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SI – The Stellar Imager

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The ultra-sharp images of the Stellar Imager (SI) will revolutionize our view of many dynamic astrophysical processes: The 0.1 milliarcsec resolution of this deep-space telescope will transform point sources into extended sources, and simple snapshots into spellbinding evolving views. SI's science focuses on the role of magnetism in the Universe, particularly on magnetic activity on the surfaces of stars like the Sun. SI's prime goal is to enable long-term forecasting of solar activity and the space weather that it drives in support of the Living With a Star program in the Exploration Era by imaging a sample of magnetically active stars with enough resolution to map their evolving dynamo patterns and their internal flows. By exploring the Universe at ultra-high resolution, SI will also revolutionize our understanding of the formation of planetary systems, of the habitability and climatology of distant planets, and of many magneto-hydrodynamically controlled structures and processes in the Universe.

I. Introduction

The Stellar Imager (SI) is a UV-Optical, Space-Based Interferometer designed to enable 0.1 milli-arcsecond (mas) spectral imaging of stellar surfaces and stellar interiors (via asteroseismology) and of the Universe in general. At the revolutionary design resolution of SI, sequences of images will show the dynamics of astrophysical processes and perhaps even allow us to directly see, for the first time, the evolution of, e.g., a planetary nebula, an early supernova phase, mass exchange in binaries, (proto-)stellar jets, and/or accretion systems. Its spectral imaging capability is designed to enable an improved understanding of:

- **Solar and Stellar Magnetic Activity and Its Impact on Space Weather, Planetary Climates, and Life**
- **Magnetic Processes, the Origin and Evolution of Structure, and the Transport of Matter Throughout the Universe**

SI is included as a "Flagship and Landmark Discovery Mission" in the 2005 Sun Solar System Connection (SSSC) Roadmap and as a candidate for a "Pathways to Life Observatory" in the Exploration of the Universe Division (EUD) Roadmap (May, 2005).

The Stellar Imager Vision Mission concept is under development by NASA's Goddard Space Flight Center, in collaboration with a broad variety of industrial, academic, and astronomical science institute partners, as well as an international group of science and technical advisors (see **Table 1**).

This paper summarizes the Final Report of the SI Vision Mission Study, for which the principal authors and their primary areas of expertise are listed in the full Vision Report. A one-page "Quick Facts" sheet summarizing the Mission's Goals and Architecture is given in **Table 2**.

The full Vision Mission Study report can be downloaded from *http://hires.gsfc.nasa.gov/si/*. That report presents the mission and its science in much more detail than this summary document.

II. Science Rationale

A. Key Objectives

The key science goals of the SI mission are:

- **To study the evolution of stellar magnetic dynamos** from the very formation of stars and planetary systems onward to the final stages of stellar evolution.
- **To complete the assessment of external solar systems** begun with the planet-finding and imaging missions **by imaging their central stars**
- **To study the Universe at ultra-high angular resolution** from the internal structure and dynamics of stars and interacting binaries to extreme conditions, e.g. in Active Galactic Nuclei and black hole environments.

Examples of scientific areas of study for the Stellar Imager include:

- **Magnetically active stars** *to study activity and its impact on stellar structure and evolution as well as on orbiting planets*
- **Stellar interiors** *in stars outside solar parameters*
- **Infant Stars-disk systems** *to image dynamic accretion, magnetic field structure & star/disk interaction*
- **Hot Stars** *and their hot polar winds, non-radial pulsations, rotation, structure, and the envelopes and shells of Be-stars*
- **Cool, Evolved Giant & Supergiant Stars** *and the spatiotemporal structure of extended atmospheres, pulsation, winds, shocks*

- **Supernovae & Planetary Nebulae** *in particular their core structure, early expansion and interaction with CSM*
- **Interacting Binaries,** *including mass-exchange, dynamical evolution, accretion, and dynamos*
- **Active Galactic Nuclei, Quasars, Black-Hole Environments,** etc. …

Primary Science Goals for the Stellar Imager: Stellar Magnetic Activity

Most of us rarely give the Sun a second thought. We do not question its presence or its apparent stability as we see it traverse the sky every day. The Sun is, however, *a variable* star. Its variability affects the Earth and the human society by modulating Earth's climate. It also affects our technology, upon which we are becoming ever more reliant: eruptions on the Sun disrupt communications; affect navigation systems; cause radiation harmful to astronauts exploring beyond the Earth's atmosphere and to airline passengers traveling through it; and occasionally push power grids to fail.

The recognition of the importance of the Sun's fickle variations has led to the development of a large National Space Weather Architecture. Within that Architecture, NASA, and in particular the Heliophysics Division is working to learn why and how Earth and human society are affected by the Sun's variable magnetism. This is the focus of NASA's *Living With A Star* program. At the core of that program is the question concerning the Sun's magnetic field: what causes the Sun to be magnetically active, and how can we develop reliable forecasting tools for this activity and the associated space weather and climate changes on Earth? The Stellar Imager aims to make crucial contributions to this field, warranting its status as a Landmark Discovery Mission in the 2005 roadmap for the Sun-Earth Connection.

The principal cause of all solar variability is its magnetic field. This intangible and unfamiliar fundamental force of nature is created in the convective envelope of the Sun by a process that we call the dynamo. There is at present no quantitative model for stellar dynamos that is useful to forecast solar activity or even to establish the mean activity level of a star based on, say, its mass, age, and rotation rate. The nonlinear differential equations for the coupling of the vectors of turbulent convection and magnetic field cannot be solved analytically. Nor can the cycle dynamo be simulated numerically in its entirety; full numerical coverage would require some 10^{18} grid points, which is a factor of order a billion beyond present computational means. Hence, both analytical and numerical studies necessarily make approximations that simplify or ignore much of the physics. Furthermore, even the approximating models are of a richness and diversity that there is no consensus on the model properties, or even on the set of processes that are important in driving the dynamo. Numerical research will undoubtedly make significant advances in the coming years, but only the comparative analysis of many Sun-like stars with a range of activity levels, masses, and evolutionary stages will allow adequate tests of complex dynamo models, validation of any detailed dynamo model, and exploration of the possible spatio-temporal patterns of the nonlinear dynamo.

The studies of average activity levels of stars have helped us piece together what some of the essential ingredients to dynamo action are on the largest scales. For example, we know that a dynamo associated with stellar activity operates in all rotating stars with a convection zone directly beneath the photosphere. In single stars, the dynamo strength varies smoothly, and mostly monotonically, with rotation rate, at least down to the intrinsic scatter associated with stellar variability. It also depends on some other unknown stellar property or properties. For main sequence stars, for example, the primary factor in determining activity resembles the convective turnover time scale at the bottom of the convective envelope. But no such dependence holds if we test the relationship on either evolved stars or on tidally-interacting compact binary systems. Apparently, other parameters, as yet unidentified, play a role, such as surface gravity and tidal forces.

The variations of stellar and solar activity on time scales of years also remain a mystery. The Sun shows a relatively regular heartbeat with its 11-year sunspot cycle, even as cycle strength and duration are modulated. Such a pattern is not the rule among the cool main–sequence stars, however. Instead, we find a variety of patterns of variability in their activity, in which only one in three of these stars show cyclic variations that resemble those of the Sun (**Fig. 1**). For main–sequence stars with moderate to low rotation rates, activity tends to be cyclic, but no clear trend of cycle period with stellar parameters has been found, although there are hints of relationships between cycle period, rotation period, and the time scale for deep convection. For truly active stars, various variability patterns exist, but generally no unambiguous activity cycle is seen.

Historical records show that the Sun can change its activity significantly on the intermediate time scale of decades (**see Fig. 2**). Activity decreased, for example, for multiple decades during the 17th Century, when Earth experienced the Little Ice Age. A sustained increase in activity – such as happened during the medieval Grand Maximum – may cause a warm spell, and will be associated with an increase in the frequency of space storms, and in the ultraviolet radiation that is harmful to life on Earth.

It would take hundreds of years to validate a solar dynamo model using only observations of the Sun, given its ***irregular*** *11-year magnetic heartbeat and the long-term modulations.* Key to successfully navigating the route to a workable, predictive dynamo model is the realization that *in order to understand the solar dynamo, we need a population study; that is, we need to study* *the dynamo-driven activity in a sample of stars like the Sun, and compare it to observations of younger stars, older stars, and stars in binary systems, etc.* Thus, the SI will enable us to test and validate solar dynamo models *within a decade, rather than requiring a century or more* if we used only the Sun.

The potential for a breakthrough in our understanding and our prediction ability lies in spatially-resolved imaging of the dynamo-driven activity patterns on a variety of stars. These patterns, and how they depend on stellar properties (including convection, differential rotation and meridional circulation, evolutionary stage/age), are crucial for dynamo theorists to explore the sensitive dependences on many poorly known parameters, to investigate bifurcations in a nonlinear 3-dimensional dynamo theory, and to validate the ultimate model.

Direct, interferometric imaging – the goal of the Stellar Imager - is the only way to obtain the required information on the dynamo patterns for stars of Sun-like activity. Alternative methods that offer limited information on spatial patterns on much more active stars fail for a Sun-like star: a) rotationally-induced Doppler shifts in such stars are too small compared to the line width to allow Zeeman-Doppler imaging, b) the activity level is insufficient to lead to significant spectral changes associated with magnetic line splitting, c) rotational modulation measurements leave substantial ambiguities in the latitude distributions, locations and sizes of spots, and cannot be used to measure dispersal of field across the stellar surface. The direct imaging by SI of stellar activity will overcome these problems. Equally importantly, the asteroseismic observations planned with SI will determine the internal properties of stellar structure and rotation, thus directly providing crucial information relevant to the physical operation of the dynamo mechanism.

Imaging magnetically active stars and their surroundings will also provide us with an indirect view of the Sun through time, from its formation in a molecular cloud, through its phase of decaying activity, during and beyond the red-giant phase during which the Sun will swell to about the size of the Earth's orbit, and then toward the final stages of its evolution as a Planetary Nebula and a white dwarf relic.

Seismic Studies of Stellar Interiors: from dynamo to fundamental (astro-)physics

The SI mission will allow us not only to image the surfaces of stars, but also to sound stellar interiors using spatially resolved asteroseismology to image internal structure, differential rotation, and large-scale circulations; this will provide accurate knowledge of stellar structure and evolution and complex transport processes, and will impact numerous branches of (astro)physics. *For arrays of 9 or more optical elements, asteroseismic imaging of structure and rotation is possible with a depth resolution of 20,000 km for a star like the Sun.*

Helioseismology has given us an extremely detailed view of the solar interior. These results are of great importance to our understanding of the structure and evolution of stars, and of the physical properties and processes that control this evolution. At the time of the launch of the SI, seismic investigations of other stars will have been undertaken by several space missions, including MOST and COROT, however, a number of key issues will remain open. These missions will only observe low-degree modes, through intensity variations in light integrated over the stellar disks. Such point-source observations will provide information about the global properties of solar-like stars, which allows the study of global structure, including, e.g., gravitational settling of helium and large-scale mixing processes. SI observations, however, will allow us to expand the discovery space far beyond that: modes of degree as high as 60 should be reachable with an array of N=10 elements, increasing as N^2 for larger arrays. By analogy with the Sun, in solar-like stars this will allow inferences with good radial and reasonable latitude resolution to be made in the radiative interior and the lower part of the convective envelope, for both structure and the patterns and magnitudes of the differential rotation with depth and latitude. With a careful choice of target stars SI observations will allow us to obtain such detailed information about the interiors of stars over a broad range of stellar parameters, in terms of mass, age and composition.

Studies of the internal rotation as a function of mass and age will provide unique information about the evolution of stellar internal rotation with age, in response to the activity-driven angular-momentum loss in stellar winds. This will provide stringent constraints on models of the rotational evolution, elucidating the processes responsible for transport of angular momentum in stellar interiors; these studies are also fundamental to the understanding of the dynamo processes likely responsible for stellar activity. By correlating the rotation profile with the profile of the helium abundance, as reflected in the seismically inferred sound speed, an understanding can be achieved of the rotationally-driven mixing processes in stellar interiors. This is of great importance for calibrating the primordial abundances in the Universe as well as to the improvement and validation of stellar evolution models. For example, the data will provide constraints on the convective overshoot at the base of the convective envelope which also contributes to the mixing. The resulting understanding can then be applied to the mixing and destruction of lithium, finally providing the means to relate the observed lithium abundance in old halo stars to the primordial lithium content of the Universe. For stars slightly more massive than the Sun the data, combined with the more extensive data on low-degree modes likely available at the time from earlier missions, will allow detailed investigations of the properties of convective cores and related internal mixing; an understanding of these processes is essential to the modeling of the evolution of massive stars, leading to the formation of supernovae.

The Universe at Ultra-High Angular Resolution:

Observing the Universe at ultra-high angular resolutions will enable a fundamental understanding of magnetic processes, the origin and maintenance of structure, and the transport of matter throughout the Universe.

Magnetic fields affect the evolution of stars and planetary systems in all phases, from the formation of the star and its planets, to the habitability of these planets through the billions of years during which they live with their stars. *But more than that,* a long-baseline interferometer in space will benefit many fields of astrophysics and physics. With its revolutionary imaging power, *SI will enable detailed study of magnetic processes and their roles in the Origin and Evolution of Structure and in the Transport of Matter throughout the Universe.*

SI will produce images with hundreds of times more detail than Hubble. **Figure 3** shows examples of SI snapshot views of diverse galactic and extragalactic sources that are far beyond the reach of the current and near future observational astronomy. Furthermore, the SI will bring the study of dynamical evolution of many astrophysical objects into reach: hours to weeks between successive images will detect dramatic changes in many objects, e.g., mass transfer in binaries, pulsation-driven surface brightness variation and convective cell structure in giants and supergiants, jet formation and propagation in young planetary systems, reverberating Active Galactic Nuclei (AGN), and many others (see **Fig. 4**). Imagine, for example, unprecedented dynamic views of evolving structures (as the examples in **Fig. 3**) of AGN, quasi-stellar objects, supernovae, interacting binary stars, supergiant stars, hot main-sequence stars, star-forming regions, and protoplanetary disks.

We highlight here with only a few examples of the vast discovery potential of the Stellar Imager; the full Vision Mission Study report lists more topics, describing them in more detail.

Star Formation, Protoplanetary Disks, and Jets

Protoplanetary disks are where planets form, migrate to their final locations, and where the materials that can ultimately produce life-bearing worlds are assembled. If we are to understand not only the history of our Solar System, but also how planetary systems develop in general, we need to understand the disks, how long they last, how they interact with their central stars, and how they evolve.

Young stellar objects (YSOs), e.g. T Tauri stars, represent the parent stars of planetary systems presumed to form from the remnant circumstellar disks that encircle them. The inner boundaries of such disks are expected to be at the corotation radius from the star, typically 3-5 stellar radii. The environment within that distance is controlled by the strong magnetic field of the rapidly spinning star. The temperatures of the accreting plasma increase from several thousand to a few million degrees in this region. Due to the high temperatures and relatively low densities, UV emission as observed by SI provides an efficient and direct means to image the regions close to YSOs. The Stellar Imager would have the capability to map the accretion flow from the co-rotation radius of the disk onto the accretion footprint of the star, using emission lines spanning a wide ionization range.

Young stars frequently drive bipolar outflows that can be traced, in some cases, over parsecs. SI can easily resolve the inner regions of such structures for the nearest star formation regions and study them in detail close to their origin. SI can also image the uncollimated wind component, which has been proposed as a means of transporting annealed silicates and processed organics from the inner parts of the protoplanetary disk into more distant icy planetesimals, thus potentially accounting for the compositional diversity of comet nuclei.

Hot stars: Rotation, Structure, Winds, and Disks

Understanding how massive stars rotate is important for the accurate modeling of stellar evolution and computing the final chemical yields of stars. Hot (O, B, Wolf-Rayet) stars tend to be the most rapidly rotating types of non-degenerate stars, and many are rotating so fast that their shapes are centrifugally distorted into oblate spheroids. It is extremely difficult to pin down the detailed properties of single-star rapid rotation. The SI will provide 10 to 1000 interferometric resolution elements across a stellar disk, which is a key for studying hot star rotation and its effects on the atmospheric structure.

An important but seldom directly measured aspect of hot-star rotation is the phenomenon of *gravity darkening*: the equators of rapidly rotating stars are dimmer and cooler than their poles. Currently, models are still changing, and observational constraints from eclipsing binary light curves sometimes yield types of gravity darkening that are outside the bounds of present theoretical understanding indicating the need for new observational data that can be obtained with SI by direct imaging. High-resolution imaging in the UV and optical would constrain how much gravity darkening actually exists for different types of stars far better than, e.g., lower-resolution, ground-based optical interferometric measurements. We could then assess how it gradually disappears as subsurface convection eventually sets in later than the early/mid-F spectral range.

For O stars and early B supergiants, radiative winds generally dominate over other mass-loss processes. These winds can be optically thick and thus resolvable in high mass loss stars such as Wolf-Rayet and interacting massive binaries. In principle, the structure of these winds provides a means to document the past ejections of shells in stars with histories of discrete mass loss episodes. Imaging winds would help us understand the density distribution and, from the continuity equation, outflow velocities in the inner wind. Anisotropies are important because they hint at a partial confinement of the wind by rotation or magnetic fields.

Be stars, non-supergiant B-type stars that exhibit emission in the hydrogen Balmer lines, are rapidly rotating. The observed properties of Be stars and their circumstellar gas are consistent with the coexistence of a dense equatorial disk and a variable stellar wind. The gas in the so-called `decretion disk' is generally believed to be ejected from the star and not accreted from an external source, and the rapid rotation of Be stars has been associated with the presence of the disk since at least the 1930s. One of the longest-standing puzzles in hot-star astrophysics is the physical origin of this disk, both from the standpoint of mass supply (the winds may be too tenuous) and from the standpoint of angular momentum supply (the disks are Keplerian but the stellar surfaces are not). Also, there are many examples of stars that have exhibited alternating Be and "B-normal" phases of activity (the latter implying disappearance of the disk), with time scales of various kinds of variability ranging from days to possibly centuries. Direct SI imaging and dynamic movies of Be stars will provide answers regarding the physical distribution of matter, structures within the disks and winds (spiral density waves or clumpy structures), wind/disk interaction regions, and ionization structure.

Wolf-Rayet (WR) stars are believed to be the central, heavy cores of evolved O-type stars that have lost most of their hydrogen-rich outer layers as a stellar wind. WR stars have observed mass loss rates at least an order of magnitude higher than other O stars (i.e., of order 10^{-4} M_{sun}/yr), and the origin of these extremely dense and optically thick outflows is still not well understood. The only way that line-driven wind theory can account for such large mass loss rates is if the opacity in the lines is utilized many times (i.e., if photons multiply scatter through the optically thick outer atmosphere before they give up all of their radiative momentum to the gas).

However, other ideas include fast magnetic rotation and "strange-mode" pulsations in the chemically enriched interiors. The direct imaging of the innermost emitting surface in the wind would lead to stringent constraints on these ideas.

Atmospheres of Pulsating Variable Stars

Pulsations are found in many different types of stars, ranging from very hot main-sequence stars to dying cool giants and stellar relics. The signatures of pulsation are very prominent in the UV (e.g. Mg H&K lines) – thus, the SI provides a perfect tool for probing the physics and dynamics of pulsating atmospheres. In many cases stellar pulsations, radial or non-radial, significantly affect the extent, composition, and structure of stellar atmospheres. The SI will have a unique capability of direct imaging of pulsation effects including surface structures and shock fronts as they propagate through the dynamical atmospheres. Rather then using model dependent fitting of visibilities, the SI will extend the discovery potential of classical interferometry, by directly imaging the effects of the pulsation at several UV and optical lines where the pulsations effects on the atmosphere are predominant. For nearby giants and supergiants the SI will produce high-resolution movies of the evolving patterns of stellar pulsation with over 1000 pixels per snapshot, which is hundreds of times more detail then using the most advanced telescopes and interferometers of today. The multiwavelength movies of pulsation in a wide range of stars will provide key inputs to 3-D hydrodynamical models, including for radial pulsators such as Miras and Cepheids, as well as non-radial pulsators such as β Cephei stars, and many others.

Interacting Binary Systems as Astrophysical Laboratories

Almost all high-energy sources in the Universe are powered through the potential energy released via accretion. Understanding accretion driven flows in binaries will directly affect our understanding of similar flows around YSOs, including the formation of planets in the circumstellar disk as well as the much larger scale accretion flows in AGN. Compact, mass transferring binaries provide us with laboratories for testing energetic processes such as magnetically driven accretion and accretion geometries, various binary evolutionary scenarios, and conditions for induced stellar activity.

In close binary stars the flow of material from one component into the potential well of the other is a key in determining the future evolution of each component and the system itself, and particularly the production of degenerate companions and supernovae. Our cosmological standard candles, the Type Ia supernovae, for example, may be a consequence of accretion onto a white dwarf in a close binary. Currently, most of our accretion paradigms are based on time-resolved spectroscopic observations. However, a number of objects challenge our standard picture and there are significant gaps in our understanding of their formation and evolution. Large uncertainties exist in our quantitative understanding of accreting processes in many interacting systems. The interaction between the components in close binaries is believed to occur via Roche lobe overflow and/or wind accretion. 3-D hydrodynamic simulations show that the accretion processes in interacting systems are very complex. Wind accretion is even more complicated.

The key to further advances in accretion studies lies in resolving a wide range of interacting binaries and studying their component, mass flows, and accretion environments. The SI sub-mas UV resolution will lead to unprecedented opportunities for detailed studies of accretion phenomena in many interacting systems and their progenitors including symbiotics, Algol type binaries, Cataclysmic Variables (CVs), and microquasars. The SI will record dynamical views of the individual components, and the intercomponent and the circumbinary environments.

Extragalactic and 3-D Universe

Supernovae

With the exception of the relatively nearby SN1987A (in the LMC), it has not been possible to obtain much information about the close-in spatial structure of supernovae. Even in SN1987A the early expansion of the ejecta could not be resolved with the HST or from ground-based observations. With the SI, direct imaging of early stages of expansion would be possible of supernovae at a distance of a few Mpc. Images obtained in several UV and optical spectral lines would provide essential information on the nature of the explosion, especially in regard to its asymmetry, and of the early evolution of its structure with time.

Active Galactic Nuclei and Their Winds

Images of AGN could resolve the transition zone between the broad and narrow emission line regions and help resolve the origin and orientation of jets. Sub-milliarcsec resolution could enable study of broad and narrow-line emission regions at 0.5 milli-arcsec resolution (0.02pc at 10 Mpc). Images of the transition zone between broad-line and narrow-line regions would answer the question: "is material being stripped from the broad-line clouds, which are in close to the nucleus, and driven out to the narrow-line region?" It is best studied in the UV/optical emission lines within a fraction of a parsec of the nucleus. Such images could also provide an answer to the question whether type-1 Seyferts have molecular tori: broad-band imaging at sub-parsec scales could tell us if tori are obscuring starlight. AGN winds cause a substantial mass loss compared with what would be needed to power the AGN continuum itself and are important to understanding the dynamics of AGN. Because these winds enrich the surrounding intergalactic medium, they have larger implications for cosmology. For AGN in the Virgo Cluster or a little beyond (D=20Mpc), 0.1 pc corresponds to 1.0 mas. Hence the 'obscuring torus' scale is readily resolved and should yield telling images of the AGN wind. If the CIV remains point-like at this level, the more radical BELR-scale hypothesis will be greatly strengthened.

Distance Measurements with SI

Mapping the 3-D geometry of the Universe involves measurement of the large "cosmic" scale distances of high redshift sources such as distant supernovae and quasars. Cosmic distance scale determination methods include relative and absolute distance estimators. Relative distance estimators often involve assumptions and correlations, and have inevitable model dependencies. Such relative distance estimates of, e.g., the brightness of supernovae of type SN1a at z~1.5 as "standard candles", suggest that that the expansion of the Universe is currently accelerating. Absolute methods on the other hand have the advantage of having lesser dependence on physical models and provide an independent way to determine the distance scale. SI will provide a new avenue for determining distances to various astronomical sources including many nearby pulsating stars and high redshift supernovae and quasars.

One way for an absolute distance measurement on scales of the size of the observable Universe is to use the sub-milliarcsecond resolution of SI to measure the angular sizes of Broad Emission Line Regions (BELRs) of quasars at $z < 1$ in several UV lines including C IV (1550Å) and Mg II h&k (2800Å). The quasar broad emission lines (v~ 5000 – 10,000 km s^{-1}) respond to changes in the continuum source in the center by changing their intensity (~20% in the UV) with a time lag of a few days to years that is induced by the light travel time from the continuum source. For low-redshift quasars the size of the BELRs is ~10 light days, corresponding to an angular size of a fraction of a milliarcsecond, which can be measured by the Stellar Imager.

B. Relation to NASA and SMD Strategic Plans and Other Projects

Fitting naturally within the NASA long-term time line, SI complements defined and proposed missions (Terrestrial Planet Finder – I, Life Finder, and Planet Imager), and with them will show us entire other solar systems, from the central star to their orbiting planets. It moreover fits on the technology roadmap that leads from interferometers like Keck and SIM to TPF-I/Darwin, MAXIM/Black Hole Imager, Life Finder, and the Planet Imager.

Stellar Imager was included in the 2000 and 2003 SEC Roadmaps and is now identified as a "*Flagship and Landmark-Discovery Mission*" in the 2005 Sun Solar System Connection (SSSC) Roadmap. SI is also a candidate for a "*Pathways to Life Observatory*" in the Exploration of the Universe Division (EUD) Roadmap (May, 2005). SI will provide an angular resolution over 200x that of the Hubble Space Telescope (HST) and will resolve for the first time the surfaces of Sun-like stars and the details of many astrophysical objects and processes.

The Stellar Imager is a natural culmination of science addressed with ongoing ground-based observatories and a series of space missions (**Table 3**). These efforts will provide information on long-term disk-integrated variability, large-scale internal structure and evolutionary status, distances and other fundamental stellar properties, binary properties, and low-resolution surface imaging for a subset of target classes. SI complements and builds on observations made by ground-based interferometers, by asteroseismology missions, JWST, and other missions. It complements the planet-finding missions by providing a view of the space-weather environment of the planetary systems studied in those missions, and thus provides critical data needed to understand fully which of the detected planets are indeed habitable.

The Stellar Imager fits in the national science priorities, the NASA strategic plan, the Living With A Star initiative, and the technology roadmap:

- SI meets scientific priorities identified by the National Academy of Sciences Astronomy and Astrophysics Survey Committee (2001, Ref. 1). With SI we can "survey the Universe and its constituents," "use the Universe as a unique laboratory," "study the formation of stars and their planetary systems, and the birth and evolution of giant and terrestrial planets," and, by focusing on the driver of space weather in past, present, and future, "understand how the astronomical environment affects Earth."
- SI is responsive to a key national priority: imaging of magnetically active stars provides the only means to test any theory of solar magnetic activity as the driver of space weather and climate that can be achieved within a decade after launch.
- *SI fits in the NASA/SMD strategic plan: it complements the Living With A Star initiative, and shares much of the scientific and technological road that leads to other interferometers such as the Terrestrial Planet Finder, Planet Imager, and the MicroArcsecond X-ray Imaging Mission (Black Hole Imager).*

C. Uniqueness or Scientific Advantages of the Proposed Approach

Direct, interferometric imaging – the goal of the Stellar Imager - is the only way to obtain adequate information on the dynamo patterns for stars of Sun-like activity. Alternative methods that offer limited information on spatial patterns on more active stars fail for a Sun-like star:

- rotationally-induced Doppler shifts in such stars are too small compared to the line width to allow Zeeman-Doppler imaging
- the activity level is insufficient to lead to significant spectral changes associated with magnetic line splitting

– rotational modulation measurements are inherently subject to deconvolution limitations that leave substantial ambiguities in the latitude distributions, locations and sizes of spots, and cannot be used to understand the facular contributions in quiet regions that are governed by field dispersal and differential rotation.

The direct imaging by SI of stellar activity will sidestep these problems. Equally importantly, the asteroseismic observations planned with SI will determine the internal properties of stellar structure and rotation, thus directly providing crucial information relevant to the physical operation of the dynamo mechanism.

Fully addressing the science goals requires high angular resolution, on the order of a 100 μarcsecs or better in the mid-UV. This requires mirror diameters or baselines between sparse aperture or interferometric elements on the order of 500 meters. Although a large monolithic mirror might possibly be considered for a precursor mission (where the resolution requirements are ~25x lower and baselines of 20m could suffice), even there the costs and technical challenges are high. Problems with obtaining sufficient rigidity without excessive mass and near-perfect manufacturing are significant for true monoliths. Segmented mirrors require precise surface control and relatively high mass can still be a problem. Both suffer from difficulties with launch because of the likely high mass and size. And it is clear that at 500m, a monolithic mirror is not feasible in the desired timeframe.

It thus appears that some type of sparse aperture mirror system using large booms or distributed spacecraft is needed. A boom arrangement can perhaps suffice for 10 - 50 m baselines, though the control of boom dynamics becomes increasingly difficult with the longer booms, and even relatively short ones are extremely challenging, as has been seen in the development of the SIM mission. As we head out to baselines beyond 50m baselines, we are led to consider either tethered formations for a limited number of optical elements (currently under study for the 3-element SPECS mission concept) or true free-flyers (e.g., the LISA mission), but the dynamics and control issues are difficult and may in the end not turn out to be any easier for a tethered system than for a system of true free-flyers. In the case of SI where a large number of optical elements are required to enable relatively rapid integrations on a given target (to avoid smearing of images due to stellar rotation, proper motion, and intrinsic variations of the stars), tethers seem fraught with dangers and a free-flying architecture is optimal. A free-flyer design does present significant challenges, including high-precision metrology and formation control over scales of hundreds of meters, but it represents the optimal solution in terms of the configuration flexibility needed to meet the science requirements.

III. Architecture and Implementation Approach

The baseline full-mission concept for SI was developed in collaboration with the GSFC Integrated Mission Design Center (IMDC) and Instrument Synthesis and Analysis Lab (ISAL). The IMDC worked on the overall design of a space-based Fizeau interferometer, located in a Lissajous orbit around the sun-earth L2 point. A variety of disciplines considered the implications of this general design, including power, guidance & navigation, flight dynamics, operations, communications, quality assurance, system engineering, etc. The ISAL concentrated its efforts on the design of the beam-combining hub in the context of the selected overall architecture, again from a multiple-discipline viewpoint, and including accommodation of the IMDC results. In addition to assisting in the development of the architecture, the Design Centers explored the technical feasibility of the mission and identified the technology developments needed to enable the mission in the 2025 timeframe. The results of these IMDC and ISAL studies and of related work carried out throughout the course of the Vision Study by Team members are presented here in Section III, as well as in Section IV (Technology).

A. Space Systems Architecture

The current baseline architecture concept (**Fig. 5**) for the full Stellar Imager (SI) mission is a space-based, UV-Optical Fizeau Interferometer with 20-30 one-meter primary mirrors, mounted on formation-flying "mirrorsats" distributed over a parabolic virtual surface whose diameter can be varied from 100 m up to as much as 1000 m, depending on the angular size of the target to be observed. The individual mirrors are fabricated as ultra-smooth, UV-quality flats and are actuated to produce the extremely gentle curvature needed to focus light on the beam-combining hub that is located at the prime focus from 1 – 10 km distant. The focal length scales linearly with the diameter of the primary array: a 100 m diameter array corresponds to a focal length of 1 km and a 1000 m array with a focal length of 10 km. The typical configuration has a 500 m array diameter and 5 km focal length. A one-meter primary mirror size was chosen to ensure that the primary stellar activity targets can be well observed with good signal/noise. Sizes up to two meters may be considered in the future, depending on the breadth of science targets that SI is required to observe – e.g., some fainter extragalactic objects may need larger mirrors, but those will come at a cost to the packaging for launch, the number of launches needed, and total mission cost. The mirrorsats fly in formation with a beam-combining hub in a Lissajous orbit around the Sun-Earth L2 point. The satellites are controlled to mm-micron radial precision relative to the hub and the mirror surfaces to 5 nm radial precision, rather than using optical delay lines inside the hub for fine tuning the optical path lengths. A second hub is strongly recommended to provide critical-path redundancy and major observing efficiency enhancements. The observatory may also include a "reference craft" to perform metrology on the formation, depending on which metrology design option is chosen (see full report for more details). **Fig. 6** provides an overview of the selected architecture: the upper panel shows a cross-sectional schematic of the entire observatory, while the lower panel shows a close-up of the hub and its major components.

The full SI mission may be built up by starting with a small number of optical (array) elements, perhaps utilizing both interferometry and high-resolution spectroscopy. Added optical elements will increase image quality and time resolution. **Table 4** summarizes the primary science requirements and the design and instrument requirements that flowdown from those science requirements for the mission.

B. Science Instrumentation

In this section we describe the optical and detector systems inside the beam-combining hub. **Fig. 7** shows a detailed block diagram of the hub and the optics, detectors, and supporting instrumentation contained therein. Light from the source is reflected off the 30 mirrors in the primary array and relayed into the hub spacecraft. The hub spacecraft effectively controls metrology, pointing and wavefront control between each of the mirrorsats and between the mirrorsats and the hub, and ultimately constructs both the UV and visible light science imagery. The baseline hub consists of multiple subsystems which include: spacecraft bus, telescope tube assembly, internal optics, entrance baffle plate, metrology subsystem, wavefront control subsystem (visible light) and science focal planes (visible & UV light).

Broadband light initially enters the hub from the 30 primary mirrors through the entrance baffle plate. This plate contains 30 holes, one per optical beam and in the same pattern as the primary mirror array. Its purpose is to minimize the amount of background sky light from between the mirrorsats that enters the hub. If other (non-subset) patterns were to be used, the plates would need to be "active", i.e. in that the number and placement of apertures would need to be commandable. After passing through the plate the light travels the length of the hub tube (~5.3 meters) and is incident on 30 redirector flats, each of which is 10 mm in diameter and also arrayed in a scaled version of the Golomb array pattern. These flats move in piston, tip and tilt to facilitate pointing, metrology and wavefront control. After reflection off the flats the light comes to focus at the field stop mask and travels to an ellipsoidal secondary mirror (SM) mounted on tip/tilt control actuators. The SM relays the beams to the focal plane instruments.

The focal plane science instrument package consists of 3 cameras: (i) UV science camera, (ii) Visible science camera and (iii) wavefront sensing camera. The UV science camera is 5243 X 5243 pixels, with a Nyquist sampling at 1550 Å of $\lambda/2B$ (where B=max. baseline) of 32 μas and a full science field-of-view (FOV) of 168 mas. The visible science camera has 5243 X 5243 pixels, while the wavefront control camera has 10486 X 5243 pixels with Nyquist sampling at 5000 Å of 103 μas and a FOV of 541 mas. The larger format of the wavefront sensing camera enables the simultaneous recording of two "diversity" images of the source on the same detector. It also could be used for visible light science, as a "wider field camera" than the dedicated (higher resolution, smaller FOV) visible science camera. Each of the channels has two identical, redundant detectors to ensure long lifetimes. The two science channels have, in this baseline design, filters wheels in front of the detectors to produce the desired bandpasses for the observations. Alternative designs are envisioned which could replace this filter + standard detector set with either energy-resolving detectors, or with a more complex optical system that re-maps the 2D distribution of the beams into a 1D non-redundant array, whose light is then dispersed orthogonally at every point to produce more complete spectral information.

C. Infrastructure and Constraints at Launch

The design and implementation plan presented in this document for the SI does not require major improvements in infrastructure for a 2025 launch. Heavy lift vehicles in the Delta IV Heavy (or the future Atlas V heavy) are assumed available to launch the entire constellation in one or two launches – which are the most efficient ways to launch and deploy the observatory, though more numerous launches on smaller ELV's could be utilized if needed. Capabilities for supporting significant science and operations telecom data rates to/from Sun-Earth L2 are assumed (rough assumptions for SI data collection rates include 900 kbps daily average for 11 months/year and 5 Mbps average for 1 month/year). The most important capability not currently available would be the ability to reach and service facilities in Lissajous orbits around the L2 point. The long lifetime goal for SI suggests that it could benefit greatly from a human and/or robotic capability to refuel at a minimum and, optimally, service the various components of the mirrorsats and hub – and the design of all the spacecraft is envisioned as modular to enable servicing/exchange of the various important components.

D. Possible Roles of Humans or Robots

Although the SI baseline design does not require that humans and/or robots be able to access and work on SI at the Sun-Earth L2 site, the mission could benefit greatly from such a capability. In particular, the long lifetime requirement for SI (5-10 years or more) is most easily met if the design can be made modular so that humans and/or robots can readily service and replace key components of the mirrorsats and hub. An obvious and simple capability that would help enable SI would be the ability to refuel the spacecraft to ensure it will be able to perform station-keeping/orbit maintenance and target-to-target maneuvering over the desired long lifetime. Servicing of the critical hub spacecraft would also be of great utility, since it, unlike the mirrorsats, is a single-point failure, unless more than one hub is launched (or is available for launch-on-need). In-space servicing of the SI hubs or mirrorsats will require provisions for access, capture, and handling by the servicing system visiting vehicles and robots or EVA astronauts. Standard features and modular designs greatly reduce the mission risks, costs, and operations impacts associated with servicing compared and are utilized in the SI design.

E. Implementation Timeline

A rough timeline for the development process for the SI mission or an equivalent long-baseline, UV/Optical, space-based interferometer is outlined below:

2005:	Complete Vision Mission Study
2005-08:	Continue studies of multi-element fine optical control with the GSFC Fizeau Interferometer Testbed (FIT)
2005->:	Continue other technology development efforts, including precision formation flying, micro-Newton level thrusters, wavefront sensing and control, methodologies for integration and test of large distributed system, energy resolving UV-Optical detectors
2006:	Develop Pathfinder Concept suitable for future Probe/Discovery-type opportunities and work with other NASA (e.g., ST-9) and ESA projects (e.g., EMMA, SMART-2/LISA-PF) to collaboratively develop relevant technologies
~2015:	Fly pathfinder mission(s)
~2025:	Fly full mission

IV. Technology

A. Requirements

Many spacecraft engineering requirements exist which are a natural consequence of the defined science goals of the SI mission. The following represent the most significant design requirements and technology issues that have been identified for the mission:

- *Telescope pointing:* In order to center the disk of a star that is approximately 3 milliarcsec across, the spacecraft configuration needs to point to the center of the disk within a fraction of a pixel (< 40 μarcsec pointing) and the jitter associated with this pointing needs to be no more than 20 μarcsec to avoid possible smearing of the image
- *Formation flying:* The individual spacecraft must be controlled to the mm-to-micron-level to place the mirror surfaces within the capture range of the actuated mirror system
- *Hub focal plane / mirrorsat mirror position*: All mirrors must be kept in phase while in science mode. This requires the following control and knowledge:
    - Mirrorsat piston position (relative to virtual parabola) controlled to < 1 mm
    - Mirror piston position controlled to < 5 nm via closed-loop-controlled piezoelectric mounts
    - Lateral position knowledge to < 10 cm
    - Tip / tilt < 4 milliarcsec
- *Precision metrology over multi-km baselines*
    - 2nm if used alone for pathlength control (no wavefront sensing)
    - 0.5 microns if hand-off to wavefront sensing & control for nm-level positioning
    - multiple modes to cover wide dynamic range
- *Mission Lifetime:* The 5-10$^+$ year mission duration raisings several concerns in several

areas, including the power system (batteries), long term reliability of components, total propellant needs, and level of redundancy at the component and/or spacecraft level

- *Target exposure time:* Observations of targets must occur within 4 to 6 hours so that the star's rotation, intrinsic variations, and proper motion do not smear the image

In contrast to the major issues discussed above, the following are considered more moderate challenges that should be readily addressable, although requiring significant work and investment in the desired frame:

- *Spacecraft Pointing:* It is crucial to keep the mirrors and detector in the shade with a modest size sunshade. Therefore the spacecraft must point to within +/- 20 degrees of the perpendicular to the sunline; the solar arrays must have continuous full sun
- *Optics*: Lightweight, UV quality mirrors 1-2 meters in diameter
- *Launch Requirements:* The launch requirements can be handled with current technology. There are several options that exist for placing all of the component parts of SI in orbit about the Sun-Earth L2 point. If the selected design includes a single Hub and no Reference Craft (an optional metrology spacecraft), then the options are: 3 Delta III launches, 1 Atlas V launch, or 2 Delta (III/IV) launches. If a Reference Craft is included in the selected design, then the options are: a single Delta IV launch using a 5mx19.1m dual launch fairing (payload enclosure) or a dual launch using two Delta IV's, one with a 5mx14.3m fairing and one with a 4mx11.7m fairing. The single Delta IV launch is preferred for a design which includes a single Hub plus a Reference Craft. If two Hubs plus a Reference Craft are to be launched, then the dual Delta IV launches are needed.
- *Power Requirements:* Although power requirements can be handled by existing solar cells, they must, on the mirrorsats at least, be body-mounted to avoid unacceptable

impact on precision formation-flying and station-keeping. Battery life and storage are also a concern for a mission which is intended to last for perhaps a decade.

- *Propellant Requirements:* Propellant requirements at L2 are modest in the current design (requirements could go up if faster slews are needed): Field Emission Electric Propulsion (FEEP) thrusters should be capable in the 2025 timeframe of generating continuous, variable μ-Newton thrust for required 10 year lifetime on approximately 3.0 kg (per mirrorsat) and 643 kg (per hub) of solid fuel. The most recent IMDC study suggests using Hall Thrusters on the (larger, more massive) Hub spacecraft to obtain the higher thrusts needed to move its mass around (relative to the less massive mirrorsats) for the hub slews, and FEEP's for Hub fine thrust. The fuel estimates above include both FEEP and Hall Thrusters.
- *Operations Concept:* The operations concept is straightforward and assumes autonomous control of array station-keeping, reconfiguration, and slewing, with ground interaction only for command uploads and anomaly resolution.
- *Thermal Design:* The main concern of the thermal engineers is keeping the mirrors isothermal and protected from the Sun. A protective coating can be added to reduce the chance of damage in case of accidental sun exposure.
- *Communications Requirements:* Communications requirements are not excessive. In normal operations the mirrorsats talk to the hub and each other, and the hub talks to earth. In contingency operations: mirrorsats can be commanded directly from earth. A desired enhancement in this area would be a central communications hub at L2 for all missions flying in that locale.

The major enabling technologies derived from these requirements are summarized in **Table 5**.

B. Key Technology Risks and Uncertainties

Probably the tallest pole among all these technologies is the precision formation flying of as many as 33 distinct spacecraft: 30 mirrorsats, 1-2 beam-combining hubs, and possibly a reference spacecraft for metrology and aspect control. This is a complicated, multi-stage controls problem. However, similar control systems will be needed for many future missions (e.g. at some level, all missions composed of distributed spacecraft flying in a formation with tight constraints), so there is a great deal of motivation for such development. The biggest risk at the moment is the lack of a well-defined sequence of intermediate demonstration missions – with the cancellation of STARLIGHT, only SMART-3 and, possibly, ST9, are currently under consideration for flight prior to attempts at flying the large strategic missions like TPF-I, SI, LF, etc. We propose to develop an SI Pathfinder mission to both fill in this development "hole", as well as to prove other technologies such as UV beam-combination and pursue intermediate science goals as well – *but even more could and should be done.*

Precision metrology over the long baselines required in interferometric missions like SI needs further development. Efforts are underway at JPL and SAO, but there is no assurance they will be supported as long as needed and to the fine levels required in the current long-term plan.

Wavefront sensing and control, based on feedback from the science data stream, especially in the context of a very sparse aperture imaging system, needs continued long-term work. The Fizeau Interferometer Testbed (FIT) is exploring this technology now with 7 elements and has plans to expand to as many as 20 elements, but it is a small effort that needs to be expanded to fully develop the needed algorithms and control laws. And it needs eventually to be integrated with a formation flying testbed, such as the FFTB (GSFC) or the SPHERES (MIT) experiment to develop and prove the staged-control laws needed to cover the full dynamic range from km's to m's to cm's to nm's.

Finally, one of the most challenging technology needs for SI and all large, distributed spacecraft missions: how does one test and validate on the ground, prior to flight a system whose components are numerous (~30) and whose separations are order of 100's of meters to many kilometers? This is also a critical need for, e.g., Darwin, MAXIM (BHI), LF, and PI.

C. Development Roadmap, with Alternative Approaches

The successful design and construction of the SI will rely on the development and validation of a number of critical technologies highlighted in the preceding sections. These include, for example, precision formation flying, coarse ranging and array alignment, high-precision metrology, on-board autonomous computing and control systems, and closed-loop optical control to maintain array alignment based on the science data, along with a host of additional, somewhat easier challenges. A high-level technology roadmap for these items is given in **Table 6.**

Study of these technologies is ongoing at NASA/GSFC, JPL, SAO, various universities, and in industry, and significant leveraging and cross-fertilization will occur across projects, e.g. with JWST, Darwin/TPF, and LISA. A series of testbeds are in operation or are under development at GSFC, including the: Wavefront Control Testbed (WCT) to study image-based optical control methods for JWST, Phase Diverse Testbed (PDT) to study extended scene phase diversity optical control with moving array elements, Wide-Field Imaging Interferometry Testbed (WIIT) to study extending the field of Michelson imaging interferometers, and the Fizeau Interferometry Testbed (FIT) to study closed-loop control of an array of elements, as well as assess and refine technical requirements on hardware, control, and imaging algorithms. Studies of the full *SI* mission as well as Pathfinder concepts continue in GSFC's Integrated Design Center and Metrology Testbeds are under development at SAO (Ref. 2), JPL (Ref. 3), and GSFC (Ref. 4). We present in **Fig. 8** a graphical representation of flow of technology development and mission capabilities for space-based interferometric facilities, from ground-based testbeds and operational interferometers to space missions that will logically precede and follow SI.

One of the more interesting technology options that is being pursued is an investigation of how much of the measurement and control job (of the various spacecraft and mirror surfaces in the distributed system) can be done purely by "external" (to the science data stream) metrology using, for example, lasers and at what point, and if, it will be necessary to handoff the measurement and control job to a system based on feedback from analysis of the science data stream. Our "baseline" mission concept in fact assumes that the external metrology system has measurement and command authority down to the millimeter or, if possible, the micron level and that a "closed-loop" optical control system, based on phase diversity analysis of the science data stream, takes over at smaller scales to obtain control down to the nanometer level. The exact point at which that handoff occurs in the multi-stage control system is one of the interesting points still to be resolved. Our technology development plan is based on pushing both technologies to their limits, i.e., driving the external metrology to the smallest attainable scales (effectively testing in the process if we can do the "entire job" this way) and driving the development of the wavefront sensing & control to the largest possible scales, in the hope that the two systems will in the end have a significant region of overlap in their control authority.

D. Validation and Demonstration Approach

1. Ground-Based Validation

The main special challenges in deploying and operating a complex formation flying interferometer successfully are likely in two areas: formation control and beam control.

Testing and characterization of the SI formation control system will validate the performance of the system in its flight configuration and prove proper operation of the GNC (guidance, navigation, and control) system using the formation control sensor inputs. A RF formation control sensor simulator will be developed in the formation control/GNC Pre-Acceptance Test for use in later integrated system tests. It will be verified in a formation control/GNC Acceptance Test, an end-to-end test of the formation control and GNC controls and interfaces using the Hub and at least one Mirrorsat at a time. Following this early testing of the formation control system on S/C mockups, the flight formation control hardware will be integrated into the actual S/C. Testing of the formation control systems on the flight units will consist of an antenna characterization measurement and formation control RF simulator aliveness and functional tests.

For the beam control validation, we must produce a test set-up with a long effective optical pathlength. Doing the whole job inside a large test chamber such as is available at LM Sunnyvale, MSFC Huntsville, or Plum Brook near Cleveland is possible if we use a parallel-mirror multi-reflection pathlength extender. To do that with a modest size extender, the optical magnification should be at least a factor of 10, which will cause a considerable increase in the effects of mirror tip and tilt, and of beamwalk. The higher the magnification, the greater the decrease in beam quality from given levels of optical surface imperfections, alignment errors, and pointing instabilities. Thus, if we can make a high-magnification demonstration achieve required system performance levels in a test chamber, we can have considerable confidence in the actual performance of the real space system operating at more modest beam compression levels. Some chambers will be large enough to test a few Mirrorsats and the Hub simultaneously in a rather complex set-up, with a test source feeding all of these with highly parallel star simulator beams. Another possible test setup is to connect two vacuum chambers with a long evacuated tube, to give a long, straight optical path between two spacecraft.

A Metrology Acceptance Test will demonstrate acquisition and fringe tracking under the expected operating conditions and over the operating range of 50 to 1000 m, despite the effects of Gaussian beam propagation, attenuation, and pointing errors. A vacuum test will measure fringe intensity, as a probe of optical alignments and wavefront errors. The final subsystem test is an End-to-End Optical Acceptance Test to validate the optics and associated control systems. This layout uses the Hub's internal optics and the metrology system between S/C.

Integrated formation control, beam control, and interferometry tests will be performed after the flight formation control and optical systems are integrated. The control systems are tested in circumstances similar to flight operation, in that the tests parallel the dominant control moving from the guidance system to the metrology and interferometer. The Metrology Acceptance Test demonstrates that the beam control system autonomously acquires the metrology system fringe lock, given the positional information provided by the guidance system. Once metrology lock is acquired, the control system is ready to transition its dominant inputs from the guidance systems to the metrology and interferometer. At this stage, the system (or a representative part) is moved into a thermal vacuum chamber for the final integrated test. The End-to-End Performance Test verifies that the interferometer can acquire white light fringes given a locked metrology system, completing the transition of dominant control input from the formation control system to the interferometer. Our sequence of subsystem and integrated tests verifies each system at an early stage of integration. The formation control system is tested in advance of the interferometer and before final S/C completion. The interferometer tests verify autonomous acquisition and maintenance of optical beams across the broad range of separations expected. The integrated tests demonstrate appropriate hand-off points in the control system, culminating in a full end-to-end vacuum performance test.

2. Space-Based Validation via Pathfinder Mission(s)

Existing useful precursor missions are limited: TPF-I, if it flies, will be a nulling, cryogenic interferometer operating in the infrared; SIM does not use the free-flying formations that will be needed for truly long-baseline facilities, and it will operate only at longer (optical) wavelengths. Furthermore, the SIM will be used primarily as an astrometer, rather than as an imager. Formation flying issues may also be addressed by SMART3 and perhaps ST-9, though the content of these missions is still uncertain at this writing.

It would therefore be desirable to have a Pathfinder mission with modest baselines (~ 20-50 m), a small number of primary elements (~ 3-5), decent size mirrors (~1 m), and the ability to perform ultraviolet beam combination and produce images in ultraviolet light. The small number of spacecraft/mirrors in this pathfinder mission would require extensive array reconfigurations and therefore limit observations to targets whose variability does not preclude long integrations. However, such a mission would both test most of the technologies needed for the full mission, as well as be capable of producing a significant scientific return. A pathfinder with 20-50 m baselines could, for example, image the surfaces of the apparently larger stars, such as the red supergiant Betelgeuse and several long-period variables (e.g. Mira), as well as cataclysmic variables exhibiting mass-exchange between the components. The addition of high-resolution spectroscopy to such a mission could increase the science return even further at modest additional cost.

One such Pathfinder mission design is described in the full SI Vision Mission Report, but the derivation of an optimal SI Pathfinder design will be the next step (post Vision Mission Study) in our overall SI development process.

V. Deployment

A. Transportation to Operational Location

Several launch concepts were examined by the IMDC and ISAL at GSFC. The IMDC recommended consideration of two options, depending on whether one or two hubs were to be included in the initial deployment. Both options include a reference spacecraft for controlling pointing of the observatory without use of the target light, i.e. by using independent guide stars tracking by the reference spacecraft (mini-interferometer). These are shown in **Fig. 9.**

The ISAL launch scenario assumed the simpler case of a single Hub spacecraft plus 30 mirrorsats, but no reference spacecraft. In this design all fine tracking and guiding of SI is done based on target light detected within the Hub. A single launch suffices in this case.

SI will be transferred to a Sun-Earth L2 libration orbit using a direct transfer trajectory. This type of transfer can be designed using a formulation of invariant manifolds that describes all the possible trajectories from the Earth parking orbit to that of the mission orbit. Using a large Lissajous or halo orbit as the mission orbit will either minimize or eliminate the need for any large insertion maneuver. The parking orbit is a generic low Earth orbit with orbit parameters of 185-km in altitude, eccentricity near zero, and an orbit inclination near 28.5 degrees if launched from the Eastern Test Range at Cape Canaveral, Florida. The parking orbit is normally restricted to less than one orbit period due to battery and power constraints. This orbit permits both long and short coast durations before the insertion from the parking orbit onto the transfer trajectory. The insertion maneuver, performed by the upper stage of the launch vehicle, is on the order of

3.14 km/s and represents an energy of approximately $-0.7\ km^2/s^2$. This energy level is important in that it is used by the launch vehicle manufacture to determine the payload capacity into the transfer orbit. An estimate of the maximum payload mass for the launch vehicle can be found on the KSC launch vehicle web site.

After the insertion maneuver, the transfer trajectory enters a coast phase that takes approximately 120 days. During this coast phase, from approximately 12 hours after insertion onward, midcourse correction maneuvers will be performed to correct any insertion energy errors and misalignments in the insertion orbit parameters. These maneuvers are segmented to take out the majority of the insertion error and to target the mission orbit goals as un-modeled accelerations due to environmental perturbations and attitude re-orientation effects on the estimated area to mass ratio will need to be corrected. Some of these maneuvers may be designed to allow a multiple day launch window. Upon arrival at the mission orbit, an insertion maneuver will be performed to balance the energy, allowing the spacecraft to be placed on the reference libration orbit. The size and orientation of the mission orbit for SI is not critical, therefore the maneuver (Delta-V) budget can be minimized for the mission lifetime. During this coast phase, routine orbit determination (navigation) will begin. The orbit determination accuracy is dependent upon the number of and duration of the tracking passes. These tracking passes use S, K, or X Band Doppler and range measurements as input into the orbit determination process. Convergence to a solution will take days to weeks and is dependent on the position and velocity with respect to the ground station in the orbit. For example, a two-week tracking arc is typical for the mission orbit while only 12 hours are needed during the early coast phase when the velocity is directed radially away from the Earth.

B. Deployment

SI will be transferred to the mission orbit as one entity. Upon arrival and insertion into the mission orbit, a deployment of the components will begin. This is a critical event as not only are the components maneuvered into their proper location, but also collision avoidance must be performed. This means that the relative navigation system and individual propulsion systems must be operating. The relative drift of the components will be in predictable directions, as the components will follow their own orbits and drift in patterns that are determined by the natural dynamics of the Sun-Earth libration region.

VI. Operations

A. Space Segment

1. Normal Operations

After initial check-out and commissioning, Stellar Imager will be an autonomously controlled constellation using onboard software to maintain the optical configuration of the system. Commands to re-point the system to a new target and reestablish the optical configuration at the end-point of the maneuver will come from a stored command area onboard. The flight software will constantly monitor and ensure that various parameters onboard stay within defined limits. The frequency of re-pointing of the SI will vary greatly, between once per hour and once per month. The sequence of re-pointings and associated science instrument commands for each pointing will reside in stored command memory. SI flight software will check each sequence of commands for health and safety rules before executing them. At each pointing, the onboard systems will automatically acquire guide stars, verify attitude, acquire the science target, and initialize the observing sequence and the optical configurations required. Data will be stored in onboard Solid State Recorders (SSRs) for later transmission to the ground. The SI design will include autonomous capability for re-configuring the component spacecraft as necessary for individual science observations. A collision avoidance backup system will ensure that this capability operates successfully or interrupts attempts to make an unsafe maneuver and alerts the ground to the interruption.

The Hub will contain the communications equipment for space-ground contact and be designed for optimal lifetime by including various redundant features for all essential functions. Optimally, there would be two Hubs in operation. If one fails, this "critical path" component has an immediately available backup. In addition, the availability of two Hubs greatly increases the efficiency of the observatory – the second Hub can be pre-positioned while the first one is in use observing a target and the observatory can be re-pointing simply by tilting the primary array to align with the second Hub, without any large slews for the numerous (~ 30) mirrorsats. The SI design will include alternate communication capability for the unlikely event of a loss of primary Hub space-ground capabilities. SI will include onboard capability for recognizing failures in any given primary mirror unit and ability to avoid collision with the other units.

Stellar Imager will have a safing subsystem hosted on an internally redundant computer independent of the main operations computers. If the safing subsystem finds that critical events have been triggered as defined in its database, it will autonomously put the SI into a safe state and notify the ground operations center.

2. Formation and Science Target Acquisition

Due to SI's distributed architecture and exceedingly stringent control requirements, a multi-step process is required to acquire a science target. This sequence includes several handoffs from "coarse" sensors to "fine" sensors with more accuracy but limited dynamic range. Please see the full Vision Mission Report for the details of each step in this acquisition sequence: 1) Deployment, 2) Formation Acquisition, 3) Laser metrology acquisition, 4) Coarse spot acquisition, 5) Pointing Refinement [Note: steps 3-5 may overlap to reduce the acquisition time, e.g. some mirrorsats may perform coarse spot acquisition while others are still in laser metrology acquisition.] 6) Fine spot acquisition, 7) Refine pointing to target, 8) Fringe acquisition in Wavefront Sensor, and 9) Fringe acquisition in the Science Sensor (UV or optical).

B. Communications

Communications services through the Deep Space Network (DSN) will be used to update onboard command memory, allow daily transmission of science and engineering data from the SSR(s) to the ground, collect tracking and ranging data for use in calculating orbital elements of SI, and send any re-configuration commanding deemed necessary for maintaining and enhancing the SI system. On an occasional basis, the contents of onboard computer memories will be dumped to ground for analysis and occasionally new software and database content will be sent to onboard memories from the ground.

All communications uplinks to SI are planned assuming use of the DSN. Primary uplink communications to the Hubs will be at 2kbps using X band, with a 2kbps S band backup. The primary link will include automatic communications from the Hubs to each of the Mirrorsats using SI internal communications subsystem. Backup link to the Mirrorsats will be via S band at 2kbps from the ground.

All communication downlinks from SI are planned assuming use of the DSN. The nominal data rate from SI to the ground is about 125 Gb/day for ~11 months per year. This requires approximately one 30 minute Ka-band downlink per day. For ~1 month per year a data rate of about 250 Gb/day is expected, assuming a 2:1 lossless compression of the science data, which will require approximately one 60 minute Ka-band downlink per day. These figures include about 15% overhead for CCSDS (Consultative Committee for Space Data Systems) formatting.

Primary downlink of stored data from the Hubs will be at 75 Mbps on Ka band. SI will automatically send data from the Mirrorsats to the Hub(s) for storage. Real-time data downlink from the Hubs will be via X band at 10 kbps with a backup of 6 kbps on S band. Backup real-time telemetry from the Mirrorsats directly to the ground will be via S band at 3 kbps.

C. Ground Segment

The Stellar Imager Mission Operations Center (MOC) will be staffed by the Flight Operations Team (FOT). This FOT will operate the prime and backup control center systems to maintain normal operations. The control center system will automatically detect anomalous conditions, warn operators, and switch to backup systems if operators do not respond. The application software systems in the control center will be based on heritage software from the SI development and I&T phases, together with IP (internet protocol) communications software between the MOC and SI. IP/COTS (Commercial-Off-The-Shelf) applications developed for control centers will be mature by the time SI requires them. These products are assumed to provide data delivery assurance technology built-in. The command and telemetry databases used in the ground system will be inherited from the SI development and I&T phases. Normal operations will include routine generation of science observing schedules and associated command loads, and transmission of these command loads at scheduled uplink times. These schedules will be generated based on the science plan residing in the operations control center system, periodically transmitted or updated from the Science Operations Center (SOC).

The FOT will also schedule contacts for downloading data, command the SSR playbacks, and receive and confirm the data at the control center. They will use control center software systems to receive, analyze and confirm engineering data from all subsystems and verify health and safety of the subsystems. The FOT will be able to process real-time telemetry and in parallel process dumps from the SSR(s). The science data received will be forwarded (level 0) to the data distribution system for processing and distribution to the SOC, normally within 48 hours of collection onboard. On an occasional basis, when the science plan warrants it, science data latency can be reduced to 6 hours by FOT selective control of the SSR pointer. Level 0 data will have duplicates removed, and quality flags attached for all the data in a downlink in chronological order.

The ground system will include a data archive facility, with a shadow backup repository for restoration in the event of a catastrophic loss of data in the prime archive. The archive will store all science and engineering data from SI in raw and processed forms as well as all versions of the SI ground system databases and software, and calibration databases. The long term average accumulation rate for the archive is expected to be approximately 400 Gbits/day or about 145 Tbits/year. This data will be online for access via web connections for general research use once the initial proprietary data rights period has elapsed for each particular dataset.

The ground system will include a software suite for monitoring the optical performance of SI. This software will be inherited from the design and development phase of SI, but the operations version will be a more user-friendly version of the development software, to enable routine use by the FOT.

On an occasional basis, the FOT will send re-configuration commands to SI (e.g. orbit maintenance, flight software updates, etc.) and confirm successful completion of these activities. Tracking and ranging data for SI will routinely be sent to the Flight Dynamics Facility (FDF) at NASA/GSFC for routine analysis. The FDF will send orbit element reports to the MOC. These reports will be used to determine orbit maintenance activities and commands, and associated critical communications schedules.

The SI ground system will include simulators at appropriate locations. There will be a training simulator in or near the MOC for training of all operations personnel. There will be a high-fidelity simulator (including engineering model hardware and flight software) inherited from pre-launch design and test activities. Post-launch, this hi-fi simulator will be used to aid in maintenance of flight software and for trouble-shooting unexpected anomalies on SI.

Throughout the operational phase of SI, all the simulators will be available at short notice to aid in trouble-shooting and developing "fixes" to problems onboard as necessary. A flight software update capability and staff will be available as necessary.

VII. Operations Assurance

A. System Resilience

The SI design is resilient in two major ways.

The most important perhaps is that the observatory is robust against the failure of one or more individual mirrorsats. If the full complement of 30 mirrorsats is put into place during the initial launch and deployment, then science observations can continue even if individual mirrorsats are lost due to hardware or other failures. The number of elements in the array has been chosen to enable efficient synthesis imaging, i.e., 30 elements covers the necessary number and diversity of baselines to adequately sample the Fourier (u,v) plane with few or no reconfigurations of the primary array during the observation of a given target. Many of the targets can thus be observed in a "snapshot" mode – where the array is pointed at a target and all the necessary data are acquired with the array elements in same pattern for the entire time. A few, more complex, extended targets may require that the array be rotated or reconfigured once or twice to get the necessary sampling, but most will not. As mirrorsats fail, the baselines covered by the remaining elements will decrease and the quality of the imaging synthesis will degrade, unless the remaining operating elements are moved around (reconfigured into new patterns and/or rotated as a whole) to fill-in the missing Fourier frequencies. Thus the "snapshot" observing mode will not be available and the observations will require more and more movement of the mirrorsats to maintain image quality – and the length of observation at each target will increase until, eventually, the efficiency of the observatory becomes so low that the "nominal" observing program would have to be halted and replaced perhaps by a different one that monitored a small number of targets for extended periods of time. And targets would be restricted to those whose variability timescale was longer than the required observation times. Our basic science requirements for the primary "typical" science targets require that a stellar surface imaging observation be complete in a period of ~5 hours to avoid smearing of the images due to stellar rotation, proper motion, and intrinsic variability of the active regions. Once the observation time exceeds that, then prime science begins to be lost and the number of suitable targets begins to decrease. There is no "magic number" at which it becomes impossible to observe, but below 20 elements the impact is very significant – so the goal should be to maintain the number of elements in the 20-30 range for the duration of the mission.

The beam combining hub is obviously a single-point failure whose failure could lead to a loss of mission scenario. The design concept addresses this in two ways. First, the hub is designed to be highly redundant at the component level, at least for all parts with plausible and significant failure scenarios over the mission lifetime. The design for the most critical components is modular, thus enabling in-situ servicing by robotic or human means. Second, it is highly desirable from both a redundancy viewpoint and an operational efficiency viewpoint to actually launch and use in normal operations two identical hubs. With two hubs, one can be in motion while the other is being used for an observation, and thus "pre-positioned" for the next target. When observation of the first target is finished, then a small change in the orientation of the array to line-up with the pre-positioned second hub is all that is needed to get setup for observation of the next target. An extreme case that well-illustrates the utility of a second hub is one in which it is actually positioned on the "back" side of the primary array, at the same distance as the first hub is positioned on the "front" side of the array (i.e., one system focal length distant, typically about 5 km, though sometimes as close as 1 km, sometimes as far as 10 km). With this setup, the observatory could actually switch which "half" of the sky is being observed, simply by flipping over the mirrorsats in-place, thus accomplishing a repointing half-way around the sky in minutes instead of what otherwise would take hours if not days (normally re-targeting will only move 10 degrees or less on the sky from target to target to avoid excessive propellant and time usage). The availability of a second hub would thus immensely increase the efficiency of the observatory at the same time as providing insurance against catastrophic loss-of-mission due to a failure of a single hub. An alternative, of course, is to have available a second (or third) hub on the ground ready for a launch-on-need should a failure in the primary hub(s) occur. This can enable a recovery from a hub failure, but at the cost of some down-time while the backup hub is launched and deployed at L2.

B. Maintenance or servicing

The SI baseline design does not require servicing at the Sun-Earth L2 site to achieve the mission goals and objectives. Nevertheless, the overall mission reliability and operations lifetime could benefit greatly from servicing. Servicing can replace key components of the mirrorsats and hub and refuel the spacecraft for station-keeping/orbit maintenance and target-to-target maneuvering over the desired long lifetime. The level of modularity and serviceability of the numerous mirrorsats is something to be determined in a future study that would trade the ease and cost of producing extra mirrorsats to hold in reserve vs. the cost of making the minimum-set mirrorsats serviceable (or with redundant components). The critical hub spacecraft is a single-point failure, unless more than one hub is launched (or is available for launch-on-need). A future systems optimization study would also be needed to determine the appropriate level of modularity on the critical hub spacecraft, considering the comparative value of the hub as a whole, the critical parts, the modularity impacts, and the user cost of a servicer vehicle visit.

VIII. Safety

A. Launch and near-Earth operations

The SI launch(es) will quickly get beyond Low Earth Orbit (LEO). The usual range safety considerations apply prior to leaving near-Earth space. No radioactive power sources or calibration sources are onboard the spacecraft in the baseline design.

B. Planetary protection

The SI will be deployed into a Lissajous orbit around the Sun-Earth L2 point. There will be no non-Earth planetary encounters and thus no "planetary protection" issues.

C. End of mission safety issues

The individual spacecraft will eventually leave their unstable L2 halo orbits after loss of station keeping ability caused by depletion of on-board propellant. The individual spacecraft will drift off into separate solar orbits that do not intersect the Earth for many years. A statistical analysis of the departure orbit will need to be performed to provide a timeframe but a number on the order of several thousand years is plausible.

IX. Conclusion

The mission of the Stellar Imager is to *enable an understanding of solar/stellar magnetic activity and its impact on the*:

- origin and continued existence of life in the Universe
- structure and evolution of stars
- habitability of planets

and *to study magnetic processes and their roles in the origin and evolution of structure and the transport of matter throughout the Universe*. The SI Vision Mission Team has executed an ~1 year study to develop in detail the scientific goals and requirements of the mission, a baseline observatory architecture, the technology development needs of that and alternative architectures, a roadmap for that technology development, considered deployment and operations scenarios and addressed operations assurance and safety issues.

The study has shown that the scientific capabilities of such a ultra-high angular resolution UV/Optical interferometer are extraordinary, that credible design options are available, and that a sensible technology development path for supporting the development of the facility can be defined. SI fits well with the NASA and ESA strategic plans and complements other defined and conceptual missions, such as TPF, LF, and PI, and supports our collective desire as a species to understand extra-solar planetary systems and the habitability of surrounding planets, as well as improve our understanding of our own sun and its impact on earth's climate and it's future habitability.

Additional information on the Stellar Imager can be found at *http://hires.gsfc.nasa.gov/si/*

Acknowledgements

Additional contributions are gratefully acknowledged from the wide range of science and technology investigators and collaborators on the Stellar Imager Vision Mission Team, as shown

in the full Vision Mission Report.

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References

[1]National Academy of Sciences Astronomy and Astrophysics Survey Committee, 2001, "Astronomy and Astrophysics in the New Millennium", Space Studies Board, National Research Council.

[2]Phillips, J.D. and Reasenberg, R.D., 2005, "Tracking Frequency Laser Distance Gauge,", Review of Scientific Instruments, 76, 064501.

[3]Lay, O.P., Dubovitsky, S., Peters, R. D., Burger, J. P., Ahn, S.-W., Steier, W. H., Fetterman, H. R., Chang, Y. "MSTAR: a submicrometer absolute metrology system", 2003, Opt. Lett. 28, 890

[4]Camp, J., 2005, "Laser Metrology and Hexapod Control Testbed", private communication.

Tables

Table 1: The Stellar Imager Vision Mission Team

- **Development led by NASA/GSFC in collaboration with:**

Ball Aerospace & Technologies Corp.	Lockheed Martin Advanced Tech. Center
NASA's Jet Propulsion Laboratory	Naval Research Laboratory/NPOI
Northrop-Grumman Space Technology	Seabrook Engineering
Sigma Space Corporation	Smithsonian Astrophysical Observatory
Space Telescope Science Institute	State Univ. of New York/Stonybrook
Stanford University	University of Colorado at Boulder
University of Maryland	University of Texas/Arlington
European Space Agency	Kiepenheuer Institute
Potsdam Astronomical Institute	University of Aarhus

- **Institutional and topical leads from these institutions include:**

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- **Additional science and technical collaborators include:**

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- **International Collaborators include:**

  J. Christensen-Dalsgaard, F. Favata, K. Strassmeier, O. Von der Luehe

- **Student Participants include:**

  Linda Watson (undergrad-Univ. Florida/CfA), Darin Ragozzine (undergrad-Harvard, grad-CalTech), Mikhail Dhruv (high school), Fonda Day (undergrad/CU)

Table 2: Quick Facts: The Stellar Imager (SI) Vision Mission

Mission Overview		
SI is a UV-Optical, Space-Based Interferometer for 0.1 milli-arcsecond (mas) spectral imaging of stellar surfaces and stellar interiors (via asteroseismology) and of the Universe in general.		
Science Goals		
To understand: - Solar and Stellar Magnetic Activity and their impact on Space Weather, Planetary Climates, and Life - Magnetic Processes and their roles in the Origin and Evolution of Structure and in the Transport of Matter throughout the Universe		
Mission and Performance Parameters		
Parameter	**Value**	**Notes**
Maximum Baseline (B)	100 – 1000 m (500 m typical)	Outer array diameter
Effective Focal Length	1 – 10 km (5 km typical)	Scales linearly with B
Diameter of Mirrors	1 - 2 m (1 m currently)	Up to 30 mirrors total
λ-Coverage	UV: 1200 – 3200 Å Optical: 3200 – 5000 Å	Wavefront Sensing in optical only
Spectral Resolution	UV: 10 Å (emission lines) UV/Opt: 100 Å (continuum)	
Operational Orbit	Sun-Earth L2 Lissajous, 180 d	200,000x800,000 km
Operational Lifetime	5 yrs (req.) – 10 yrs (goal)	
Accessible Sky	Sun angle: $70° \leq \beta \leq 110°$	Entire sky in 180 d
Hub Dry Mass	1455 kg	For each of 2
Mirrorsat Dry Mass	65 kg (BATC) - 120 kg (IMDC)	For each of 30
Ref. Platform Mass	200 kg	
Total Propellant Mass	750 kg	For operational phase
Angular Resolution	50 μas – 208 μas (@1200–5000Å)	Scales linearly ~ λ/B
Typical total time to image stellar surface	< 5 hours for solar type < 1 day for supergiant	
Imaging time resolution	10 – 30 min (10 min typical)	Surface imaging
Seismology time res.	1 min cadence	Internal structure
# res. pixels on star	~1000 total over disk	Solar type at 4 pc
Minimum FOV	> 4 mas	
Minimum flux detectable at 1550 Å	5.0×10^{-14} ergs/cm^2/s integrated over C IV lines	10 Å bandpass
Precision Formation Fly.	s/c control to mm-cm level	
Optical Surfaces Control	Actuated mirrors to μm-nm level	
Phase Corrections	to λ/10 Optical Path Difference	
Aspect Control/Correct.	3 μas for up to 1000 sec	Line of sight mainten.

Table 3: The Stellar Imager is part of an array of missions addressing magnetic activity.

Project	Role in activity studies	Observational Technique and/or Technology
Stellar Imager	Dynamo patterns, (internal) dif. rotation binary interaction	UV/Optical interferometry <0.1 mas (milli-arcsecs)
MAXIM	Coronal structure	X-ray interferometry
Terrestrial Planet Finder	Binary properties	SI Technology precursor, IR, free -flying, nulling interferometer, 0.75 mas
Space Interferometry Mission	Binary properties	SI Technology precursor, boom interferometer
James Webb Space Telescope	Stellar mass loss, giant chromospheres	IR imaging, 100 mas
Ground-based interferometry: Keck, Large Binocular Telescope, Very Large Telescope Interferometer	Giant-star imaging, binary properties	Technology precursors
GAIA	Determination of stellar properties	High -precision parallaxes
MOST, COROT, KEPLER	Internal stellar structure	Asteroseismology
Ground-based spectroscopy	Activity monitoring, limited imaging	Automatic telescopes,(Zeeman) Doppler imaging

Table 4: Overview of the SI science, design, and instrument requirements

Science requirement	Design requirement	Instrument requirement
Allow imaging in UV and optical of astrophysically interesting targets with 0.1 mas (milli-arcsec) resolution.	Optical system to be optimized for observing from 1200 Å to at least 5000 Å, in multiple UV pass bands of 2-10 Å width.	Variable effective aperture or interferometer baselines from 100 - 1000 m.
Enable imaging of stars and extended complex sources such as star- and planet-forming regions, accretion disks and jet-forming regions, interacting binaries, super massive black hole environments, etc.	Image frequency components to be high enough for complex sources, and point spread function with well-defined core regions.	20-30 apertures in non-redundant pattern to provide sufficient Fourier (u,v) coverage for ultimate image reconstruction
Image the chromospheric or transition-region emission of a star like the Sun with sufficient resolution to locate large active regions and to map the large-scale surface field.	UV/optical imaging to yield ~700 resolution elements on the disk, or 30 across its equator, for a Sun-like star at 4 pc, equivalent to a *resolution of ~0.1 milli-arcseconds.*	Effective aperture or interferometer baselines of at least 500 m.
Time to complete one full image should be short enough that rotational smearing does not compromise the required resolution of stellar images.	Image integration time to be less than $P/30\pi$ for a stellar rotation period P (e.g., 6 h for a Sun-like star, or 2.5 h for a star with $P = 10$ d.)	Individual primary mirrors at least 1 m in diameter; # of interferometer elements ~30, unless fast reconfiguration
Observe at least 25 magnetically-active (cool) single and binary stars over five years, each at least twice per year, to study field pattern evolution and properties of cycles.	Baseline mission to exceed 5 yr; baseline target list to include at least 25 core program stars.	Slew speeds > 10 deg/hour and accessible band on the sky (solar beta angle from 70 to 110 degrees)
Observe at least 25 cool single and binary stars with 30 images within a rotation period, each at least once per year, to measure the field source properties, differential rotation, and other large-scale flows.	Re-targeting must be completed within 2-3 h to enable observing of at least 3 Sun-like targets within a 24 h period. SI pointing to allow imaging of stars for at least 30 days continuously.	Design to allow imaging at least in a 20-30°range centered 90°from the Sun-SI direction
Enable astero-seismology in near-UV or optical to measure internal differential rotation and effects of magnetic fields on internal stellar structure.	Asteroseismological resolution of 30 elements on stellar disks, at a cadence of 1 min. for at least a stellar rotation, at a duty cycle of better than ~90%, in up to three visible passbands of up to 100 Å wide.	Effective aperture to collect 10^{12} photons/band per star per rotation period. Instantaneous number of independent baselines to exceed ~60, and thus # of optical elements to exceed ~8.

Table 5: The major enabling technologies needed for Stellar Imager

- ***formation-flying of ~30 spacecraft***
  - *deployment and initial positioning of elements in large formations*
  - *real-time correction and control of formation elements*
    - *staged-control system (km → cm → nm)*
  - *aspect sensing and control to 10's of micro-arcsec*
  - *positioning mirror surfaces to 5 nm*
  - *variable, non-condensing, continuous micro-Newton thrusters*

- ***precision metrology over multi-km baselines***
  - *2nm if used alone for pathlength control (no wavefront sensing)*
  - *0.5 microns if hand-off to wavefront sensing & control for nm-level positioning*
  - *multiple modes to cover wide dynamic range*

- ***wavefront sensing and real-time, autonomous analysis***
- ***methodologies for ground-based validation of distributed systems***
- ***additional challenges (perceived as "easier" than the above)***
  - *mass-production of "mirrorsat" spacecraft: cost-effective, high-volume fabrication, integration, & test*
  - *long mission lifetime requirement*
  - *light-weight UV quality mirrors with km-long radii of curvature (likely through active deformation of flats)*
  - *larger format (6 K x 6 K) energy resolving detectors with finer energy resolution (R=100)*

Table 6: Technology Roadmap for the Stellar Imager

Technology Needed by SI	Development Plan and/or Candidate Technologies	Readiness Date
Wavefront Sensing and Control	Phase Diverse Testbed (PDT), Fizeau Interferometry Testbed (FIT), Wavefront Control Testbed (WCT)	2004 2007 2007
Closed-loop optical path control	Phase Diverse Testbed (PDT), Fizeau Interferometry Testbed (FIT)	2004 2006
Mass-production of spacecraft (SI "mirrorsats")	TBD (but see BATC approach in section 3.18 of full SI Vision Mission Report)	2007?
Lightweight, UV-quality mirrors with km-long radii of curvature	Chen (2002), etc.	2007
Large format energy-resolving UV detectors with resolution >100	TBD – but driven by many missions	2008?
Methodologies for combining 20-30 simultaneous beams	Ground-based interferometers, FIT	2006?
Variable, non-condensing micro-newton thrusters	Field Emission Electric Propulsion units (FEEP's), etc.	2007?
Precision Formation Flying	GSFC Distributed Space Systems Roadmap (Figure 3.20 in full SI Vision Mission Report)	2009 SI PF, 2013 full-SI
Aspect Control to 10's of micro-arcsecs	Trade external metrology vs. wavefront sen.	2013
Precision Metrology over long baselines	JPL & SAO metrology labs	2010
Methodologies/control processes for deployment and initial positioning of elements in large formations	GSFC Distributed Space Systems Roadmap (Figure 3.20 in full Report)	2013

Captions to Figures

Fig. 1: Records of the relative Ca II H+K fluxes of main-sequence stars: x, Wilson's records (1966–1977); triangles and dots, Ca II HK survey (1977–1992); open circles 30-day averages. The top of each panel shows the stellar identification, color index B–V, and a classification of the long-term variability or period(s) in case of cyclic activity (figure from Baliunas et al., 1995).

Fig. 2: Short term variations in Solar activity and their impact on Earth.

Fig. 3: Simulations of some of SI's capabilities for UV imaging, assuming 30 mirror elements in a non-redundant pattern.

Fig. 4: Minimum time interval between successive SI images required to resolve the motion of a feature moving at different speeds (line labels) as a function of the object's distance.

Fig. 5: an artist's concept of the baseline SI design, a Fizeau Interferometer with 20-30 one-meter primary mirrors, which are mounted on formation-flying "mirrorsats" distributed over a parabolic virtual surface whose diameter can be varied from 100 m up to as much as 1000 m, depending on the angular size of the target to be observed. The individual mirrors are fabricated as ultra-smooth, UV-quality flats and are actuated to produce the extremely gentle curvature needed to focus light on the beam-combining hub that is located from 1 – 10 km distant. The focal length scales linearly with the diameter of the primary array: a 100 m diameter array corresponds to a focal length of 1 km and a 1000 m array with a focal length of 10 km.

Fig. 6: An overview of the Baseline SI Design derived during the Vision Mission Study.

Fig. 7: A detailed look at the hub design, showing optics, detectors, metrology components, and support systems.

Fig. 8: A Roadmap for the development of Space Interferometry.

Fig. 9: Two launch options for SI, a single Delta IV heavy vs. two Delta IV launches.

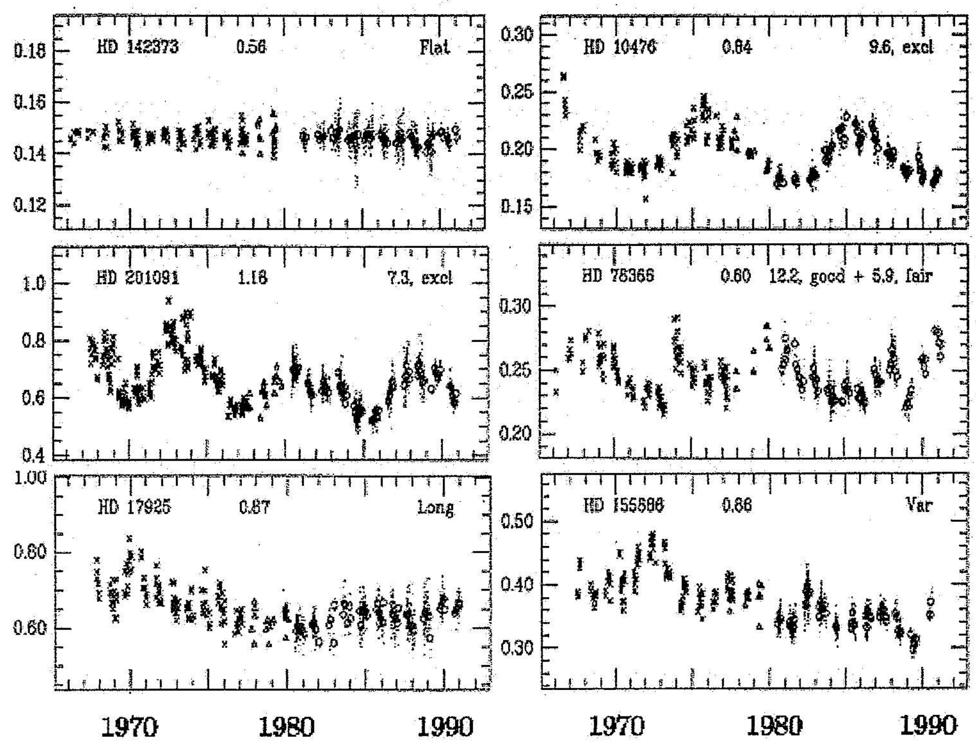
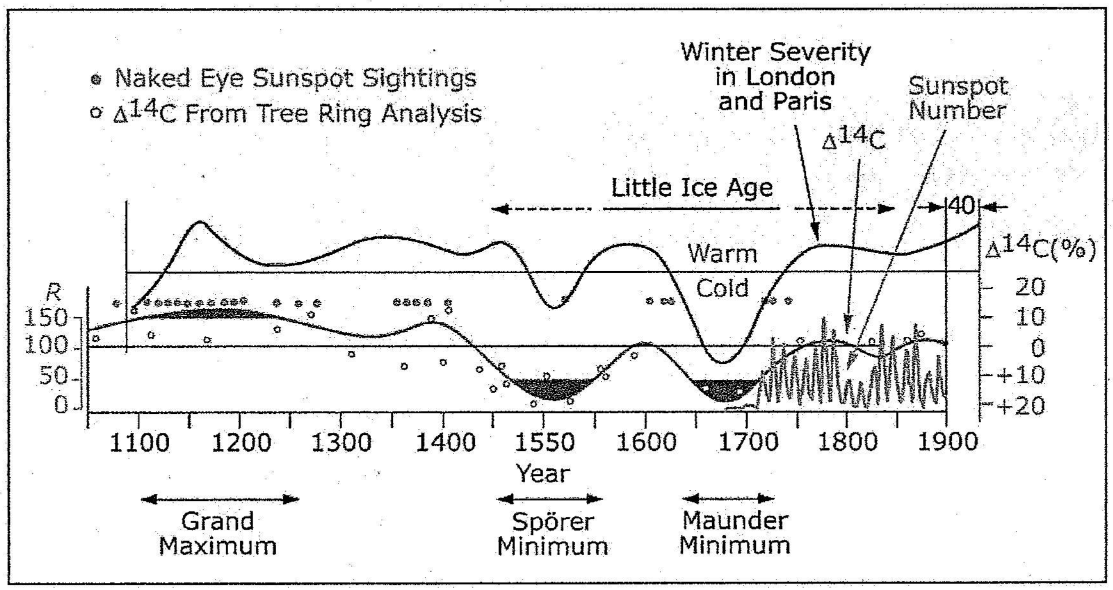
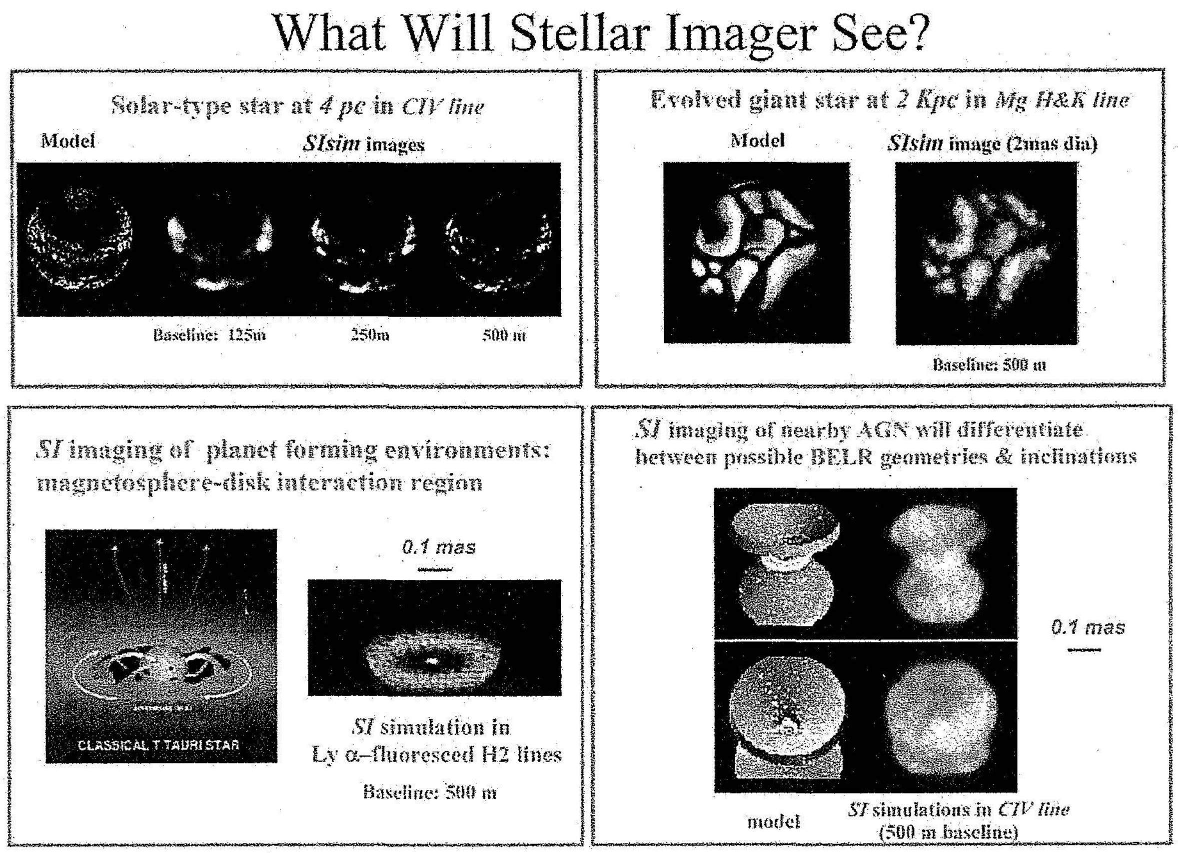

HD 142373
0.56
Flat
HD 10476
0.84
9.6, excl
HD 201091
1.18
7.3, excl
HD 78366
0.60
12.2, good + 5.9, fair
HD 17925
0.87
Long
HD 155886
0.86
Var
1970
1980
1990
1970
1980
1990

Fig. 1



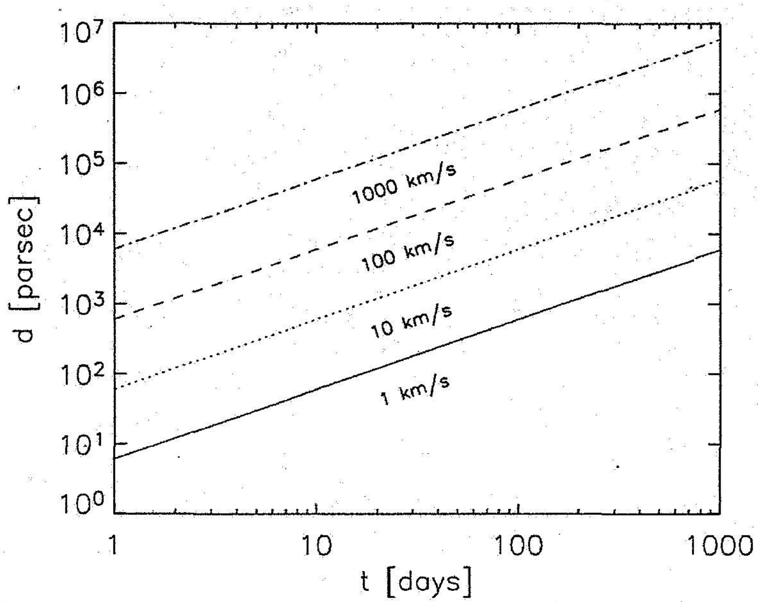
Naked Eye Sunspot Sightings
Δ14C From Tree Ring Analysis
Winter Severity in London and Paris
Sunspot Number
Δ14C
Little Ice Age
40
Δ14C(%)
Warm
Cold
R
150
100
50
0
20
10
0
+10
+20
1100
1200
1300
1400
1550
1600
1700
1800
1900
Year
Grand Maximum
Spörer Minimum
Maunder Minimum

Fig. 2



What Will Stellar Imager See?
Solar-type star at 4 pc in CIV line
Model
SIsim images
Baseline: 125m
250m
500 m
Evolved giant star at 2 Kpc in Mg H&K line
Model
SIsim image (2mas dia)
Baseline: 500 m
SI imaging of planet forming environments:
magnetosphere-disk interaction region
CLASSICAL T TAURI STAR
0.1 mas
SI simulation in
Ly α–fluoresced H2 lines
Baseline: 500 m
SI imaging of nearby AGN will differentiate
between possible BELR geometries & inclinations
0.1 mas
model
SI simulations in CIV line
(500 m baseline)

Fig. 3



10⁷
10⁶
10⁵
10⁴
10³
10²
10¹
10⁰
d [parsec]
1000 km/s
100 km/s
10 km/s
1 km/s
1
10
100
1000
t [days]

Fig. 4

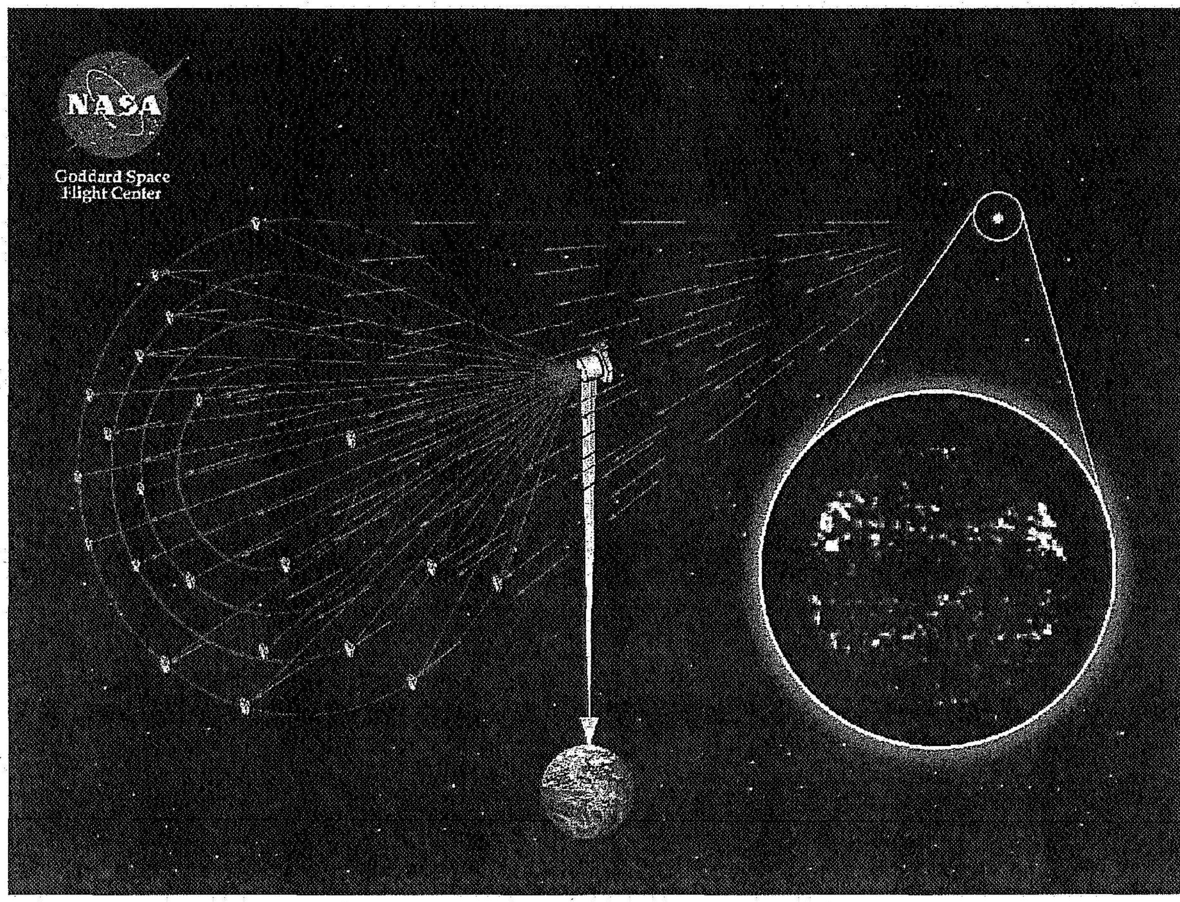
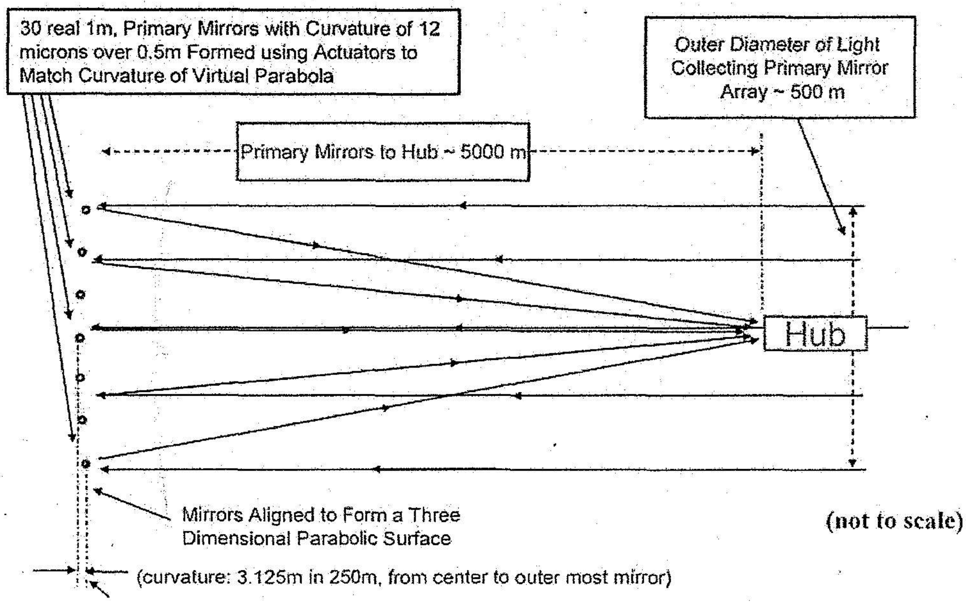


Fig. 5

SI Cross-Sectional Schematic



Principal Elements of SI Hub

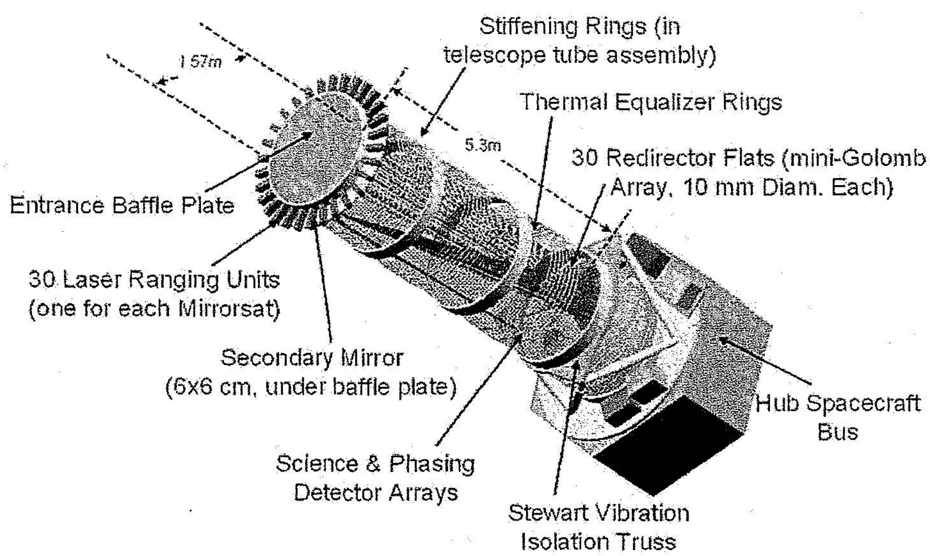


Fig. 6

Hub Block Diagram

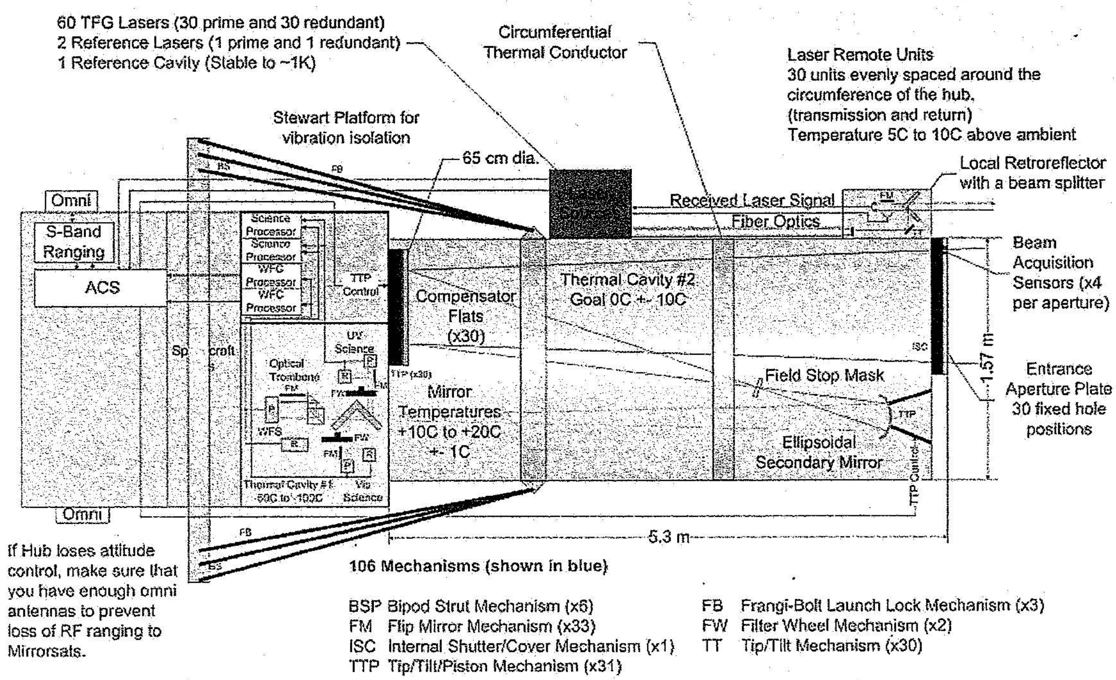


Fig. 7

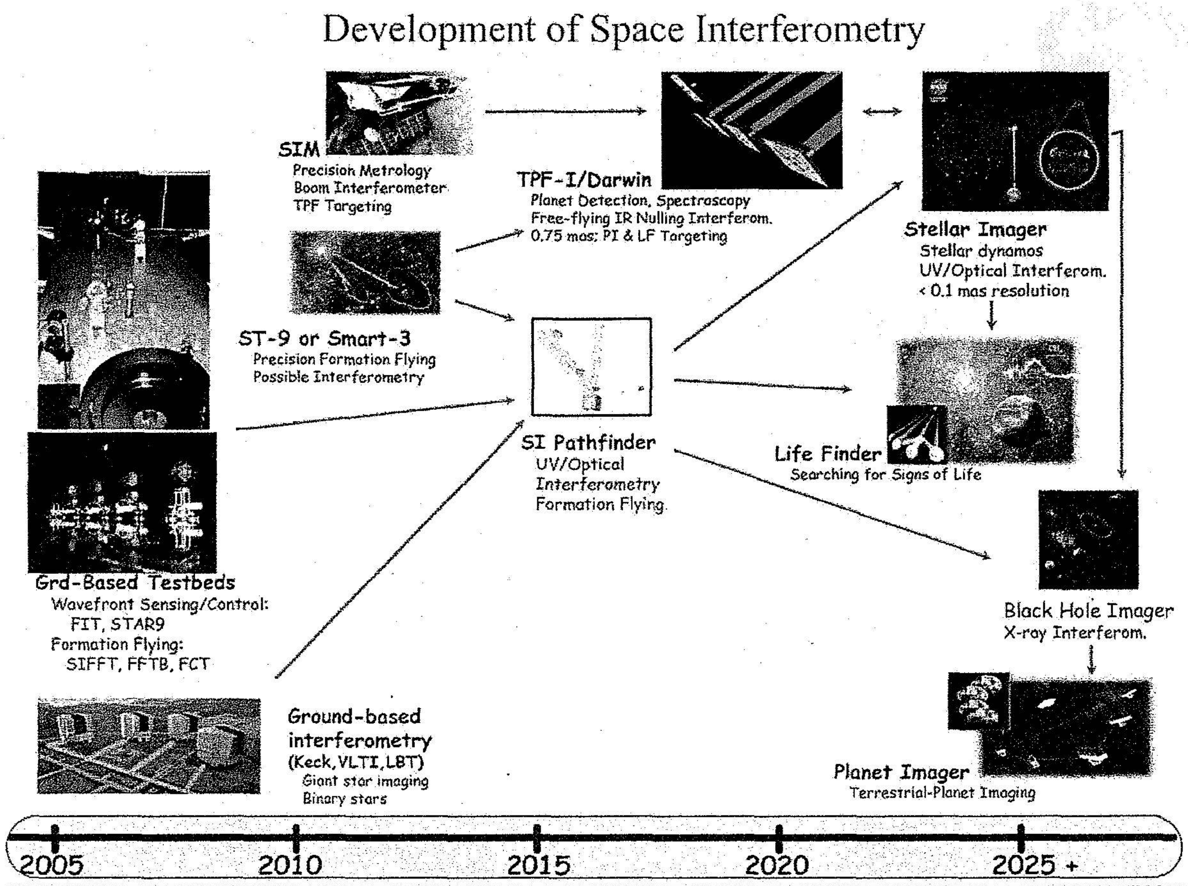

Development of Space Interferometry
SIM
Precision Metrology
Boom Interferometer
TPF Targeting
TPF-I/Darwin
Planet Detection, Spectroscopy
Free-flying IR Nulling Interferom.
0.75 mas; PI & LF Targeting
Stellar Imager
Stellar dynamos
UV/Optical Interferom.
< 0.1 mas resolution
ST-9 or Smart-3
Precision Formation Flying
Possible Interferometry
SI Pathfinder
UV/Optical
Interferometry
Formation Flying
Life Finder
Searching for Signs of Life
Grd-Based Testbeds
Wavefront Sensing/Control:
FIT, STAR9
Formation Flying:
SIFFT, FFTB, FCT
Black Hole Imager
X-ray Interferom.
Ground-based
interferometry
(Keck, VLTI, LBT)
Giant star imaging
Binary stars
Planet Imager
Terrestrial-Planet Imaging
2005
2010
2015
2020
2025 +

Fig. 8

Launch Configuration
Dual vs. Single Launch

Integrated Mission Design Center

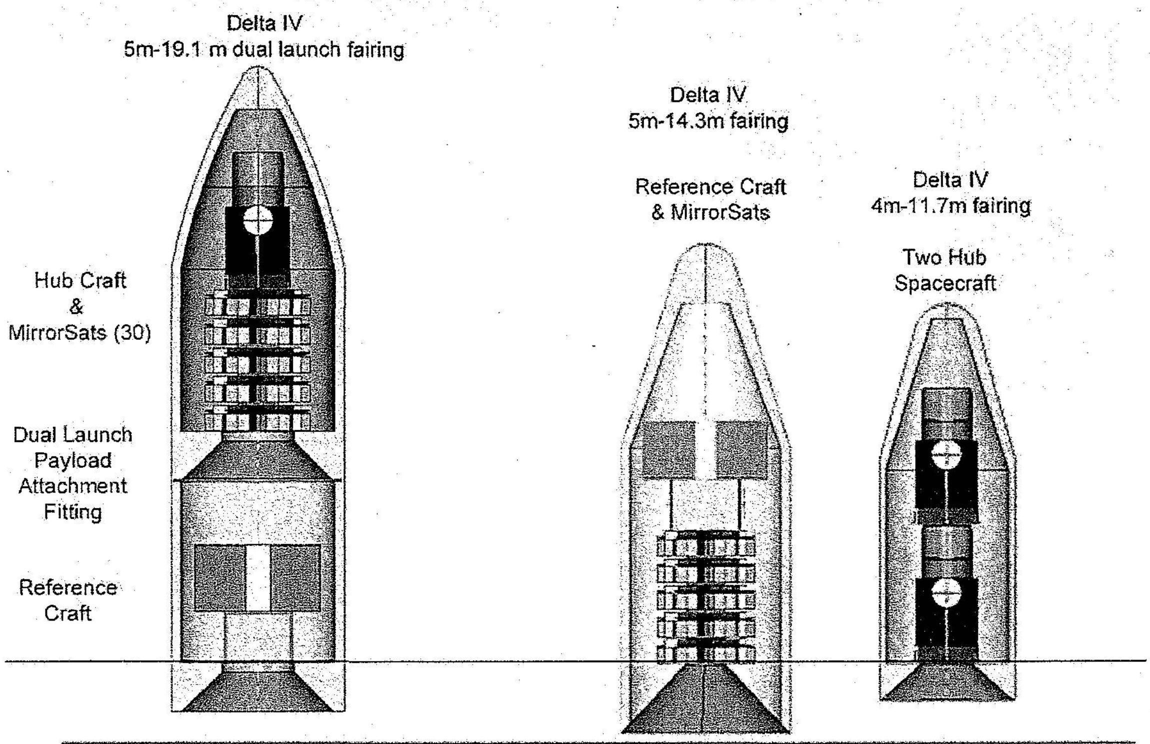


Fig. 9