2.3.

After target acquisition and verification, one of the acquisition cameras is operated conventionally for guiding and tip/tilt reference (it could, in principle, be used as one of the photometric reference channels, but we'll assume it is not playing that as its primary role as its exposure time is dictated by the needs of the guiding system). The other two acquisition cameras: one of the optical and the NIR cameras are configured for imaging their full field of view at a roughly 60 second cadence (can be faster if a number of bright stars are available, slower if only fainter stars within the field of view).

Note that we do not need a star of comparable brightness to the transit target, provided there are enough stars whose brightnesses add up to the brightness of the target star. In the galactic plane, where many (if not most) of transiting planet hosts will lie, we expect multiple reference stars. Because MOVIES has optical and NIR acquisition cameras, we have two independent monitoring channels corresponding to the wavelengths of the two spectral channels, and have tie-breakers in the event of problem data on one or other channel (and backup should one camera fail during the transit – we can keep rolling so long as at least one acquisition camera is working). MOVIES use of EMCCDs or CMOS allows optimization of the readout scheme to maximize photometric precision in the monitoring image sequence, and with fast time sampling, the actual optimal cadence may be determined after the fact in post-processing. The flexibility offered by this type of architecture is a great advantage to this type of observation.

A 5-arcsecond wide slit is used for the target star to get all the light without slit losses and mitigate seeing variations, but we first center the target on the narrow slit with the slit-viewing cameras, then insert the wide slit so we are confident of the good centering of the target. If there are providentially non-target stars on the slit-viewing camera, we can acquire images with them at longer integration times during the transit run to provide an additional stream of simultaneous monitoring data.

Meanwhile, the spectroscopic channels hammer away at the target. If the transiting planet host star is very bright and MOVIES has implemented the use of large format EMCCDs in the spectrograph optical channel (not to be confused with the 1k x 1k EMCCDs that could be used in the acquisition channel), we can use the readout architecture to optimize the sampling cadence to avoid saturation in the actual seeing conditions at the time of the observation.

The resulting data set, made of spectroscopic and multiple imaging time series, will make it possible to de-trend many systematics that otherwise limit the science results of such an experiment. Not just transmission but also seeing variations and telescope image jitter/motion can be measured independent of the spectroscopic channel. Because the acquisition system and spectrographs are common-path, a number of problems associated with non-common path variations are simply eliminated.

We stress that, with this type of observing program, Gemini/MOVIES could be the ultimate instrument for spectroscopy from the UV to the NIR for exoplanet atmospheres.

2.6.5 Deep Multiband Imaging

In this mode, the PI uses MOVIES as a deep multiband imager at optical and NIR wavelengths. This example observing scenario imagines the PI wants to acquire deep griz/yJH imaging of a field down to faint limiting magnitudes.

MOVIES has three acquisition cameras with standard photometry filters: Blue (ugr), Red (riz), and NIR (yJH). There are two options available to the PI when it comes to guiding and tip/tilt correction for MOVIES used in imaging mode.

- If observations are required in all three bands – blue, red, and near-IR – at the same time (e.g., for a rapidly varying object), then we will be operating MOVIES with all three acquisition cameras running in long-integration time deep-imaging mode. Therefore, we will be using the telescope peripheral probe to provide the tip/tilt correction to the telescope. This would enable the telescope to acquire long, simultaneous 3-band photometric time series at nearly any cadence deliverable by the high cadence detector systems in the imaging mode. Note that rapid acquisition will not be possible in this mode, since rapid acquisition requires the use of at least one of the MOVIES imaging cameras.

- If observations do not require all three bands, or rapid acquisition is required, then at least one of the imaging cameras must be used as the A&G unit. Depending on the filters that are required (and therefore also depending on which arms are required in the imaging system), it may be that one arm can always act as the A&G unit for the entire program (e.g., if only deep NIR imaging is required), or it may be that some choreography is required to cycle through combinations e.g., Blue+Red, Blue+NIR, Red+NIR, Blue+Red. In this example, the channel not engaged in deep imaging taking the guide/tip/tilt correction role, allowing simultaneous observation of all relevant color combinations, so that deep multi-color observations can be acquired even during intervals of variable atmospheric transmission.

2.6.6 Target of Opportunity

Most Target-of-Opportunity (ToO) objects are likely to be straightforward – provided they are good coordinates, the object will be bright enough to appear in all bands on acquisition and slit-viewing cameras, at which point the observation is the same as that of a simple spectroscopic target (Section 2.6.1). Examples of such targets are unobscured gamma-ray bursts, supernovae, or other relatively isolated broad-spectrum transients.

The fun starts when we don't know what we're going to get. Here the modularity and operational flexibility of MOVIES come to the fore.

We don't know if it will be visible in all bands, very blue or very red, so we hit the field with all three acquisition cameras and keep all three cameras rolling while the queue observer or automated software decides the call: both channels? visible-only? IR-only? Once the target is ID'd and the decision made, the guide camera is selected and the object positioned down the hole to the spectrograph. The images in all three bands taken during the initial acquisition phases, their wide field and multiple simultaneous color information allows the PI to back out the brightness of the target relative to the triggering/discovery image.

Given rapid advances to date in on-the-fly astrometry, we expect to be able to put a good-enough astrometric solution on acquisition images fast enough to ID even the most not-in-your-face ToO, again provided the triggering agency is doing their job. This can allow a very rapid target ID and positioning into the spectrograph.

Once the target is in the slit and integrating the acquisition cameras not engaged in guide/tip-tilt correction are used to image the surrounding field to establish a good photometric reference frame from the non-target stars (since the target is down the spectrograph entrance, we get no more photometry). We could, however, elect to swap in the full-field imaging mirror between spectroscopic integrations to get an instantaneous measurement of the source, then switch back for the next spectrum.

Crucial to making Gemini/MOVIES a workhorse for spectroscopic identification of ToOs is fast acquisition, multi-wavelength information to verify the target and put the spectra into the light-curve context, by providing contemporaneous common-path imaging, and the ability to rapidly decide what kind of data should be taken. This also puts requirements on quick-look spectra reduction/display software so a continue/abort judgement can be made (if required by the ToO program; see REQ-SCI-009).

3 Technical Requirements and Instrument Design

We start the technical section with the flow down of technical requirements before presenting the design decisions and current design status of MOVIES.

3.1 Top-level requirements and flow down

This section presents the flow down from the science requirements to the top level Functional and Performance Requirements (FPR) for MOVIES. Done in a fully manual manner, this transforms the requirements to a language that can be further developed into deeper and deeper technical requirements.

For a successful instrument, it is important to ensure that it can be operationally efficient as well as have a high performance; a slightly degraded, but consistent and reliable, performance operation is of more use for a work-horse instrument than a temperamental instrument that is difficult to maintain and only performs periodically.

It is noted that there is often a somewhat arbitrary distinction between Functional and Performance requirements. We retain the separation here more for historical sake than for any other reason.

In many cases there is an almost direct translation from the science requirement (eg "Wavelength range"), and in others some analysis or interpretation is required (eg "Throughput"). In all cases we define and reference the derivation for future considerations. Many requirements receive the ubiquitous "Obvious" source, where we attempt to specify why it is obvious. In a fully developed instrument these will often transform into "Statement of Work" as they'll be required in contract.

We repeat the science requirements table (from Section 0, Table 3) here for convenience sake.

ID	Name	Requirement
REQ-SCI-001	Wavelength range	Gemini/MOVIES will obtain complete spectral coverage from 360nm to 2.45um in a single exposure for all spectra.
REQ-SCI-002	Spectral resolution	Gemini/MOVIES will be able to operate at a range of spectral resolutions between R~2000 and R~10000
REQ-SCI-003	Sensitivity	At a spectral resolution of R=5000, an extracted spectrum from Gemini/MOVIES will have a signal to noise per resolution element at a given wavelength that is greater than or equal to one for a 1 hour observation of a point source with a flux density of 3.6 x 10^-29 ergs/sec/cm2/Hz at that wavelength, for all wavelengths intervals between 0.36 - 2.45um free from airglow emission-line contamination and strong telluric absorption.
REQ-SCI-004	Acquisition time	Gemini/MOVIES will be able to acquire any target and begin taking a scientific spectral observation within 90 seconds

REQ-SCI-005	Sky coverage	Gemini/MOVIES will be able to identify suitable guide stars over at least 90% of the sky
REQ-SCI-006	Sky subtraction	(i) Gemini/MOVIES must allow for removal of (100 +/- 0.2)% of the sky flux, as estimated for sky-subtracted sky spectra. (ii) Gemini/MOVIES shall achieve a sky subtraction accuracy for atmospheric airglow emission-lines such that the mean residual error for spectral pixels, within 1 resolution element of known atmospheric emission-lines, is <N.n (TBD) times the Poisson limit indicated by the propagated variance spectrum for each resolution element.
REQ-SCI-007	Velocity accuracy	For any object with a known velocity, observed at multiple epochs by Gemini/MOVIES with a signal to noise ratio per resolution element of 5 at R=5000, the contribution from Gemini/MOVIES to the rms difference between the known velocity of the object and the measured velocity of the object will be less than or equal to 12km/s, and will have no systematic dependence on the wavelength region of the spectrum that is used (providing suitable features exist, i.e., any strong absorption or emission lines)
REQ-SCI-008	Spectrophotometry	For a spectrophotometric standard star, observed at multiple epochs by Gemini/MOVIES with a signal to noise ratio per resolution element of 5, the rms variation in the ratio of fluxes measured in any two wavelength intervals will be less than 1% (TBC) of the mean measured value.
REQ-SCI-009	Quick look data tools	Gemini/MOVIES will allow for initial inspection of science spectra within 60 seconds of completion of the observation, including the detrended detector image, extracted and sky-subtracted 2D and 1D spectra.

Table 5 Copy of Science Requirements

3.1.1 Top Level Functional Requirements

This section presents the top level functional requirements for MOVIES. These are nominally to include those requirements that will ensure that MOVIES will work on the Gemini Telescopes and perform the basic operations that are required.

3.1.1.1 Gemini Telescope Optical Compatibility

REQ-FPR-0100: MOVIES will accept the raw Gemini telescope beam as defined in the as-built optical prescriptions provided by Gemini to the project, with the pupil at the secondary mirror, either directly on the bottom ISS port or either science instrument side-looking port fed by the Science Fold Mirror. The instrument must operate at any ISS rotation angle achievable by the telescope.

Derived from: Obvious requirement (Les Saddlemyer)

3.1.1.2 Gemini Facility Instrument/Mechanical Capability

REQ-FPR-0200: MOVIES will be adhere to standard Gemini mechanical interfaces as defined in ICD 1.5.3/1.9 and be capable of mounting to either the up-looking or side-looking ISS ports.

Derived from: Obvious requirement (Les Saddlemyer)

3.1.1.3 Automatic Operation

REQ-FPR-0300: MOVIES shall be capable of locking on and starting an exposure once the Gemini telescope has settled on-target to within 10 arcsec of the correct position, without manual intervention.

Derived from: REQ-SCI-004

NOTES: This is in support of one of the primary science cases, rapid follow-up of targets of opportunity. Automatic operation will form part of the timing budget in order to remove human intervention delays.

3.1.1.4 Downtime

REQ-FPR-0400: The downtime of the instrument shall be less than 1 %, with a goal of less than 0.5%. This is measured as lost night-time scheduled observing.

Derived from: Obvious requirement for a work-horse instrument (Les Saddlemyer)

NOTES:

1. MOVIES is predicated on being a work-horse instrument.

3.1.1.5 Lifetime

REQ-FPR-0500: MOVIES shall be designed to operate for 10 years at a duty cycle of 10 hours/night 100 nights per year before requiring replacement of any components. This excludes regular scheduled maintenance (of more than 1/year) of vacuum conditions, CCR heads or consumables such as desiccants or filters.

Derived from: Obvious for a work-horse instrument (Les Saddlemyer)

NOTES:

3.1.1.6 Wavelength Coverage

REQ-FPR-0600: MOVIES shall cover, in a single exposure, from 0.36 to 2.45 microns without any wavelength coverage gaps.

Derived from: REQ-SCI-001

NOTES:

3.1.1.7 Spectral Resolution

REQ-FPR-0700: MOVIES shall allow a selection of resolutions between R=2000 and R=10,000. This does not need to be infinitely selectable, but must include at least 4 settings.

Derived from: REQ-SCI-002

NOTES:

3.1.1.8 Quick Look Data Analysis

REQ-FPR-0800: MOVIES shall include the software, and infrastructure, to present an initial display of the science spectra within 60 seconds of the end of the exposure. This shall include, but not be limited to:

- Detrending
- Science target extraction
- Sky-subtracted
- 2D and 1D spectra
- Display with scaling, zooming

Derived from: REQ-SCI-009, + obvious requirement for observing (Les Saddlemyer)

3.1.1.9 Acquisition/Guide FoV

REQ-FPR-0900: MOVIES shall incorporate an acquisition and guiding system that can operate over at least a 3 x 3 arcmin FoV. The full FoV must be available for acquisition, with all but the central < 20 arcsec diameter available when integrating on the spectrograph(s).

Derived from: REQ-SCI-004, REQ-SCI-005

NOTES:

1) It is assumed that the full field is available during acquisition.
2) There is no requirement on the entire field being available when observing in spectroscopic mode, only that a guide star(s) be available within the region.

3.1.2 Top Level Performance Requirements

This section lists the performance capabilities of the instrument.

3.1.2.1 Throughput

REQ-FPR-1000: MOVIES shall have a minimal combined throughput of 25% from 0.36 to 2.45 microns.

Derived from: REQ-SCI-003

NOTES: This is a derivation of the science requirement, translated into a simple throughput requirement in order to drive the technical choices

1) This is for detected photons at the science detector(s)
2) This does not include atmosphere, telescope or slit losses
3) Although goals are not stated, it is expected that throughput will be maximized at all wavelengths.

3.1.2.2 Acquisition Time

REQ-FPR-1100: MOVIES shall have an acquisition time of less than 90s. This is defined as being the delay between the telescope settling 'on target' to a prescribed RA and Dec to within 10 arcsec and starting spectroscopic data collection at all wavelengths defined by REQ-FPR-0600 and any one of the resolutions defined in REQ-FPR-0700.

Derived from: REQ-SCI-004

NOTES:

1) One of MOVIES prime motivations is to provide rapid acquisition of targets of opportunity, which can have rapid changes in characteristics.
2) Although goals are explicitly not entertained for MOVIES, a faster acquisition significantly less than 90 seconds will be under constant consideration provided it doesn't drive cost or risk at any significant level.

3.1.2.3 Sky Coverage

REQ-FPR-1200: MOVIES shall be able to observe at more than 90% of the sky reachable by the telescope. As this does not make any demands on the nature of the target itself, we define this as being able to find and lock onto at least one guide star in the acquisition & guide system to allow guiding.

Derived from: REQ-SCI-005

NOTES:

1) This does not make any assumptions about the quality of the guiding offsets to the telescope other than to maintain lock to keep the average position of the target onto the aperture of the spectrograph(s).

3.1.2.4 Sky Subtraction

REQ-FPR-1300: MOVIES shall provide a target slit of at least 10 arcsec in length to simultaneously, through the same optical path, sample the sky adjacent to the target object.

Derived from: REQ-SCI-006

NOTES:

1) The assumption here is that providing a long slit that includes both the object and adjacent sky will achieve the necessary sky subtraction capabilities. This prevents having to either observe sky before and/or after the object, or having a different optical path (ie fibres) for the sky and object.
2) This requirement is one of the driving reasons to avoid a fibre-fed instrument.

3.1.2.5 Spectroscopic Stability

REQ-FPR-1400: MOVIES shall have a opto-mechanical stability sufficient to limit systematic errors to less than 12 km/s during a 24 hour period, at any orientation of the telescope for normal operating ranges.

Derived from: REQ-SCI-007

NOTES:

1) We interpret this to mean that the instrument will control, or compensate, thermal and flexure aberrations to a level where the contributions between day-time wavelength calibrations is less than 12km/s.

3.1.2.6 Throughput relative stability

REQ-FPR-1500: MOVIES shall not exhibit a throughput relative degradation of more than 1% during any one year in the life-span of the instrument.

Derived from: REQ-SCI-008

NOTES:

1) This is to ensure that relative spectrophometry can be maintained during a reasonable period of operation. Degradation of the throughput on its own isn't too bit an issue, unless it is chromatic.

2) We assume that a throughput calibration of MOVIES could be performed once/year, although in practice the data will exist to perform tests on throughput on a more regular basis (e.g., library of flat fields, etc.).

3.1.2.7 Zenith Distance Limits

REQ-FPR-1600: MOVIES shall meet all requirements at zenith distances of 1 to 50 degrees, independent of the tracking performance of the telescope.

Derived from: REQ-SCI-005

NOTES:

1) Any tracking stability issues that might be due to the telescope being at the zenith inflection point are outside the control of MOVIES.

3.1.2.8 Seeing Condition Limits

REQ-FPR-1700: MOVIES shall meet all requirements, at all zenith distances defined in Section 3.1.2.7, representing the 70%ile seeing conditions.

Derived from: Obvious in order to operate in most of the Gemini conditions (Les Saddlemyer)

3.2 Systems Engineering Aspects

3.2.1 Gemini Involvement

For MOVIES we envision a simple, yet tightly integrated approach. We feel that a close integration and involvement with the Gemini Observatory can reduce the effort required to produce a consistent, unambiguous product. As well, it will avoid some of the complications that can arise when the product is 'handed over'. For these reasons we propose, for further work/effort, the following:

- Gemini provide the infrastructure for documentation version and configuration management from within their organization for the project. This will not only simplify, but eliminate the efforts, complexity and errors that occur when migrating from one system to another. As well, Gemini would then hold the entire history of the instrument development process.
- Gemini provide a System's Engineer with sufficient, dedicated time allocation (e.g., 25% FTE), to participate actively in the project from the beginning. Although not officially responsible for providing direction or instruction, this would gain Gemini an invaluable component of "ownership" which would significantly ease the instrument into the Observatory.

3.2.2 Methodology

Although MOVIES is an efficient and sophisticated instrument, it is in reality a fairly simple instrument that gains its power from the combination of sub-systems, and the utilization of current technologies. With the careful allocation of responsibilities between the partners, the nature of the sub-system interfaces are minimal, and able to be well defined.

With these aspects in mind, we would retain a simple, manual, tracking of requirements and interfaces. However, if Gemini has an existing infrastructure/application/tools that they can recommend and contribute we would be interested in involving them.

3.3 Performance trades

3.3.1 Blue Performance

In the proposed version of MOVIES (prior to the start of the Feasibility Study), the nominal blue-end cut-off for the spectrograph, as set by an early version of the requirements, was at 400nm. This study focuses on the adoption of a suitable blue wavelength cut-off for MOVIES, specifically if the blue-end cut-off should be shortward of 400nm.

To focus the study towards quantitative analyses, we consider two separate regimes of "blue performance".

- Regime 1: 360 – 400nm
- Regime 2: < 360 nm

3.3.1.1 Design options for enhanced blue performance

The baseline version of MOVIES uses a dual arm design for optimizing the throughput in the optical and NIR. While the original science requirement for the blue end cut-off is at 400nm, the optical design still managed to place the wavelengths 360 – 400nm on the detector in the optical arm. What options exist for further optimizing the system for enhanced sensitivity in the two regimes described above?

Regime 1: 360 – 400nm

Option A: Specialized detector coatings and/or specialized optics to enhance blue sensitivity in the existing optical arm

The MOVIES optical spectrograph arm is already optimized for good throughput across the optical wavelength range. While there are ways to optimize optics/detectors specifically for blue/UV wavelengths, these generally come at the expense of decreasing throughput at red wavelengths. Figure 23 shows an example of this for the case of detector coatings (data courtesy of E2V Technologies). The standard single layer broadband coating is shown as the blue line. This coating gives good performance in the blue, but at the cost of sub-optimal performance for the rest of the spectrum. The graded coating (orange line) is a single layer coating with the thickness varied across the detector array to match the spectral content of the echellogram. The curve assumes a perfect match, which is difficult to achieve with the curved echelle output. The graded coating gives the best blue performance without sacrificing sensitivity in the rest of the band, but requires a custom designed coating. The multilayer M2 coating is a standard coating that provides very good performance across almost the entire spectrum, but is inferior at wavelengths shortward of 370 nm.

Option B: Specialized detector for at least the blue end of the echellogram in the existing optical arm (in addition or instead of Option A)

The spectral format of MOVIES is shown later in Figure 38. Currently, this fits on a single detector. In principle, we could use a mosaic in the arm, with the bluer end of the echellogram landing on a blue optimized CCD. The penalties here are increased cost and complexity, and it could introduce gaps in the spectral coverage of this arm. Ultimately, this idea was rejected due to the modest gains relative to the use of specialized coatings (see Option A), the increased cost, technical complexity, and the increased complexity of the data read-out/data reduction efforts.

Regime 2: < 360nm

Option C: Addition of a third arm to the spectrograph, including specialized detectors, coatings and optics.

This new UV arm would operate at wavelengths <~450nm to the new blue cutoff. In this way, everything about the arm could be specialized to blue wavelengths, and the existing optical arm is redesigned to be a "green/red" arm.

This idea was considered to be impractical for MOVIES. Specifically, as the mechanical packaging discussion in Section 3.6 makes clear, there is no space to include a third arm in this ISS-mounted instrument. The alternative of having a bench mounted spectrograph was rejected since it is important for MOVIES to enable high throughput and good sky subtraction, both of which are severely compromised by a bench mounted spectrograph that necessitates a fiber feed.

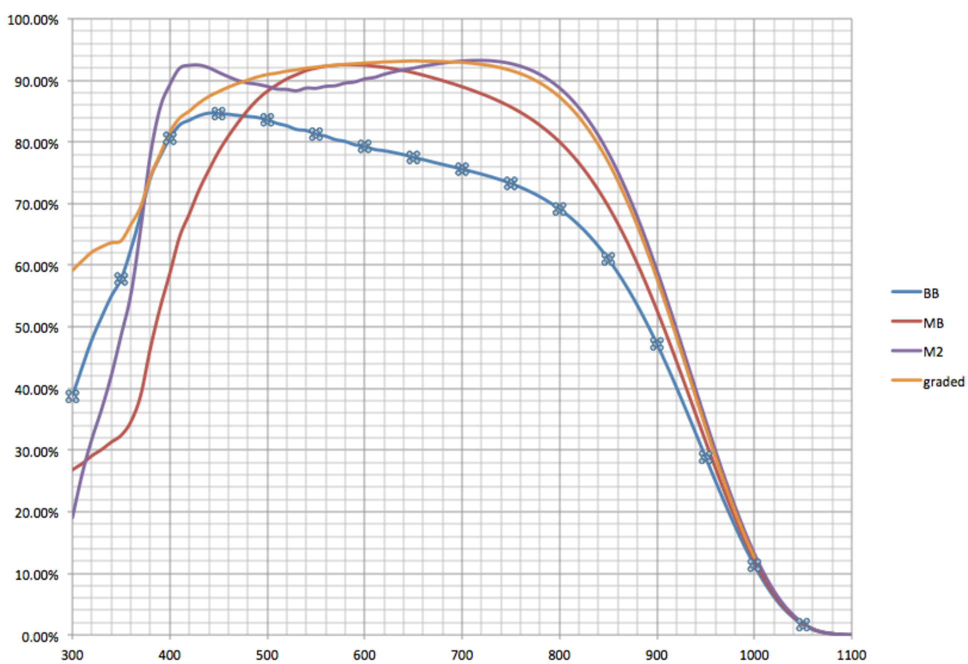

Figure 23: Quantum efficiency of 4 different detector coatings from e2v. BB is a standard single layer astronomy broadband coating; MB is a mid-band coating M2 is a multilayer coating; graded is a graded coating.

3.3.1.2 Science drivers for enhanced blue performance

As a workhorse instrument, it is important that MOVIES is able to cater to a broad and diverse range of science cases. The science drivers for MOVIES are described in Section 2.3.

A major science enabling capability of MOVIES is its extremely broad bandwidth, and many of the science cases described in Section 2.3 are specifically highlighted because of the need to access features in the blue, red and NIR simultaneously. However, with respect to the bluest wavelengths only, there are several important points with respect to the science:

- Blue wavelengths are particularly important for science cases in the zero-redshift Universe (i.e., **stellar astrophysics, stellar populations** in nearby galaxies, etc). This is because there are a large number of chemical species that have transitions in the UV, and the fact that cosmic expansion has not redshifted these features. For stellar population studies, some key features accessible at intermediate resolution include:

    - HI Balmer series (3835, 3880, 3970, 4101, 4304A)
    - CaII H&K (3933, 3968A)
    - CN band (3883A)
    - CH band (4320A)

- In objects in the **Outer Solar System**, the optical gap feature is centred in the UV at ~0.39 μm. The location and profile of the optical gap absorption depends critically on the structure of the hydrocarbon chain; laboratory work on PAHs has revealed small absorption bands in the ~0.35-0.4 μm range, and these features have been tentatively associated with the vibration mode splitting of the optical gap centre. There is the potential for much new science and discovery in this field if MOVIES is able to access this wavelength range, which clearly holds much structural and compositional information.

- For extragalactic science, a science area not described in Section 2.3 for which we can expect MOVIES to be useful is in the study of the **Intergalactic Medium** i.e., using intervening gas clouds along sight lines to galaxies to probe the chemistry of the Universe as a function of redshift. Here, blue coverage is particularly useful in its ability to pick up metal lines in gas clouds at low redshift. However, to be most useful requires very blue coverage, as the addition of a few 10s of nanometers make little qualitative difference (Lyman-alpha at z=2.125 has a wavelength of 380nm, and going to 360nm corresponds to Lyman-alpha at z=1.96)

3.3.1.3 Other considerations

There are a number of additional technical constraints concerning blue throughput at Gemini. In particular, the Gemini mirrors all have silver coatings. The reflectivity curve for silver, taken from the Gemini webpages, is shown in Figure 24. While silver is an excellent choice for Gemini giving very broad reflectivity across the OIR range (and therefore playing to the strength of MOVIES), the reflectivity of silver decreases sharply shortward of 400nm. In general, light will undergo three such reflections before entering the MOVIES system (primary, secondary and science fold, although the latter may not be necessary if MOVIES is placed on the up-looking port of the ISS). The overall transmission of the Gemini telescope is therefore given by the cube of the reflectivity data for silver, which is also shown in Figure 24.

In addition to the transmission of the Gemini telescopes, the atmospheric extinction at an airmass of 1.2 is also shown in Figure 24. Again, this curve makes pushing into the blue difficult.

There are occasional rumors that suggest Gemini may one day consider changing the coatings on their mirrors to aluminium or some other broad band coating with enhanced reflectivity shortward of 400nm. However, in keeping with the design philosophy of MOVIES to be a practical and robust instrument, and in keeping with instructions from Gemini to not expect any changes to the telescope in its current configuration, we choose to optimise the design of MOVIES given the current, knowable, performance of the Gemini Observatories.

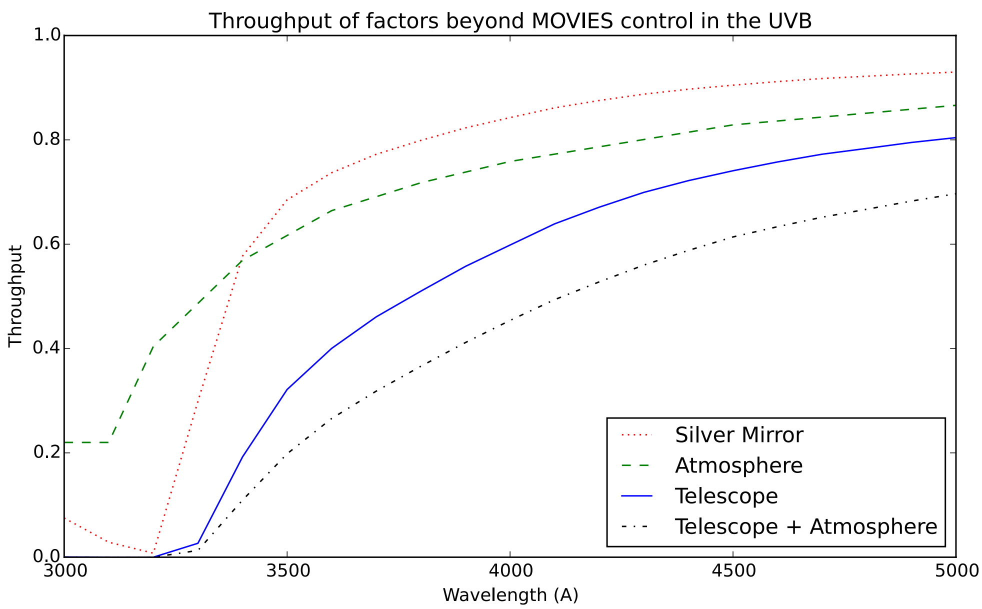

Figure 24: The dotted line shows the reflectivity of silver as a function of wavelength. The Gemini telescope throughput is modelled as three silver reflections (primary, secondary, science-fold) and is shown as the solid line. The atmospheric extinction at an airmass of 1.2 is shown as the dashed line. The overall throughput of the atmosphere+telescope (i.e., factors that cannot be controlled that affect the overall efficiency of MOVIES is shown as the dot-dashed line.

3.3.1.4 Conclusions

Pushing the throughput of MOVIES shortward of 360nm was **rejected**. This is based on

- the limited science case (as it pertains to science topics that otherwise require a very broad wavelength coverage)
- the impracticalities of adding a third arm to MOVIES
- diminishing gains; the environmental difficulties of getting good throughput at these wavelengths given the increasing atmospheric extinction and rapidly diminishing reflectivity of the Gemini telescopes

Making the wavelength range requirement of MOVIES to be REQ-SCI-001: 0.36 – 2.45um (changing from 0.4 – 2.45um) was **approved**. This is based on

- The significant number of scientifically interesting features that are accessible in this region that strengthens several of the MOVIES science cases
- The utility of the MOVIES optical design to access the region 0.36 – 0.4um
- The range of practical options that exist to get good throughput across the full range covered by the optical arm of the MOVIES spectrograph

3.3.2 The suitability of GCAL for MOVIES calibration

Robust and repeatable calibration is essential to the successful science exploitation of MOVIES. For high efficiency, the ability to conduct daytime calibrations is particularly important to remove overheads during the night. This study focused on the determination of the suitability of GCAL for providing the necessary calibration observations, with the alternative being the inclusion of a dedicated calibration module for MOVIES.

An overview of the science calibration measurements required for MOVIES can be found in Section 2.5.4. Here, we focus on the suitability of GCAL to provide the daily calibration exposures. Night-time calibrations (e.g., spectroscopic skyflats, radial velocity/telluric/spectrophotometric standards) are obtained independent of the calibration module and are not discussed here. We reiterate that MOVIES is a relatively standard spectrograph, and no unusual calibration exposures are anticipated.

3.3.2.1 Required calibration exposures

The required calibration exposures for MOVIES that the calibration unit should provide include:

- **Imaging: Mandatory**
  - **Bias (VIS):** CCD bias properties
  - **Darks (NIR)**: bad pixel map
  - **Flats (VIS & NIR):** pixel-to-pixel variations

- **Spectroscopy: Mandatory**
  - **Bias (VIS):** CCD bias properties
  - **Darks (NIR)**: bad pixel map
  - **Slit flats (VIS & NIR):** pixel-to-pixel variations, blaze function correction
  - **Slit arcs (VIS & NIR):** spectral resolution, wavelength calibration, and wavelength shift between multi-pinholes and slits (see below).

The spectral format for MOVIES is reasonably complex, with curved echellogram orders, variable line tilt, and more importantly, variable dispersion and spatial scale along each order. In order to calibrate the spatial scale variation a slit arc may not be sufficient (a single slit height measurement usually provides insufficient accuracy), and therefore a multi-pinhole mask is desirable. VLT/X-shooter, for example, uses a dedicated mask with 9 equidistant pinholes forming a pseudo-slit, which is illuminated by a ThAr lamp. Consequently, the following exposures are highly desirable to obtain:

- **Spectroscopy: Highly desirable**
  - **Multi-pinhole flats (VIS & NIR)**:, order localization, and multi-order definition
  - **Multi-pinhole arcs (VIS & NIR)**: first guess of dispersion solution and spectral format check; wavelength and spatial scale determination/calibration

3.3.2.2 GCAL in Gemini

GCAL provides continuum and line emission light sources for wavelength and flat-field calibrations. Each GCAL is located permanently on one port of the instrument support structure, and light is directed into the instrument by the science fold mirror. The GCAL optics simulates the f/16 telescope beam, illuminating the instrument pupil in the same way as light from an astronomical source. A reflector/diffuser unit replaces the integrating sphere more normally found in calibration systems. As with an integrating sphere, the diffuser removes structure from the image to provide a uniform beam over small spatial scales, but the efficiency of this system is an order of magnitude greater than for an integrating sphere.

Lamps

The available line and continuum lamps are:

- Arc lines:
    - Ar and Xe (replaced Kr lamp and has higher line density) for NIR.
    - CuAr for low and medium resolution optical, and ThAr for high resolution optical spectra (up to R ~ 50,000).
- Continuum:
    - Quartz halogen (QH) for optical and NIR flats.
    - Grey Body (1100 K) for NIR flats.

As per the GCAL Interface Control Document (ICD), the illumination system allows more than one arc lamp to be used simultaneously.

Filters

A single eight-position filter wheel with neutral density (ND) and color balance (CB) filters is available in the GCAL unit for flux attenuation and for flux gradients reduction of the QH lamp. Filters include ND1.0, ND2.0, ND3.0, ND4.0, ND4-5, GMOS CB and NIR CB. This range of neutral density filters will prevent observations from 300 nm to 2500 nm from saturating.

Diffusers

Visible and IR diffusers are provided. According to Ramsay et al. (2000) and the GCAL documentation, either diffuser may be used with any lamp. However, their detailed pan-chromatic behavior is critical for MOVIES.

- The IR diffuser is coated with Infragold from LabSphere. The coating has a very high reflectance in the IR, but is >60% only past 550 nm--and it drops to 35% at 400 nm. Additionally, the IR diffuser features two emission lines in the optical (approximate wavelengths 692.7 and 694.2 nm) that may affect flats, and is therefore not ideal for MOVIES.

- The VIS diffuser is coated with OP.DI.MA, a synthetic material from Gigahertz-Optik. The specifications indicate >90% reflectance in the 250-2500 nm range. The behavior of the visible diffuser in the IR was further investigated by Rubén Díaz (Gemini) at our request. A comparison between flats taken with the visible and IR diffusers indicates that the VIS diffuser will not introduce any sharp feature in the spectral range 900 to 2000 nm. Beyond 2000 nm there is stronger variations with wavelength, with the narrowest feature being wider than 40 nm.

- If one of the diffusers has to be replaced by another with smoother reflectance through spectral range of interested for MOVIES, the Spectralon coating from LabSphere looks like an ideal candidate. According to the manufacturer, it "gives the highest diffuse reflectance of any known material or coating over the UV-VIS-NIR region of the spectrum. The reflectance is generally >99% over a range from 400 to 1500 nm, and >95% from 250 to 2500 nm."

Intensity stability

The intensity stability of the Grey Body source reflects the stability of the power supply and is expected to be +/-1%. The intensity stability of the QH lamp (from the manufacturers' specification) is +/-0.4% rms.

Output beam stability

The original instrument requirement states that the output beam should be flat with a monotonic roll-off in intensity of <10% to the edge of the 7' diameter field, and that variations over the 3' field should be 1%. To achieve a flatter beam than this requires calibration of the GCAL against the sky with each of the instruments.

3.3.2.3 GCAL suitability: a comparative analysis

The calibration requirements of MOVIES (in terms of the exposures described earlier in this section) are very similar to those of VLT/X-shooter. Its calibration unit at the VLT contains the following elements:

- Ar, Hg, Ne and Xe Penray lamps operating simultaneously for wavelength calibration;
- A wavelength calibration hollow cathode ThAr lamp;
- Three flat-field halogen lamps equipped with different balancing filters to optimize the spectral energy distribution for each arm;
- A D_2 lamp for flat-fielding the bluest part of the UV-Blue spectral range ($\lambda < 350$ nm).

Compared to these components, GCAL differs in:

- The D_2 lamp, but this is obviously not needed since MOVIES does not observe in the $\lambda < 350$ nm wavelength range. However, GCAL can be used to calibrate instruments in the 300-5000 nm wavelength range. According to investigations by

Rubén Díaz (Gemini), the spectroscopic flats reach 350 nm, with enough signal in typical exposure times of 4-8 seconds for 1 arcsec slit and B600-B1200 gratings, respectively.

- The optical arc lamp combination. However, the existing CuAr lamp seems to provide sufficiently dense spectral sampling and intensity in the 400-1000 nm wavelength range.

From this comparison, we conclude that GCAL has the necessary lamps to provide suitable calibration exposures for MOVIES, and the tests by Rubén Díaz suggest that GCAL performs “as advertised”, at least in relation to spectroscopic flats, ensuring these exposures can be obtained efficiently with the existing set-up.

As a result of this study, the baseline version of MOVIES does not include its own calibration unit; MOVIES is designed to use, and not limited by, GCAL.

3.3.3 Optimization of the acquisition system for MOVIES

The purpose of this study is to determine the optimal acquisition system to enable new science with MOVIES and ensure that it can fulfill the role of a workhorse spectrograph for the Gemini community. Note that at the proposal phase (prior to the initiation of the Feasibility Study) MOVIES was envisioned to have two acquisition cameras (an optical camera and a NIR camera), each with a 2 x 2 arcmin field of view.

The acquisition procedure for MOVIES – derived as part of this study – is described in Section 2.5.3. Here, we focus instead on the decision regarding the number (and bandwidth) of acquisition arms, and the field of view of each camera.

3.3.3.1 Science considerations

There are three main science considerations with respect to the number and bandwidths of the acquisition cameras.

Simultaneous imaging

The primary purpose of MOVIES is spectroscopy. However, the acquisition camera(s) provide a significant science imaging capability in their own right, and there is a clear efficiency gain in doing two bands simultaneously. There are multiple science drivers for MOVIES that make full use of imaging capabilities, as described in Section 2.3.

Unsurprisingly, the addition of a third camera will increase the imaging efficiency of MOVIES even more. This increase is not trivial. As is described in Section2.3, color-color diagrams are powerful tools for SED characterization and object identification and require a minimum of three filters. They are particularly powerful tools when using a long baseline i.e., optical and NIR colors are preferred. To enable efficient execution of this science case requires a third acquisition camera. This also means that MOVIES will be a powerful tool for both the preselection of targets through color-color analysis and their subsequent spectroscopic observation.

Spectrophotometry

As described in detail in Section 2.3, accurate spectrophotometry is essential both to combine together the spectra in each of the two arms of the spectrograph, but also to enable compositional analyses of Solar System bodies with broad absorption features that span much of the OIR spectrum. Quasi-simultaneous imaging of the target is therefore necessary in order to normalize the observed spectra in the appropriate passbands. In addition, transit spectroscopy of exolanets requires precision monitoring of atmospheric conditions to record changes in sky transparency and other systematic effects; here, simultaneous monitoring of sources in the field using the imaging cameras of MOVIES is essential and has the potential to be a defining field of research for MOVIES.

Given the significant variations in the response of the atmosphere, telescope, spectrograph optics and detectors across the optical bandpass, but in particular at the bluer end of the spectrum, two optical bands that can provide simultaneous imaging is clearly advantageous to those programs that require precision spectrophotometry (as described by REQ-SCI-008).

Acquisition

MOVIES is optimized for observations of unknown, transient phenomena. Many of these objects may not have precise astrometry available (e.g. Swift GRB alerts). Direct imaging of these sources prior to centering on the slit is therefore advantageous. Further, rapid acquisition helps increase the efficiency of observing even for "workhorse" applications, independent of time-variable phenomena.

As described earlier, multiple acquisition cameras working in different passbands helps to ensure that at least one of the acquisition cameras is close(r) to the peak of the SED of the target, and therefore will be able to image it with reasonable SNR in a reasonable time, to verify its position, to record its luminosity, and to center it in the slit. In the high redshift Universe, for example, a i-band drop-out galaxy will be impossible to acquire if the optical camera(s) were it only operating in the g-band.

3.3.3.2 Sky Coverage Considerations

It is a high level science requirement (REQ-SCI-005) that the A&G module for MOVIES have sky coverage of at least 90%. This is driven by the need for it to be a workhorse instrument, and so be able to acquire targets anywhere in the sky.

The original baseline design for MOVIES had 2 acquisition cameras, each with a 2 x 2 arcmin field of view. While large, this means that the area inside of which we are able to selection guide stars (in our case, the field of view) has a modest field with respect to the Gemini PWFS (in its case, an arm which can reach within an annulus spanning a radius from about a 5 to 7 arcmin). We therefore carefully studied the accessibility of suitable guide stars for the MOVIES A&G system.

Using the ETC described earlier, Figure 25 shows the SNR as a function of magnitude for a 0.05s exposure of the acquisition camera i.e., a frame rate of 20Hz, of order the cadence with which to determine appropriate corrections to M2 for acceptable guiding and tip/tilt corrections. Given a seeing of 0.7 arcsec, a SNR=5 – 10 is required in order to calculate the center of the star to an accuracy of FWHM/SNR~0.07 – 0.14; this accuracy corresponds to ~0.1 x slit width for a nominal slit width of 1 arcsec. From Figure 25, this implies that we can guide using stars that have an AB magnitude of 19 – 20 magnitude in the optical, and 17.5 – 18 magnitude in the NIR (J,H bands).

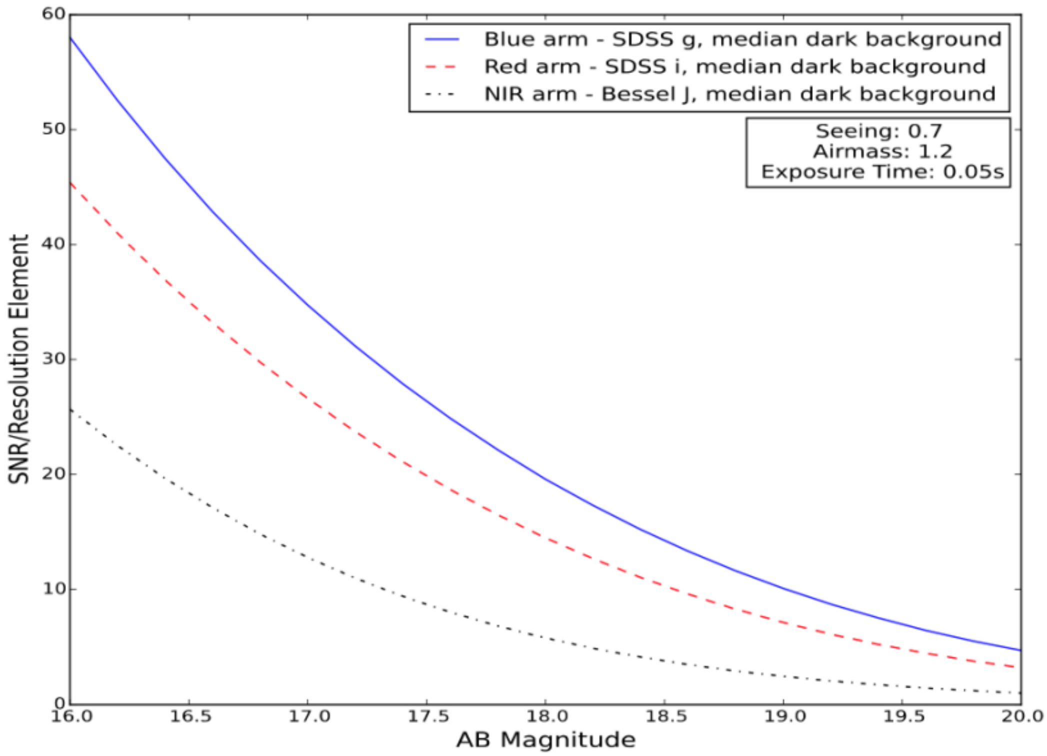

Figure 25: SNR as a function of magnitude for the three acquisition cameras working in the g, i and J bands, in a 0.05s exposure (i.e., operating at 20Hz).

To determine the resulting sky coverage of MOVIES, we proceeded to analyze point sources in the GSC2 and 2MASS catalogues; these were selected for their overall completeness in the visible and near-infrared respectively to relatively faint magnitudes, thus providing suitable catalogs for guide star collection. We generated 2 x 10^6 coordinates uniformly distributed on the surface of a unit sphere. These are taken to be random target coordinates in Galactic longitude/latitude for MOVIES. We then used the VizieR catalogue access tool maintained by the CDS in Strasbourg, France in order to find all stars in the GCS2 and 2MASS catalogs within a square field centered on these coordinates, with a size matching the acquisition cameras. From this, we then determined the fraction of fields as a function of Galactic latitude that had at least 1 star brighter than 20 mag in the optical and/or brighter than ~18 mag in the NIR; this is the nominal sensitivity of the acquisition cameras @ 20 Hz. Figure 26 shows the sky coverage of MOVIES in the optical and NIR separately, and also the combined sky coverage based upon the 2MASS and GSC catalogs. Note that nearly all sources in 2MASS are brighter than J=18 (survey completeness limit of J=15.8[10].

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[10] http://www.ipac.caltech.edu/2mass/releases/allsky

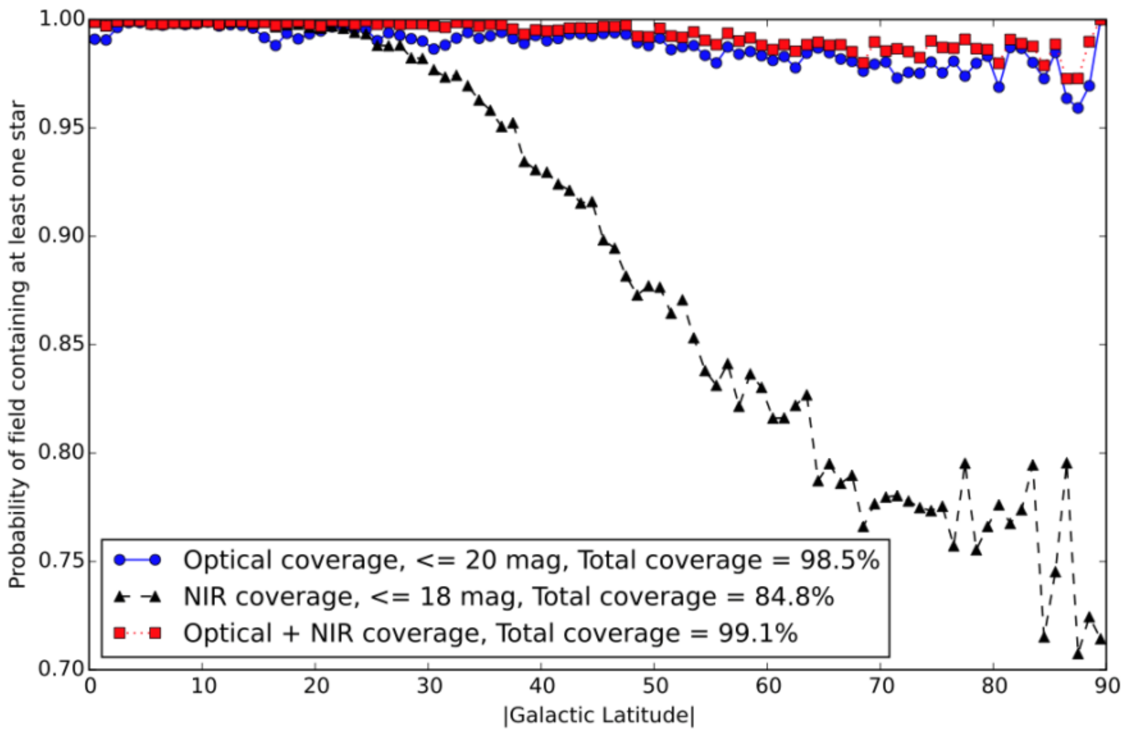


Figure 26: Sky coverage as a function of Galactic latitude in the optical and NIR using GSC2 and 2MASS to select suitable guide stars (brighter than 20 mag in the optical and brighter than 18 mag in the NIR). The total sky coverage is given in the key.

While it appears from Figure 26 that the NIR band does not increase the sky coverage significantly, we note that the 2MASS catalog is flux limited at magnitudes brighter than the nominal 20Hz depth of the NIR acquisition arm. However, even without including the NIR, the overall sky coverage of MOVIES, is anticipated to be close to 99%, safely exceeding the requirement stated in REQ-SCI-005 (90%).

During this calculation, it was determined that the sky coverage of MOVIES could be increased marginally by increasing the field of view of the optical cameras while still maintaining critical sampling of the PSF for detectors of the same physical size. Thus, the results of the calculation shown in Figure 26 corresponds to optical and NIR guide cameras that are 3 x 3 arcmins, These have a pixel scale of 0.18 arcsec, ensuring good sampling even for very good conditions.

3.3.3.3 Packaging

The addition of a third acquisition arm makes sense from a scientific and calibration perspective. However, volume and mass is required to realize a third arm, and this is particularly important since there is a well-defined volume/mass budget for MOVIES as a result of the instrument being mounted on the ISS. However, the packaging solution developed for MOVIES and discussed in Section 3.8.8 provides ample room for a third acquisition arm. This is shown explicitly in Figure 43.

3.3.3.4 Summary of Acquisition System

As a result of this study, the functionality of the acquisition and guiding system for MOVIES consists of:

- An optical arm working at blue wavelengths (ug) with a 3 x 3 arcminute field of view;
- An optical arm working at red wavelengths (riz) with a 3 x 3 arcminute field of view;
- A near infrared arm working at yJH wavelengths with a 3 x 3 arcminute field of view.

In addition to the filters stated, each arm will also have at least one empty slot in the filter wheel to be used to maximize the flux hitting the cameras.

3.3.4 EMCCDs versus classical CCD comparison

This section offers a comparison between a ”classical” CCD and the frame transfer UdeM EMCCD. Large format EMCCDs are discussed from an operational perspective in Section 2.5.6. This section focuses on more technical aspects, in particular on developing an understanding of the scenarios in which EMCCDs provide a significant sensitivity gain over standard CCDs for studies of faint objects (a primary driver for MOVIES).

Three are a number of unique aspects of EMCCDs and the way that they are operated that must be considered when comparing them to classical CCDs. For a short tutorial on EMCCDs that explains these aspects and provides definitions of terms such as excess noise factor and clock-induced charge, please visit http://www.nuvucameras.com/emccd-tutorial/.

A technical comparison between the UdeM EMCCD and a classical CCD is given in Table 6.

Table 6: EMCCD vs CCD

Quantity	EMCCD	Classical CCD	Notes and explanations
Effective readout noise	~10^{-3} e-	2-5 e-	For the EMCCD, this is not a true readout noise, but clock-induced charges. CICs behave as readout noise
Readout overhead	<10^{-3}s	>10s	The EMCCD readout takes0.25s, but this is performed in a different part of the array that is not light-sensitive. This readout does not lead to observational overheads.
Typical frame rate	0.25s	>1 minute	Faster rates possible for smaller arrays or subarrays
Effective readout noise for 5 minute exposures	<1.2 e-	2-5 e-	We assume the maximum frame rate (0.25s) for the EMCCD, which is a worst-case scenario. One could decrease the frame rate to, say, 1s and get a much lower effective readout noise.
Relative photon detection efficiency	~91%		For the EMCCD in photon-counting mode, a fraction of photons are missed due to thresholding in the detection method. This number can be

			raised slightly at the cost of increasing the effective readout noise.
Relative photon detection efficiency for 5 min exposure		95%	We assume a 15s readout overhead for the classical CCD
Bright target readout noise	7-10e-	2-5 e-	For bright targets that would saturate the EMCCD at high gain, the gain can be decreased to 1 and the frame rate decreased to reach a readout noise close to that of classical CCDs
Bright/faint regime limit for MOVIES	g~19-20		This is strongly dependent on the instrumental design

3.3.4.1 *Classic CCD vs EMCCD Scenarios*

In order to assess the impact of reduced readout noise on spectroscopic observations, we defined 3 observation scenarios and computed the gain and losses in signal-to-noise ratio and observing efficiency for targets ranging from g_{sdss}=16 to 26. The 3 scenarios represent a short visit (5 minutes open shutter), a typical visit (1 hour open shutter) and a long visit for a faint target (4 hours open shutter). In all cases the EMCCD provides much improved performances for fainter (*g*>20) targets. For intermediate flux targets (> 1 photon/EMCCD frame), a classical CCD would provide better performances, as it is not impacted by the excess noise factor. One can alleviate this problem in large part by reducing the gain of the EMCCD to 1, which removes the excess noise but leads to a larger readout noise than for a standard CCD. This additional readout noise is not detrimental to the observation of bright targets (>100 e-/pixel/frame).

The comparison with a classical CCD is done assuming that we would use a 2048x4096 CCD with 3 e- readout noise and 21s readout overhead. This corresponds to the CCD42-90 from e2v (http://www.e2v.com/resources/account/download-datasheet/1228) operated at 200 kHz (see page 3 of that document). Table 7 lists the assumptions made in determining the signal and noise budgets for the 3 scenarios described here (using two different EMCCD frame rates). These assumptions are consistent with the notional MOVIES design at R=10 000.

Pixel scale	0.125 arcsec
Slit width	0.50”
Width of the extraction box	0.6”
Overall throughput including slit and extraction box losses	15%
EMCCD CIC	0.001 e-/frame
Standard CCD readout noise	3 e-
EMCCD readout noise with gain=1	10 e-
Readout overhead for CCD	20.9s
Efficiency loss due to EMCCD thresholding	10%
Sky background[11]	0.15 photon/s/nm/arcsec^2/m^2
Resolution	10 000
Bandpass	g_{sdss}

Table 7: Strawman MOVIES design with and without EMCCD

[11] Values taken from : https://www.eso.org/observing/etc/bin/gen/form?INS.MODE=swspectr+INS.NAME=SKYCALC ; no moon, airmass=1.15, heliocentric-ecliptic lat=135, long=90

3.3.4.2 First observing scenario: short visit on a target of unknown brightness.

Sub-case 1

- Open-shutter time: 300s
- Frame-time for CCD: 60s, EMCCD frame rate : 0.5 Hz

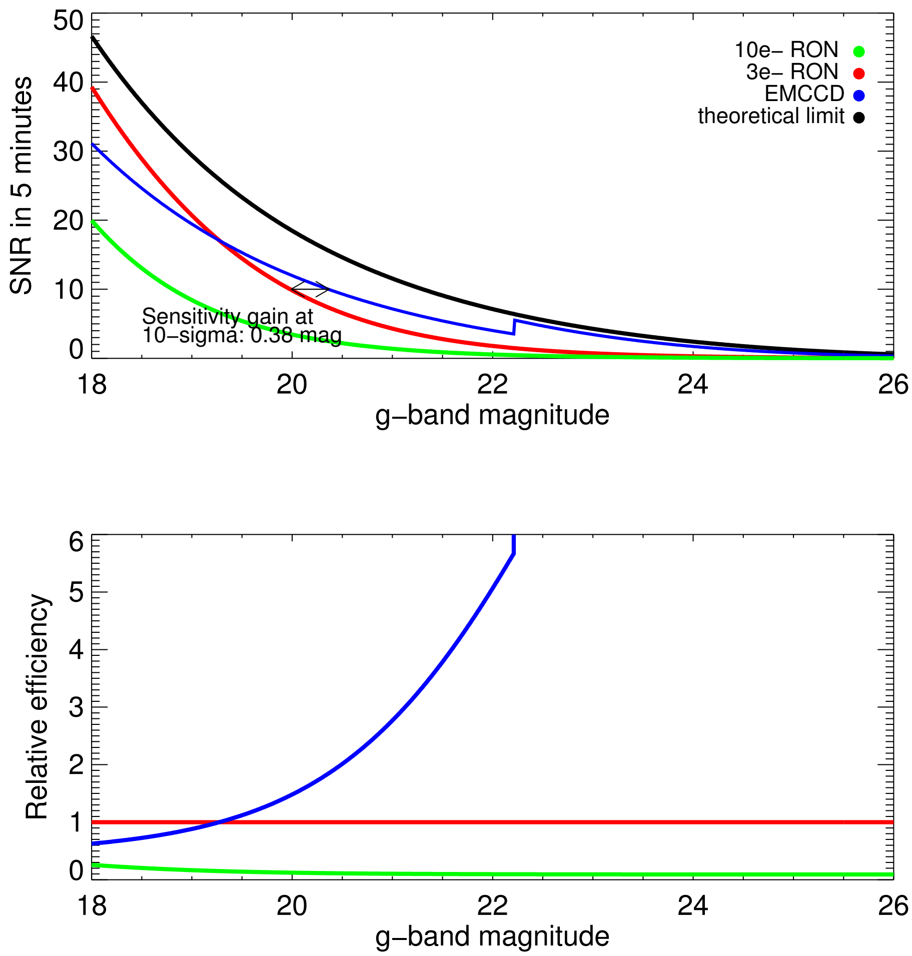
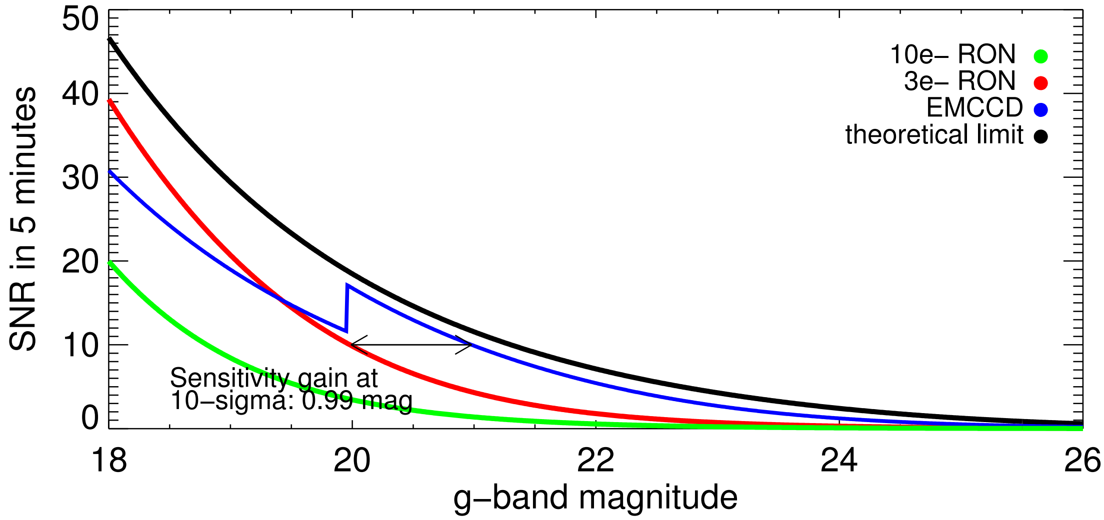


Figure 27: [Top] Signal-to-noise ratio for targets between g_{sdss}=18 and 26 for the strawman MOVIES design. The black curve illustrates the best-case scenario where all photons reaching the detector would be detected, and where only sky and target Poisson noise are present. The blue curve represents the EMCCD, including the efficiency losses due to thresholding and clock-induced charges. The loss in efficiency around g~22 arises from the transition between a photon-counting regime (i.e., <0.3 photon/pixel/frame) and a multi-photon-per-frame regime with excess noise due to the uncertainty on the effective gain. The red curve illustrates a standard CCD with a 3e- readout noise. The green curve represents the "bright target" mode where the EMCCD would be read with a gain of 1 and a much lower frame rate (comparable to the classical CCD). [bottom] This panel illustrates the relative observing efficiency compared to the standard CCD as a function of stellar magnitude. The 10-σ detection threshold is increased by 0.38 mag with the use of the EMCCD, but is limited by the fact that it does not operate in photon-counting mode.

Sub-case 2:

- Open-shutter time: 300s
- Frame-time for CCD: 60s, EMCCD frame rate : 4 Hz



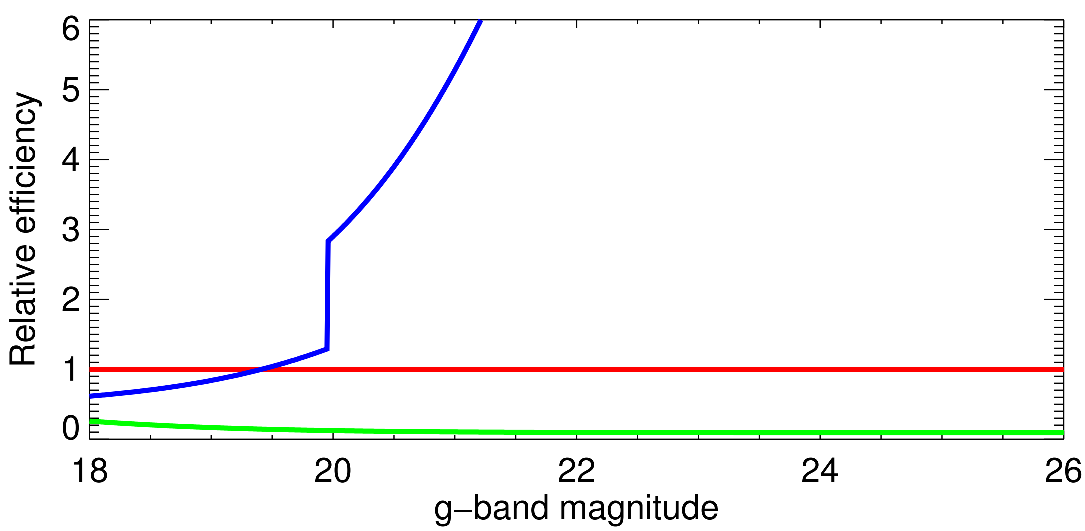
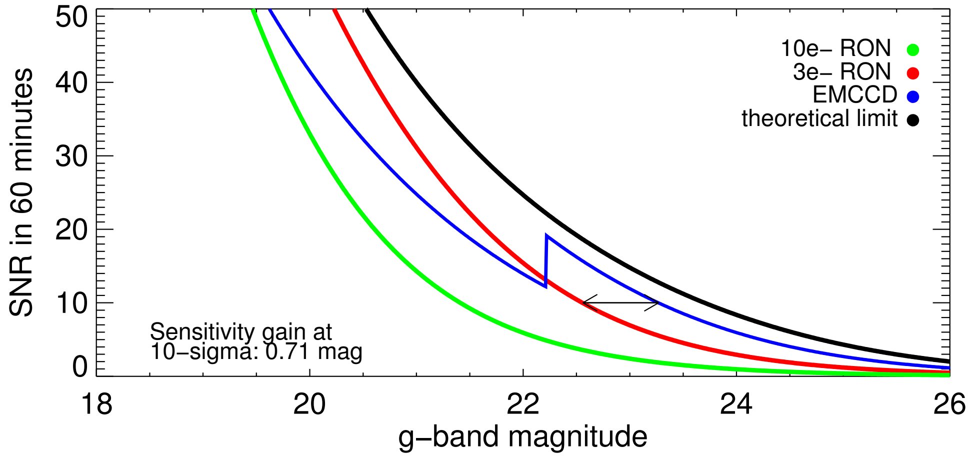


Figure 28: Same as above but with a faster EMCCD frame rate. The EMCCD reaches brighter targets in the photon-counting mode and is much more efficient for targets in the g=20-22 range than the setup with a slower frame rate shown above.

3.3.4.3 Second observing scenario: hour-long observation of a faint target.

Sub-case 1:

- Open-shutter time: 3600s
- Frame-time for CCD: 600s, EMCCD frame rate : 0.5 Hz



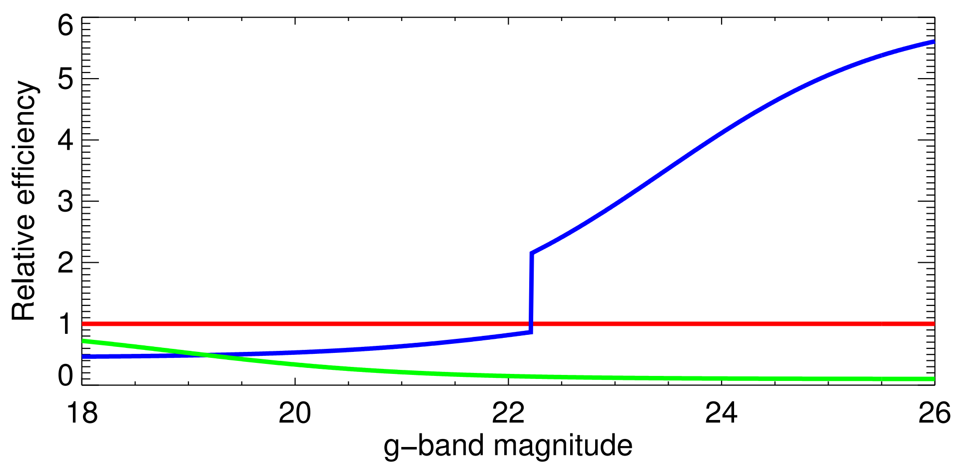


Figure 29: Same as Figure 27 for a 1-h integration. The 10-σ detection limit is improved by 0.36 mag and the gain in observing efficiency for targets close to the detection limit (~3) is a factor of >3. The time required to detect a g=24 target at an SNR of 3 is reduced from 3h to 1h.

Sub-case 2:

- Open-shutter time: 3600s
- Frame-time for CCD: 600s, EMCCD frame rate : 4 Hz

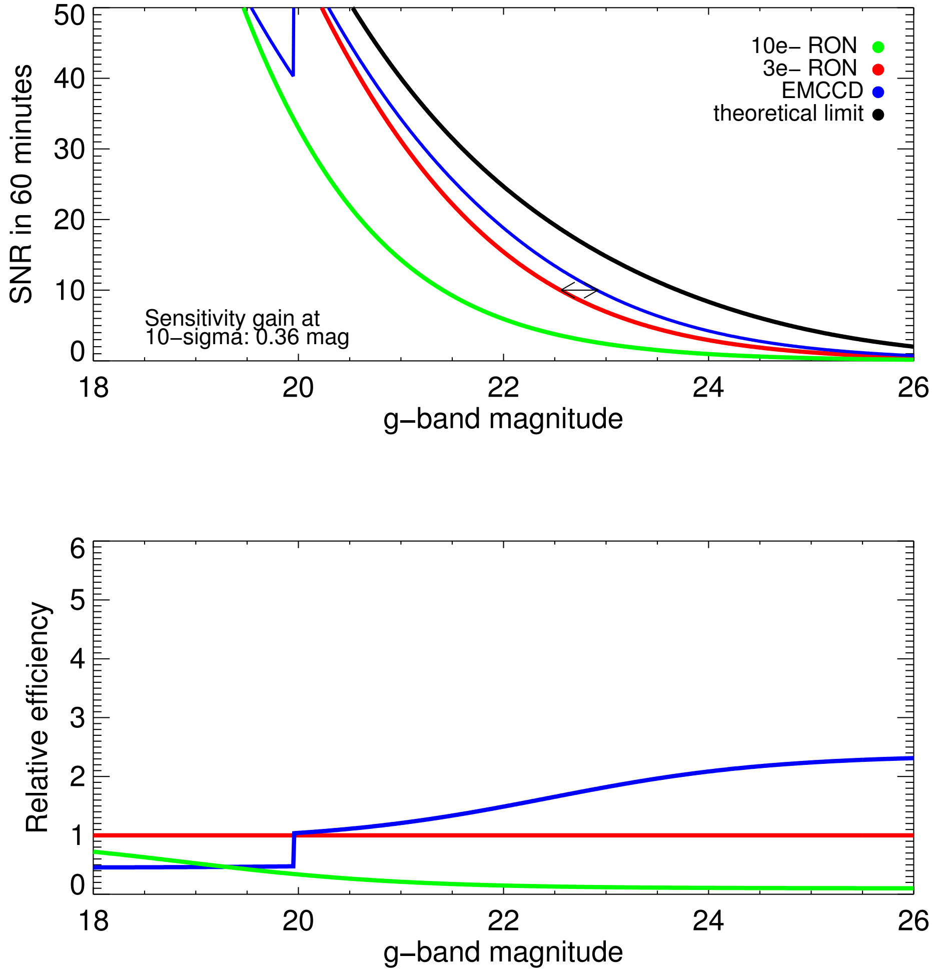


Figure 30: Same as above but at a faster frame rate. This mode can observed brighter targets but at a significant cost for faint target where the sensitivity gain compared to the 3e- CCD is much smaller.

3.3.4.4 Third observation scenario: a 4-h integration on a very faint target.

Sub-case 1:

- Open-shutter time: 4h
- Frame-time for CCD: 600s, EMCCD frame rate : 0.5 Hz

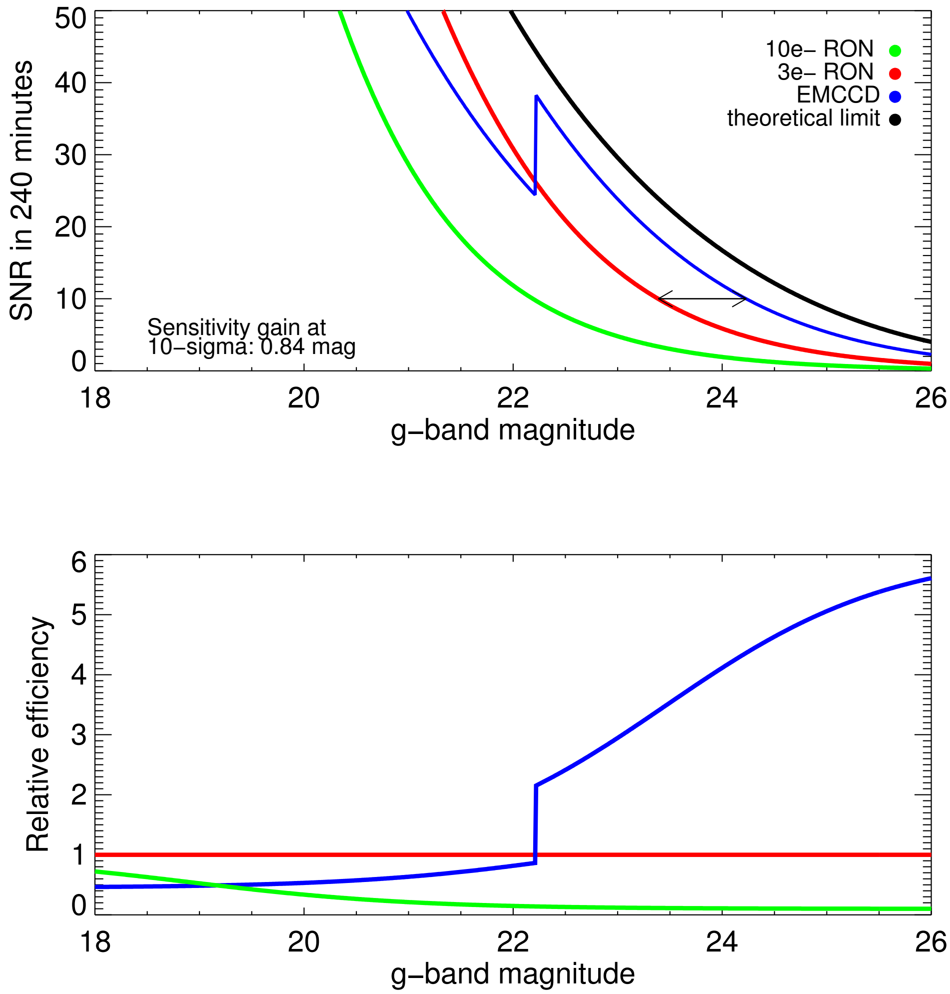


Figure 31: same as Figure 27 for a 4h integration. There is a 0.84 mag gain in sensitivity for a 10-σ detection when using an EMCCD compared to a 3 e- RON CCD. At the faint limit (i.e., g~24), MOVIES observing efficiency is increased by a factor ~4. Performing the same observation without an EMCCD would necessitate ~16h.

Sub-case 2:

- Open-shutter time: 4h
- Frame-time for CCD: 600s, EMCCD frame rate : 4 Hz

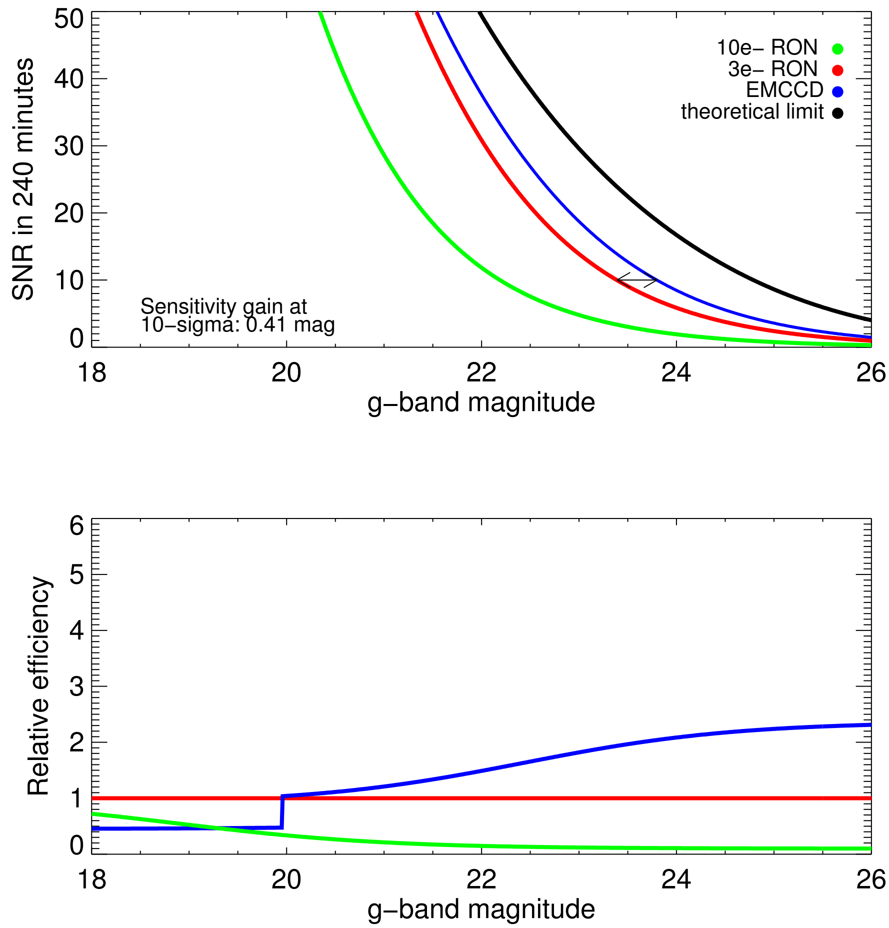


Figure 32: Same as above but with a faster frame rate for the EMCCD. As in the previous examples, there is a high cost at the faint-end in terms of sensitivity.

3.3.4.5 Conclusions

The analyses presented in this section indicate that large format EMCCDs provide a significant gain in sensitivity when dealing with faint targets. Currently, these detectors are being developed for astronomy purposes by a team lead by UdM collaborators. At present, MOVIES adopts a standard CCD as the baseline for the optical spectrograph arm. However, this decision will be revisited throughout the design of MOVIES. We believe that the gains in sensitivity at the faint end, combined with their operational advantages (discussed in Section 2.5.6) and general suitability for time domain science, means that the development of these devices should be closely monitored and their inclusion in MOVIES seriously considered when they reach a more mature state of development.

3.4 Design Overview

The design of MOVIES was predicated on the utilization of existing technology as much as possible. The innovative result is due to the combination of capabilities that are included, and the decision to minimize mechanisms and components and emphasize rapid acquisition. With a modular approach, and the open structure, it is possible to select baseline components now, and remain open to later final selections or easy upgrades as technology develops.

Figure 33 provides a schematic overview of MOVIES. Contained within a single cryostat, the sub-assemblies are readily accessible once the cryostat is open. Sub-modules can be integrated and tested in lab cryostats so as to be pre-validated.

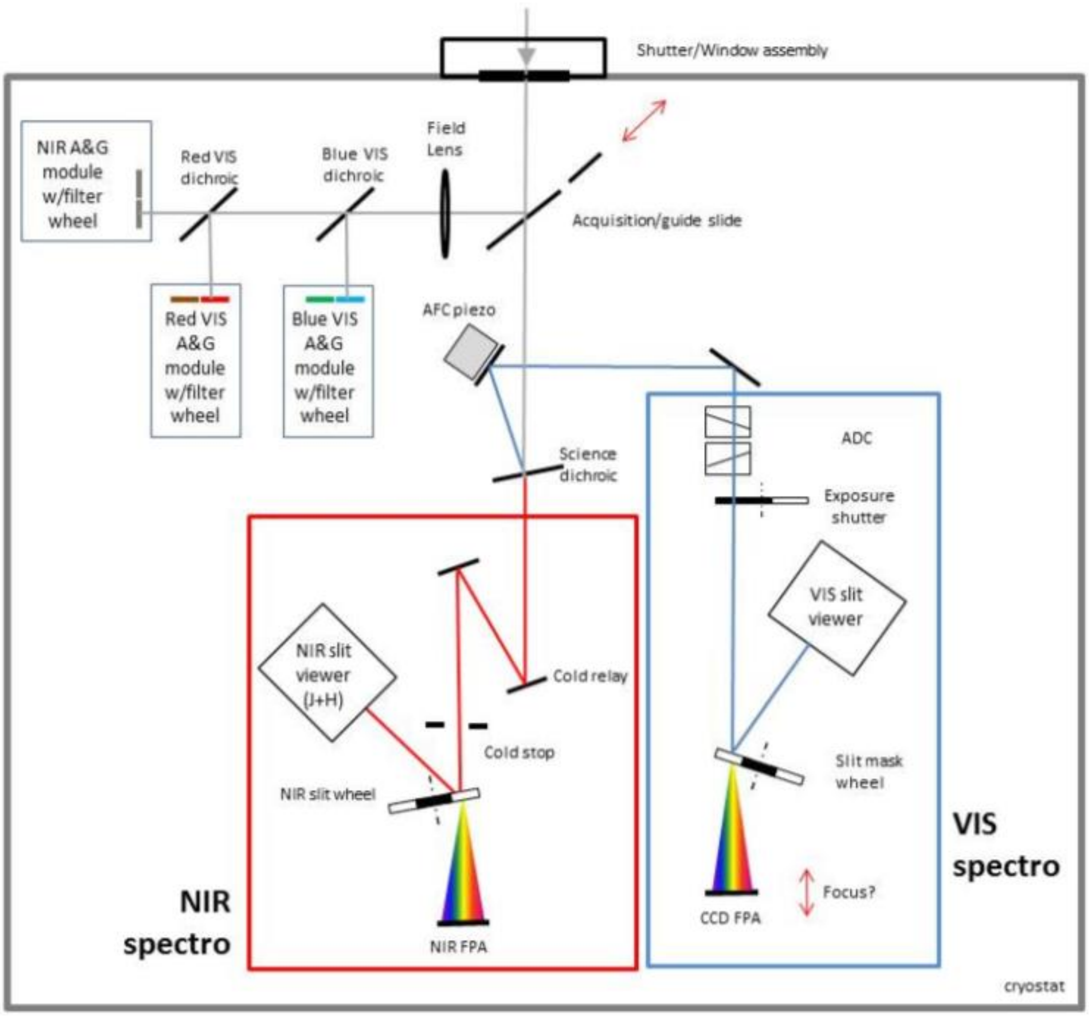


Figure 33: MOVIES design schematic (copy of Figure 1).

3.5 Optical design

The optical design has undergone only minor changes since the feasibility study proposal.

- A third acquisition/imaging channel has been added in the A&G section in order to improve the scientific returns and provide a more robust acquisition during the acquisition phase.
- The two spectrograph legs have been folded to be parallel, to accommodate the single optical bench approach that has been adopted inside a single cryostat/housing.
- An input window is now present for the initial entry into the cryostat.

3.5.1 A&G unit

After passing through the cryostat window, the A&G camera will reimage a 3x3 arcmin field of view simultaneously into three different cameras: a blue VIS channel, a red VIS channel and a NIR channel. A plate scale of 0.18 arcsec/pixel has been chosen for all bands in order to adequately, but not over, sample the seeing for acquisition, guiding and science purposes.

For the visible channels a 1024^2 pixel detector provides the full 3x3 arcmin coverage. For the IR channel, we will baseline the largest InGaAs detector available, up to 1024^2, in order to sample as much as possible of the field (there are currently a limited selection of InGaAs detectors of greater than 640x512 pixels). See Section 3.7.2 for details on the A&G cameras.

The size of the lenses has been limited to about 20 cm for the common entrance lens, while all other optical elements (doublets, triplets, single lenses) are spherical and < about 50 mm diameter. The first element, the field lens is shared between the three arms to improve packaging and drastically reduce the size of the dichroics that work at a moderate incidence angles. Figure 34 shows an unfolded layout with one channel. Image quality (80% encircle energy diameter) is less than 2 pixels on-axis, and 3 pixels off-axis, good enough for accurate target centroiding. High throughput is achieved by proper glass selection and appropriate AR coatings. The common field lens has a single quarter-wave coating able to reduce reflection losses to ~1% on average, using a Solgel coating.

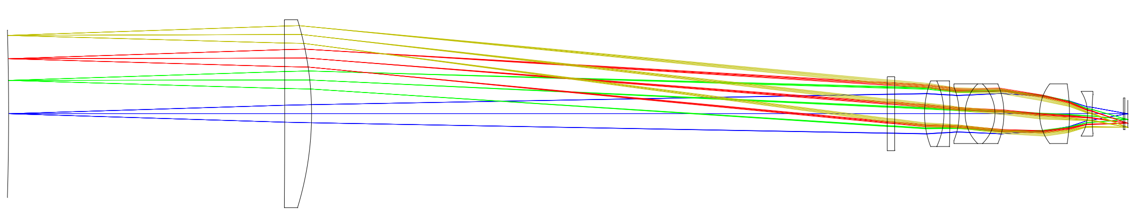


Figure 34: A&G Field Lens (without fold mirrors and single acquisition camera)

Slot	Blue VIS Camera	Red VIS Camera	NIR Camera
1	u	r	y

2	g	i	J
3	TBD	z	H
4	open	open	open

Table 8: Baseline acquisition filters sets

3.5.2 Preslit optics

When the acquisition/guide mirror is in the spectroscopic position, the telescope on-axis beam (~ 10 arcsec) continues to the dichroic. The transition wavelength will be defined between 900 and 1000 nm. Final optimization will depend on the locations of any features of science value in this region, as well as the measured values of the detector quantum efficiencies and optical throughput, in order to maximize the signal-to-noise ratio over the transition region. Leaving this transition 'soft' would facilitate data reduction by allowing matching between the two beams, and potentially allowing a higher performance dichroic by not requiring a sharp wavelength cut.

The dichroic is quite small (1" clear aperture required) and is tilted by a small angle that will enable low polarizations on both the transmitted and reflected beams. Efficiency losses are ~2% and 4% across the full bandwidth for higher throughput and reduced NIR emissivity.

The reflected beam is folded by two plano mirrors to the visible ADC. The ADC is nested between two doublets the will reimage the F/16 telescope onto the F/6.5 spectrograph entrance slit. The ADC is made by i-line glasses and it delivers a very high 97% overall throughput across the whole 360-950 nm range, including reflection losses. The last folding mirror is located at the telescope pupil image and is mounted on a active piezo stage to correct for flexures. A field lens will reimage this pupil to the spectrograph entrance pupil. The ADC will correct the atmospheric dispersion up to 65 degrees zenith angles within ±0.1 arcsec over the 360-950 nm range. The overall throughput, including the folding mirrors, the dichroic and the ADC, is about 93%.

The transmitted beam continues to the NIR spectrograph. The rear side of the dichroic is slightly powered, to remove a ghost image. Then, two mirrors will recreate an F/13.4 telescope focus on the entrance slit of the spectrograph. One mirror is spherical, and the other has some mild cylindrical power, to correct for astigmatism. A pupil is created well inside the NIR cryostat, in order to locate a cold stop to control the thermal background. The overall throughput, including the dichroic, is very high, about 96% average, thus minimizing the instrument thermal emissivity in K-band. No ADC is foreseen in the NIR arm due to the small atmospheric dispersion in the NIR.

3.5.3 Visible spectrograph

The visible spectrograph is a fixed-format, prism cross-dispersed echelle spectrograph. Its design is inspired by the successful experience of VLT/XShooter, based on the "4C" configuration (Collimator Correction of Camera Chromatism). The layout is compact, facilitating the tight volume constraints.

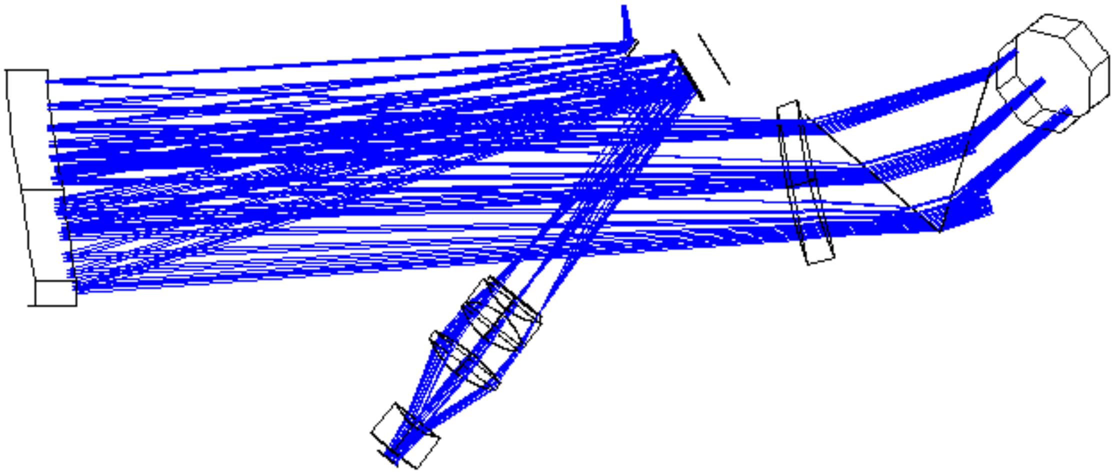


Figure 35: Optical layout of the visible arm. Light enters from above in this figure.

The spectrograph is designed to provide an R=5000 resolving power for a 1" slit width with a 100 mm collimated beam dispersed by an echelle grating. All wavelengths from 360 to 1100 nm are imaged over a 2kx4k CCD with a spectral sampling of 6 pixels at the 5000 resolution. Slit widths from 0.4" to 1.6" allow a change in resolution from 3000 to 10000, with good sampling even at the highest resolution (we anticipate the inclusion of a 5 arcsec pseudo-slit as well for transit spectroscopy and calibration). Slit height is 10" to permit efficient sky background subtraction.

A possible optimization in the future is to move the red-end coverage from 1100 nm to 1000nm and increase the order separation.

Figure 35 shows how light is processed inside the spectrograph. The entrance slit is located near the middle of the longest dimension and a small folding mirror redirects light toward the collimator (a mirror and a spherical corrector lens). Dispersion is done via the echelle grating (an existing, very high blaze efficiency, master ruling is available) and a Silica prism used in double-pass to gain in cross-dispersion power. Light is refocused back from the collimator. A pupil mirror then sends the light to the F/2.3 camera optics. Camera lenses are relatively small, the largest element having a 100 mm diameter. One aspherical lens will boost image quality to less than 2 pixels (EE80 diameter) everywhere over the echellogram. Glasses have been selected to provide very high throughput over the whole 360 – 1100nm range. The baseline coating for the mirrors will be the Denton UV350AG with, with a search for a higher efficiency dielectric coating and all lenses will have high-performance multi-layer anti-reflection coatings. The optical throughput is estimated around 65% at the echelle blaze peaks.

As the spectrograph will operate at a fixed temperature (about 80K), a focus mechanism for the detector in unlikely to be required.

At the entrance slit, a slit viewer properly centers the target onto the slit and corrects for mechanical flexures. One slit position is equipped with a mirror and auxiliary optics for pupil viewing. Active mechanisms are kept at minimum, including the slit exchange and an optical shutter.

3.5.4 Near-infrared spectrograph

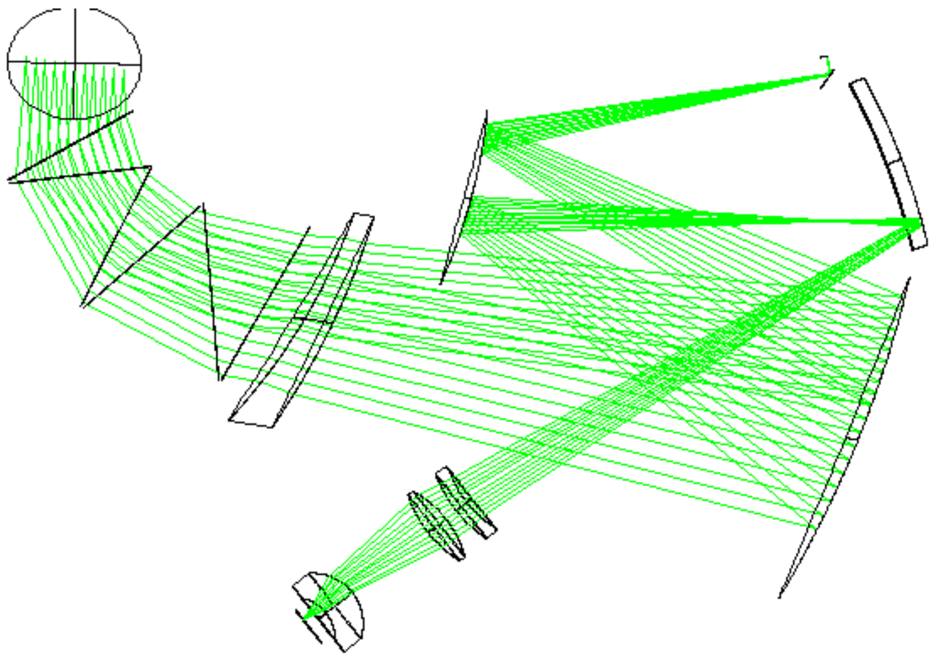


Figure 36: Optical layout of the near-infrared arm.

The NIR arm design is influenced by XShooter with design changes to extend the spectral coverage below 1µm in order to have more overlap between the visible and the NIR arms, for improved reconstruction of the cross-over region and to take advantage of the higher efficiency of the HAWAII-2RG detector and its real estate. The fixed spectral format is obtained by an echelle grating illuminated by an 85mm collimated beam and a series of 3 prisms (ZnSe and Infrasil) used in double-pass. The collimator is based on two mirrors and a spherical lens, to have a more compact layout (see Figure 36). The F/2 camera is based on three lenses only, to increase throughput and reduce ghosting. The 1" slit is sampled by 4 pixels. Image quality (EE80 diameter) is about 2 pixels. The spectral coverage is complete from 900 nm to 2450 nm without gaps. With a 10" slit height, inter-order separation is always larger than 4 pixels.

Like the visible arm, a slit viewer will be used to enable active control of target centroiding and flexure compensation. The baseline detector is a InGaAs detector covering up to the H-band. No camera focusing is required, because the spectrograph optics will be thermalized at a fixed temperature about 80K. The slit wheel is equipped with auxiliary optics to image the telescope pupil over the slit viewer detector for alignment purposes.

The NIR spectrograph and its relay optics will be hosted inside a cryostat near the center of gravity of the whole instrument. The weight of the NIR arm is estimated at ~500 kg, including cooling systems.

3.5.5 Spectral resolution and spectral sampling

Due to utilizing single, fixed, gratings, the spectral resolution and sampling are a function of only the slit width. Both arms will have the same geometrical resolution-slit product, but a selection of different slits for each arm will be selectable by the user. Spectral and spatial sampling will be different in the two arms for the same slit width, due to different pixel scales.

A plot of both resolution and sampling vs. slit width is shown in Figure 37. Resolution can vary from 3000 to 10000, being about 5000 for a 1” slit. Spectral sampling in the visible channel will be ~6.5 pixels for the same slit width, and ~4.5 pixels in the NIR channel.

A potential selection of slit widths is given in Table 9.

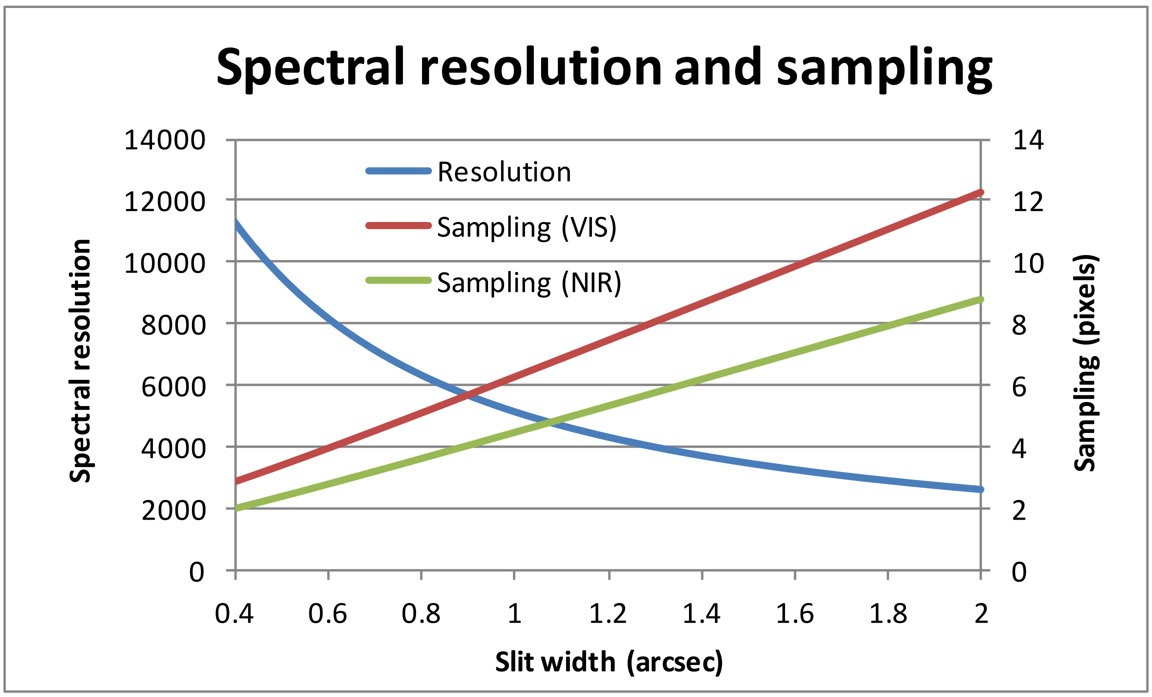


Figure 37: Resolving power and sampling for both arms as function of slit width.

Table 9: Slit wheel sets

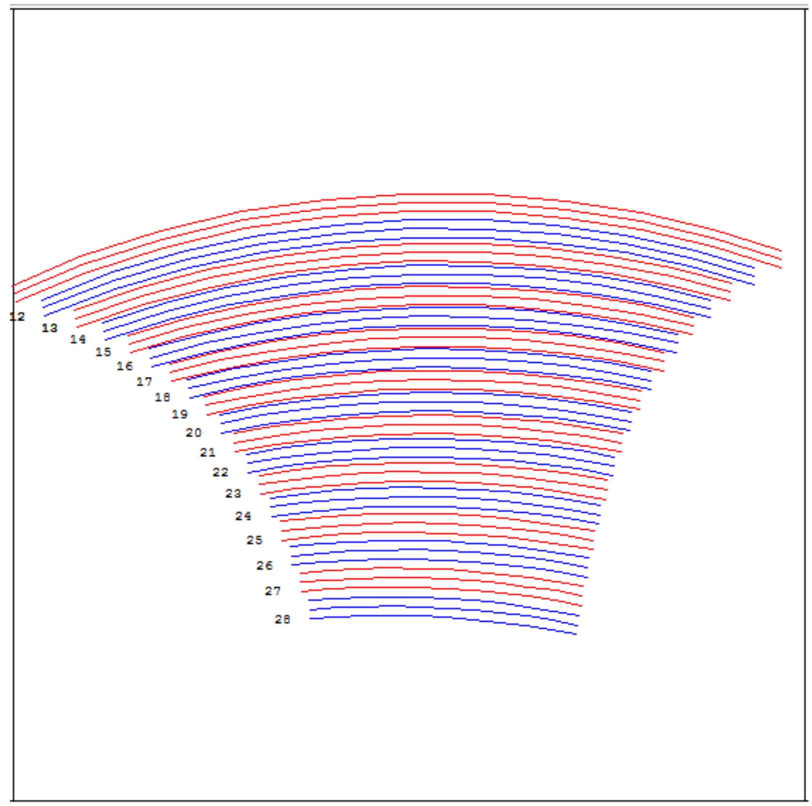
Slot	VIS Slits [arcsec]	NIR slits [arcsec]	Spectral resolution
1	0.4	0.4	11000

2	0.7	0.7	7000
3	1	1	5000
4	1.5	1.5	3500
5	2	2	2800
6	Alignment mask	Alignment mask	
7	TBD	PUPIL VIEWING LENS	
8	5	5	~1000

3.5.6 Spectral format

The visible spectrograph will cover wavelengths from 0.36 to 1.1 µm in 14 diffraction orders and the NIR spectrograph from 0.92 to 2.45 µm in 18 orders, giving a fairly large overlap between the two arms. This will allow us to optimize overall throughputs based on the as-delivered detector QEs and available dichroics, even relatively late in the project. We currently expect that the cross-over will be a soft cut between 0.90 and 0.95 microns.

The two echellograms are given in Figure 38, utilizing a 2k x 4k CCD and a 2k x 2k NIR detector. These have been generated by ray-tracing of the full optical model of each spectrograph. The minimum gap between adjacent orders is 18 pixels for the visible arm and 4 pixels in the NIR.



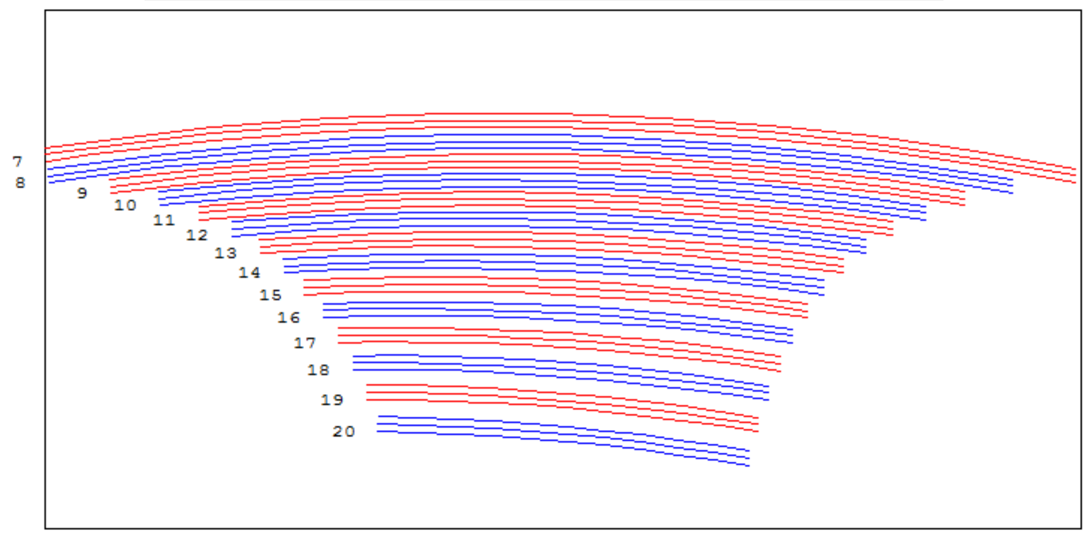


Figure 38: Visible (bottom) and NIR (top) echellograms. Boxes represent the detector area. Each order is 1 free spectral range.

3.5.7 Throughput

An overall throughput budget can be built, using state-of-the-art technologies on glass materials, reflective and anti-reflection coatings, and detector quantum efficiencies. Figure 39 shows the estimated throughput (at the blaze peaks) across the two arms, compared with VLT/XShooter, MOVIES outperforms Xshooter above ~400 nm due to its reduced optics and 2-arm configuration. XShooter performs better in the UV, due to the three-arms and the aluminum coatings of the telescope mirrors.

At red wavelengths, emissivity and sky subtraction are both major factors, along with throughput, that limits the overall sensitivity of the instrument. MOVIES will excel in these areas and so its sensitivity relative to other spectrographs will be greater than that suggested by throughput alone.

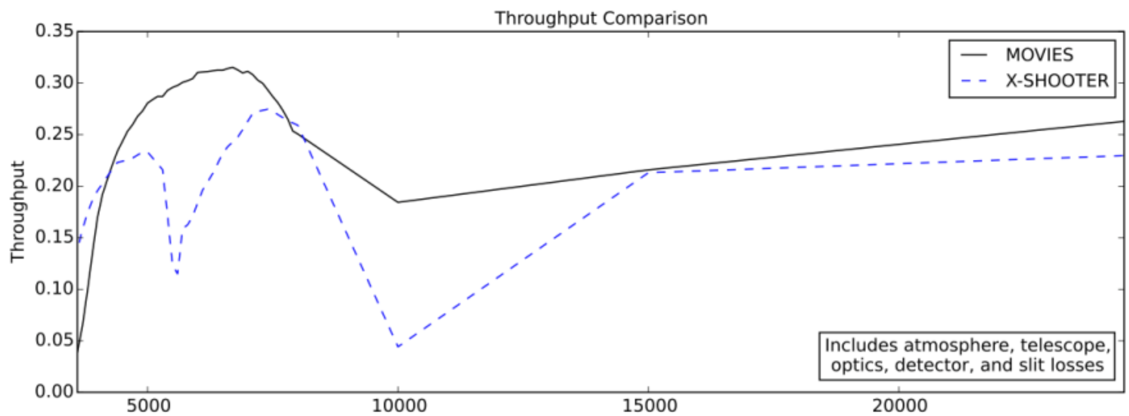


Figure 39: Overall instrument throughput including telescope optics and detector quantum efficiency, but not slit losses and atmospheric losses. This is at the blaze peak, so it represents the envelope of all echelle orders.

3.6 Mechanical design

3.6.1 MOVIES Packaging Overview

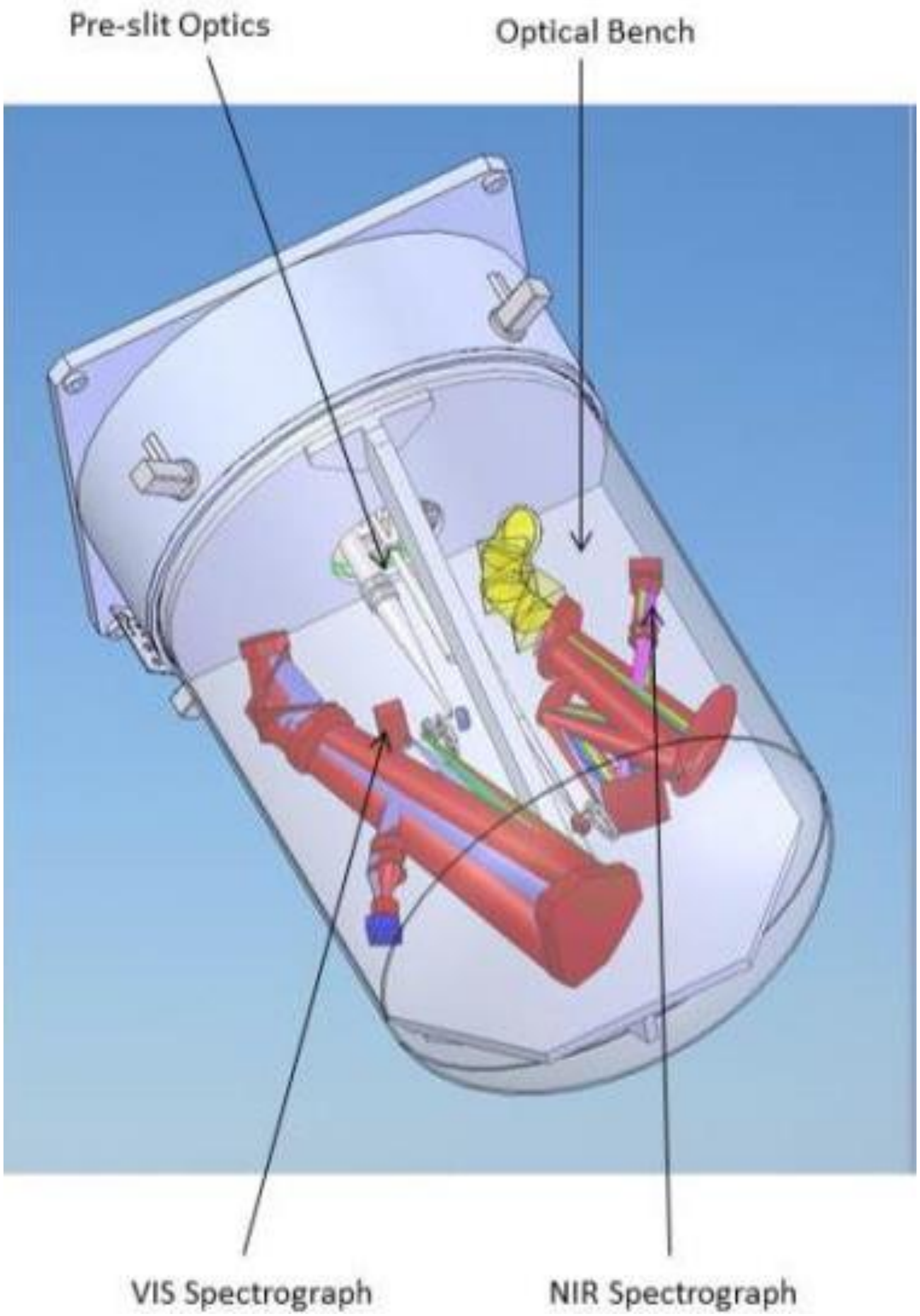


Figure 40: MOVIES packaging overview with transparent vacuum shell and window disk "TOP VIEW"

The MOVIES instrument packaging concept utilizes a single cryostat to support all 4 major modules of the instrument: the A&G module with the pickoff dichroics and three imaging cameras, the Pre-slit optics module with VIS/ADC relay and NIR relay, the VIS spectrograph, and the NIR spectrograph. The single cryostat approach results in a highly integrated instrument with many significant performance and operational advantages. The cryostat design details will use lessons learned by the OSU Imaging Science Lab (ISL) during the construction of several NIR cryogenic imagers and spectrographs[12].

Although the MOVIES cryostat is substantially larger and heavier than those previously built by OSU, the important design concepts - like the cantilevered monolithic optical bench – should scale gracefully. The structural and thermal performance of the cryostat is very amenable to accurate analysis which will mitigate risk. In addition, the techniques used and lessons learned from other large cryogenic instruments (e.g. APOGEE and SPIRou) will inform the development of the MOVIES cryostat.

It should be noted however, that the optical mounts and mechanisms are about the same size as in previous instruments, so provide no new challenges in that area.

A consequence of the large cryostat is that no components (e.g. Vacuum Shell, ISS Collar, Optical Bench) can be lifted without handling equipment. Therefore the handling equipment required to manipulate the assembled cryostat and its major removable components for laboratory development and observatory operations must be carefully defined and designed.

Figure 40 and Figure 41 illustrate the overall layout.

[12] Bruce Atwood, Thomas P. O'Brien, "Practical Considerations for LN2 Cooled, O-Ring Sealed, Vacuum Insulated Dewars for Optical and IR Detectors", Further Developments in Scientific Optical Imaging, pp. 176-181, M. Bonner Denton Ed. ISBN 0-85404-784-0

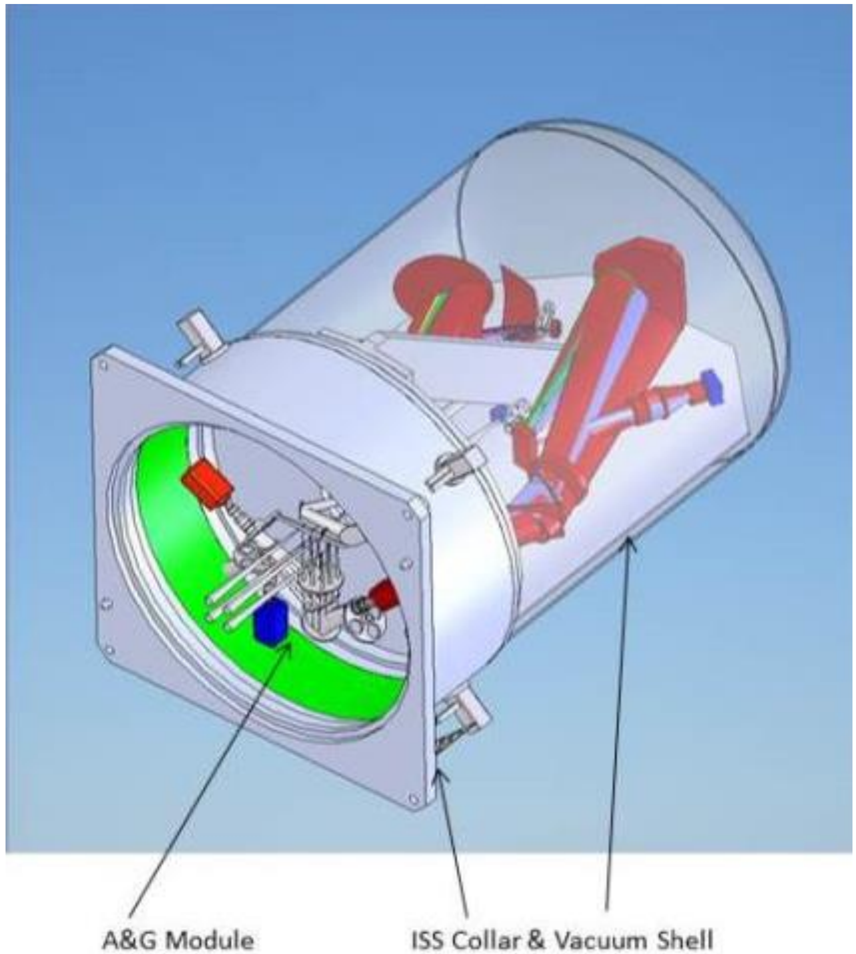


Figure 41: MOVIES packaging overview with transparent vacuum shell and window disk "FRONT VIEW"

The single cryostat encloses the aluminum optical bench onto which all instrument optics and mechanisms are mounted. This unified optical bench is extremely stiff and provides a very direct structural load path between the different sections of the instrument minimizing differential flexure. Also, the load path from the optical bench to the Gemini ISS support structure is very stiff and is nearly identical for all instrument sections.

The instrument cryostat provides an exceptionally stable thermal and mechanical environment. The temperature of the entire instrument interior will be independent of ambient conditions enhancing calibration and observational stability.

There are a total of seven detectors in the MOVIES instrument operating at a range of temperatures. All the detectors have direct thermal access to the low temperature sink of the cold optical bench. Each detector can be connected to the cold bench with a custom engineered thermal link that will establish the optimal operating temperature range for that particular detector, with a small heater for fine control. This feature of the single cryostat approach significantly simplifies the detector thermal management.

Given the very low sky and telescope thermal background levels of GEMINI, it is critical to keep instrumental sources of thermal radiation very low to fully realize the sensitivity potential of MOVIES. The single cryostat design maintains all optics after the entrance window at cryogenic temperature. This will essentially eliminate thermal background into the NIR spectrograph from difficult to baffle near-on-axis thermal emitters like dust on optical surfaces, lens and mirror cells, etc. All baffles, field stops, slits, and pupil stops will also be at cryogenic temperatures further reducing instrumental thermal background.

A consequence of this fully cryogenic design is the fact that all service access requires warmup and opening of the cryostat. This places very high reliability requirements on all system components and mechanisms. Also, all mounts for lenses, mirrors, gratings, etc. must be designed for cryogenic service. However, the A&G optics can be maintained at an intermediate "cool" temperature (e.g. -40C) to permit the use of commercial cameras if desired.

Care and attention will be required to ensure proper baffling of the relatively warm VIS spectrograph detectors from emitting radiation into the NIR arm. This will require attention, but we do not consider it a major issue.

The possibility of providing a third spectrograph arm was investigated (for the UV sensitivity). The current layout provides a compact split, in a logical cryostat volume. Incorporating a third arm would have required protruding beyond this cylinder into the side volumes. This would have required a major step up in structural components to support the third arm, and would have involved a significant volume increase in the pre-slit area. Together with the increased mass required and complexity, this option was dropped in favor of optimizing the VIS spectrograph.

3.6.2 MOVIES Opto-mechanical Modules

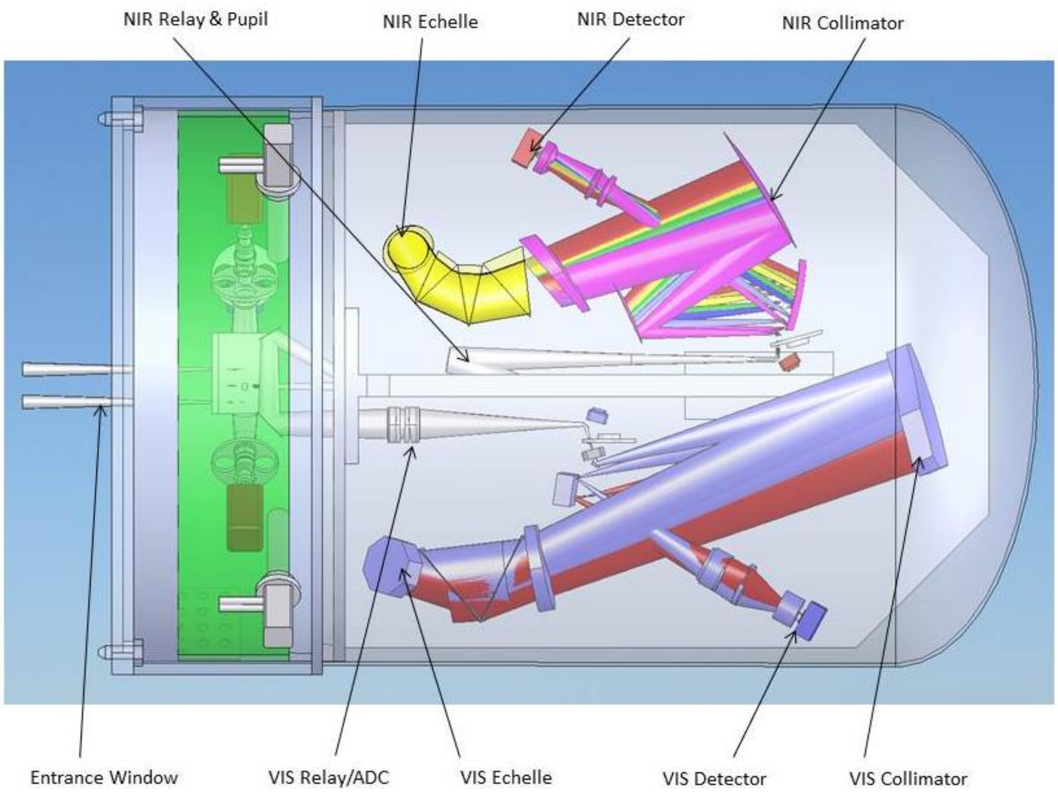


Figure 42: MOVIES top view showing A&G, VIS and NIR relay optics, VIS and NIR spectrograph modules

3.6.2.1 Entrance Window and Shutter Assembly

The entrance window must have a clear aperture that does not vignette the 3 arcminute square A&G field of view. The window material must be very durable and strong enough to withstand atmospheric pressure loading with adequate stress safety margins. The window must have excellent internal transmission over the entire wavelength range of MOVIES and be a suitable substrate for broad band coatings.

A window design which meets all of these requirements is a fused silica plane parallel disk 15mm thick with a 200mm outside diameter and a minimum clear aperture of 172mm. The window will be mounted in the Window Disk and will use an O-ring to make the vacuum seal. The temperature at the center of the window will be many degrees below ambient due to radiant cooling so a curtain of dry air must be flowed across the front of the window to prevent condensation. A side benefit is a protection of the window from dust collection.

3.6.2.2 A&G Module

The converging f16 beam from the Gemini telescope produces an image plane that is 300mm inside the MOVIES cryostat.

A 45 degree flat pickoff mirror is located at the image plane. The mirror reflects a 3 arc minute square field of view to the A&G cameras and is coated with a broad band reflective coating. The rectangular pickoff mirror is mounted on a two position linear slide mechanism which can move the mirror between imaging mode and spectroscopic mode positions.

In the imaging position the rectangular slot in the mirror is beyond the edge of the 3 arc minute field of view so all three cameras can be used for full field acquisition and imaging of the science target.

In the spectroscopic mode the rectangular slot in the mirror is centered in the field which allows the light from the science target to enter the spectrographs. The slot is sized to be large enough to pass all the light for a 10 arcsec long by 5 arcsec wide slit into the spectrographs with no vignetting. The large pickoff area outside the slot directs light to the A&G cameras for offset guiding during science exposures.

Each of the three A&G channels has a 4 position filter wheel to enable imaging of the target in a wide range of wavelength bands. The nominal filter selection is shown in Table 8.

All A&G optics and mechanisms will be mounted to a sub-plate which is kinematically installed into the instrument. This modular design approach will allow assembly, alignment and testing of the entire A&G module outside the instrument and simplify installation and service.

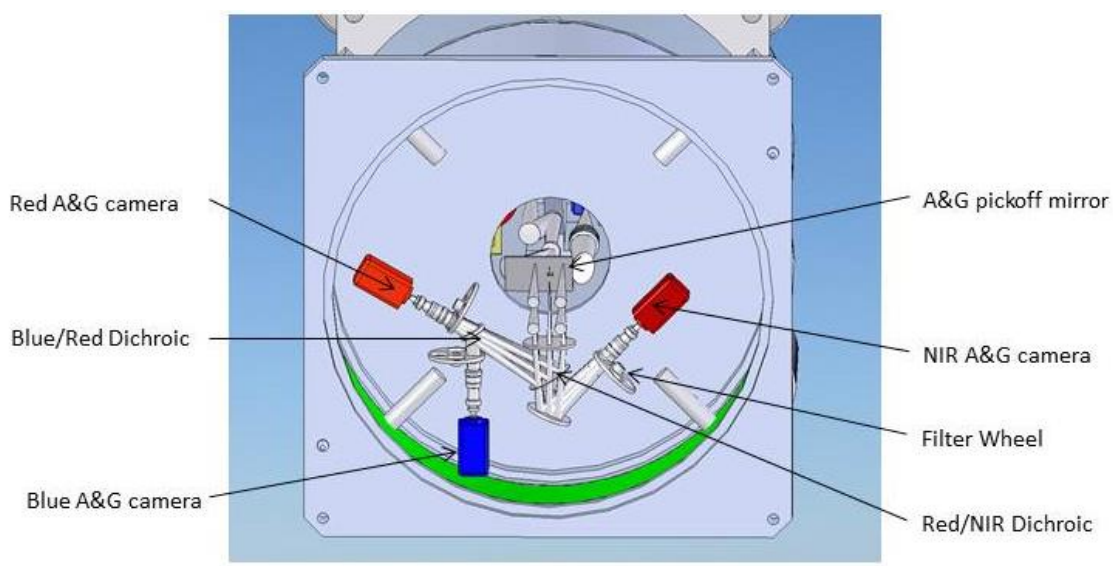


Figure 43: MOVIES front view showing A&G module through the Window Disk with the pickoff mirror placed in the spectroscopic mode

3.6.2.3 Pre-Slit Module

The VIS channel pre-slit optics convert the telescope f16 beam to the correct f # for feeding the VIS spectrograph and also contains the ADC optics. The VIS pre-slit section also has several flat fold mirrors that enhance the flexibility of the overall instrument packaging.

The NIR channel pre-slit optics convert the telescope f16 to the desired f# for feeding the NIR spectrograph. The pre-slit optics also produce an intermediate pupil image for convenient placement of a cold pupil stop which will effectively block thermal background radiation from entering the NIR spectrograph.

3.6.2.4 VIS Spectrograph

The VIS spectrograph will be a removable modular unit comprising: the slit wheel, slit viewing camera, shutter, collimator, prism cross dispersers, echelle grating, piezo fold mirror, camera, and detector. These items will all be mounted to a separate sub-plate which will enhance modular instrument development, integration, and support.

3.6.2.5 NIR Spectrograph

The NIR spectrograph will be a removable modular unit comprising: the slit wheel, slit viewing camera, white pupil collimator mirrors, prism cross dispersers, echelle grating, camera, and detector. These items will all be mounted to a separate sub-plate which will enhance modular instrument development, integration, and support. For instance, a lab cryostat independent of the MOVIES cryostat can be utilized to fully build and characterize the spectrograph.

3.6.3 MOVIES Cryostat Structural Design and Analysis

The primary structure and optical bench of MOVIES is shown in Figure 44. The principal elements of the structure are described below.

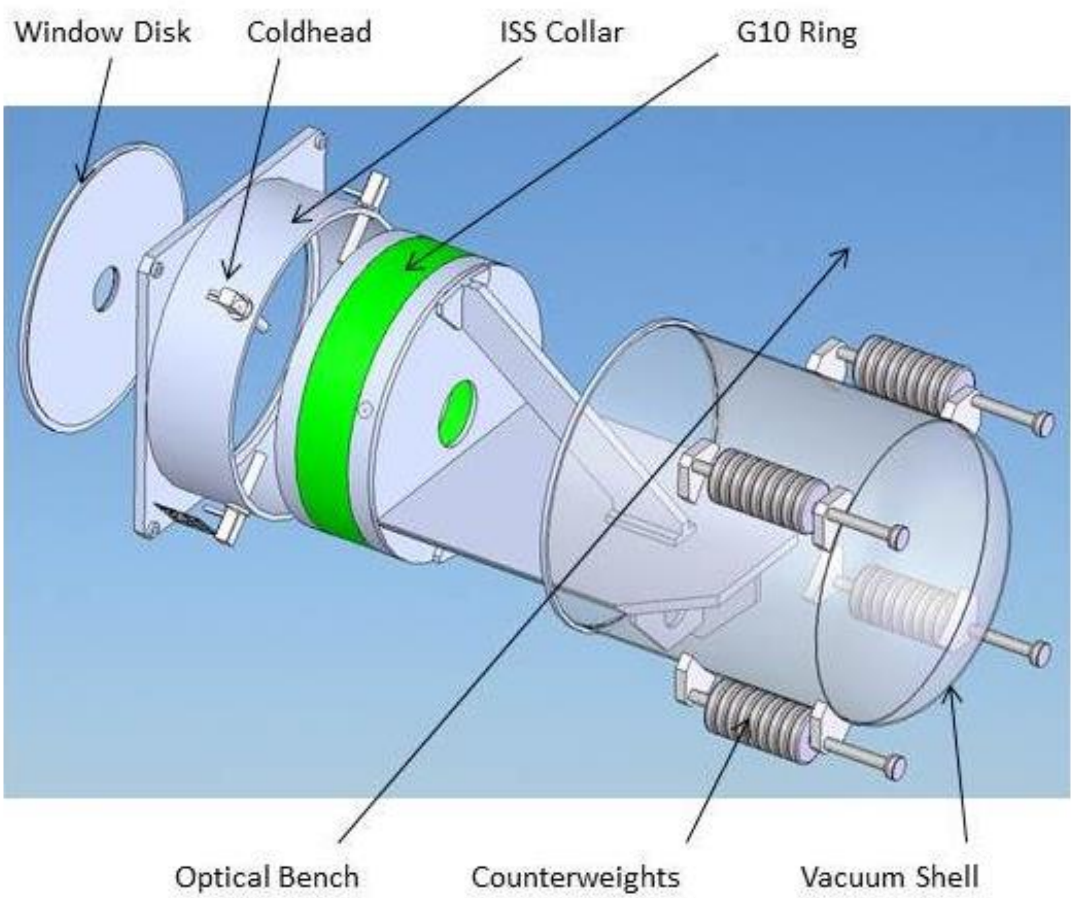


Figure 44: MOVIES structure and optical bench

The ISS Collar attaches MOVIES to the GEMINI ISS cube using 4 bolts in the 4 corners of the ISS Collar. There are 2 guide pins with large chamfers that extend beyond the face of the ISS Collar to assist with instrument mounting and alignment on the ISS. This is modelled on the method used by GPI. The ISS Collar also provides a cylindrical section for externally mounting the cryocooler cold heads and the hermetic electrical connectors and providing a rigid interface to the Vacuum Shell. This structurally sound ISS Collar will be fitted with the necessary "pintles" to allow rotating MOVIES from the vertical to the horizontal orientation, similar to GPI.

The Vacuum Shell attaches to the ISS collar and encloses the majority of the instrument. It is removable in one piece to gain service access to the instrument interior without disrupting any services. The vacuum shell has no perforations or feedthroughs and will be removed utilizing a handling cart (possibly built-in to the L-Frame).

The G10 Ring connects the room temperature ISS mounting collar to the cold optical bench. It provides a very stiff structural connection with very low thermal conductivity.

The cold end of the G10 Ring is connected to a round bulkhead called the A&G Bulkhead which is a disk of aluminum perpendicular to the optical axis. There is a cylindrical volume inside the G10 Ring within which the A&G module including pickoff mirror, dichroics, A&G cameras, and A&G filter wheels are located. The A&G module is installed through the large hole in the ISS Collar and mounted to the A&G bulkhead.

The Optical Bench is cantilevered from the A&G Bulkhead and is reinforced with a large Diagonal Brace and two Cross Braces. The Optical Bench and A&G Bulkhead and braces will be fabricated as a large weldment and post machined and treated, providing a stiff and precise structure.

The remaining three major opto-mechanical modules (Pre-slit relays/ADC optics, VIS spectrograph, and NIR spectrograph) will be pre-assembled and aligned on sub-plates. These sub-plates will then be kinematically referenced to the Optical Bench. As with the A&G module, this approach will allow assembly and alignment of each module outside the instrument and simplify integration and maintenance. This highly modular approach will enable early testing on an optical table of modules (e.g. the VIS spectrograph) prior to completion of the other optics modules or the primary instrument structure.

A gravity self-weight static deflection study of the G10 Ring and Optical Bench shows that the optical bench is very rigid. Peak deflections are ~ 30 microns. The results are shown in the Figure below. Of course, further refinement would likely improve these values if necessary.

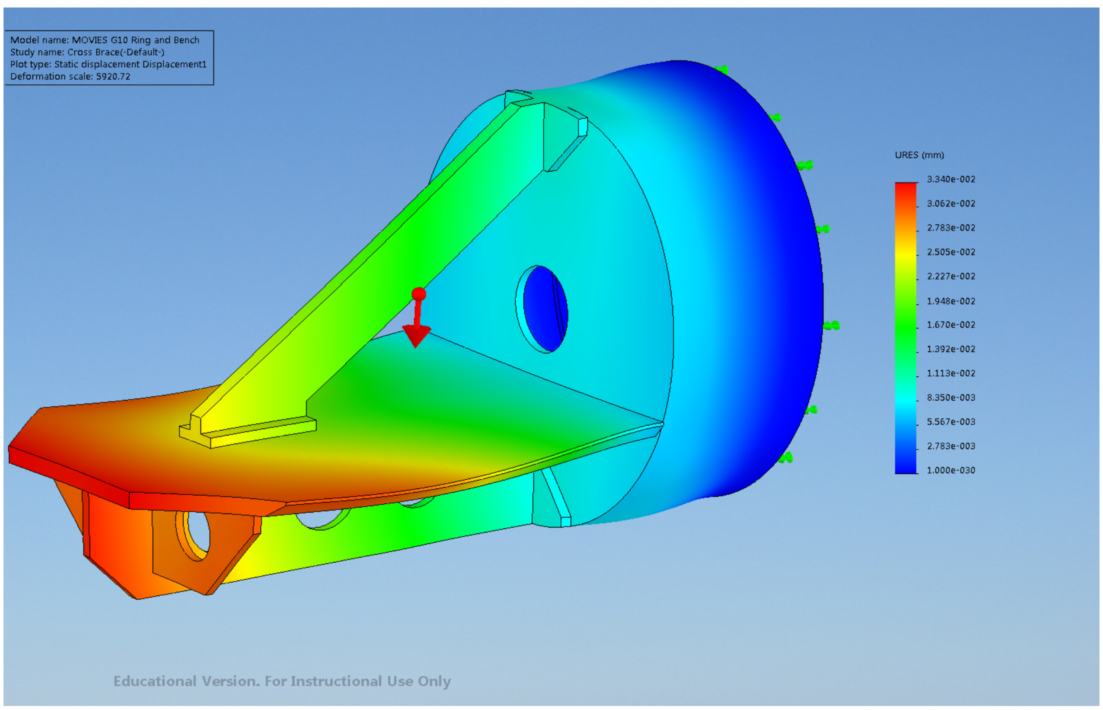


Figure 45: Gravity Self-weight static deflection of MOVIES Optical Bench

3.6.3.1 MOVIES Cryostat Thermal Design and Analysis

The steady state heat load of the MOVIES cryostat is estimated to be ~ 75 watts including radiation through the window, radiation into the cryostat through the multilayer insulation (MLI), and thermal conduction through the G10 Ring. The optical bench temperature will be maintained at ~75K to provide a low enough thermal sink temperature for the NIR science detector. The required cooling can be achieved with 2 or 4 Gifford McMahon cold heads which fit into the corners of the ISS Collar. These cold heads will use the Gemini facility helium supply and return lines.

An activated charcoal getter will be used to maintain high vacuum in the cryostat for up to several years of operation. Charcoal canisters will be thermally connected to the cryocooler coldheads to maintain the charcoal at the lowest possible temperate which maximizes the capacity of the cold charcoal to adsorb gas.

The estimated cool-down time is about 60 hours with 600 watts of continuous cooling. Depending on the final numbers, there is the option of utilizing 4 cold-heads for the I&T phase to reduce the cool-down delays during development, then go into operation with fewer in order to reduce the load on operations and minimize vibration.

Electrical warmup heaters will be used to achieve warmup times of ~ 36 hours. This will be limited by the maximum permissible warmup rates of the most thermally sensitive lenses. It will be investigated as to whether the natural warm-up rate is sufficient for operations, in which case the heaters will be removed to reduce risk.

The spectrograph controller will have a liberal contingent of RTD temperature sensors to monitor a selection of critical temperatures, with redundant sensors to minimize the need to open up the cryostat.

3.6.4 Cryogenic Optics Mounting

All of the lenses, mirrors, and gratings used in MOVIES must be mounted using methods which are safe for the optics and do not degrade optical performance at cryogenic temperatures. The OSU team has developed and successfully utilized cryogenic lens and mirror mounting techniques for several previous instruments.

The successful mounting of lenses and mirrors for cryogenic service requires very careful attention to such design issues as cooling rates, cooling induced lens stress, management of the local stress at the glass to metal interface, and maintenance of the optical figure and optical alignment. All of these issues have been successfully addressed and solved resulting in proven lens/mirror mounting approaches. Dozens of lenses (up to ~125mm) and mirrors (up to ~ 200mm) using materials ranging from Calcium Fluoride and fused silica lenses to Zerodur mirrors have been in cryogenic field service for years using the cryogenic optics mounting techniques developed by the OSU ISL [13]

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[13] T.P. O'Brien, B. Atwood, "A Lens Mounting System for Cryogenic Applications", Proc. SPIE Vol. 4841, pp. 398-402, Instrument Design and Performance for Optical/Infrared Ground-based Telescopes; Masanori Iye, Alan F. Moorwood; Eds. (2003)

Another challenge of cryogenic optics is the accurate prediction of the warm to cold changes in the optical design and implementing the compensations needed to ensure that optimal performance is achieved at the cold operating temperature. Methods for verifying warm and cold optical alignment must also be developed early in the design process.

3.6.5 Cryogenic Mechanisms

A summary of the cryogenic mechanisms is given in Table 10.

Mechanism	**Description**
Instrument Input Shutter	Slide
Acquisition mirror	Single mirror on a slide
A&G filter wheels	3 mechanically identical filter wheels
VIS ADC	Two rotatory stages
VIS shutter	Cryogenically prepared solenoid commercial shutter
VIS and NIR slit wheels	Copies of the A&G filter wheel mechanisms
VIS pointing mirror	Cryogenic piezo T/T mirror

Table 10: Mechanism Summary

MOVIES utilizes several types of mechanisms to enable the highly flexible operational modes of the instrument. All mechanisms operate in the cryo-vacuum environment of the cryostat interior and must be designed for extremely high reliability. The MOVIES mechanisms described in detail below will use design techniques, materials, components, and performance verification methods which have already been developed and extensively field proven in several instruments built by OSU [14] [15] [16] [17].

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[14] D.L. DePoy, B. Atwood, P. Byard, J. Frogel, T. O'Brien, " The Ohio State Infrared Imager/Spectrometer (OSIRIS) SPIE Vol 1946 Infrared Detectors and Instrumentation (1993)

[15] DePoy, D.L. et al. (12 authors) "A Novel Double Imaging Camera (ANDICAM)", Proc. SPIE, 4841, pp. 827, (2003)

[16] R.W. Pogge, D.L. DePoy, B. Atwood, T.P. O'Brien, P. Byard, P. Martini, A. Stephens, "The MDM/Ohio State/ALADDIN Infrared Camera (MOSAIC)", Proc. SPIE Vol. 3354, pp.414-418, Infrared Astronomical Instrumentation, Albert M. Fowler Ed. (1998)

[17] Atwood B., T. P. O'Brien, et al, "Design of the KMTNet large format CCD camera" Proc. SPIE Vol. 8446-246 (2012)

In order to minimize risk, mechanisms are duplicated where possible. For example, the two slit wheels are identical (except for the details of the slit in each opening), which are in turn identical mechanisms to the A&G filter wheels.

3.6.5.1 Instrument Input Shutter

The instrument input shutter blocks external radiation entering the instrument and is positioned immediately in front of the Entrance Window. Its purpose is to protect the input window (dust and mechanical damage) when not in use. The instrument input shutter will use a 2 position linear mechanism translating an opaque plate into place to cover the entrance window.

3.6.5.2 Pickoff Mirror Slide

The A&G module has a 2 position linear mechanism to translate the pickoff mirror between the imaging and spectroscopic modes. This mechanism uses a stepper motor driving a linear screw. Two hard stops precisely define the 2 operating positions. The two positions will be encoded so the mechanism state can be queried at any time. The mirror will be rectangular in shape, with the spectrograph 'hole' offset, so that it is out of the FoV of the acquisition cameras when extracted.

3.6.5.3 A&G Filter Wheels

The A&G module has a single 4 position filter wheel for each of the three A&G cameras. The filter wheels are driven by cold stepper motors using a simple pinion spur gear driving a large diameter ring gear. The filter positions are very accurately defined with a mechanical roller detent. The filter positions are encoded absolutely with micro-switches so that the filter positions can be queried at any time.

3.6.5.4 ADC Mechanism

The VIS pre-slit section contains the ADC which requires 2 continuous rotary mechanisms. These will utilize a stepper motor and worm gear to produce the required slow speed continuously variable motion.

3.6.5.5 VIS Spectrograph Mechanisms

The VIS spectrograph has an exposure shutter, slit wheel (8 Positions), and piezoelectric tip/tilt steering mirror. The necessity for a camera focus mechanism will be evaluated, but is expected to be a trade between simplicity and the possible need for additional cool-down cycles to finalize focus.

The VIS exposure shutter is a solenoid driven vane type shutter. This will be based on a commercially available product modified slightly for cryogenic service. This approach has been successful with the commercial vane type shutters up to 100mm aperture.

The VIS slit wheel will use identical technology and components as the A&G filter wheels. The slits are removable elements and have a highly reflective tilted face to direct the reflected light to the slit viewing camera. The baseline slits are tabulated in Table 9.

3.6.5.6 NIR Spectrograph Mechanisms

The NIR spectrograph has a slit wheel which is identical to the VIS spectrograph slit wheel. We will investigate the option of utilizing one NIR slit wheel position to carry an auxiliary lens to enable pupil viewing with the slit viewing detector. The baseline slits/lens are tabulated in Table 9

3.6.6 OSU Cryogenic Mechanism Design Heritage

Previous OSU built instruments have incorporated a wide range of cryo-vacuum mechanisms including: filter wheels, slit wheels, image rotators, rotary camera select turrets, precision linear camera focus stages, tangent arm grating tilts, and dithering mirrors. The numerous OSU heritage design approaches, components, materials, lubrication methods, fabrication techniques, and testing methods required for high reliability cryogenic mechanisms will be extensively re-used for the MOVIES instrument mechanisms. This will expedite development and guarantee high reliability. Although MOVIES is a physically larger instrument than those previously built by OSU, the size and complexity of the MOVIES mechanisms is very comparable to those built by OSU in previous instruments.

A rich inventory of cryogenic service rated components including motors, ball bearings, linear screws, flexures, roller detents, electromechanical switches, springs, spur and worm gear sets, lubricants, metals, self-lubricating polymers, etc. are immediately available to the OSU design team.

OSU has developed and tested cold stepper motors based on a commercially available disk magnet stepper motor which is inherently a-thermal by design. The only required modification is the thorough cleaning of the motors and replacement of the two ball bearings with cryogenic service rated ball bearings.

3.6.6.1 Field Reliability of OSU Cryogenic Mechanisms

Good examples of the exceptional field reliability of OSU cryogenic mechanisms are the tip/tilt dithering mirror and filter wheels used in the ANDICAM instrument.[4] These have been in service at the CTIO observatory on every clear night since 1992 without any periodic maintenance and zero failures. The tip/tilt dithering mirror is used to frequently dither the NIR channel on the sky and has more than a million dither cycles. The filter wheels are exercised several times per target and have ~ 150,000 cycles.

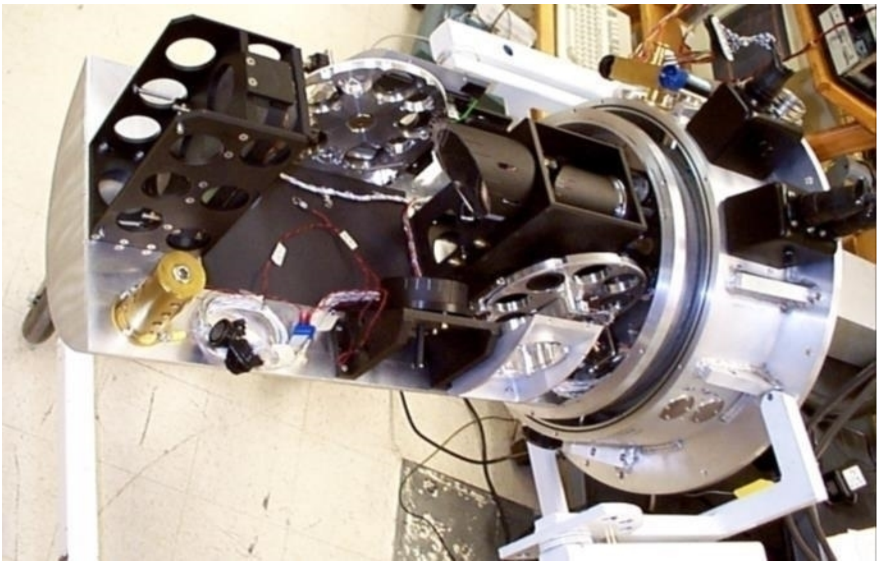

Figure 46: ANDICAM with vacuum shell removed showing optical bench, filter wheels, and dither mirror

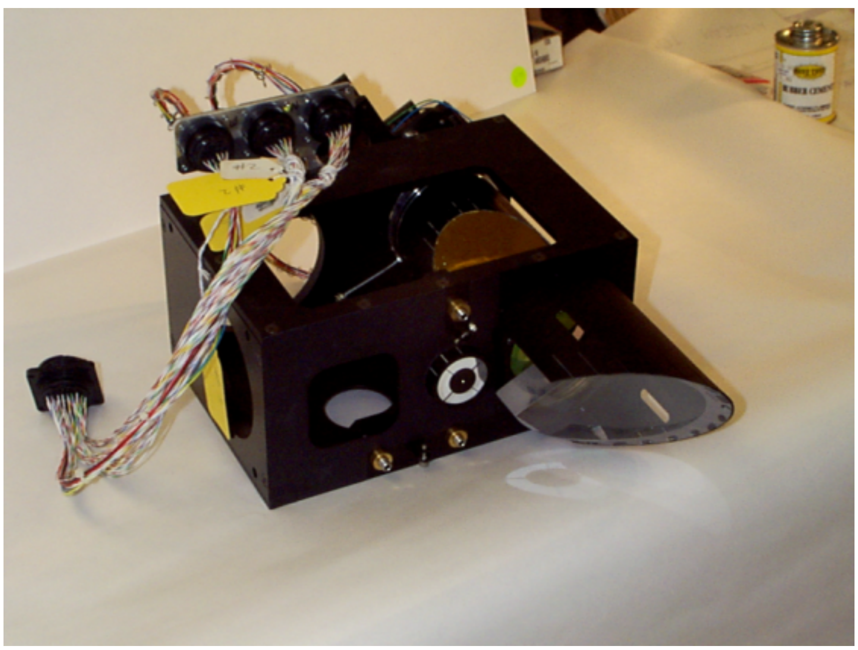

Figure 47: ANDICAM mechanism showing VIS/NIR dichroic, & dither mirror (gold)

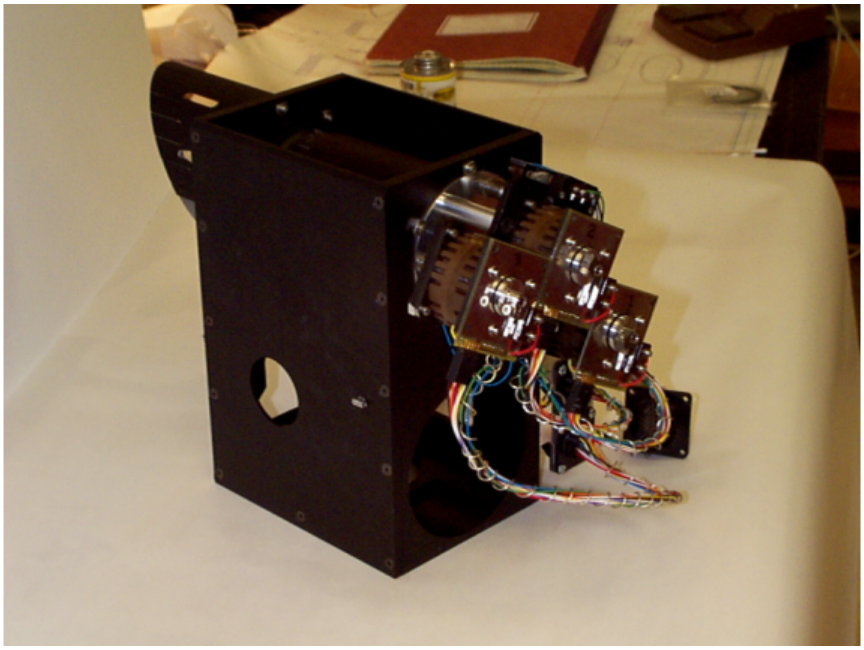

Figure 48: Dither mirror mechanism showing 3 cryogenic motors, switches, and electrical interconnect

3.6.7 Spectrograph Controller

The MOVIES Spectrograph Controller is based on the controller used on the MODS, KOSMOS and DESI instruments. The design is very mature with field proven hardware and software heritage.

The MOVIES Spectrograph Controller is a compact electronics box that houses all of the hardware and software necessary to control the spectrograph mechanisms and record telemetry data like temperatures and pressure. The Spectrograph Controller includes motor controllers for the A&G mirror slide, filter wheels, ADC, and slit wheels; electronics for VIS shutter and piezo tip/tilt mirror; and connections for the temperature and pressure sensors. The Spectrograph Controller is connected to the Instrument Control System (ICS) via an Ethernet. Commands from the ICS are converted into mechanism commands via the mini-PC, which also records telemetry data.

Each of the MOVIES mechanisms is controlled by a separate motor controller, an Applied Motion Products STAC5-IP-N120. This is a programmable, micro-stepping digital stepper motor controller with 12 digital inputs and 6 digital outputs. The inputs from the mechanisms are switches which encode the mechanism state. Motor control commands are stored on the mechanism's motor controller non-volatile memory. These translate ICS commands such as open/close or a Slit Wheel request into the requisite number of motor steps required to complete a given action, as well as use sensor information to determine that the mechanism was in the correct position before and after the motion.

There are two types of sensors: temperature and pressure. All of the RTD temperature sensors are read through RTD expansion modules connected to a WAGO 750-881 Ethernet Fieldbus Controller. The RTD sensors will be mounted at several locations on the optical bench, detector mounts, mechanisms, and one inside the Spectrograph Controller. The WAGO Fieldbus supports many types of expansion modules like relays, A/D converters, etc. so that many instrument control functions can be supported.

The cryostat pressure will be measured with a Granville Phillips Micro-Ion vacuum gauge which covers the full pressure range from atmospheric to 10E-9 Torr. This unit has an Ethernet interface.

The Spectrograph Controller contains a CISCO router and a network-connected mini-PC that runs a common version of Linux. The computer includes a Spectrograph Controller Interface Library, which controls the mechanisms and can access telemetry data. This python module is run by the ICS to interact with the hardware, including the query of telemetry data. It is also designed to protect the spectrograph against false commands and invalid operating parameters. The computer connects to the motor controllers and the WAGO fieldbus via Ethernet through the CISCO router. The router also isolates the Spectrograph Controller from the outside network, and establishes a single IP address for the Spectrograph Controller. All communication between the ICS and the Spectrograph Controller is through a single Ethernet connection to the CISCO router.

The Spectrograph Controller is housed in a compact NEMA box enclosure. The Controller will be mounted with external brackets to the ISS collar in manner that permits removal of the vacuum shell from the cryostat. The power consumption is expected to be ~60W in normal operation and ~90W at peak.

The spectrograph controller will be a sub-system of the Top Level Computer (TLC) which is further described in Section 3.8.1. This allows OSU to concentrate on the control aspects of MOVIES, while NRC-H concentrates on the interface to the Gemini Observatory software and coordination of the observing operations.

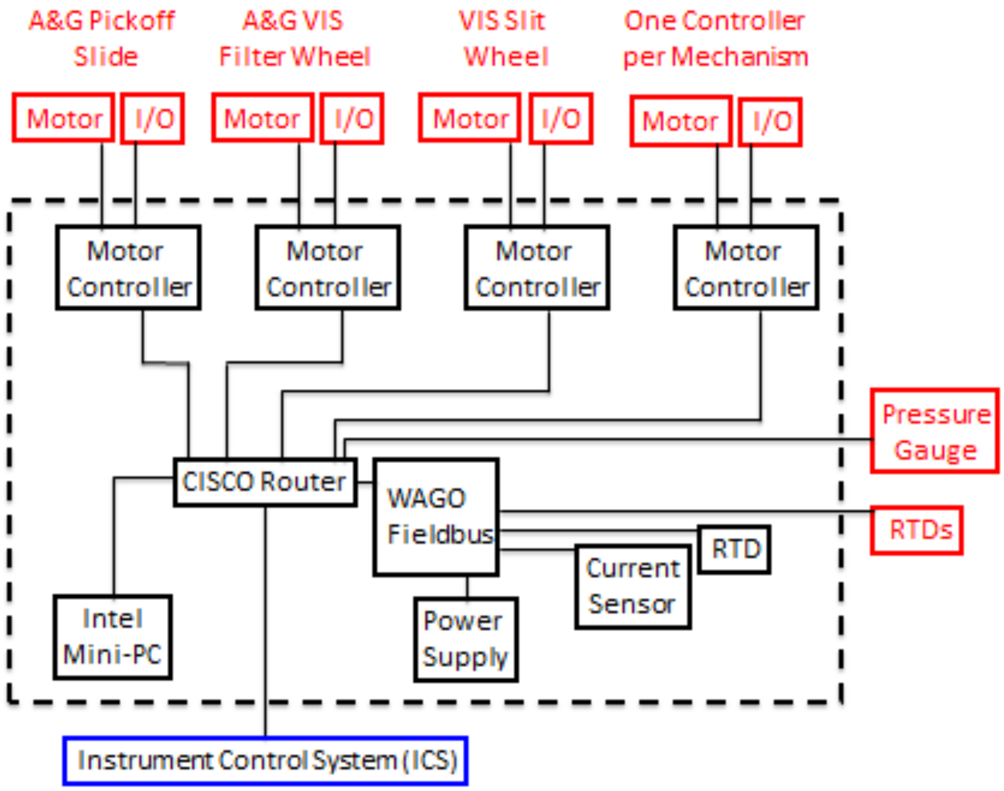

Figure 49: MOVIES spectrograph Controller Block diagram

3.6.8 Slit Viewer Detectors

Both the VIS and NIR spectrographs have slit viewer cameras that image the reflected light from the slit jaws through a camera lens onto a detector to verify target alignment on the slit. The slit viewer detectors are expected to be OEM module unpackaged versions of commercially available cameras, with the possibility of being 'bare' detectors with external controllers. The cameras have very low power dissipation of < 2 watts in the cryogenic environment. There are several cameras available which meet the slit viewer requirements at a reasonable price. See Section 3.7.3 for more details on the detector possibilities and baselines.

The detector electrical interconnect will be routed to the ISS collar, pass through hermetic connectors, and connect at the instrument patch panel.

3.6.9 NIR & VIS Science Detectors Thermal Considerations

The NIR science detector will be maintained at its optimal operating temperature (~ 80K) by connecting it to the cold optical bench with a very heavy copper cold strap engineered to conduct the heat generated by the detector to the bench and minimize the temperature rise between the cold bench and the detector. A small resistive heater (fraction of a watt) and temperature sensor on the detector mount will be used to regulate the NIR science detector temperature to the required accuracy if necessary.

The slit viewer and VIS science detectors will be maintained at their optimal operating temperatures (about -105C VIS science and slit viewer CCDs) by connecting their detector mounts to the cold optical bench with a copper strap engineered to conduct to the bench the heat generated by the detector at the required temperature rise between detector and bench. This copper strap can be "tuned" so that the equilibrium temperature of the detector is just slightly below the optimal operating temperature. A small resistive heater and temperature sensor on the detector mount will then be used to raise the detector mount temperature to the optimal value and regulate the temperature to the required accuracy.

3.6.10 Gemini Mechanical Interfaces

3.6.10.1 Instrument Volume

The MOVIES instrument is designed to fit on any of the three GEMINI telescope ISS ports (side or bottom/uplooking). The cryostat, spectrograph controller, and the detector electronics boxes all fit within the instrument volume required by GEMINI as shown in Figure 50. The final placement of the electronics boxes will be selected for easy service access and to help adjust the instrument CG location once more details are finalized.. The model shows the cryostat with the permitted GEMINI instrument volume superimposed.

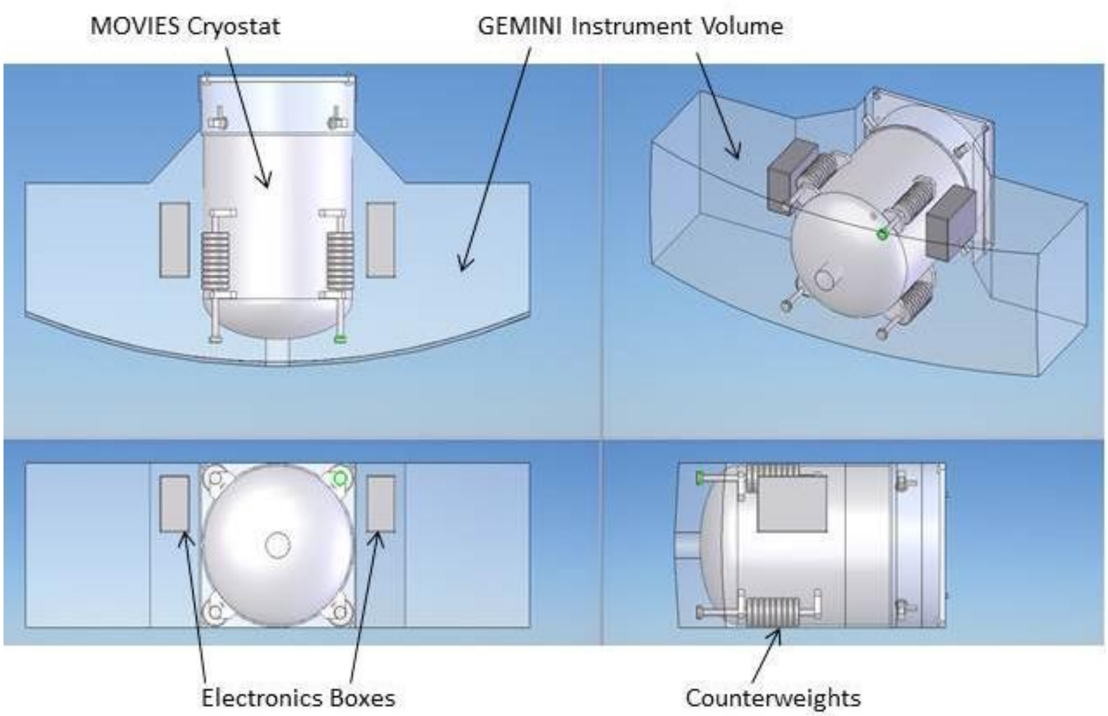

Figure 50: MOVIES cryostat with GEMINI allowable Instrument Volume superimposed

3.6.10.2 Mass & CG

GEMINI requires that the MOVIES total mass be equal to 2000Kg with a CG located on the X-Y origin and 1m away from the ISS mounting surface in the Z direction.

The table below summarizes the major elements for the Mass and CG budget. The MOVIES estimated mass is currently smaller than the required 2000Kg therefore counterweights will be used to bring the mass up to the required value and to tune the CG location. Of course, the counterweight mass translates to mass contingency as we can reasonably expect the mass to grow during further design phases.

MOVIES Mass & CG Table		
Description of Item	Mass (Kg)	Z location (mm)
Vacuum Shell	440	525
Optical bench cold structure	460	932
A&G optics and mechanics	45	150
Spectrograph optics and mechanics	170	1200
Electronics boxes, wiring, & brackets	175	900
Handling features for cart	100	100
Counterweights	610	1510
Total	2000	1000

Table 11: MOVIES Mass and balance estimate

A rough mass and balance spreadsheet including the cryostat, structure, optics, electronics, etc. estimates the total mass of MOVIES to be 1390 Kg with the CG located ~ 775mm from the ISS mounting surface. This is summarized in Table 11.

Counterweights with a total mass of 610 Kg located ~1510mm from the ISS (Z direction) will bring the mass and CG into compliance with the GEMINI requirements. Four sets of counterweights will be attached to the outside of the vacuum shell in the four corners of the ISS. This arrangement will allow complete X,Y,Z adjustment of the CG location with easily adjustable modular counterweights. This external mounting arrangement of the counterweights has the added benefit of adding no bending forces to the cold optical bench, and provides the mandatory Gemini interface 'feet' for the upward looking orientation. As previously stated, the balance mass indicates a significant contingency.

3.6.10.3 Electrical Interconnect

MOVIES will route all internal electrical cables to O-ring sealed hermetic connectors mounted on machined features on the cylindrical surface of the ISS Collar. Short cables will go from the hermetic connectors to an array of conventional electrical connectors mounted on a patch panel just above the hermetic connectors. This patch panel enables convenient access at a single location for all MOVIES electrical interconnect, greatly reduces the number of mate/de-mate cycles on the expensive hermetic connectors, and enables the removal of the cryostat vacuum shell without requiring any electrical disconnection. Operations like removal of a spectrograph controller electronics box in the lab will also be simplified.

3.6.10.4 Thermal impact on Gemini environment

The thermal impact of the MOVIES instrument on the Gemini environment must be less than +/- 100 watts. The only sources of external heating to the environment will be waste heat from the spectrograph controller which is estimated to be ~60 watts based on scaling a similar instrument controller and the detector controllers which can be liquid cooled. The MOVIES cryostat will cool the GEMINI environment by ~75 watts. The net thermal impact on the GEMINI environment will therefore be substantially less than the 100 watt requirement.

3.6.10.5 Instrument Handling for Gemini

As a consequence of the requirement that MOVIES be usable at any of the ISS instrument ports, a complete suite of instrument handling carts, rotation fixtures, and lifting fixtures must be designed and built.

The MOVIES instrument handling approaches will be based on the GPI instrument handling hardware and experience. Electronics boxes, counterweights, vacuum valves, cold heads, etc. will all remain in their final positions on the instrument during all handling operations.

A custom designed "horizon handling cart" or "L-Frame, will be fabricated which will duplicate the mounting features of the GEMINI ISS and allow mounting MOVIES off the telescope in the same way it is mounted onto the ISS. The cart will have casters, levelling feet, etc. for easy instrument handling. This cart will support the instrument in the horizon pointing orientation and will be the primary cart used in lab integration and in the handling of MOVIES at the telescope. This will be supplemented with a cart to allow save, efficient removal of the cryostat shell.

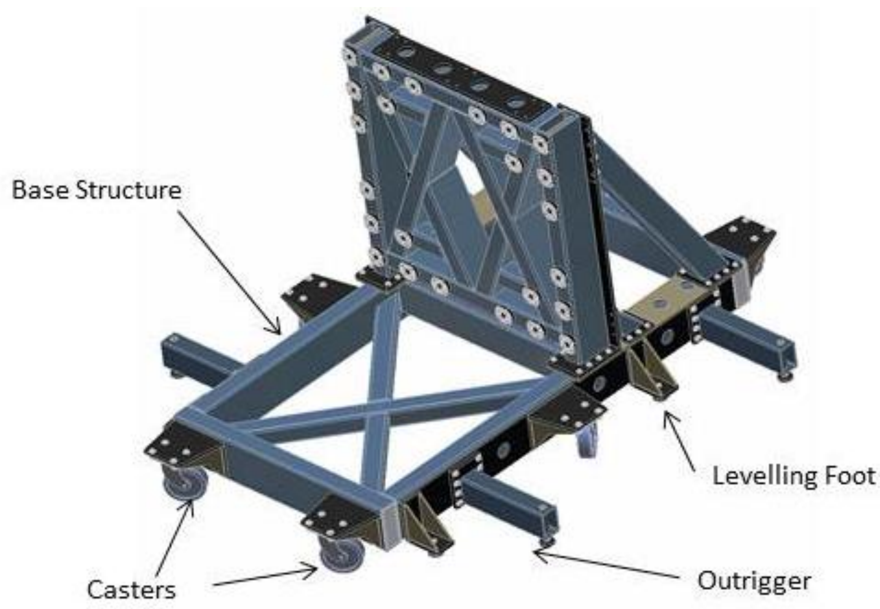

Figure 51: MOVIES L-Frame, copied from GPI

A low-profile handling cart, identical to the GPI handling cart, will be provided. The counter-weight legs extend to provide the standard four Gemini interface pads. The cart, with GPI installed for example, is shown in Figure 52.

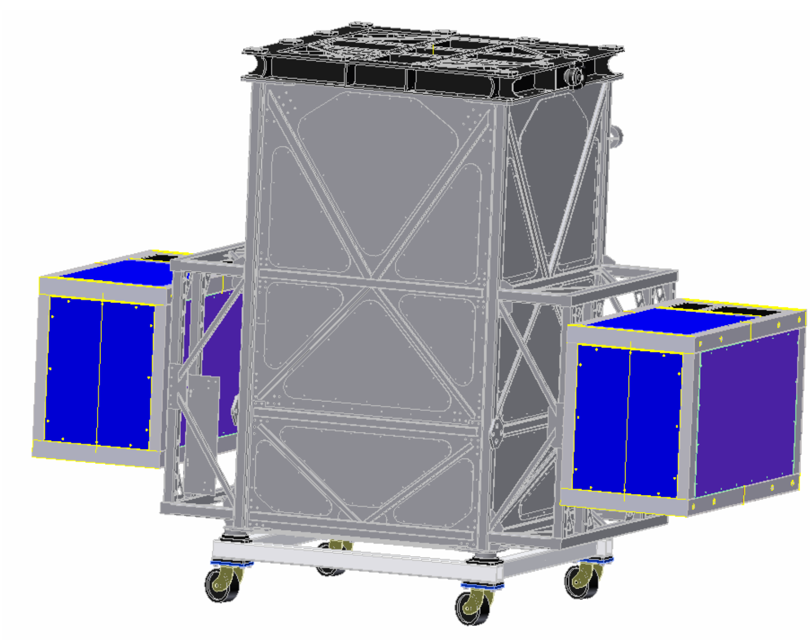

Figure 52: Low profile handling cart with GPI installed.

Rotation of MOVIES between the horizontal and vertical orientations will be accomplished in the same manner as GPI, except that instead of requiring a spreader bar at the rear a single eyelet will be provided to allow a simple connection with the second crane.

3.7 Image Detectors and Electronics

MOVIES requires seven imaging detector systems: two spectrographs, two slit viewers, and three acquisition cameras. The basic requirements are summarized in Table 12

Sub system	Required Image area (pixels)	Wavelength range [nm]	Baseline Detector
NIR spectrograph	2048 x 2048	900 – 2500	H2RG
VIS spectrograph	2048 x 4096	360 – 1000	E2V CCD42-90
NIR slit viewer	128 x 128	900 – 1700	Sofradir Snake SW
VIS slit viewer	128 x 128	400 – 1000	E2V CCD57-10
NIR acquisition camera	1024 x 1024	900 – 1700	Sensors Unlimited GA1280-SXJ-60
Red VIS acquisition camera	1024 x 1024	500 – 1000	E2V CCD201-20
Blue VIS acquisition camera	1024 x 1024	400 – 750	E2V CCD201-20

Table 12: Summary of imaging detectors

Because of the large number of detector subsystems, it is desirable to find common solutions as much as possible to make integration, testing, and maintenance simpler.

3.7.1 Spectrograph Detectors

The spectrograph detectors are large format detectors operating in long-exposure modes.

3.7.1.1 *NIR Spectrograph Detector*

The baseline , and probably final selection, for the infrared spectrograph is the HAWAII-2RG hybrid imager from Teledyne Imaging Sensors. This 2048x2048 pixel mercury-cadmium telluride based sensor is widely used in the astronomy community, partly because there are very few other appropriate options for large format infrared detectors.

The basic characteristics of the HAWAII-2RG are given in Table 13.

Format	2048 x2048, 18µm pixels
Number of outputs	1, 4, 32 (selectable)
Readout rate	100 kpixels/s per output (slow mode)
Frame readout time	10 s
Power dissipation	4 mW
Quantum efficiency	> 70% (800 – 2500 nm)
Dark current	< 0.05 e-/s (77K operating temperature)
Read noise	< 18 e- (single CDS read) < 5 e- (multiple sampling)
Pixel capacity	> 80,000 e-

Table 13: HAWAII-2RG characteristics

3.7.1.2 VIS Spectrograph Detector

There are more detector options for the visible arm spectrograph, but for the purposes of this study we have considered two devices from E2V Technologies.

The baseline option for the visible spectrograph detector is the conventional CCD42-90. Like the HAWAII-2RG, the CCD42-90 is widely used in the astronomy community, frequently in large mosaics because of the three-side buttable package. It is available in the "deep depletion" silicon, which extends the quantum efficiency in the near infrared.

An optional device is the CCD282, which is the product of a development effort by E2V for the University of Montreal. The CCD282 is a 4096x4096 pixel EMCCD with a split-frame architecture and 8 outputs. We only require 2048x4096 pixels to cover the spectrograph output, so only one half of the device would be used. Because it is a frame transfer device, a shutter would not be necessary. At this time the EMCCD CCD282 is NOT available in a deep depletion version. The performance advantages of the EMCCD are described in detail in Section 2.5.6.

The characteristics of the CCD282 and CCD42-90 are summarized in Table 14.

Although the graded coating (which has an AR peak that varies across the detector in order to try and match up with the spectral region) has a slightly higher peak in the 500 to 600nm region than the "M2" coating, it is balanced out by the peak at around 400nm of the M2 coating. Due to the simpler nature of the M2 coating, this will be the baseline coating for the CCD42-90. See Figure 53.

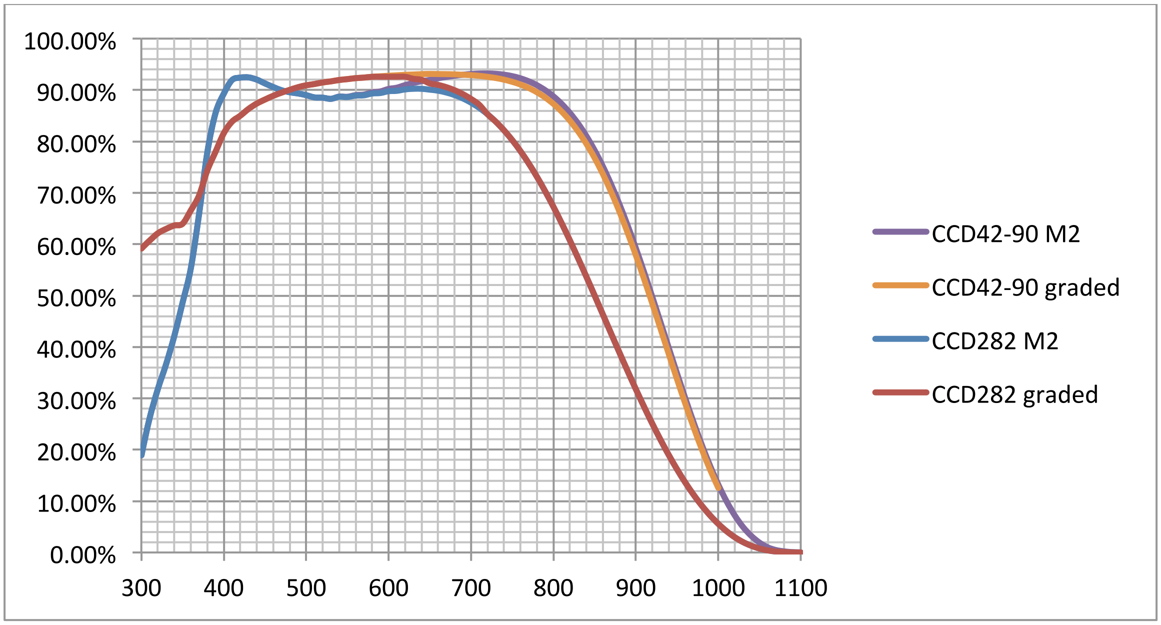

Figure 53: Quantum efficiency curves for candidate visible spectrograph detectors. The CCD42-90 curve is for deep depletion silicon. "M2" curves are for E2V's multilayer coating. "Graded" curves are for a graded single layer coating.

Table 14: Visible spectrograph CCD characteristics

	CCD282 (photon counting mode)	**CCD282 (bright target mode)**	**CCD42-90**
Format	4096 x 4112, split-frame transfer, 12µm pixels (4096 x 2056 in use)		2048 x 4612, 13.5 µm pixels
Package	125mm x 70 mm aluminum nitride AN242, PGA connector		28.2mm x 67.3mm invar, mounting studs, PGA connector
Number of outputs	8 (4 in use)		2
Frame transfer time	12 ms		N/A
Readout rate	15 Mpixels/s per output	100 kpixels/s per output	100 kpixels/s per output
Frame readout time	0.2 s	21 s	47 s
Power dissipation	3400 mW	1400 mW	71 mW
Read noise	0.001 e-	10 e-	3e-
Output sensitivity	1.1 µV/e- [x EM gain]	5.3 µV/e-	4.5 µV/e-
Output noise	60 µV	60 µV	13.5 µV
Quantum efficiency	> 80% (400 – 700nm) [including thresholding]	> 90% (400 – 700nm)	> 90% (400 – 800nm)
Dark current	0.0003 e-/s (163K)	0.0003 e-/s (163K)	0.0002 e-/s (163 K)
Pixel capacity	1.5 e-/s (at maximum 5Hz full frame rate)	50,000 e-	150,000 e- (300,000 binned)

3.7.2 Acquisition cameras

The VIS acquisition cameras are required to have a 3 x 3 arcminute field of view with an appropriate sampling for acquisition and guiding. A plate scale requirement of 0.18 arcsec/pixel leads to an array size of 1024 x 1024 pixels.

Although the infrared arm of the spectrograph is sensitive out to a wavelength of 2.5 µm, to reduce costs, the infrared acquisition camera is only required to be sensitive out to 1.7 µm, which allows for less expensive indium gallium arsenide (InGaAs) arrays to be used. The nominal FoV requirements are the same as the VIS cameras, but the detector requirement is currently relaxed to 512x512 pixels. This is in anticipation of the availability of more larger format InGaAs detectors, which are just becoming available on the market.

3.7.2.1 VIS acquisition cameras

Baseline

The "blue" and "red" visible cameras can be served by the same detector model, with separately optimized anti-reflection coatings. Because of the high frame rate required for guiding, an EMCCD is a good fit. The CCD201-20 from E2V is a 1024x1024 frame transfer EMCCD, with 13 µm pixels, and is the baseline detector for the VIS acquisition cameras. The CCD201 is available in commercial camera systems from Andor, Nuvu, and Princeton Instruments. Princeton Instruments offers a special enhanced quantum efficiency option that provides a large improvement in the blue (300-400nm).

A full frame can be read at a maximum of around 25 frames/s, which means that even in guide mode the full field of view is available. The signal levels in the acquisition cameras are too high to make use of the photon-counting mode (due to sky background levels with the relatively wide-band filters), so the EMCCDs must be run in the linear gain mode that adds the excess noise characteristics (due to the stochastic nature of the gain structure).

For use as a slower imaging camera, the CCD201-20 also features a classic, low-noise, output amplifier. This permits using at least one of the cameras in the slow, low-noise mode when and if desired. This flexibility is an additional reason to utilize the CCD201-20.

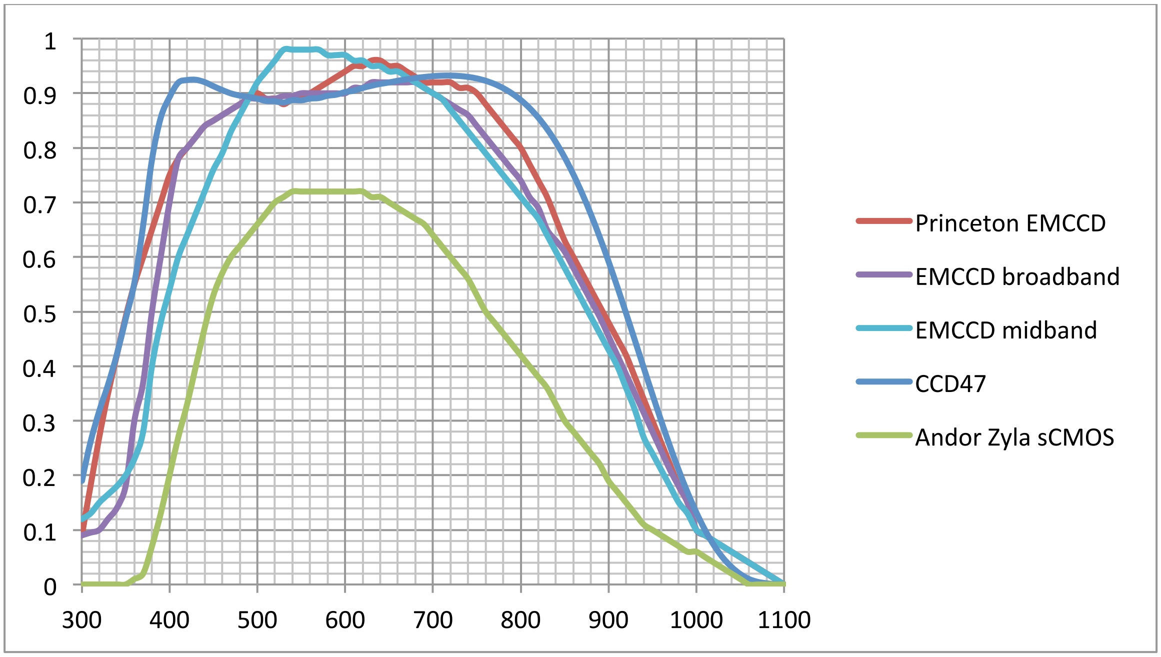

Figure 54: Quantum efficiency curves for candidate visible acquisition camera detectors. The EMCCD and sCMOS curves are estimated from manufacturer's data sheets. The CCD47 curve assumes a deep depletion devices with multilayer coating.

Backup

E2V also makes a conventional CCD in the same basic architecture (CCD47-20). This is reserved as a backup in case issues arise with the CCD201-20. The CCD47 is available in the deep-depletion silicon, giving an advantage in quantum efficiency in the near infrared, but the readout rate must be lowered to achieve good read noise. Using both outputs of the CCD47 at 1MHz each, full frame readout rate would be about 2 fps with a read noise of 5 e-. To get to the guide rate of 20 fps, the CCD would have to be subrastered to about 256x256 pixels.

sCMOS

There are also some very low noise "scientific" CMOS (sCMOS) imagers available that are capable of high frame rates (e.g. Andor Zyla) which could be considered. These devices have smaller pixels (<6.5 μm), but larger formats (>2048x2048), so the overall physical array size is similar. If we use the same optical plate scale as for the CCDs, the sCMOS device would be oversampled even in the best seeing conditions, and unlike CCDs does not have the option of on-chip binning The read noise level is only 1 e- for a single pixel, but a readout would require 4 to 15 times as many pixels (depending on seeing), so the overall effective noise is much higher.

In addition, currently available sCMOS devices are front-side illuminated, and therefore have lower quantum efficiency. The Zyla has a peak QE of 72% at 600nm and it drops rapidly on either side of this (seeFigure 54). Overall, the signal-to-noise ratio is significantly lower compared to an EMCCD or even a low-noise, backside-illuminated conventional CCD except at higher frame rates. The performance of these devices will likely continue to improve, but unfortunately the pixel size is not likely to increase.

In imaging mode (as opposed to guiding with a single small subraster), two advantages of the sCMOS over the EMCCD are the speed and the dynamic range.

The signal handling capability of the EMCCD is limited because of the internal multiplication. At a gain of 50 (just enough to overcome the raw read noise) it has a range of about 8000:1. This can be improved by dividing the exposure into multiple frames and coadding, but this must be traded against a lower maximum frame rate or a reduced raster size.

In contrast, the Zyla sCMOS camera is capable of reading the full array at 100 frames/s, with a dynamic range of about 60,000:1 (when summed 2x2 to get equivalent pixel sampling). Therefore, for high-speed imaging of a field containing objects with a range of brightness, the sCMOS camera may have an advantage.

All in all, the EMCCD remains the baseline choice (CCD201-20). However, this choice could be easily changed if the sCMOS detectors see an improvement in QE over the next couple of years. Due to the nature of the opto-mechanical design of MOVIES, changing detectors even closer to final design is not a risk or issue.

3.7.2.2 Infrared acquisition camera

There are several models of InGaAs detector array of appropriate size for the infrared acquisition camera. Currently, the dominant format is 640x512 pixels with pitch varying from 15 to 25 µm. Higher pixel count detectors are now becoming available. Quantum efficiency is typically 65-80% from 900 – 1600nm and read noise is 25-50 e-. Most are capable of frame rates of over 100 frames/s, with even faster rates possible by subrastering. This might enable a noise reduction by combining multiple non-destructive reads in each guide period.

Table 15: Candidate InGaAs detectors; default is the GA1280JSX-60

Model	Read Noise	Full Frame Rate	Size	Pixel pitch	Max QE
Sensors Unlimited GA1280 JSX-60	25	60	1280 x1024	12.5 µm	65%
Sofradir Snake SW	30	300	640 x 512	15 µm	70%
Raptor OWL	50	120	640 x 512	15 µm	85%

The current baseline is the Sensors Unlimited GA1280 due to its frame size, low read noise and similar pixel size to the VIS acquisition cameras.

The Sensors Unlimited GA1280 camera is of particular interest because it is currently the only one we found with a format larger than 640 x 512. This device is 1280x1024 pixels on a 12.5 µm pitch. The quantum efficiency of this camera is only 65%, but the read noise is an impressive 25 e-. Due to the larger format, the maximum frame rate (full frame) is 60 fps; fully sufficient for guiding. It is expected that by later MOVIES design stages more large format detectors will be available and that performance will improve. However it is a suitable baseline detector for this application.

We currently consider the Sofradir Snake SW as a backup, with it still good read noise. It would, however, not meet the FoV requirement due to its 640x512 format.

3.7.3 Slit viewers

The slit viewer cameras need only very small format detectors, just large enough to image the slits at an appropriate resolution. This should require less than 100 pixels in the long direction. The frame rate is low because the data is only used for slow flexure compensation. However, the signal is quite weak because the camera only sees the wings of the PSF, so high sensitivity is important.

For the visible slit viewer, a low-noise, back-illuminated frame transfer CCD would be a good fit. The E2V CCD57-10 is such a device, with 512x512 13 µm pixels. It is available in deep depletion silicon for high near-infrared sensitivity and has a read noise of 2e- at slow readout rates.

The infrared slit viewer could be fitted with one of the common 640x512 pixel InGaAs detectors, such as the Sofradir Snake SW, which is available in a compact OEM module. This device is shown in Table 15.

3.7.4 Detector electronics

Since the smaller detectors for the acquisition cameras and slit viewers are available in commercial camera systems, this is an attractive option compared to developing a custom controller or purchasing and modifying a generic controller system like those from Astronomical Research Cameras (ARC). The complication comes from the fact that the cameras are located inside the vacuum envelope of the instrument.

The preslit region of the instrument can be operated at a warmer temperature than the spectrograph regions, so it is possible to have this region at a temperature compatible with commercial electronics (typically > 230K). However, the electronics are not usually rated for operation in a vacuum, so it is not clear that putting them inside the vacuum enclosure is feasible. This option could be explored with the camera manufacturer. Nuvu has done some development in this area for balloon-borne experiments and produced custom versions of their cameras that are vacuum compatible.

The interfaces to commercial cameras are based on the industrial machine vision standards of either CameraLink or GigE. Both standards can operate over long cables so they can be connected through the vacuum enclosure wall to a remote host computer. The GigE interface is attractive because it uses a standard 1 Gb Ethernet network connection and does not require a separate frame grabber installed in the host.

The highly specialized, large format detectors in the spectrograph arms require custom electronics to drive them and these must be isolated from the cryogenic environment of the detectors. Both the CCD42-90 and the HAWAII-2RG detectors have been successfully operated using ARC controllers, which could be mounted outside the vacuum enclosure. For the HAWAII-2RG there is also the option of using the Teledyne SIDECAR ASIC, which provides all the control electronics required to operate the detector and is available in a compact cryogenic package that could be mounted with the detector in the spectrograph. We would down-select at a later time to take advantage of the best option at the time.

The EMCCD requires a high voltage (40-50V), high speed (15MHz) clock signal, which cannot be produced by the standard ARC controller, so this will take some development effort. There are commercial EMCCD cameras (with smaller detectors) that are capable of providing the appropriate signals to drive the CCD282, and it may be possible to adapt them for the larger detector. Laboratoire d'Astrophysqiue de Marseille (LAM) is currently developing a controller for the CCD282 with the Laboratoire d'astrophysique experimental de Montréal / Observatoire du Mont-Mégantic (LAE/OMM). This controller will be in operation in November 2015. LAE is also working with Nuvu Cameras to provide a second solution for a controller for the CCD282.

A significant challenge for the EMCCD controller is making it compatible with the location of the detector deep in the cryogenic spectrograph. Either the controller is placed inside close to the detector, in which case special consideration must be given to thermal shielding and temperature control, or the controller is placed outside, which will require special attention to the interconnects because of the high-speed clock signals.

The slit viewer cameras are in formats that are available from commercial camera vendors, but again the problem is thermally isolating the drive electronics because the slit viewers will be in the cold spectrograph region. Since the readout rate is low, both slit viewers could be served by a remote ARC controller.

3.8 Software

The software for MOVIES would leverage as much proven existing systems, code and expertise as possible. The top level, the responsibility of NRC-H, would rely on the gained expertise from Gemini instruments such as GPI. Mechanism monitoring and control would likewise leverage the expertise gained by OSU on instruments such as DESI1 and 2. For additional requirements, such as in the real-time image processing, automatic target acquisition and selection, we would rely on adopting and modifying existing capabilities from the community at large.

3.8.1 Top Level Instrument Software Design

3.8.1.1 Gemini Interface and Software Reuse

There are two interface options available at Gemini: EPICS and GIAPI. At NRC-H, we have experience with both options. The major advantage of using the GIAPI is the flexibility it will give to the software design and the ability to re-use software from other projects. The GIAPI is an efficient and simple interface that we have acquired significant expertise through our development with the Gemini Planet Imager (GPI). The risk of the software development is low. For GPI we were able to create a software base that would provide a software structure for groups of mechanisms or Assemblies. This can easily be reused for MOVIES, incorporating the robust mechanism control routines from OSU. The command and status interface could also be re-used, including the software base for the graphical user interfaces.

In addition, the GIAPI supports the Red Hat Linux OS with real-time kernel. The experience gained from using the real-time kernel in Gemini Planet Imager (GPI) enable us to develop predictable real-time software with sub-millisecond, typically tens of microseconds, in response time. With this level of real-time performance we are confident that GIAPI will meet the MOVIES software performance requirements.

3.8.1.2 Design Considerations

The Top Level Computer (TLC) will contain the software that will control and monitor MOVIES. The Instrument Sequencer and Components Controller will be designed at two different sites. Because we are a distributed environment, extra time and effort will be needed to detail interfaces. Success with the integration will be aided by following similar development guidelines, such as:

- Common programming languages (a small set of languages makes for easier integration and maintenance).
- Similar structure in programming environment.
- Common GUI interface.
- Global SVN (or equivalent) repository (so that releases amongst our partners can be done easily).
- Common software standards (such as those provided in the Gemini Software Standards document).

- Common testing procedures (will also make the global testing of the instrument easier).
- Common documentation tools that provide in-line documentation that can automatically produce html for the complete software package. Our recommendation is, “Doxygen” (http://www.stack.nl/~dimitri/doxygen/index.html)

3.8.1.3 Software context

As detailed above, the software design is based on previous Gemini projects, in particular the Gemini Planet Imager and the GMOS CCD upgrade. Movies will operate within a similar context, communicating with the various observatory subsystems as shown in Figure 55.

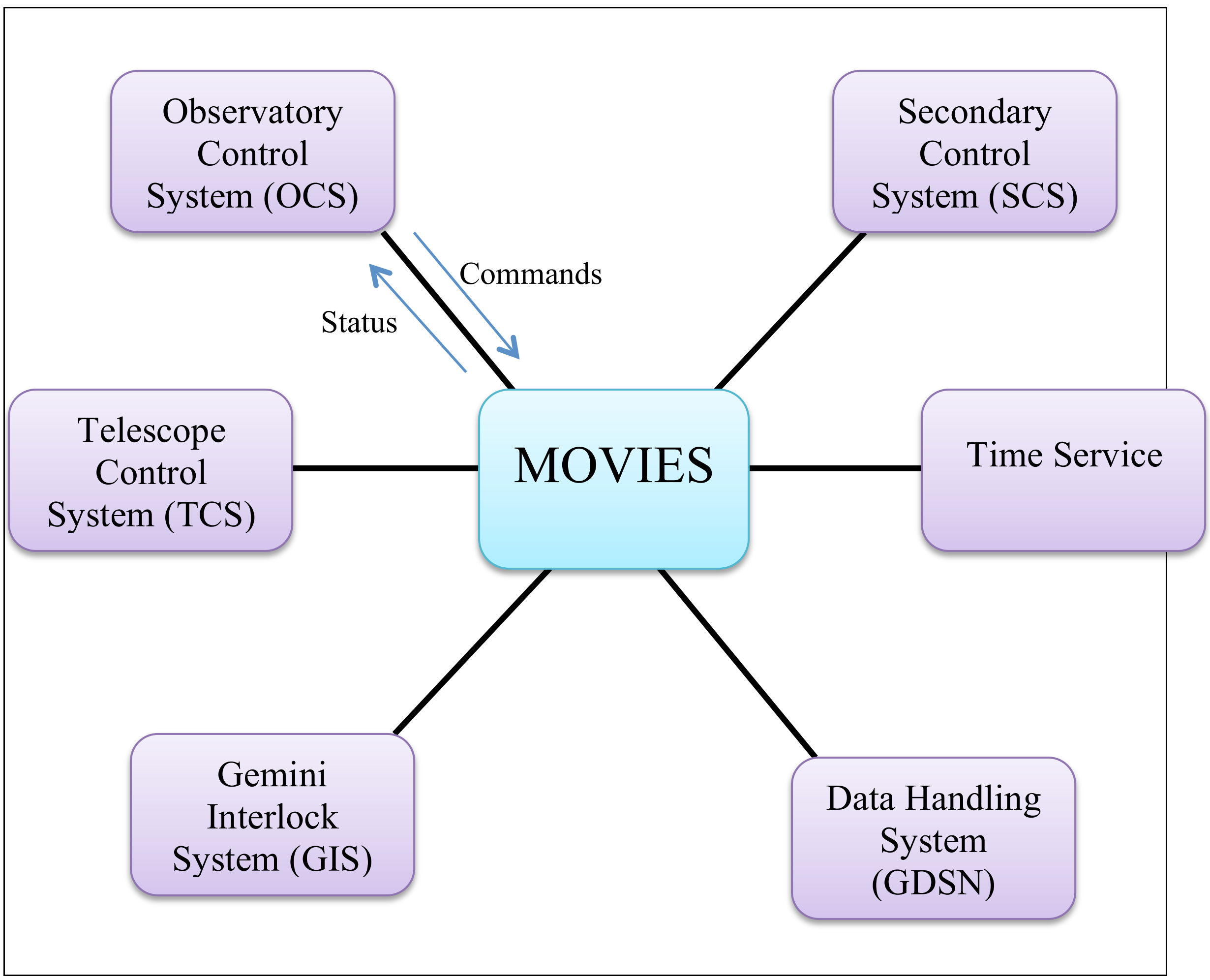

Figure 55: Movies Software Context

The primary interface between MOVIES and Gemini is through the GIAPI. The MOVIES external interfaces are:

The Observatory Control System (OCS) commands MOVIES and reports status back to the OCS. This includes status, alarms and events.

The Telescope Control System (TCS) provides World Coordinate information that enables MOVIES to fulfill the requirements for making World Coordinate System data available for headers. It also provides information to set the Atmospheric Dispersion Corrector (ADC).

The Gemini Interlock System (GIS) provides an interlock demand as a way of locking out MOVIES systems and MOVIES provides an interlock event to the GIS. Although provided, we don't expect any necessary interlock events to be handled.

MOVIES will write datasets to the Gemini Data Storage Network (GDSN) file system and then notifiy Gemini of the data arrival through Observation Events which trigger the addition of FITS keywords and ingestion of data to the Data Handling System (DHS).

Science Data is stored on the Gemini Data Storage Network (GDSN).

Time is available through the NTP service provided.

Guiding offsets to the Secondary Control System (SCS) for M2.

3.8.1.4 Software Design

The main responsibility of the MOVIES software is to provide:

- high level sequencing of MOVIES
- status data to Gemini required for the observation
- science data
- low level control of the mechanisms
- offsets for M2 guiding and offsetting

The top level software design of MOVIES is shown in Figure 56.

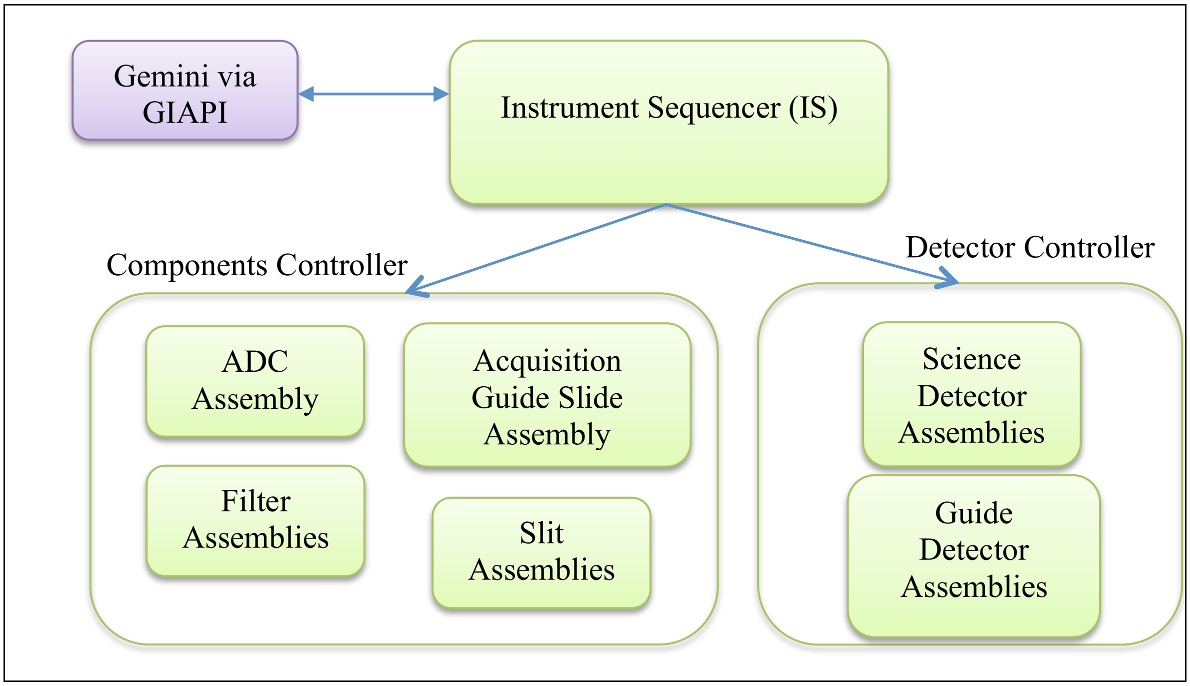

Figure 56: MOVIES Top-Level Data Flows

The Top Level Computer (TLC) contains all of the software described in the following design. The software contains five main processes:

- The Instrument Sequencer (IS) handles the general sequencing of MOVIES and is the receptacle for commands and status from Gemini. The interface with Gemini is via the GIAPI
- The Detector Controller (DC) handles the interface with the science detector controls and composition of the FITS files along with indicating observation transitions. It will also handle the Acquisition and Guide and slit Detectors and the processing of the data from the acquisition cameras and transforming that into offloading information to the M2 via the Secondary Control system.
- The MOVIES Components Controller (CC) handles the control of the individual sub-components, specifically the ADC, Acquisition and Guide Slide, all of the filters and slits and the piezo fine T/T stage.

Also included in the MOVIES software is the Acceptance Test Engineering User Interface (GUI), which provides a convenient means of interacting with the instrument during testing.

3.8.2 Operational Software Requirements

This section describes any non-standard pieces of software that are required to enable the scientific operation of MOVIES i.e., what software requirements flow down from our operational considerations described in Sections 2.5 and 2.6?

- *Acquisition: Automated retrieval of guide star positions for a given target location, and derivation of astrometric solution for acquisition cameras*

With reference to Figure 20, during the telescope slew, we need to retrieve the positions of the expected guide stars for the new target position and overlay their expected positions on the acquisition camera feeds (expected to be continually displayed on a GUI). Once in position, a program like Astrometry.net running on a local host will provide a quick astrometric calibration relating pixel position on each camera to RA and declination. In the case of WCS acquisition, commands to M2 will center the target coordinates in the center of the field (i.e. the slit) by moving the guide stars to their required position; in the case of Direct acquisition, the target will be confirmed either through automated identification in the software and/or by confirmation by a human operator. The acquisition software would measure the centroid of the target and proceed with the steps to put the target into the slits as described in Section 2.5.3.

We stress that it is important from a science perspective for the acquisition procedure to be as fully automated as possible. Human intervention should be required only in a troubleshooting capacity due to the incredible long response times of humans in comparison to software, given the importance of rapid acquisition to enable new science.

- *Guiding/imaging: Storage of all A&G camera frames throughout course of spectroscopic observation and delivery to the PI*

(Pseudo-)Simultaneous imaging and spectroscopy is a science enabling capability of MOVIES through the ability to monitor the initial brightness of the source (via the acquisition frames) and to monitor the atmospheric transparency and flux entering MOVIES during the spectroscopic observation via the imaging of the A&G cameras. Both allow for precision spectrophotometry of the source. The A&G imaging should therefore be saved as a time series and delivered to the PI with the spectroscopic data.

For those cases where spectrophotometry is particularly important and the source is rapidly varying, we envisage the need to either do small offsets (>10 arcsecs) during the observation – to send the target to the A&G cameras while empty sky enters the spectrograph – or to slide the acquisition mirror back into position so the target light is send to the A&G cameras temporarily. This allows measurement of the source flux at intermediate times with nearly no penalty to the spectroscopic observation.

- *Quick look data processing: specifically, first-pass detrended detector images, extracted and sky subtracted 2D and 1D spectra*

A quick-look spectroscopic data reduction is required to allow the queue observer to judge the quality of the data being acquired. A quick reduction with MOVIES is facilitated by having a good library of recent flat fields, and previously deriving the empirical mapping between slit position (x_{slit}) and wavelength (λ) to detector (x_{det},y_{det}) position by using calibration images of spectral calibration lamps taken with the MOVIES pinhole slit. Having these maps allows the quick-look software to bypass the usual *ab initio* wavelength calibration step and apply a good-enough wavelength scale for target evaluation to the raw 2D spectrum.

Similarly, a quick sky subtraction using mature 2D fitting methods like 2D B-splines means that a good-enough for quick-look sky subtraction can also be applied. An image browser would then display these 2D sky-subtracted empirically wavelength calibrated spectra in raw pixel coordinates (eliminating the considerable overhead of remapping the pixels), with the interactive cursor reading (x_{det},y_{det}) pixel position, corresponding wavelength, and ADU per observed pixel so that the queue observer may quickly assess the observation depth. OSU have developed a package like this for the MODS spectrographs at LBT which can deliver such quick-look 2D spectra in around 1 minute after the newly acquired spectral image is delivered to the control computer's hard drive (noting that the MODS program is written in IDL and decidedly not optimized for speed). The analogous program for MOVIES would deliver to the queue observer an image for inspection shortly after the next spectrum in sequence has begun integrating. This can greatly accelerate making decisions about how to tailor exposures times for rapidly-evolving transient sources whose brightness can be assumed to be unknown to a factor of a few, as well as providing crucial data for informed continue/abort decisions during marginal observing conditions.

3.8.3 Data Reduction software considerations

The format of Gemini/MOVIES spectroscopic data is relatively complex, insofar as the echellograms are curved, with variable slit tilt across each order and changing spatial/spectral scales. However, the suite of calibration data that will be obtained (Sections 2.5.4 and 3.3.2) in combination with the stable MOVIES system will ensure high quality, repeatable, science data will be obtained.

Basic detrending of the data will occur in the usual way. Pinhole slit-masks will provide checks and first guesses of the order localization and spectral scales (to be refined by the arcs), and the spatial scale. Various techniques will be investigated to best extract the curved spectra while preserving the noise properties of the data, and here we will leverage the extensive experience obtained by the community in detail with echelle data over the last decade and more, prominent examples of which include VLT/XShooter, Keck ESI and many others.

A&G camera frames should be provided to the P.I. as a time series data cube, or at least the option to have these provided should be made to the P.I. These frames are essential for precision spectrophotometry. Further, if large format EMCCDs are used in the spectrograph optical arm, then these data will also be in the form of a data cube. A few additional tools could be developed in order to best navigate these data cubes and make them more manageable for initial inspection, for example a tool that automatically stacks the frames to a certain cadence.

We anticipate making modules available to perform all basic data reduction steps, written in a language convenient for the astronomy community (likely Python).

3.9 Technical risks

Minimizing risks was one of the driving principles behind the realization of the design of MOVIES. The instrument is a careful selection, and arrangement of proven technology solutions that expressly avoids unproven components. Specifically:

3.9.1 Flexible Design

The MOVIEs team are dedicated to a design that is flexible in nature with respect to the sub-components; at all levels.

Realizing a single, large, cryostat, the inner working space is actually quite generous and open. The front acquisition region provides a large clear area to mount the selection mirror slide and three almost identical acquisition arms. In the 80K spectrograph section, a full side is dedicated to each spectrograph. Orientation of the spectrographs in a plane simplifies the implementation and alignment of these systems, as well as providing flexibility for potential upgrades.

This makes it easier to consider alternative detectors and mechanisms during the design phases, and minimizes the impacts should a change be necessary, such as due to availability issues or the availability of a superior, low-risk, alternative.

3.9.2 Integrated Cryostat

The overall infrastructure (single cryostat) is a well-established methodology, both at Gemini and at all of the partner institutes, and in particular at the mechanical lead institute of OSU. Managing mid-sized cryostats is well understood, and provides a protected, constant environment for the spectrographs and acquisition components.

The sub-components also benefit from a common mechanical platform, which significantly, and simply, minimizes flexure concerns.

The long and successful heritage of the cryogenic mechanisms provides a proven 'library' of mechanisms and processes to produce highly reliable sub-components. We feel that the added complexities are well justified. These include:

- Requirement to align the VIS spectrograph at cryogenic temperatures. This will be a copy of the NIR arm alignment process, so will not be done in isolation.
- Having a two-temperature cryostat. The front-end will operate at a temperature of about -15C in order to leverage commercial camera assemblies for the acquisition cameras. However, this is also a well-established concept.
- Operating the VIS CCDs (spectrograph and slit viewer) in an 80K environment. This will be accomplished by the thermal path design and heater control. The primary detail to address is baffling to prevent the NIR arm from 'seeing' the radiation from these devices operating at about 120K.

3.9.3 Detectors

The baseline detectors and controllers for the spectrographs are both well-established Astronomical workhorse devices: the EEV 42-90 and the Teledyne Imaging Sensors H2RG (as already used by other existing Gemini instruments). In both cases there is no question about their low-risk technical capabilities.

For the VIS acquisition cameras, the baseline camera systems are from commercial vendors (with at least three potential vendors). The NIR camera module has at least three vendors producing suitable models (although at the moment two of these are smaller pixel counts), although we expect that within a couple years more, and even better modules will be available in commercial versions.