Feasibility Report for 

`IMAKA

the GLAO/OTCCD one-degree visible camera for CFHT

1 October 2008
Image quality performance of `IMAKA versus HST's ACS and CFHT's MegaCam. The top left panel represents a 50 by 50 square arcsecond section of the COSMOS field captured by ACS (0.5h integration in the i' band, sampling 0.05''/pixel). Top right is the ACS image smoothed to a 0.2'' image quality, the best `IMAKA could deliver. Bottom left is the ACS image smoothed to a 0.3'' image quality, the median behavior expected from `IMAKA. The bottom right panel represents what CFHT can do at its best now with MegaCam: 0.6'' image quality on a 8 hour stack.
## The `IMAKA` Team

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Executive Summary

CFHT is scientifically competitive with 8-10m telescopes as a result of the CFHT Wide-Field Imaging Plan started in 1996 which culminated with MegaPrime and WIRCAM, two innovative and technically challenging wide field imaging capabilities taking full advantage of the superb site and well matched to key science issues. Scientific needs and strategic positioning now indicate that the single most important observational parameter to improve is the image quality, while retaining the field size at about one degree. Mauna Kea, once again confirmed as the best site in the world for its free-atmosphere seeing by the Thirty Meter Telescope's five years site campaign, is one of the defining assets for CFHT, thought to be built on the best location of the summit ridge. We propose an instrument concept that builds on these key strengths: the heritage of wide-field of view imaging, the site, and its community.

`IMAKA will keep CFHT as the worldwide powerhouse in high resolution wide field imaging, working in an image quality regime usually only associated with space bound facilities. Better images in the optical increase sensitivity depths to a level where CFHT will play an important role in z>7 galaxy searches, high redshift supernova cosmology, weak lensing and galaxy and stellar evolution. Moreover, better images quickly reduce confusion noise in crowded fields such as star clusters and dense regions in the Milky Way allowing greatly improved photometry and astrometry.

Even with HST equipped with the new Wide-Field Camera 3, there will not be near-diffraction limited optical imaging capability in the optical region over such a wide field available anywhere other than CFHT. On the ground, current 8-10m telescopes to be equipped with multi-conjugated adaptive optics (MCAO) and ground-layer adaptive optics (GLAO) are limited to fields of about one arcminute diameter (MCAO) and ~5-10 arcminutes (GLAO) in the near-infrared. To be most effective, `IMAKA should come online at roughly the same time as JWST in 2013. This will require timely decisions.

Our technical study finds that the requirements are best met with a ground-layer adaptive optics system using an adaptive secondary. Our modeling finds that GLAO combined with OTCCDs can provide images with resolutions of 0.2-0.3”. In the galactic plane the sky coverage is very high and only limited by field crowding. At the North Galactic Pole, the GLAO-only sky coverage is > 95% and full GLAO+OTCCD sky coverage is ~ 40%. The approach provides the potential to benefit all downstream instruments at CFHT and provides a straight forward upgrade path to diffraction limited observations in the visible and near-infrared regimes. It must be emphasized that this is a state-of-the-art instrument that relies on recent GLAO concepts and AO components. The “rough order of magnitude” cost is $12M. Our report establishes the desirability and feasibility and urges a deeper design study.
1. Introduction

Wide field imaging surveys with modest telescopes have produced a surprising number of the most significant discoveries in astrophysics of the past decade. These discoveries include the approximate redshift of the epoch of re-ionization, the realization that dark energy dominates the energy budget of the Universe, and the discovery of major new satellites around all the giant planets in our Solar System. These have served to inspire specialized telescopes designed in the knowledge that well-calibrated imaging data will always be fundamental to virtually any investigation. We present a new capability for CFHT that has an angular resolution within a factor of 2-3 of that of the Hubble Space Telescope, but with a field of view that is about 400 times larger in area than that of HST’s widest Camera, the ACS. Its combination of angular resolution, field of view, and aperture give it a scientific capability unmatched by any ground-based telescope.

Mauna Kea is well established as having superb seeing and the location of CFHT is believed to be one of the premier sites on its summit. Atmospheric studies on Mauna Kea find two important results: (1) the free-atmosphere seeing on Mauna Kea is excellent and (2) the turbulence near the ground is confined to within tens of meters above the ground with little or no optical turbulence within the range of 100m<h<1km. Roughly half of the total optical turbulence arises within 30-50 meters of the telescope. The likely causes of this are the usual suspects: ground-layer seeing, dome seeing, and mirror seeing. To overcome these problems, one might be tempted to build a pier (30-50 meters tall), improve the enclosure design (preferably no enclosure), and mitigate all of the heat sources within the CFHT enclosure and building. This brute-force approach has its merits though it seems highly implausible that such an approach can be implemented, fiscally and logistically, to achieve its intended goal.

We propose a more creative and cheaper solution. A ground-layer adaptive optics system addresses the source of half of the total optical turbulence: the turbulence arising close to the ground. This correction is isoplanatic over the full one-degree field of view and removes atmospheric turbulence and turbulence arising around or within the enclosure. CFHT will be limited only by the free-atmosphere seeing. The next worst offender of image quality, wavefront tip/tilt arising at high altitudes, is then addressed by orthogonal-transfer CCDs in a clone of the PanSTARRs1 1.4-gigapixel camera. The net result is a delivered image quality of 0.2-0.3” in the visible over one-degree fields of view.

We present here the results of the ´IMAKA feasibility study for the Canada-France-Hawaii Telescope completed through a collaborative effort of members from all of the CFH partners. In summary, we find that (1) the instrument is scientifically compelling, (2) the instrument is feasible and (3) image resolutions of 0.3” or better can be obtained at visible wavelengths over one-degree under median or better intrinsic seeing conditions. Recent technological advances provide the means to image quality improvements but the CFH telescope itself and the historical strengths of the CFHT observatory and its community are equally important ingredients to the instrument's feasibility.

CFHT is uniquely positioned to deliver and exploit the capabilities of ´IMAKA.

In the following sections we present the broad scientific case for ´IMAKA, the baseline instrument and its performance, and a plan to develop ´IMAKA to the next stage of its design.
2. CFHT Science with `IMAKA

Science Goals of Ground-Based Wide Field Imaging

The following science cases were contributed by the members of the `IMAKA team. They remain true to CFHT's current scientific legacy spanning the Solar system, stellar physics, galactic structure, galaxy evolution, and cosmology. Overall the goal here is to provide a capability that has an angular resolution about a factor of 2 (ideally) to 3 (more realistically) worse than HST, but, with a field of view that is about 400 times larger in area than the HST ACS camera. What are some of the science opportunities that `IMAKA could exploit?

The Outer Solar System

The outstanding questions in the study of the Outer Solar System and its small bodies are determining the luminosity function of the various dynamical populations, obtaining a representative census of the resonant populations, finding the intermediate to large separation Kuiper Belt Object (KBO) binaries (0.5" and above), and finding very distant objects.

Probing the luminosity function past the roll-over at magnitude = 27 (up to magnitude = 28 in pencil-beam mode) probes both the accretion phase (shown by the slope at the bright end of the luminosity function) and the collisional erosion phase (at the faint end). Comparing the luminosity functions for the classical, resonant and scattering objects will tell us the original location of each of these populations which may have been pushed to their current location from widely separated formation zones.

The resonant populations are fossil markers of the past migration of Neptune and hence probe the early spreading of the giant planets to their current positions. Because of their restricted direction of pericenter (with respect to Neptune), these objects can be seen only in a small portion of the sky, above a given magnitude. In the PanSTARRS era, which is expected to discover all Trans-Neptunian Objects (TNO) brighter than R-magnitude 24, the capability of `IMAKA to reach magnitude = 26 or fainter in a single 5 minute exposure over a large field means that it will be able to find many more resonant objects than PanSTARRS ever will.

Due to `IMAKA's superb image quality and depth, we will find a sizeable sample of intermediate to large binaries (separations 0.5" or more) with a difference in brightness of up to 1 magnitude or more. Binaries are essential probes of the dynamical and collisional environment in the early stage of the Solar System. The very large separation ones are also extremely sensitive to the collisional environment throughout the Solar System history.

Large scale, shallow surveys have shown the existence of large, distant bodies like Sedna and Eris. The depth reachable with `IMAKA will allow searches for smaller and/or more distant objects. These distant objects are the link to the Oort cloud, and the remnant of the strong scattering that occurred on the outskirts of the early Solar System.

Another probe of this period is given by the irregular satellites of the giant planets, thought to be small bodies captured after their formation. The number, dynamical grouping and size distribution of these
small bodies are indicative of the capture mechanism and the collisional environment of the giant planets after their small satellites were captured.

**Extrasolar Planets**

Planet transits are a potentially powerful discovery tool and a powerful probe of the properties of systems discovered via radial velocity techniques. The ideal instrument needs exceptional PSF stability, exceptional astrometric stability, exceptional calibration stability and the ability to work well in the dense star fields that allow these properties to be fully exploited to search for milli-magnitude brightness variations. The desirability of this type of measurement is immense. There are estimated to be about 1 in 10,000 planetary systems that cause eclipses above 10 milli-magnitudes (Jupiter eclipsing our Sun is very close to ten milli-mag) which is at best a 1 sigma detection with the current MegaCam, given considerable care and specialized calibration. "IMAKA should have specifications that will allow it to work at 2-3 milli-magnitudes over a large field, which will open up entirely new exploration space.

**Sub-Stellar Astrophysics**

Investigating the origin and physical properties of brown dwarfs has been a hot topic in stellar astrophysics over the last decade. In terms of their formation, their interior structure, and their atmospheric physics, brown dwarfs sample the transition between low-mass stars and giant planets and thus represent a testbed for our understanding of stellar and planetary physics. Major outstanding problems include:

a) Formation: As of today, we do not have a good understanding of the physics that determines the low-mass end of the Initial Mass Function. A number of processes have been put forward as potentially important ingredients for the formation of very low mass objects, including dynamical interactions, photoevaporation and turbulent fragmentation. Future surveys should aim to provide observational diagnostics like binary statistics, spatial distribution, kinematics, and the slope of the IMF, to constrain the relative importance of these mechanisms.

b) Fundamental parameters: The currently available models for the fundamental properties of brown dwarfs (i.e., interior structure, evolution, atmospheres) are poorly constrained by observations. Only one substellar eclipsing binary (EB) has been found to date, which has already revealed severe problems with the current generation of models. Identifying EBs in the very low mass regime for various ages is the way to provide a better framework to improve the models.

c) Rotation: Rotation, a key parameter in the evolution of stars and planets is strongly coupled to the formation processes, the interior structure, multiplicity, and the properties of the magnetosphere. Comparing rotation rates of brown dwarfs with models for the angular momentum evolution can in principle provide strong constraints on the physics of these objects. In addition, rotational data provides a means to estimate ages and radii. Currently, only about 30 rotation periods are known in the substellar regime, most of them at very young ages.

All three problems are even more acute in the planetary-mass regime, i.e. for objects with masses below the deuterium burning limit (<15M_{Jup}). Initial studies on these isolated planetary mass objects demonstrate that they constitute the natural extension of the brown dwarf regime to even lower masses, but the current constraints on the nature and physics of these objects are very limited.
With `IMAKA we will be in the position to tackle these issues. The combined properties of `IMAKA, i.e a square degree field, excellent spatial resolution, high photometric accuracy and depth, are crucial for further progress in this field. Two programs would be particularly useful to address the aforementioned problems.

1) Extremely deep imaging: Multi-filter surveys in the optical are the established method to identify very low mass candidates in star forming regions, young clusters, and the field. In addition to the photometry, proper-motion measurements are feasible, with estimated accuracies <4mas/yr (for >3yr baseline), easily allowing for the detection of objects in many classical young clusters (e.g., Pleiades, Praesepe, Alpha-Per, IC4665) and providing re-assurance for the membership of the candidates. The current mass limits are \(~10M_{\text{jup}}\) for ages <10 Myr, \(~30M_{\text{jup}}\) for 100 Myr and \(~50M_{\text{jup}}\) for 500 Myr. In a few regions, deeper surveys are underway, using 8-m telescopes, but they are limited to small area coverage. `IMAKA has the potential to push the limits to \(2M_{\text{jup}}\) for ages <10 Myr, \(5-10M_{\text{jup}}\) for 100Myr, and \(10-20M_{\text{jup}}\) for 500Myr. With the wide field of view, surveys can fully cover about a dozen known star forming regions and young open clusters. With the excellent spatial resolution, such surveys will be able to detect all wide binaries with separations \(>50\text{ AU}\), an excellent constraint on the early dynamical evolution of the objects. `IMAKA will allow us to obtain a census of all products of the star formation process, and investigate frequency, multiplicity, spatial distribution of brown dwarfs and planetary mass objects as a function of environment and age. Additional science goals include studies of kinematics and cluster evaporation at very low masses.

2) Photometric monitoring: Variability surveys in the optical provide a wealth of information about the targets, and can be used to search for eclipsing/transiting systems, to measure photometric rotation periods, and to obtain limits on flare rate and spot activity. In ultra-cool objects, there is additionally the potential of observing ‘weather’, i.e. photometric variations due to dust clouds in the atmospheres. The limiting factor for all these goals is the photometric accuracy. With `IMAKA, the anticipated photometric noise will be in the range of \(~\text{mmag}\) and thus a factor of at least 3 better than the current generation of variability surveys. Combined with a high dynamic range, this will give excellent signal-to-noise for very faint objects. The high spatial resolution helps to avoid source crowding, while the square degree field is an advantage in terms of observing efficiency. About ten young clusters are sufficiently compact and nearby, so that mmag variability surveys down to planetary masses would be feasible with `IMAKA.

**Stellar Astrophysics**

Stellar research involving imaging, whether in star clusters or in the field, benefits enormously from a smaller PSF and a wider field of view. The smaller PSF allows fainter stars to be discovered against the noisy sky background – particularly if it has a sharp core containing a significant fraction of the total energy. HST has such a PSF and this is one reason that it has done so well in this research – allowing detection and measurement of lower luminosity/mass objects. This has pushed the detected main sequence mass limit, even in globular clusters, down to and below the hydrogen-burning limit, and allowed for the discovery of the coolest white dwarfs in ancient star clusters. A sharper PSF also allows for better centroiding of the stellar image yielding improved proper motion measurements which help in isolating pure cluster samples or in the search for exotic stellar objects in the field. Proper motion surveys with `IMAKA on CFHT will produce open cluster CMDs devoid of field stars which will be used to age the system (providing a detailed star formation chronology of the Galaxy), explore the mass function to the limits of hydrogen burning, yield samples of white dwarfs which will feed spectroscopic studies on 8
to 30m class telescopes and provide dynamical information via proper motions. Such studies using CFHT imaging data have already solved a potential crisis in stellar astrophysics where the white dwarf cooling age was found to be significantly younger than the turnoff age of an old open cluster. In the field, stellar streams can be isolated via proper motions providing a history of galactic accretion. Ancient white dwarfs, the only observable remnant of the high mass end of the Pop II mass function, will also be located answering whether they contribute significantly to the MACHO population and providing an independent age estimate of the Galactic halo.

The European Space Agency's GAIA mission, due to be launched in 2011 stands as probably the most ambitious space experiment ever attempted. This astrometric satellite will measure the parallaxes and proper motions of up to a billion stars in our Galaxy. A small number of bright stars in nearby Local Group galaxies will also be surveyed. The GAIA data is expected to revolutionise our understanding in many areas of astrophysics, particularly the formation and evolution of galaxies, by revealing the various dynamical structures out of which our Milky Way was assembled (be it by wholesale accretion of satellites or in-situ formation in giant star-forming structures). However, a major limitation of GAIA is that the survey is very shallow, reaching only $g \sim 20$. This means, of course, that although GAIA will provide us a full census of nearby stars, the survey will become very incomplete at larger distances. IMAKA could play a key role in complementing GAIA in selected fields, where GAIA targets are too sparse for analysis. If stellar centroids can be measured to $1/30$th of a resolution element, as is readily achieved with conventional cameras, IMAKA could become a powerful proper-motion machine. The S/N required to achieve this centroiding accuracy is $\sim 20$. If an accuracy of $1/100$th of a resolution element was required, S/N $\sim 70$ would be necessary. Over a 5-year operational lifetime one could then measure the proper motions of stars to 0.8mas.

This would open up many scientific studies. For instance, measuring the structure of globular cluster streams is expected to reveal rich details about the properties of the abundant dark matter substructures that CDM theory predicts. Most of these streams (the Palomar 5 stream at 23~kpc is an excellent example) must lie at substantial distances ($>10$kpc), and therefore the GAIA magnitude limit will allow the detection of only a handful of the brighter giant stars in the structure. For the particular example of Palomar 5, by probing down to $g = 25$ instead of $g = 20$, for instance, there is an approximately 16-fold increase in the statistics of member stars.

**Resolved Stellar Populations**

IMAKA can potentially offer unrivaled opportunities for the study of the resolved stellar populations of nearby galaxies out to the distance of the Virgo cluster. Many of the key predictions of galaxy formation theories - such as the spatial distribution and morphology of the structure and substructures in the outer regions of galaxies - are only testable for the nearby Universe. Thus observations of the stellar populations of these galaxies provide direct tests of – and constraints on - cosmological models of galaxy formation.

Much of our detailed knowledge on the stellar structures of galaxies come from observations of Local Group galaxies which subtend large areas on the sky. Here, IMAKA will be unrivaled in its ability to probe large areas to significant depths with high resolution. Typically, IMAKA will be able to survey galaxies in the Local Group to well below the red clump/horizontal branch. These features provide key diagnostics for disentangling age/metallicity degeneracies in resolved stellar population studies. This will enable spatially resolved star formation histories to be derived which will allow for the baryonic
evolution of these systems to be reconstructed from early times to the present day over very large areas. For example, there is accumulating evidence that the IMF is likely to be Universal. 'IMAKA will be able to measure the IMF for the Galactic Bulge and the nearest dwarf spheroidals. By doing so it will test the universality of the IMF as a function of metallicity and environment. 'IMAKA will also be able to conduct these studies in otherwise crowded fields such as the important disk/halo interface regions in M31 and M33 and the inner regions of many of the more distant dark matter dominated dwarf galaxies.

New surveys in both the Milky Way and M31 have recently uncovered dozens of dwarf galaxies (e.g., SDSS). Yet, both the luminosity function of these objects and the expectations from simulations of galaxy formation indicate that many more lower luminosity dwarfs exist. 'IMAKA offers a wide field of view with increased sensitivity, ideally suited to finding these objects in a large stellar halo such as M31. A more complete census of dwarf galaxies directly confronts hierarchical cosmological models on small scales. The sharper PSF will also allow the giant and horizontal branch populations of these galaxies to be traced into the core, and therefore lead to a much more detailed analysis of the structural properties and radial gradients of these systems. Such data, even for the currently discovered satellites, will aid in our interpretation of the causes of the different properties of the satellite system (both internally and when comparing Milky Way dwarfs to M31 dwarfs). For example, it is still unclear whether the observed differences are caused by in situ processes within the dwarf satellites or through dynamical interactions with the host.

'IMAKA will extend the science which is currently only possible in the Local Group to all galaxies within 5Mpc. Its large field of view and high resolution means 'IMAKA is ideal for probing the faint outer regions of galaxies to low surface brightness allowing for the detection of ultra-faint stellar streams, dwarf galaxies and stellar halos. Did galaxies accrete most of their mass/stars at early or late times? How many mergers does a typical galaxy undergo? What is the lowest mass dwarf galaxy which can form stars? Currently, these questions are restricted to the Milky Way, M31 and M33. While 'IMAKA will be able to probe the outer haloes of these latter galaxies to typically 35 mag/sq.arcsec - at least one magnitude deeper than current CFHT/MegaCam studies - it will also allow for similar science in the M81 and Sculptor groups. Obtaining a significant sample of resolved stellar halos to low surface brightness is central to advancing cosmological models of galaxy formation. 'IMAKA will provide a new perspective on our nearest neighbors.

We note that current HST-based projects are probing some nearby galaxies with these science goals, but all are placed at a serious disadvantage due to the impossibility of observing a large fraction of the area of nearby galaxies with the (relatively) small field of ACS/WFC3. High resolution wide field cameras such as 'IMAKA are an essential pre-requisite for this science. A lesson learned from these surveys is that no firm conclusions regarding the properties of the outskirts of galaxies can be drawn from observations sampling unrepresentative galactic volumes. An eloquent example of this is the single pointing ultra-deep ACS observations of a minor-axis field in the halo of M31 (GO-9453) that was realized later to fall close to a highly disturbed and clumpy structure discovered in the panoramic survey of M31. Panoramic coverage provides the only avenue to unlock the secrets of the outskirts of galaxies, and to fully exploit what they have to tell us about galaxy assembly.

'IMAKA can contribute enormously to this field by surveying the halo populations of all northern galaxies out to ~10Mpc, thereby extending the studies of the central regions performed with HST. At 10Mpc, the 1 square degree field corresponds to 175kpc. Such data would allow one to measure the spatial structure of extra-planar stars, measure axial ratios, map halo flattening to very faint isophotes,
determine the metallicity distribution of halo stars and their spatial variation, search for substructures, investigate their properties, search for clumpiness due to tidal streams or dissolving dwarf galaxies and asymptotic giant branch (AGB) stars associated with intermediate-age stellar populations. It will be necessary to measure at least the top 1 magnitude of the RGB out to 10Mpc. At that distance the RGB tip occurs at $i = 25.8$, so we require data that reach $i = 26.8$, $g = 28$ with S/N $\sim 10$.

Contamination from Galactic foreground populations can be removed by comparison to the Galactic synthesis models, although this is minimal given that the RGB stars will be substantially fainter than the Milky Way disk dwarf sequence at the same color. One of the main factors that limits the ability to detect faint stellar components with normal ground-based observatories is contamination by faint background galaxies that are misclassified as stars. This should not be significant however with 0.3 arcsecond resolution images. Extant ACS data can be used to ascertain the level of completeness and contamination.

More distant still, IMAKA will be able to resolve the tip of the red giant branch (TRGB) in the Virgo cluster ($i \sim 27$), and so measure direct distances to these galaxies based upon their resolved stellar content. The TRGB is a robust distance indicator used extensively in the nearby Universe. Thus we have the opportunity to measure, for the first time, the three dimensional structure of the Virgo cluster.

The Structure of Nearby Galaxies from Nuclear to Cluster Scales

Galaxy merging and feedback mechanisms associated with accretion onto supermassive black holes (SBHs) are thought to be two of the most important processes regulating galaxy evolution. A powerful approach to understanding the modalities by which these processes unfold is through a deep, wide field, high spatial resolution study of local galaxies, designed to map their structural properties from parsec to 100kpc scales.

Galaxy cores. At one extreme of this range, the structural and dynamical properties of galaxy cores – a term hereby used loosely to describe the innermost few tens of parsec regions - are strongly affected by the evolutionary history of their host galaxy. For instance, the low-density cores detected in the brightest early-type galaxies are thought to be scoured by the evolution of the SBH binaries that form as a consequence of galaxy merging; at higher redshifts, accretion onto these SBHs is responsible for regulating the level of star formation in the host galaxy. Comparison between the present-day structural properties of the cores and N-body simulations of merging galaxies and their central SBHs, have the potential to set tight constrains on the merging history of the host, as well as to the amount of dissipation accompanying such events. Fainter galaxies are characterized by steep density cusps and compact stellar nuclei; indeed recent HST studies have revealed such nuclei to be a defining characteristic of galaxy cores and a natural by-product of galaxy evolution. Because of their privileged location at the bottom of the potential well, stellar nuclei act as repositories of the gas and dust accreted during merging events, so their detailed ages and metallicities provide a direct link to the evolutionary history of the host galaxy. Moreover, the discovery that nuclei and SBHs are linked to global galactic properties by identical scaling relations suggests that both types of object share a common formation mechanism, and that the same mechanism is also responsible for shaping the global galactic structure.

Stellar nuclei have half light radii of order 4 pc, or 0.05 arcsec at the distance of the Virgo cluster (16.5 Mpc). High angular resolution therefore is essential for the study of galaxy cores, and it is not surprising that much of the current knowledge of these regions comes from HST imaging surveys. Such knowledge is based largely on HST observations of a magnitude limited ($M_B < -15$) sample of 143 early-type
galaxies in the Virgo and Fornax clusters, and a sample of 39 late-type galaxies, mostly in low density environments. Late-type galaxies in cluster environments, as well as early-type galaxies in low density environments, remain largely unexplored.

**The Intracluster Light.** On hundreds of kiloparsec scales, the intracluster space is permeated by stars that have been stripped from their parent galaxies via gravitational interactions with other galaxies or with the cluster potential. The structure, mass and dynamical properties of this intracluster light (ICL), which can comprise as much as 40% of the total cluster luminosity, are direct probes of a cluster’s assembly history and of its current evolutionary state. Individual ICL streams can also be used to trace interactions between individual galaxies.

The ICL has characteristic $V$-band surface brightness fainter than 26.5 mag arcsec$^2$. Deep images, a wide-field of view and an extremely well characterized instrument coupled to optimal observation methods (at the 0.2% of the sky level) are a prerequisite.

**'IMAKA’s advantage.** 'IMAKA will enable us to build a comprehensive picture of the fossil record of galaxy evolution from intracluster to nuclear scales. Thanks to its high spatial resolution (indispensable in the study of galaxy cores), and wide field of view (a prerequisite for the study of the ICL), 'IMAKA will be able to efficiently carry out extensive surveys of the core, global and intracluster properties for galaxies in groups and clusters within 20 Mpc, sampling both low and high density environments. Imaging in the optical from the blue up to 1 micron will allow us to study the distribution and amount of ICL, measure the incidence of morphological peculiarities (e.g. dust, stellar disks, rings, streams, etc.), quantify the prevalence of stellar nuclei and (in the nearest galaxies) constrain their structural properties, and map stellar populations over unprecedented volumes and across widely differing environments.

The data will provide a wealth of information critical to our understanding of galaxy evolution. For instance, 'IMAKA will be able to address whether galaxies in the field undergo a more protracted star formation history than those in a cluster environment, a process that is expected to affect the characteristic galaxy magnitude at which the transition from low density cores to stellar nuclei occurs. More generally, by quantifying the difference in the core and intracluster structure as a function of the local galaxy density, 'IMAKA will provide an observational backdrop for CDM simulations of galaxy formation. The latter predict that environment affects the structure and stellar populations of galaxies by controlling the merging rate, regulating the efficiency of gas cooling and subsequent star formation (in competition with AGN feedback), and through processes, such as stripping and harassment, that operate preferentially in dense regions.

**Galaxy Formation and Evolution**

HST and the 8m class telescopes have pushed the study of galaxy formation activity up to nearly redshift 7. Although galaxies are greatly reduced in numbers and are relatively low mass, it is clear that galaxy formation must be initiated at a yet higher redshift. There are two broad directions to future research. First, the existing samples are pathetically small with huge discrepancies in number density between discovery methods and fields—nearly two decades of difference in the numbers per unit area in some cases. Increasing the survey areas will reduce the uncertainty and more importantly it will allow studies of clustering which is a key tool in associating galaxies with a dark halo mass which then helps set physical scales and provides a knowledge of the gravitational potential well. A second direction is to go to even higher redshifts. The detections will be made in the near infrared bands, but the optical bands
remain crucial for the null detections that are the cornerstone of the “drop-out” technique.

Further progress requires studies of much larger areas of sky imaged with 0.2-0.3” resolution which will allow us to reach ~27 magnitude depth that JWST and 30m telescopes will routinely probe. Also at redder wavelengths, 0.3” resolution will allow us to perform a morphological galaxy survey up to redshift \(z\sim1\) on very large scales and confront the predictions of galaxy evolution models from the forthcoming generation of cosmological simulations.

At lower redshift, we will be able to reconstruct the star formation histories of nearby galaxies using multi-band photometry of their resolved stellar populations. In a complex population hosting a mix of chemical abundances and ages, an accurate star formation history can be reconstructed from photometry reaching \(M_i = -4\), which for 'IMAKA will reach out to the Virgo Cluster.

The enhanced resolution provided by 'IMAKA will impact on this work in at least three ways. First, because galaxies at \(z > 5\) are expected (and so far have been found) to be very compact, the enhanced resolution boosts survey depth enormously; if point source extraction can be performed with apertures as small as 0.5 arcsec, the CFHT will be able to detect galaxies significantly fainter than \(L^*\), even at \(z > 6\). Second, 'IMAKA imaging will provide important constraints on galaxy size, even for objects which remain unresolved, constraints which recent HST-based studies have shown to be of crucial importance for understanding the physics of galaxy evolution. Third, it will be possible, even at \(z > 6\), to explore the connection between galaxy formation and merger driven starbursts. Finally, by enabling the imaging of such large numbers of high-redshift objects, this instrument will play a crucial role in selecting rare or representative objects for targeted follow-up with JWST, ALMA and ELTs (TMT and E-ELT).

**Extragalactic science and photometric redshifts**

Constraining the cosmological scenarios for galaxy formation and evolution implies the availability of statistically significant samples of galaxies from \(z\sim0\) to look-back times as large as possible beyond \(z\sim1\). The combination of wavelength coverage, image resolution, photometric depth and quality achieved by 'IMAKA on a large effective area provide a privileged framework for the study of galaxy evolution based on photometric redshifts, extending the existing spectroscopic datasets both in terms of sampling factor and towards the faintest limits in magnitude. Large and complete samples of galaxies will be selected in luminosity, density, and (photometric) redshift, containing enough galaxies to be compared to samples in the local universe. The relationship between galaxy morphology, luminosity, color (type) and environment as a function of redshift could be understood in greater detail with photometric redshifts used to achieve a uniform coverage in the parameter space of interest. The efficient sampling of the different galaxy environments all the way from the local universe to high-z requires a large field of view (minimum 1 square degree), which is also required for clustering studies and to mitigate field-to-field variance. The evolution of the overall properties of galaxies (Luminosity and Mass Functions, color/type distributions, ...) as a function of redshift and environment constitutes a powerful test to discriminate between the different scenarios of galaxy formation, in particular for galaxies at \(z > 1-2\). This is indeed a key redshift domain where most galaxies were affected by major merging/assembly processes requiring deep optical photometry, extending as far as possible towards the near-IR to probe stellar masses, thus constraining the cosmic star formation history.

Photometric redshifts with 'IMAKA are particularly interesting for the identification and study of high-redshift clusters and proto-clusters in a cosmological context, when used together with standard
cluster/structure finding algorithms, because they optimize otherwise time-consuming or simply unfeasible spectroscopic observations. Photometric redshifts are also useful in lensing studies to discriminate between foreground and background galaxies, and to determine the background redshift distribution of sources in order to derive masses from weak lensing analysis. Photometric redshifts with IMAKA could be used to pre-select galaxies in the sensitive redshift domain for subsequent spectroscopic surveys aiming at constraining the dark energy via precision measurements of the baryon acoustic oscillations (BAOs).

The improved spatial resolution, photometric accuracy and depth achieved by IMAKA on the goal wavelength domain should provide high-quality photometric redshifts ($\sigma(z) \sim 0.03-0.05 (1+z)$) at least up to $z \sim 1.3$ and beyond $z \sim 2.5$, with only a few percent of catastrophic identifications. The precise redshift domain where accurate photometric redshifts could be obtained depends on the final wavelength coverage of IMAKA. Extending the use of photometric redshifts all the way from $z \sim 0$ to $z \sim 10$ requires the addition of near-IR bands, at least up to 1.4 microns. Without near-IR photometry, the goal wavelength coverage towards the UV is important to mitigate the fraction of catastrophic identifications between low ($z < 0.2$) and high ($z > 1.5$) redshifts, and also to lower the redshift limit accessible to high-$z$ studies based on the detection of the Lyman alpha break (ideally $z > 2.2$). The wavelength coverage towards the near-IR obviously determines the upper limit in redshift for the detection of the major spectral discontinuities, namely the 4000A break (leading to $z < 1.3$ without near-IR) and the Lyman alpha break. The gain when enlarging the wavelength domain is also sensible for the determination of rough spectral types (early to late type galaxies, star-galaxy-qso discrimination).

Because high-quality photometric redshifts require the time-consuming acquisition of a large and representative training set of spectroscopic redshifts, photometric accuracy and stability (both in time and over the field) are key issues for IMAKA.

**Cosmology**

The remarkable discovery that the expansion of the Universe is accelerating is considered by many as the greatest discovery in cosmology in the past 80 years. The implications of this discovery are profound: 70% of the energy density of the Universe is in the form of some unknown repulsive field, which we call dark energy. Understanding dark energy is the "holy grail" of cosmology and fundamental physics.

Observations of Type Ia supernovae out to redshifts 0.8-0.9 reveal that, to first order, dark energy appears to act as a pure cosmological constant - that is, the equation of state parameter, $w=dP/d\rho$, is -1. To constrain the nature of dark energy any further than this, and to distinguish among several possible models for dark energy, requires a measurement of the variation of $w$ with redshift. Current limits on redshift variation are not strong enough to be constraining on fundamental physics at the present time.

To advance beyond our current knowledge requires, among other things, a larger sample of Type Ia supernovae at redshifts $z > 1$. At these redshifts, the peak in the spectral energy distribution is shifted to the z band and beyond; clearly detection of these supernovae requires much better red sensitivity than MegaCam, and superb image quality to cut down both sky contamination and confusion with host galaxies. IMAKA is ideally suited to such observations.

To effectively undertake supernova measurements requires sufficient imaging area so that substantial numbers of supernovae are followed in every image -- for a 4m there is a fairly hard “barrier” at one
degree, below which multiple fields are required. The `IMAKA field is thus well-matched to studies of supernovae.

Both strong and weak lensing measurements are also developing rapidly as powerful independent constraints on dark matter and dark energy properties. However, to extend lensing measurements to both higher redshifts and smaller scales means pushing towards source plane samples with higher sky densities and larger redshifts. This inevitably means fainter objects, with redder colors and smaller sizes. The gain of `IMAKA with respect to any other imaging capabilities in 2013 will be its outstanding image quality and its percent level absolute photometry. `IMAKA will hardly compete against the next generation extreme wide-field surveys covering 5,000-20,000 square degrees like Pan-STARRS, DES or KIDS/VIKING. `IMAKA will neither be competitive with respect to JSWT for extremely deep imaging surveys. However, it will out perform all of them on surveys covering fields of 10 to 1,000 square degrees. `IMAKA will provide better photometry, better photometric-redshift of sources, a higher galaxy number density of background sources and better shape measurement of lensed galaxies. The coupling of such regions of sky with ESO's VISTA true wide field near infrared capabilities would be a perfect match. The niche of `IMAKA will therefore be galaxy-galaxy lensing, weak lensing of optically selected clusters of galaxies, and accurate weak lensing tomography. A survey covering 1,000 square degrees with such image quality will also provide a huge sample of rings and giant arcs around galaxies and clusters of galaxies. Arcs, objects of angular scale smaller than the atmosphere induced seeing disk suffer dramatic contrast decrease on natural seeing ground-based observations. For example, since sources are generally at \( z > 2 \) and have sizes of \( \sim 0.1-0.2 \) arcsecond and the \( \text{dN}/\text{dm} \) is very steep, clusters like A1689 have \( \sim 500 \) arcs at HST resolution but only \( \sim 10 \) at 0.7" resolution. `IMAKA should produce \( \sim 100 \) arcs at 0.3" images.

From a technical point of view, the most critical issue for lensing studies is the PSF stability. GLAO on `IMAKA solves in principle most of the main limitations of MegaCam for lensing studies. The implementation of wavefront sensors inside the cryostat near the science detector ensures a very stable PSF over the whole field over short (night) to very long (year) stretches of time. There is not yet comprehensive tests of shape measurement carried out with `IMAKA images. However, taking into account its expected image quality and photometric performances, `IMAKA should be able to easily improve the accuracy of ellipticity measurement by at least a factor of 2 as compared to MegaCam, to reduce the field to field scatter produced by PSF instabilities and, together with its outstanding photometric performances, drop the limiting shear amplitude down to the one percent level. To a good approximation both the numbers of lensed galaxies and the maximum magnification are inversely proportional to the angular resolution - meaning that `IMAKA will allow factors of 3 to 4 improvements in lensing measurements.

We now turn to the very high redshift Universe and the nature of the most distant known galaxies. The highest redshift quasar currently known was discovered with CFHT. Such objects probe the era of reionization, a complex process that advanced at different rates in different locations. More quasars at redshifts \( z > 6 \) are required to characterize the onset and development of reionization. Clearly `IMAKA's red sensitivity and image quality are of enormous benefit to detecting such objects.

Even with JWST and 30m class telescopes it will be a huge challenge to push down to the nano-Jansky (mAB ~ 31 mag) range. Strong lensing can, through magnification, raise the brightness of high redshift sources into a much more accessible regime, but it still requires the detection of objects that are 0.1” across and a few arc-sec (or more) long. These are rare and can appear anywhere along highly irregular
critical lines at ~5-20 arc-minute radius in a galaxy cluster. The challenge is to build the sample to a large enough size that it becomes a statistically understood representation of the properties of the high redshift galaxies. This requires deep imaging at ≤0.2” image quality over nearly a square degree per cluster for hundreds of clusters.

**Instrument requirements as dictated by core science requirements**

<table>
<thead>
<tr>
<th>Science Objective</th>
<th>Brightness (for CFHT)</th>
<th>FWHM (arcsec)</th>
<th>Area of sky</th>
<th>Minimum Competitive FOV</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>KBO’s</td>
<td>22-26 mag</td>
<td>0.3</td>
<td>Ecliptic plane+</td>
<td>1 degree</td>
<td>&lt;0.1% relative photometry</td>
</tr>
<tr>
<td>Extra-solar planets</td>
<td>20+ mag</td>
<td>0.3</td>
<td>Galactic plane</td>
<td>1 degree</td>
<td>1% absolute photometry</td>
</tr>
<tr>
<td>Star Clusters</td>
<td>16-27 mag</td>
<td>0.3</td>
<td>All sky</td>
<td>30’</td>
<td>1% absolute photometry</td>
</tr>
<tr>
<td>Structural Properties of Local Galaxies</td>
<td>V &gt; 26.5 mag arcsec²</td>
<td>&lt; 0.3</td>
<td>All Sky</td>
<td>1 degree</td>
<td>Background known at the 0.2 of the sky level</td>
</tr>
<tr>
<td>Galaxy evolution</td>
<td>20-27 mag</td>
<td>0.2-0.3</td>
<td>High latitude</td>
<td>1 degree</td>
<td>3% absolute photometry</td>
</tr>
<tr>
<td>Supernova Cosmology</td>
<td>20-26 mag</td>
<td>0.2-0.3</td>
<td>High latitude</td>
<td>1 degree</td>
<td>1% absolute photometry</td>
</tr>
<tr>
<td>Galaxy clusters at high redshift</td>
<td>18-27 mag</td>
<td>0.2-0.3</td>
<td>High latitude</td>
<td>30’</td>
<td>3% absolute photometry</td>
</tr>
<tr>
<td>z&gt;7 objects</td>
<td>25+ mag</td>
<td>0.2-0.3</td>
<td>High latitude</td>
<td>1 degree</td>
<td>5% absolute photometry</td>
</tr>
<tr>
<td>Transients</td>
<td>23+ mag</td>
<td>0.2-0.3</td>
<td>All sky</td>
<td>1 degree</td>
<td>1% relative photometry</td>
</tr>
<tr>
<td>Weak Lensing</td>
<td>20-27 mag</td>
<td>0.2-0.3</td>
<td>High latitude</td>
<td>1 degree</td>
<td>PSF stability</td>
</tr>
</tbody>
</table>

**Comparison with other ground-based optical wide-field imaging facilities**

Wide-field optical imaging is truly a burgeoning domain with many high profile facilities expected to come online over the next decade. Only two of the following instruments/facilities are planned for running exclusively in survey mode (PS1/PS4, LSST). The other observatories are developing these large wide-field imaging facilities for Principal Investigators type programs and moderately sized surveys (e.g. Dark Energy Survey will not use more than 30% of the Blanco telescope time, this is less than the CFHT Legacy Survey).

The typical etendue estimator quantifies the capabilities of a given instrument to conduct a survey, but it typically lacks the image quality delivered by the telescope plus site, and it does not include the overheads (readout time, filter change), nor the fraction of telescope time the instrument is used to conduct the survey. Since `IMAKA would be a community instrument, we propose a slight evolution for a more tangible metric to evaluate the relative performance of these instruments not at running a survey but covering large areas of skies with good image quality. The metric is essentially the rate at which signal is collected across the field for background limited observations.

\[
\text{Metric} = \frac{A \times \text{FOV}}{(\text{IQ}^2)}
\]

where,

\[
A = \text{collecting area}
\]
FOV = field of view
IQ = image quality

The data are presented in the following table:

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Year</th>
<th>Site</th>
<th>D</th>
<th>FOV</th>
<th>IQ</th>
<th>Scale</th>
<th>Readout</th>
<th>U_band</th>
<th>Y_band</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFH12K</td>
<td>1999</td>
<td>Mauna Kea</td>
<td>3.5</td>
<td>0.33</td>
<td>0.75</td>
<td>0.20</td>
<td>50</td>
<td>N</td>
<td>N</td>
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<tr>
<td>SuprimeCam</td>
<td>2002</td>
<td>Mauna Kea</td>
<td>8.1</td>
<td>0.25</td>
<td>0.65</td>
<td>0.20</td>
<td>50</td>
<td>N</td>
<td>N</td>
</tr>
<tr>
<td>MegaCam</td>
<td>2003</td>
<td>Mauna Kea</td>
<td>3.5</td>
<td>1.00</td>
<td>0.75</td>
<td>0.19</td>
<td>40</td>
<td>Y</td>
<td>N</td>
</tr>
<tr>
<td>PS1</td>
<td>2009</td>
<td>Haleakala</td>
<td>1.6</td>
<td>7.30</td>
<td>0.70</td>
<td>0.26</td>
<td>6</td>
<td>N</td>
<td>Y</td>
</tr>
<tr>
<td>DEC</td>
<td>2012</td>
<td>Cerro Tololo</td>
<td>3.9</td>
<td>3.00</td>
<td>0.95</td>
<td>0.27</td>
<td>20</td>
<td>N</td>
<td>Y</td>
</tr>
<tr>
<td>HyperSuprimeCam</td>
<td>2012</td>
<td>Mauna Kea</td>
<td>8.0</td>
<td>1.50</td>
<td>0.65</td>
<td>0.20</td>
<td>20</td>
<td>N</td>
<td>Y</td>
</tr>
<tr>
<td>‘IMAKA</td>
<td>2012</td>
<td>Mauna Kea</td>
<td>3.5</td>
<td>1.00</td>
<td>0.30</td>
<td>0.10</td>
<td>6</td>
<td>N</td>
<td>Y</td>
</tr>
<tr>
<td>ODI</td>
<td>2012</td>
<td>Kitt Peak</td>
<td>3.3</td>
<td>1.00</td>
<td>0.60</td>
<td>0.11</td>
<td>6</td>
<td>N</td>
<td>N</td>
</tr>
<tr>
<td>PS4</td>
<td>2012</td>
<td>Mauna Kea</td>
<td>3.1</td>
<td>7.30</td>
<td>0.55</td>
<td>0.26</td>
<td>6</td>
<td>N</td>
<td>Y</td>
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<tr>
<td>LSST</td>
<td>2015</td>
<td>Cerro Pachon</td>
<td>6.7</td>
<td>9.60</td>
<td>0.70</td>
<td>0.20</td>
<td>2</td>
<td>Y</td>
<td>Y</td>
</tr>
</tbody>
</table>

- **Year** = year of scientific operation
- **D** = effective diameter (m) [accounting for central obscuration]
- **FOV** = field of view in square degree
- **IQ** = median image quality delivered by the instrument
- **Scale** = pixel scale in arcsecond
- **Readout** = camera readout time (sec)
- **U_band** = N(o) or Y(es) access to the UV (~300nm)
- **Y_band** = N(o) or Y(es) access to the near-infrared (~1 um)

IQ represents the median image quality delivered by the instrument, it is not the intrinsic IQ of the site. The data come from either existing data, or extrapolation based on the expected performance (e.g. PS1/4 and ODI plan on a 0.2” improvement using the OTCCD function) for the given observing site.

The following table lists the facilities with an increasing metric value, normalized to MegaCam, as well as the magnitude in the r band for both a point source and a field galaxy with a signal to noise ratio of 7 (15% photometric error) on a 1 hour exposure for the median seeing listed in the previous table.
<table>
<thead>
<tr>
<th>Instrument</th>
<th>Year</th>
<th>Site</th>
<th>Metric</th>
<th>Point Source</th>
<th>Field Galaxy</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFH12K</td>
<td>1999</td>
<td>Mauna Kea</td>
<td>0.3</td>
<td>26.1</td>
<td>25.4</td>
</tr>
<tr>
<td>MegaCam</td>
<td>2003</td>
<td>Mauna Kea</td>
<td>1.0</td>
<td>26.1</td>
<td>25.4</td>
</tr>
<tr>
<td>ODI</td>
<td>2012</td>
<td>Kitt Peak</td>
<td>1.4</td>
<td>26.3</td>
<td>25.6</td>
</tr>
<tr>
<td>SuprimeCam</td>
<td>2002</td>
<td>Mauna Kea</td>
<td>1.8</td>
<td>27.1</td>
<td>26.4</td>
</tr>
<tr>
<td>PS1</td>
<td>2009</td>
<td>Haleakala</td>
<td>1.8</td>
<td>25.4</td>
<td>24.7</td>
</tr>
<tr>
<td>DEC</td>
<td>2012</td>
<td>Cerro Tololo</td>
<td>2.3</td>
<td>25.9</td>
<td>25.2</td>
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<tr>
<td>`IMAKA</td>
<td>2012</td>
<td>Mauna Kea</td>
<td>6.0</td>
<td>27.0</td>
<td>26.3</td>
</tr>
<tr>
<td>HyperSuprimeCam</td>
<td>2012</td>
<td>Mauna Kea</td>
<td>10.7</td>
<td>27.1</td>
<td>26.4</td>
</tr>
<tr>
<td>PS4</td>
<td>2012</td>
<td>Mauna Kea</td>
<td>10.7</td>
<td>26.4</td>
<td>25.7</td>
</tr>
<tr>
<td>LSST</td>
<td>2015</td>
<td>Cerro Pachon</td>
<td>40.4</td>
<td>26.8</td>
<td>26.1</td>
</tr>
</tbody>
</table>

This table shows that `IMAKA will be in the same league as HyperSuprimeCam when it comes to detection and sky coverage, with the added advantage of far superior image resolution, allowing the exploration of a new scientific window.

In the immediate future, HST's upgrade with the Wide-Field Camera 3 will offer a 16 Mpixels optical channel imager optimized for the UV covering 7 square arcminutes with 0.04" pixels to sample the 0.12" PSF. Gemini's MCAO will offer a 1.7 square arcminutes field of view with a PSF of 0.05"-0.08" only in the infrared.

**A comparison of `IMAKA with the main ground-based competition: LSST, PS4, HyperSuprimeCam**

**LSST (2015-2017)**

The LSST plans on covering a 9.6 square degree field of view using an innovative and challenging optical concept consisting of a 8.4m primary, followed by a convex 3.4m secondary, and then a tertiary 5.2m focusing the light on the camera at the center of the secondary through a wide-field corrector. This leads to a very compact f/1.2 design. The very fast focal ratio will likely cause significant implementation problems in achieving the mathematically designed PSF, and, like Sloan, will either lead to long delay and cost increase or else compromise in the quality and uniformity of the PSF.

The budget for the LSST is currently approaching US$200 millions (design and construction only, the operation cost is not included), and the survey is planned to begin in 2016. The project is still not fully funded and relies on private funding for long lead procurements.

Ninety percent of the LSST time will be devoted to a wide survey aimed at visiting the same area of the sky every three nights in various filters for a total of 20,000 square degrees. The final depth of $r=27.5$ mag. at 5 sigma (SNR=5) will be slowly reached over the 10 years of the survey planned lifetime. The remaining ten percent will be allocated to specific programs such as very deep and fast time domain surveys.
How does `IMAKA compare to the LSST in achieving extensive sky coverage and depth? `IMAKA has about a quarter of the collecting area of LSST but it concentrates the light of point sources into a PSF which is only a quarter of the size of LSST's, so for point sources `IMAKA has just about the same speed as LSST for surveying the sky. However, a big difference in the science from LSST and `IMAKA comes from the proposed usage. LSST intends to sweep over the entire visible sky every 3 nights by spending only 30 sec on each pointing, so each visit is very shallow -- in fact only half the net collection of the Pan-STARRS1 Medium Deep fields. Therefore for transients, LSST will be very shallow, barely reaching $z=0.5$ for SN1a for example. We have seen from the CFHT Legacy Survey the value of high signal to noise light curves of SN1a, and these will be even more important in the next decade as we probe the systematics of determinations of dark energy. `IMAKA should therefore not try to replicate LSST's goal of fast, shallow passes over the sky, but could devote 10 or 20 times more integration on a huge, but limited, subset of the sky (1,000-2,000 sq. deg.) and probe much fainter into the luminosity function and deeper into the volume of transients. Of course this limited area can move around the sky during the full mission of `IMAKA, eventually reaching the same depth as LSST everywhere.

**PanStarrs4 (2012)**

PanStarrs4 will have a light gathering power equivalent to CFHT with a field of view seven times larger than `IMAKA. Just like the LSST, it will be fully dedicated to surveys. `IMAKA makes use of the PanStarrs camera, and it is the GLAO bringing the median image quality to 0.3" instead of 0.55" for PanStarrs4 that will make the difference for specific scientific interests. Again, the etendue of `IMAKA and PS4 are roughly comparable, but it is far easier for `IMAKA to probe the faint end of transients than PanSTARRS4.

As of today, the PanSTARRS4 is something of an unknown, both from the standpoint of funding but also how its medium deep surveys will trade off depth versus area. In addition, PanSTARRS4 does not have any commitment of operating funds, so the provider of such funds may be able to specify that PanSTARRS4 data be proprietary and not available to the Canadian and French communities, on a scientifically competitive timescale. `IMAKA is therefore a very worthy competitor.

**HyperSuprimeCam (2012)**

`IMAKA will go deep as fast as HyperSuprimeCam (a fully funded project), with a comparable field of view, with the added benefit of image resolution. The largest light gatherer in the competition, HyperSuprimeCam on Subaru will however likely suffer from limited access to sky time. It is unlikely to see the telescope's community change its current observing strategy of serving a large suite of instruments and focus instead a very large number of nights to rip off the benefits of such powerful wide-field imager. Punctual deep surveys are to be expected though.

**A comparison of `IMAKA with the space competition: JDEM and EUCLID**


The design is just starting at NASA & DOE and its launch is announced today "for the middle of the next decade". The mission has to address Dark Energy through at least distances to supernovae, BAOs and weak shear. Although the hardware is still undefined, one may guess that these goals impose some wide-
field imaging capability (e.g. a remnant of the SNAP concept with a gigapixel optical channel camera on a 2m class telescope covering a full square degree providing similar image quality as WFC3), but not necessarily a multi-band wide field imager in the visible. Even if JDEM eventually were to benefit of multi-band wide-field imaging capabilities in the visible, 'IMAKA still keeps a window of opportunity of several years open and will offer anyway an easy access to high resolution imaging. One may also note that the supernova cosmology program of JDEM will very likely miss the vital nearby supernovae, to be measured from the ground in consequence. Depending on the choice of the space based minimum redshift, 'IMAKA could provide this high quality ground-based low-to-intermediate redshift supernova sample.

EUCLID (ESA, ~2017)

Still at the competing state, the ESA EUCLID observatory, a 1.2 meter telescope offering a diffraction limited PSF of 0.25 arcsecond over a half square degree not to be launched before 2017, would also bring true wide-field imaging capabilities in space. EUCLID will have simultaneous visible and near infrared imaging channels as well as spectroscopic capabilities, an instrumental setup likely to be found on JDEM as well. Both projects are designed for weak lensing and are expected to provide very stable high image quality. However, it its present design EUCLID has only one single very broad band visible filter (r+i+z) for ellipticity measurements and will rely on multi-band wide-field surveys in the visible from the ground. 0.3 arcsecond wide-field visible surveys with 'IMAKA would turn out to be very useful for EUCLID. In summary, until 2017, 'IMAKA will therefore outperform any other wide-field instrument on the image quality front but will still be useful for ground based follow up later on.
3. Instrument concept

The key subsystems for 'IMAKA are: a wide field corrector for the telescope optics, a ground-layer adaptive optics system, and a visible-wavelength one-degree field of view camera with orthogonal-transfer CCDs. From the science requirements we derive the following top-level instrument requirements:

Top-Level Instrument Requirements:
- Field of view: 1 deg diameter
- Wavelength Range: 0.35 – 1.1 micron
- Delivered image quality of 0.3” or better at r band, FWHM uniform within 10% over entire field
- Photometric measurements with an accuracy of 1% absolute, 0.1% relatively
- Astrometric measurements with an accuracy of 40mas absolute and 0.8 mas relative
- Sky coverage 100% in Galactic plane and ≥ 50% at North Galactic Pole

3.1. Baseline Instrument

Our approach in developing the concept for this instrument focused on the feasibility of the instrument. In this sense the study was not an exhaustive design but focused on the components presenting risk to achieving the full potential of the instrument. We identified the optical design and the deformable mirror as the key feasibility issues for 'IMAKA. We consider the orthogonal-transfer CCD devices, multiple wavefront sensors, and the wide field corrector as low risk subsystems. The OTCCDs are now available from two sources (Lincoln Labs and DALSA). Wavefront sensing using multiple guide stars, is a proven approach with on-sky confirmation (Marchetti et al. 2007, “On-sky Testing of the Multi-Conjugate Adaptive Optics Demonstrator” ESO Messenger, 129, 8 and Lloyd-Hart et al 2005, “First tests of wavefront sensing with a constellation of laser guide beacons”) and multi-WFS facility systems imminent (Gemini MCAO). Finally, the wide field correcting optics while large are viable meeting the image quality requirements with common materials.

Table: Baseline 'IMAKA Instrument

<table>
<thead>
<tr>
<th>GLAO</th>
<th>Adaptive secondary with 6 deployable 10x10 Shack-Hartmann natural-guide star wavefront sensors.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wide-Field Corrector Optics</td>
<td>Three-element transmissive corrector using BK7</td>
</tr>
<tr>
<td>Science Camera</td>
<td>One-degree square OTCCD detector array (PanSTARRs1 clone)</td>
</tr>
</tbody>
</table>

The basic subsystems and their interactions are shown in Figure 1 below. The light from the telescope primary mirror is corrected by an adaptive secondary. The corrected wavefront is passed through the wide field correcting optics to facility wavefront sensors and the science camera. The wavefront sensors pick off only the light from the small portion of the field containing the bright natural guide star. The rest of the corrected field is sent to the science camera. The figure also shows the interaction of the various subsystems. The OTCCD correction is specific to a particular region of the sky and as such is isolated from the rest of the system. The GLAO correction drives the secondary but large slow motions are off-loaded to the hexapod stage and/or the telescope pointing.
3.1.1. Optical Design

The optical design of IMAKA was done by John Pazder (HIA) and Harvey Richardson. To guide the initial optical design we developed a set of optical design requirements. In addition to requirements derived directly from the top-level instrument requirements, we included a second set of requirements based on our initial choices in the baseline instrument:

Science Requirement:
- FOV: 1 deg diameter
- Wavelength Range: 0.45 – 0.9 microns with goal to 0.35 – 1.1 micron
- The optical design should have a FWHM < 0.1” across full field at 0.5 microns

Derived Requirement:
- Final focus plate scale of 100 microns/arcsecond to match PS1 camera
- Variations (RMS) of less than FWHM across the field in any one bandpass < 0.05”.
- Fit within the space constraints at the Prime/Cassegrain focus of the CFHT telescope
- Correcting element conjugation to within 40 meters of the ground turbulence.

The last requirement, the conjugation altitude of the deformable mirror turns out to be the driving requirement for the system. This was not anticipated at the start of the study and flows from the desired
field of view. We present more on this requirement in the following section on the instrument performance.

During the course of the study, several approaches were considered. The progression of optical designs is outlined in Appendix A1. A key question at the onset of the optical design was whether an optical design could accommodate such a wide field of view with good delivered image quality and provide a useful location for an off-the-shelf deformable mirror. These are typically small (diameters~100mm) and the optical design of AOSs usually places the DM at a plane conjugate to the telescope pupil within an optical relay. For these DMs the pupil magnification and the packaging constraints lead to large incident angles and a large tilt of the DM. These large angles exacerbate typically minor issues in non-ground layer adaptive optics systems. First, the tilt of the DM blurs the pupil on the deformable mirror. This is true for any field angle including the on-axis beam. To make matters worse, the effect varies in two-dimensions across the surface of the deformable mirror. Second, the tilted DM effectively gives rise to a DM conjugation altitude that varies across its face. Opposite edges of the DM are conjugate to different altitudes. Finally, for large angles of incidence, the projection of the correction of the DM onto the wavefront varies (as a cosine) across the field. Wavefronts from different field angles see a different correction on the DM surface. To alleviate these problems the size of the deformable mirror is driven to larger sizes (diameter ~ 200mm). With such a DM the optical beams can be packaged with a modest tilt (+/-~6deg) and the pupil demagnification is reduced. Even still the blur radius effect is not negligible. With these tilts, the blur radius corresponds to between 1/10 and 1/5 of a subaperture spacing (for 10x10 and 20x20 subapertures respectively). This limits the spatial resolution of the correction. Larger DMs however increase the volume of the system. For the example given here, the collimator and camera mirrors would be at least 700mm in diameter with separations between optics of order 1.5meters. An optical relay approach is not precluded by our study but results in a very large relay at the Cassegrain focus. Given the resources and time available, we did not pursue this approach. It deserves further consideration with a detailed opto-mechanical design and costing along with improved simulations to compare to other approaches. It is not clear that this approach would be more cost effective than the baseline presented next. However, we note that at least one commercially available DM exists at these sizes for correcting the optical beams of lasers (CILAS 400mm square DM with 48 actuators). The largest conventional DMs designed for astronomical use are currently no larger than ~100-150 mm.

Ultimately, we settled on a baseline approach using an adaptive element within the telescope optics (secondary or other). This provides a cleaner optical system and the potential to benefit other scientific instrumentation. In the baseline instrument, the secondary of the telescope is replaced with an adaptive mirror that provides the wavefront correction. This technique is not new and the adaptive secondary on the MMT telescope had been operational since about 2004. However, while several AM2 systems are being planned or considered (e.g. LBT, Gemini, VLT, GMT, and TMT), only one such system is operational and an AM2 that directly replaces the CFHT f/8 secondary would be one of the largest.

A dedicated feasibility design of an adaptive secondary for CFHT is clearly necessary. For now, given the cost and complexity of such a system, we drove the optical designs to minimize the size of the adaptive secondary keeping the diameter as close to the existing MMT/LBT mirrors as possible while staying close to the optimal conjugation altitude. Note however the desire to minimize the size of the adaptive secondary and to keep the conjugate altitude close to the ground work in opposite directions for the baseline optical configuration. Given the uncertainty in the design parameters of the adaptive secondary, we arbitrarily set a limit of 1 meter for the diameter of the adaptive secondary. The feasibility design for the adaptive secondary will optimize these parameters for the CFHT requirements folding in
The baseline optical design of IMAKA is shown in Figure 2 below. It uses a 1-meter diameter convex adaptive secondary placed 10.5 meters after the primary mirror. This places the adaptive secondary a couple meters beyond the location of the current f/8 secondary and pulls the final focal plane up towards the top end of the telescope. This places mechanical and thermal constraints on the camera and wavefront sensor packages, but allows the use of a much smaller adaptive secondary. A three-element BK7 corrector shows the feasibility of getting good correction over the field (Figure 3). Further work on this design will explore tolerance analysis and ghosting analysis including consideration of 4 element designs which may improve image quality.

Figure 2: Optical Layout of IMAKA fore-optics: 3 element, 1m secondary, F/5.7, +/-0.5 degree field of view. The CFHT 3.6m primary mirror is at the right of the figure. The adaptive secondary (left) is moved approximately 2.4m further from the primary than the location of the existing f/8 secondary (shown as a line between the secondary and the field corrector). The adaptive secondary is 1 meter in diameter, has very little optical power (R~26m), and is conjugate to -46.6 meters. The final (f/5.7) focal plane is located about 2 meters below the location of the existing secondary.
Figure 3: ‘IMAKA baseline optics RMS Spot Radius (focal plane).  At the design plate scale, 10 micron = 0.10 arcsecond.  Note that the GLAO will statically correction some component of this. Its correction, if not at a pupil, will be complex but will tend to reduce the variation in the outer portions of the field where the guide stars are most likely to be.

A key optical design requirement is the altitude the adaptive correction is conjugate to. The details of this calculation are given in Section 3.2 below. As noted previously, for the baseline optical design the diameter of the adaptive secondary mirror was limited to 1 meter and as a result the mirror is conjugate to 46 meters below the ground. For reference the current adaptive secondary is conjugate to -21m and 1.4 meters in diameter. We incur a performance penalty for the fact that the DM is not conjugate to the optical turbulence (h~0). This is accounted for in the instrument performance but note that a detailed design will trade the AM2 cost/complexity with the performance that can be obtained.

While meeting the basic optical design requirements, we note that the baseline optical design is not the only design solution. A diffraction-limited design by Harvey Richardson exceeds the optical design requirements and is presented in Appendix A1. In that design a deformable tertiary mirror is conjugate to the ground and concave in shape. It was not chosen as the baseline design due to the large size and large number of optics in the design but it should be further developed. In addition, a design with a flat secondary is possible. There are multiple optical design approaches that are expected to work.

### 3.1.2. GLAO system

#### Wavefront sensors

From the Gemini Mauna Kea Ground-Layer site characterization campaign (Chun, M. et al 2008, "Gemini Mauna Kea Ground Layer Study", Gemini Report), we conclude that about half of the optical turbulence seen by the telescopes on the summit arises within a thin layer of turbulence between the ground and 30 meters. The order of correction necessary to compensate for this local turbulence on CFHT is modest by today’s standards and the simulation results, presented in Section 3.2, suggest that a 10x10 Shack-Hartmann system will correct for most of the optical turbulence arising within this region. For the wavefront sensors we baseline six deployable Shack-Hartmann (SH) wavefront sensors. With the large field of view of ‘IMAKA, this will provide full sky coverage at even at the Galactic pole. Other approaches are possible (e.g curvature, pyramid, etc.) and may in fact provide advantages over the
baseline configuration. However, the 'IMAKA requirements are not demanding so this simple approach is certainly viable. From the wavefront sensing perspective, 'IMAKA uses existing and proven adaptive optics components. A number of possible improvements for the wavefront sensing exist and optimizing the wavefront reconstruction appears fertile for innovative ideas. Examples that could be explored in the design phase are WFS techniques other than Shack-Hartmann, NIR wavefront sensing, and techniques to monitor and improve the already good PSF uniformity. NIR wavefront sensing may provide benefits of higher sky coverage/higher-order correction, use of the Teledyne Speedster chips, and dichroic beam splitting for the wavefront sensing.

While laser guide stars are becoming more common, the large field of view of 'IMAKA allows the use of natural guide stars and we favor this as the baseline for cost and simplicity. Using natural guide stars is a cost savings, increases the observing efficiencies by avoiding downtime (cirrus, planes, space command, interference with Keck/Gemini/Subaru), and is a potential performance gain (no cone effect, no spot elongation, tip-tilt-focus in NGS, same WFS/science focal planes).

The sky coverage with natural guide stars is greater than 95% at the North Galactic Pole for 6-8 stars brighter than R=12 within the field of view of 'IMAKA. With the baseline Shack-Hartmann wavefront sensors with 10x10 subapertures operating at an update rates of 300Hz, we expect a photon flux of several thousand photons per subaperture per sample per wavefront sensor. Existing CCD detectors with readout noises of 3 electrons (for example EEV39) are adequate.

The technical challenge with the natural guide star WFSs will be the design of the deployment mechanism. Here the challenges are to keep the vignetting of the field to a minimum (keeping probe arm as close to the final focal plane as possible) and to minimize any vibrations in the WFS arm. The placement of the WFSs will have to be part of the AOS control servo as placement errors and errors in the position of stars in catalogs will generate static tilt offsets between wavefront sensors. The atmospheric tilt has an zero mean so a slow control servo will position the probe arms to null any long term tilt. Fortunately CFHT has an equatorial mount so the probe arms nominally only move during this acquisition. Alternatively, fine tuning of the WFS position on the sky could be done with steering mirrors within each WFS's optical path. We note that the PS1 GPC1 includes a parfocal, deployable Shack-Hartmann system which can be moved into the optical beam to intercept a star. While as designed this is not suitable for 'IMAKA, it provides a proof of concept. In addition, the WFS probe arms are expected to be placed as close to the focal plane (before the bandpass filter). The current design has space available for this.

Adaptive Secondary

The wavefront correction will come from an adaptive secondary. Current adaptive secondaries such as the 1.2m diameter AM2 for the VLT, being built by members of our team at Laboratoire d'Astrophysique de Marseille (Ferrari) with Société Européenne de Systèmes Optiques (SESO), contain the following subsystems. A thin optical shell is the front surface of the secondary. This roughly 2mm thick glass is held in place using a set of magnetic pucks that attaches the shell to a set of voice-coil actuators. The actuators are connected to a metal 'cold plate' that serves as the mechanical foundation for the adaptive secondary as well as the heat sink for the actuator power dissipation. This cold plate is typically mounted to a hexapod structure to provide gross motion control. Between the cold plate and the thin shell is a polished glass reference body. The spacing between the thin plate and the reference surface is controlled by a set of capacitive sensors which provide the feedback on an internal control servo. The mirror
electronics (including the wavefront reconstructor) are housed in a thermally isolated enclosure behind the cold plate and hexapod.

If one scales the design parameters of the MMT and LBT adaptive secondaries to the CFHT AM2, we would obtain an AM2 with many more actuators than required. However, unlike a standard DM, the number of actuators in an AM2 is a structural element. As such the density of actuators must be carefully traded against required stroke, dynamic response, and heat dissipation. Following simple scaling laws for adaptive secondaries (Brusa and Del Vecchio (1998, “Design of an adaptive secondary mirror: a global approach”, Applied Optics, 37(21)) and Michael Lloyd-Hart of the University of Arizona (“Adaptive secondary mirror scaling laws”, internal memo), an adaptive secondary specifically designed for CFHT with visible wavelengths corrections could have a factor of two fewer actuators than obtained by keeping the actuator density the same as the MMT/LBT mirrors. This is a potential substantial cost savings. We have not done the detailed design trade for an AM2 for CFHT so the requirements and cost of the CFHT AM2 are highly uncertain. We note however, that the performance requirements for the CFHT AM2 are substantially reduced from those for the LBT AM2.

3.1.3. Science Camera

The science focal plane will provide a full one-degree square field of view sampled at approximately 0.1 arcsecond per pixel. The baseline camera is a duplicate of the PanSTARRs-1 1.4 giga-pixel science camera. This design is working on the PS1 telescope and has been operational for over 14 months. In addition, a similar array controller is being developed by the IfA for the ODI camera. There will be a strong heritage on which to base the ‘IMAKA camera. In addition a filter wheel (g-, r-, i-, z-, and y-) will be placed ahead of the focal plane. The current optical design has space for this.

The development of PS1/4 and ODI has produced two vendors (Lincoln Labs and DALSA) that are capable of providing the orthogonal-transfer CCD devices. Importantly, we note that the use of these devices is the least expensive means to populate a focal plane of this size. Using E2V detectors, such as in MegaCam, with this field of view and pixel sampling, would cost more than $13M for just the detectors.

3.1.4 Control Systems

There will be a number of separate control systems for the adaptive secondary, the wavefront sensor mechanisms (probe arms) and the the various detector controllers. The interaction of the controllers is shown schematically in Figure 1. At the final focal plane, shuffling of charge on the orthogonal-transfer CCD science arrays corrects for any residual tip/tilt motion as sensed by a multitude of guide stars directly from the science arrays. This jitter motion should be devoid of locally induced turbulence (ground seeing, dome/telescope seeing, and telescope motion) and will be specific to particular regions in the focal plane image. This shuffling of charge occurs largely independent of the rest of the system. This is the final stage of correction.

The GLAO system provides a wavefront correction correlated over the full field. This is driven by a set of wavefront sensors observing bright natural guide stars about the field. Nominally there are six wavefront sensors. They are placed just above the science focal plane but after as much of the wide field corrector optics as possible. Wavefront sensor offsets for each wavefront sensor will need to account for static optical differences between field positions. The combination of all of these wavefront sensors provides the GLAO correction and drives the adaptive secondary mirror. The slow-speed differential tilt
of each wavefront sensor (e.g. its mean tilt with respect to the global mean tilt) drives the position of the wavefront sensor probe arm to a zero mean. This occurs at a very low temporal frequency but accounts for catalog position uncertainties and any mechanical flexure of the arms. The ground-layer adaptive correction will account for the optical turbulence arising in the atmosphere within the first ~ 100 meters, enclosure/telescope seeing, and pointing/tracking errors. Large-scale but slow changes in pointing an focus can be offloaded from the adaptive secondary to the secondary hexapod and telescope pointing.

3.2 `IMAKA Performance

`IMAKA includes a ground-layer adaptive optics system, an array of orthogonal-transfer CCDs, and by the standards of adaptive optics, a very large field of view. This presents a number of challenges in simulating the performance. To make the problem tractable, we have divided the performance calculations into two separate components: GLAO over the full field of view, then OTCCD performance over smaller 10 arcmin fields of view. We have studied the performance of the `IMAKA using an analytic simulation package (PAOLA-Laurent Jolissaint) and two monte-carlo packages (yao and simul.pro-Rigaut/Gemini). The two monte-carlo approaches, yao and simul, provide a detailed accounting of most of the error terms in an adaptive optics system. However, due to limited memory and computing power, these packages can not simulate the long time scale phase correlations or the very large angular phase correlations in layers from the upper atmosphere (above ~6km). The analytic approach (PAOLA) makes approximations to the system response and atmosphere and provides estimates of the long-exposure images but can still suffer from artifacts on the very largest angular scales (~1 deg or larger). Specifically, PAOLA suffers from limitations when the ratio of the sampling of the PSF and the field becomes too large; either the field is limited by sampling constraints or the sampling has to become coarser and aliasing takes place in the frequency plane. The effects of this behavior are difficult to estimate, but generally cause a saturation of the phase variance and thus an overestimate of the performance. The author of PAOLA is aware of these limitations and has advised us as to the range of validity. We have employed all three packages to cross-check the two approaches when possible and obtain insight into the global as well as detailed trades.

We note that the simulations to date do not take into account the specifics of the AM2 correction (e.g. influence functions, dynamic response, efficiencies, etc.). We have made the assumption that the AM2 can provide a similar order of correction.

The Monte-Carlo and analytic approaches are two very different approaches to estimating the performance of `IMAKA. As a cross check of the three packages, we calculated performance (FWHM) from the baseline instrument at R-band from GLAO. The three cases agree within 10%.

GLAO

The performance of ground layer adaptive optics is determined predominantly by the vertical profile of the turbulence, especially the relative amount of turbulence at the ground (which naturally has very large isoplanatism) with respect to the free atmosphere seeing. The turbulence profiles used in these simulations are the median of measurements carried out over a period of 18 months for the Gemini GLAO study. These were obtained using a SLODAR/LOLAS instrument installed on the roof of the UH-88’’ building. The data clearly shows that the free atmosphere seeing accounts for approximately half of the turbulence, and this is the limiting factor in the image quality delivered by the GLAO system. It is worth noting that the requirements for a GLAO system are very different from a classical adaptive optics system. It does not deliver a diffraction-limited image across the field and the residual wavefront errors
are dominated by the free-atmosphere seeing as opposed to being bandwidth error or fitting error limited.

For the performance simulations we have assumed a median total seeing of 0.65” at 0.5 microns. This is taken from statistics on the seeing in the wavefront sensor of CFHT’s AOS PUEO and represents the variance in the wavefront delivered by the telescope. We have also used a total seeing of 0.5” as representing good, but not rare, seeing conditions. MegaCam delivered image quality has a median of 0.75” in r-band and 0.8” in g-band. The difference between these are the static aberrations in the telescope and instrument, telescope tracking and guiding errors, and focus errors. These are not accounted for in the AOB/PUEO seeing estimate.

The optical turbulence profile is given in Figure 4 and the table below.

Figure 4: Gemini study of vertical turbulence profile. High resolution (LOLAS) measurements show that most of the turbulence is within 70 meters of the ground. Data from Gemini GLAO site testing study (Chun et al. 2008)

<table>
<thead>
<tr>
<th>Altitude (m)</th>
<th>Fractional strength</th>
<th>Wind speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.295</td>
<td>6.5m/s</td>
</tr>
<tr>
<td>15</td>
<td>0.141</td>
<td>6.5m/s</td>
</tr>
<tr>
<td>30</td>
<td>0.039</td>
<td>6.5m/s</td>
</tr>
<tr>
<td>80</td>
<td>0.020</td>
<td>6.5m/s</td>
</tr>
<tr>
<td>280</td>
<td>0.024</td>
<td>6.5m/s</td>
</tr>
<tr>
<td>1000</td>
<td>0.290</td>
<td>15m/s</td>
</tr>
<tr>
<td>12000</td>
<td>0.191</td>
<td>30m/s</td>
</tr>
</tbody>
</table>

The main result of the simulations is that a well-designed AO system should be able to deliver full-width at Half Maximum of 0.44”, 0.38” and 0.35” at V, R and I respectively in 0.65” seeing and 0.36”, 0.30”, and 0.28” respectively in 0.5” seeing on bright stars. Given the optical turbulence profile, the expected
FWHM from GLAO is the seeing corresponding to roughly half the optical turbulence. At 0.5 microns in 0.65” seeing this expectation corresponds to a GLAO corrected image of 0.43”. The simulations confirm the expectation that the GLAO system removes half of the total optical turbulence.

DM Altitude Conjugation

The single most important design parameter for the GLAO system turns out to be the altitude conjugation of the deformable mirror. This is understandable given the wide field of view and the desire to correct for as much of the ground-layer turbulence as possible. This places very tight constraints on the optical design. For a given field of view, high spatial frequencies decorrelate faster as the thickness of the turbulence increases or if the intersection between the gray zone and the turbulence is reduced. Following Tokovinin (2004, PASP, 116, 941), the height at which the full correction is applied and below which all the turbulence is corrected, namely $H_{\text{min}}$, depends on the order of the correction.

$$H_{\text{min}} = \frac{d}{2} \theta_0 \sim 10\text{ m} \quad (\text{IMAKA})$$

$$H_{\text{max}} \sim \frac{\lambda}{\beta \theta_0} \sim 30\text{ m} \quad (\text{IMAKA})$$

where $d$ is the interactuator spacing, $\theta_0$ is the FOV, and $\beta$ is the angular resolution. For turbulence at altitudes less than $H_{\text{min}}$, the turbulence will be equally well corrected. Turbulence at altitudes greater than $H_{\text{max}}$ will not be corrected at all, and turbulence in the gray zone between the two heights will be partially corrected.

To obtain an estimate of the tolerance on the altitude that the DM is optically conjugate to, we ran simulations using the yao/Yorick simulation package. At this point the simulations are crude but do take into account the sheared optical footprints of the different wavefront sensors on the deformable mirror. Figure 5 below shows the degradation of the FWHM across the FOV for a 10x10 and 20x20 system. Recall that the baseline optical design has an AM2 conjugate to ~46 meters. For this baseline design there is a 5% hit in the FWHM for a 10x10 SH system.

We can see from Figure 5 that a 20x20 system is able to correct higher spatial frequencies than a 10x10 provided that turbulence is all within $\pm H_{\text{min}}$ of the deformable mirror conjugation altitude. The shear between off-axis beams translates directly into a spatial frequency for a given thickness of the turbulence. Therefore where the curves overlap, the performance is limited by the limited spatial frequencies that can be corrected and a 10x10 and 20x20 provide the same level of performance. In other words, for the level of misconjugation in the baseline design, a system with more than 10x10 actuators does not help. A better conjugated system (e.g. like the current f/8 secondary) would be able to take advantage of the higher-order corrections. The results of the yao simulation are consistent with the Tokovinin picture but predict a slow degradation.

We have also generated the equivalent of Figure 5 using the analytic simulation package PAOLA but the field considered may be beyond the capability of its current implementation (Laurent Jolissaint private communication). As a test of the PAOLA results we checked to see how the FWHM sensitivity on the DM conjugation altitude depends on the size of the field of view. We scaled the placement of the guide stars and the science field of interest from 1 deg to 0.5 degrees and 0.25 degrees. From simple geometric arguments as well as Tokovinin's formulation, $H_{\text{max}}$ should increase as the field of view gets smaller. The PAOLA results are opposite to this and suggest that the absolute FWHM degrades more rapidly for the smaller field of view.
At this point, Figure 5 below is our best estimate of the tolerance on the DM conjugation. We recognize that this is a critical performance issue to resolve and further work to develop the simulations packages is needed.

Figure 5: Mean R-band FWHM as a function of deformable mirror conjugation. The thick black line shows the average of a centered 5x5 grid 20’ on a side, while the dashed thick line shows the same for a 20x20 system. The red (10x10) and blue (20x20) crosses and diamonds represent the average extracted from a set of different simulations (see Figures 6 and 7 below). The crosses show the average image quality inside a 40’ diameter circle, while the diamonds show the image quality on the outer degree. The dashed lines at the bottom show the residual spatial fluctuations (sigma). There is an indication that this is limited by the finite number of steps of the Monte Carlo simulations that do not average out the free atmosphere fluctuations: it is flat and the same for the 10x10 and the 20x20 system. The simulations assume a seeing of 0.65” at 0.5 microns.

We note that this effect may pose a problem when it comes to stability and homogeneity of the PSF across the field. Varying turbulence thickness may affect the order up to which the wavefront can be corrected, and this also depends on the direction of the guide stars and overlap of the beams [from different directions] on the DM. The PSF characterization across the field may seem daunting; however, it should be remembered that the isoplanatic field size of aberrations close to the pupil is large, and the variations across the field should be rather smooth. Optical aberrations introduced by optical misalignment and mechanical flexure will also be reduced to relative flexure between the focal plane and the wavefront sensor (the aberrations are actively corrected). The uncorrected, free atmosphere is believed to provide homogeneous (and most likely isotropic) PSFs in long exposures, although the Monte Carlo simulations have not shown this yet.

However, as can be seen from Figures 6 and 7 below, mis-conjugating degrades the uniformity of image quality across the field. In the above figure, the image quality is much more degraded on the outer parts of the field. However, in the inner corrected part, there is no gain with a 20x20 system compared to a 10x10. Proper conjugation therefore appears critical to extract the maximum amount of correction and scale the deformable mirror properly.
Figure 6: Example of FWHM spatial variation at R Band over 1 square degree. Median ground layer and free atmosphere, 10x10 SH. In all cases the frame rate is 1kHz. Location of guide stars indicated by crosses. The figure on the left shows the performance for a DM conjugate to the ground (<FWHM>_{10x10} is 0.40") while the figure on the right shows the performance for a DM conjugate to -46meters (<FWHM>_{10x10} = 0.42" within a 40'-diameter circular field). Residual FWHM fluctuations are dominated by the short exposure limitations of the Monte Carlo simulation.

Figure 7: Same as Figure above but for 20x20 SH. In the figure on the left the <FWHM>_{20x20} is 0.36" while on the right <FWHM>_{20x20} = 0.42" within the circular field 20' in radius.

Given that the residual wavefront is dominated by the free atmosphere, the delivered performance of the GLAO system is largely insensitive to parameters such as the order of the system, the number of guide
stars, their location or relative separation, and even their brightness. We explore the performance dependence of these parameters here.

**Order of the system**

The number of actuators on the deformable mirror or the number of sub-apertures on the wavefront sensor was also found to be of little impact for a correction greater than about 6 x 6. For larger order systems, the performance at short wavelengths (U, V and even R) is improved with a 20x20 with respect to a 10x10 Shack-Hartmann wavefront sensor. From the standpoint of delivered image quality, the GLAO system does not require many degrees of freedom. These results are similar to what other GLAO studies have found (e.g. Andersen et al 2006, PASP,118.1574A)

**Number of Guide Stars/Wavefront sensors**

The required number of guide stars to obtain a uniform and high-order GLAO correction was calculated using both yao and PAOLA. Both find that the delivered performance in FWHM depends slightly on the number of guide stars with more guide stars providing a better FWHM (Table below). This matches the expectation that the wavefront reconstruction will, for bright stars, be dominated by the thinness of the optical turbulence profile. PSF across the field, as measured by the standard deviation of the FWHM and the elongation of the PSFs about the field, also depends only weakly on the number of guide stars used. This is true even in the case of a non-uniformly distributed set of natural guide stars. To test this, random guide star asterisms were generated and passed through the PAOLA simulation. Point spread functions were calculated about the field on a 3x3 grid of locations with spacings of 20 arcminutes. The median and variation of the R-band PSF width/shapes are listed in the table below. These values exclude PSF locations if they happen to lie within 2' of a GS. This is the area over which the largest PSF variations are found but their exclusion in the 6-GS case amounts to only 2% of the one degree field of view. They are not representative of the field as a whole. The default case of a fixed 6-guide star asterism is shown for reference. The values are given for R-band but simulations at V-band show identical trends but with median FWHMs ~ 0.04’’ larger.

**Table: R-band FWHM and PSF uniformity random guide stars asterisms from PAOLA simulations**

<table>
<thead>
<tr>
<th>Number of guide stars</th>
<th>FWHM at R-band</th>
<th>Elongation (major/minor)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Median (arcsec)</td>
<td>Standard deviation (arcsec)</td>
</tr>
<tr>
<td>6-ring (fixed asterism)</td>
<td>0.35</td>
<td>0.009</td>
</tr>
<tr>
<td>4</td>
<td>0.37</td>
<td>0.023</td>
</tr>
<tr>
<td>6</td>
<td>0.35</td>
<td>0.022</td>
</tr>
<tr>
<td>8</td>
<td>0.34</td>
<td>0.019</td>
</tr>
<tr>
<td>10</td>
<td>0.34</td>
<td>0.017</td>
</tr>
</tbody>
</table>

From this we conclude that for bright guide stars more guide stars provide better correction but that the uniformity of the correction is independent of the number of guide stars. The variation of the PSF from the randomly drawn guide star asterisms is worse than the fixed, uniformly-spaced 6-GS case but on
average is still very uniform. Note that the fluctuations of the PSF FWHM found in the yao simulations (Figures 6 and 7) are largely influenced by the variations of the atmosphere in different directions in the short effective exposure time of the simulation. They are expected to average out over long periods. As such, the PAOLA results are taken to be more representative of the field variations due to the number and distribution of guide stars.

The effect of the brightness of the guide stars was assessed by comparative simulations in IDL and yorick using the same parameters as a test of validity and coherence. A 10x10 Shack-Hartman system with $3e^-$ read noise in 0.5'' seeing was simulated and the performance starts to degrade at magnitude 12. However for fainter guide stars, the number of WFSs is important for the reduction of noise. As expected once noise becomes a dominant factor in the wavefront estimate, more WFSs help reduce noise propagating into the correction. The simple algorithm used in the simulations to date does not make any attempt to take advantage of the fact that the noise is uncorrelated across the field other than in the averaging of the slope measurements. This is an area of the AO control system that will certainly benefit from further study.

The very large field of `IMAKA works to its advantage as it is found that there is a >95% probability of finding 6-8 stars of $m_R<12$ within one square degree at the North Galactic Pole. The sky coverage was determined by estimating the probability of finding at least $n$ stars brighter than magnitude $m$:

$$P(m, > n) = 1 - \sum_{i=1}^{n} (\mu(m))^i \frac{e^{-\mu(m)}}{i!}$$

where $\mu(m)$ is the mean star density of magnitude $m$ from the Besançon model of star counts for a field of view of 1 degree ($r=30')$. Results are shown on Figure 9. **With currently available CCD detectors, a GLAO system with six 10x10 Shack-Hartmann WFSs provides full sky coverage** and excellent performance. If lower read noise detectors are available, a higher order correction can be implemented.
improving the performance at the bluer wavelengths.

The trade between using natural guide stars and laser guide stars is driven by the technical challenges of deploying a laser at CFHT and the uniformity of the correction across the field required for the science. It is not driven by the number of stars available for the wavefront sensing. Our sky coverage calculations suggest that there are ample stars within the one degree field of view of 'IMAKA to reach a sky coverage of greater than 95% for the GLAO performance and about 40% for full OTCCD correction over the 'IMAKA field of view at the North Galactic Pole.

The uniformity of the image quality across the field is driven by the number and spacing of the guide stars about the field. With laser guide stars the image quality still varies across the field but the spacing of guide stars provides for as uniform a field as possible. The table above shows that the PSF variability is better by a factor of about two for a uniformly distributed set of guide stars but that variations in both cases are small $\sigma_{\text{FWHM}} \sim 10-20\text{mas}$.

![Figure 9: Estimated number of guide stars available for wavefront sensing at North Galactic pole. The probability of finding 8 stars brighter than magnitude 12 within a degree is high enough to ensure very high sky coverage.](image.png)
A summary of the FWHM obtained from the variation of the GLAO system parameters from the yao package is given in Figure 10. This figure is a summary of all the plots shown in the Appendix A.3 (figures 17 and up). The quartile (25% best) free atmosphere seeing case is also plotted to illustrate that these results are statistical and at times of good seeing, the performance can be dramatically improved.

**GLAO + OTCCD**

Finally, the combined effect of the GLAO module and the OT-CCD was simulated. Guiding with the OTCCD provides a second, independent level of image quality improvements. As shown above, the residual wavefront after the GLAO is mostly limited by the free-atmosphere seeing. The baseline GLAO system performance does an excellent job of correcting the optical turbulence near the ground.

The global tip/tilt of this residual wavefront arises from optical turbulence in the free atmosphere. Here multiple guide stars across the one-degree field are required each used to determine the residual tip/tilt specific to a portion of sky roughly equal to the isokinetic angle (angle over which the wavefront tilts are correlated). This is typically a 2-4 arcminutes (Christian and Racine (1985, “Dependence of seeing correlation on image separation at the CFH telescope on Mauna Kea”, PASP, 97, 1215).

The results were obtained in two steps: first the GLAO module was simulated. The final FWHM was then set as the starting point for an OTCCD (i.e. tip-tilt only) simulation, where the vertical turbulence profile took into account that the ground layer had been corrected. The OTCCD correction was computed every one arcminute from on axis (i.e. in the direction of the tip-tilt guide star) to 10’ away (> isokinetic patch size, presumably). This approach was taken to simplify the simulations. It makes the implicit assumption that the GLAO system removes all of the turbulence near the ground which for orders higher than the system is not true. It does however correctly account for the fact that in combination with the GLAO system, the OTCCD guiding benefits from the GLAO improved image quality.

A few more points are worth mentioning: in the direction of a tip-tilt star, the GLAO-only and OTCCD-only performance are comparable, although the OTCCD image quality decreases as the distance to the tip-tilt star increases while the GLAO performance is largely independent of the distance to the guide star. Combining the two techniques, it is possible to reach 0.2” to 0.3” as afar as 10’ from a tip-tilt star. Ideally in the long run, the entire system will be simulated in a single step instead of manipulating the turbulence profile at each step.
Figure 11: GLAO and OT-CCD performance as a function of wavelength (blue: 0.38um, green: 0.5um, yellow: 0.7um, and red: 0.9um) and distance from the nearest OTCCD guide star. It can be seen that the OT-CCD in the direction of a guide star provides similar correction to a GLAO system, but it degrades as the distance from the tip-tilt star increases. At the edge of the field (10') the OTCCD correction goes to zero and the OTCCD+GLAO curves converge to the GLAO-only case. The plotted curves are smoothed and contain an artifact that makes them appear to get worse at the edge of the field than the GLAO-only case. Note also that the slope of the OTCCD+GLAO curves are a reflection of the isokinetic angle at high altitudes.

Figure 12: Same as Figure 11 but for 0.5" seeing.

As with GLAO, guide stars are required to derive the OTCCD wavefront tilt correction. In the case of 'IMAKA, of order 150-200 stars are required to reach the full OTCCD correction of the upper atmosphere tilt. For any one OTCCD tip/tilt field of view we set the requirement that the error in the jitter correction should not increase the delivered image quality by more than 10%. This sets a requirement on the tilt sensing of at least a signal-to-noise ratio of 5. Using the current read noise of the PanStarrs1 camera and noting that OTCCD guide star sensing is necessarily in a particular science band pass, we find a limiting magnitude of about R~ 14.4. Following the sky coverage calculations presented in the 'IMAKA performance section, we find the following probabilities of finding a single OTCCD guide star within various sized patches at the North Galactic Pole.
Table. OTCCD Sky coverage calculations at North Galactic Pole using Besançon Model.

<table>
<thead>
<tr>
<th>OTCCD Tip/Tilt Field of View (diameter)</th>
<th>R&lt;14</th>
<th>R&lt;15.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>4'</td>
<td>0.32</td>
<td>0.45</td>
</tr>
<tr>
<td>6'</td>
<td>0.58</td>
<td>0.75</td>
</tr>
<tr>
<td>8'</td>
<td>0.78</td>
<td>0.91</td>
</tr>
<tr>
<td>10'</td>
<td>0.91</td>
<td>0.98</td>
</tr>
</tbody>
</table>

The expectation for ODI is that ~150-200 guide stars are needed over the one degree field to obtain the full performance of the OTCCD. This corresponds to a little over 4 arcminutes between guide stars. The numbers presented here suggest that only about 1/3-1/2 of the fields at the NGP will have enough guide stars to obtain the full performance. Put another way, the field of view of `IMAKA is reduced to 1/3 - 1/2 of a degree for the full performance (GLAO+OTCCD on-axis) illustrated above in Figures 11 and 12. Our simulations also calculated the combined performance of GLAO+OTCCD at a larger separation (10 arcminutes) which represents a nearly full sky coverage at the NGP. At this separation, there is a clear loss in performance from the tip/tilt correction but the performance is still excellent across all wavelengths under good seeing conditions (0.5”).

Note that an OTCCD without a GLAO system will have slightly worse sky coverage probabilities since `IMAKA's OTCCD correction can take advantage of the better delivered image quality from the GLAO system. Nonetheless, we compared our sky coverage calculations for OTCCD guide stars with Daniel Harbeck's ODI sky coverage calculations. We find a similar limiting magnitude and the overall conclusion that full OTCCD correction over the one-degree field is not possible at the NGP. His approach queries star catalogs and searches for guide stars on the actual layout of ODI detectors. He has done this at the Galactic plane and while there are subtleties when there are too many stars, the general result is that in the Galactic plane the full guiding of OTCCDs is highly probable.

`IMAKA's combination of GLAO plus OTCCD in 0.5” seeing provides images with a FWHM in the visible of 0.2-0.3” with a sky coverage of ~40% at the North Galactic Pole. GLAO alone provides images with a FWHM of 0.3” under similar seeing with a sky coverage of >95% at the North Galactic Pole.

Final End-to-End `IMAKA Performance Estimate

The cumulative performance estimates are provided in the table below. This table represents an average performance of the baseline system including the effects of the GLAO, OTCCD, and mis-conjugation of the deformable mirror.
Table: **IMAKA End-to-End performance for the baseline instrument** in 0.65” (median) and 0.5” (good) seeing conditions. The conjugation is taken into account by increasing the h=0 conjugated GLAO corrected FWHM by 10%.

<table>
<thead>
<tr>
<th>Band/Wavelength</th>
<th>GLAO+Full OTCCD AM2 conjugate to -46m ~40% sky coverage at NGP</th>
<th>GLAO+No OTCCD AM2 conjugate to -46m &gt;95% sky coverage at NGP</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Seeing=0.65” at 0.5um</td>
<td>seeing=0.65” at 0.5um</td>
</tr>
<tr>
<td></td>
<td>seeing=0.5” at 0.5um</td>
<td>seeing=0.5” at 0.5um</td>
</tr>
<tr>
<td>b/0.37 micons</td>
<td>0.39”</td>
<td>0.42”</td>
</tr>
<tr>
<td></td>
<td>0.30”</td>
<td>0.33”</td>
</tr>
<tr>
<td>v/0.5 microns</td>
<td>0.35”</td>
<td>0.40”</td>
</tr>
<tr>
<td></td>
<td>0.27”</td>
<td>0.31”</td>
</tr>
<tr>
<td>r/0.7 microns</td>
<td>0.31”</td>
<td>0.37”</td>
</tr>
<tr>
<td></td>
<td>0.24”</td>
<td>0.30”</td>
</tr>
<tr>
<td>i/0.9 microns</td>
<td>0.28”</td>
<td>0.35”</td>
</tr>
<tr>
<td></td>
<td>0.21”</td>
<td>0.28”</td>
</tr>
</tbody>
</table>

As a final remark on the performance of IMAKA, we note that the K-band, GLAO-only image quality is 0.3” under 0.65” seeing in the visible.
4. Development requirements/Risk Mitigation

The principal technical risk in constructing the baseline ‘IMAKA is the adaptive secondary mirror. However, the largest key technical issue for ‘IMAKA is optimizing of the optical design with consideration for the cost, performance (conjugation), and risk to implementation. These two issues are tightly coupled and involve issues greater than ‘IMAKA itself. An AM2 impacts the entire CFHT observatory, its direction, and its future instrumentation. As such to develop the feasibility design we need input from CFHT as a whole with consideration to current and other future CFHT instrumentation.

From the feasibility standpoint, the adaptive secondary we presented here is technically conservative. After discussions with Michael Lloyd-Hart and Jeff Kingsley of the University of Arizona and the costs and basic trades they made for the construction/design of the adaptive secondaries for MMT and LBT, we simply scaled the design parameters of the LBT AM2 to the CFHT baseline AM2. Doing so leads to a mirror with more actuators than required for ‘IMAKA but whose structural properties are a proven set of design parameters that scale with mirror diameter (e.g. the University of Arizona's approach for GMT). While we feel that adaptive secondaries are becoming a mature AO component, understanding the performance, cost, and risk trades for a mirror specific to CFHT's needs is a clear development requirement for ‘IMAKA's design to proceed. A dedicated study of the CFHT adaptive secondary needs to be undertaken. The Laboratoire d'Astrophysique de Marseille and the University of Arizona and their collaborators Microgate in Italy have expressed interest in developing the CFHT AM2 concept and there may be other groups/companies within the CFHT partnership that may want to participate in such a study. The optimal adaptive secondary for CFHT considers the observatory as a whole.

Coupled to the design of the adaptive secondary is the optical design of the telescope and ‘IMAKA and the scientific trade between delivered performance of ‘IMAKA and the cost/risk of the AM2 subsystem. These need to move in unison with the AM2 study. In addition, an opto-mechanical design of an adaptive optics relay needs to be developed along with detailed simulations that account for the details of the opto-mechanical design.

In addition to these engineering studies, we need to experimental verify that the optical turbulence seen by CFHT is as expected. There are three components to this. First, we need to confirm that the distribution of atmospheric turbulence shows the dominant layer near the ground and turbulence rising within the CFHT enclosure needs to be identified and characterized. Profiling from within the CFHT dome should include the CFHT optical train (e.g. M1 and M2) for their optical aberrations and profile at as high a spatial resolution as possible. Ideally these tests are done while the UH Mauna Kea GL profiler is operating on the UH2.2m Coude roof to tie the experiment into the Gemini MK ground-layer study. Second, the spatial order and temporal frequencies of the optical turbulence near the ground need to be measured. Preferably this is done with a spatial resolution better than that required for GLAO. Finally, experimental verification of the high-altitude tilt correlations would provide a foundation for the OTCCD performance estimates. Christian and Racine (1985, “Dependence of seeing correlation on image separation at the CFH telescope on Mauna Kea”, PASP, 97, 1215) performed this experiment at CFHT so data already exists. A similar experiment but with a concurrent measure of the full-atmosphere optical turbulence profile would complete the verification. We note that we are preparing an experiment for CFHT with a SLODAR/LOLAS optical turbulence profiler on CFHT to address these specific issues for later this year. We want an independent check of the profile and Paul Hickson (UBC) may be able to bring his LunarShabbar to Mauna Kea during that run.
5. Operations and Data Processing

5.1 Operational Concepts

CFHT's New Observing Process

Today, CFHT provides service observing for 95% of its time under the New Observing Process (NOP, a proven concept put in operation in 2001 with the CFH12K) for its three main instruments: MegaCam, WIRCAM, and ESPaDOnS. 'IMAKA is essentially a “MegaCam on steroids” so it naturally fits within the NOP. The following paragraphs describe the punctual evolutions needed in the NOP to accommodate this new instrument.

The MegaCam NOP encompasses the Queued Service Observing (QSO), the New Observing Environment (NEO), the Elixir data processing pipeline, and DADS, the Data Archiving and Distribution System.

Queued Service Observing

There will be three possible modes of operation of 'IMAKA made available to the user based on the scientific requirements and the availability of guide stars in the field:

- GLAO and OTCCCD correction (expected as the dominant mode)
- GLAO and only global tip-tilt OTCCCD correction
- No GLAO correction, but global tilt OTCCCD correction (MegaCam mode)

Compared to MegaCam, the only evolution needed in the the QSO interface allowing the users to enter their observations (Phase 2 Tool, PH2) will be the inclusion of an automated interface defining how given sky regions will provide enough bright stars for GL correction (a handful is needed) and/or OT correction for the local tip-tilt OTCCCD correction across the field of view (up to 200 stars are needed over one square degree).

'IMAKA leads itself naturally to queue operation. Other instrumentation can be adapted or designed for the feed from the adaptive secondary (for example ESPaDOnS) and would provide a natural suite of instruments to accommodate all seeing conditions.

New Environment for Observing

The entire instrument must comply with the CFHT NEO interfaces. The Pan-Starrs camera planned for use in 'IMAKA turns out to have adopted the MegaCam NEO interfaces back in 2006: software agents operating within the "director" environment. This means the camera will basically be a plug-and-play device at CFHT.

The GLAO system comprises the adaptive secondary and the wavefront sensing, two entire new blocks. Their operations and calibrations will need to be developed and worked into the NEO environment. We expect that there will be subtleties in the acquisition and calibration of the GLAO and OTCCCD systems.
For example, during acquisition of the GLAO guide stars, stellar catalog position errors, mechanical flexure, and misalignment in the individual wavefront sensors will need to be compensated by active control servos that automatically position WFSs with their respective guide stars. While we expect that these controls are less sensitive than for systems like MCAO where variations of things such as the focal plane plate scale are not possible, further study is needed to detail the algorithms to automate the systems. This is a key requirement of the system from the onset. An additional complication of a convex adaptive secondary is the calibration of the actuator response with the wavefront sensor response. Software and techniques to calibrate this on the sky are an example of system calibrations that will need to be automated and incorporated into the instrument control software from the onset.

The whole MegaPrime development within NEO has proven that this environment and model of development is apt for very large scales instrumental projects.

**Elixir data processing pipeline**

See section 5.2

**Data Archiving and Distribution System**

An `IMAKA FITS file will be very similar to a MegaCam file (Multi-FITS Extension, MEF) and no change in DADS is needed except for the handling of some new FITS keywords.

**5.2 Data Processing**

**Detrending**

The Elixir data processing pipeline has transitioned from supporting the past two generations of CFHT wide-field optical imagers: CFH12K from 2000 to 2003, and MegaCam up to today. The nature of the data changed very little between these two instruments (MegaCam simply had more CCDs and stronger fringing in the i' and z' bands) and the recipes have required rather limited tuning.

The operation mode of `IMAKA will be very similar to past instruments: observing runs of several weeks alternating with other instruments depending on the community pressure. The granularity of an observing run is expected to remain of at least two weeks like MegaCam. In consequence, the handling of data to produce master detrending frames by Elixir still applies (unlike PanStarrs1 which operates its camera continuously, calling for a different detrending strategy) and no change is needed in the current Elixir operational model.

Looked at the pixel scale, OTCCDs call for a standard data processing, except in the red part of the spectrum where the fringe correction is complicated by the fact that the interference pattern, a static function of the geometry of the detector (thickness), will get smeared by the OT function. This can be modeled as long as the "transfer" history for each file is preserved. But fortunately, the PanStarrs OTCCDs manufactured by MIT/LL are high resistivity substrate devices generating very low fringing to start with.
Photometric calibration

Photometric accuracy was a major technical challenge encountered on MegaCam by the Supernovae Legacy Survey (SNLS) with systematic errors severely limiting the Cosmology. Large efforts were produced by the SNLS team and CFHT to tackle these systematics and recent findings indicate that high quality photometry over a large field of view can be achieved: a 1% absolute calibration to the Landolt system is now achieved from the g to the i band, 2% for the z-band, and 4% for the u-band. To fully unleash the scientific potential of the SNLS, the entire photometric calibration must be brought into the Sloan system where we expect a percent, or better, absolute photometric accuracy in all bands. This effort is believed to be an important legacy for the next generation of wide-field imagers being put in operation throughout the world. The groups that led this effort are part of the `IMAKA science team, guarantying a passing of the expertise to the new instrument.

Astrometric calibration

The OT function causes an "elasticity" to the image throughout the field of view. This is however just another evolution in the complexity of CCD mosaics astrometry where each device requires its own astrometric calibration. Elixir roughly derives the MegaCam astrometry on a chip basis to within one arcsecond, leaving the field open for advanced softwares such as the Terapix' SCAMP to tackle very effectively precise astrometry at the scale of the whole focal plane. Mean RMS external of 45 mas with respect to SDSS-R6 and mean RMS internal error of 4 mas are currently achieved at Terapix on CFHTLS data. The SDSS astrometric catalog does not cover the entire sky but the GAIA mission ought to resolve that issue by 2015.

PSF modeling

A software such as Terapix' PSFEx is able to model an arbitrary PSF and its variations such as those expected from `IMAKA. The constraints are very similar to those of SCAMP (stability versus number of well-detected point-sources per image area). In both cases, one may actually contemplate replacing the current polynomial variation models with specific ones centered adaptively on the OTCCD guiding stars (ideally one per 4 by 4 square arcminutes). Registration and stacking of dithered exposures with variable PSFs may benefit from a sophisticated "image fusion" approach using e.g. Bayesian inference to reconstruct an image with a constant PSF.
6. Development Roadmap and first cost estimate

6.1 Development Roadmap

The development steps to take prior to the instrument's detailed design are clear. First, a conceptual design of an adaptive secondary in unison with an optimized optical design is paramount. At the same time, a detailed trade between the adaptive secondary and an AO optical relay is also needed. We feel that both of these can be explored with a down select midway through the next phase. Second, the simulations need to be developed to include more details specific to the `IMAKA program (e.g. the adaptive secondary, tilted DMs, and simultaneous GLAO and OTCCD corrections). It is our intent to develop both the analytic and monte-carlo simulations. Finally, experimental verification that the optical turbulence CFHT experiences and its relation with the Gemini MKGL study must be done.

We envision a separate study for the design of an adaptive secondary including the baseline optical design and larger secondaries. The study should address the following key areas:

- Design parameter trades for an AM2 that meets the performance requirements of `IMAKA. This should include a identifying and performing the engineering trades between performance, risk, and cost.
- Fold in CFHT requirements as a whole
- Size versus conjugation altitude
- Identification of the individual subsystems and their conceptual design.
- Identification of risk in the subsystems and design
- Costing at the level of each subsystem

The optical design of CFHT/`IMAKA is a necessary input to the AM2 study. Since what we propose has implications extending beyond `IMAKA, this next step in the optical design should intimately involve the CFHT staff.

The experimental verification is outlined in Section 4. The goal of this is to make quantitative measurements of the optical turbulence at CFHT to set the optimal conjugation altitude.

For `IMAKA as a system, the next phase in the design over an approximately 12 month period will include:

- Develop management plan and approach for the instrument and the observatory integration.
- Detailed scientific trade study on the capabilities, costs, and risk of the instrument.
- A baseline conceptual design will be completed. This will take into account trades and may well differ from the feasibility design. At the completion of this phase the optical design will be mature (optimized and toleranced). The electrical and mechanical designs should be down to the subsystem levels. Individual components will be identified and sourced.
- WFS deployment mechanism design will be developed.
- In the next phase of the study for `IMAKA, simulations will be used as a tool to provide a detailed instrument concept and to further the trade studies. Including realistic noise for the wavefront sensing detectors, understanding in greater detail the impact of the relative guide star
brightness, and improving the estimation of the long exposure FWHM variation across the field are key goals. Software development will be needed to simulate the combined effect of GLAO + OTCCD high altitude tip-tilt correction in one step, to improve the final performance estimate. The simulations will also incorporate the adaptive secondary corrections (e.g. Influence functions, mapping onto WFSs, and conjugate altitude), DM conjugation, DM tilt, and compare different wavefront sensing techniques and guide star references (natural guide star and laser guide star).

- Explore NIR WFS advantages: dichroic split, image sharpening from GLAO, sky coverage.
- Complete requirements for all subsystems.
- Preliminary plan for integration, commissioning, and operations for `IMAKA.

6.2 Cost Estimate

This cost estimate for the baseline `IMAKA instrument includes the GLAO system with its adaptive secondary and multiple wavefront sensors, the wide-field corrector optics, and the final science camera. Also included in this costing are the modifications to an existing CFHT top-end to mount the new secondary and camera package. We have explicitly assumed that a completely new top-end is not required. These however assume that the Cassegrain instrumentation is as given in the baseline design. Importantly, not explicitly included in the costing are (1) the technical staff costs for telescope specific changes (e.g. AM2 integration, telescope guiding controls, changes to electrical/cooling infrastructure) and (2) labor costs for management (assumed CFHT) and “P.I.” and “co-I” involvement. These are significant contributions from the partnership.

In developing this costing the subsystems, we have used the costs provided to us by the respective instrument teams for the PanSTARRS1 camera, the costs for ODI, and the cost for the LBT and MMT AM2.

For the AM2, we have scaled the optics and electronics costs by the surface area of the secondaries and assumed that the design parameters of the CFHT adaptive secondary are similar to the LBT AM2. This latter assumption in fact leads to a larger number of actuators than required by `IMAKA but at this point we have taken a conservative approach to the costing of the AM2. In addition, the University of Arizona noted that the cost to fabricate and test a convex optical shell and reference plate for an adaptive secondary is about a factor of two more than a concave secondary. This factor of two is included in the optical cost estimate since the baseline uses a convex AM2.

For the wide field corrector, we have adopted the cost of the WIYN ODI field corrector optics. These are similar in size but there is one more elements in the ODI design than in the `IMAKA baseline but the final design and number of surfaces in the `IMAKA field corrector are likely to be similar to ODI's.

The wavefront sensor package assumes a total of six Shack-Hartmann wavefront sensors using off-the-shelf CCD detectors with standard array controllers. The opto-mechanical design of the WFS probe arms is costed as a full design/development including 2.5 Man-years of mechanical design and one year each of electrical and optical design effort. As noted in the instrument description, a number of options exist for the WFSs though we don't anticipate substantial cost savings in any of these approaches.

The science camera is taken to be a duplicate of the PanSTARRS1 camera but we have included a detector chip cost assuming the less expensive second source arrays from DALSA (ODI detectors). This
is not an entirely consistent assumption since these detectors have different pixels sizes. However, the array controller for ODI is being built by the same team at the IfA that built the PS1 camera controller so engineering costs are saved in the array electronics, and our team will develop experience with these detectors.

The cost summary is given in the table below. The full cost estimate is provided in an Appendix A2.

Table: `IMAKA Costing Summary

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Adaptive Secondary</td>
<td></td>
<td>$5.30M</td>
</tr>
<tr>
<td></td>
<td>Optics (shell/reference plate fabrication, test)</td>
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<tr>
<td></td>
<td>Electronics (including wavefront reconstructor)</td>
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<td>Mechanics and plumbing (mounting at top-end)</td>
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<td>Wide Field Corrector</td>
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<td></td>
<td>Electronics</td>
<td>$1.980M</td>
</tr>
<tr>
<td></td>
<td>Mechanics</td>
<td>$0.832M</td>
</tr>
<tr>
<td>TOTAL</td>
<td></td>
<td>$11.65M</td>
</tr>
<tr>
<td>Contingency</td>
<td>0.33 of TOTAL</td>
<td>$4M</td>
</tr>
</tbody>
</table>

We recognize that the overall scope of this project is large and new optics for the telescope is a significant undertaking. An appropriately scaled contingency will need to be carried until better costing and a detailed design is developed. In the table above we have noted that a contingency of ~33% is about $4M. However, we note that an adaptive secondary with a facility wavefront sensing subsystem has the potential to feed more than a wide field optical imager. In fact, a diffraction-limited narrow field visible wavelength imager is almost already included in `IMAKA. In this sense the costing of the scientific instrumentation for `IMAKA is around $4.25 million dollars (the cost of the camera and wide field corrector) but requires the facility infrastructure to be upgraded with an adaptive secondary in order to obtain the full potential of the system. We note that MegaPrime was certainly a necessary infrastructure for the $4M MegaCam. Nonetheless, even at this early stage we recognize the need to understand the
scientific trades with the performance and delivered capabilities of the instrument. A number of potential cost savings exist.

In addition, this instrument, like other advanced adaptive optics systems, will be highly integrated with the telescope and observatory. ‘IMAKA will require a concerted effort across the entire observatory staff. We have not explicitly included this cost except in the mechanical and electrical design effort to integrate the AM2 with the telescope. Labor costs for the individual subsystems is included and are given in Appendix A2.

There is considerable uncertainty in the costing of the adaptive secondary. As noted in the Development Requirements section, a full feasibility study of an adaptive secondary for CFHT is needed. One of the key requirements of this study will be to perform a trade on the design parameters of the secondary. For the feasibility study we have assumed that the basic design parameters of the existing MMT and LBT mirrors are translated to the CFHT ‘IMAKA secondary. In particular, the shell thickness and actuator density are kept the same. An adaptive secondary specifically designed for CFHT and visible wavelengths corrections could have a lower actuator density than the MMT and LBT mirrors and thus a lower total actuator count. The performance requirements for ‘IMAKA call for a factor of two fewer actuators than obtained by keeping the actuator density the same as the MMT/LBT mirrors. This is of order a $1M savings in the electronics/actuator costs.

The field of view drives the secondary size, final focal length and number of detectors to populate the field of view. It is a clear science requirement. However, the required sampling of the focal plane to obtain the astrometry and photometry is an unstudied issue. We believe a Nyquist sampling under the very best conditions anticipated is reasonable but given the cost to populate the focal plane, a trade on the science requirements and sampling is needed. The sampling in the final focal plane also drives the shape of the adaptive secondary. In the base line design the optical power of the secondary is very small. It is almost flat. A flat secondary would likely dramatically drop the cost of the optical element (recall the factor of two included in the cost for fabrication of the convex surface). All other things being equal, a flat secondary would however make the sampling in the focal plane too coarse under the best expected performance unless the wide field corrector had optical power. This is a clear scientific trade to consider.

The ground-layer adaptive optics system accounts for nearly 2/3rds of the cost outlined in this study. Rightly one should question whether the added expense is worth undertaking given the competition. The scientific competitiveness of ‘IMAKA is given in Section 2 (Science Case). We note that the costs of the principal competing facilities (HyperSuprimeCam, PS4, and LSST are substantially larger than ‘IMAKA). No published costs were found for these facilities but the clear competition is HyperSuprimeCam. ‘IMAKA is competitive with a major 8-m class facility and significantly cheaper than the dedicated survey telescopes. Notably ‘IMAKA is the only wide-field capability at these angular resolutions. Other facilities with OTCCDs will have resolutions better than the natural seeing but our sky coverage calculations suggest that for full sky coverage, GLAO is the only option. For any portion of the sky with sufficient numbers of guide stars for full OTCCD correction, our resolution will still be a about a 0.2” better. This brings us to an unprecedented resolution over such large fields of view.
APPENDIX A1. AO relay designs vs. adaptive secondary designs

John Pazder (HIA) and Harvey Richardson have worked on the optical design of `IMAKA. They have looked at a number of different approaches to meet the initial optical design requirements (see Section 3.1). The major design challenges to the design have been the large field angles and angles of incident on the deformable mirror. Diffraction-limited performance can be obtained over the field but packaging the deformable mirror is problematic. For completeness, we list here the approaches that have been considered along with their salient features.

**AO relay with a deformable mirror**

An adaptive optics relay that collimates the light, places the deformable mirror at (or near) the pupil plane, then refocuses the light was considered first. The packaging and pupil demagnification drive the design to larger deformable mirrors.

In the design of wide field instruments for large telescopes practical limitations on pupil reimaging are always a concern. Keeping beam size small to reduce the size of optics and element separations can often have the opposite effect as the pupil mapping magnifies the field of view. These problems are more complex in adaptive systems. In order to keep the beam (from any field angle) from interfering with the optical beam on reflection there is a minimum distance we must be away from the DM. The following plot shows the variation of the angle of incidence as a function of the pupil mapping ratio (DM diameter / Telescope diameter) assuming we can get within one meter of the DM and the the field of view has a half angle of 0.5 degrees at the entrance pupil. The black line is the on-axis field and the red and blue curves are for the extremes of the field of view. Note that when we constrain the distance allowed for folding the beam off the DM there is a minimum in variation of the angle of incidence of the beam with pupil mapping ratio.
The principal technical challenge identified with this approach is the tilt required on the deformable mirror surface to package the relay. For very small DMs this leads to multiple complications. First, the pupil is now blurred on the DM surface if the DM surface is not coincident with the pupil (e.g. if its tilted with respect to the pupil plane). The size of this effect must be kept small with respect to the actuator pitch or it will introduce a blurring between actuator responses. The large tilt of the DM also effectively places different parts of the mirror at different conjugate altitudes. For small DMs (d~100mm or less) this amounted to a change in conjugation that is larger than the tolerance in DM altitude conjugation. Finally, given the large field angles and the magnification of angles at the deformable mirror, the projection of the phase correction in different directions amounts to a variation of the wavefront correction across the field. This is a variation of the amplitude of the phase correction with field angle and position on the deformable mirror. This projection effect varies with position on the deformable mirror and is not symmetric since the DM is tilted about only one axis.

These problems are minimized for a DM with a diameter of about 200-300mm. The pupil blur is less than 1/10 of an actuator pitch for a 10x10 actuator DM. The worst case conjugation variation is less than 10m and is well the tolerance found from simulations. Finally, the projection effect of the phase correction is small (< 10% at edge of field). This amounts to a smooth predictable variation of the correction across the field of view. **We believe that it is possible to package a relay for DM diameters about 200-300mm with relay optics.** We note that in this case, the collimation and focusing optics will be ~600-700mm in diameter with separations ~ 1-2 meters. The approach was not pursued as time and resources limited us to carrying forward only one optical approach.

**AO relay with a transmissive correcting element**

The above technical problems could also be overcome if the correcting element is transmissive. There is no tilt of the correcting element with respect to the telescope pupil and the angles of incidence on the corrector are at least symmetric. The element is still preferentially large (diameters > 50mm) due to the magnification of the field angles but the correcting element is fully conjugate to the pupil and the beam does not need to clear an incoming beam.

Such transmissive correcting elements exist. Spatial Light Modulators (SPM) based on liquid crystals can introduce phase changes to unpolarized light by changing the orientation of the molecules in the liquid crystal. In a transmissive liquid crystal phase retarder individual cells of liquid crystals are subjected to electric fields that orient the molecules accordingly. Devices with ~128 correcting elements are commercially available (e.g. Meadowlark Optics).

The difficulty applying these devices to adaptive optics has been (1) the slow response orienting the molecules and (2) the amount of phase that can be introduced. Response times vary depending on the direction of the alignment and typically are 10 millisecond to 50 milliseconds. In addition the dynamic response of a cell/actuator to a move is complex with large swings in response (equal to or larger than the command move) before settling to the command position. The devices are also naturally small in part due to the requirement of an optical quality thin piece of glass to cover the liquid crystal. For GLAO, the characteristic frequency of the turbulence phase near the ground is ~20Hz so an update rate of the corrector of the 50 millisecond response time is too slow to introduce any corrections at this frequency. Faster response SPMs exist (e.g. Boulder Nonlinear Systems) with sub-millisecond response times but these are reflective elements. Finally polarized light propagating through transmissive SPM can incur amplitude variations in addition to the phase modulations.
Spatial Light Modulators were deemed unacceptable principally due to (1) response speed, (2) the amount of phase correction possible, and (3) existing sizes.

**Tilted pupil image**

An optical design that relays a tilted pupil plane to matches the tilt of the deformable mirror would solve the blurring of the actuators but still suffers from the projection effects with field angle (and position on the deformable mirror). This could be mitigated by moving to a significantly larger deformable mirror.

**Inverse telescope relay**

The adaptive optics relay mimicking the telescope (in reverse) was considered briefly but the central obscuration turned out to be too large (~ 0.6). This also required an deformable mirror that is powered and has a central obscuration.

**Adaptive Secondaries**

Allowing the correction to be made within the telescope itself allows for the possibility of a cleaner solution to the adaptive optics system. Two key technical constraints on this approach are the feasibility of a large adaptive secondary and the strong constraint on the altitude the correction is conjugate to.

In considering the feasibility of an adaptive secondary for CFHT, we considered that adaptive secondaries for MMT (0.67m) and LBT (0.91m) are working or in the integration phase and that an adaptive secondary similar to these in size, shape, and actuator density is the lowest risk path in lieu of a full design study for an adaptive secondary for CFHT (a key requirement in our Development Roadmap).

For development of a feasibility optical design, the size of the adaptive secondary was the principal parameter we tried to minimize. The second most important criteria for the adaptive element is its conjugation altitude. As presented in the performance section (3.2), the wide field of view of the instrument necessitates a tight constraint on the optical conjugation of the deformable mirror. We note that the choice of shape of the mirror (concave or convex) affects the fabrication and testing of the mirror and Jeff Kingsley (University of Arizona) estimates that the fabrication of the optical shell of a convex mirror is roughly double that for a concave mirror.

**Adaptive Tertiary Mirror**

The constraints of the conjugate altitude of the correcting element and the diameter of the secondary work in opposite directions. The baseline optical design comes close to satisfying both of these constraints. However, Harvey Richardson has developed a design that surpasses all of the performance requirements (conjugate altitude, image quality, and wavelength coverage). The design is presented here as an alternative to the baseline optical design. The design's large optics and large number of optics make it a challenging design to implement but it nonetheless offers a diffraction-limited solution for the IMAKA optics.
Figure 13: Optical design with adaptive tertiary mirror. The three-mirror + eight-lens design delivers diffraction-limited performance across the one degree field of view. The design incurs a larger central obscuration than the current Cassegrain optical prescription.

Flat adaptive secondary

An essentially folded prime focus could be made by using a flat adaptive secondary. This would greatly simplify the fabrication and testing of the mirror but would provide too coarse a pixel scale. It's features a coarser pixel scale of 0.152”/pixel which would result in a one-degree camera with less than half the number of CCDs! A wide field corrector with optical power may be possible to provide the desired final focal length beam. This approach however at first look suffers from increased field curvature.