NEXT GENERATION SPACE TELESCOPE

NGST

Prepared for:

Panel on Ultraviolet, Optical,
and Infrared Astronomy from Space,

Astronomy and Astrophysics
Survey Committee,

National Research Council

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THE SEARCH FOR ORIGINS

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NGST

1.0 INTRODUCTION

- NGST a key component of Origins
- 8 m radiatively-cooled telescope at L2
- High resolution, large field, deep sensitivity, low background
- 10-years of observing to meet astronomers' needs
- Opens door to future affordable observatories

The Next Generation Space Telescope (NGST) is a key component of NASA's Origins Program. Reflecting major current astrophysics research themes as restated in NASA's Space Science Enterprise strategic plan [1], Origins responds directly to the questions:

- *How did the Universe, galaxies, stars, and planets evolve? How can our exploration of the Universe and our Solar System revolutionize our understanding of physics, chemistry, and biology?*
- *Does life in any form — however simple or complex, carbon-based or other — exist elsewhere in the Universe? Are there Earth-like planets beyond our Solar System?*

AT A GLANCE

Primary Mirror
8m

Wavelength Range
$.6$-10^{+} µm

Mission Lifetime
5 years, 10-year goal

Passively Cooled
<50 K

Orbit
L2

NGST has been under study since 1995 and is planned to be launched around 2008, nearly 400 years after Galileo discovered the moons of Jupiter, over 60 years after Lyman Spitzer proposed space telescopes, and 50 years after the National Space Act created NASA. The mission is a logical successor to the Hubble Space Telescope (HST), and fits in the context of the other Origins missions: FUSE, SOFIA, SIRTF, SIM, and the Terrestrial Planet Finder and Planet Imager, which are planned or under construction. The schedule for these missions is shown in Fig. 1.1. NGST logically depends on technology developed by SIRTF and HST, and, in turn, future missions will use NGST technology to search for terrestrial-sized planets.

NGST will be an 8 m class deployable, radiatively cooled telescope, optimized for the 1 – 5 µm band, with background limited sensitivity from 0.6 to 10 µm or longer, operating for 10 years near the Earth-Sun second Lagrange point (L2), 1.5 million km from Earth. It will be a general-purpose observatory, operated by the Space Telescope Science Institute (STScI) for competitively selected observers from the international astronomy community. NASA, the European Space Agency (ESA), and the Canadian Space Agency (CSA) will build NGST, with construction to start in 2003. The planned NASA part of the construction budget is $500 M (FY96), but the combined total of NASA, ESA, and CSA contributions, including launch, operations, grants, technology development, and inflation, will be around $2B (in real year dollars). This sum represents about one-quarter the amount invested in HST.

NGST will be a unique scientific tool, with excellent angular resolution over a large field of

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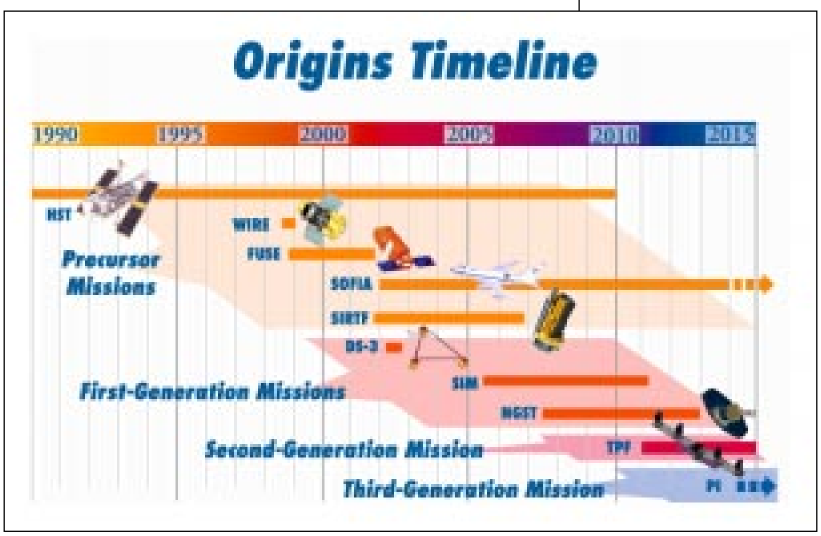

Figure 1.1: The Origins Mission Plan. Each mission builds upon the science and the technologies of its predecessors.

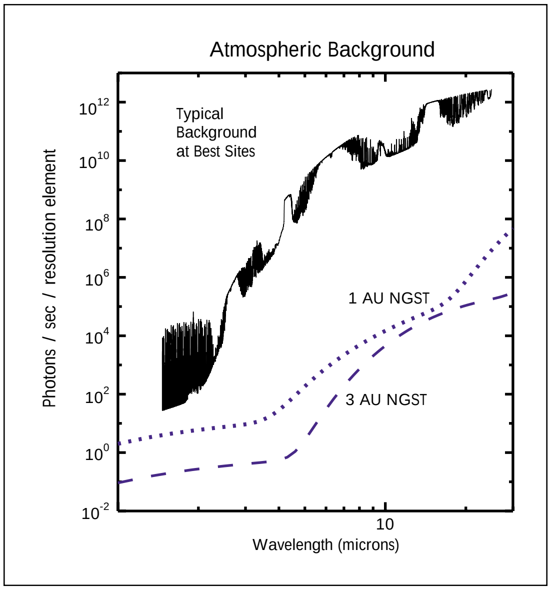

Figure 1.2 NGST takes advantage of the lower infrared background of space. The upper curve shows a model of the atmospheric and telescope backgrounds for Mauna Kea (1 mm water). The two lower curves show the zodiacal background at 1 and 3 AU respectively, with a contribution at longer wavelengths from the 50 K optics.

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view, deep sensitivity and a low-infrared (IR) background. As a cold space telescope, NGST will achieve far better sensitivities than ground-based telescopes. Figure 1.2 [1.2] shows the background levels from Mauna Kea and in space. They differ by one to six orders of magnitude, depending on wavelength. NGST will have diffraction limited resolution at 2 µm or better, and will achieve much higher Strehl ratios and wider fields of view than anticipated from ground-based telescopes using adaptive optics. NGST's aperture is an order of magnitude larger than SIRTF's, with a factor of 100 better sensitivity.

NGST will be able to observe the first generations of stars and galaxies, including individual starburst regions, protogalactic fragments, and supernovae out to redshifts of z = 5 - 20. NGST will resolve individual stars in nearby galaxies, penetrate dust clouds around local star-forming regions, and discover thousands of isolated substellar and Kuiper Belt objects. In 2008, it will be NASA's premier general-purpose observatory, serving the needs of thousands of astronomers and pushing frontier knowledge far beyond the currently known Universe. The NGST design also opens the door for an affordable "product line" of observatories for the future.

2.0 SCIENCE GOALS

- HST & Beyond Committee defined need for NGST
- Observe the origin & evolution of galaxies
- Study structure & chemical enrichment of the Universe
- Limitless potential to study star & planet formation—a key Origins topic
- Design Reference Mission includes 5 strategic themes enabled by NGST

2.1 The Dressler "Core" Mission: The Origin and Evolution of Galaxies

Motivated by the spectacular success of HST in pioneering the exploration of high-redshift (z > 1) galaxies and clusters, the HST & Beyond Committee [2.1] foresaw the enormous potential of a scientific successor to HST, optimized for the near infrared (1 - 5 µm), that would

"…be an essential tool in an ambitious program of study in many areas of astronomy; it will be especially powerful in studying *the origin and evolution of galaxies*. By making detailed studies of these distant galaxies, whose light is shifted into the infrared portion of the spectrum, we will be able to look back in time to study the process of galaxy formation *as it happened*."

In fact, the NGST Project has many technical and scientific antecedents. Among them are the Edison proposal to ESA [2.2], the High-Z and MIROS proposals to NASA [2.3-2.4], and a number of workshops concerning missions to follow the Great Observatories [2.5]. However, the report by the HST & Beyond Committee made the key scientific case and created the initial momentum for NGST.

Since 1996, when the report was written, many of the advances foreseen by the HST & Beyond Committee as well as several unanticipated ones have occurred:

- Distant star-forming galaxies have been observed and studied down to magnitudes as faint as B ~ 29 and z ~ 5.6 by HST and ground-based 8 and 10 m telescopes. [2.6-2.12]
- The low but detectable metallicity of the Lyman-alpha forest and damped Lyman-alpha systems have provided evidence for the early formation of stars at z > 4. [2.13-2.16]
- Observations of the ultraviolet luminosity density at high redshift by Keck and HST have placed a lower limit on the early chemical history of the Universe. [2.17-2.19]
- The far-infrared (FIR > 100 µm) extragalactic background has been found to be comparable in strength to that of the visible and NIR (1-5 µm). The Submillimeter Common User Bolometer Array (SCUBA) has unveiled a population of faint sub-mm sources that may be dust-covered regions of intense star formation or Active Galactic Nuclei (AGN) at z ~ 1. [2.20-2.23]
- Observations with HST/NICMOS have established the importance of small and faint galaxies at high redshift and the early creation of galactic spheroids at z > 2. [2.24-2.27]
- Collaborative and independent ground and HST observations of Type 1a supernovae suggest that the Universe is accelerating, $\Lambda = 0.8$, and hence has an age consistent with the ages of the oldest stars. [2.28-2.29]

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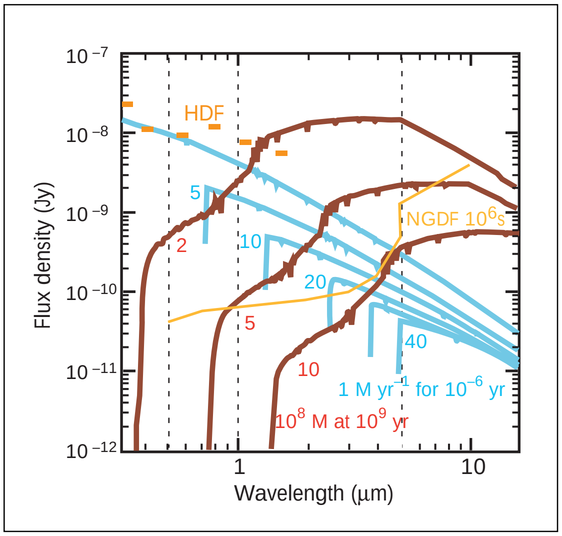

Figure 2.1: The sensitivity of an NGST deep field (10^6 s in 30% bandwidths, 10-sigma detection). Also indicated are the spectra of starburst regions (10^6 solar masses in 10^6 years) and established populations (10^8 solar masses at 1 Gyr) at various redshifts ($\Omega_m = 0.2$). Comparable sensitivities also are shown for the HDF using NICMOS. (Lilly, University of Toronto)

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We will see many more such dramatic advances over the next nine years leading up to the launch of NGST in 2008. With more than a dozen large, IR-optimized ground-based telescopes, with HST and its Advanced Camera for Surveys (ACS) and possibly an NIR channel in the Wide Field Camera 3, and especially with SIRTF, we expect that by 2008 [2.30]:

- Morphological and spectroscopic surveys of galaxies with $0 < z < 1$ will be reasonably complete — likely showing that the assembly of many galaxies has occurred before this relatively modern epoch.
- Large samples of luminous galaxies with redshifts $1 < z < 4$ will be obtained by HST, SIRTF, and the 8 to 10 m diameter ground-based telescopes. We may know when large, mature galaxies first appear but not how.
- Redshift records will continue to be broken. However, we will likely *not* know whether the redshifts of the first, crucial episodes of "galactogenesis" have been reached. Rare, bright, J-band dropouts (high-redshift galaxies with $z > 9$) will be detected and confirmed. However, without NGST, the samples will remain too small and of little use in constraining models of early galaxy formation.

In 2008, NGST will be poised to build upon these foundations to complete our understanding of the formation and early evolution of galaxies such as the Milky Way. Other facilities will have exploited their capabilities and have "hit the wall" as they attempt to reach fainter, redder targets. Although ground-based NIR observations will benefit from adaptive optics, their "wall" will be the dramatic increase in atmospheric emission at NIR wavelengths. For HST, it will be the thermal emission from the entire telescope at $\lambda > 1.8$ µm; for SIRTF, it will be the inherent limitation of a 0.8 m aperture. The NGST Ad Hoc Science Working Group (ASWG) and oversight bodies such as the Science Oversight Committee (1996-97) and the NGST External Science Review (NESR, 1998) concur that understanding the origins and evolution of galaxies is NGST's primary science goal. To do that, we need attributes that only NGST will possess, capabilities that will make it the premier observatory at the end of the next decade, enabling such studies as:

- Detecting the earliest phases of star and galaxy formation — the end of the "dark ages" (Fig. 2.1) [2.31]. This requires superb NIR sensitivity (< 1 nJy, 1-4 µm) in deep broadband imaging (~ 10^5 s).

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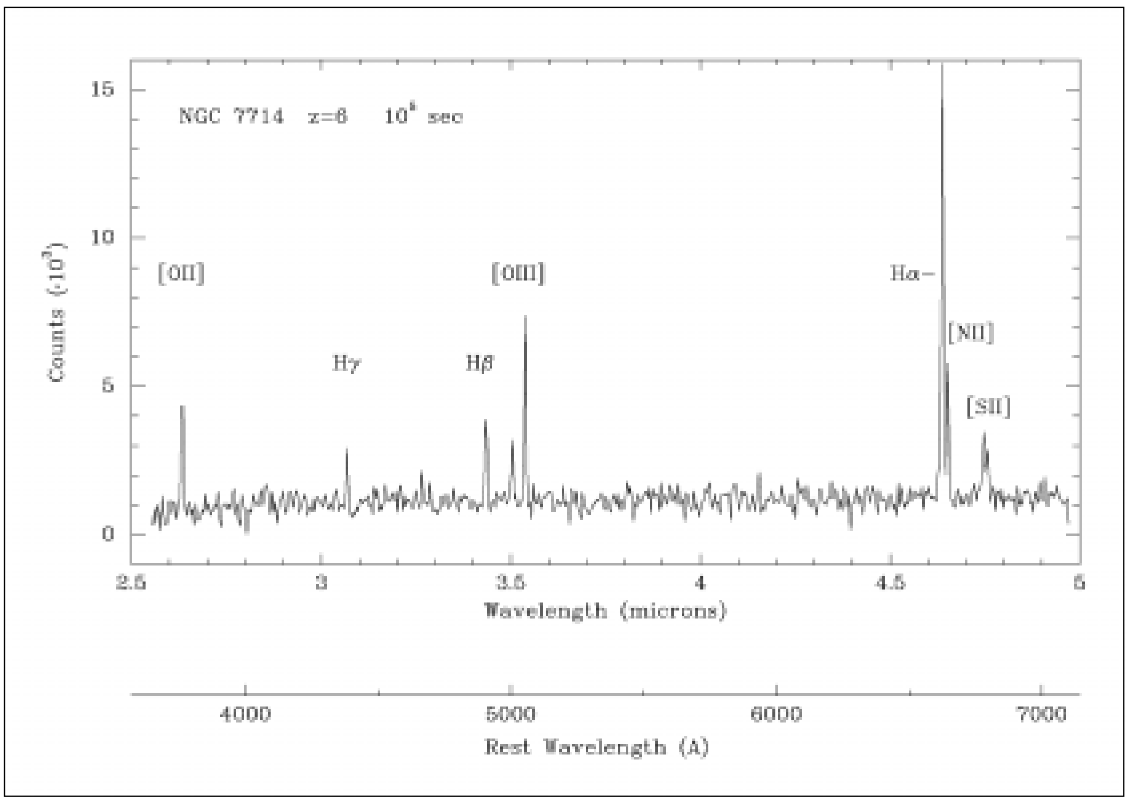

Figure 2.2: Simulated NGST spectrum of the nearby starburst galaxy NGC 7714, observed at z = 6. (Kennicutt, Steward Observatory) [2.33]

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- Resolving the first galactic substructures larger than individual star clusters (~ 300 pc for $0.5 < z < 5.0$). This requires HST-like resolution in the NIR (~ 0.060" at 2 µm) [2.32].
- Quantitatively measuring the fundamental properties of individual galaxies. This will be enabled by emission-line and absorption-line spectroscopy, with broad spectral coverage and low-to-moderate spectral resolution ($R = \lambda/\delta\lambda$):

  R ~ 300 (0.6-5.0 µm) for redshift confirmation, cluster membership, and ages of stellar populations;

  R ~ 1000 (0.6-5.0 µm or longer) for star formation rates, metallicity, and reddening (Fig. 2.2);

  R ~ 3000 (1.0-10 µm) for dynamics (mass).
- Statistically analyzing high-redshift galaxy properties, clustering, and rates of interaction. This will be accomplished with wide field (~ 4' x 4') imaging and spectroscopic surveys. This angular size corresponds to restframe scales ~ 1 Mpc x 1 Mpc (for $0.5 < z < 5.0$ and all reasonable cosmologies) and will include all likely progenitor substructures within galactic regions comparable to the Local Group, as well as the central regions of distant clusters of galaxies. (Fig. 2.3)
- Detecting and diagnosing dust-enshrouded regions hiding massive star formation or active galactic nuclei during the epoch of greatest star formation to a minimum of z ~ 2. Resolving the mid-infrared (MIR) and far-infrared (FIR) backgrounds would be enabled with the NGST stretch goal of MIR imaging and spectroscopy (5-28 µm). (Fig. 2.4)

2.2 The Structure and Chemical Enrichment of the Universe

The geometry and structure of the Universe, as well as its history of element formation, is intimately related to the formation of galaxies. In the coming decade, the MAP and Planck missions will measure the power spectrum of the Cosmic Microwave Background (CMB) at z ~ 1300 and, using standard models, will provide or constrain key cosmological constants. NGST will play a powerful complementary role in determining the distribution of mass and light on small scales. Large microlensing imaging surveys will use the wide field, superb angular resolution, and excellent 0.6-5.0 µm sensitivity of NGST to measure the mass structure of the Universe at z = 1 - 5 on scales smaller than those probed by CMB measurements from space or possible from the ground or HST.

Anticipated science programs include:

- The dark matter halos of galaxies to redshifts of z ~ 5 will be weighed statistically by deep imaging of selected fields.
- The growth of galaxy clusters to redshifts of z ~1-3 will be measured using multi-color deep imaging of selected high-redshift clusters and proto-clusters discovered by AXAF, Planck, and ground-based surveys.
- The statistical properties of the distribution of matter on scales of 1-10 Mpc can be found from wide-area, high-resolution NGST imaging surveys (>1 deg^2). These scales are larger than those of galaxy clusters and smaller than those probed by the CMB satellites and ground-based surveys. [2.35]

These imaging programs are comparable in depth and required field of view to those used for the study of galaxy evolution. Such surveys also provide an excellent method for discovering Type 1a and Type 2 supernovae (SNe) at redshifts between $1 < z < 5$. Supernovae at even higher redshifts could be confirmed by NGST and followed, using ground-based survey telescopes, to detect their brief but luminous ultraviolet precursor transients. Measuring the rates and galactic associations of Type 1a and Type 2 supernovae will provide an independent assessment of the history of element production. We

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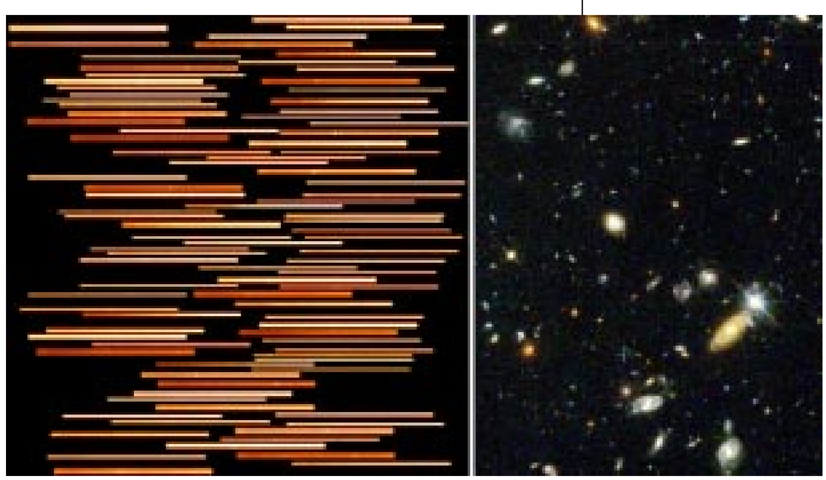

Figure 2.3: A simulated image of the HDF (right panel) and a simulated 20 orbit, 0.08-1.6 µm, R ~ 300 HST multi-object spectrum of the same field with a limiting magnitude of J_{AB} ~ 25.1. A comparable spectrograph for NGST would have twice the field of view and be an order of magnitude more sensitive. (Stiavelli, STScI) [2.34]

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expect that NGST will be crucial in extending the observations of Type 1a supernovae beyond z ~ 0.9 to z ~ 5. Only at the higher redshifts is it possible to distinguish between the behavior of Type 1a supernovae with cosmologies involving only H_0, Ω_m and Λ, and models with significant SNe evolution or smoothly distributed gray obscuration (Fig. 2.5). Such data will provide measurements of the cosmological parameters, which are independent of and complementary to those derived from the CMB missions.

These science programs will require coordinated preparation and data analysis efforts by the community to optimize the science return:

- The microlensing surveys will require well-characterized, high-resolution, point-spread functions over the entire wide field of view and wavelength range (0.6-5 µm). This can be accomplished either by special calibrations or some form of continuous figure sensing of the individual primary segments.
- To follow the light curves of supernovae, the NGST science operations must respond to new supernovae discovered in NGST fields within ~ 1 week. The time dilation at high redshift helps relax this requirement compared with that needed for nearby supernovae. NGST also must return to the same field, perhaps in a different orientation, over periods of two weeks to six months (for the highest redshift supernovae).

2.3 The Processes of Star and Planet Formation

This key Origins topic will be addressed by many ground and space observatories and over a broad range of wavelengths (Angstroms - millimeters). Nevertheless, NGST, with an extended MIR wavelength coverage (5-28 µm), will have a unique role in this area, comparable in importance to MMA/LSA. The potential studies in this arena are essentially limitless and depend crucially on the available spectral resolutions and MIR wavelength coverage. We foresee the following examples:

- Characterizing the infall and outflow processes through which stars are built and their final masses determined. MIR spectroscopy will diagnose the accretion shocks in protostellar systems, while NIR imaging will reveal outflow shocks and jets near their source, with a resolution of ~ 2 AU.

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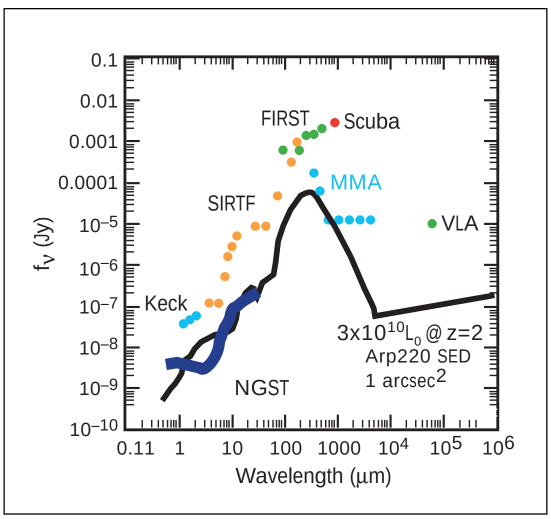

Figure 2.4: The imaging sensitivity of NGST compared with other facilities in the MIR for a 1 arcsec² target. We include a spectrum similar to that of Arp 220 at z = 2 and with 1% intrinsic luminosity. Only the Millimeter Array/Large Southern Array (MMA/LSA) will have a comparable sensitivity to such dust-enshrouded star-formation regions. (Lilly, University of Toronto)

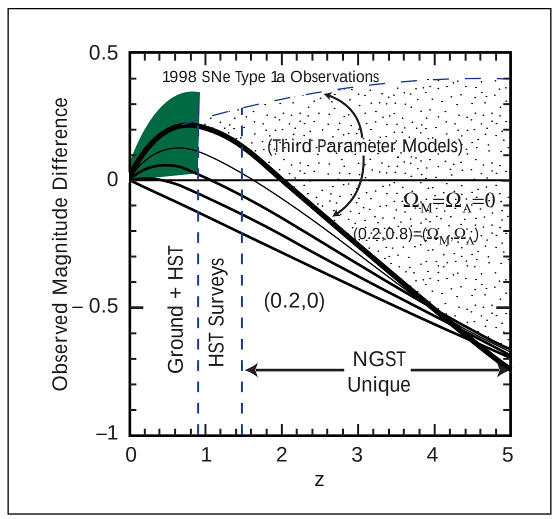

Figure 2.5: The deviations of observed brightness of Type 1a SNe at maximum light compared with the prediction for an empty Universe (Ω_m = 0.0) and those with Ω_m = 0.2) and differing acceleration parameters (Λ = 0.0, 0.2, 0.4, 0.6, 0.8). We also indicate the trend expected for Λ = 0.0 and an evolutionary effect that causes high-redshift supernovae to be ~0.5 magnitudes fainter at z > 1. (STScI)

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- Tracing the structure and evolution of circumstellar material, from the massive envelopes of Class 0 protostars to the protoplanetary disks of pre-main sequence stars, and finally to the dissipation of these disks into mature debris disks of main sequence stars. NIR and MIR spectroscopy of gas and dust features, their excitation, and their radial variation within the circumstellar region will permit study of the growth of dust grains toward planetesimals, the chemical processing of disk gas, and the disk dissipation mechanisms that define the time available for planet formation. High resolution NIR and MIR imaging with NGST will be a powerful probe of the distribution of cool material in dense circumstellar regions, allowing the resolution of AU-scale structures. Images in thermal emission, and perhaps also in reflected light if a coronagraph is provided, will enable direct study of central holes and radial gaps in massive protoplanetary and tenuous debris disks. Such dynamically driven internal structures provide indirect evidence of the presence of planets.

- Detecting and characterizing substellar objects. Ground-based sky surveys and adaptive optics programs are now beginning to discover significant numbers of isolated and companion brown dwarf stars. However, these observations will be limited to the bright (high mass / low age) end of the substellar luminosity function and to wide binary companions. Only NGST will have the needed combination of high-angular resolution, high sensitivity, and a stable PSF for high-contrast imaging of faint substellar companions in planetary orbits. By observing at 5 μm with a graded-mask coronagraph, the baseline NGST configuration will be able to directly detect planets with Jupiter's mass, age, and orbital semi-major axis in more than 90% of the single stars within 8 pc of the Sun (> 50 systems). By detecting planetary photons directly, NGST will provide the first opportunity to spectrally characterize exoplanet atmospheres. In conjunction with mass determinations for the companions from astrometric surveys, NGST observations will allow the theoretical cooling curves for substellar objects to be checked against actual luminosity and temperature measurements. Finally, by taking the first direct images of planets orbiting other stars, NGST will make a strong impact on the minds of the general public.

2.4 The Design Reference Mission

The NGST science described above is part of the Design Reference Mission (DRM), a set of science programs enabled by NGST [2.35]. The goals of the DRM are to:

- Provide examples of NGST science to stimulate further inputs from the astronomy community.
- Provide descriptions of science programs in sufficient detail to derive secondary requirements / capabilities of the observatory.
- Provide a semi-quantitative basis for trade studies (e.g., sensitivity versus field of view).

These science programs have been assembled by the NGST Ad Hoc Science Working Group under five themes and can be accessed through the NGST science website [2.36]. During the Formulation phase (Phase A / B), we will continue to solicit programs for the DRM from our international partners and the astronomy community.

Cosmology and Structure of the Universe
Origin and Evolution of Galaxies
History of the Local Universe
Birth of Stars
Origin and Evolution of Planetary Systems

2.5 Summary: Addressing Strategic Science Goals

NGST science goals address key objectives in NASA's Strategic Plan as well as major research themes articulated by the astronomy community. These investigations are crucial to our understanding of the early formation of galaxies and their subsequent evolution. The statistical analyses of deep fields and the observations of distant supernovae and star-formation regions will unveil clues to the underlying structure and chemical evolution of the Universe. Investigations of star and planetary systems through observations in the MIR will clarify formation processes in new systems and discover the fossil evidence of formation in stars like the Sun. The key science goals detailed in the Design Reference Mission clarify the technical requirements for NGST and represent a broad range of investigations. With its high resolution, large field of view, deep sensitivity and low background, NGST will be the next major step in enabling Origins research.

- Three mission architectures studied; NASA "Yardstick" used as reference
- Three-mirror anastigmat provides accessible pupil and fast primary
- 8 m segmented primary — central mirror with eight petals
- Instrument complement of NIR camera, multi-object NIR spectrometer, MIR camera/spectrometer
- Passive cooling uses multi-layer shield, baffles, stops, large surface area
- 40% immediate sky accessibility; full-sky in 6 months
- Deployed by next generation medium launcher or Atlas IIAS.
- STScI as Science and Operations Center

3.0 MISSION CONCEPT

The science goals for NGST require a telescope with high sensitivity covering the wavelength range from 0.6 to 10 µm, with capability out to 28 µm, and with NIR angular resolution comparable to that of HST. Ball Aerospace, TRW, and NASA studied three mission architectures during pre-Phase A [3.1]. For simplicity, the NASA architecture, referred to as the Yardstick, is presented here. The other concepts are similar, responding to the same high level requirements. The Yardstick architecture established the technical and financial feasibility of the mission, and serves as a reference design to which proposed architectures and instruments can be compared. Figure 3.1 shows the observatory and its main components: the Optical Telescope Assembly (OTA), the Integrated Science Instruments Module (ISIM) and the Spacecraft Support Module (SSM).

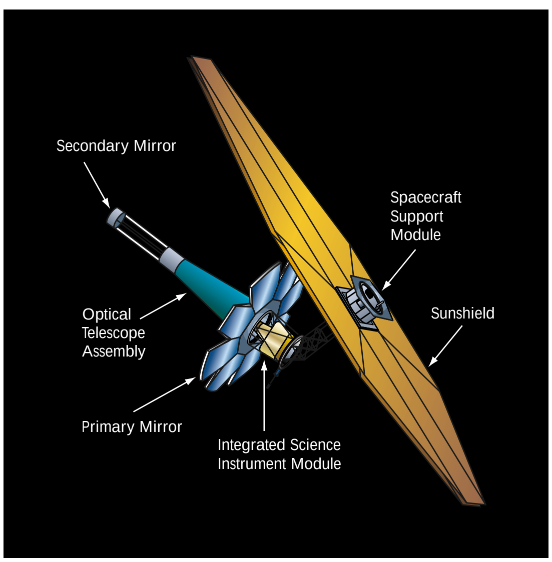

Fig.3.1: The Elements of the Yardstick Concept.

3.1 The Yardstick Optical Telescope Assembly

The Yardstick optical configuration is a three-mirror anastigmat that provides a real, accessible pupil and permits a relatively fast primary mirror to minimize telescope length. This design provides excellent imaging over a field of more than 20 arcminutes with achievable alignment tolerances. A real pupil permits the use of a deformable mirror (DM) for wavefront correction, and a fast-steering mirror for fine pointing using image compensation. The primary mirror is a compact 8 m diameter segmented aperture. It is composed of a central mirror segment, with a diameter of 3.3 meters, surrounded by eight petals. The petals are folded alternately up and down and deployed after launch (Fig. 3.2).

The Yardstick mirror is made of beryllium, thermally controlled with very low power heaters (20 mW total) so that its figure remains insensitive to rapid or large positioning slews. The areal density of the primary mirror assembly (mirror, actuators and backup structure) is 13 kg / m^2. The DM provides a design margin for figure errors in the primary mirror, including those due to gravity release, thermal gradients, or edge effects. The DM will correct the wavefront so that the system will be diffraction limited below 2 µm.

Unlike telescopes such as HST that are launched fully assembled, NGST must be able to compensate for errors in deployment position, long-term dimensional changes, and on-orbit thermal variations. Optics are aligned and phased by observing the image of a star and deriving mirror position corrections. Wavefront errors are determined by obtaining defocused star images and analyzing the image with a "phase retrieval" computer algorithm [3.2].

Simulation of typical wavefront errors due to polishing, thermal gradients, etc., and diffraction effects due to aperture notches, gaps and obstruction of the secondary mirror support, indicate that

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the final image will have a Strehl ratio of about 81% at 2 µm, and 60% at 0.6 µm without additional DM correction.

3.2 The Yardstick Integrated Science Instrument Module

The Integrated Science Instrument Module (ISIM) consists of a cryogenic instrument module integrated with the OTA, and processors, software, and other electronics located in the Spacecraft Support Module. The ISIM provides the structure, environment, and data handling for several modular science instruments as well as components of the OTA system - the tertiary mirror, DM, and fast-steering mirror.

This ISIM design is illustrative and is not intended to define NGST's final complement of instruments. A wide range of pre-Formulation phase (pre-Phase A) studies of ISIM architecture and individual science instruments are being conducted by science community teams in the US, Europe, and Canada [3.3]. Procurement responsibility for the science instruments will be allocated among NASA, ESA, and CSA during the Formulation phase (Phase A / B), and instrument proposals solicited by those agencies following selection of the flight NGST architecture.

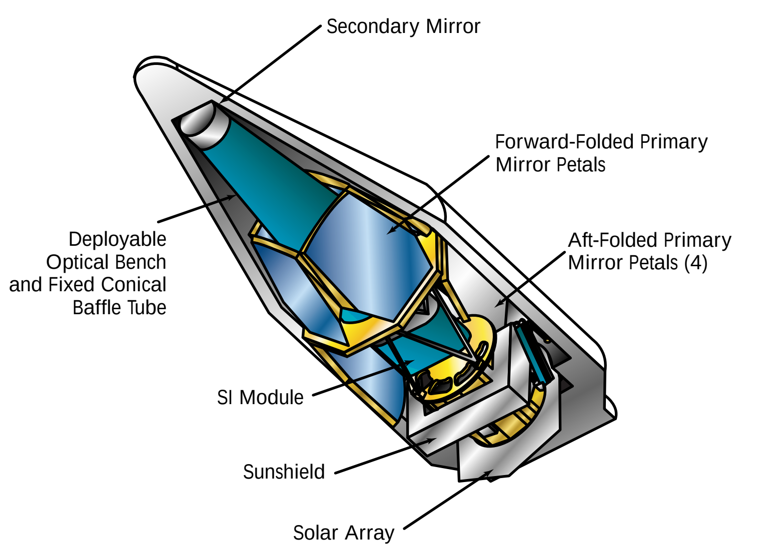

Fig. 3.2: The Yardstick Launch Configuration.

The Yardstick instrument suite includes:

- A NIR camera covering 0.6 to 5 µm, critically sampled at 2 µm. Efficient surveying capability, as well as guiding requirements, set the field at about 4' x 4', apportioned over four subcameras each covering a field of 2' x 2'. The NIR detectors (InSb or thinned HgCdTe) are radiatively cooled to 30 K.

- A NIR multi-object spectrometer, with spectral resolutions of 300 and 3000 and a spatial resolution of 100 mas, covering a field of 3' x 3'. Multi-object capability is enabled by an array of 2048^2 micro-mirrors used to form a reflective slit mask, directing light into or away from the spectrometer.

- A MIR camera / spectrometer covering a field of 2' x 2' with a spectral range of 5 - 28 µm using a 1K x 1K Si:As array as detector, and a long slit cross-dispersed grism. Its spectral resolution is ~10^3. The camera employs a selection of slits and a no-slit option to enable direct imaging with filters. The MIR detector is cooled to 6 K by a miniaturized reverse turbo-Brayton cooler; open cycle solid hydrogen cooling has been identified as a viable alternative.

Following the 1996 NGST study [3.4], the NASA Project undertook a detailed design study of the ISIM [3.5] to demonstrate engineering feasibility of the mission's science goals, assess the required technologies, and revisit the cost estimates. This study concluded that all engineering requirements of the baseline instrument complement including detector, thermal, and data system requirements are feasible with technology that is expected to be mature in 2003 at the beginning of the Implementation phase (Phase C / D). In addition, this study suggested that a highly modular approach for the ISIM is possible, enabling procurement of individual instruments from science community teams.

3.3 Passive Cooling and Thermal Control

All NGST designs solve the problem of cooling to the cryogenic temperatures required for NIR and MIR operation passively by:

- Protecting the observatory from the Sun with a multi-layer shield;

- Using a heliocentric orbit to decrease the Earth's thermal input; and

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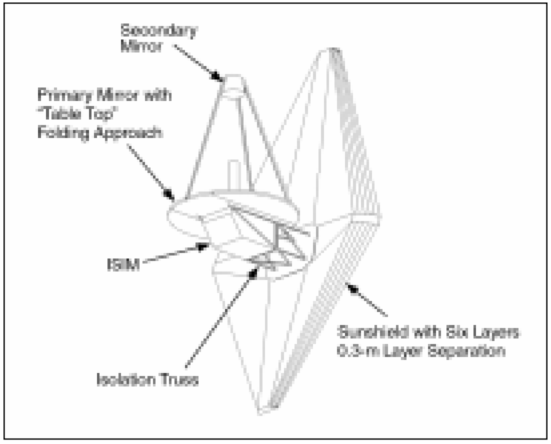

Figure 3.3: The Yardstick passive cooling design features a multi-layer sunshield.

- Configuring the telescope to have a large area exposed to space to improve radiative cooling. Baffles and stops prevent the science instrument detectors from directly seeing any surface other than the mirrors in the optical system. To make the thermal emmisivity negligible compared with the zodiacal light, the back of the sunshield must be below 100 K (Fig. 3.3). This is accomplished by adding five low-emissivity layers behind the surface of the shield facing the Sun. The main optics then reach very low temperatures (< 40 K) and do not contribute significantly to the overall emmisivity of the observatory [3.6].

3.4 Attitude Control and Sky Coverage

An offset geometry characterizes many NGST designs: the warm spacecraft support system is several meters away from the telescope. The problem of rigid pointing of the OTA to the required milli-arcsecond stability is solved by using an *image compensation system* [3.7]. The system is composed of a guiding sensor that monitors a star in the telescope's field of view [see Scientific Field of View in Section 4] coupled to a fast-steering mirror to stabilize the line of sight. In the Yardstick concept, the NIR camera is used as a guiding sensor to eliminate the cost of a dedicated guiding system.

The observatory can be pitched +/-25° off the sunline and rolled 360° about the sunline. The portion of the sky accessible is a 50° wide spherical band centered 20° away from the perpendicular to the sunline. This represents ~40% of the entire sky. Full sky coverage is achieved in slightly less than 6 months. At any time, any target in the accessible zone can be tracked for a minimum of 7 weeks.

3.5 Launch and Orbit

The overall mass of the Yardstick NGST is approximately 3300 kg, within the capability of an Atlas IIAS or the next generation of medium launchers (EELV Medium). The launch sequence is shown schematically in Fig. 3.4. Deployment of the OTA occurs soon after launch, before the sunshield is deployed, while all the mechanisms are still relatively warm. Optics alignment can then begin, followed by science calibration as the telescope cools. The halo orbit at L2 is reached about 3 months later.

3.6 Science and Mission Operations

NGST's Science and Mission Operations will be simple and efficient because of the telescope's location at L2. Operations for NGST will be based upon an optimized long-range observing plan that consists of sequenced science programs ranging from large imaging surveys, often with pre-planned spectroscopic follow-ups, to intensive studies of individual objects. This long-range optimization is required since the amount of time needed at some target positions will be more than is available in a single observing season (because of sun-angle constraints) and to minimize overheads. Development of detailed observing calendars will be relatively simple due to the lack of significant Earth occultations.

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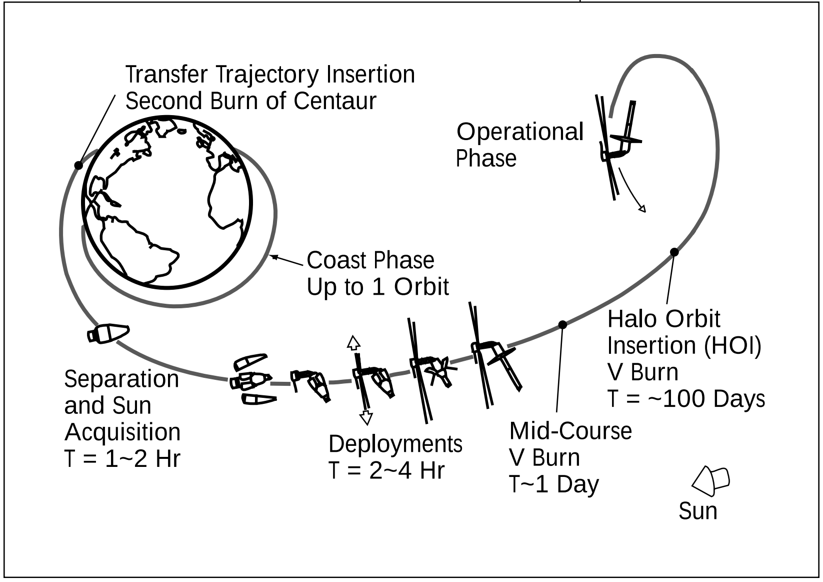

Figure 3.4: The Launch and Deployment of the NGST Yardstick Concept.

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STScI, with its long history and experience operating HST, will conduct NGST's science and operations. Maximizing NGST's science return within the constraints of a cost-capped mission is a major challenge. Making design choices based on total life-cycle costs is basic to meeting this challenge, as is reliance on a well-conceived Design Reference Mission as a primary discriminator in design trades. STScI's early involvement ensures that the organization charged with these tasks will have an effective voice in decisions that affect science and operations.

NGST grant and general observer support will be based upon the infrastructure developed for HST at STScI, modified to reflect the existence of "Legacy"-style programs that will comprise a significant fraction of the long-term science program. Legacy programs, a type of large program devised by the SIRTF mission, are a special class of observations conducted to meet the multifaceted research needs of the scientific community.

- Trade studies address cost and feasibility of meeting science goals.
- Orbit, launcher, communications, primary mirror, sunshade, temperature and field of view

4.0 KEY TRADES AND DISCOVERY POTENTIAL

The current concepts for NGST evolved from a series of trade studies during 1996-97 [4.1] and the feasibility studies done by TRW and Ball Aerospace in 1997-98 [4.2-4.3]. These focused on the cost and feasibility of accomplishing the NGST science goals described in the 1996 DRM [4.4]. A secondary goal was to maximize NGST's discovery potential, which, in addition to being a noble scientific goal, creates a science "contingency" and reduces the risk of science erosion during implementation.

4.1 Key Trade Study Results

- Orbit / Launcher: This most fundamental trade involves available launch capacity, thermal stability, and the cost of astronaut deployment. The chief scientific driver is the need to maintain a stable thermal and low aerotorque environment for the passively cooled optics. This will require a high-Earth orbit (HEO) or heliocentric orbit and effectively eliminates astronaut construction due to the difficulty of launch from low-Earth orbit (LEO) to HEO or beyond. Heliocentric orbits other than L2 were studied. The most intriguing case is the 1 x 3 AU elliptical orbit that might offer significantly lower zodiacal backgrounds at 2-3 AU. A smaller but significant improvement can be obtained by orbits inclined to the zodiacal disk (by ~17°). Such orbits require significantly greater launch capabilities than the Atlas 2AR baseline. It was found that the expected NIR detectors (InSb) would not take full advantage of the lower zodiacal backgrounds at 3 AU. Hence it was more advantageous to launch a larger mirror to L2 than a smaller mirror to 1 x 3 AU.
- Communications: Both RF and optical / laser communications were considered for the L2 orbit, with the former deemed adequate for the wide field NIR camera and typical integration periods of 1000 s. The cost of the three ground observatories required for reliable optical communications was significantly higher than the radio ground station.
- Monolith or deployable primary mirror: The lack of a launch shroud with a diameter greater than 4-5 m means the mission will require a deployable primary mirror and sunshade.
- Sunshade design and deployment: Both closed (like HST) and open sunshades were studied. Closed designs were either too heavy or difficult to deploy. For the open design, the scattering of starlight from dust on the optics is significant but acceptable for a 1 AU orbit (~10% of the zodiacal background at 1 AU for 1% dust coverage.)
- Long wavelength cutoff (primary mirror temperature): A recent study [4.5] considered a spectrum of passive cooling solutions. At one extreme, the primary mirror is temperature stabilized at 100 K and the science instruments actively cooled to their operating temperatures, <30 K. The principal savings are testing and validating the telescope optics in chambers cooled by LN_2 alone. Thermal emission from the optics and scattered radiation from the back of the sunshade precludes sensitive imaging and low-resolution spectroscopy at wavelengths longer than 5 µm. The other extreme uses a very efficient sunshade and minimizes parasitic heating from the warm spacecraft. The Formulation phase (Phase A / B) requirement to be zodiacal-light-limited to 10 µm at beginning of life reflects an intermediate design that uses an efficient sunshield and eliminates the need for active cooling of the NIR detectors. While not guaranteeing the minimum MIR background, the telescope background at 28 µm is still ten thousand times lower than the atmospheric background.
- Short wavelength cutoff: This trade will be completed during the Formulation phase (Phase A / B) studies. The technical issues are detector quantum efficiency (QE), mirror coatings, and contamination:
- Both InSb and HgCdTe NIR detectors have demonstrated good QE (>0.5) at visible wavelengths (0.4-0.6 µm).

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- Gold (0.6 µm cutoff) is a relatively simple and durable coating to apply to all optical surfaces, whereas over-coated silver (0.4 µm cutoff) is more complex and delicate.
- The impact of contaminants accumulated during cool-down on the primary mirror is felt most strongly at wavelengths shorter than 0.5 µm.

For these reasons, the Formulation phase (Phase A/B) requirement is that NGST will be capable of operating at wavelengths as short as 0.6 µm, while diffraction-limited at ~2 µm.

- Scientific Field of View: The 4' x 4' field of view provides a 99% probability of obtaining a NIR bright guidestar (K_{AB} ~ 16) in the NIR camera for fine guidance control at 30 Hz. The current baseline for the ISIM provides a 10' diameter field of view for all science instruments and, if necessary, a dedicated guider. Larger fields of view require better control of residual primary mirror errors, a difficult matching of pupil and the DM, and field dependent defocus during the 2.5" RMS fine guidance region.

Still to come are trades involving operations (e.g., level of real-time operation), the choice of ultra-lightweight mirror technologies, and the choice (by peer review) of the scientific instruments.

4.2 Discovery Potential

The trades described above outline an observatory with enormous discovery potential both at 0.6-10 µm and at longer wavelengths. This is illustrated in Fig. 4.1, which shows the time to achieve a broad-band, high-resolution wide field image with a variety of facilities: NGST, HST, Gemini (representing IR-optimized ground-based 8 m telescopes), and SIRTF. NGST enjoys a significant background advantage over the ground at all wavelengths, a larger field of view over which high-resolution images can be obtained (4' x 4' assumed) and a significant aperture advantage over SIRTF. The shorter times required to achieve a given threshold sensitivity can translate into larger fields observed (more targets) or greater sensitivities.

At wavelengths between 2.2 and 10 µm, NGST is many orders of magnitude faster than any other planned facility. In practice, it will have sensitivities several orders of magnitude better than even SIRTF because of source confusion in very deep observations. In this regard, SIRTF is a superb instrument for surveys of 10-100 square degrees. NGST is best used for deeper observations of smaller pre-selected fields. At wavelengths longer than 10 µm, NGST will surpass SIRTF by an order of magnitude in sensitivity despite a much higher MIR background. For NIR and MIR spectroscopy, it will be unsurpassed between 0.9 and 28 µm

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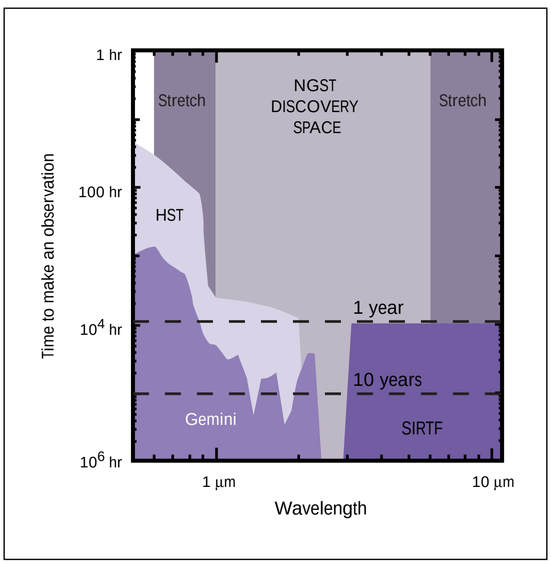

Figure 4.1: NGST Discovery Space. The relative speed of broadband NGST high resolution, wide field imaging compared with other observatories (HST/ACS/NICMOS, Gemini, and SIRTF).

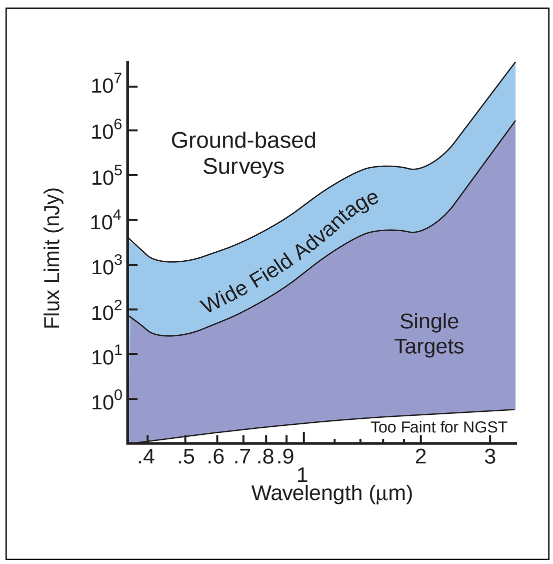

Figure 4.2: NGST uniqueness space for high-resolution imaging compared to an IR-optimized 8 m ground-based telescope with AO. (STScI)

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(28 µm is the cutoff for Si:As detectors) because NGST's thermal background is much reduced at high spatial resolution.

The "uniqueness space" [4.6] for NGST is defined relative to the many large ground-based telescopes that will be operating by 2008. The criterion is that NGST be at least 100 times faster than an optimally operated and equipped 8 m telescope with laser guide stars and adaptive optics. In Fig. 4.2, we show the uniqueness space for broadband, high-resolution imaging over fields comparable to those of NGST. NGST has a significant but limited range of uniqueness at visible wavelengths, bounded by the sensitivity achievable in a long NGST observation (10^5 s of co-added integrations) and the point where source noise becomes comparable to the background noise. In the NIR, the NGST imaging uniqueness space is very large — the chart does not indicate the regions of atmospheric absorption or the region beyond 3.5 µm where NGST is essentially unchallenged from the ground. For moderate spectral resolution 2-D spectroscopy (Fig. 4.3), the effects of detector noise significantly narrow the uniqueness space. At this resolution and detector dark current, ~ 0.02 e^{-1} / pixel / s, NGST is no longer background limited in the visible or NIR (< 4 µm). For spectroscopy of single faint targets, for instance, NGST would be used primarily in the NIR (> 0.9 µm). For high-resolution spectroscopy in the visible and J and K bands (R > 5,000) or for visible imaging of large fields with 0.4" resolution, large ground-based telescopes are competitive with NGST. This is where the large telescopes planned for the next decade will make major contributions.

It is instructive to consider the relative power of NGST compared with that of HST. HST is currently unique in the windowed ultraviolet (0.1-0.3 µm, a factor of three in wavelength). It has comparable sensitivity but superior resolution over ground-based telescopes in the visible and NIR (0.3-1.8 µm, a factor of 6). NGST will have 10 to100 times more imaging sensitivity and superior resolution at 2.5 µm (a factor of 4) to comparable at 0.6 µm. It will be unique in imaging and spectroscopy from 2.5-28 µm (a factor of 10 in wavelength). It is clear from this simple analysis that NGST will have at least as great an impact on astronomy as HST.

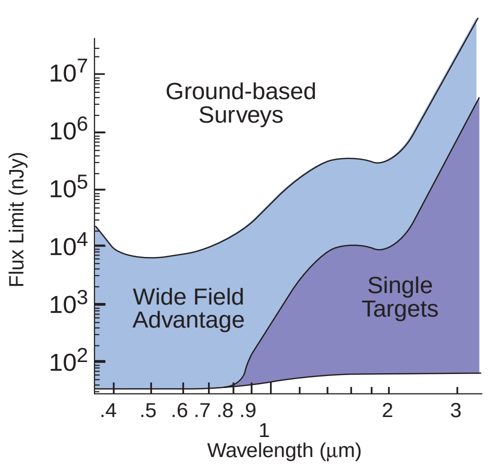

Figure 4.3: NGST uniqueness space for moderate-resolution spectroscopy (R= 1000). (STScI)

- Substantial early investment, aggressive development roadmap
- Ultra-lightweight, cryogenic optics
- Wavefront sensing & control;
- IR detectors
- Lightweight sunshields
- Test-beds and Pathfinder flight validations

5.0 TECHNOLOGY DEVELOPMENT

The NGST Project, in collaboration with industry and academia, has identified significant technology challenges that must be addressed to enable the key capabilities of NGST: excellent image quality over a wide field of view, deep imaging and spectroscopic sensitivity, and reduced background from 0.6-10 µm. The challenges are:

- Ultra-lightweight, active cryogenic optics
- Wavefront sensing and control
- Large-format, high-sensitivity infrared detectors
- Lightweight, deployable sunshield

A detailed, aggressive technology development roadmap for NGST is shown in Fig. 5.1. The maturation of three of these enabling technologies is synchronized to the selection of the prime contractor in mid 2001. The fourth technology, the sunshield, will be validated in the space environment in 2000 on the Space Shuttle (STS 107). In general, most (>75%) of the NGST technology development is done through competitive, peer-reviewed acquisition processes. Developing the technologies at the source vendor ensures that the technology products will be available to the prime contractor when the time comes to build NGST.

The NGST technology program builds on the successes of prior missions, such as SIRTF and HST, and supports future Origins missions. Requirements are derived from NASA and industry mission studies and trades. These in turn are facilitated by the parallel development of integrated system modeling tools. Data obtained from the technology development program will be used to anchor and improve these models and the cost estimates for NGST. In addition to component-level technology development, a number of testbeds and two Pathfinder flight validations are

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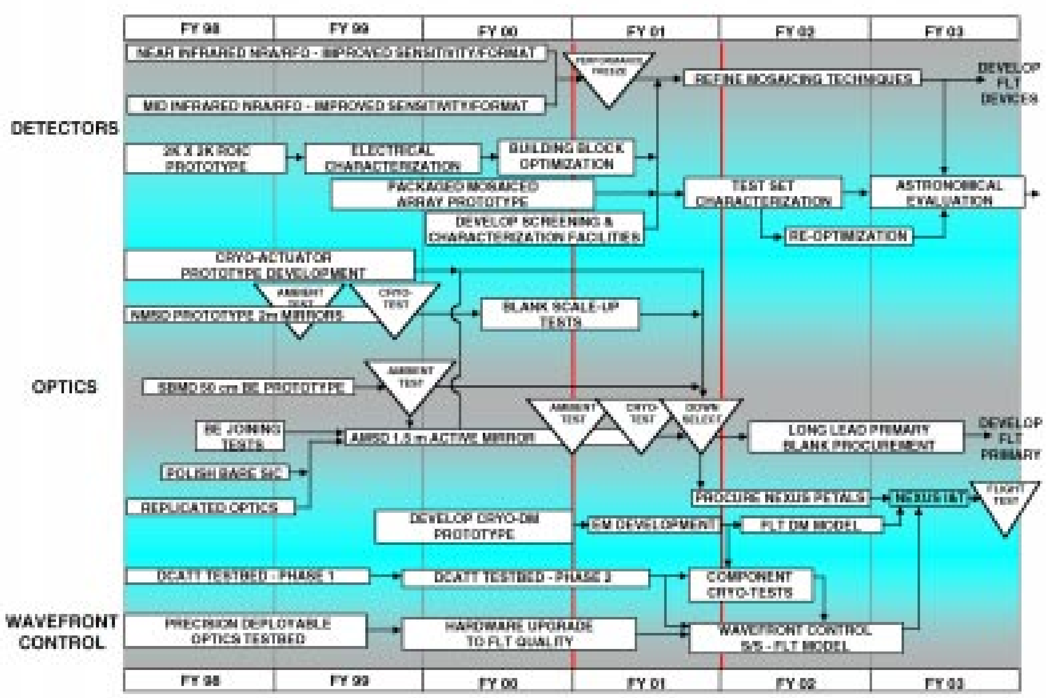

Figure 5.1: The NGST Technology Roadmap.

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planned to evaluate component, subsystem, and system level technologies for NGST. The most significant of the testbeds and flight experiments are enumerated below and illustrated in Fig. 5.2:

- Developmental Comparative Active Telescope Testbed (DCATT)
- Deployable Optical Telescope Assembly (DOTA)
- Pathfinder 1 - Inflatable Sunshield in Space (ISIS)
- Pathfinder 3 - Controlled Optics Flight Experiment (Nexus)

5.1 Cryogenic Active Optics.

NGST requires an ultra-lightweight, low-areal density (<15kg / m^2) segmented primary mirror, capable of being stowed, surviving ascent to orbit, and deploying to within the capture range of the wavefront control system. These optics must be aligned and phased to the 2 µm diffraction limit at temperatures approaching 40 K. The goal of the program is to ensure that more than one viable technology is available to the prospective prime contractors.

- Teams led by the University of Arizona (UAz) and Composite Optics Inc. (COI) are under contract to produce 2 m class active optics segments to NGST Project specifications for mass, surface roughness, and cryogenic performance. Both concepts use a thin spherical glass membrane on lightweight composite support structures, and differ primarily in actuator strategy. The COI mirror (Fig. 5.3) is a stiff, passive segment with a single radius of curvature actuator, whereas the UAz approach (Fig. 5.4) uses an array of actuators and load spreaders on 10 cm centers to control figure at low- and mid-spatial frequencies. These optics will be interferometrically tested at both ambient and cryogenic temperatures in 1999.

- Three alternate materials are being studied on a smaller scale (0.5 m optics segments): beryllium, by Ball / Tinsley; the carbonized form of silicon carbide, by a German firm, IABG, and General Optics in the U.S.; and nickel, by the Marshall Space Flight Center. These mirrors are in the final stages of manufacturing and scheduled for cryogenic testing later this year.

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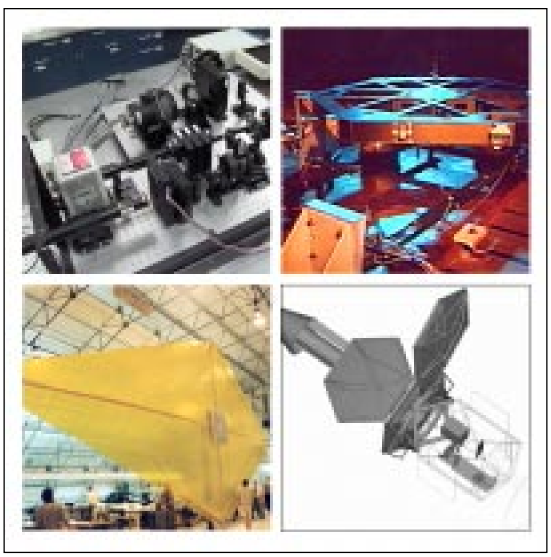

Figure 5.2: Major Testbed and Flight Demonstrations of NGST Technologies. Clockwise from the upper left: The DCATT active optics testbed; the DOTA demonstration of primary mirror deployment; and the Nexus flight demonstration of precision optical control; the ISIS flight demonstration of a deployable sunshade.

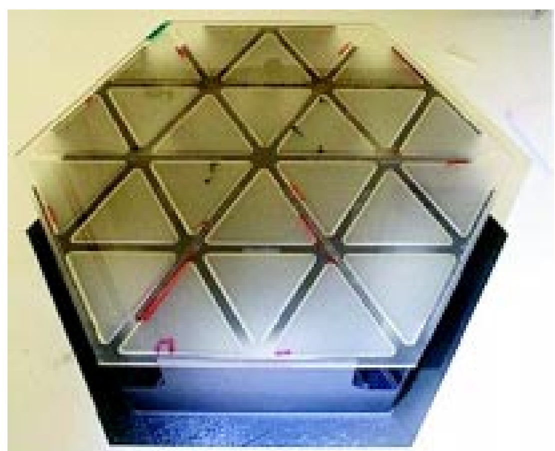

Figure 5.3: The Composite Optics Mirror System. A thin meniscus is mounted to a stiff composite backing structure. A single actuator adjusts the radius of curvature.

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- The NGST Project has established a partnership with the Department of Defense (DoD) to release another large mirror development procurement, aimed at reducing the risk of rapid manufacturing of aspheric mirrors to NGST specifications [5.1].

5.2 Wavefront Control

Optical control on NGST involves deployment and adjustment hardware, wavefront sensing, and algorithms for the deploy / capture, alignment, phasing and observation phases of the mission. Key technologies include:

- Precision deployable structures: This technology is relatively mature. Considerable expertise resides in the U.S. aerospace industry to fabricate and test structures for deploying the primary and secondary mirrors on NGST.

- Cryogenic actuators: Prototype versions of long stroke, high-resolution cryogenic actuators meeting the NGST requirements for power dissipation, mass, and cryogenic performance are being developed and will be tested at cryogenic temperatures in late 1999. AEH Inc., Energen, Burleigh, and NASA's Langley Research Center (LaRC) are developing position actuators for tip / tilt / piston control. Energen, Thermotrex, and LaRC are supplying force actuators for mirror figure control. The first prototype position actuator recently delivered to JPL for cryogenic testing is shown in the photo in Fig. 5.5.

- Cryogenic deformable mirror: Xinetics and American Superconductor are producing 10 x 10 actuator array modules targeted at meeting NGST requirements for stroke, resolution, power, mass, and cryogenic performance. Based on recently obtained strain data from doped electrostrictive ceramic materials at low temperature, Xinetics has begun a focused effort, with NASA funding, to breadboard a full-scale cryogenic DM and miniaturized, low-power, multiplexed drive circuitry.

- Wavefront control systems: GSFC and JPL are collaborating on a hardware / software system for capture, alignment, initial phasing of mirror segments, and wavefront control with a DM. JPL has developed the modeling and control software as well as an optical stimulus. In summer 1999, these will be tested on DCATT, a testbed with a 1 m primary mirror (Fig. 5.6).

5.3 NIR and MIR Detectors

The NGST requires NIR focal planes with enhanced sensitivity, low read noise (<15 e^- single sample), low dark current (<0.02 e^- / s), and high-quantum efficiency (>80%), and comparable developments in the MIR.

- Large-format, space-qualified arrays (~ 4K x 4K pixels modules): A number of competitively selected developments are underway to demonstrate acceptable performance in time for instrument selection in mid-2001. In the 0.6 – 5 µm spectral region, corporate and university teams are developing state-of-the-art arrays using Indium Antimonide (InSb) and 5 µm cutoff Mercury Cadmium Telluride (HgCdTe) with reduced dark current and read noise. The University of Rochester and Rockwell are developing a 1K x 1K InSb array readout, while a 2K x 2K format HgCdTe readout is being developed by the University of Hawaii and Rockwell. In addition, technology efforts to extend the visible response of NIR arrays are being funded to support both science imaging and guiding modes of operation.

- MIR detectors: NASA is funding the University of Rochester / Rockwell team to develop HgCdTe 10 µm cutoff arrays with low dark current at 30 K. the NASA Ames Research Center and Raytheon are pursuing Si:As arrays with low dark current in both 512 x 512 and 1K x 1K formats. Boeing is studying whether Si:Ga detectors can be operated satisfactorily at 12 K, compared with Si:As, which require ~ 8 K temperatures (too cold for a solid H dewar).

- Large-format multiplexors: Ball Aerospace, with NASA funding, is pursuing concepts for large-module packaging and cabling, evaluating the benefits of 1K x 1K versus 2K x 2K building blocks. In 2000, NGST will fund efforts to address multi-chip module production and demonstrate concepts for electrical interconnects and close butting of these arrays.

5.4 Lightweight Deployable Sunshield:

Passive cooling of the NGST telescope requires a ~ 200 m^2 multi-layer shield, capable of being stowed for launch and deployed in space prior to the unfolding of the telescope primary mirror. The NGST Project has led the following technological developments:

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- ILC Dover has fabricated and deployed a 100 m^2 engineering model sunshield (Fig. 5.7).

- The Inflatable Sunshield in Space (ISIS) flight experiment on the Space Shuttle (STS-107) in October 2000 will test the controlled deployment, dynamics, and thermal performance of this type of structure in the space environment.

5.5 Wavefront and Sensing Control Technology Validation:

The complex, interrelated issues of zero-g release of the optics, slew and settle times, dynamic and quasi-static performance, and efficacy of science camera guiding and image-based wavefront sensing and control with real stellar sources will be addressed in a space-based technology demonstration in the 2003-04 timeframe through a Pathfinder mission called Nexus.

Figure 5.4: The University of Arizona Mirror System. A thin glass meniscus is mounted with a bed of active actuators to a stiff backing structure.

Figure 5.5: A position actuator developed by AEH Inc.

Figure 5.6: The 1 m Segmented DCATT Aluminum Mirror. The mirror figure was provided by Oak Ridge diamond turning. It is being polished at the University of Arizona.

Figure 5.7: The Half-Scale Model of the NGST Sunshield.

- Innovative systems engineering & advanced, lower cost technologies
- Science involvement, core requirements and full life cycle costs guide trades
- Risk management includes predictive modeling and "off-ramp" strategy
- Optimized teaming, timing and contracting decisions
- Five independent estimates of NGST cost feasibility

6.0 PROGRAM MANAGEMENT

Meeting NGST's science goals in a cost-capped environment requires the *infusion of advanced technology, innovative management and systems engineering,* and the ability to *accurately predict and control costs.* Successful applications of these principles in other regimes like computing have led to remarkable performance strides and decreased hardware costs. The core NGST science requirements serve as a guide for "science system engineering" tradeoffs in the all phases of development, should technical or cost problems be encountered.

6.1 Advanced Technology and Risk Mitigation

The NGST observatory is enabled by advanced technology; the risk associated with such technology will be mitigated prior to final approval for implementation. The risk management approach is threefold (Fig. 6.1):

- Execute an aggressive technology development roadmap during program formulation (Phase A / B) to demonstrate acceptable readiness prior to system implementation. The NGST investment ratio (technology investment vs. implementation cost) is >40%; the HST ratio was <1% for comparison.
- Develop a strategy of specific "off-ramps" for enabling technologies and provide recovery plans should technology elements fail to mature in a timely manner.
- Manage by performance margin via disciplined systems engineering. This requires a quantitative understanding of the core science requirements and building appropriate performance margin into the design up front. This ensures that the architecture is robust to technology shortfalls. For example, the areal-density goal for the NGST primary mirror is <15 kg / m^2. The reference architecture (with a 5 m diameter fairing and a medium-lift launcher) can accept 20-22 kg / m^2 optics. The first mirror developed under the technology program by University of Arizona achieved 20 kg / m^2 at the 0.5m scale with acceptable wavefront quality.

6.2 Management Approach

The NGST development and acquisition plan is based on a detailed trade study, using similar-sized efforts in NASA and DoD as benchmarks. The selected strategy optimizes the key elements of teaming, timing, and contracting. It also addresses the daunting challenge of accurately predicting and then controlling the cost throughout the mission lifecycle.

Teaming – Science and Engineering:

A strong, government-led systems team throughout the Formulation phase (Phase A / B) includes the contractors and a significant science component — STScI as the NGST Science and Operations Center. The team performs detailed analyses and simulations at the system and subsystem level, treating cost as an independent variable from the outset. In a cost-capped mission, requirements and performance are traded against cost to obtain solutions that optimize science and minimize lifecycle costs. The NGST team continues to develop tools and metrics to predict cost growth as a function of "requirements creep." It is important to note that core science requirements will guide descope strategies to keep the mission within bounds.

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NGST Risk Management Approach

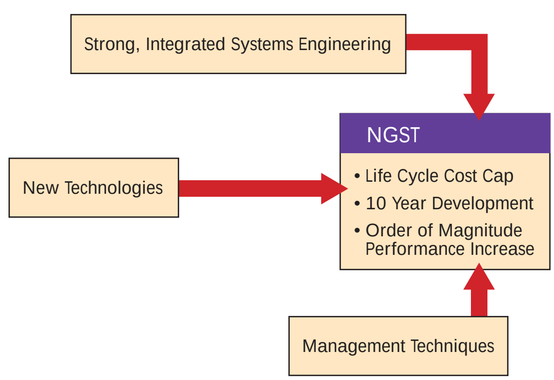

Figure 6.1: The NGST Risk Management Strategy.

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Teaming – Science Community:

A key Project responsibility is to keep the astrophysics community informed and involved throughout NGST development. The community plays a major role in first defining the science requirements and ultimately in building instruments for and using the new observatory. NASA formally involves the community through Announcements of Opportunity for detector and instrument development, and will convene a Science Working Group when the project is in the Implementation phase. To facilitate early and continuing community involvement in observatory formulation and development, and in the conduct of the science program, NASA named the Institute as the Science and Operations Center in June 1998.

The Institute and the Project jointly sponsor special workshops such as the April 1999 detector workshop at STScI and the combined NGST engineering and science workshop to be held at Woods Hole in September 1999. The Institute organizes special sessions at the AAS and other professional meetings, provides NGST information through exhibits and websites (www.ngst.nasa.gov and www.stsci.edu), has expanded the Institute newsletter to include a special NGST section and has broadened its distribution to include SOFIA and IPAC users. The Institute, working with the NGST Project, assembled the Ad Hoc Science Working Group (ASWG) as an advisory body for the pre-Formulation phase (pre-Phase A) period. The Institute and Project have reported regularly to other science advisory committees, including the NGST Science Oversight Committee, the NGST External Science Review Committee, and the Origins Subcommittee of the Space Science Advisory Committee.

The Institute sponsors studies and convenes independent science advisory committees as necessary, such as its current study concerning the optimal spectrometry capability for NGST, chaired by John Huchra. Finally, the Institute's parent organization, the Association of Universities for Research in Astronomy (AURA), with 27 U.S. institutions and 4 foreign affiliates, provides the Institute (and thus NGST) with a high level of community interaction and oversight.

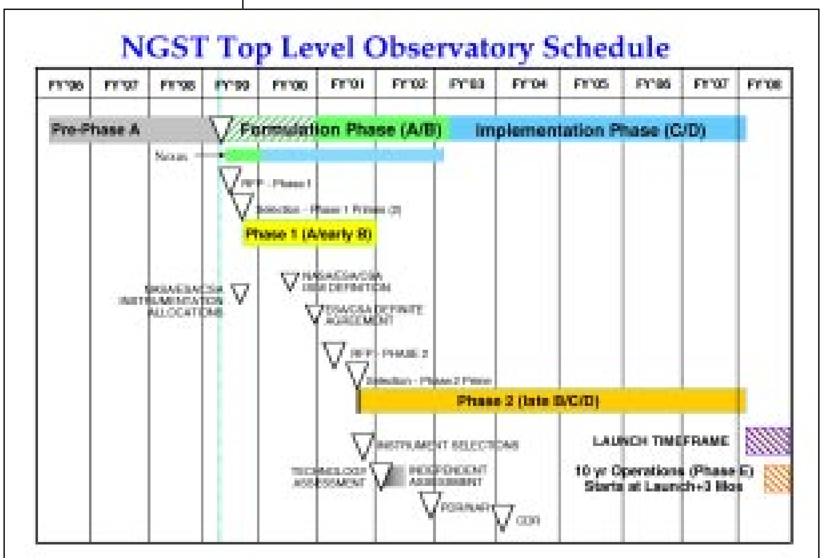

Figure 6.2: The Top-Level NGST Schedule.

Teaming – International Partners:

International contributions are integral to NGST cost feasibility. The $200M ESA and $50M CSA contributions increase available resources to well above the $500M allocation for the Implementation phase (Phase C/D). Contributions of instrument and spacecraft subsystems both expand science capability and provide contingency.

Timing:

The acquisition strategy maximizes competitive benefits prior to technology maturation (~mid-2001). The NASA team guides technology development and ensures competition and peer review during formulation, while the two prime contractors design architectures incorporating both government-provided and proprietary technologies. The selection of a single prime contractor in the middle of the Formulation phase (Phase A/B) reduces unnecessary duplication of effort prior to the end of detailed design.

Contracting:

An acquisition trade study suggested the optimal procurement strategy was a performance-based prime contract with on-orbit performance incentives and the selection of the prime in mid-Formulation phase (Phase A/B). This approach streamlines transitions between Formulation and the costly Implementation phase. NASA Headquarters recently endorsed this strategy.

6.3 The Schedule

The NGST launch date is nominally set for mid-2008, with the proviso that NGST will not proceed to Implementation (Phase C/D) in mid-2003 until key technologies are demonstrated. The top-level NASA schedule (Fig 6.2) shows the time phasing of various elements of the project plan. The schedules of the international partners are fully integrated with NASA's schedule.

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6.4 The Roles of Industry, Government, and Academia

The NASA-led team, including STScI, will lead or participate in key areas where expertise and experience warrant. These include science oversight, detector technology, instrument integration, wavefront sensing and control, ground-system development, and operations.

The U.S. scientific instruments will be acquired via a NASA Headquarters-released Announcement of Opportunity (AO), while Canadian and European instrument contributions will be developed according to the respective communities' methods. The instruments will be delivered, after functional performance tests at the developer's site, to the GSFC-led science instrument Integrated Product Team (IPT). The ISIM IPT will include engineers and scientists from the international partners and the instrument development teams.

6.5 Cost Credibility

NASA's cost target for the Implementation phase is $500M (FY 96), with significant additional resources coming from the international partners (up to $250M). Over the last 2 to 3 years, the prime contractors and the NASA-led team have developed cost estimates. Some were parametric while others were "bottoms up" engineering estimates. A summary of those estimates shows that different mission concepts cost approximately the same (Fig. 6.3). The total resource pool for NGST includes other partnerships within NASA and DoD funding technology development and providing labor, bringing the total budget to $1.6B. (All are in constant FY96 dollars.)

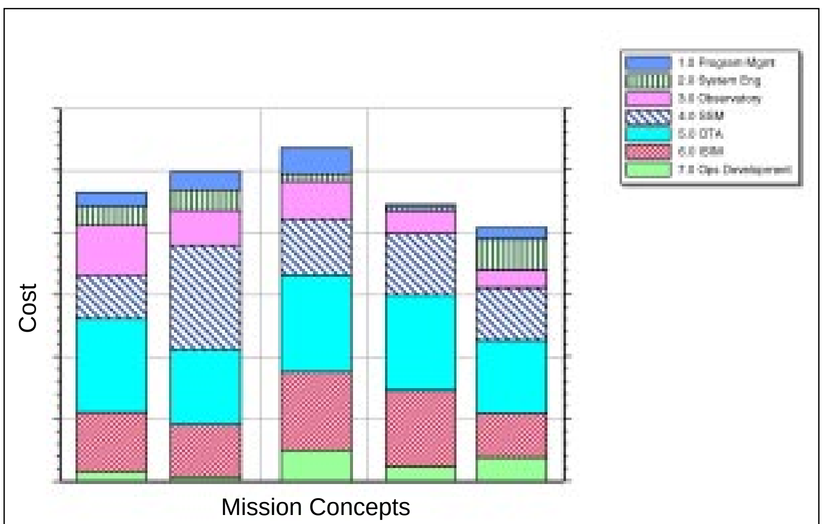


Figure 6.3: Estimates for different mission designs all cost approximately the same, ~$500M (FY 96).

- NGST pivotal to NASA's long-term program
- Technology facilitates affordable, technically advanced future missions

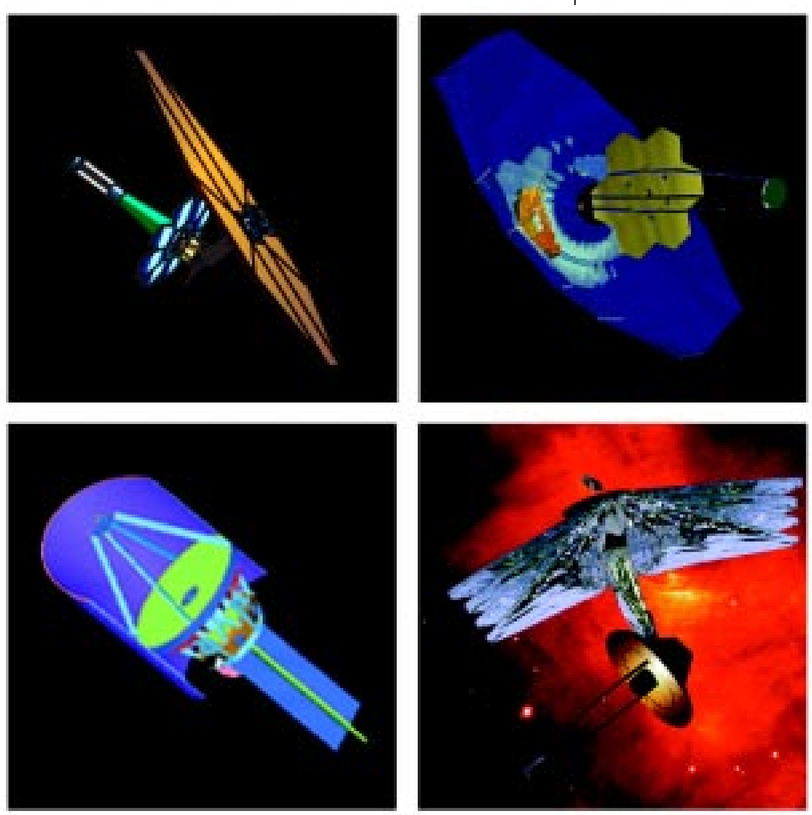
7.0 BEYOND NGST

Ideas for using NGST concepts and technologies for future space missions abound. The NGST concept enriches the possibilities for the long-term NASA plan by opening the door to additional missions in the product line. Ultraviolet and visible astronomy could benefit from much larger collecting areas, as offered by NGST, when combined with alternative contamination control, mirror coatings, detectors, and thermal control. As deformable mirrors are developed for NGST, the path to increased angular resolution will become clear. These methods could be exploited for an ultraviolet telescope or coronography at longer wavelengths to better penetrate the glare of nearby stars in search of planets.

A longer wavelength version of NGST, starting around 10 µm instead of 0.6 µm, would use straightforward extensions of the mirror and cooling concepts and be built to relaxed mechanical and optical tolerances. A long wavelength NGST might benefit from an orbit 2 to 4 AU from the Sun, outside most of the interplanetary dust. An even longer wavelength FIR version, working at 50-100 µm, would be remarkably powerful if outfitted with suitable detector arrays. Such a facility could be orders of magnitude more sensitive than proposed precursors like FIRST (with a 70 K telescope) or the Japanese H2L2 mission (with a 3 to 4 m cold aperture). Such a telescope could test interferometric techniques needed by such FIR space interferometers as the Submillimeter Probe of the Evolution of Cosmic Structure (SPECS) [6.1], under study by a GSFC-JPL team.

NGST itself is a major stepping stone and prerequisite for the Terrestrial Planet Finder (TPF). TPF is designed to answer the question: Are there other worlds in the universe capable of supporting life? TPF relies on NGST's development of a large aperture cryogenic IR telescope as part of its own technology development program.

NGST, while only one of the Office of Space Science missions, is pivotal to NASA's long-term plans for affordable, yet technically advanced space observatories. This key mission will provide a powerful instrument to enable a large community of users to significantly advance astrophysics research. HST has clearly shown the productivity of such facilities, and NGST offers a fiscally responsible evolutionary path. With broad application to a variety of scientific challenges, and a wide range of new technologies made ready for future missions, NGST will be the basis for breakthrough discoveries for generations of astronomers.



Four early NGST concepts.

Acronyms

AO	Adaptive Optics
ASWG	Ad Hoc Science Working Group
AURA	Association of Universities for Research in Astronomy
AXAF	Advanced X-Ray Astrophysics Facility
CMB	Cosmic Microwave Background
COI	Composite Optics, Inc.
CSA	Canadian Space Agency
DCATT	Developmental Comparative Active Telescope Testbed
DM	Deformable Mirror
DoD	Department of Defense
DOTA	Deployable Optical Testbed Assembly
DRM	Design Reference Mission
ESA	European Space Agency
FIRST	Far-Infrared Space Telescope
FOV	Field of View
FUSE	Far Ultraviolet Spectroscopic Explorer
GSFC	Goddard Space Flight Center
HgCdTe	Mercury Cadmium Telluride
HST	Hubble Space Telescope
InSb	Indium Intimonide
IPAC	Infrared Processing and Analysis Center
IPT	Integrated Product Team
ISIM	Integrated Science Instrument Module
ISIS	Inflatable Sunshield in Space
JPL	Jet Propulsion Laboratory
L2	Lagrange point 2
LaRC	Langley Research Center
MAP	Microwave Anisotropy Probe
MIR	Mid Infrared
MMA/LSA	Millimeter Array/Large Southern Array
NASA	National Aeronautics and Space Administration
NESR	NGST External Science Review Committee
NGST	Next Generation Space Telescope
NIR	Near Infrared
OTA	Optical Telescope Assembly
PSF	Point Spread Function
QE	Quantum Efficiency
RMS	Root Mean Square
SCUBA	Submillimeter Common User Bolometer Array
SI:As	Arsenic doped Silicon
SI:Ga	Gallium doped Silicon
SIM	Space Interferometry Mission
SIRTF	Space Infrared Telescope Facility
SOFIA	Stratospheric Observatory for Infrared Astronomy
SPECS	Submillimeter Probe of the Evolution of Cosmic Structures
SSM	Spacecraft Support Module
STScI	Space Telescope Science Institute
TPF	Terrestrial Planet Finder
UAz	University of Arizona

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