

AURA

MAXAT Workshop II

*A Technology Roadmap to Extremely Large
Astronomical Telescopes of the Future*



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MAXAT Workshop II

A Technology Roadmap to Telescopes of the Future

1 Overview

As a new generation of 8-to-10-m aperture astronomical telescopes comes into operation at excellent observatory sites around the world, it is time to address the question of how future optical-infrared (OIR) capabilities can and should evolve in the next century. For the last hundred years groundbased telescopes have in each successive “generation”, grown by a factor of 2 in diameter, culminating at the turn of this Century in the explosion of 8m – 10m telescopes. However, continuing this approach may no longer be either scientifically or cost effective. NASA for its “Next Generation Space Telescope” is now contemplating taking the leap from the 2.4m Hubble Space Telescope to an 8m telescope in space. In this context what is the future the role of groundbased optical/infrared facilities?

One avenue warranting exploration is the historical extension of telescopes to larger apertures. Throughout the 20th century aperture increase has been primarily undertaken to enhance the collecting area. Image quality, as set by the atmospheric “seeing”, did not improve with larger OIR telescopes, and in some cases modest degradations in delivered image quality were accepted as part of the price for increased light gathering capability. This paradigm is now shifting. The 8-to-10-m aperture telescopes, which are coming into operation, are achieving gains in resolution as well as in collecting area. In addition, our groundbased perspective has been changed as we have realized that the turbulent structure of the atmosphere is amenable to analysis and correction. The recent emergence of adaptive optics techniques has shown that at near infrared wavelengths at least, we can build large telescopes that will be essentially diffraction limited, re-energizing the debate on the future of large groundbased astronomical facilities.

Looking to the future the possibility exists that high angular resolution will be a new domain for ground-based OIR observatories. OIR interferometers will map high surface brightness, compact sources, such as stellar surfaces, accretion disks, jets, and active galactic nuclei. Giant OIR telescopes with apertures of 30-meters to 100-meters will be equipped with adaptive optics to yield unparalleled combinations of sensitivity and resolution over reasonable fields of view. The latter class of instrument will further complement planned multi-wavelength facilities, including the Atacama Large Millimeter Array (ALMA), as well as space observatories like the Next Generation Space Telescope (NGST; planned as an 8-m class orbiting telescope).

The objectives of the AURA-sponsored ‘Maximum Aperture Telescope’ workshops are to develop a roadmap for the development of future extremely large aperture OIR telescopes. By ‘maximum aperture’ we are not asking what is the largest aperture OIR telescope that one could conceivably build, but rather what extremely large telescope *should* be built as cost-effective

tools to achieve key scientific objectives. The MAXAT I meeting, held in Madison, Wisconsin in 1998, built on the foundation of international discussions of extremely large telescopes to investigate potential science drivers. If these are absent or weak, then a MAXAT would be a low priority. On the contrary, the MAXAT I workshop found that an extremely large aperture telescope of 30-m or more in combination with adaptive optics (AO) capable of yielding near-diffraction limited performance in the JHK-infrared bands would be extraordinarily powerful. Primary scientific drivers included the formation and evolution of solar systems; chemical evolution of gas and stars; measurements of the ages of the oldest stars as a counterpart to the cosmological distance scale, and studies of the assembly of galaxies at redshifts of $z > 3$.

That these and a host of other astrophysical problems benefit from the combination of resolution and sensitivity is clear. A primary mission for a MAXAT is to study the astrophysics of nearby planetary systems. Planets are faint and necessarily found close to stars, so excellent angular resolution and large light gathering power are essential. Extremely large telescopes (ELTs) with diffraction-limited performance over small fields are essential for programs to observationally define the evolution of planetary systems (Figure 1). These capabilities also are required if we want to understand the internal structures of distant galaxies seen at look back times of more than 5 billion years. Deep images obtained with STIS on the Hubble Space Telescope, such as that associated with the Hubble Deep Field South (Figure 2), illustrate the issues. Even though these observations make use of the properly sampled 50 milliarcsec full angular resolution of HST, most faint galaxies are effectively unresolved. Angular resolution of 10 milliarcsec or better is necessary for studies of the assembly of luminous objects at cosmological distances.

Solar System @ 10 pc

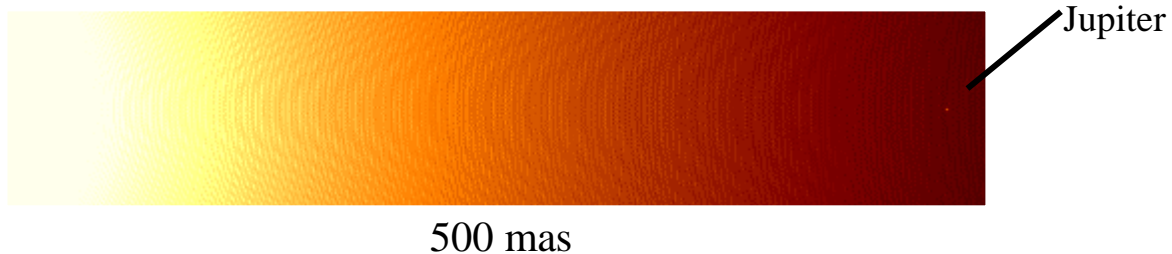


Figure 1: A simulation of the solar system imaged from 10pc by a 100m groundbased, adaptively corrected groundbased telescope (Gilmozzi et al 1997).

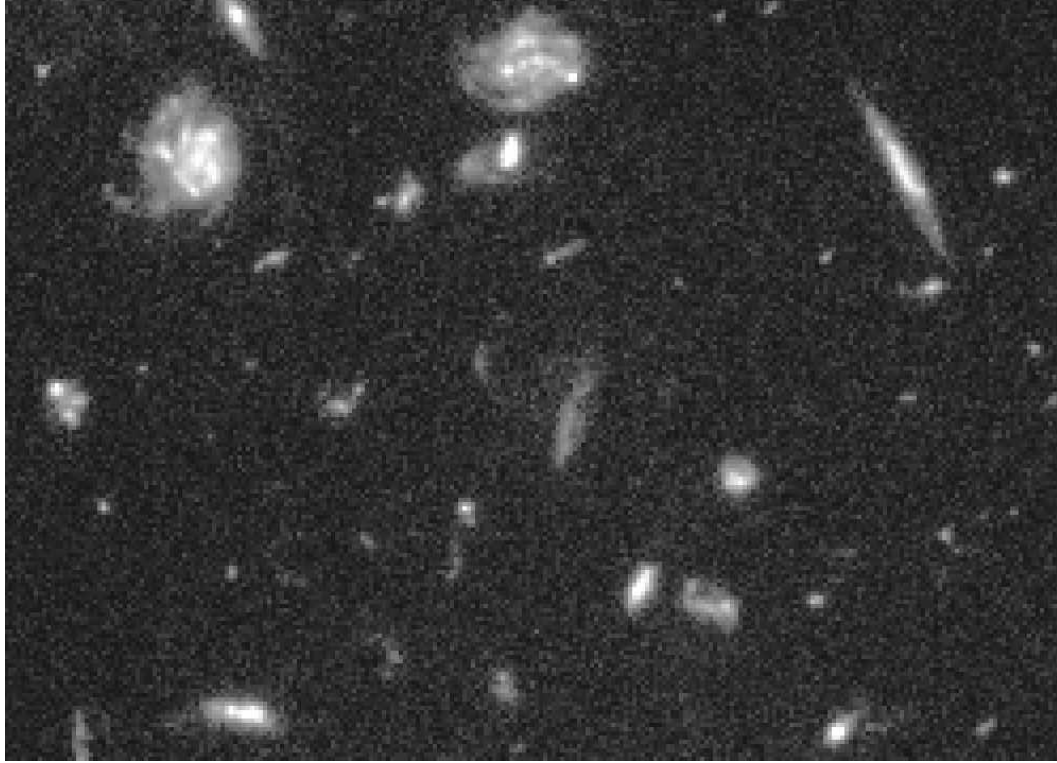


Figure 2. A small section of the Hubble Deep Field South shows the structures of faint galaxies, which are only marginally resolved with the Hubble Space Telescope. In this dithered STIS image the scale is 0.025 arcseconds per pixel.

The view from the MAXAT I workshop that extremely large telescopes could provide major scientific benefits agrees with results from similar studies carried out elsewhere, such as the ESO Overwhelming Large (OWL) telescope, the Swedish extremely large telescope project, and informal explorations in the United States. However, this is only a first step. To proceed further a detailed science reference case is needed and a technological roadmap must be drawn to lay out the path towards designing and costing an extremely large OIR telescope as well as predicting its likely performance. The MAXAT II AURA meeting addressed these issues with an emphasis on drafting a first edition of the technology roadmap (see §7).

The bulk of the MAXAT II meeting was devoted to technological issues (§6, 9-13). Meeting invitees included representatives from key industries in North America and Europe, as well as engineers and scientists with experience in the construction of very large radio and optical telescopes (Appendix 15.1). Astronomers not involved in major instrumentation research were in the minority, and focused their attention on further refinement of the science case and coordination of this case with the technological roadmap (§3, 4).

A new perspective on requirements for a MAXAT presented in this report is the value of having the largest possible angular field of view for deep studies of the origins of large-scale structure in the universe. A careful consideration of this possibility will require a better understanding of telescope optical system designs and the options for instruments to take advantage of the large physical area that would go with wide fields of view in a extremely large aperture telescope. A related problem is how to effectively use times of poor seeing. In addition to the wide field

option, it will also be useful to explore image slicing to feed high resolution spectrographs or other instruments that could use high focal plane fluxes over small fields of view effectively under conditions of poorer than median seeing.

2 Introduction – the case for resolution and sensitivity

Ultimately, astronomical telescopes are used to observe faint astronomical objects, which are typically much fainter than the instantaneous sky background or, in the case of some IR measurements, several orders of magnitude fainter than the background from the thermal emission of the telescope. For point like sources, in this limit the measured Signal to Noise ratio of the astronomical observation is related to the physical parameters of the telescope and instrument by the following equation:

$$\frac{S}{N} \propto \frac{\text{Telescope Diameter}}{\text{Delivered image diameter}} \cdot \frac{h^{1/2}}{\epsilon_b^{1/2}} \quad (1.)$$

Where S is the signal from a faint astronomical object, N is the noise in the background in a given integration time, η is the total system throughput (including atmospheric, telescope and instrument transmissions as well as the detector quantum efficiency), and ϵ_b is the effective background emission.

For diffraction limited pixels, equation 1 becomes simply:

$$\frac{S}{N} \propto \frac{\text{Telescope Diameter}^2}{l} \cdot \frac{h^{1/2}}{\epsilon_b^{1/2}} \quad (2.)$$

If the spatial and/or spectral resolution of an observation drives the background down sufficiently that the detectors become the dominant noise source, then of course,

$$\frac{S}{N} \propto \frac{\text{Telescope Diameter}^2}{\text{Detector Noise}} \cdot h^{1/2} \quad (3.)$$

In both cases 2 & 3 the S/N gain grows as Telescope Diameter². An alternative is to put a large telescope in space where the sky background levels (ϵ_b), especially in the infrared, can be reduced by between factors of 10² – 10⁶. For a space telescope of equivalent aperture and imaging performance as a groundbased telescope this can produce signal to noise gains of between 10 and 1,000. It is this dramatic increased sensitivity which is the principal science driver for the “Next Generation Space Telescope” (NGST), the 8m telescope NASA is contemplating launching into space.

In Figure 3 we plot the relative performance of both near-diffraction limited 20m and 50m telescopes compared to a 8m NGST using the methods of Gillett and Mountain (ref x.) and with aperture sizes, through-put efficiencies in and assumed detector properties given in Appendix A.

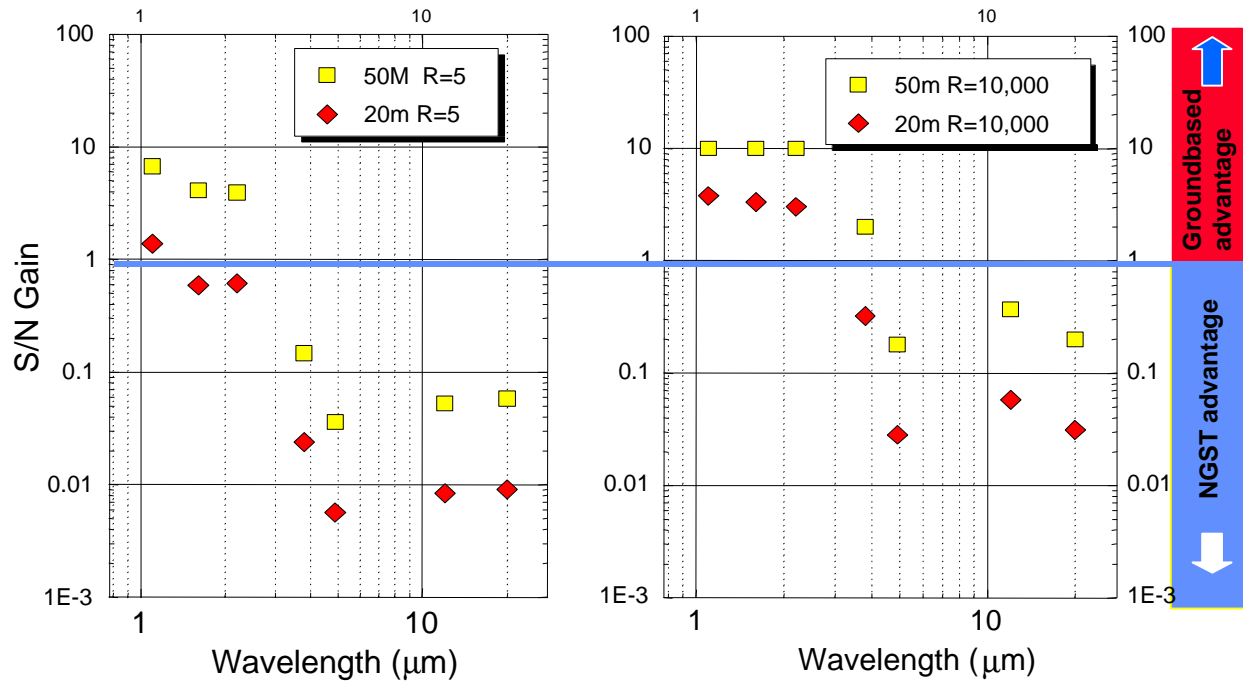


Figure 3: The performance of ground-based 20-m and 50-m telescopes compared with an 8-m next-generation space telescope. The relative S/N gain of a 20-m telescope is shown as diamonds and the 50-m telescope as squares. The S/N gain for a ground-based telescope is plotted as a function of wavelength, assuming that NGST makes an observation of a point-like source in an integration time of 4,000s achieving an S/N of 10. We assume that the objects we need to observe are very small (less than 0.01 arcsec), such as a star-forming cloud or stellar cluster at high redshift, or a planet around another star. Two cases are shown, a comparison for imaging observations with $R(\lambda/\delta\lambda) = 5$ and the relative performance for a spectroscopic observation with $R(\lambda/\delta\lambda) = 10,000$. For imaging, NGST has a clear advantage over a 20-m telescope in the infrared. For spectroscopic observations, a diffraction-limited 20-m ground-based telescope has an SNR or 2-3 over an 8-m NGST making the same $R = 10,000$ spectroscopic observation at 2.2 μm . For wavelengths beyond 2.5 μm , NGST offers substantial S/N advantages. In contrast, a diffraction-limited 50-m telescope making the same observation, the S/N advantage increases to an order of magnitude greater than is possible with an 8-m NGST in the same observation time for any wavelength up to 3.8 μm . Once the wavelength of observation becomes greater than 10 μm , a 50-m ground-based telescope becomes comparable to an 8-m NGST.

What emerges from this comparison, in a era of an 8m NGST, is a new and complementary role for future “second generation” groundbased observatories.

- **NGST will be extremely effective for:**
 - Deep infrared imaging,
 - Spectroscopy at wavelengths longer than 3 microns
- **Groundbased telescopes will provide powerful optical and near-infrared capabilities for:**
 - Moderate to high resolution spectroscopy
- **Groundbased facilities can also exploit large baselines**
 - High angular resolution observations

3 Science

3.1 Science Case

A decade from now, astronomers will have access to major new tools on the ground (ALMA) and in space (NGST). To exploit these tools fully will require a new generation optical/infrared telescope: of angular resolution matched to ALMA, sensitivity sufficient to characterize the faintest sources imaged by NGST, and a combination of field of view and collecting area matched to efficient study of the first emerging large-scale structures in the distant universe—a major scientific driver for both ALMA and NGST.

As a baseline, we have assumed the minimum-size facility capable of satisfying these requirements: a $d \sim 30$ -m diameter telescope, capable of delivering diffraction-limited images (Strehl ~ 0.5) at wavelengths $1\mu\text{m}$ and longward during atmospheric conditions which enable adequate adaptive corrections (thereby providing 10 mas images matched to ALMA); sensitivity to faint sources enabling $R \sim 5000$ spectroscopy at $I(\text{AB}) \sim 27$ mag (sufficient to obtain redshifts and global kinematics for $z > 1$ galaxies); and a field of view sized to enable efficient statistical studies of large-scale structure on spatial scales ~ 100 Mpc at $z > 1$ via multiplexed spectroscopy of hundreds of background QSOs and thousands of galaxies simultaneously; in practice, this requires fields of projected linear size no smaller than 10 Mpc (at $z > 1$, this corresponds to ~ 20 arcmin for $h \sim 100$ and $\Omega = 1$).

A facility providing this combination of sensitivity and angular resolution will not only be an essential complement to ALMA and NGST, but will enable science qualitatively different from that of current generation ground- and space- based O/IR telescopes.

3.2 Formation of the Star-Disk System

ALMA observations will provide detailed maps on scales from several AU to several parsecs of the physical, chemical and kinematic structure of the birthplaces of stars and stellar aggregates—molecular clouds—as well as the cores from which individual stars form, using as primary diagnostics a wealth of molecular emission lines in the sub-mm and mm-wavelength region. These observations will chart the initial conditions for formation of the star-disk system.

Observations with MAXAT will provide essential complementary information by enabling observations of:

- The morphology of the inner regions (on scales of 2 to 200 AU) of the molecular core from mid-infrared images of thermal emission from dust, and from near-infrared observations of starlight scattered earthward by dust embedded within the inner regions of infalling envelope
- Ionized jets traced in near- and mid-infrared emission lines, from their launch point in the inner regions of the accretion disk (within ~ 1 AU of the star's surface) well into the molecular cloud (on scales of thousands of AU)
- Physical conditions (temperature and density) and kinematics of infalling material located inward of 10 AU of the central star from observations of resolved mid-IR molecular

absorption features (e.g. CO 4.6 μ m) viewed against the background light of the star/disk system

- The spectral type for the central star via observation of faint envelope-scattered light in the near-infrared—essential to understanding the linkage between *local* initial conditions in a star-forming molecular core, and the mass of the forming star
- Spectral types and photometry for the newly-formed stellar population in molecular cloud complexes. The ability of a MAXAT to obtain $R \sim 5000$ spectra of stars down to $K(AB) \sim 24$ will enable mapping the frequency distribution of emerging young stars and substellar objects over a mass range from 10 Jupiter masses to 100 solar masses—critical to linking *global* initial conditions in the molecular cloud complex

3.2.1 The Key Roles of MAXAT

- Sensitivity sufficient to enable high resolution *mid*-infrared spectroscopy ($R \sim 50,000$) of key molecular diagnostics
- Angular resolution sufficient to probe structures (jets; inner envelope morphology) on scales $r < 5$ AU out to the distance of Orion ($d \sim 500$ pc)
- Sensitivity sufficient to enable moderate resolution *near*-IR spectroscopy ($R \sim 5000$ with OH suppression) of stellar and substellar objects to limits ($K(AB) \sim 24$) sufficient to probe the mass function down to $10 M_{\text{Jupiter}}$.

3.2.2 Requirements on MAXAT Performance

- Performance Strehl ratios > 0.5 at wavelengths 1.6 μ m and longward to enable high angular resolution imaging
- AO-corrected FOV of 0.5 to 1 arc minute to enable imaging and resolution and spectroscopy of faint substellar sources in source-confused regions such as the Orion Nebula Cluster, or faint stellar sources in extragalactic (Local Group) star-forming regions (NB: NGT is capable of obtaining spectra of unobscured PMS stars with masses as small as the hydrogen burning limit in the LMC: $I(AB) \sim 27$)
- Native seeing-limited FOV of 20 arc min (or greater, if possible) to enable efficient mapping of 'brighter' sources in nearby molecular clouds (where sizes are several degrees)

3.3 Assembly of Planets During the Disk Accretion Phase

Recent radial velocity observations have led to the discovery of tens of extrasolar planets with masses comparable to or somewhat larger than that of Jupiter. The distribution of their orbital properties—with large numbers of extrasolar giant planets (EGPs) located within 1 AU of their parent stars—has led astronomers to rethink the timing of planet-forming episodes and the role of orbital migration prior to establishing a 'stable' solar system. In particular, these observations suggest that—contrary to (most) previous expectations—EGPs most likely form during time when stars are still surrounded by massive, optically thick accretion disks, and that these planets

are driven inward as a result of the accretion process. Some have even speculated that multiple episodes of planet-formation take place during the accretion phase—with post-accretion phase solar systems representing what remains after a vigorous period of planet-formation.

Progress in understanding where and when planet formation begins requires the combination of sensitivity and angular resolution provided both by ALMA and MAXAT. ALMA will enable molecular line observations at 1-2 AU scale (in the nearest star-forming regions)—providing the tools to search (indirectly) for kinematic evidence of EGP formation: indirectly, through spectroscopy of optically thin molecular line emission arising within 'gaps' produced as Jovian mass planets partially clear ring-like regions in the accretion disk via the effects of tidal torques, and directly, through observations of those gaps via molecular line maps of accretion disks in nearby star-forming regions.

Observations with MAXAT will provide essential complementary information through:

- Measurement (from $R \sim 50,000$ mid-IR spectra) of characteristic 'double-horn' profiles in mid-IR spectral tracers (e.g. CO fundamental at $4.6\mu\text{m}$) that diagnose hotter ($T \sim 500$ K) gas located in the inner ($r < 1$ AU) regions of accretion disks, where some Jovian planets may either form or migrate, and where mm-wave observations—more sensitive to emission from cooler gas—are likely to be less effective. These measurements enable estimates of the distance of the forming planet from its parent star, and of the planet's mass.
- MAXAT observations thus enable us to learn both where EGPs form and what mass they have. Spectroscopic and photometric observations with 6-10m class telescopes will provide the information necessary (stellar luminosity and effective temperature—and thus an estimate of mass and age) to understand when planets form, or when they migrate to particular locations within the disk.
- Direct imaging of tidal gaps via near-infrared scattered light observations of disks surrounding nearby young stellar objects.

3.3.1 The Key Roles of MAXAT

- Sensitivity sufficient to enable spectroscopic *surveys* of a sufficient number of systems ($n \gg 1000$) to provide statistical information regarding where and when planet-formation takes place during the accretion phase; and whether orbital migration takes place. In practice, this requires the high sensitivity of NBT in order to obtain $R \sim 30,000$ spectra of YSOs out to the distance of Orion and beyond (in order to obtain a sample of sufficient size)—in practice, to $M(\text{AB}) \sim 16$ mag.
- Angular resolution sufficient to resolve a gap of size ~ 1 AU in a disk located at a distance $d \sim 100$ pc

Extant 6-10m class telescopes can enable 'pilot' searches among bright, nearby YSOs; only a MAXAT can provide the required large statistical samples.

3.3.2 Requirements on MAXAT Performance

- AO capable of delivering high Strehl (> 0.9) at wavelengths $2.2 \mu\text{m}$ and beyond (in order to enable high contrast, possibly coronagraphic imaging of scattered light from the inner regions of circumstellar accretion disks)
- Tip-tilt corrected FOV as 'large as possible' to enable feeding a multi-object mid-IR spectrograph; in practice, this might be 'several' arc minutes

3.4 The Evolution of Galaxies and Large Scale Structure in the Universe

The past two decades have witnessed the detection of subtle fluctuations in the cosmic microwave background (CMB) imprinted during the 'big bang', of structure in the distribution of galaxies on ~ 100 Mpc scales, and of 'dark matter', which dominates the mass of luminous matter in the universe and appears to control the evolutionary paths followed by galaxies and the larger scale structure they trace.

How are the fluctuations in the CMB linked to the emergence of the first luminous, pre-galactic entities, and to the larger-scale structures traced both by these entities and by intergalactic gas not yet assembled into bound structures? How does dark matter orchestrate the assembly of gas into pre-galactic entities and affect the distribution and kinematics of intergalactic gas in the early universe? What morphologies and kinematics characterize pre-galactic entities? How do present day spiral, elliptical and irregular galaxies evolve from pre-galactic forms? What role does environment play in affecting the evolution of galaxy morphology, star-formation rate and chemical abundance?

Over the next several years, completion of the Sloan Digital Sky Survey will provide a clear picture of large-scale structure mapped by galaxies out to redshift $z \sim 0.3$ through its imaging and spectroscopic surveys -- expected to provide spectroscopic redshifts for an objectively chosen sample of $\sim 10^6$ systems and photometric redshifts for a much larger sample. The SDSS will thus provide the basis for understanding the 'endpoint' of galactic and large-scale structure evolution, along with critical constraints on cosmological parameters complementary to those provided by next generation CMB measurements through thorough understanding of the 3-dimensional structure of the 'local' universe.

However, recent deep imaging surveys with 4-m class telescopes and HST, combined with deep spectroscopic surveys with the Keck 10-m telescope suggest that the epoch between $z \sim 1$ and $z \sim 5$ is central to understanding the galaxy assembly phase: at $z \sim 1$, mature galactic forms are already evident, while at larger redshifts ($z > 2$), pre-galactic forms may begin to dominate.

While current-generation ground-based facilities will continue their pathfinder studies, it has become clear that more powerful tools will be necessary in order to explore the $z > 1$ universe: facilities sensitive to near- to thermal- infrared radiation (NGST) where high redshift galaxies are brightest, or to mm- and sub-mm radiation, which carry information diagnostic of early galactic evolutionary phases obscured from direct observation in the infrared. The primary mission of NGST will be to study the character of galaxies and pre-galactic forms at $z \gg 1$; it will be the supreme instrument for imaging galaxies and pre-galactic entities and determining their redshifts and star-forming rates owing both to its size and low thermal background—enabling analysis of

systems with redshifts of 10 or more. ALMA will play an essential role as well through its ability to detect dust continuum and molecular gas emission from dust-obscured high redshift, possibly merging systems undergoing bursts of star-formation, nuclear activity or both.

A MAXAT will play a central role in studying the epoch between $z \sim 1$ and $z \sim 5$ by enabling:

- Studies of the distribution of redshifts of large samples of galaxies (10^7 , or comparable per unit redshift to the $z < 0.3$ SDSS survey) sufficient in number to enable tracing the emergence and evolution of visible large scale structure and its response to the dark matter component of the universe. These studies will be critical in distinguishing between competing theories of structure formation. A survey of this magnitude, to the depth required, $K(AB) \sim 26$ at $R \sim 5000$) will require access to a native seeing field of view of at least 20 arc minute, in order to explore structures on scales comparable to the largest structures observed in the 'local' universe (~ 100 Mpc) on reasonable timescales: several years. The surface density of galaxies with redshifts $z > 1$ and bright enough to enable spectroscopic redshifts to be determined is $n > 1000$ per 20' field of view.
- Studies of the kinematic structure and chemical composition of intergalactic gas from high resolution ($R \gg 20000$) spectroscopy of Lyman forest line systems viewed against the background continuum of QSOs with $z > 3$ and spanning $\sim 10,000$ lines of sight (each sampling > 10 Lyman forest systems). These studies represent a crucial complement to the galaxy redshift survey by providing information regarding the evolution of large-scale structure in the IGM, how intergalactic gas is assembled into pre-galactic and galactic systems, and how star-formation and chemical processing in stellar systems affects the chemical history of the IGM. In practice, this program requires R- and I- band spectroscopy of QSOs with typical brightness $I(AB) \sim 28$. The relatively low surface density (INSERT) of these targets places a premium on field of view.
- High angular resolution imaging and spectroscopy of pre-galactic forms in order to understand and quantify their morphology, kinematics, chemical composition and local star-forming rates on spatial scales of a several tens of parsecs—comparable to those achievable on Virgo galaxies from the ground under good seeing conditions. This will require imaging and IFU spectroscopy with Strehl ratios > 0.5 at wavelengths $1.6\mu\text{m}$ and longward.
- Imaging and spectroscopic surveys of multiple 1 Mpc volumes (~ 2 arcmin at $z \sim 1$) spanning a wide range of environmental conditions aimed at identifying (via their kinematic properties) pre-galactic entities destined to form a single mature galaxy, and determining empirically the path from pre-galactic to galactic forms.
- High angular resolution imaging and spectroscopy of candidate merger events among $z \sim 1$ galaxies aimed at isolating the gaseous, new- and old- stellar components in order to understand in detail how mature galactic systems are produced from multiple mergers.

3.4.1 The Key roles of MAXAT

- Field of view sufficient to enable surveys comparable to SDSS among galaxies in the range $1 < z < 5$ in timescales not exceeding 5 years (in practice, this requires a field of at least 20' in

order to fully sample 10 regions, each of 100 Mpc dimension (an angular size ~ 3 deg at $z > 1$)

- Angular resolution sufficient to define the morphology of pre-galactic entities and to enable spectroscopic studies of kinematics, chemical composition and star-formation activity on scales of 30-100 pc (10 - 30 mas)
- Sensitivity sufficient to enable high spectral resolution studies of Lyman forest lines against background QSO continua, and deep redshift surveys of $0.1 L_*$ galaxies out to $z \sim 5$ (I (AB) ~ 28 for QSO spectroscopy; K(AB) $\sim 26-30$ for deep redshift surveys)

3.4.2 Requirements on MAXAT Performance

- Field of view 20 arcmin or greater to enable efficient sampling of redshifts and Lyman forest systems. These applications make superb use of times when meteorological conditions preclude full AO corrections (e.g light cirrus) and are fundamental science drivers for building a large aperture telescope.
- Strehl $> \sim 0.5$ at wavelengths $1\mu\text{m}$ and longward to enable studies requiring high angular resolution (pre-galactic forms; merging galaxies) and sensitivity (spectroscopy of pre-galactic forms)

4 Summary Of Key Design Drivers And Issues

The group assembled in Hyannis comprised 12 scientists, selected to study the top-level requirements placed on a MAXAT from the point of view of two communities: those studying (1) evolution of galaxies and large-scale structure, and (2) the formation and early evolution of stars and planetary systems. In the limited time available prior to and during the meeting, these two groups were able to identify large classes of problems that are either enabled by a MAXAT, or in which a MAXAT plays a central role as part of a 'system' comprising ALMA and/or NGST. In the course of discussion, they identified key design drivers and a set of issues to guide early conceptual design studies; they are summarized below.

It is, however, essential to point out both that these design drivers are very top level and approximate; far deeper and more quantitative studies are required before a full up "design reference mission" is available to guide a proper science to engineering requirements flowdown. Moreover, we hasten to note that there was no representation from wide areas of active astronomical research—ranging from stellar populations to stellar physics—which stand to benefit significantly with a facility of the power of a MAXAT, but whose list of requirements could well differ from those that emerged from the Hyannis meeting.

4.1 Top Level Requirements

- Native seeing FOV of at least 20', with a goal of 30'
- 'Moderate' Strehl AO-corrected images ($> \sim 0.5$) at wavelengths $1.6\mu\text{m}$ and longward, with a goal of similar performance at $1\mu\text{m}$ over a FOV 0.5 arc minute, with a goal of 'several' arcmin
- Primary operating wavelength: $1\mu\text{m}$ and longward (AO-corrected); $\sim 0.4\mu\text{m}$ (native seeing)

4.2 Issues

- What are realistic limits on 'ultra-high' Strehl for high contrast scenes (e.g. detecting low surface brightness scattered light disks or faint EGPs against the PSF wings of a bright central star)? Are Strehl's of 0.99 achievable with natural guide stars and realistic deformable mirrors? Are specialized (as opposed to 'facility') AO systems required for such problems?
- What are the requirements on telescope emissivity placed by the near- and mid- infrared imaging and spectroscopy programs and how do these requirements trade against emissivity of competitive AO system designs? Against native-seeing FOV?
- What are realistic limitations on native seeing FOV; how does FOV trade against thermal background, telescope and instrumentation design complexity, and cost compared to a 'small' (1 arcmin) FOV telescope?
- How can we better quantify and refine the flowdown from science to requirements and goals regarding:

(1) Strehl vs. wavelength

(2) Strehl vs field of view?

(3) Native seeing field of view

NB: (1) and (2) will benefit from analysis of problems related to star formation and stellar populations in other galaxies; (3) will benefit from deeper analysis of required sample sizes and sample surface density deriving from analysis of numerical simulations of galaxy and IGM evolution under different assumed cosmologies

- What are the systems-level issues involving design of key instrumentation fed (1) by AO systems of various designs; and (2) by native seeing (thermal background; overall throughput; complexity; risk; cost)?

5 Next Steps

Prior to preparing a proposal to support CoD studies for a MAXAT, we recommend:

- Developing detailed science proposals for (1) the cases outlined above; and (2) additional cases. These could be focussed on stellar population studies both within the Milky Way and extending to systems as distant as Virgo and the related issue of the state and heavy element abundance enrichment of diffuse matter within and between galaxies. These proposals should include more detailed descriptions and justifications of the measurements needed, sample sizes required, exposure time estimates, the implied requirements on key telescope and instrument design parameters, and the roles of both extant ground-based O/IR facilities, and of frontier facilities which will be in place in 2010 – both on the ground and in space.
- Developing from these proposals a “Design Reference Mission” that provides an overview of key science programs enabled or enhanced by a MAXAT, and the requirements they place on MAXAT performance. The output from the Design Reference Mission should be an initial cut at a science to requirements flowdown.
- Developing from the Design Reference Mission an understanding of the requirements placed on the instrumentation needed to carry out first priority NBT science.
- Developing an understanding of the challenges faced in designing the instrument complement, the possible role of new technologies in reducing cost and/or complexity or enhancing performance, and how the design and performance of each key instrument is linked to the overall MAXAT system design.

6 Technology

6.1 Overview – quantifying innovation and bypassing extrapolation

Beyond our scientific curiosity, reinvigorated by the discoveries made in the latter part of this Century, the most profound impact on our vision of future telescopes, whether on the ground or in space, has been the revolution in computer and materials technology that has occurred over the last few decades. These new innovations have enabled completely new approaches to building large telescopes and instruments. This has encompassed the detailed analytical modeling of complex structures to the construction and control of large, fully active primary mirrors and the development of near perfect detectors with quantum efficiencies approaching 100%.

In addition, our groundbased perspective has been changed as we have realized that the turbulent structure of the atmosphere is amenable to analysis and correction. The recent emergence of adaptive optics techniques has shown that at near infrared wavelengths at least, we can build large telescopes that will be essentially diffraction limited, re-energizing the debate on the future of large groundbased astronomical facilities.

When thinking how to approach the design task of building a 50 to 100 meter optical/IR telescope, we are tempted to simply scale from our existing experiences. If one does this, it becomes obvious that the costs alone become prohibitive. In addition, some of the performance drivers change and one can find that the recent ‘more traditional’ approaches will not lead to the performance desired. Many of the science cases driving the MAXAT concept lead to the requirement for advanced Adaptive Optics (AO) systems. These systems simply cannot be scaled from today’s AO systems. Newer thinking is required for the MAXAT concept from the outset; that includes the full time use of adaptive optics (in some form) as an integral part of the telescope design. For example, with this approach, we can now ask the question “do we really need to produce a “perfect” mirror?” Perhaps instead we can accept, over some spatial scales, less than perfection using (in addition to the active optics techniques already in use on our 8m telescopes) adaptive techniques to correct for the overall effect of wind buffeting a 30m – 100m mirror?

To understand the enormous change that has already occurred in the approach to telescope building, it is instructive to compare today’s 8m – 10m telescopes with those built in the heady days of 4m-telescope construction in the 1970’s – 1980’s. If we take as an example the Kitt Peak 4m telescope, completed for ~\$10m in 1970 (\$64M in 1998 dollars), scaling this approach for an 8m telescope using a “canonical” scaling law of $D^{2.7}$ would imply a cost today of ~\$400M. In contrast a Gemini 8m telescope (with support facilities and enclosure) costs ~\$88M. The use of modern design approaches and new technologies, (meniscus mirrors and active, computer controlled support systems for example) have enabled a what we will call a “cost gain” over the 1970’s approach of ~ 5. In addition to cost, these modern 8m – 10m telescope were designed to deliver better performance in terms of image quality. For example, the image quality specification for the Kitt Peak 4m telescope was 1 arcsecond. For a Gemini 8m telescope the requirement was for 0.1 arcseconds at 2.2 microns, which relative to diffraction is a “performance gain” of a factor of 5 compared to the Kitt Peak 4m, (assuming the same 1 arcsecond image quality requirement applied to 2.2 microns). Using this approach we can define an “innovation factor” for a 1998 Gemini 8m telescoped compared to a 1970 4m telescope of:

$$\begin{aligned}
\text{Innovation "factor"} &= \text{Cost "gain"} \times \text{Performance "gain"} \\
&= 5 \times 5 \\
&= 25
\end{aligned}$$

Alternatively, modern analytical modeling methods and the use of new technologies have allowed the Gemini designers to innovate by a factor of 25 over the approach taken to build 4m telescopes in the 1970's. It is this new approach to analytical design (where the performance of an 8m telescope can now be predicted to sub-arcsecond precision) which is responsible for today's telescope designers (both in space and on the ground) breaking free from the more traditional "factor of two paradigm" in response to the scientific drivers for telescopes such as NGST, and the new 30m – 100m telescopes now under consideration. In Table 1 we tabulate some of the "innovation factors" being contemplated for these new telescopes.

Table 1: Comparing the "innovation factors" of current generation and contemplated "second generation" 30m – 100m telescopes. The "innovation" achieved in going from the 1970's 4m KPNO telescope to one of today's 8m telescopes.

"First Generation" Telescope (approximate cost)	"Second Generation" Telescope (estimated cost)	Required "innovation factor"	Notes:
KPNO 4m (~\$61M in 1998)	Gemini 8m (\$88M)	25	
HST 2.4m (\$2,400M)	NGST 8.0m (\$1,000M)	27 – 70	1. 2. 3.
VLT 8.1m (\$100M)	100m (\$1,000M)	80	1. 4.
Keck 10m + LGS AO (\$100M)	30m (\$400M)	5	1. 4.
Gemini 8m + MCAO (\$100M)	50m (\$1,000M)	12	1. 4.
	50m (\$600M)	20	1. 4. 5.
Notes: <ol style="list-style-type: none"> Both "first generation" and "second generation" telescopes are assumed to deliver near-diffraction limited performance, either through design or with the use of adaptive optics systems. For groundbased facilities, the approximate costs include the costs of the AO systems. For NGST we have assumed a "conservative" estimated cost To calculate a scaled cost for NGST relative to HST we used a range of $D^2 - D^{2.7}$ To calculate a scaled cost for the "second generation" groundbased telescopes relative we used $D^{2.7}$ By increasing the "innovation factor" to 20, a 50m MAXAT could be reduced in cost to ~\$600M 			

Designing a MAXAT both to support the key science goals being discussed *and* to ensure future larger ground based optical/IR telescopes *are affordable* will require significant innovation and presents many technical challenges. To develop these new ideas, and the technology on the required time-scale, it is crucial that a very organized systematic approach is taken that strives to coordinate the new designs and developments with efforts going on throughout the national and international communities. The purpose of this MAXAT-II workshop was to bring together people various organizations and corporations from the US and world to help organize the beginning steps or road map towards the eventual goal of producing telescopes in the 50-100 meter realm.

An overall roadmap has been produced which is described in the next section. We also discuss specific technology considerations and approaches, including “mini-roadmaps” for several of the key sub-systems that will be required. The MAXAT road map is an effort to complement efforts at institutions already attempting some initial design work for both the ground and space in a way that would benefit any group working on such endeavors. Our goal was to explore some potential new approaches and systems thinking to bring this challenge into the realm of the ‘doable’ for an affordable cost. The ultimate goal of the MAXAT technology studies is to launch us on a road that will lead to the production of these large instruments to enable the scientific discoveries that we are looking forward to in the next decade and beyond.

7 Road Map

The road map given in Figure 4 attempts to show how the development path in the early phases of building a large telescope should fit in the context of other know efforts throughout the world. It begins with defining the science goals while recognizing the state of current technology and other activities such as the NGST and ALMA projects. With recognition of these projects and input from various community sources, an initial balance of science desires, current capabilities, top level engineering goals for new methods and some initial assumptions on site characteristics, the “Design Reference Mission” is defined as a document to focus the efforts on in the future.

From here, the road map center path balances systems concepts development with enabling technology development, continuously balancing top level cost trades to lead to what might be ‘final’ science and system requirements for large telescopes. This is a path that would take some number of years to fully develop.

System considerations include several other areas traditionally not considered much in telescope design. Several examples include:

- Site characteristics
- Active and adaptive approaches
- Instrument and telescope considerations
- Logistics of building
- Logistics of maintaining

And of course the typical systems trades:

- Optical Design trades
- Mirror Technology approach
- Mount approach
- Reliability and Maintenance

Of these considerations, site characteristics, particularly wind, was seen as potentially one of the largest factors to consider in the design. Scaling from existing designs, wind may be far more of a challenge than seeing considerations that often dominate site selection. In this case, it may be better to pick a site with lower average wind and slightly poorer seeing as a way to have a better overall systems design (with adaptive optics).

The top half of the road map given in the figure shows some of the system level concept areas that need to be studied. Specific examples of early systems studies may include:

Optical system design

- Survey to summarize options and effects on quality, FOV, complexity

Multi-conjugate AO system studies

- Developing concepts to fit with representative telescope designs
- Propose demonstrations

Instrumentation Concepts

- Diffraction limited and seeing limited concepts
- Integration with Optical/structure design
- Creative ways to combine instrumental capabilities

Telescope and Enclosure concept studies

- Looking at potential low cost solutions for protecting the telescope from the wind

Site environment studies

- Bound the initial problem of wind buffeting
- Impact on any site survey work

The bottom half depicts some of the technology development one may wish to pursue to enable the system concepts to consider. Potential examples of technology development programs, beginning with initial studies that complement other efforts may include:

Low cost aspheric segment production concepts

- Methods to bring aspheric production to near spherical production costs
- Planetary polishing with stressed lap or stressed substrate concepts

Concepts for adaptive Primaries

- Complement adaptive secondary work
- Use of NGST type materials development to form large adaptive surfaces

Actuator and Sensor concept development

- Production cost and reliability is major driver

Active or smart structure component concepts

- How to 'stiffen' large structures?

Sodium Laser Development

- Low cost reliable laser development

On both sides, relationships to other programs are shown. The purpose is to pursue ideas (systems and technology) that complement the other efforts. In this method, the 'world' effort for large telescopes is greatly expanded and more people may benefit from any developments that may evolve from this plan.

Given the size of the system some wished to see, it was also generally agreed that some intermediate step be considered to demonstrate some of these new methods and to lower the risk of the larger system.

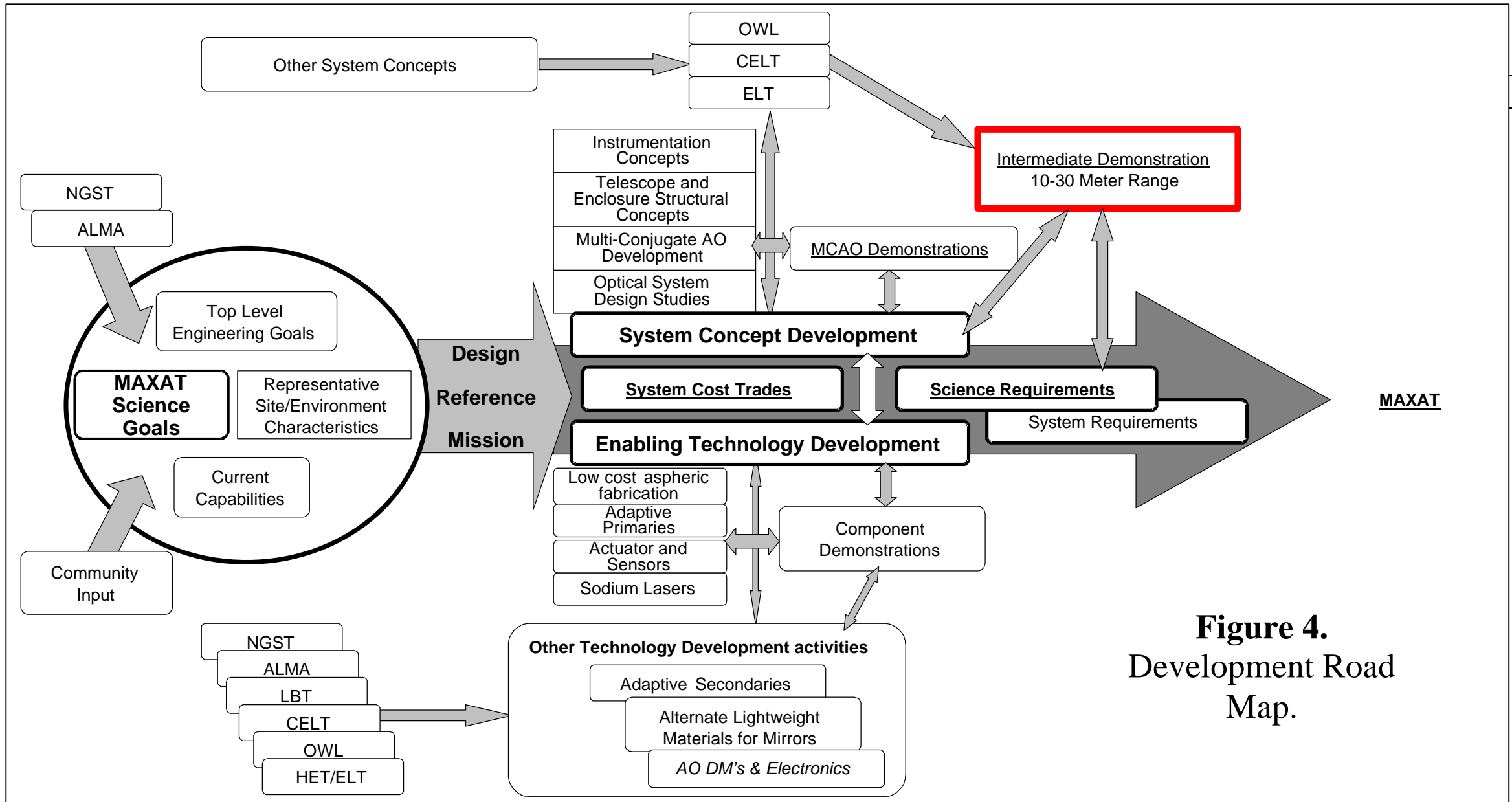


Figure 4.
Development Road
Map.

9 Technology subgroups

To feed into the systems discussions and road map, we formed several technical subgroups for the meeting to focus on key areas. The groups formed were:

Optics	Chaired by Larry Stepp
Structures	Chaired by David Halliday
Adaptive Optics	Chaired by Brent Ellerbroek
Controls	Chaired by Pat Wallace

Each Group was asked to discuss some specific questions that would effect both systems and subsystems aspects of large telescope design. Cost was also to be considered and groups were encouraged to both come up with potential cost drivers and suggested areas of development that would enable cost effective systems design.

The top-level discussion subjects given to each group was as follows:

9.1 Optics

Overall Optical design:

- Consider Spherical, parabolic, or aspherical for M1, M2, ...Mn
- How do surface parameters drive system complexity and cost?
- FOV possibilities and drivers?
- The Impacts and considerations of incorporating AO?
- What are the trades of active verses passive correction regimes?
- What are the wind buffeting considerations?
- What are the fabrication, testing, integration issues?

How to apportion risk between M1 and the rest of system:

- What are the spherical, parabolic, or aspheric possibilities for M1?
- How does this drive cost & schedule?
- What are the active optics issues?
- What are the support system complexity issues?
- What are the reliability issues?

9.2 Structures

Telescope mount concepts:

- Cost / size drivers
- Active structures
- Pointing
- Support considerations
- Wind

Enclosures & Service / protection considerations:

- New / 'open' ideas for lower cost
- Wind

9.3 Adaptive Optics

- How to approach AO system designs that is integrated with the telescope?
- If telescope used with AO most/all of the time, are there potential areas of simplification by treating this control system as permanent part of telescope optical system?

Multi-Conjugate Adaptive Optics (MCAO)

- How many deformable mirrors (DM's), laser beacons, and wavefront sensors (WFS's) will be required?

FOV drivers

- How do we scale our needs from current technology
- How do we trade AO performance against active optics (aO) telescope requirements?
- Will telescope control requirements drive the dynamic range requirements of wavefront sensing and DM's

Laser system

- What power and how many lasers are required?
- How do we develop low cost 'turn key' systems?

9.4 Controls

The control system should be considered an integral part of the telescope mount and optical system

- Overall complexity
- Scaling issues from current concepts
- How do the AO control issues impact the overall controls systems design?

The resulting reports of the discussion groups are given in the next sections.

10 Optics subgroup report

10.1 Introduction

To be diffraction limited (to have a Strehl ratio of 0.8) a telescope must produce a wavefront better than 0.07 waves RMS. For example, at a wavelength of 2.2 microns, the wavefront must be no worse than 154 nm RMS. This is a challenging goal for the current generation of 8-meter telescopes, so it will not be easy to accomplish on a telescope an order of magnitude larger.

To put the problem in perspective, it is useful to look at some first-order scaling laws for mirrors (based on isotropic, uniform-thickness flat plates):

- The fundamental resonant frequency of a circular plate will scale as t/r^2 , where t is the thickness and r is the radius. For example, an 8-meter diameter ULE meniscus mirror of 20-cm thickness has a free mode fundamental frequency of about 15 Hz. A 50-meter diameter mirror of the same thickness would have a fundamental frequency of about 0.4 Hz, close to the peak frequency for wind energy.
- Self-weight support print through will scale as a^4/t^2 , where a is the spacing between supports and t is the mirror thickness. The existing 8-meter telescopes with meniscus mirrors have supports 40-70 cm apart for mirrors 17.5-20 cm thick.
- For a mirror on a traditional floatation support system, an uneven wind pressure on the mirror will cause astigmatic bending whose magnitude will scale as r^4/t^3 . A 50-meter diameter mirror 20 cm thick would deform more than 1500 times as much as the Gemini primary mirror.
- For a given delta from front to back in either temperature or coefficient of thermal expansion, the resulting thermal deformation will scale as r^2/t .

It is clear that to simply scale up current designs will not result in diffraction limited performance. Scaling up current designs would result in prohibitive costs as well.

With these issues in mind, the August 1998 MAXAT workshop defined the following key considerations for the primary mirror:

- Fully active and adaptive optics-friendly
- Structural issues; segmented design with segment sizes of <8-m to allow transportation
- Studies of mirror phase control important
- Wind loading on the mirror and structure major issues for mechanical control of MAXAT

The performance of MAXAT optics will be highly dependent on their structural support. The interactions between the optics and structures are discussed in Section. 10.3.1.

The solution to the structural problems will be largely dependent on the success of the adaptive optics system. The interactions between the optics and the adaptive optics systems are discussed in Section 10.3.2.

Producing the mirror segments for MAXAT is not beyond the current state of the art in optical finishing and testing. However, feasibility is not the main question – since the cost of the optics will be a large fraction of the total cost of the observatory, the challenge for optical fabrication is to obtain excellent mirrors at the lowest possible cost. This will be discussed in the next section on Key Issues.

10.2 Key Issues

10.2.1 Primary mirror segment size

The debate over primary mirror segment size involves segment control, adaptive optics performance, blank availability and cost.

Allan Kreutzer of Schott reported the cost of Zerodur mirror blanks would be relatively constant per kilogram of material for blanks from about 0.5 meter to 2 meters diameter. (For a given thickness of mirror blanks or facesheets, the cost per kilogram would be the key metric.) The cost per kilogram of smaller sizes would be higher because of increased labor costs, while the per-kilogram cost of larger sizes would increase because of manufacturing difficulty and risk.

Alternative mirror materials were also discussed, including Beryllium and Silicon Carbide in different forms. These materials offer substantially higher specific stiffness than glass or glass ceramics, but are not currently available in sizes larger than 1.5 – 2 meters diameter.

David Crowe of Composite Optics described the current state-of-the-art in replicated mirrors. Some replicated mirrors have been made up to 2-meters across, with figure accuracies of several microns. Eric Ruch of REOSC reported that replicated mirrors can be improved by ion figuring. Replication could potentially reduce the cost of optical finishing, at least for spherical segments, if the problems of surface accuracy and stability can be overcome.

Marc Cayrel and Eric Ruch of REOSC and Andreas Nonnenmacher of Raytheon commented on the relative costs of spherical and aspherical segments of different sizes. A significant reduction in optical finishing cost can be achieved if the segments can be polished on a planetary polisher, in the same way the segments of the Hobby Eberly Telescope were produced by Kodak. The maximum practical size for segments to be finished in this way would be around 2 meters, and this approach produces segments with a spherical figure. The cost reduction compared to more traditional polishing techniques, such as would be used for aspheres, would be dramatic – probably a factor of 4 or 5. Very preliminary cost estimates give the total optical finishing cost for a 50-meter MAXAT primary mirror at around \$60 M for 2-meter spherical segments, about \$250 M for 2-meter aspherical segments polished by traditional techniques, and somewhat more for larger aspherical segments up to 8-meters across.

Some participants were concerned about the difficulty of controlling a large number of segments. However, Jerry Nelson reported studies that indicate segment edge sensor noise only increases as

the square root of the number of segments across the diameter. To go from 8-meter segments to 2-meter segments would only increase the sensor noise by a factor of two.

Roberto Gilmozzi reported the ESO OWL program favors segments smaller than 2.3 meters so they can be produced on planetary polishing machines and because the transportation costs would be significantly lower than for larger sizes. Blanks of this size will fit in standard shipping containers.

All of these factors lead to the conclusion that the maximum practical segment size is around 2 meters, and that there would be little penalty (in terms of sensor noise) in not going larger.

An interesting alternative view was proposed by Roger Angel. The primary mirror itself might be made an adaptive optic if the segments were as small as 30-cm. Each segment could be controlled in piston, tip and tilt at frequencies of tens of hertz. Other participants raised questions, however, about: (1) the difficulty of controlling the 25,000 segments required to make a 50-meter telescope; (2) the difficulty of providing adequate information from wavefront sensors at the required rate; and (3) the difficulty of avoiding vibration problems on a structure with resonances starting at about 1 Hz. Until these questions can be answered, the practicality of the approach will be uncertain.

10.2.2 Spherical or aspherical primary mirror

Because of the large potential cost advantages of producing spherical mirrors on planetary polishers, several proposals for extremely large telescopes have incorporated spherical primary mirrors. However, these designs normally require 4 or 6 mirrors to form a good image, and the correctors are generally several meters across and highly aspheric. Optically, there are advantages to using an aspheric primary (see section 10.2.4).

At the meeting, two proposals were advanced to produce aspheric segments, similar to those in the Keck Telescopes, using planetary polishers. Marc Cayrel suggested polishing the segments as spheres and then bending them into aspheres on their mountings. Jerry Nelson proposed bending the segments during spherical polishing, then allowing them to relax into aspheric shape. In either case, it would only be necessary to get the segment figure within a few microns of the correct shape, since the rest of the error can be corrected in a deterministic manner with ion figuring. The peak-to-valley departure of a 2-meter segment at the edge of a 50-meter f/1 paraboloidal MAXAT primary mirror from the best-fit sphere is about 292 microns (this is the worst-case segment). A 3-phase approach would be possible: (1) use a bend-and-polish technique to eliminate 80-90 percent of the asphericity; (2) correct the segment figure within 2-3 microns using the active optics actuators; and (3) correct the print-through and other residual aberrations using ion figuring. This appears to be a promising area for further development, as it offers the potential of producing aspherical segments at a cost close to that for spherical segments.

10.2.3 Field of view

The science case was made for having a nearly diffraction-limited field of view of ~2 arc minutes, plus a seeing-limited field of view as large as possible, perhaps tens of arc minutes

across. At the meeting, Sam Barden presented an optical design for a 30-meter telescope, using four aspheric mirrors (references 1, 2). This design provides near-diffraction limited image quality on axis, and seeing-limited image quality over a 1-degree field.

During the meeting, Jim Oschmann produced a strawman design for a 50-meter Ritchey Cretien telescope that produced ~ 0.5 arc second images over a 24 arc minute field diameter. Jim made the point that the optical design can take advantage of the ability of the adaptive optics system to help correct the center of the field of view, so the optimization can favor the outer edge of the field over the central portion, but still achieve diffraction-limited performance at the center with adaptive optics.

Roberto Gilmozzi presented a graph (Dierickx, Figure 7) showing that for field angles less than 5 arc minute radius, the OWL 6-mirror design would produce better images than a Ritchey-Chretien. Their design uses a spherical primary and flat secondary.

10.2.4 Optical design

The studies cited demonstrate the feasibility of achieving diffraction-limited images on axis while also being able to produce seeing-limited images over a field of view greater than 10 arc minutes diameter, with designs having either spherical or aspherical primary mirrors. Still, it is clear that an aspherical primary would simplify several other aspects of the optical design:

- Equivalent performance over a relatively wide field of view can be achieved with fewer mirrors, which is important to minimize system emissivity
- The central obscuration can be smaller
- No need for large, highly aspheric correctors
- The designs with 4 or 6 mirrors are hard to baffle against stray light

Therefore, at present it would be wise to produce strawman designs having both spherical and aspherical primaries. The parameters to be studied should include:

- Image quality over the central field of view, assuming adaptive optics correction
- Field of view for which seeing-limited images can be produced
- Focal ratio
- Options incorporating a relatively small mirror that can be used for fast guiding of the seeing-limited field
- Baffling
- Field Curvature
- Central obscuration

- Ensure design accommodates beam paths for multi-conjugate adaptive optics with multiple laser guide stars
- Study of aberrations produced by misalignments
- Suitable locations for instruments

The science instruments must be defined at the start of this study, in order to set requirements for focal ratio, field of view, baffling, instrument positions, etc.

10.2.5 System complexity and reliability

Several issues of system complexity and reliability have been identified, particularly in the control of the position and figure of the primary mirror segments.

1. Segment position actuators

To keep the mirror surface in shape in the presence of wind buffeting, each segment will need to be positioned in piston, tip and tilt to an accuracy of tens of nm at rates of a few Hz. To compensate deformations of the telescope structure, these actuators will need ranges of 1-2 cm. The amount of heat dissipated by these actuators must be limited to avoid disturbing local seeing conditions. Reliability is also particularly important, because of the quantity of actuators required. Assuming three actuators per segment, a 50-meter MAXAT with 2-meter segments would require about 1700 actuators. If it had 30-cm segments, it would require about 75,000.

2. Segment position sensors

If the segment control is similar to the system on the Keck Telescopes, edge sensors will be required to measure the relative positions of the segments with a resolution and repeatability of a few nm. For a MAXAT with 2-meter hexagonal segments, a system with one sensor at the corner of each segment would require about 3400 sensors. This type of system would also put heavy demands on computing power.

3. Segment figure actuators

Each segment will need active optics actuators to control its figure to within tens of nm using either force or displacement control. The exact number will depend on the structural details of the segments, but could easily reach 20,000 actuators for a 50-meter MAXAT. This will place stringent demands on actuator reliability.

10.3 Interactions with other systems

10.3.1 Telescope structure

The telescope structure must hold the primary and secondary mirrors in position and in shape under the influence of gravitational sag and wind buffeting. At the 50-meter scale, this is very difficult. The gravitational sag of the secondary mirror relative to the primary, and the sag of the supporting structure for the primary mirror, will likely be millimeters or tens of millimeters.

However, these are slowly changing effect that can be compensated by actuators. A more difficult problem is the wind buffeting.

In existing telescopes with more traditional designs, the pressure exerted on the primary mirror by the wind is two to three orders of magnitude lower than the self-weight of the mirror blank. However, for a 50-meter MAXAT with a lightweight primary, the wind loading is likely to be only one order of magnitude lower than the mirror weight. To make matters worse, the resonant frequencies of the telescope structure will start around 1 Hz. If the structure is highly elastic (for example, steel) there will be dynamic amplification of the wind-induced vibration that could produce structural oscillations as large as the deflections caused by gravity.

Possible remedies for this problem include using structural materials with higher specific stiffness and higher damping, for example, graphite-epoxy composites, as well as using smart structures to effectively make the telescope act much stiffer than it really is. However, these approaches may not be affordable for this size of structure.

To preserve pointing accuracy, existing telescope designs have minimized structural hysteresis by using highly elastic materials with welded joints. However, Tom Sebring pointed out the cost advantages of using prefabricated structures with bolted joints. Similarly, composite materials often exhibit hysteresis and dimensional instability. Cost and structural damping considerations may require trade-offs in telescope pointing accuracy.

If the structure is highly elastic with a low fundamental resonance, this will place limitations on the operating bandwidth of the segment positioning actuators. It will also place limitations on the bandwidth of the mount control system. This heightens the need for a relatively small steerable mirror in the optical train that can control image motion, not just for the diffraction-limited field that has the advantage of adaptive optics correction, but for the seeing-limited field as well.

10.3.2 Adaptive optics

The adaptive optics system could potentially help to relax many of the requirements on the structural performance, segment positioning and segment figure. The AO system would need a wavefront sensor and one or possibly two deformable mirrors conjugate to the primary mirror. The deformable mirror(s) will need to have high resolution and large amplitude, but should only have to operate at a bandwidth of a few Hz. To adequately measure segment figures, this wavefront sensor will need a number of subapertures similar to the number of active optics actuators in the primary mirror.

The interaction between active and adaptive optical systems will be further complicated if more than one mirror is segmented. As David Crowe pointed out, a system with more than one segmented mirror in series (for example, the ESO OWL design) will have greater difficulty accurately sensing the phase differences caused by segment misalignment.

In contrast to the hierarchical approach of moving the largest optics at the lowest bandwidth, and doing adaptive pointing and wavefront corrections with the smaller mirrors, Roger Angel has proposed making the primary mirror adaptive. This could have significant performance advantages if the structural and control system difficulties can be solved.

10.3.3 Instruments

As mentioned in Section 10.2.4, it is very important to define the first order requirements of the science instruments as early as possible in the design process. To break away from the traditional cost curve, a MAXAT will have to be designed for a limited mission, not as a telescope that supports every possible observing program.

The MAXAT design must be optimized to meet the requirements of the instruments for the seeing-limited field as well as the diffraction-limited field. In particular, the size, number and location of instruments for the seeing-limited field must be understood.

Another question is whether it is necessary to maintain a fixed plate scale. For example, some radio telescopes use homologous design techniques that allow the focal length to vary as the optics sag under gravity. It is also likely that wind buffeting could dynamically change the radius of curvature of the primary and therefore the focal length of the telescope. The change in plate scale could be significant and simply refocusing the image will not correct it.

10.4 Road map for near-term developments

The following near-term design studies are needed:

1. **Develop one or more strawman structural designs for lightweight segments.** The goal for segment weight should probably be in the range of 50-100 kg per square meter (this compares to 460 kg per square meter for the Gemini primary mirror, not including mirror cell). This work should be coordinated with NGST studies to ensure complementarity, however there is no reason to believe the best NGST mirror solution will be directly applicable to MAXAT, since the NGST weight goals are an order of magnitude more ambitious. (NGST has to be light so it can be launched into a high orbit, but it does not have to withstand gravity sag or wind buffeting during operation.)

These studies should lead into a second phase, involving prototype fabrication of the most promising lightweight segment designs.

2. **Study the feasibility of making the MAXAT primary mirror adaptive.** Among other things, this study should address issues of segment control, wavefront measurement, and vibration control.
3. **Prototype fabrication of aspheric mirrors on planetary polishers using bend-and-polish techniques.** This study would involve the development of tooling and the production of one or more thin aspheric segments, perhaps one meter in diameter, on existing planetary polishing machines.
4. **Develop strawman designs of the MAXAT science instruments.** This study would contribute to the preliminary science requirements for MAXAT.
5. **Develop strawman optical designs using both spherical and aspherical primaries.** The strawman instrument designs will be needed to define the requirements for this study.

6. **Develop prototype segment position actuators.** Two or more competing designs for the segment position actuators should be designed, built and tested. These actuators should provide resolution and repeatability to a few nm, have high stiffness (~20 N per micron), have a range of 10-20 millimeters, and operate at a bandwidth of several Hz. They should dissipate no more than a few watts of heat into the environment. The mean time between failure should be several years.
7. **Develop prototype segment edge sensors.** These sensors should be compatible with the most promising segment design developed in item 1, above. The mean time between failure should also be several years.
8. **Develop prototype segment figure actuators.** Two or more competing designs should be developed that are capable of controlling the segment optical surface to an accuracy of a few nm.
9. **Study the properties of segmented mirror systems.** Segmented mirror systems with several hundred segments should be modeled. The control system requirements should be determined, and the system response to errors and disturbances should be simulated. If possible, this study should be a joint effort between MAXAT and the CELT Project.
10. **Measure wind loading on large existing optical and radio telescopes.** The spatial and temporal variation of wind pressure on existing large telescopes, particularly at the primary mirror, should be measured to improve our ability to model the effect of wind on a MAXAT.
11. **Study correction of primary mirror segment movement by adaptive optics.** Simulations should be run to determine how well segment misalignment could be measured and corrected with a multi-conjugate, multi-DM adaptive optics system. This study should also model the effect of having two perturbed segmented mirrors in series.

11 Structures Sub-group Report

Based on preliminary scientific goals outlined in the first part of the workshop session the structures group considered the real challenges in supporting high performance optics where the aperture could be as large as 100 meters

The group decided to focus initial attention on the lower aperture size range outlined in the workshop objectives in order to form a baseline for discussion

Telescopes structures used for radio astronomy were used as a reference for scale and performance. Structures having apertures (30m to 100m) were either operating or under stages of construction and could provide a comparative benchmark.

The majority of the group had first hand experience in the design of radio antenna structures and could bring to the table hard performance data

The conclusion reached was that it should be possible to build an optical telescope structure to provide the required structural characteristics up to a maximum aperture of 50 m. Beyond the 50m meter it was the consensus that new design concepts would have to be developed.

Considerations in the development of a telescope structural design are, control of stiffness, resonance and thermal mass. Cost effective design has to consider long term operation where the impact of maintenance, down time and risk are also considered. Low cost solutions, based on the overall life of the telescope, should be part of design considerations.

Topics affecting design were discussed and a list of key cost drives was established. The idea was that this list might influence designers considering new concepts.

The latter part of the discussion was devoted to brainstorming toward a concept for a 100m design solution. The individual experience of the group members made this a valuable exercise. The object was to move away from conventional telescope design solutions and think more openly about the challenges of going to a 100-meter solution.

An optical telescope carries a high “glass” payload compared to that of a radio telescope where the panels are manufacture from either aluminum or composite material. Although the mirror cell is well supported in an optical alt-azimuth configuration it was felt that structural stiffness issues would be encountered in going much beyond the 10-meter level. The same stiffness problem apply in following conventional radio antenna design, however it was felt the size bounds were higher.

The investigation of a design solution that would better support the mirror cell was considered fundamental to a new design approach. If the mirror cell could be cradled, removing the need for a cantilever structure there would be a marked increase in stiffness and a resulting reduction in weight. Several concept solutions were discussed.

The payoff would be within the interface between the mirror and the structure where actuators are necessary to preserve the mirror shape during observations. It is believed that two layers of

actuators may be required, a long stroke system to look after gravity deflection and short high precision system used for individual mirror control.

It was recognized that elimination of one set of actuators could result in a considerable financial reward. A marked increase in structural stiffness would be required to make this possible

Structural support for the secondary optics was reviewed and options were discussed. The optical configuration of the telescope significantly affects the geometry of the secondary supporting system. Optical and structural trade-off issues should be considered together this way issues on blockage and stiffness can be properly addressed.

It was assumed that an environmentally hostile site would be selected for this telescope. It was agreed that it would be necessary to protect the telescope with an enclosure. The design of the enclosure should consider, but not be limited to, three major issues. Protection of the telescope under survival conditions; wind shielding under operating conditions and structural support for maintenance handling equipment.

Site topography and wind loading influence the design of the enclosure. It is therefore important to review environmental conditions of several typical sites and understand how site characteristics affect overall telescope performance.

A roll-on roll-off solution was suggested having four elements positioned 90 degrees apart. By combined movement of the enclosure segments wind shielding may be possible.

The traditional dome style enclosure was considered but it became hard to visualize a dome with 100m slot. This requirement would push the dome diameter to over 400 meters.

11.1 Structural Issues to be considered during design development

1. Power requirements (minimize structural weight and inertia to reduce driving power) (aim to design a balanced structure)
2. 30 to 50 m could be conventional radio telescope alt-azimuth design.

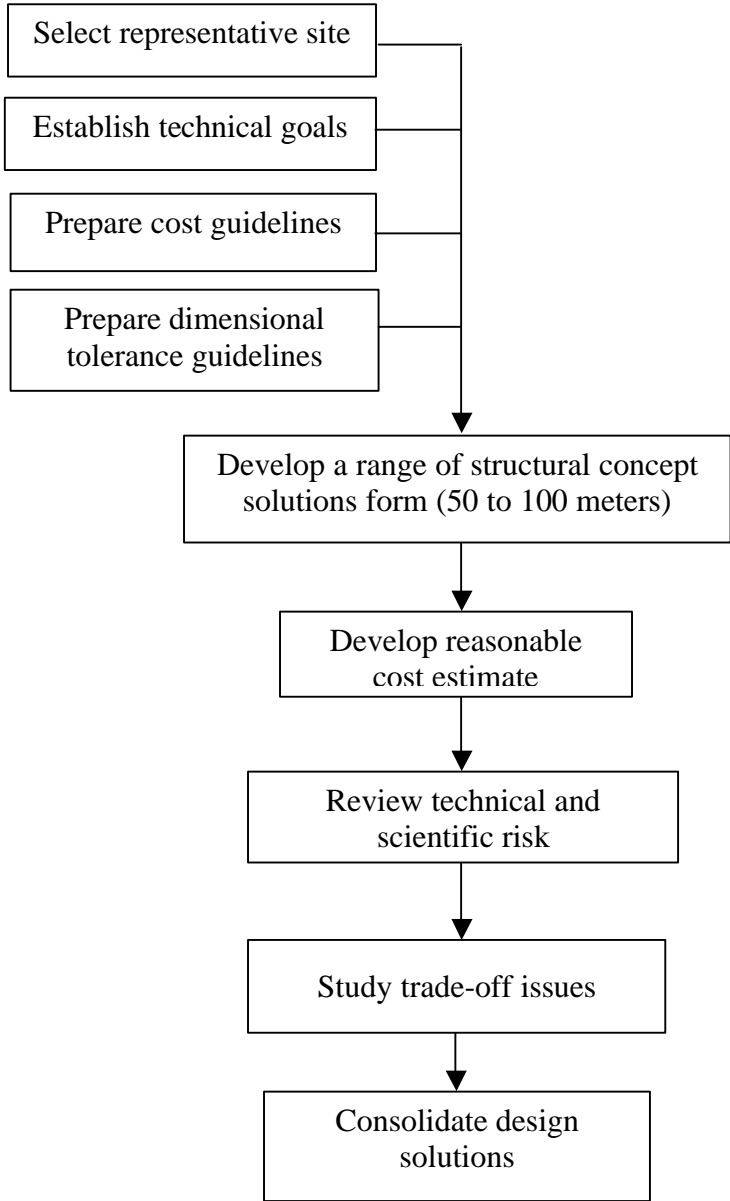
Simplicity of construction (symmetrical structure, try and make backing structure nodes similar to ease manufacture)
3. Transportation (piece size and weight, access to most sights difficult design pieces to go in shipping containers.... 8ftx40ft)
4. Keep form of structure simple (wide flange shapes are easier to connect that tube sections. Minimize requirement for field welding)
5. Stick with simple mechanical design (maintenance issues and down time)
6. Structural design to consider dynamic frequency and damping (primary only)
7. Review dynamic interaction between first and second level primary mirror actuators (structural stiffness)

8. Simplify access and equipment handling (modular concept) (mirrors on structural rafts)
9. Study thermal issues related to the structural configuration
10. Minimize primary mirror blockage from secondary support structure
11. Study active control of secondary coupled with dynamic performance of support structure
12. Try and keep surface area and weight of secondary low (windage and dynamic issues)
13. Study site trade-off issues (affects windage, thermal, enclosure design etc.)
14. Protection of telescope (mechanical, structural, survival wind and thermal)
15. Protection of telescope during operation.
16. Optical configuration versus secondary dynamic performance
17. Fast steering at secondary not desirable
18. Bolted versus welded structure, look at trade-off (try for bolted construction reduce field welding)

11.2 Suggestions

1. Support of primary backing structure (get away from cantilever after 50m)
2. Reduce requirement for high tolerance machined surfaces
3. Develop series of structural solutions and do cost analysis
4. Produce cost guidelines for design, manufacturing and construction
5. Provide dimensional tolerance guidelines for structural and mechanical solutions
6. Review site with respects to soil conditions (study structure foundation design)
7. Organize a technology task group
8. Study range of structural performance (crude)
9. Get information on instrument size and weigh, relate to concept design.

Figure 5. Development Roadmap - Structures Group



12 Adaptive Optics Sub-Group Report

12.1 Performance Requirements Summary

Table 1 summarizes our distillation of the top-level AO performance requirements provided by the science task group. The requirements for planet detection differ significantly from the remaining applications in terms of the field-of-view (FOV) and the desired Strehl ratio, which is nearly unity so that the variations in the image of the central star do not overwhelm the image of the dim companion. Also, a relatively bright natural guide star (NGS) will always be available for wave front sensing when searching for planets around nearby stars. For these reasons a separate adaptive optics implementation may be most cost-effective for this application.

Parameter	Planet Detection	Other Applications
FOV (diameter)	10''	1-2'
Wavelength range, μm	1-5	1-5
Desired Strehl ratio	~ 1	0.7 +/- 0.05
Technique	Classical NGS	Multi-conjugate

Some members of the AO group felt that a 1-2' compensated FOV was too conservative for the MCAO system, citing recent measurements at Keck and Palomar which suggest isoplanatic angles perhaps a factor of two larger than theoretical predictions. Increases beyond 3-4' appear very unlikely, however. Finally, it is important to note that the Strehl ratios in Table 1 are for the AO system alone, and that additional Strehl ratio losses must be allocated for the telescope and instrument optics.

12.2 AO System Parameters

Beginning with the performance requirements listed in the "other applications" column of Table 1, the AO group developed the following top-level parameters for the AO system:

- Order of correction: 2-4 deformable mirror (DM) actuators and wave front sensor (WFS) subapertures per meter. This corresponds to 60-120 actuators across the pupil of a 30 meter telescope, 100-200 for 50 meters, and 200-400 for 100 meters!
- Sampling rate: 500-1000 Hz.
- Number of DM conjugate ranges: 3 to 4. Note that the order of correction given above applies only to the DM (or DM's) conjugate to dominant turbulence layer.
- Number of guide stars and wave front sensors: 5 or more. For this parameter, the AO group was unclear how to scale the limited body of MCAO performance predictions for

8-meter class telescopes to much larger diameters. We were also unable to select either natural- or laser guide stars as the preferred approach.

These parameters are for a site with approximately 0.65" seeing, an atmospheric correlation time of 5-7 milliseconds, and an isoplanatic angle of 2-3" (all values at 0.5 microns).

The order of correction and sampling rate for planet detection should be higher to capitalize on the availability of a bright NGS, and the number of DM's and WFS's can be reduced to 1 since only a small FOV is required. Upper bounds on the order of correction and sampling rate could be determined from the desired limiting magnitude of the NGS, but we unfortunately neglected to ask for this value at the meeting.

12.3 Implications for Components

This subsection summarizes some initial thoughts on the implications of the above parameters for the hardware components comprising the AO system. These components include deformable mirrors, wave front sensors, signal processors, and laser sources for generating laser guide stars. The new requirements imposed by MAXAT upon AO modeling and simulation techniques are also considered.

12.3.1 Modeling and Simulation

Existing modeling and simulation tools must be upgraded if they are to provide useful estimates for the performance of AO on extremely large telescopes. For applications involving MCAO, these improvements are necessary to answer basic questions such as:

- The required number of guide stars as a function of aperture diameter and FOV;
- The relative performance of MCAO with natural- and laser guide stars; and
- Sky coverage for systems employing multiple NGS's, either for higher-order or tip-tilt wave front sensing.

A central issue in answering these questions is the development of wave front reconstruction algorithms that will optimally combine measurements from multiple WFS's to determine commands to multiple DM's. The modeling approaches which have so far provided the greatest success for smaller and lower-order MCAO systems all require the calculation and manipulation of large matrices which describe the second-order statistics of turbulence across the telescope aperture. The storage requirements for these matrices scale approximately as the fourth power of the number of actuators across the telescope aperture, and the computation requirements scale approximately as the sixth power. The 30 and 50 meter systems outlined in section 1.2 will require about 10 to 100 times the memory and 100 to 1000 times the computations than the lower-order AO systems for smaller telescopes, calculations which can be evaluated in about a day on a high-performance workstation. This should be feasible if supercomputers can be made available, although the numerical precision of these very high-order matrix calculations may be a concern.

The development of wave front reconstruction algorithms for a very high-order, classical AO system used for planet detection is less of a concern, and the results already obtained on the shape and stability of the AO-compensated PSF for smaller telescope can be extrapolated with some confidence. The effects of calibration errors and systematic drifts will be equally important as the theoretical turbulence-limited performance of the AO system, and considerable simulation and component modeling will eventually be necessary to verify that the desired levels of PSF stability can be achieved. This is not an issue at this early stage of the project, however.

12.3.2 Deformable Mirrors

The AO group was not able to agree on a breakpoint in the scaling of current piezostack DM technology. However, neither this approach or any known innovative concept (liquid crystals, MEMs mirrors,...) is likely to provide the combination of large dynamic range and very high number of actuators which will be required for compensation of the dominant turbulence layer. This will be even truer if the AO system is expected to correct for dynamic telescope aberrations or local dome seeing. The optical design for a MAXAT should include two locations for deformable mirrors conjugate to the dominant seeing layer, so that a combination of large stroke, low order and small stroke, high order mirrors may be employed.

R & D efforts to demonstrate a low-stroke, 4000 actuator DM are currently underway. MAXAT should consider extending this effort towards larger numbers of actuators if the current demonstration is successful. Efforts towards liquid crystal and MEM's wave front correctors should be monitored, but there is skepticism that these either of these approaches can achieve the combination of temporal bandwidth, spectral bandwidth, wave front quality, and optical throughput required by a ground-based astronomical AO system. An adaptive primary mirror would of course change everything, and this approach should be investigated further to seem if the apparent bandwidth limitations imposed by the resonant frequency of the telescope can be overcome.

12.4 Roles of Natural Guide Stars (NGS)

1.1 The requirements for higher-order wave front sensing are somewhat different for natural- and laser guide stars. The LGS case appears to be a more direct extension of current technology, since the guide stars can be placed within the compensated field-of-view and the wave front measurements can be made closed-loop. Shack-Hartmann WFS's with 32 by 32 subapertures have been demonstrated at sampling rates up to 1500 Hz using 128 by 128 pixel CCD's with about 7-12 noise electrons per pixel per read. For the 30 and 50 meter telescope options outlined in section 1.2 above, the array size would need to be increased to somewhere between 256^2 and 1024^2 pixels. It should be feasible to maintain the same sampling rate by increasing the number of output amplifiers, but the read noise would need to be reduced by about a factor of two for optimal wave front measurement accuracy with the expected laser guide star signal levels. The Shack-Hartmann spots at the edge of a 50 meter aperture could be elongated by as much as 5" due to the nonzero thickness of the sodium layer, but this must be dealt with by increased laser power rather than any fundamental change in WFS design.

The NGS case appears to be more challenging. The AO group understands from the OWL conceptual design that sufficiently bright natural guide stars may be distributed over fields as large as 10'. The wave fronts from stars in the outer portions of this field will not be compensated by the AO system, both because of anisoplanatism and practical limitations on the unvignetted FOV of the AO instrument. These wave front measurements must therefore be made open loop, and conventional Shack Hartmann WFS designs based upon quadrant detector tilt sensing do not have sufficient dynamic range to operate in this mode. Some of the alternative approaches which occurred to the AO group include:

- Shack-Hartmann sensors with larger numbers of pixels, lower detector read noise, and increased signal processing requirements
- A WFS module including its own dedicated DM and wave front reconstructor for compensation of the guide star wave front. In this case the sensor measurement supplied to the MCAO control system is the sum of DM figure plus the residual wave front measured by the WFS proper. This appears to be a costly approach due to the very high order required for the auxiliary DM's.
- Some entirely different wave front sensing approach, such as phase shifting interferometry, which is more efficient in terms of pixels per subaperture.

It is difficult to know how to proceed in this area before the basic question of NGS vs. LGS wave front sensing is resolved, but larger high-speed CCD arrays with reduced read noise will be required in either case.

12.4.1 Signal Processing and Control Algorithms

The signal processing requirements for very high-order AO systems will clearly be dominated by the wave front reconstruction algorithm. In existing systems this reconstruction is generally accomplished as a generic, or full rank, matrix multiply, with signal processing requirements which scale roughly as the forth power of the number of actuators and subapertures across the pupil diameter. More sophisticated approaches based upon FFT's or sparse matrix methods have much more benign scaling, and can probably be used to keep the total FLOPS necessary for a classical AO system used for planet detection within manageable limits. The AO group was not comfortable invoking improved algorithms for the MCAO case, however, at least until greater intuition is developed into how commands to multiple DM's are optimally synthesized from multiple WFS measurements. For conventional matrix multiply algorithms, the computation requirements for a 30 to 50 meter MAXAT will be on the order of 20 to 2000 times what has been demonstrated in the highest-order DoD systems fielded today, even accounting for the relative sampling rates of the two systems. The MAXAT wave front reconstruction hardware might cost from 4 to 400 million dollars for today's technology, or no less than about 0.4 to 40 million dollars for a system which might be purchased 10 years from now. More sophisticated algorithms which might reduce these costs should be investigated, although once more the direction to take depends upon the choice of NGS or LGS wave front sensing.

12.4.2 Laser Guide Stars

This is not an issue for planet detection, because the bright central star should always be sufficiently bright for wave front sensing purposes. For the remaining science cases, the power requirement for an individual LGS in a MAXAT MCAO system will be several times greater than for a smaller telescope due the increased elongation of the guide star images for WFS subapertures at the edge of the pupil. A single MAXAT LGS might require 20 to 40 Watts of CW-equivalent power if current estimates of the power required for smaller telescopes are correct. A much larger uncertainty is the number of guide stars that will be required as a function of telescope aperture diameter and the compensated field-of-view. Modeling studies to estimate the necessary number of guide stars should begin quickly. If this number is not too large and a LGS MCAO option appears attractive, R & D efforts to scale sodium lasers to the required power levels will definitely be necessary. Several different approaches should be pursued in parallel given the slow pace of recent progress in this area.

12.5 Adaptive Active Optics

There appears to be considerable interest in utilizing the AO system to compensate for telescope vibrations and local seeing effects with temporal bandwidths beyond the range of conventional active optics systems. While the AO group is gratified in the level of confidence in adaptive optics implicit in this proposal, there are a number of caveats to be noted:

- Telescope and dome seeing disturbances at the highest spatial and temporal frequencies should be smaller than the wave front distortions due to atmospheric turbulence. Otherwise it will be necessary to increase the order and sampling rate for the AO system, thereby increasing laser power requirements and/or reducing the limiting magnitude for natural guide stars.
- AO compensation may not be available over the entire FOV of a wide-field optical design.
- AO compensation may not be available for all observing runs, and large initial active optics errors must be at least partially corrected before the AO loop is closed. Some sort of active optics WFS viewing bright stars in the peripheral field may be useful for these purposes.

12.6 Technology Roadmap

Figure 4 is a block diagram of a very top-level roadmap for AO technology development towards MAXAT. Although some areas requiring technology development are already obvious (e.g., higher-order DM's and larger low noise, high frame rate CCD's), near-term work should place an emphasis on further system-level modeling to identify basic AO parameters such as

- Number, type, and location of guide stars;
- Number and conjugate range of DM's;
- Order of wave front sensing and correction.

This modeling will lead to the development of an overall AO system architecture and set of component requirements. Parallel component development activities and system design studies will eventually provide the basis for the design of the AO system itself. Desirable component demonstrations along the way include:

- Sodium lasers with CW equivalent power of at least 10 watts;
- High-order deformable mirrors;
- Innovative wave front sensing approaches suitable for wide-field NGS wave front sensing.

System-level demonstrations for the AO system concept as a whole are also strongly recommended before embarking upon the final design. This is probably a laboratory demonstration for a MCAO system. For a very high-order classical NGS AO system to be used for planet detection, an actual field test on a 4 to 8 meter telescope at visible wavelengths would be feasible, and might also be useful for less stressing cases of companion detection in and of itself.

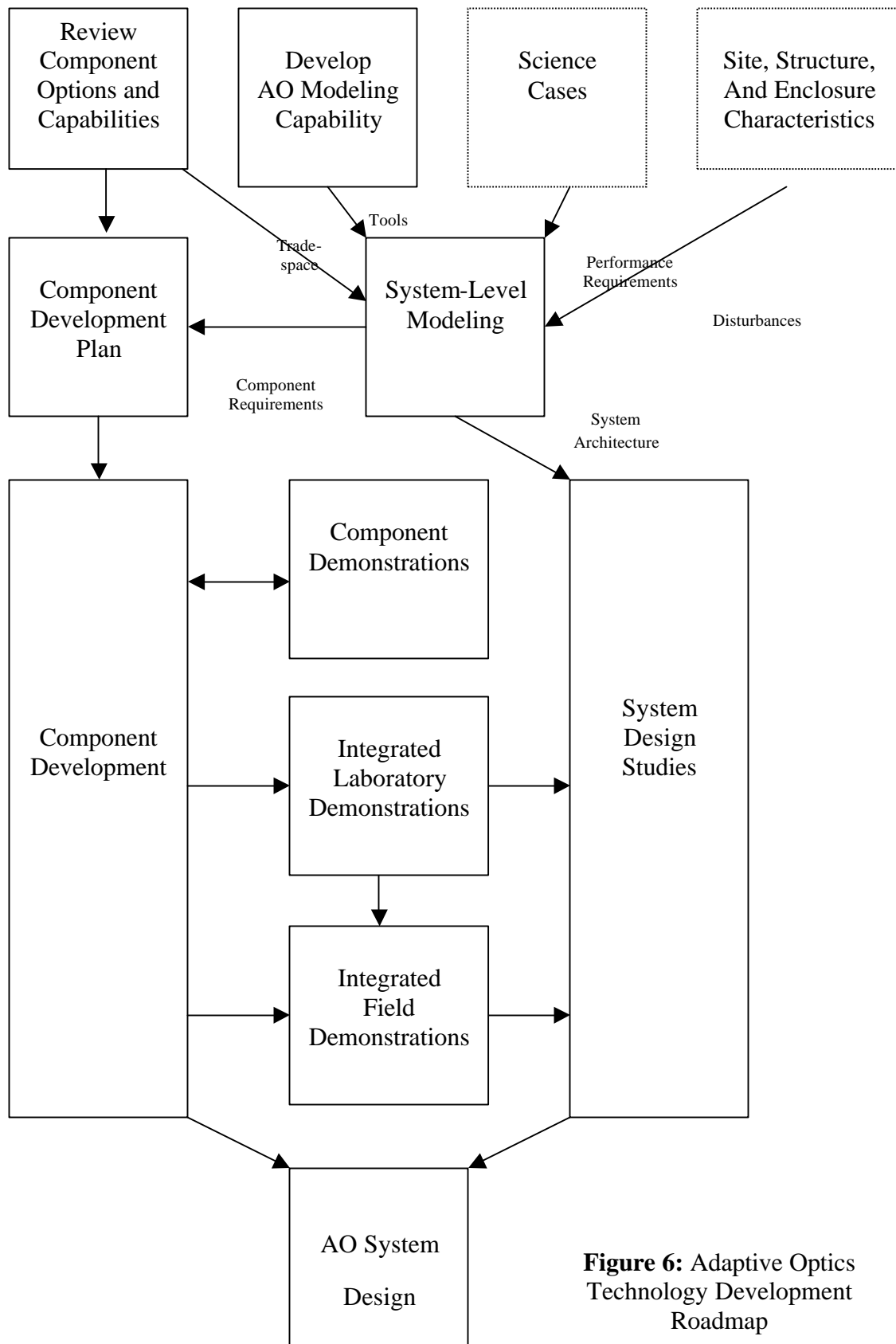


Figure 6: Adaptive Optics Technology Development Roadmap

13 Controls Sub-Group Report

13.1 Mount Control

Experience with existing radio telescopes suggests that it is feasible to point and track a steerable MAXAT to of order 1 arcsecond, about ten times worse than what is achievable for present-day optical/IR telescopes. Significantly better performance than this, for a structure that is exposed to the wind, is unlikely to be achievable. Fortunately, the optical performance goals mean that image quality will be achievable only by rapid corrections using active surfaces, not by precise open-loop tracking. This means that mount control may, if anything, be a less challenging area for MAXAT than it is for existing 4-10m telescopes. As long as the mount has enough performance to achieve preliminary target acquisition and to absorb the low-frequency components of the tip/tilt corrections, that will be sufficient. To aid calibration procedures and to limit AO dynamic range requirements, open-loop pointing Performance at about the levels currently being achieved is worth aiming for, but there is no need to study ways of doing better.

13.2 Active Optics

A segmented mirror will contains hundreds, perhaps thousands, of mirrors, compared with Keck's 36. The number of simultaneous equations that have to be solved at high frequency will increase by several orders of magnitude, and the calculation load and rounding errors accordingly. However, extrapolating from the Keck experience suggests that this is not likely to be a problem.

13.3 Adaptive Optics

There are significant challenges in providing enough processing power to cope with the Adaptive Optics systems that are being considered for MAXAT. The systems need to be simulated using existing supercomputers (ideally using languages and approaches that mean the trial software can eventually become the operational software) and sober estimates made of the cost of acquiring the required power at the time MAXAT is about to be commissioned.

If it is decided to attempt part of the AO correction through the primary itself, an option that is available if the segments are below about 0.3m in diameter, the problem arises of how to provide simultaneously the high-frequency response required by the AO and the large-amplitude performance required to compensate flexure and temperature effects in the backing structure. It seems likely that a damped, multi-layer system would be required, and there need to be studies of how this would be done.

Here are some further notes, from David Smith, concerning structural issues.

13.4 M1

Due to the size of the primary reflector, it is certain to have a natural frequency in the <2 Hz (and perhaps even <1 Hz) range. This implies that the dynamics of the telescope will be excited by wind buffeting. Additionally, it indicates that high-bandwidth control of the primary reflector for adaptive optics must take into account the dynamics of the primary mirror support structure. The largest such effect is likely to disturb primarily the pointing of the telescope, which will

need to be removed by another reflecting surface downstream in the optics. From available data on existing radio telescopes, it appears likely that the surface vibrations of the primary will be on the order of tens of microns for a 30-50m structure in moderate wind, and even larger for a 100m. It does not appear practical to develop a primary support structure that reaches the necessary vibrational stiffness ($\lambda/10$) passively, and active damping techniques are difficult to implement on very low frequency structures. As a result, the residual vibrations in the structure will need to be removed by an adaptive system, either at the primary itself (in which case the control-structure interaction must be taken into account) or at a deformable mirror. The structures group was very strong in their recommendation for an enclosure for at least survival conditions. The vibrational response of the telescope suggests strongly that an enclosure which can provide wind protection during operation is very desirable from the controls point of view.

13.5 M2

The secondary is likely to be supported on a very long cantilevered structure, suggesting that it too will have a support with low natural frequency. Any rapid positioning of the secondary must take this into account. Indeed, such positioning will be limited at some frequencies by the response of the support structure.

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15 Appendices

15.1 Attendance

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15.2 Agenda

Sept 16

9-10:15 **Introduction** – Jay Gallager

Overview - Matt Mountain

ESO view of Science- Roberto Gilmozzi

10:30 – 12:00 Science and Technical group sessions

10:30-10:50 **Science Group:** Steve Strom

Overview of science case

Science and top level system requirements to support cases

Instrumentation needs/drivers

10:50-12 **Technical Group:**

Technical Group Detailed Overview and Plans - Jim Oschmann

- Case study system presentation

1-4:30 **Detailed subgroup discussions**

Science: Steve Strom

- Science Drivers

- Top level requirements (aperture, image quality, sky coverage, wavelength regions)

- Instrumentation

Technical:

- Optics: Larry Stepp

- Structures: Dave Halliday

- AO: Brent Ellerbroek

- Controls: Pat Wallace

4:30-5:30 **Combined Science and Technology session**

Subgroup summary reports

Sept 17

9- 10 Science and technology discussions - Steve Strom & Jim Oschmann

- Summarize science desires
- Summarize technical drivers
- Discussions

11:15-12 Plan and organize round two of separate science and technology groups

- Major areas for further discussions

1-3 Technical and Science follow-on group meetings

3:15 –4:30 Combined meeting to summarize and refine roadmap to MAXAT

4:30-5 Summary

15.3 Presentations

15.4 Assumptions used in computing Figure 3

Table 15.1: Assumed point source size (mas)

Telescope Diameter	20M	1.2 μ m	1.6 μ m	2.2 μ m	3.8 μ m	4.9 μ m	12 μ m	20 μ m
Point source size (θ mas)	(θ mas)	20	20	26	41	58	142	240
	50M	1.2 μ m	1.6 μ m	2.2 μ m	3.8 μ m	4.9 μ m	12 μ m	20 μ m
	(θ mas)	10	10	10	17	23	57	94
Percentage point source flux within q		70%	70%	50%	50%	50%	50%	50%

Table 15.2 Assumed detector characteristics

1 μ m	$< \lambda <$	5.5 μ m	5.5 μ m	$< \lambda <$	25 μ m
I_d	N_r	q_e	I_d	N_r	q_e
0.02 e/s	4e	80%	10 e/s	30e	40%

where I_d is the dark current (e/s), N_r the read noise(e) and q_e the detector quantum efficiency.