APPENDIX 2.A

NOAO PANEL WORKSHOP ON SCIENCE WITH THE GSMT

NOAO Panel Workshop on Science with the GSMT

Joan Najita (NOAO)

1. Background

The highest priority ground-based recommendation of the astronomy decadal survey was an ~30m aperture telescope (a.k.a. the Giant Segmented Mirror Telescope; GSMT). Reflecting the high priority given to the GSMT, the AASC recommended that technology development for the GSMT commence immediately so that construction could begin in the coming decade. In anticipation of this recommendation, NOAO had initiated in 1999 efforts to define the flowdown from science to design requirements and to identify the design challenges for the telescope and instruments. In 2000, our goal was to develop a technology roadmap, guided by a vision of the kind of ground-breaking science that a GSMT could carry out, and to present the roadmap to the NSF in early 2001. As part of the process of determining the telescope and instrument capabilities of the GSMT, our intention is to fund detailed scientific trade studies to help refine the prioritization of capabilities. In addition, achieving the ambitious goal of a 30-m telescope requires a strong partnership with the community. Therefore, we also intend to hold a community workshop in the coming year that will focus on defining the scientific goals at a level sufficiently quantitative to specify a prioritized flowdown from science to telescope and instrument design requirements.

In order to develop a strawman science case for discussion at the community workshop, and to draft statements of work for the scientific trade studies, panels of astronomers from across the U.S. community (and Canada) were convened in Tucson on September 11–12 and 18–19, 2000. The goal of the panel meetings was to identify and highlight broad but fundamental astrophysical problems that would take advantage of the unique capabilities that might be included in the design of a 30-m telescope. These include: high sensitivity, a large field-of-view, high precision photometry and astrometry, high angular resolution and/or high contrast imaging, significant multi-object spectroscopic capability, and thermal IR sensitivity. Ideally, the telescope and instrument capabilities would enable scientific programs that are scientifically compelling, technically feasible, as well as cost effective.

There had been 2 previous workshops on the GSMT (in Madison and Hyannis, both organized by AURA), primarily focused on identifying broad science themes (REFs). In our September 2000 workshop, we hoped to develop more detailed science cases and to have a more in-depth look at the overlap between telescope and instrument capabilities that will enable the most scientifically compelling programs and those capabilities that can be implemented in the coming decade.

Rather than consider all areas of astronomy, we convened panels on 3 broad topics: Galaxy Evolution and Large-scale Structure, Stellar Populations, and Star and Planet Formation. We
expected that the needs of the 3 different communities would drive the telescope and instrument capabilities in different directions, and we wanted to identify the critical scientific trade studies for each of these. We also hoped to see which telescope and instrument capabilities might produce the biggest scientific bang for the buck. The panel memberships were as follows:

<table>
<thead>
<tr>
<th>Galaxy Evolution</th>
<th>Stellar Populations</th>
<th>Star &amp; Planet Formation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Marc Postman (chair)</td>
<td>Rosemary Wyse (chair)</td>
<td>Frank Shu (chair)</td>
</tr>
<tr>
<td>Arjun Dey (co-chair)</td>
<td>Knut Olsen (co-chair)</td>
<td>Joan Najita (co-chair)</td>
</tr>
<tr>
<td>Andrew Connolly</td>
<td>Brent Ellerbroek</td>
<td>Geoffrey Blake</td>
</tr>
<tr>
<td>Julianne Dalcanton</td>
<td>Jay Frogel</td>
<td>Jonathan I. Lunine</td>
</tr>
<tr>
<td>Mark Dickinson</td>
<td>Mario Mateo</td>
<td>Anand Sivaramakrishnan</td>
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<tr>
<td>Richard Ellis</td>
<td>Robert O'Connell</td>
<td>Alan Tokunaga</td>
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<td>Neal Katz</td>
<td>Cathy Pilachowski</td>
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<tr>
<td>Simon Morris</td>
<td>Michael Rich</td>
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<tr>
<td>Chuck Steidel</td>
<td>Ralph Wijers</td>
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<td>John Tonry</td>
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</tbody>
</table>

Each panel was asked to prioritize potential GSMT telescope and instrument capabilities based on their ability to produce ground-breaking science in their field in 2010. These capabilities included parameters such as sensitivity (aperture), wavelength coverage, field of view, spectral resolution, angular resolution, photometric and astrometric accuracy, PSF quality and stability, thermal emissivity, and desired instrumentation. The panels were also asked to identify scientific trade studies that would be needed to refine their prioritization. Rather than asking the panels to provide a comprehensive list of possible science cases, we asked the panels to provide example science cases that illustrate the need for the capabilities they advocated.

In order to ensure some overlap in the discussions of the 3 panels, the panels were asked to consider as a common reference point, a fully steerable telescope with a 30m filled, segmented aperture. The reference system would have diffraction-limited AO capability in the 1–2.5 μm region and over a ~1' field, with 50% Strehl. The reference system would also have a seeing limited capability over a ~20' field. The panels were asked to identify the science that could be carried out with such a system and to identify the thresholds that would be crossed with enhanced capabilities. In their exploration of enhanced capabilities, the panels were asked to consider the likely development time for AO and complementarity between facilities available in space and on the ground.

In the next section, we summarize the outcomes of the each of the panel discussions, including a preliminary prioritization of telescope and instrument capabilities, the scientific trade studies that would be needed to refine the prioritization, and examples of the kinds of science that would be enabled by those capabilities.
2. Galaxy Evolution and Large-scale Structure

2.1. Science Overview

The history of galaxy formation is a story with several interwoven themes: the formation of stars and its consequences for chemical enrichment; the assembly of galaxy masses; the morphological evolution of galaxies; and the formation of central black holes. Each of these themes plays out differently depending on galaxy environment and galaxy mass, and each unfolds in the context of largescale structure. One of the primary goals of observational cosmology for the next decade is to understand the relationship between the assembly of galaxy masses and the evolution in the luminous properties of galaxies (e.g., morphology and star formation). With the GSMT, we will be able to measure the properties (star formation rates, metallicities, morphologies, stellar ages, internal dynamics, etc.) of millions of galaxies spread out over cosmic time. By examining the properties of the ensemble as a function of environment, mass, and redshift, we will be able to reconstruct the evolutionary history of galaxies. In particular, with the high sensitivity of the GSMT, we will be able to study galaxies over an unprecedented large range of masses, and in the unprecedentedly distant past. These data will provide a clearer elucidation of each of the themes of galaxy evolution, and, in sum, a richer, more vibrant history of galaxies.

Galaxy Masses: To reconstruct the history of galaxy formation, we need to have some way of connecting present day galaxies with their progenitors to high redshift. This could be done most directly by measuring galaxy masses. One possible approach is galaxy-galaxy lensing, where lensed images of background galaxies are used to probe the masses of foreground galaxies. With the high sensitivity of the GSMT, we will be able to use the lensing signal from a large number of faint background galaxies, > 20 times the number accessible with 10-m telescopes. Consequently, we will be able to measure more accurate masses, and to measure the masses of lower mass galaxies than is currently possible. Even with this high sensitivity, however, there are typically only a few lensed background galaxies per foreground galaxy so one needs to "add up" the signal for multiple foreground galaxies in order to get a statistically meaningful result. For a large enough sample (∼ 2′ FOV), the foreground galaxy population can be divided into populations of galaxies with similar properties, and individual mass estimates obtained for each population.

Galaxies, the IGM, and Large-scale Structure: Several fundamental questions about galaxy formation concern the relation of galaxies to the IGM and large-scale structure. For example:

- Simulations predict that the formation of galaxies involved the draining of voids into filaments, which drained into the nexes of filaments, etc. Is this picture correct? How does the formation and evolution of a galaxy depend on the large-scale structure in which it is embedded?

- What is the underlying mass distribution within which galaxies form? The Lyman α forest has been suggested to trace the same underlying mass distribution as galaxies,
but in a much less biased way. Is this true? If so, measurements of the Lyman $\alpha$ forest could be used to directly test theories of structure evolution.

- The Milky Way, surprisingly, has no zero metallicity stars. This indicates that the Galaxy formed from an enriched IGM. How were the heavy elements created by the first generations of stars distributed throughout the IGM?

The role of the GSMT will be to answer these and other questions by characterizing both the structure and metal content of the IGM, and the large-scale structure and detailed properties of galaxies (star formation rates, metallicities, morphologies, stellar ages, internal dynamics, etc.), in the redshift range $1<z<3.5$. The redshift range $1<z<3.5$ encompasses roughly half the star formation history of the Universe and, in this redshift range, structures seen at $z<1$ will be in their initial stages of assembly. With the GSMT, we will be able to measure the properties of absorption line systems in QSO and galaxy spectra on scales down to $\sim 1$ Mpc scales. This size scale is a natural limit. On smaller scales, the IGM is not expected to closely trace the underlying distribution (due to thermal and hydrodynamical effects).

With the high sensitivity of the GSMT, it will be possible to probe Mpc scales in 3 dimensions. That is, since the surface density of background beacons (quasars and galaxies) depends very sensitively on apparent magnitude, we will have access to an unprecedentedly high surface density ($>5000$/sq.deg.) of faint ($R \sim 24$) background beacons and, consequently, be able to produce a map of the IGM on fine angular scales. The high sensitivity of the GSMT will also enable spectroscopy at high enough resolution ($R = 5,000 - 20,000$) to probe Mpc scales along the line of sight.

With the high sensitivity of the GSMT, we will also be able to use moderate resolution spectroscopy ($R = 1000 - 5000$) to measure redshifts and the detailed properties of large numbers of galaxies ($>50,000$/sq.deg.) to faint magnitudes ($R \sim 26.5$). We will thereby be able to probe, at high redshift, the equivalent of $L^*$ densities in the present-day Universe. By probing comparable number densities at each epoch, we would be able to make robust evolutionary connections between present-day galaxies and their progenitors. With the high throughput of the GSMT, we will also be able to survey large areas (several degrees on a side), covering volumes large enough to provide an accurate measure of clustering statistics and to characterize the largest structures ($several 10^6$ Mpc$^3$). All aspects of this program require multi-object spectroscopy over very large fields of view ($>10^7$). The observations can be carried out under seeing limited (or preferably enhanced seeing) conditions.

**Resolved Dynamics, Star Formation Rates, and Chemical Abundances of Galaxies:**
With its high sensitivity and angular resolution, the GSMT will open another new window on galaxy evolution: the study of spatially resolved kinematic and metallicity structure, and the stellar content, of distant galaxies. With spatially resolved, moderate resolution ($R = 2000$) spectroscopy, we would be able to address issues such as evolution of galaxy metallicity and mass-to-light ratio in the context of star formation and morphological evolution. In addition, galaxy masses measured
using galaxy kinematics would complement masses measured through lensing. Sensitivity is the primary challenge of these observations, which are beyond the reach of current 10-m class telescopes. Due to the low surface brightness of the outer regions of galaxies, even a 30-m telescope will be able to probe only the high surface brightness regions of galaxies ($\mu_H = 22$ mag/sq.arcsec), e.g., the inner regions of “giant” galaxies at $z > 1$. Such high surface brightness regions are relatively rare. Approximately 0.7% of the sky would be above the limiting surface brightness threshold accessible to a 30-m telescope. As a result, the focal plane need not be fully sampled, and a system of deployable IFUs may be an appropriate instrumentation solution.

**Black Holes and Galaxy Formation:** Mounting evidence argues that many, if not all galaxies have central black holes. Even more strikingly, the masses of black holes appear to be correlated with bulge masses over at least 4 orders of magnitude. Is the formation of a central black hole linked to the formation of the galaxy? If so, how? The role of the GSMT will be to answer these questions by charting the history of black hole formation using studies of galaxies at cosmologically significant look-back times. (These studies are beyond the current generation of 10-m telescopes, which are only expected to complete a census of black holes in nearby galaxies of all types.) With its high angular resolution capability, the GSMT will be able to probe $\sim 70$ pc scales to high redshift, and thereby study motions around massive black holes ($> 10^9 M_\odot$). We will also be able to study motions in much less massive ($\sim 10^8 M_\odot$) systems in Virgo. These observations require the combination of an IFU and high Strehl narrow-field AO in order to probe the 2-dimensional dynamics in the vicinity of black holes.

**Integrated Light Studies** Resolved population studies of more nearby galaxies (see next section), coupled with high signal-to-noise integrated light observations of the same objects, will provide fiducial calibrations to extend studies of integrated galaxy light to the very distant universe. Significant work would be possible out to the distance of the “Great Wall” ($c_v = 8000$ km/s; $m - M = 35$) with a 30-m or larger telescope. Within this volume, we will be able to study the stellar populations and internal dynamics of hundreds of thousands of galaxies, spanning a range of environments and morphological types.

### 2.2. Required Capabilities

The GSMT capabilities required to carry out the programs described in the previous section are listed in Table 2. Note that the projects require several combinations of angular resolution and field of view. These range from seeing limited capability over large fields ($\sim 20''$) for studies of large scale structure to diffraction limited ($\text{Strehl} > 0.5$) capability over smaller fields for studies of, e.g., galaxy-galaxy lensing (few arcmin FOV) and central black holes ($< 10''$ FOV). A low order AO system capable of producing $0.3''$ angular resolution would be particularly useful for larger area surveys. By greatly improving the sensitivity of the GSMT for spectroscopy, this capability would greatly enhance the scientific return. The required spectral resolution extends from $R = 20,000$ for spectroscopy of the IGM, to $R = 300 - 5000$ for spectroscopy of galaxies,
Table 2. Required Capabilities: Galaxy Evolution & LSS

<table>
<thead>
<tr>
<th>Capability</th>
<th>Required</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensitivity</td>
<td>30-m adequate</td>
</tr>
<tr>
<td>Wavelength Coverage</td>
<td>3200Å–2.5μm (high); 2.5–5μm (medium);</td>
</tr>
<tr>
<td>Angular Resolution &amp; FOV</td>
<td>Narrow Field AO</td>
</tr>
<tr>
<td></td>
<td>1–3″ Diffraction Limited AO</td>
</tr>
<tr>
<td></td>
<td>Low order (0.1″–0.3″) AO over 10″</td>
</tr>
<tr>
<td></td>
<td>Native seeing (0.3″–0.7″) over 20″</td>
</tr>
<tr>
<td>Spectral Resolution</td>
<td>$R = 5 - 2000$ with OH suppression $R = 1000 - 20,000$</td>
</tr>
<tr>
<td>PSF quality</td>
<td>Predictable for lensing studies</td>
</tr>
<tr>
<td>Instrumentation</td>
<td>Narrow Field, diffraction limited IFU (high); Highly multiplexed MOS</td>
</tr>
</tbody>
</table>

to $R = 5$ for measurements of galaxy-galaxy lensing. OH suppression spectroscopy at resolutions $R = 5 - 2000$ would also improve sensitivity and greatly enhance the scientific return. The desired wavelength range is bounded on the short wavelength end (3200Å) by the need to probe the IGM over the required redshift range. Wavelength coverage to 2.5μm would cover the primary spectral features of interest over a significant redshift range. By extending the wavelength coverage to 5μm, we would be able to study the same spectral features over a larger redshift range (e.g., Hα at $z > 3$). The availability of integral field spectroscopy was judged to be critical.

2.3. Required Studies

**PSF Prediction:** How sensitively does the accuracy of galaxy masses derived from galaxy-galaxy lensing depend on our ability to predict PSFs? What is the required accuracy for PSF prediction for this application?

**Resolved Spectroscopy of Galaxies:** Since this seemed to be difficult even with a 30-m telescope, it would be good to have a more in-depth study of the prospects for carrying out this project. How accurately can we measure metallicities, star formation rates and kinematics and to what limiting surface brightnesses? What is optimal wavelength, angular resolution, spectral resolution for the measurements? Can we use stellar absorption lines or only emission lines? What aperture telescope is really needed to cross a significant science threshold?

**OH suppression:** What is the expected performance of OH suppression systems for imaging and low resolution spectroscopy? What throughput hit is acceptable?

**“Enhanced” Native Seeing or “Boundary Layer” AO Systems:** What are the prospects for 0.3″ angular resolution over large fields of view ($\sim 10′$) at optical through near-IR wavelengths? Brent Ellerbroek indicated that significant gains in image quality would be made if we were to correct just the boundary layer turbulence that is present 500m – 2 km above the telescope. Since
we would need to sample more rapidly than is needed to recover native seeing, we would need somewhat brighter natural guide stars than in the native-seeing case. Correction to $\sim 0.1 - 0.3'$ angular resolution may be possible over a $10'$ field using $5 - 6 V = 11 - 15$ natural guide stars (alternatively, a scanning laser guide star) over a wavelength range $\sim 0.6 - 1.65\mu m$.

The actual magnitude requirements for this system would depend on the spatial and temporal characteristics of the telescope disturbances to be corrected, which need to be defined. As usual, correction would be increasingly poor, and less uniform, at shorter (optical) wavelengths. The exact number of guide stars that are required is an item that requires study. We might be able to predict the performance of such a system for a 30m by looking at current performance on existing surrogate systems, e.g., the FWHM vs. $\lambda$ currently achieved at SOR with its 240 subaperture system.

3. Stellar Populations

3.1. Science Overview

Resolved stellar populations provide critical complementary evidence that can be used to reconstruct the formation and evolutionary history of galaxies. While the studies described in the previous section use ensembles of galaxies spread out over cosmic time to reconstruct history, we can also use the ensemble properties of resolved stars (age, kinematics and metallicities) to decipher the past evolutionary histories of individual galaxies—their star formation, chemical enrichment, and mass assembly histories.

With the luxury of resolved stars, studies are not limited to only the high surface brightness regions of galaxies, but may span the entire range of galaxy types and components, including dwarf galaxies and the disks and halos of giant galaxies. With high spatial resolution, it is also possible to study substructure, e.g., stellar clustering and the interaction of stars with the interstellar medium. Moreover, the galaxy evolutionary timeline produced through stellar populations studies is completely independent of the assumed cosmological model, instead relying on the stellar evolutionary clock. The constant push for improved stellar evolutionary theory provided by the study of resolved stars spills over into benefits for our understanding of distant galaxies, through population synthesis, and for studies of star formation within the Milky Way. The Achilles' heel of current stellar populations work is the small sample of accessible nearby galaxies and our consequent inability to study the entire Hubble sequence. With the GSMT it will be possible to extend the study of resolved stellar populations beyond the Milky Way and its immediate satellites, recovering the histories of a more representative sample of galaxies, including a broader range of Hubble types, than is currently possible. The panel set three increasingly challenging milestones to be considered in the context of GSMT: the ability to detect stars below the oldest main sequence turn-offs in (1) M31 and its companions, (2) the M81 and Sculptor Group dwarfs and spirals, and (3) the Virgo cluster galaxies, including giant ellipticals.
Generically, in order to characterize the star formation, chemical enrichment, and mass assembly history of a galaxy, we would derive age distributions from CMDs that reach at least one magnitude below the oldest main sequence turn-off stars ($M_V \sim 5.5$) in the galaxy. We would also measure the kinematics and metallicity distributions from moderate resolution ($R = 4000$) spectroscopy of stars on the lower red giant branch ($M_V \sim -0.5$) which have been identified from CMDs. The metallicity measurements would help to break the age-metallicity degeneracy in CMDs. The kinematics would discriminate between different stellar populations, and aid in decomposing CMDs and characterizing phase space structure. The kinematics would also probe galactic potential wells. Additional measurements of detailed elemental abundances would be obtained from higher resolution spectroscopy ($R = 40,000$) of the brighter red giants ($M_V \sim -2.5$). These observations will trace the relative contributions of Type Ia and II SNe in the enrichment process. Note that this suite of observations place similar requirements on telescope aperture. That is, if we can reach below the turnoff with a given aperture telescope, we also have the sensitivity to carry out the complementary spectroscopy.

These measurements, when carried out for a diverse sample of galaxies over a range of morphological types, would allow us to address a wide range of fundamental questions such as:

- Is the Milky Way a typical spiral?
- When did disks form stars? (A test of hierarchical clustering scenarios.)
- Is there a chemical abundance “floor” in galaxies? (Related to the enrichment history of the IGM.)
- What is the age distribution of ellipticals? (Makes a connection with the interpretation of high-$z$ galaxies.)
- Are spiral bulges and ellipticals the same apart from the addition of a disk? (A prediction of some merger models.)
- What is the underlying mass distribution of dwarf spheroidals? (Constrains the nature of dark matter.)

3.2. General Considerations

Since concensus was achieved quickly on the general scientific goals and required observations, much of the panel deliberation focused on the aperture and wavelength coverage that would be needed to to achieve scientifically compelling goals that are beyond the reach of other current and future facilities (e.g., HST, ground-based 10-m telescopes equipped with AO, NGST). Several general considerations indicate the GSMT capabilities that will be needed to cross existing scientific thresholds.
Sensitivity: In order to overcome “cosmic variance” in reconstructing a representative history of galaxies, we need to study multiple examples of each morphological type. While the nearest dwarf galaxies are only tens of kpc away, the nearest large spiral, M31, is $\sim 850$ kpc distant. Farther away, at distances of $\sim 2-3$ Mpc, many dwarfs and some large spirals are found in the nearby Sculptor, M81, and M82 groups of galaxies. Large numbers of elliptical galaxies, including giant ellipticals, are not encountered until the Virgo cluster, at a distance of $\sim 15$ Mpc. For reference, Table 3 gives the distance moduli of galaxies and clusters, and the angle subtended by 1 pc at those distances. For comparison, the diffraction limit of a 30m telescope is $0.002''$ at 300nm, $0.006''$ at 800nm, $0.018''$ at K-band (2.2μm.)

Table 3 suggests several important milestones. Since M31 is already known to have significant structural differences from the Milky Way, we need to reach faint stars in the M81 or Sculptor Groups in order recover a representative history of spirals. Observations of the resolved stellar populations over the entire Hubble sequence, including giant elliptical galaxies, would represent a quantum leap in our understanding of stellar populations; this requires that we reach the Virgo cluster. These milestones set thresholds for the telescope requirements.

<table>
<thead>
<tr>
<th>Stellar System</th>
<th>$m-M_\odot$</th>
<th>$\theta$ corresponding to 1 pc</th>
</tr>
</thead>
<tbody>
<tr>
<td>LMC</td>
<td>18.5</td>
<td>$4''$</td>
</tr>
<tr>
<td>M31</td>
<td>24.3</td>
<td>$0.3''$</td>
</tr>
<tr>
<td>Sculptor Group</td>
<td>26.5</td>
<td>$0.11''$</td>
</tr>
<tr>
<td>M81</td>
<td>27.4</td>
<td>$0.07''$</td>
</tr>
<tr>
<td>M82</td>
<td>27.8</td>
<td>$0.06''$</td>
</tr>
<tr>
<td>Cen A</td>
<td>28.5</td>
<td>$0.04''$</td>
</tr>
<tr>
<td>NGC3115</td>
<td>30.2</td>
<td>$0.02''$</td>
</tr>
<tr>
<td>Virgo Cluster</td>
<td>30.9</td>
<td>$0.014''$</td>
</tr>
<tr>
<td>50Mpc</td>
<td>33.5</td>
<td>$0.004''$</td>
</tr>
<tr>
<td>Perseus Cluster</td>
<td>34.5</td>
<td>$0.002''$</td>
</tr>
<tr>
<td>Coma Cluster</td>
<td>35.0</td>
<td>$0.002''$</td>
</tr>
</tbody>
</table>

Angular Resolution & Confusion: In addition to possessing the sensitivity required to reach systems of interest, the GSMT must also provide the angular resolution needed to resolve crowding at the relatively high surfaces brightnesses of interest. For example, spiral bulges and arms have typical surface brightnesses of $\mu_V = 20$ and 21, respectively; the half-light radius of a typical elliptical galaxy is $\mu_V = 21.5$. The most stringent requirement comes from the need to measure accurate CMDs for stars near the main sequence turn-off. In the near term, imaging studies will be dominated by the high angular resolution imaging systems of HST (optical and IR; WF3 and ACS) and AO-systems on ground-based 10-m class telescopes (primarily IR). These will be able to obtain CMDs down to within a magnitude of the older turn-off in the outer regions of the M31 bulge and disk. For ground-based 10-m telescopes operating in native seeing mode ($\sim 0.5''$ resolution), photometry to the oldest main sequence turnoff will be limited to galaxies closer than M31. With its higher angular resolution (and greater sensitivity), the GSMT will give us access to a wider
variety of systems at larger distances.

**Wavelength Coverage and Photometric Accuracy:** Several factors strongly favor carrying out the required measurements at optical wavelengths. Observations at optical wavelengths offer the possibility of higher (diffraction-limited) spatial resolution and, consequently, an improved ability to resolve confusion in high surface brightness regions. In addition, the lower terrestrial sky background in the optical enables deeper imaging, and therefore the study of CMDs to fainter magnitudes. Typically, we would be able to reach 6 magnitudes fainter in $V$ than in $K$. At optical wavelengths, we would be able derive stellar parameters such as age and metallicity using robust, well-studied diagnostics (e.g., for spectroscopy, resonance lines in the optical/UV). Furthermore, CMDs that include an optical band are more sensitive discriminants of age and metallicity. As a result, CMDs that include an optical band typically place much less stringent requirements on photometric accuracy ($\sim 5\%$) than CMDs constructed with near-infrared bands ($\sim 1\%$). Figure 1 shows Bertelli et al. (1994) isochrones of $J - K$ vs. $M_K$, $V - I$ vs. $M_V$, and $V - K$ vs. $M_V$, for metallicities of $Z = 0.0004$ and $Z = 0.02$ and ages of 8, 10, 11, and 12 Gyr (roughly spanning the evolution in stellar populations from $z = 1$ to $z = 3$). Including an optical filter clearly gives better age discrimination near the turnoff and better metallicity discrimination from the RGB slope, by a factor of $\gtrsim 2$.

**Comparison with NGST:** Both GSMT and NGST are expected to drive stellar populations studies beyond the era of HST and ground-based 10-m telescopes. With its high sensitivity, high angular resolution, and stable photometric imaging capability, NGST is likely to contribute significantly to stellar populations studies. By virtue of the low background environment in which it will operate, it will in general provide superior imaging and low-resolution spectroscopy in the infrared compared to GSMT. The advantages of the GSMT relative to NGST are its potentially higher angular resolution, possible optimization at optical wavelengths, its high resolution spectroscopic capability, and superior capability for more highly multi-plexed multi-object spectroscopy at moderate spectral resolution. A potential disadvantage of the GSMT compared to NGST is the less stable PSF, which may compromise its photometric and astrometric performance. The achievable photometric and astrometric accuracy of the GSMT is an issue that requires study.

### 3.3. Required Capabilities

In examining the telescope and instrument capabilities that would drive significant advances in the study of stellar populations, there emerged a clear preference for enhanced capabilities relative to the “reference GSMT” discussed in section 1, specifically for diffraction limited capability at optical wavelengths, and a larger, 100-m aperture. The need for these enhanced capabilities is driven by desire to study the stellar populations of ellipticals at the same level of detail that will be available for spirals. This requires the study of stellar populations at the distance of the Virgo cluster.
Although it may be difficult to implement all these enhanced capabilities on a short timescale, we identified an interesting trade between aperture and wavelength that suggests a possible development strategy. Typically, diffraction-limited capability in the \( V \) band on a 10-m telescope would allow us to detect and resolve the same stellar population that can be studied with diffraction-limited capability in the \( K \) band on a much larger (30-m to 100-m) telescope. For example, for imaging below the turnover, we could reach one magnitude below the oldest turnover population in M31 to \( \mu_V = 25 \) with a 30-m telescope that is diffraction limited at \( K \) and to \( \mu_V = 22 \) (characteristic of the inner bulge/disk) with a 10-m telescope that is diffraction limited at \( V \). Similarly, at \( \mu_V = 25 \), we could study the oldest turnover population in M81 with either a 100-m telescope that is diffraction limited in \( K \) or a 10-m telescope that is diffraction limited in \( V \). At the distance of Virgo, stars one magnitude below the turnover are only accessible with a 100-m telescope that is diffraction limited at \( V \).

Note that the above comparisons consider only the detectability of sources and ignore the signal-to-noise that is required to accomplish the science. Given that much higher signal-to-noise is required for IR, compared to optical, photometry in order to measure turnover ages, implementing diffraction limited imaging in the optical on existing 10-m telescopes would represent a significant increase in capability, one that is arguably more cost-effective than increasing the GSMT aperture to \( \geq 50 \)-m if we are limited to diffraction limited capability at infrared wavelengths. Thus, one possible approach is to preserve the capability of the GSMT for diffraction limited performance at optical wavelengths, and to implement AO at optical wavelengths on the GSMT once it has been developed and tested at smaller apertures. For the GSMT in the near term, where diffraction limited performance will likely be limited to IR wavelengths, \( JHK \) colors will be very useful for stellar populations work if 1–2% photometric accuracy can be achieved in the IR at the diffraction limit of a 30-m aperture. In this case, it will be possible to study regions more crowded than those accessible to NGST.

Along the upgrade path to a 100-m aperture and diffraction limited imaging in the optical, we would cross the following thresholds in stellar populations science. A 30-m GSMT equipped with diffraction limited imaging at infrared wavelengths would allow study of stars below the oldest

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**Table 6. Required Capabilities: Stellar Populations**

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Specification</th>
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<tbody>
<tr>
<td>Sensitivity</td>
<td>milestones passed at 30-m, 50–70-m, and 100-m</td>
</tr>
<tr>
<td>Wavelength Coverage</td>
<td>Optical (to 3000 Å) (high), near-IR (medium), mid-IR</td>
</tr>
<tr>
<td>Field of View</td>
<td>~ 1' for AO; ( \gtrsim 10' ) for native seeing</td>
</tr>
<tr>
<td>Spectral Resolution</td>
<td>( R = 5, , 4000, , 40000 )</td>
</tr>
<tr>
<td>Photometric Accuracy</td>
<td>5% in optical; 1% in IR</td>
</tr>
<tr>
<td>Astrometric Accuracy</td>
<td>relative positions to ( &lt; 10^{-4} ) over years</td>
</tr>
<tr>
<td></td>
<td>1mas per measurement</td>
</tr>
<tr>
<td>PSF quality</td>
<td>Stable PSF across field</td>
</tr>
<tr>
<td>Instrumentation</td>
<td>MOS, IFU + echelle spectrographs,</td>
</tr>
<tr>
<td></td>
<td>image slicer for native seeing</td>
</tr>
</tbody>
</table>

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turnoffs out to the distance of M31, but limited to the lowest surface brightness regions such as the edges of globular clusters and the outer M31 halo. Pushing the diffraction limit to optical wavelengths would allow a comprehensive study of the resolved stellar populations in all Local Group galaxies, with the exception of the inner bulge of M31. Based on these studies, we would have a fairly complete knowledge of the stellar populations of two large spirals and many dwarf galaxies, both gas-rich and gas-poor. With a 50–70m aperture telescope that is diffraction limited in the optical, we would reach the next threshold, the study of the spiral-rich M81 and Sculptor groups down to below the old main sequence turnoff. With these studies, we would increase the known sample of large disk and LMC-type galaxies. Finally, with a 100m aperture telescope that is diffraction limited in the optical, we would reach below the turnoffs in the elliptical galaxies of the Virgo cluster.

Table 6 summarizes the desired GSMT capabilities for stellar populations science. There is, as mentioned above, a high premium on access to the full optical spectrum, and down to 3400Å, in order to retain the use of well-tested age and metallicity diagnostics. Diffraction limited imaging is, of course, critical, although only moderate fields of view (1') are needed. The required spectral resolution extends from $R = 5$ to image turn-off population, to $R = 4000$ to measure kinematics and metallicities of stars on the lower red giant branch, to $R = 40,000$ to measure detailed elemental abundances of brighter red giants. As described in section 3.2, measuring turn off ages requires a photometric accuracy of $\sim 5\%$ in the optical and $\sim 1\%$ in the near-infrared.

It was recognized that new frontiers would be crossed if high precision astrometric measurements could be carried out with the GSMT. Here the greater sensitivity and angular resolution of a 30-m telescope could be used to greatly extend measurements that will be made with space missions such as GAIA (ESA). While GAIA is designed to measure positional differences of 160µas at $V = 20$, a 30-m GSMT will be able to make similarly accurate measurements at much fainter magnitudes even if we are able to measure positions accurate to only to 1/100 of a pixel. This will allow us to map out full space motions of, e.g., RR Lyraes in M31 ($V = 24$) which are expected to have proper motions of 18µas/yr, which would be easily measurable over a $\sim 10$ year baseline. If the much more challenging goals for high precision astrometry that are discussed in section 4 ($\sim 1\muas$) can be met, similar observations could be made in galaxies much beyond M31.

It was also recognized that significant advances would come from observations made in the AO-corrected infrared or seeing-limited optical with a 30-m aperture. For example, with infrared AO the environments of gamma ray bursts could be studied with spatial resolution comparable to the size of giant molecular clouds. In the optical, studies of the integrated light of globular clusters and super star clusters would only require seeing limited conditions. With a 30-m telescope, the integrated light of globular clusters below the peak in the cluster luminosity function could be studied to the distance of Virgo. Seeing limited observations would also be ideal for studies of stellar populations in low surface brightness regions of galaxies in the Local Group and beyond (e.g., CMDs of evolved stars and spectroscopy of red giants). We could also carry out high resolution spectroscopy of rare stellar populations, e.g., candidate extremely low-metallicity stars in the halo.
of M31. By studying intergalactic stars in Virgo that are fainter and more numerous than the known intergalactic planetary nebulae, we would in addition be able to better map out the history of galaxy harassment, which may have left behind streams of stripped stars detectable through kinematics. Many of these seeing-limited applications would push for fields of view as large as possible, \( \gtrsim 10' \).

3.4. Required Studies

Photometric and Astrometric Performance in Crowded Regions: This issue is, of course, critical to understanding the potential of the GSMT for a large number of stellar populations questions. But our understanding of the performance that can be expected from a real GSMT system is as yet poor, and studies are needed to remedy this. For example, in looking at the trade between wavelength and aperture for resolving crowding (see previous section), we have assumed that we can study with the required accuracy point sources that are isolated objects within an area of 9 resolution elements; in his own study, Renzini assumed that a much larger area of 100 resolution elements is needed. Which of these estimates is closer to the truth? More specifically, in order to improve the prioritization of capabilities, we need to know what is the expected photometric accuracy over how large a FOV, over what range of wavelengths, and for how many nights a year, as a function of crowding. Under what conditions can we expect to achieve, for example, 1\% photometric accuracy at infrared wavelengths and 5\% accuracy at optical wavelengths?

Obtaining good photometric performance may depend on optimizing and integrating the data-taking and analysis "system", which would include the AO system (of course), but also PSF prediction, and photometric and astrometric analysis techniques. In particular, we may need to develop analysis tools beyond those currently available (e.g., DAOPHOT). For example, in terms of imaging spectroscopy or multi-band data, one approach might be to carry out a joint analysis of an entire datacube \((x, y, \lambda, \text{band})\) using, e.g., the best PSF (obtained at short wavelengths) to interpret the rest of the data, and treating all wavelengths as pseudo-redundant samples of the same scene. An additional advantage may come from incorporating prior knowledge of the possible functional form of the stellar spectra. The outputs would be the \(x\)- and \(y\)- positions and the spectrum for each source.

In terms of estimating what performance over how many nights per year, we can quantify this aspect using known site characteristics, if available. Although specifying the site characteristics involves several parameters, e.g., Strehl vs. FOV vs. wavelength vs. seeing), the Strehl vs. FOV curves are parallel for different wavelengths, and these scale up and down together with seeing, so we should be able to get some idea just from seeing statistics. The Cerro Pachon seeing survey for Gemini-South suggests that the joint statistics of seeing and isoplanatic angle are fairly well behaved, with very few cases of good seeing couple with a small isoplanatic angle (or vice versa). One subject which deserves more attention is future site surveys is the correlation of seeing with other conditions influencing AO and telescope performance, such as ground-level winds and thin
In order to predict the likely performance, we might carry out simulations using “true” and
“predicted” PSFs. We might start with a 1-parameter family (based on Strehl?) of “true” PSFs of
varying quality (e.g., generated by Brent Ellerbroek or Francois Rigaut) and also create artificial
“predicted” PSFs that reflect the uncertainties of the PSF prediction process. (Alternatively, this
could be another “true” PSF calculated for slightly different conditions (seeing, turbulence layer
altitudes, calibration errors in the WFS, or WFS detector noise). The “true” PSFs would be used
as inputs in creating simulated observations of crowded stellar regions (e.g., globular clusters), and
the “predicted” PSFs would be used in the photometric or astrometric analysis.

We also need to characterize the expected astrometric performance of AO/MCAO on the
GSMT. Astrometric space missions such as GAIA will have positional accuracies of 150µas for
stars brighter than $V = 20$. The nominal precision of SIM is 3µas at $V = 20$. The current estimate
for the positional accuracy with MCAO is 1mas. This is only 0.12 of the resolution element of a
30-m at 1µm—not highly impressive. Can we expect significantly better positional accuracy of an
AO/MCAO system on GSMT?

**Diffraction-limited Capability at Optical Wavelengths:** What are the prospects for this
capability? One of the pacing items is laser development. Since more actuators are needed in
the optical, higher power lasers are required. The standard scaling law for the required guide star
signal level as a function of observation wavelength is $\lambda^{-18/5}$. Thus, we would need $\sim 75$ W lasers,
$\sim 10$ times more powerful than is currently available. A possible development roadmap would be
to first develop these lasers; then test first AO systems for optical wavelengths on smaller aperture
telescopes; and then scale up to large aperture systems. The likely time scale for availability is
+15 years? Note that significant science gains would come from implementing optical diffraction
limited imaging capability on existing 10-m telescopes.

**Utility of IR Imaging and Spectroscopy:** We appear to be much less familiar with IR diag-
nostics and their discriminatory power compared to optical diagnostics. We need a more detailed
study of optical vs. IR in terms of their ability to determine ages from CMDs, and metallicities
and elemental abundances from spectroscopy, over a range of metallicity and age. In particular,
the utility of IR diagnostics at low metallicities has not been much explored.

**Spectroscopy in Crowded Fields:** What is the expected spectrophotometric performance of
different spectroscopy implementations (MOS, IFS, etc.)? Which produces an adequate decompo-
sition of stellar spectra in crowded fields?
4. Star and Planet Formation

4.1. Science Themes

The panel on star and planet formation identified four areas in which the GSMT can make ground-breaking contributions. Many of the problems require observations of very high spatial and spectral resolution at thermal infrared wavelengths. In addressing these problems, the GSMT would be highly complementary to facilities such as ALMA and NGST.

Structure and Evolution of Protoplanetary Disks: The discovery of extra-solar planets has placed our solar system in a new context and has reenergized the theoretical investigations of the formation and evolution of planetary systems. These theories can be tested directly with the high spatial ($\theta \lesssim 0.08\mu$) and ($R \sim 100,000$) spectral resolution observations that will be possible with the GSMT at thermal infrared wavelengths. The capabilities of the GSMT would be highly complementary to those of ALMA and NGST in this effort. ALMA will be able to measure the dust continuum morphology of the sites of planet formation, protoplanetary disks, but will not have the sensitivity to carry out spectroscopy of the gaseous component. The role of the GSMT would be to measure the spatially resolved gas phase dynamics and chemical structure of disks and thereby test theories of the origin of planetary systems. The suppression of the bright central star and disk would enable improved spectroscopy of the outer, planet-forming regions of disks. Thus, achromatic nulling coronagraphs and integral field spectrographs are highly desired. These capabilities would complement NGST, which is unlikely to have spectral resolution much greater than $R = 5,000$. The desirability of making observations of the same planet forming systems with both the GSMT and ALMA suggests a southern hemisphere site for the GSMT. An exciting future capability for the GSMT is its use as an imaging interferometer, both to probe planet-forming regions at smaller disk radii, and to image the small-scale structure (e.g., giant planet wakes) that will test detailed dynamical aspects of planet formation theories.

Evolution of Giant Planets in Planetary Systems: Giant planets are the alpha and the omega of solar system formation. They must form before the gaseous disk is dissipated, and as they grow, they set up the dynamical stirring that defines the formation and habitability of terrestrial planets and the delivery of volatiles to earth-like planets. The role of the GSMT will be to characterize extra-solar giant planet atmospheres (structure, composition), in order to enable comparative planetology and enable new lines of investigation into the cosmogony of extra-solar planets. From observations of an ensemble of systems, we would derive the early dynamical evolution of planetary systems, including our own. These observations would require high spectral ($R \simeq 10,000$) and spatial resolution ($\theta \lesssim 0.1\mu$) in order resolve orbital separations of $\gtrsim 1$ AU at 10 pc. Observations at thermal IR wavelengths are needed to probe molecular species of interest (e.g., CO at $\sim 5\mu$m, NH$_3$ at $7 - 8\mu$m). The suppression of the bright central star (e.g., $J \sim 5$) with an achromatic nulling coronagraph is needed to allow the study the much fainter surrounding planets. In order to correctly identify and obtain spectra of true planets, as distinguished from speckles, an integral field spectrograph may be necessary.
Astrometric Detection of Earth-like Planets: The detection of the second Earth would be revolutionary. Indeed, the Decade Survey Report in Astronomy and Astrophysics identified the detection and characterization of earth-like planets around other stars as a high-priority goal. The report recommends that a commitment by NASA to build a Terrestrial Planet Finder (TPF) be contingent on the prior demonstration of the existence of terrestrial planets outside the solar system. If high precision relative astrometry can be achieved with the GSMT, the GSMT would be able to provide the required demonstration for the most important potential TPF targets, i.e., sun-like stars within 10 pc. Detecting the reflex motion of a central star due to an earth-mass planet orbiting at 1 AU in a planetary system 10 pc away requires an astrometric precision of 0.3 μas (or 10^-4 of a pixel under diffraction limited conditions at 1 μm) relative to a background of reference objects. The required angular resolution is an order of magnitude smaller than the limiting angular resolution of SIM. The need for a sufficiently large number of background reference objects motivates a field of view of at least 1′.

Toward a Predictive Theory of Star Formation: Stars illuminate the Universe. What processes govern their formation and determine their most fundamental property (their masses)? To answer this question, we need to measure the initial conditions of star formation (i.e., molecular cloud properties, e.g., density, temperature, chemical abundances, ionization fraction, magnetic field strength), the physical processes relevant to star formation (e.g., winds and jets, disk accretion), and the end products of star formation (e.g., IMFs of stars). Using the resulting knowledge of physical processes, and by relating end products to initial conditions, will bring us closer to a predictive theory of star formation. The GSMT has a fundamental role in each of the required measurements. In the measurement of initial conditions, high spectral resolution ($R = 100,000$) absorption line measurements of molecular clouds made with the GSMT at thermal infrared wavelengths will complement emission line studies made with ALMA. The high sensitivity of the GSMT translates in the ability to probe molecular clouds through a larger number of lines of sight, using background beacons located outside of molecular clouds. High resolution spectroscopy ($R = 30,000$) with the GSMT will also enable the detailed study of the physical processes governing star formation under a wide range of initial conditions, i.e., in star forming regions more distant than 500 pc (the current limit with 10m telescopes). With lower resolution spectroscopy ($R = 3000$), we will be able to study the resulting initial mass functions in an even wider range of initial conditions (e.g., the Galactic center and outer Galaxy; the LMC and other nearby galaxies).

4.2. Required Capabilities

These problems place the following requirements on the telescope and instruments.

The wavelength coverage is set at the short end by the desire for the highest possible spatial resolution, and at the long wavelength end by the need to study the 17μm H$_2$ line which is an excellent probe of gaseous disks (and jets?). The great majority of the problems require observations at
thermal infrared wavelengths, hence the emphasis on low emissivity and thermal IR optimization. High spectral resolution is required to resolve the dynamics of forming stars and planetary systems at the few km/s level. The tightest constraint on the field of view comes from the need for high precision astrometry. Large numbers of background objects that can serve as astrometric reference points appear necessary in order to reach 0.3 mas astrometric accuracy. The most stringent constraint on the PSF stability comes from the need for high dynamic range coronagraphy.

4.3. Required Studies

Site Selection: What are telluric opacity sources near wavelengths of interest? How significant a concern is $H_2O$ opacity?

Sensitivity Calculations: How large a sample of protoplanetary disks can be studied at the required angular and spectral resolution with 30m aperture? Consider spectral diagnostics over a range of wavelengths. What are the optimal spectral resolution and wavelength range at which to study giant planet atmospheres? What sample of extra-solar giant planets (distance, age, mass) is accessible with a 30m? Is this adequate to reconstruct the history of planetary systems? In both cases, include the expected performance of coronagraphic suppression of the star and inner disk.

Nulling Coronagraphy: How to optimize the suppression of the star + inner disk? How to implement achromatic nulling coronagraphy? With what fidelity can we reconstruct the data cube given the limitations of speckle noise?

Speckle Noise: The “seeing halo” in AO images is not smooth, but pock-marked with bright “speckles”. Speckle noise causes the noise in the seeing halo to integrate down more slowly than $\sqrt{t}$ due to long range correlations in the atmospheric turbulence. The outer scale of the atmospheric turbulence sets how rapidly speckle noise will integrate down. A smaller outer scale (might be $\sim 30$ m to 1 km) allows more uncorrelated measurements, faster averaging, and therefore a more rapid decrease in speckle noise. This may be an important aspect of site selection.

Open questions include the following. What are effective techniques for the reduction of speckle...
noise? These might include aspects of the experimental design such as the use of multiple bands (Racine paper) or optimal sampling rates (Angel paper), etc. As one example, speckles will have the color of the star and will dance around. Long-term averages of the speckles will be highly correlated for nearby stars within an isoplanatic patch. Can we use this information to distinguish true astronomical structures from speckles? More attention to analysis techniques could also result in significant gains.

What properties of the AO system need to be specified to constrain the resulting speckle noise? That is, if we want to specify a system that produces “low speckle noise”, how do we do that? According to Brent Ellerbroek, one standard measure of the “speckleyness” of a time-varying point spread function is the speckle transfer function (STF), which is the time-averaged square of the modulus of the optical transfer function (OTF). The amount of temporal variation in the PSF depends upon the difference between the STF and the square of the modulus of the time averaged OTF, that is $\langle |OTF|^2 \rangle - |\langle OTF \rangle|^2$.

Quantities such as these are standard inputs to image processing algorithms which operate upon ensembles of short exposure images such as the bispectrum algorithm. Blind and myopic deconvolution algorithms for long exposure imagery can also use available information on the STF to optimize the “gain” of the deconvolution filter as a function of spatial frequency. Current efforts to model/optimize AO systems for future telescopes should evaluate these quantities to estimate the combined performance of AO and (at least simple) image postprocessing algorithms. Precise modeling of the “speckleyness” of very long exposure images may be difficult, at least until better measurements of the outer scale of turbulence become available. Practical limitations on the long term stability of AO system performance are also important. This is one reason for studying the actual astrometric accuracy of existing AO systems.

**Integral Field Spectroscopy:** What is the best implementation of a high spectral and angular resolution IFS? With what fidelity can we reconstruct the data cube given the limitations of the IFS implementation (slicers, fibers, etc)?

**High Precision Astrometry:** One strategy for achieving an astrometric accuracy of $10^{-4}\lambda/D$ would be to achieve a centroiding accuracy of $0.01\lambda/D$ in a single image. We might also average over many uncorrelated images ($\sim 100$) and use many ($\sim 100$) background stars (or galaxies) as astrometric reference points to further improve the astrometric accuracy. The temporal variability of the AO-corrected PSF (“speckle”) is a factor in achieving an accuracy of $0.01\lambda/D$ in the first step, and in determining how many images are necessary to average over. The magnitude distribution of the background objects will affect their centroiding errors. These errors may limit the achievable astrometric accuracy.

This capability appears to be more of a “pure AO” capability in that it mostly relies on the ability of AO to put most of the light of a point source in a tiny “spot” from which the astrometric measurements can be made. The precise shape of the point spread function appears to be less important, and the development of new analysis techniques do not appear to be as
critical to success. Critical questions include the following. What is the fundamental astrometric limit for a single telescope? What are the systematic errors of MCAO system? What are the non-AO systematic effects? What is the limit if background stars are used as reference system? If background galaxies are used as a reference system? Implementation: how to handle the large (\(\sim 15\) magnitude) dynamic range between the target star and background sources without compromising astrometric accuracy?

To test centroiding fidelity with AO, Brent Ellerbroek suggested studies that might be done using existing facilities. First, using a narrow field, high Strehl, natural guide star system, obtain multiple observations of (even) small clusters of stars and galaxies with zero relative motion. The observations would be made on time scales long enough for anisoplanatism effects to average out. Then measure the relative separations and see how robust the AO + analysis is. Second, to evaluate astrometric performance on wider fields, use observations made with current AO systems, which will have lower Strehl (\(\sim 10\%\)). The difference between the narrow and wide field results will provide an estimate of the potential performance advantage of MCAT, assuming that the MCAO system works as advertised. Some relevant measurements may have been reported in the literature, e.g., a paper by Julian Christou and Dominico Bonnacini that might discuss some related measurements of a 4-star system made at SOR.

**Spectroscopy in Crowded Regions:** How to recover 5-10\% relative photometric accuracy in crowded regions? (Both AO requirements and analysis techniques.) What is the optimal implementation for spectrophotometric accuracy? IFS or MOS?

**Imaging Interferometry:** Explore the early implementation of MIR interferometry (nulling with subapertures, etc.) Is it possible to combine the 2 Kecks with a 30m GSMT, and what interferometric performance would result? Preserving the capability for imaging interferometry with multiple apertures is a consideration for site selection.