An Astrophysics Strategic Mission Concept Study

Dilute Aperture Visible Nulling Coronagraph Imager (DAViNCI)

Imaging and Spectroscopy of Exo-planets from Nearby Stars

Principal Investigator: Michael Shao, 818-354-7834 (mshao@jpl.nasa.gov)
Jet Propulsion Laboratory, California Institute of Technology

Contributors: Elizabeth Deems[1], Leigh Fletcher[1], B. Martin Levine[1], Glenn Orton[1], Gautam Vasisht[1], Leonard Wayne[1], Feng Zhao[1], Mark Clampin[2], Richard G. Lyon,[2] Olivier Guyon[3], Benjamin F. Lane[4], Keith Havey[5], Rocco Samuele[6], Gopal Vasudevan[7], Robert A. Woodruff[8], Volker Tolls[9], Fabien Malbet[10], Alain Leger[11]

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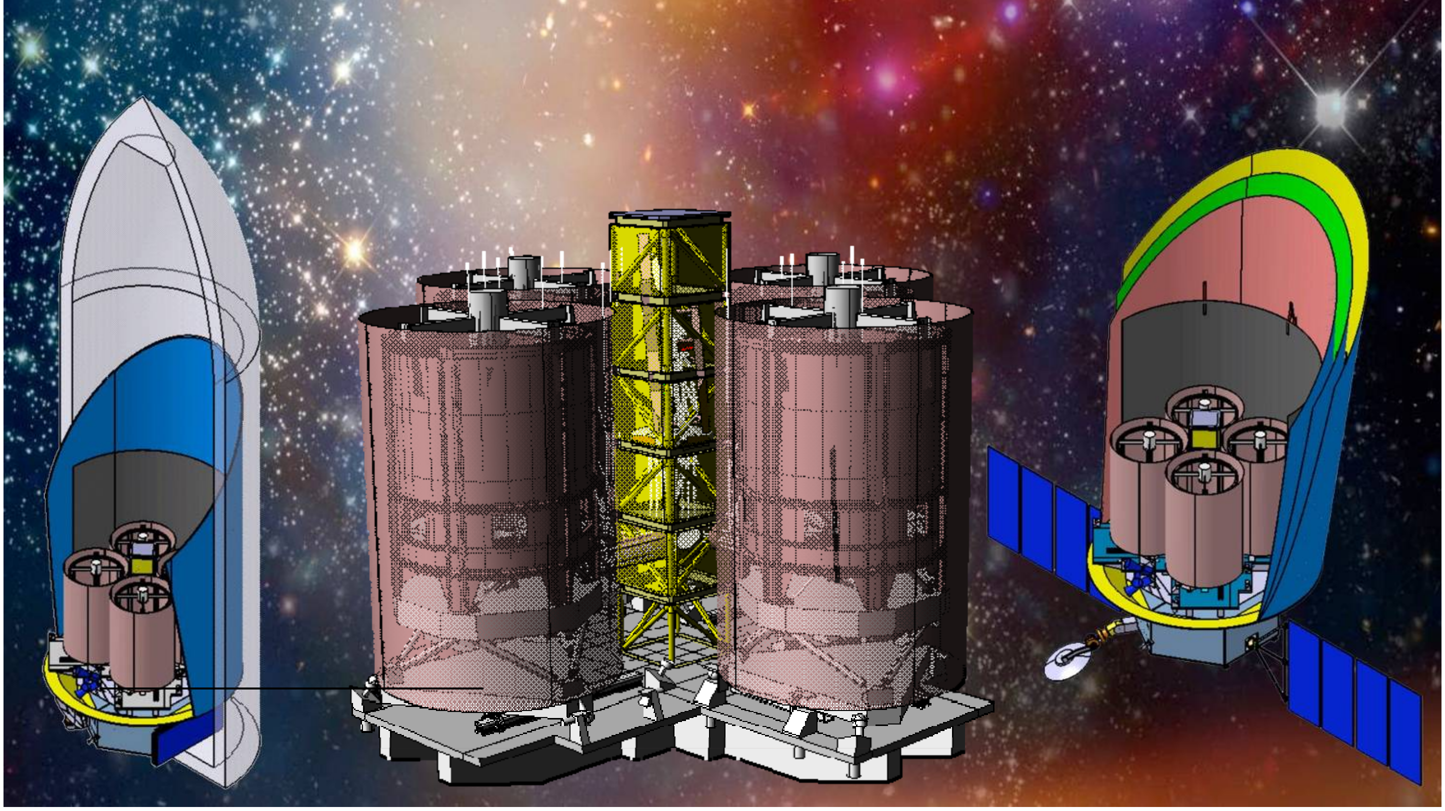

[1] Jet Propulsion Laboratory, California Institute of Technology
[2] NASA/Goddard Spaceflight Center, Greenbelt, MD
[3] University of Arizona / Subaru Telescope
[4] C.S. Draper Laboratory, Cambridge, MA 02139
[5] ITT Space Systems, LLC, Rochester, NY 14606
[6] Northrop Grumman Aerospace Systems, Redondo Beach, CA 90278
[7] Lockheed Martin Space Systems Co., Advanced Tech. Center, Palo Alto, CA 94304
[8] Lockheed Martin Space Systems Co., Louisville, CO 80027
[9] Smithsonian Astrophysical Observatory, Cambridge, MA 02138
[10] University of Grenoble, France
[11] Institut d’Astrophysique Spatial (CNRS), Universite Paris-Sud, Orsay, France

EXECUTIVE SUMMARY

The field of exoplanet astronomy is experiencing an exponential growth phase with ground based techniques finding 350 planets outside our solar system. Space missions like Kepler have just been launched to look for terrestrial planets. In the late 1990's, the radial velocity (RV) technique could detect Jovian planets in close orbits. Transit observations of exoplanets have also made tremendous progress, but RV has improved dramatically since 1995 and has now detected a number of "super earths" in several day orbits. While RV measures the orbital period and hence orbital semi-major axis, transit detections (when the planet goes in front of the star) of exoplanets measure their size. With sufficiently precise photometry the secondary transit (when the planet goes in front of the star) measures the spectra of the planet. The combination of transit and RV measurements lets us characterize virtually all of the important physical parameters of the exoplanet, potentially down to Neptune mass. Ground based extreme AO coronagraphs under construction for 8-10m telescopes will be able to detect self luminous Jovian mass planets, and perhaps have sufficient contrast for a few Jovian planets in reflected light.

The next major step, and the ultimate goal of exoplanet research, is the discovery and characterization of Earthlike planets in the habitable zone (HZ) of nearby stars. For this we need to go to space. The Kepler mission will measure the frequency of terrestrial sized planets around solar-like stars, but these planets are too distant for either astrometric or direct detection follow up observations. An astrometric mission, such as SIM, will find Earth like planets in the HZ of nearby stars and measure their mass and orbit for follow on observations, such as by the Terrestrial Planet Finder (TPF), a direct detection telescope-coronagraph/interferometer that separates the light of the planet from the star and measures the planetary spectra. A common characteristic of exo-Earth astronomy is that it must be done from space and each step, from Kepler to SIM to TPF-C/I is several times more expensive than the last step. A prohibitively high cost could stop the exponential expansion of the field.

The DAViNCI concept was one of the concepts studies funded in2008 by NASA in its call for future science missions. It is unique in its ability to search over 100 candidate stars for Earth clones and measure the planet spectra at a cost that is dramatically less expensive than competing approaches. DAViNCI is a multiple telescope interferometer composed of four 1.1m telescopes on a two position baseline that uses a nulling interferometer/coronagraph to achieve an inner working angle of ~40 milliarcsec (mas) at its longest baseline. With collecting area roughly equal to the Hubble telescope, it will detect an Earth-Sun at 10 parsecs in approximately 10 hours of integration. DAViNCI has an inner working angle equal to a filled aperture 8m coronagraph (IWA~2 λ/D) and an exoplanet science capability of a ~7m coronagraph. With a wavelength range from 550-1700nm, it will measure spectra at R~80 and SNR=10 on a number of critical biomarkers.

DAViNCI is a nominal 5-year mission to be launched on an Atlas V 521 in an earth-trailing orbit, with its payload fitting within a 5m fairing. The mission cost estimated by JPL TEAM-X is $1.2B. Costs have been moderated through the maximum use of existing commercial technology, namely, ITT Space Systems LLC NextView telescope, Northrop-Grumman thermal control systems and spacecraft, and SIM laser metrology. DAViNCI's other major partnership includes Lockheed-Martin for instrument design and construction. Technology will be developed to demonstrate the high contrast imaging needed for imaging Earthlike planets, which is 10^{-10} contrast over a 1as field of view. Future technology development will produce components such as 1000 element segmented deformable mirrors and 1000 subaperture single mode fiber arrays. These will be integrated into existing test beds for the final technology demonstrations.

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1 Introduction and Background

The field of Exoplanet research is poised to make major advances in the upcoming decade. Nearly 350 exoplanets have been discovered. Planets as small as 5 earth mass have been found. Astronomers have measured the diameter of planets when they traverse their parent star. The IR spectra of Hot Jupiters have been measured when those planets have gone behind the parent star in a secondary transit. The next major advance is the discovery and characterization of Earthlike planets in the habitable zone.

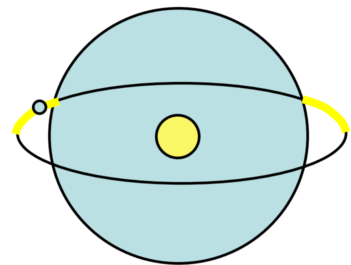

Figure 1: Observable IWA and planet orbit

The end of the first decade of the 21st century is also marked by the biggest economic crisis since the great depression. While the field of exoplanet research is poised to make great advances, none of these advances will happen if we don't find significantly less expensive approaches to obtaining the needed scientific data. The DAViNCI mission is an approach for detecting the light from exo-Earths and measuring its spectra at a cost that is a small fraction of competing techniques, including coronagraphs that can work at 2λ/D and also external occulters.

1.1 Inner working angle: the key to finding Exo-Earths

Detecting the light from an Earth sized planet a fraction of an arcsecond from a star 10 billion times brighter is one of the most challenging technical problems in astronomy. When the Hubble telescope takes a picture of a nearby star, the image is the diffraction pattern of the star. At an angle of 0.1as from the star, where a planet might be, the diffraction side lobe might be lower by 1000X. The diffracted and scattered light needs to be optically suppressed to a level below the surface brightness of the local and exo-zodi. In the case of DAViNCI, this is done with a nulling coronagraph described in Section 3.

All coronagraphs have an inner working angle (IWA) (Figure 1). If the star-planet separation is less than the inner working angle, the coronagraph will block the planet light as well as the starlight. The most aggressive conventional coronagraph has an IWA of 2λ/D, based on the PIAA concept (Guyon, 2006). An Earth-Sun system at 10pc has a separation of 0.1as and 0.05as at 20pc, assuming we are primarily interest in 1-10 M_{earth} planets in the HZ. If the IWA is decreased by a factor of 2, the volume of searchable space increases by a factor of 8. Figure 12 shows the number of stars that can be searched for an Earth in mid-habitable zone as a function of IWA. The blue line in Figure 2 is derived from a list of ~3000 stars within 30pc of the Sun, while the green line is a power law representing the growth in number of targets with $(1/IWA)^3$.

If the maximum star-planet separation is just barely larger than the IWA, say the planet is observable only over 10% of its orbit, in practice, it is not possible for a direct detection mission to measure the planet's orbit in a ~5year mission. Measuring the orbit

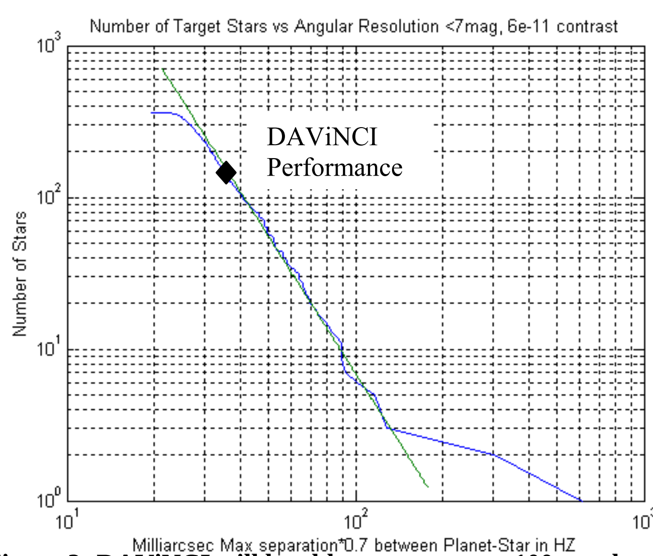

Figure 2: DAViNCI will be able to target over 100 nearby stars brighter than 7 magnitude and star planet contrast > 6×10^{-11} to search for an Earth clone in the mid-habitable zone.

of a planet with multiple images is practical only when the IWA is ~√2 smaller than the maximum star-planet separation. (Shao 2009).

1.2 Cost of large space telescopes

IWA is inversely proportional to the diameter of the coronagraphic telescope. There is considerable debate on the cost of large space telescopes, sometimes with claims of dramatic cost reduction, but the common "rule of thumb" is that cost is proportional to $Diameter^{2.5}$(Bely, 2000, vanBelle et al, 2004, Stahl et. al., 2005). Nevertheless, the relationship can be used to estimate the cost savings of a dilute aperture coronagraph over a monolithic telescope. DAViNCI, with 4x1.1m telescopes, has an IWA of ~ 40mas at 800nm. An 8m coronagraph working at 2λ/D has an IWA of 41mas.

The first ITT Space Systems LLC NextView telescope is already in orbit (on which DAViNCI's telescopes are based), and a second is scheduled to be flown soon. The JPL TEAM-X cost estimate for the first unit is $56M. Using the $D^{2.5}$ scaling law, an 8M telescope would cost ~$8B. If $56M is the cost of the 1st telescope, subsequent build-to-print copies cost significantly less. The difference in cost of 4x1.1m telescopes versus a monolithic 8m telescope is astronomically large (~$130M vs. $8B). While the telescope cost is not the total cost of a mission, it does dominate the mass of the science payload; and much of the supporting spacecraft subsystems will also grow as the telescope mass increases.

1.3 How many stars need to be surveyed?

From radial velocity survey for exoplanets, Mayor has estimated that as much as 30% of stars have planets of 5~50 earths in the range of orbital periods between 2 and 50 days. If this density of planets in logM and logP phase space holds up for terrestrial planets in the HZ, we would expect ~10% of stars to have a habitable planet in the HZ. For a "robust" search for exo-Earths, the mission should cover from 60~100 nearby stars. The Exoplanet task force came to the same conclusion in their report to AAAC and Congress (Lunine et. al., 2008).

Figure 2 shows that a coronagraph needs to have an inner working angle of ~40 mas in order to have ~100 target stars to survey where the max star-planet separation is > √2*IWA, making the planet observable over ~40% of its orbit. A coronagraph working at 2λ/D at 800nm would need to have a telescope of diameter ~8m. An external occulter would have to be ~75m in diameter flown at a distance of ~160,000km to have similar performance.

1.4 Collecting area and integration time

DAViNCI has collecting area roughly equal to the Hubble telescope. An Earth at 10pc would be a 29.5mag object, and HST/ACS would need ~4.5 hours to get an SNR=5 image. DAViNCI would need ~10 hours of integration time. The detection is background-limited by local and exo-zodi, so an Earth at 20 pc would require 160 hrs (~ 1week). With 4x1.1m telescopes, a distance of 20pc would be the limit at which one would want to attempt the detection of an Earth. Spectra with R=80 resolution and SNR=10 per spectral channel would require 50~100 times longer. A larger version of DAViNCI could detect the planet or measure its spectra in a shorter time by the ratio $(D/1.1)^4$.

1.5 Architecture of the DAViNCI Instrument

The dilute aperture coronagraph is very similar to many other coronagraphs with a few exceptions. First, DAViNCI gets its high angular resolution, and small inner working angle by the separation of its four telescopes instead of the resolving power of a single telescope. As explained in more detail in Section 3, the nulling coronagraph concept is one of a few types of coronagraphs that can work efficiently with dilute and segmented aperture telescopes. One advantage is 100% Lyot efficiency. In many types of Lyot coronagraphs, the Lyot stop can block over 50% of the planet light from the science detector. This partially offsets the smaller collecting area of DAViNCI compared to a filled aperture telescope with equivalent angular resolution. Second, nulling coronagraphs also have a property where the null pattern can be aligned to block the light from two stars in a binary system. Since roughly half of the stars in the solar neighborhood are binaries, the ability to image planets in binary systems increases the number of Earth-like planets that we will be able to discover and characterize. Third, DAViNCI's nuller uses fiber bundle technology, whereas TPF-I's infrared nulling interferometer generates an image through aperture synthesis, or rotation of the array of telescopes. DAViNCI's coherent fiber bundle (described in Section 3) produces an image of the whole field without the need for rotation. The null pattern, however, does not transmit starlight or planet light in certain parts of the sky, and full sky coverage may require the array to be rotated to 2-3 positions.

2 Science Goals

Exoplanet science has made remarkable progress over the past 15 years. There are presently over 300 known planets outside our solar system (http://exoplanet.eu/catalog.php), a vast majority of which have been found using radial-velocity (RV) methods. RV and transit methods favor planets with close separations from the parent star; while most of the known sample of exoplanets is of Jovian mass, the distribution now extends to a significant number of Neptunes, and a handful of super-Earths (5-10 Earth masses).

A number of new instruments are either under construction or about to become operational. A new generation of RV instruments, with precisions better than 1 m/s, is being built. Ground based extreme Adaptive-Optics coronagraphs (ExAOC) capable of directly imaging self-luminous Jovians are under construction and will see first-light around 2011. The space borne platforms Corot and Kepler (just launched) will conduct a census of transiting planets over targeted portions of the sky. Spitzer (in warm mode), HST and eventually JWST will be able to measure phase-curves and infrared spectra of the most favorable transiting gas giants, and in the case of JWST, favorably located transiting super-Earths (i.e. orbiting an M-dwarf). This next generation of instruments will undoubtedly extend our understanding of gas-giant exoplanets and atmospheres over a range of masses, orbital separations, and ages by measuring radii (transits), masses (RV and transit), and transmission and emission spectra (primary and secondary transits from e.g. JWST, and ExAO coronagraphy from the ground). Kepler is designed to discover a number of transiting terrestrial planets ranging from highly irradiated ones to real Earth analogs.

The next obvious major advance is in the detection of terrestrial planets at habitable zone separations orbiting nearby stars. The reference technology for this is space-based astrometry. After Earth-analogs have been discovered, characterization of their atmospheres via spectroscopy will require separation of the starlight from the reflected or thermal emission of the planet. Photometric detection of a hot-Jovian in secondary eclipse is relatively easy. In opposition (e.g. when the 1400K hot-Jovian goes behind a G2V parent star), the total flux dims by a fraction (10^{-4} to 10^{-3}) in the near to thermal infrared. Such photometric or spectrophotometric contrasts are within the capabilities of Spitzer and HST now, and JWST in the future. However, as the planet gets smaller and further away from the star, the technique of using secondary transits quickly approaches a limit. The fundamental limitation is not the photometric signal-to-noise, but fluctuations in the photoemission of the star. On the timescale of an Earth-analog transit (10 hr), solar variability is at the level of tens of parts-per-million. In the visible, the Earth–to-parent star contrast at 1AU at full-moon phase is about 4×10^{-10}, which is 10,000 times smaller than the solar photometric variations. In the thermal IR, where the contrast improves to 10^{-7} and solar variability is smaller, spectrophotometric measurements require a very large (20m), cooled space borne telescope. Therefore, the only way to measure low resolution visible and near-infrared spectra of Earth twins in the habitable zone is to block out the offending starlight, as DAViNCI is designed to do.

DAViNCI is designed for direct imaging of terrestrial and gas-giant planets. Its combination of imaging and spectroscopic modes, and wavelength coverage, address the following critical scientific issues pertinent to terrestrial planets.

2.1 Habitability

Terrestrial planets are considered habitable if they can maintain liquid surface water. However, this is not a sufficient condition because a planet may have poor levels of water at formation or insufficient mass to maintain an atmosphere or an ocean over time. To conclusively establish if a planet is habitable, DAViNCI takes two approaches: 1) to directly address the presence of an ocean via a phase dependent measurement of an ocean glint or 2) to undertake a comprehensive study of the mass, size, orbit and atmospheric composition to determine whether the surface is conducive to stable liquid water.

Although the mass, density and orbital elements serve as zeroth order parameters of habitability, a definitive determination of whether a planet can support liquid water comes from studying its atmosphere. The presence and abundances of greenhouse gases, coupled with a climate model, can determine the surface temperature. For instance in the Solar System, Earth and Venus have surfaces that are 17ºK and 430ºK hotter than their global effective temperatures. This difference between surface and effective temperatures is due to the greenhouse heat-trapping, and leads to drastically different surface conditions. Although early characterization of the atmosphere (and surface) of a planet can be undertaken with time-resolved photometry at a few wavelengths, the potential diversity of planets, and the diversity of factors leading to similar photometric colors means that DAViNCI's low resolution spectroscopic mode (R ~ 80), designed to measure molecular band-absorption, is essential.

Low resolution spectroscopy in the visible and near infrared allows for unambiguous detection of anticipated molecular band shapes. With sufficient wavelength coverage, ambiguities in absorption signatures can be resolved by searching for multiple bands for a given species. The three most dominant greenhouse gases, H_2O, CO_2 and CH_4 have strong absorption bands in the near IR. Water vapor also has strong bands in the visible part of the spectrum. A theoretical spectrum of an exo-Earth can be seen in Figure 3.

Multicolor photometry over 50% to 60% of the orbital phase can be used to measure changes in the brightness, color and spectra of a planet. If, like Earth, the planet has a lot of surface water, the polar ice caps would grow and shrink with the seasons. An ocean has an albedo of 20%, while ice and snow are highly reflective at 80 to 90%. If primarily viewing one of the polar ice caps, DAViNCI would see measurable seasonal changes in flux.

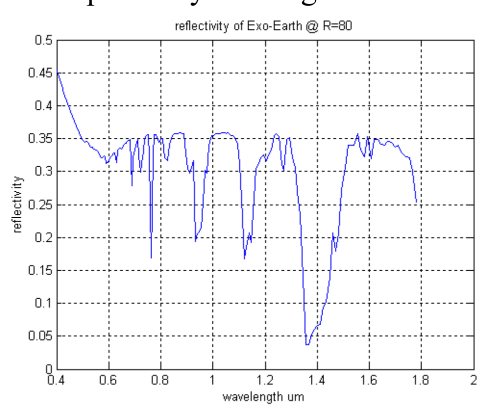

Figure 3: Theoretical spectrum of an exo-Earth at R=80.

2.2 Searching for Biospheres

Any truly global and long-lived biosphere has a chance of being detected in disk-averaged DAViNCI spectra. First, observations of the atmosphere could show constituents that exist in disequilibrium with the atmosphere and the environment (such as oxygen and its products on Earth). Second, observations could show anomalous surface bio-signatures such as the red-edge of plant-life, which shows significantly enhanced reflectivity long wards of 700nm. Finally, observations could show temporal bio-signatures, where an atmospheric constituent, the surface-albedo or signature shows marked seasonal variation due to seasonal fluctuation of its underlying biology. In the life-history of any planet, a varied set of environmental, evolutionary and metabolic conditions may have a range of biospheric impacts that are different from that seen on the Earth today or during any past period on the ancient Earth.

On the Earth, photosynthesis produces the only global primary signature of life i.e. atmospheric oxygen and ozone in the presence of liquid surface water, and pigmentation that can be distinguished from an otherwise mineral surface. However, given a paucity of hypotheses, the presence of an oxidizing atmosphere -- O_2, O_3, simultaneously with liquid water and reduced gases such as CH_4, are widely agreed as strong priority for spectroscopy for future exoplanet missions. A much more challenging observation would be the detection of a signature such as the vegetation red-edge (the strong contrast in red absorption and NIR reflectance), although this would have to be present at a higher level than the 2-3% signature seen in the Earth's disk averaged spectrum.

Every coronagraphic mission plans to cover the visible spectral range 500-900nm, because of the Oxygen line at 760nm. But if the instrument can gain a factor of 2X improvement in IWA, the spectroscopic science between 900 and 1700nm becomes possible for comparable costs. DAViNCI's 900-1700 nm range is essential to characterize a range of different terrestrial planets (Shao et. al, TPFC-ICS, 2006) --visible detection in the 550-900nm region is designed with only modern Earth in mind. The spectral region beyond 1000nm is essential for detecting the terrestrial gases CO_2 and CH_4. The numerous strong CO_2 features between 1000nm-1700nm will allow CO_2 identification. CH_4 is an important biomarker gas and is expected to be considerably more abundant in the early Earth due to the metabolism of methanogenic bacteria (e.g., 3Gyr ago CH_4 may have been 1000 times more abundant in Earth's atmosphere than it is today).

Qualitatively, the benefits of using an extended wavelength range is given by Meadows' table (Meadows, 2004, 2006). Extended spectral sensitivity enables full detection of CO_2 and water-ice. Meadows has shown that many of the important biomarkers of planetary spectra lie within the 550-1700nm spectral band. There are three much deeper H_2O absorption features between 900-1500nm. On a terrestrial planet covered with high clouds, the H_2O features will be obscured in the 550-900nm region, and only the deeper H_2O features beyond 900nm will be detectable, (Demarais, et.al., 2002). O_2 also has an additional absorption feature at 1270nm. Newly discovered terrestrial planets have the potential to be extremely different from Earth, Venus and Mars---planets that appear very similar over a short wavelength span in the visible may show substantially greater differences when observed over an extended wavelength region 550nm-1700nm.

2.3 DAViNCI Target Lists and Capabilities:

Table 1 DAViNCI Tartget List

Stellar Type	Total	Single-Stars	Multiple Stars
F-stars:	239	142	97
G-stars:	251	179	72
K-stars:	71	41	30
M-stars:	2	0	2
All:	563	362	201

The DAViNCI target list (Table 1) is a subset of the TPF target list with targets selected based on the following criteria: 1) an IWA of 38mas, 2) main sequence F, G, K and M stars only, and 3) stellar luminosity less than 10 L_{sun}. The culled list consists of 563 stars of which 362 are single, the rest being in multiple systems. Note that about 36% of all nearby stars are in multiple systems. Because of the nature of its transmission function, DAViNCI can observe a significant population of binaries with possible S-type (satellite-type, where the planet orbits one star) and

P-type (planet-type, where the planet orbits binary or all stars). Using the stability criteria for both types of orbits (Kuntz et al. 2007, Eberle 2007, Pilat-Lohinger 2007), the HZ is viewable with DAViNCI in roughly 60% of the multiple systems.

While ~500 stars would have their habitable zone planets be > 40mas, only ~170 of them would have a maximum star planet > √2*IWA, where enough of the orbit would be observable to measure the planet's orbit with multiple images taken at different epochs. Of these slightly over 100 could be observed in a ~1.5 year "search and discovery" phase of the mission.

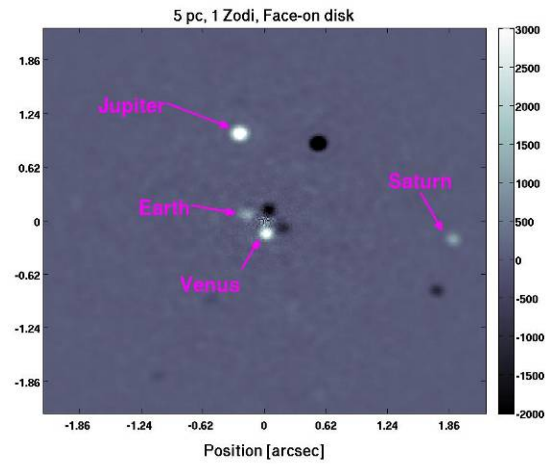

Figure 4: Simulated DAViNCI solar system image at 5pc; 12hr exposure, 1as field of view. This is a 2 image subtraction (taken 2.5 years apart) to eliminate the effects of zodiacal light.

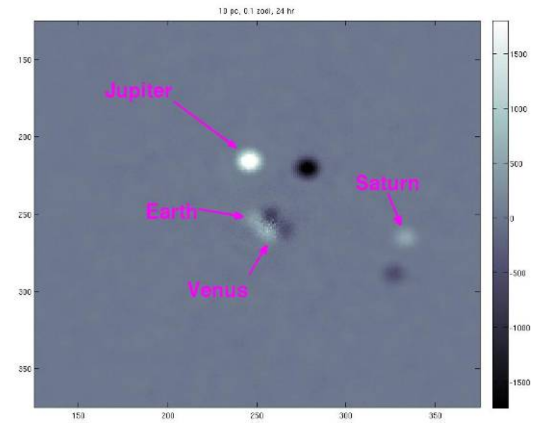

Figure 5: Simulated DAViNCI solar system image at 10pc; 24hr exposure. This is a 2 image subtraction (taken 2.5 years apart) to eliminate the effects of zodiacal light.

2.4 Relevance to NASA Science Goals

The science derived from DAViNCI falls within Science Mission Directorate's Astrophysics research objective: 'To 'Discover the origin, structure, evolution, and destiny of the universe, and search for Earth-like planets'. Both direct imaging and spectroscopy support this research objective.

3 Technical Overview

3.1 Mission Description

The main science objectives of the DAViNCI mission are 1) to directly detect Earthlike exoplanets, and 2) to determine their atmospheric planetary composition. These science goals flow into measurement, instrument, mission, and spacecraft requirements, as listed in Table 2. An interferometer based nulling coronagraph will achieve an inner working angle small enough to detect Earthlike planets within their habitable zone. A nuller and a post-coronagraph wavefront sensor are necessary to remove the starlight and the residual speckle pattern from the nuller so that DAViNCI will be able to take images of exoplanets with its science camera.

To have a worthwhile and successful mission, DAViNCI should characterize approximately ten planets. Scientists estimate the occurrence of Earthlike planets around a star to be around 10% (Shao et. al, 2009), meaning DAViNCI must be capable of observing 100 potential stars. DAViNCI uses its two position baseline to have access to nearly all stars with the required contrast and inner working angle. To characterize the exoplanets, a spectrometer will identify key biomarkers in the planetary atmospheres. In order to identify the narrowest spectral line (oxygen), the spectrometer must have a spectral resolution of approximately 80, in addition to a spectral range that covers the visible and part of the IR.

Table2: DAViNCI Science Traceability Matrix

Science Objectives	Measurement Requirements	Instrument	Instrument Requirements	Mission & Spacecraft Requirements
Directly detect Earthlike planets	Find planets outside of the IWA of the telescope	Telescope Interferometer	Inner Working Angle = 38 mas	
	Null out star light to see planet	Nuller and post-coronagraph wavefront sensor	Total Contrast ≥ $5*10^{-11}$	Maintain thermal stability of the instruments and of the orbit
	Detect planets without prior knowledge of planet location			Rotate observatory to image entire null pattern
	Determine orbit of planet	Science Camera Imager		Image target at different epochs (several months separation)
Determine Planetary Atmospheric Composition	Characterize approximately 10 planets	Variable baseline	Telescopes on variable baseline with ≥ 2 positions	Mission length ≥ 4 years to detect and characterize planets.
	Search for biomarkers (CO_2, CH_4, H_20, CO, and O_2) in planetary atmospheres	Spectrometer	Spectral range: 0.55-1.7 μm Spectral resolution = 80	

DAViNCI's science objectives will be completed over a five year mission that is broken down into two main phases: discovery and characterization. In the discovery phase, the team will verify the Space Interferometer Mission (SIM) results (if it has flown) or search for Earthlike planets by observing at least100 stars three to four times each over the first two years. Characterization of planets will then be completed over three years, spending approximately three months of total integration time on each planet.

3.2 System Description

DAViNCI (Figure 6) consists of an observing payload that is supported in orbit by a spacecraft bus and on the ground by the mission operations center. The payload includes four telescopes; the instrument, containing the beam combiner, dual nulling interferometers, imaging, and spectroscopy cameras; the wavefront sensing camera, tracking cameras, and the laser metrology package; and the thermal system to maintain the proper temperatures. The spacecraft bus is the communication link between DAViNCI and the Deep Space Network (DSN), and it also provides power, attitude control, propulsion, vibration management, and command and data handling. Ground and mission operations, including science data management, will be handled by JPL's DSN and Multi Mission Systems (MMS) Center as well as Caltech's Infrared Processing and Analysis Center (IPAC).

The dry mass of the observatory is 3026 kg with 1487 kg of mass margin (49%). The average observatory power is 2260 W, and the maximum is 2530 W.

3.2.1 Payload

DAViNCI is a phased dilute aperture telescope array with a nulling interferometer, imager, and spectrometer designed to detect and characterize extra-solar planets performing imagery and R~80 spectroscopy over the wavelength range from λ = 550 to 1700nm. All major optical components are reflective in nulling the interferometer and beam train (except

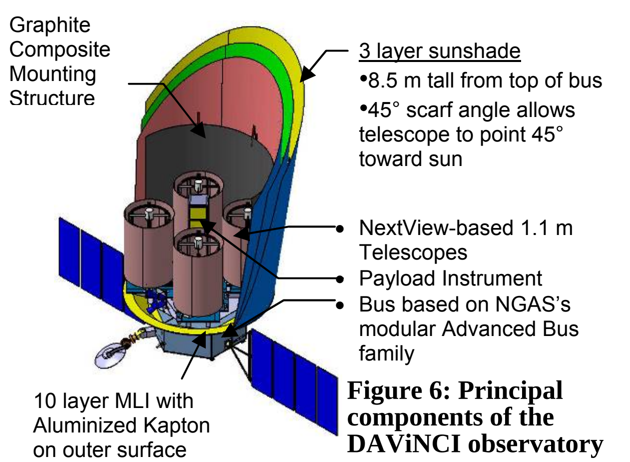

Figure 6: Principal components of the DAViNCI observatory

for achromatic phase plates, the Spatial Filter Array, and the prism disperser). This affords wavelength coverage and simplicity of design and alignment.
Four afocal collection telescopes form the dilute aperture along with a compressor telescope (not shown) that feeds the instrument. The 110 mm diameter parallel beam exiting each collector telescope is directed to the Science Instrument (SI) by four flat mirrors to the smaller shared compressor telescope. In each of the four paths, the first two of the four flats are delay line mirrors for wavefront phasing, the third mirror is a fine steering mirror for line of sight control and stabilization, and the fourth flat mirror directs the beams into the compressor telescope aperture. The geometry of these sixteen flat mirrors compensates polarization, permits phase and pointing control, and permits modification of the aperture baseline in-orbit with simple linear motions of the collector telescopes. The collector telescopes are configurable into two baselines of differing length .The SI further compresses the afocal telescope beams to four parallel 11 mm diameter beams. From here, the payload block diagram is shown in Figure 7. The beams are combined pair wise and destructively interfered to null-out the parent star, allowing observation of dim companions. These beams interfere with each other using a dual crossed beam version of a Mach-Zehnder Visible Nulling Interferometer (VNI) (top green boxes) followed by a second nulling Michelson interferometer (middle green box), each with dispersive achromatic phase plates to create a spectrally broad nulled output. Four beams enter and two beams exit the interferometer stage of the SI. The complete system, from the collector telescopes to the output

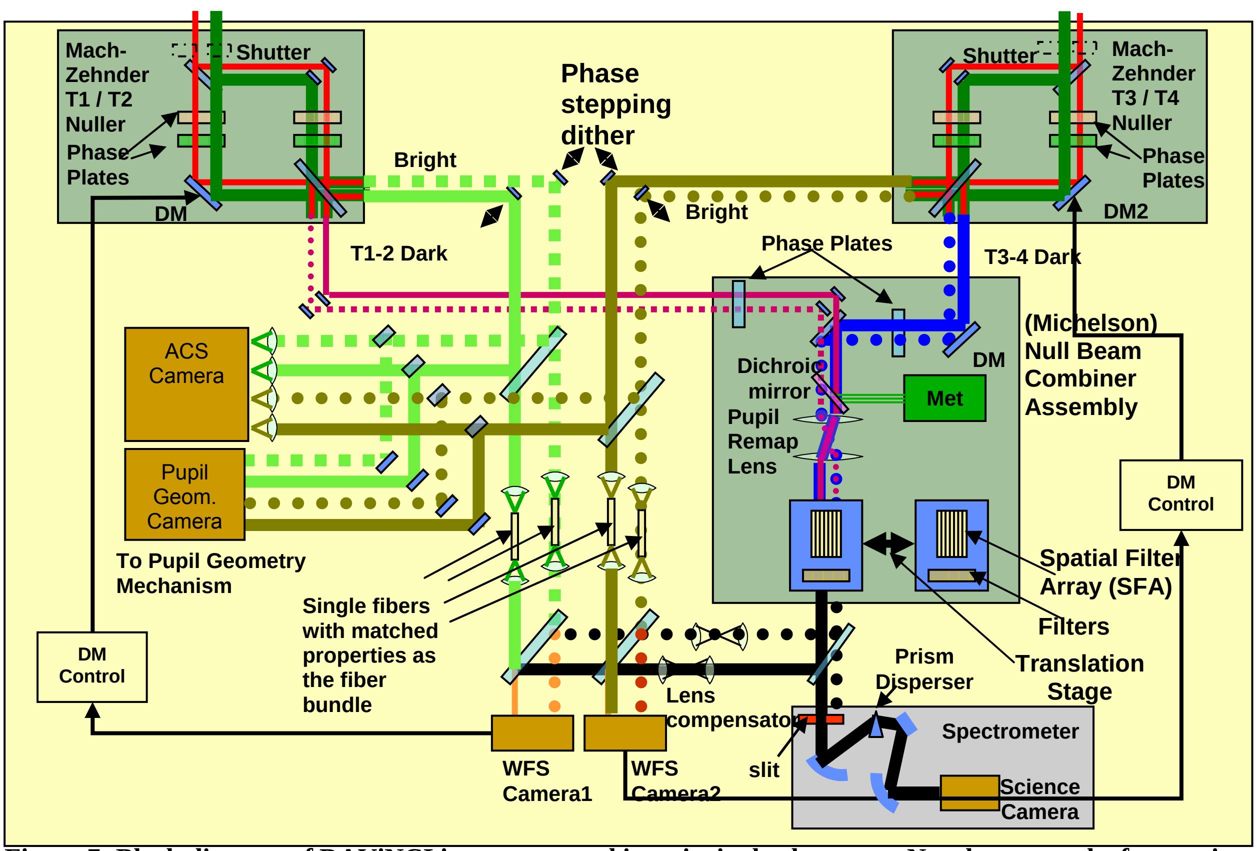

Figure 7: Block diagram of DAViNCI instrument and its principal subsystems. Not shown are the four main telescopes and the compressor telescope that feeds this instrument.

of the Michelson, is interferometrically phased as a single full-baseline coherent system. The transmission pattern shown in Figure 8.

Each of the interferometers produces a bright and dark output. For beam position control, we use the bright output with two pupil relay optical systems included in the SI at the pupil

Geometry Cameras and the ACS Cameras. The first camera images the collector telescope apertures (the aperture stop of DAViNCI) onto the deformable mirrors in the VNI, and the second images the deformable mirrors onto the Fiber Optic Spatial Filter Array (SFA). The two output beams from the SFA are imaged to place the star/planets image onto a selectable entrance slit. Planet light is reflected by a mirror on this mechanism to the Focal Plane Array (FPA) (not shown). Instead, the spectrometer optical path (bottom grey box) is shown with numerous slits positioned by a mechanism to become selectable entrance slits for the prism spectrometer, permitting slit-spectroscopy with the spectrometer FPA. Each FPA is a Teledyne Hawaii 2 RG 1.7 micron cut-off HgCdTe array with 18 micron pixels (Beletic, et. al, 2008), although a photon counting capability in this wavelength regime would be a welcome technology development.

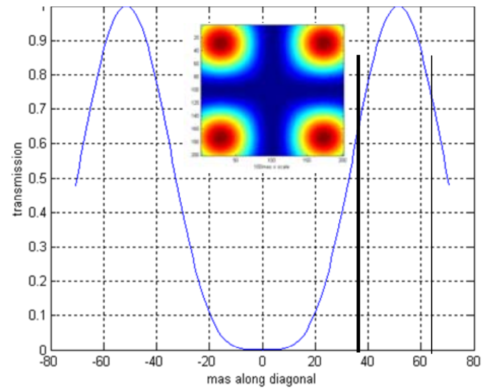

Figure 8: Transmission pattern of long baseline DAViNCI.

3.2.1.1 Telescope

The collector optical telescope assembly (OTA) design is highly leveraged from the recently launched 1.1m high resolution NextView Electro-Optical payload developed by ITT Space Systems LLC as shown in Figure 9. The optical prescription was chosen to maximize use of the high technology readiness level NextView design, particularly the primary mirror and forward metering structure, as well as the proven manufacturing processes. Thermal stability needs of the collector telescopes drive some changes relative to NextView, which include proportional heater control and improved metering structure thermal blanketing. The telescope outer barrel assembly (OBA) and metering structure blankets, in combination with the spacecraft thermal shade, provide three levels of thermal isolation for DAViNCI, very similar to ITT’s thermal design for Chandra’s High Resolution Mirror Assembly (HRMA). The HRMA temperature has only changed 0.05ºC since launch in 1999. In summary, infrastructure, capabilities, and past experience are in place to provide a cost-effective set of fully aligned and optically tested collector telescopes for DAViNCI.

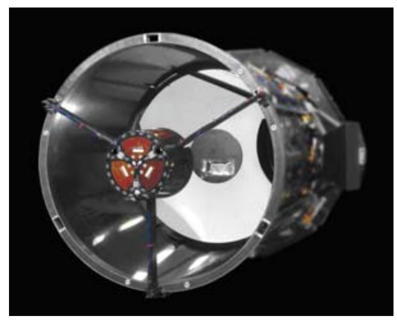

Figure 9: ITT, 1.1m Aperture NextView Telescope.

3.2.1.2 Laser Metrology

The laser metrology system (Figure 10) provides two main functions: (1) monitor optical path length difference (OPD) among the four telescopes for close-loop stabilization of nulling combiner OPD; and (2) measure pointing of the telescope array rigid body pointing measurement with respect to the inertial space to obtain a stable nulling image at the instrument cameras. The

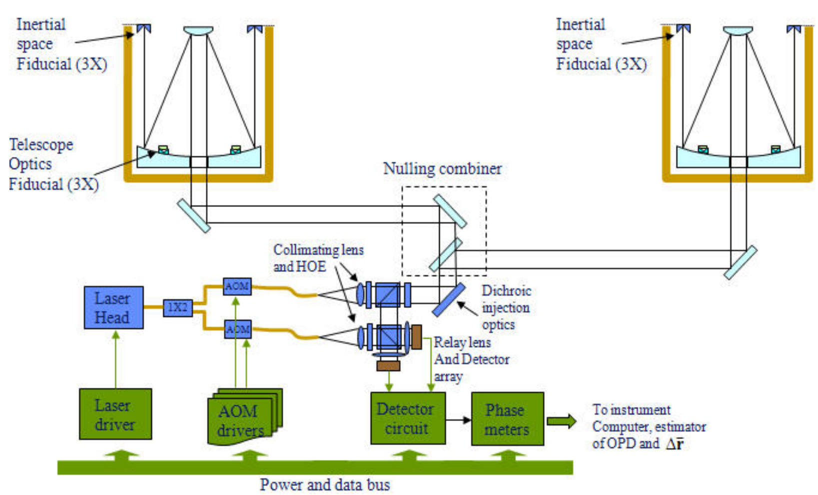

Figure 10: DAViNCI laser metrology system concept diagram

proposed laser metrology concept is based on common-path heterodyne interferometer developed for SIM (Zhao, 2005).

3.2.1.3 Sunshade

The sunshade (see Figure 6) mitigates thermal changes of the telescope environment within the payload due to changes in observatory orientation. The sunshade is designed to provide a factor of 6000 in solar attenuation. Coupled with internal heaters and insulation, the sunshade will be able to maintain 1mK stability over one hour.

3.2.1.4 Variable Baseline and Structure (Figure 11)

The variable baseline mechanism (Figure 11) allows for two positions of the DAViNCI telescopes while maintaining a rigid structure. The telescopes are mounted atop the rail-guided Telescope Transfer Mechanism (TTM), which mounts to a rigid Glass Fiber Reinforced Polymer/Aluminum Honeycomb structure for light weight vibration damping. The TTM moves the telescopes from the minimum to maximum baseline, allowing for sixty repositioning cycles over the five-year mission life. The TTM is composed of three subsystems: the **Precision Positioning System (PPS), Rail Transport System (RTS), and Motor Drive Mechanism (MDM).** The MDM drives the telescopes along the RTS to each baseline position and applies sufficient force at each PPS, allowing for proper mating into the kinematic mounts with no redundant forces on the telescopes. The structures joining the PPS on both the cruciform and telescope sides have matched coefficients of thermal expansion.

Rail As Seen With Telescope Removed **With Telescope Mounted (Max Baseline)**

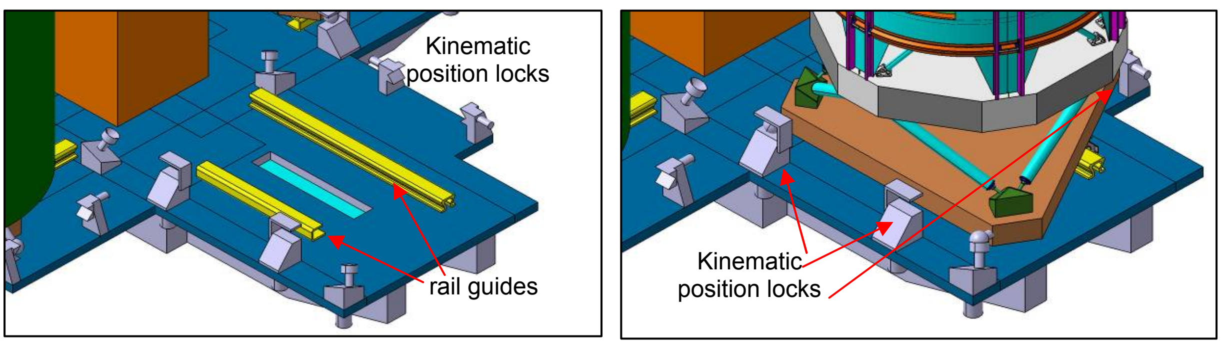

Figure 11: Rail Transport Mechanism of the Variable Baseline Structure.

3.2.2 Flight System

The spacecraft bus provides all housekeeping functions for the observatory, and the bus serves as the primary structural interface to the launch vehicle, the sunshade, instrument platform and telescopes. The bus was designed and sized consistent with the payload specifications.

The **Electrical Power Subsystem** (solar array, battery, and power distribution module) supplies continuous electrical power to the spacecraft, instrument and telescope for all mission modes. The **Attitude Control Subsystem** (ACS) provides attitude control and determination, high gain antenna (HGA) pointing control, thruster control for mid-course corrections, station keeping, observatory momentum management control, and system level fault management. The ACS is designed to meet the pointing requirements of the observatory and is designed with a high degree of redundancy to ensure accurate observatory pointing. The **Thermal Control Subsystem** (TCS) uses high-heritage parts to maintain bus components within required temperature limits. An aluminum bus structure was selected to reject heat more efficiently. The **Propulsion Subsystem** is responsible for repointing, station keeping, and orbit maintenance once per orbit. For the **Structures and Mechanisms Subsystem**, the DAViNCI spacecraft draws from Northrop-Grumman Aerospace Systems (NGAS) modular Advanced Bus family of products. A central cylinder is used to carry the primary structural loads, while six radial shear webs support equipment panels and provide load-bearing paths

To meet the data rate requirements in DAViNCI's Earth-trailing orbit (0.55 AU from Earth at the end of the mission), X-band was selected for both the science data and command and telemetry links of the **Communications Subsystem**. The main components of the this subsystem are: X-Band Transponder, X-Band TWTA, Omni Antenna, and a High Gain Antenna (Gimbaled). The **Command and Data Handling (C&DH) Subsystem** uses a spacecraft processor (SCP), which contains a RAD750 processor and interfaces to all subsystems via a MIL-STD-1553 bus. The SCP is designed to meet the 80 Gb requirement. The observatory's on-board **Flight Software** is modular and table-driven to provide for easy incorporation of mission-specific upgrades without impacting the core software.

3.3 Launch System and Operations Concept

Launch will occur on an Atlas V 521 into an Earth trailing orbit. The hyperbolic escape velocity, or C3, of the launch vehicle is 0.4 km^2/s^2 in order to safeguard against launch dispersions so that the spacecraft can achieve its drift-away orbit.

The operations concept plan includes launch, spacecraft and instrument checkout, discovery, and characterization, telecommunications, science with telecommunications (nominal plan), and a safe mode. Spacecraft checkout, subsystem deployment (antenna and solar panels), and instrument checkout will occur once the drift away orbit is achieved.

For the discovery and characterization phases, there are three sub-phases: telescope pupil alignment, target acquisition (0.1as pointing), and instrument calibration and alignment (deep null). In the discovery and characterization phases, once the baseline is set, telescope pupil alignment and target acquisition are performed.

In a blind search, instrument calibration and alignment is completed, science data is recorded (for two to four hours), and then the spacecraft rolls multiple times about the telescope array axis to different positions so as to image the entire null pattern. For discovery with prior knowledge, the spacecraft is rolled to the exoplanet's position, instrument calibration and alignment is performed, and the science data are read. Total integration time per star will be on the order of eight to 16 hours. For characterization, the spacecraft is rolled to the exoplanet position, the deep null is acquired, the desired band filter is activated, and data are recorded from the spectrograph and WFS cameras. The total integration time depends on the target star and planet, but on average is expected to be three months per target.

3.3.1 Mission Operations System

Mission Operations will be led by JPL, which has extensive experience in the operations of deep space missions. The spacecraft will communicate with the DSN twice per, primarily for navigation purposes. The 1.2 Gbits per day of science data will be returned to Earth during each of the passes with the DSN. For the first three years of the mission, the passes will be approximately one hour long at 1.5 Mbps; the last two years will have 1.8 hour passes at 750 kbps. Both of these standard data rates exceed DAViNCI's requirement of 82 kbps.

The Multi Missions System teams will collect and prioritize requests from the remote science users, and targets will be chosen based on restrictions on the field of regard. JPL will send one to two week-long observation campaigns, including spacecraft and instrument commands, once per week.

3.4 Science Data Collection, Analysis, and Archive

Science data collection, analysis, and archival will inherit previous mission experience by working through JPL and the California Institute of Technology's IPAC, NASA's multi-mission center of expertise for astrophysics. On the order of 100 scientists will be direct recipients of the DAViNCI science data. At IPAC, analysis algorithms will be developed and tested for

DAViNCI utilizing their expertise and experience from previous missions. IPAC will archive the 300 Gbyte of data from the mission as well as distribute the data to the remote science users.

4 Activity Organization, Partnerships, and Current Status

4.1 Partnerships, Roles, and Responsibilities

Dr. Michael Shao of JPL is the PI of this investigation. The Co-I's report to and take direction from the PI and will provide all technical and management data needed to ensure that the he can effectively manage the entire task. Table 3 shows the DAViNCI team members, their organizations, and their primary roles.

We are leveraging experience (and minimizing costs) through the maximum use of existing commercial technology, namely, ITT Space Systems LLC NextView telescope, Northrop-Grumman thermal control systems and spacecraft, and Lockheed-Martin for instrument design, construction, and integration. We also use the past developments at JPL in SIM laser metrology, as well as those of JWST for Visible-Near IR detector array heritage.

4.2 Current Status

We are completing a conceptual design phase for DAViNCI with this report to NASA. Remaining activities will be to perform continued development of critical technology as written in the proposal.

Table 3: DAViNCI Team members

Investigator	Institution	Role
Michael Shao	Jet Propulsion Laboratory	Principal Investigator
Elizabeth Deems	Jet Propulsion Laboratory	Systems Engineering
Leigh Fletcher	Jet Propulsion Laboratory	Science Team
B. Martin Levine	Jet Propulsion Laboratory	Instrument Team & Management Oversight
Glen Orton	Jet Propulsion Laboratory	Science Team
Gautam Vasisht	Jet Propulsion Laboratory	Science Team and Instrumentation
Feng Zhao	Jet Propulsion Laboratory	Laser Metrology
Mark Clampin	NASA/Goddard Spaceflight Center	Science Team
Richard G. Lyon	NASA/Goddard Spaceflight Center	Science Team and Instrumentation
Olivier Guyon	University of Arizona/Subaru Telescope	Science Team
Benjamin F. Lane	C.S. Draper Laboratory	Science Team
Keith Havey	ITT space Systems, LLC	Telescope Development and I&T
Rocco Samuele	Northrop Grumman Aerospace Systems	Spacecraft, Variable, Sunshield, Variable Baseline Mechanism
Gopal Vasudevan	Lockheed Martin Space Systems	Instrument Design
Robert A. Woodruff	Lockheed Martin Space Systems	Instrument Design
Volker Tolls	Smithsonian Astrophysical Laboratory	Science Team
Fabien Malbet	University of Grenoble, France	Science Team
Alain Leger	Institut d'Astrophysique Spatial (CNRS), Universite Paris-Sud	Science Team

4.3 DAViNCI Schedule

Figure 12 shows the DAViNCI mission schedules. Initial technology development will occur pre Phase A to retire any significant risks.

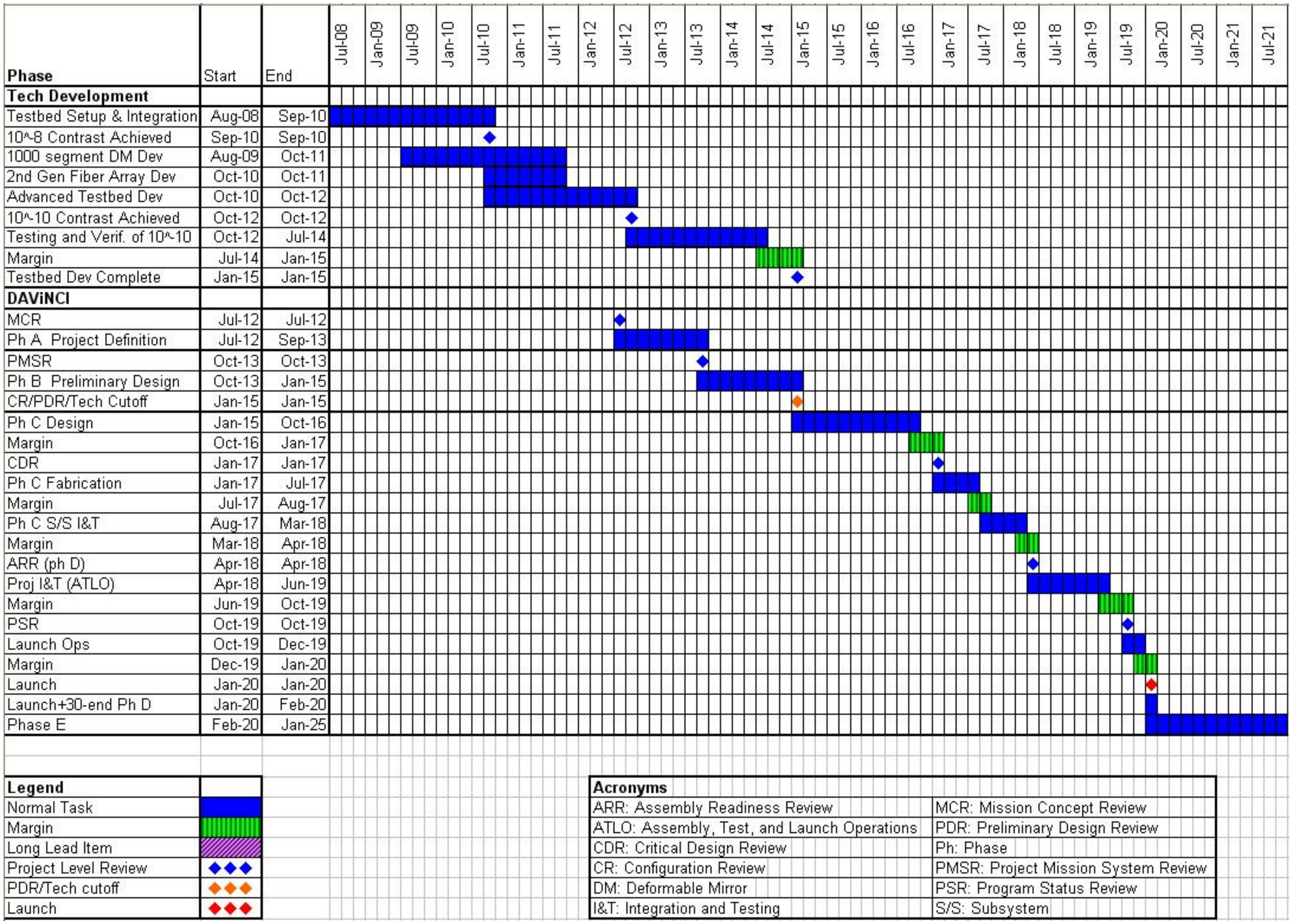

Figure12: DAViNCI Technology Development and Mission Implementation Schedule

5 Funding Requirements

5.1 Cost Estimation Methodology

JPL's TeamX was used to do the cost estimation of DAViNCI, which is categorized as a class A mission. In 2009, multiple TeamX sessions were held for both the instrument and the overall mission to get an accurate total cost. For the mission and its component costs, mission class and phase lengths play a large role in determining the final cost.

Team X guidelines for this study were to provide independent design and costing analysis for each mission concept. Project-provided designs were used, but not project-provided cost estimates. The cost estimates summarized in this document were generated as part of a Pre-Phase-A preliminary concept study, are model-based, were prepared without consideration of potential industry participation, and do not constitute an implementation-cost commitment on the part of JPL or Caltech. The accuracy of the cost estimate is commensurate with the level of understanding of the mission concept, typically Pre-Phase A, and should be viewed as indicative rather than predictive. Team X typically adds 30% reserves for development (Phases A-D) and 15% for operations (Phase E). **All costs rounded to two significant digits**.

The project cost is roughly $1.2B FY09 with appropriate contingencies, including five years of science operations. The cost breakdowns (rounded to two significant digits) can be seen in Table 4 and Table 5. TeamX also explored several descope options to baseline cost impacts of changing the mission specifications for purposes of cost containment. Utilizing smaller telescopes (ITT Ikonos–class, 70cm diameter, to analyze approximately 60 star systems), a single fixed baseline, and visible detectors, the cost could be reduced to by up to $380 M.

Table 4: TeamX DAViNCI Mission Cost Summary

Item	Cost ($M FY09)*	Notes
Management, Systems Engr., Mission Assurance	84	
Payload System	390	1
-- Instrument	390	2
Flight System	190	
Mission Ops Preparation/ Ground Data System	58	
Launch vehicle	170	Atlas V 521
Assembly, Test, Launch Operations	23	
Science	40	
Education and Public Outreach	8	
Mission Design	7	
Reserves	230	
Total Project Cost	1200	

Notes: *Individual WBS elements have been rounded to 2 significant digits. 1. Payload system includes instrument. 2. 4 telescopes, metrology package, thermal shield, mounting structure

5.2 Phased Mission Costs Summary

Table 5: Cost by Mission Phase

Mission Phase	Cost ($M FY09)*
Phase A	10
Phase B	86
Phase C/D	1030
Phase E/F	70
Total	1200

6 Technology Development Requirements

The driving requirements to demonstrate technology readiness come from optical contrast levels of 10^{-9} for Jovian planets and 10^{-10} for earth-sized planets in starlight over an extended field of view. Ultimately we need to show an imaging contrast of 2×10^{-11} over an inner working angle less than 38mas using a wide band pass of starlight (25%). In order to meet this demanding TRL-6 requirement, deformable mirrors, spatial filter arrays and null control algorithms must act together in a stable environment within a vacuum tank.

To image a planet around a nearby star, we need to suppress the light from the star at the position of the planet, down to a level where photon noise from the stellar leakage is smaller than the photon noise from the local and exo-zodi dust. Light at the first airy ring is ~2% of its peak intensity. *For DAViNCI, this 2% must be reduced to ~10^{-9} to be below the local/exo-zodi.* Residual stellar speckles are still ~10X brighter than the planet. Next we need a method for measuring the residual starlight speckle pattern (wavefront calibration) down to ~1/5 of the planet light, meaning the residual speckles must be subtracted to ~2×10^{-11} for a Earth @ 10^{-10} contrast.

We have divided the technology tasks into **wide band starlight suppression** and **demonstration of high contrast imaging** using the VNC over an extended field of view. These demonstrations run concurrently with component development of **segmented deformable mirrors** and **fabrication of coherent single mode fiber arrays**.

6.1 Wide bandwidth starlight suppression

We have already achieved a deep, 10^{-6} null over a wide 16% spectral band (Samuele et. al, 2007) (Figure 13). When combined with a 1000 element single mode fiber array, this would yield a 10^{-9} contrast. The major challenge of achieving deep starlight suppression is the precise control of both amplitude and phase. The residual 10^{-6} leakage is due in part to phase errors and in part to amplitude errors, while the optical path in the two arms is matched to ~40 picometers, and the intensity difference of the two interfering beams is matched to 0.06%. These measurements were made with the interferometer in the quiescent environment of a vacuum chamber, but at atmospheric pressure. This level of performance is satisfactory for EPIC but needs another factor of 2-3 for DAViNCI.

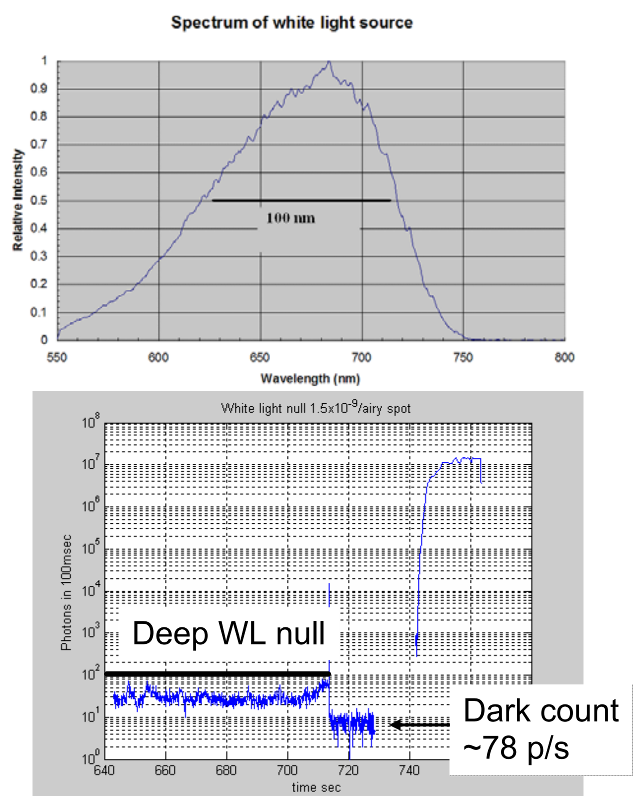

Figure 13: (Upper) The 15% white light spectrum after propagation through one arm of the interferometer. The Full width at half maximum is 100 nm. (Lower) The resulting null plot showing 10^{-6} starlight suppression.

Starlight suppression of 10^{-6} is required to produce an overall contrast of 10^{-9} (suitable for DAViNCI). (Earth-like planets) at an equivalent angle of 1-2λ/D. Final image contrast needs to be achieved with using the calibration wavefront sensor data to subtract speckles to the 2×10^{-11} contrast level (5x lower than an Earth planet contrast of 10^{-10})

6.2 High Contrast Imaging

An early attempt to demonstrate the nulling architecture and post coronagraphic wavefront sensing is in the fabrication of the Planet Imaging Coronagraph Testbed Using a Rocket Experiment (PICTURE) nuller, a sounding rocket instrument. Shown in Figure 14, it is an all glass optical bench and instrument in a 'sandwich' structure. Such a configuration minimized

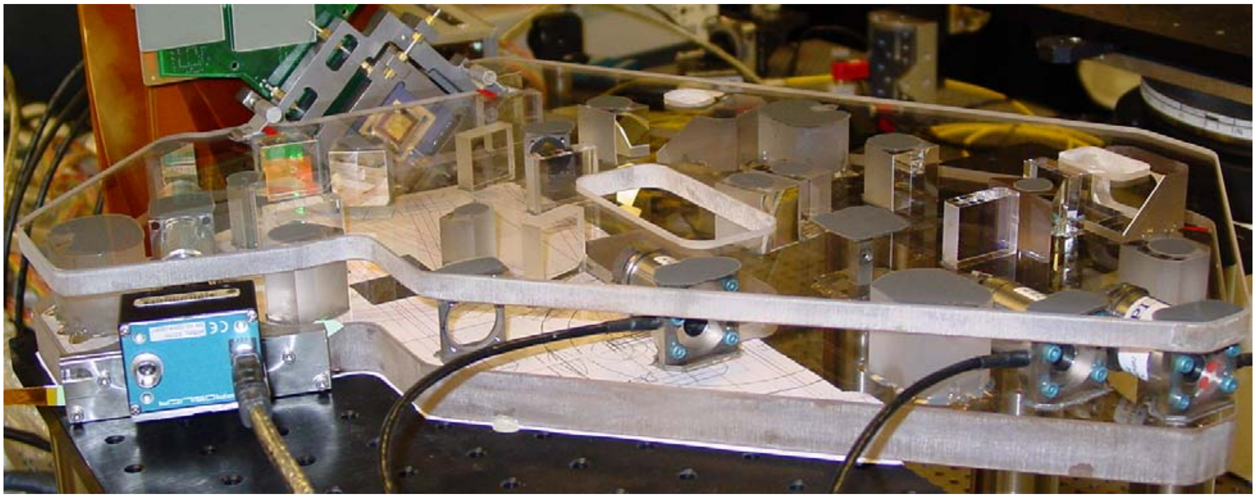

Figure 14: The PICTURE nulling instrument is of all glass sandwich design and construction.

thermal variations and also made the interferometer less sensitive to vibrations in that it eliminated differential movement of the individual optical components.

To demonstrate high contrast imaging for DAViNCI, we need a testbed that is capable of demonstrating starlight suppression over a multiple 'pixel' field of view. In the DAViNCI architecture, the output of the nuller is coupled to a coherent array of optical fibers in the pupil plane. Each segment of the segmented DM controls the amplitude and phase into one fiber in the array. The output of the fiber array is focused onto the science camera as in Figure 15. Both JPL and GSFC are developing parallel test beds. Significant advances

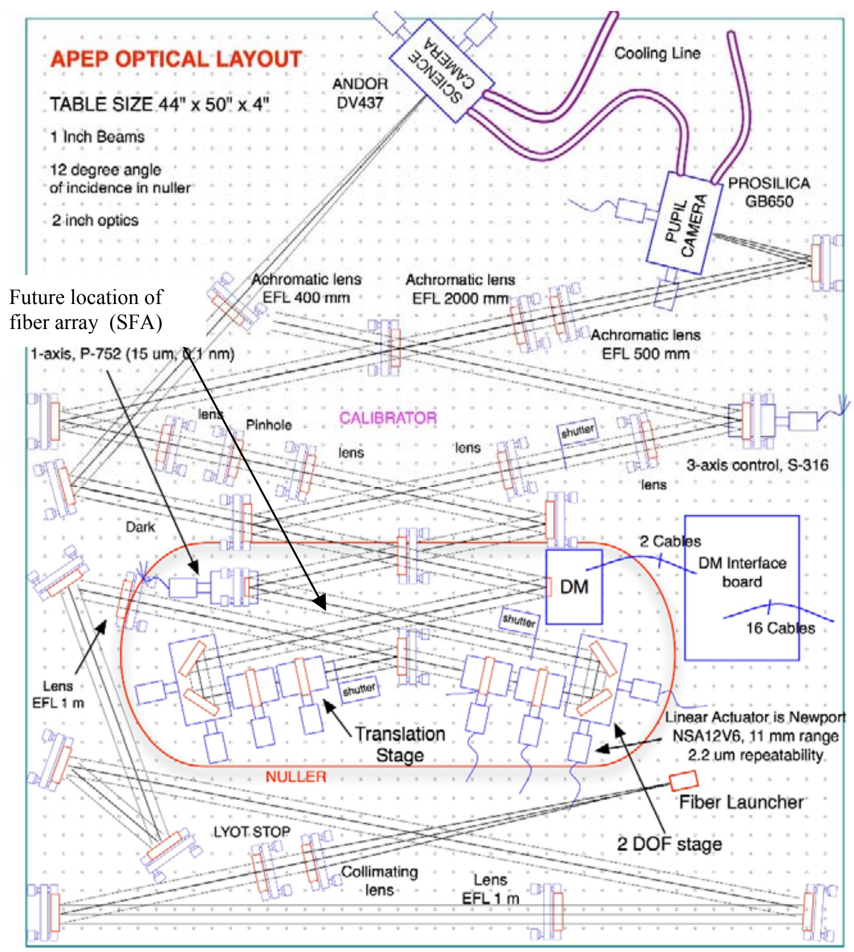

Figure 15: JPL Nulling Test bed for demonstration of high contrast imaging using a nulling interferometer, DM, fiber array, and with a post-coronagraphic wavefront sensor.

have occurred at GSFC in the development of an imaging test bed with null control algorithms resulting in stable closed-loop control in a noisy lab environment at 6.7 Hz.

APEP is an advanced optical testbed (Figure 15) that will ultimately demonstrate high contrast imaging to the required levels for both DAViNCI and its medium calss mission counterpart, EPIC. It will be capable of remote access, so both JPL and GSFC will be able to use the testbed to demonstrate high contrast imaging and also demonstrate control algorithms. The nulling interferometer with a DM and calibration wavefront sensor are shown. The fiber array is not yet shown. It will be located in front of the 400mm achromatic lens before the science camera.

6.3 Component Development

6.3.1 Deformable Mirror Technology

The deformable mirror consists of hexagonal mirror segments, each having 3 degrees of freedom. The Boston Micromachines Corp (BMC) concept (Figure 16) uses three actuators connected to the hexagonal mirror segment via posts that resemble vertices of an equilateral triangle. This actuator geometry provides the mirror with unlimited degrees of tip/tilt motion, and when the actuators are deflected by equal amounts, the mirror segment can be moved in

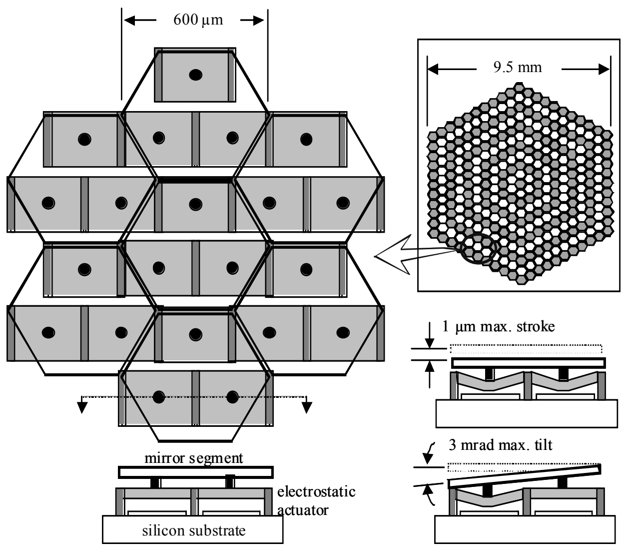

Figure16: Top and side view of the BMC MEMS DM architecture for tip/tilt and piston motion (left).

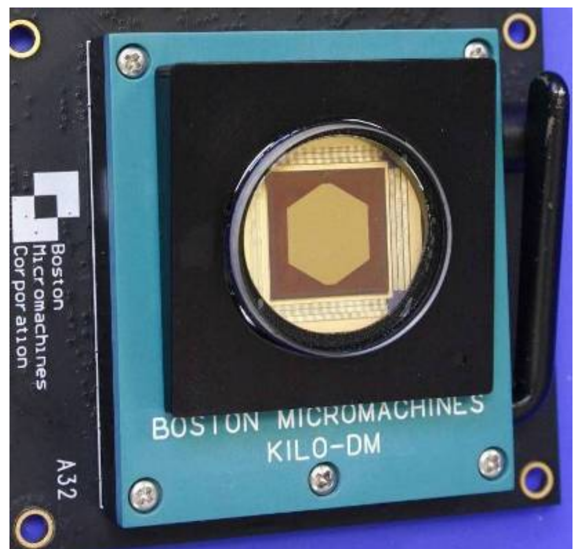

Figure17: 331 Segmented DM technology demonstrator

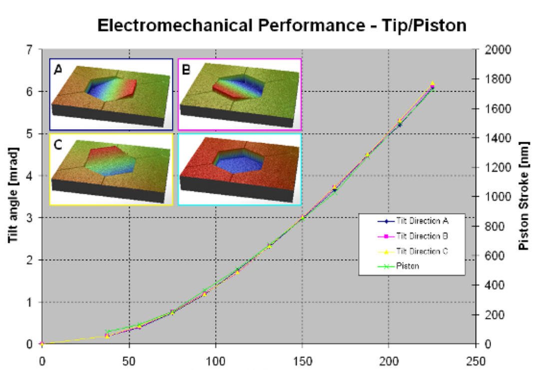

Figure 18: Performance characterization of 331 segment deformable mirror for each actuator separately and for all actuators together.

piston. The mirror segments are designed to have 1µm of piston stroke when they are tilted to 3mrad. In other words, if the mirror elements remained flat, the mirror could experience 2µm of piston motion before reaching the actuator limit. However, 1µm of this motion is reserved for tip/tilt behavior.

Under TPF funding, Boston Micromachines Corporation (BMC) developed an architecture for a segmented deformable mirror and produced a 61 segment demonstrator. The main drawback was that the segments were not uniformly flat. Under subsequent SBIR funding, BMC has mitigated this problem and has delivered a 331 segment deformable device (Figure 17 and Stewart et.al, 2007).

They have demonstrated segment flatness to 4m radius of curvature and 5nm rms roughness. Figure 18 shows the mirror response to each of its three actuators per segment.

IRIS AO is developing a deformable mirror that is a hybrid of surface micromachining and bulk micromachining (Figure 19). Also under SBIR funding IRIS AO is developing a DM through a combination of fabrication techniques resulting in a DM that has demonstrated 7.6µm of stroke at 125V, 98.6% fill factor, and optical quality of better than 16nm of rms after packaging. Preliminary cyclic tests over 110 hours and 10^7 cycles show no noticeable changes to the actuator positions after cycling.

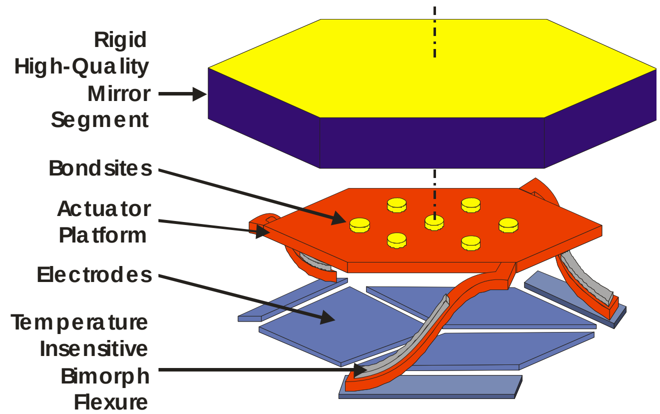

Figure 19: Diagram of a single Iris AO mirror segment. Dozens or even thousands of these of these may be tiled into a deformable array

Hexagonal mirror segments are tiled to form a DM array. Thick (20µm) single crystal silicon mirror segments are assembled onto surface micromachined platforms using flip chip bonding. The rigid segments maintain high optical quality (<20nm rms figure errors) after packaging. Each actuator platform is anchored to the chip substrate via three bimorph flexures that elevate them after release because of engineered residual stressing in the top material of the bimorph flexure. The top layer of high stress material bends the polysilicon suspension into position. The three underlying electrodes allow for piston motion when energized with equal voltages and tilt motions when energized with different voltages (Helmbrecht et. al., 2006). They have delivered a 367 segment demonstration mirror and a 925 segment demonstration mirror proving that this architect is capable of fabrication at flight like sizes (Figure 20). Current funding is devoted toward fabrication of a 163 segment fully functional mirror. Future work will concentrate on producing an interconnect scheme to provide electrical access to all actuators, and to develop a lower segment surface error.

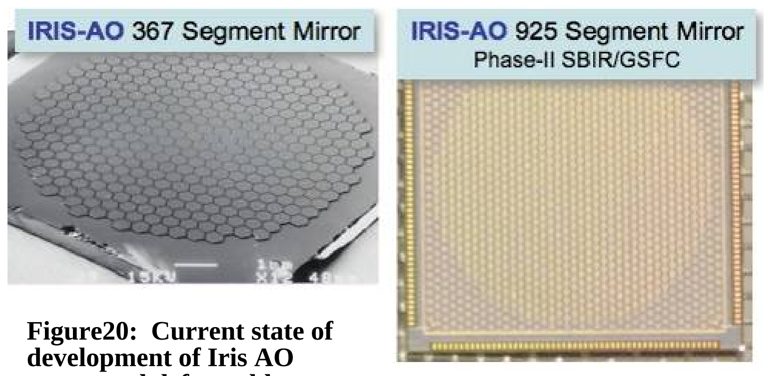

Figure20: Current state of development of Iris AO segmented deformable

Although key technology requirements have been met by both BMC and Iris AO, future development will work toward realizing 1000 segment deformable mirrors with no dead actuators with both architectures.

6.3.2 Fiber Optic Array Technology

The JPL fiber array design uses three precision equilateral prisms placed on a flat base plate as shown in Figure 21 (Liu et. al, 2005). The middle prism has one of its vertices polished flat to a width

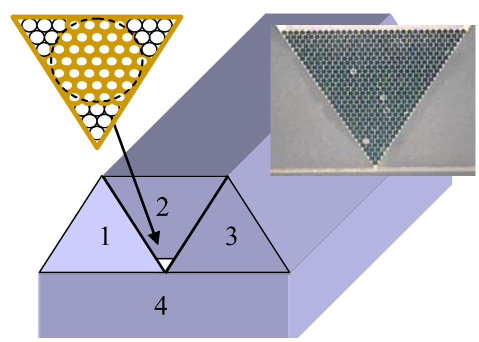

Figure 21: Fiber array is made by confining fibers by equilateral prisms 1 and 3 and equilateral prism 2 with one vertex beveled (polished off) to have a width given by that of the fiber array plus the diameter of one fiber.

approximately equal to the side length of the fiber array. The fiber array is confined by two facing sides of the upright prisms and the flat top of the middle prism.

The state of the art in Fiber optic arrays is also a 331 hexagonal array of single mode fibers. <u>The key technology challenge has been to align and bond a lens array to this fiber array to produce a single monolithic assembly.</u>

Both GSFC and JPL are working with Fiberguide Industries to develop such a custom subscale monolithic assembly consisting of 217-fibers which is specified to meet all the requirements for flight except for the number of fibers (Figure 22). It is expected that two units will be delivered (one to GSFC and one to JPL) by the end of 2009.

In addition GSFC has an ongoing phase-I SBIR to develop an alternative waveguide based approach. We need to develop an integrated array with 1000 fibers for the ultimate flight instrument, and successful demonstration of these subscale technologies is the first important step.

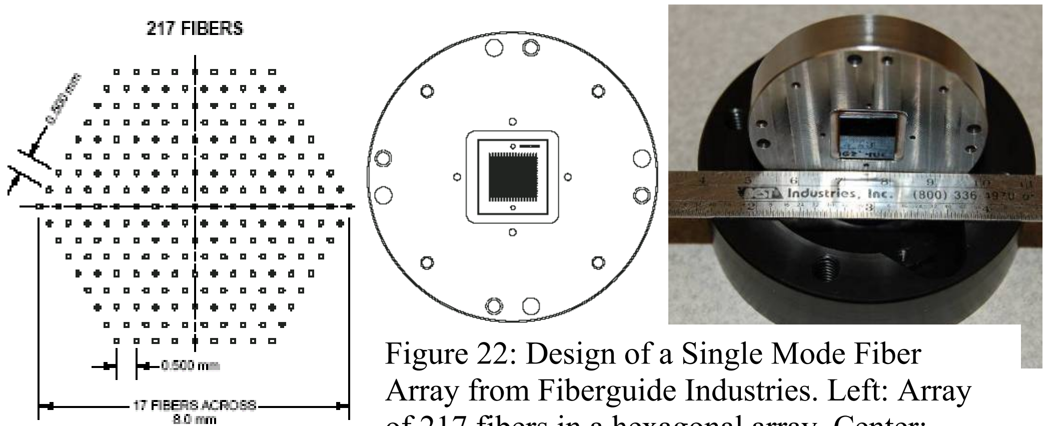

Figure 22: Design of a Single Mode Fiber Array from Fiberguide Industries. Left: Array of 217 fibers in a hexagonal array. Center:

6.4 Technology Development Program

We also recommend a technology development program to demonstrate the levels of contrast needed for the imaging earth-like exo-planets and spectroscopic investigations of their atmospheres. Starlight suppression of 10^{-6} is required to produce an optical contrast of 10^{-9} Final image contrast after speckle subtraction needs to be $2x10^{-10}$ for Jovian planets, and $2x10^{-11}$ for Earth-like planets at an equivalent angle of 1-2λ/D. This is ultimately achieved with using the calibration wavefront sensor data to subtract speckles to their required levels.

Optical nulls using a single mode fiber have already been demonstrated to 10^{-7} in laser light and 10^{-6} in broad band light. These levels are acceptable within a factor of 2 for EPIC and within an order of magnitude for DAViNCI. Optical contrast has yet to be demonstrated with the combination of the nulling architecture (including the calibration wavefront sensing system).

Future demonstrations would support medium class missions such as EPIC and the final demonstration would support large missions such as DAViNCI. We need an advanced test bed in vacuum to demonstrate the required contrast levels. Concurrent with these demonstrations are technology development in segmented deformable mirrors and single mode fiber arrays. Vendors have shown that 1000 segment DM's can be fabricated. To date, we have 300 segment subscale devices available for test. We have also shown that large fiber arrays can be built, but they also need to be integrated with lens arrays to form a monolithic module. We recommend a 4 year technology development program, to fabricate full scale DM's and fiber arrays, and to perform demonstrations of the ultimate contrast levels. We estimate that such a program would cost less than $20M.

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8 Appendix

8.1 Team X Study Summary for ASMCS DAViNCI

Team X Study Summary for ASMCS DAViNCI

Jet Propulsion Laboratory,
California Institute of Technology

with contributions from the DAViNCI Team
Bruce Martin Levine, NASA Jet Propulsion Laboratory
Elizabeth Deems, NASA Jet Propulsion Laboratory
Michael Shao, NASA Jet Propulsion Laboratory
Jeffrey Booth, NASA Jet Propulsion Laboratory

This study was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. DAViNCI, Dilute Aperture Visible Nulling Coronagraph Imager, was studied by a Team X at JPL starting in 2008. An initial design study was used to scope the instrument and the mission. This was followed by two instrument design studies to understand the resources required for the instrument. During this time, the customer was working with and industry partner to refine their design. Team X then did a final study of the customer design with the final instrument design to cost the mission.

Overview of Mission
The mission studied here is an Astrophysics Strategic Mission Concept Studies (ASMCS) Strategic Large class mission. The scientific objective of the mission is to image and take spectroscopic measurements for Earth-like planets around 100 nearby stars. This is done via dilute aperture telescope using interferometry to function as a coronagraph. A class “A” mission with a five year observing lifetime in a drift-away heliocentric orbit was baselined.

Science Objectives
The primary science objective for the DaVinci mission is to image and take spectroscopic measurements for Earth-like exo-planets around 100 nearby stars

This mission has two phases of operation. The Discovery phase will verify SIM results as well as discover more earthlike planets. The Spectroscopy phase will be focused on performing detailed spectroscopy of discovered planets over 3-4 years.

- Discovery phase: Observe 100 stars, ~4 times each over the course of 1-2 years, ~10-15 hrs total integration time for each observation, each observation has ~ 4 rotations; duration 1-2 years (note that 100 stars requires ~ 4400 hours (including slews) or about 0.5 year for Discovery activity
- Spectroscopy phase: Observe planets that have been discovered, ~3 month total integration time on each planet, spectroscopy ~ 0.4-1 micron, R=100. Note there is time to view ~ 16 objects at 3 months each with current 5 year mission. Spectral range 0.5-1.7 microns.

Technical Details
The baseline spacecraft and mission parameters are summarized in the table below. Key design features are:

System	Launch Mass (kg)		4430
	Spacecraft Power (W)		2529
	Total Mission Cost ($M FY08)		1200
	Radiation TID (krad)		27
Science	Science Goals		Image and take spectroscopic measurement for Earth-like exo-planets around 100 nearby stars
	Key Measurements		Discovery: observe 100 nearby starts 3-4 times each (discover Earthlike planets); Spectroscopy: observe discovered planets with 3 month integration time on each planet
	No. of Scientists		10
	Total Data Volume (Gbits)		2190
Mission Design	Launch Date		January 1st, 2020
	Launch Vehicle		Atlas V 521
	Launch Mass Allocation (kg)		4513
	Target Body		Exo-planets
	Trajectory/Orbit Type		Earth Trailing Orbit
	Mission Duration (months)		60
	Key Mission Phases		Launch, Calibration, Science
Instruments	Telescope	Type	Dilute aperture array (4 heritage Telescopes)
		Size	1.1 m telescopes (4): 4.4 m diameter
		Frequency Range	Spectral Range: 0.5 - 1.7 microns
	No. of Instruments		1
	Instrument Types		one payload element included: 4 telescopes, combiner/nuller instrument, and metrology package
	Payload Mass (kg) - CBE		2093
	Payload Power (W)		974
	Payload Data Rate (Mbps)		0.08
	Operating Temperature (K)		283-303 tlescope; 120 focal plane
ACS	Pointing Control (arcsec)		0.1
	Pointing Knowledge (arcsec)		1
	Pointing Stability (arcsec)		0.1
	Stabilization Type (3-axis, spin, gravity grad.)		3-Axis
	Pointing Technologies		Star Trackers, 6 reaction wheels, sun sensors, DMs, telescope ACS camera
CDH	Processor Type		RAD750
	Redundancy (hot, cold, single string)		hot
	Data Storage (Gbytes)		16
Telecom	Bands		X
	Antenna Types		Two SDSTs, One 1m parabolic HGA, two omni LGAs
	Uplink Rate (kbps)		1

	Downlink Rate (kbps)	153,600
	Gimbaled? (Y/N)	Y
Power	Solar Array Area (m^2)	9.6
	Solar Array Type	Triple Junction (30%)
	Articulated SA? (Y/N)	Y
	EOL Power (W)	2529
	Battery Storage Size(s) (A-hrs)	24
	Battery Type(s)	Li-Ion
Propulsion	No. of Prop Systems	1
	Type(s) of System(s)	Blow down mono-propellant system
	Propellant Mass(es) (kg)	103
Structures	Primary Structural Mass (kg) - CBE	302
	No. of Mechanisms	7
Thermal	Active/Passive	Passive
	Key Operating Temperature(s) (K)	120 (detectors); 293 (telescope)
	Thermal Stability (mK/hr)	1
	Thermal Control Technologies	MLI, coating, tank heaters, thermostats, telescope radiators
Ground System	Ground Antenna(s)	DSN: 70m
	Average Pass Duration (hrs)	1-2
	Links/week	2

• TELECOM. X -band redundant telecom system with bit error rate of 1e-04; gimbaled 2 degree of freedom high gain antenna. Primary data link is X-band with margin of >3 dB.

• GROUND SYSTEM. Observatory scenario similar to Spitzer, with IPAC coordinating science observation requests to provide information to the sequence planners. Use DSN 34 m X-band systems with two passes per week during science phase.

• MECHANICAL. Rigid body pointing of telescope and rail mounted, movable telescopes are major design requirements.

• PROPULSION. Conventional blowdown hydrazine monopropellant system with two branches of thrusters for trajectory correction maneuvers and attitude control system, for full redundancy. Low risk, but contamination of optics and sunshade materials by hydrazine decomposition products should be studied and mitigated.

• POWER. 970 W instrument power is the major driver. Gimbaled solar arrays are baseline; 1.2 square meter 29% efficient arrays providing total maximum power = 2.5 kW.

• RADIATION. Flight system must survive a total mission radiation dose of 27 krad behind 100 mil of aluminum. This estimate is based on 5 year mission duration with a radiation dose margin (RDM) of 2.

• CDS: Dual string system with shared 128 Gbits Solid-stare Recorder. Hot spare per customer's design.

• INSTRUMENTS. The total CBE mass is 2093 kg; power is 975 W, which includes telescopes, metrology package, thermal shield, mounting structure, and the instrument/beam combiner.

• TELESCOPE. Based on a commercial product line, the four telescopes are each 1.1

meter in diameter.

• ATTITUDE CONTROL SYSTEM (ACS). Fine pointing done with reaction wheels. Spacecraft pointing accuracy (0.1 arcsec) is comparable to what has been achieved with Spitzer. Baseline is for the science instrument to be used as fine guidance sensor (FGS).

• MISSION DESIGN. 2020 launch into Earth-trailing orbit and mission duration of 5 years. Atlas V521 launch vehicle with launch capability of 4510 kg launches payload launch mass of 4430 kg.

Key Trades or Options studies in Team X

Team X also looked at a smaller design with fixed smaller telescopes, visible only detectors, aimed at a medium class cost cap. This mission had a reduced lifetime of three years. This was costed as a class B mission, although it ended up too expensive for the Class B designation. The performance difference was not quantified. This system was about 2 tons less massive. Cost savings were ~$350M, but since this would not be a class B mission, actual cost savings would less.

Cost Estimate Interpretation Policy, Reserves, and Accuracy

Team X guidelines for this study were to provide independent design and costing analysis for each mission concept. Project-provided designs were used, but not project-provided cost estimates. The cost estimates summarized in this document were generated as part of a Pre-Phase-A preliminary concept study, are model-based, were prepared without consideration of potential industry participation, and do not constitute an implementation-cost commitment on the part of JPL or Caltech. The accuracy of the cost estimate is commensurate with the level of understanding of the mission concept, typically Pre-Phase A, and should be viewed as indicative rather than predictive. Team X typically adds 30% reserves for development (Phases A-D) and 15% for operations (Phase E).
Project

Cost Estimate

Cost is roughly $1.2B FY09 with appropriate contingencies, including 5- years of science operations

Item	Cost ($M 2009)*	Notes
Management, Systems Engr., Mission Assurance	84	
Payload System	390	1
-- Instrument	390	2
Flight System	190	
Mission Ops / Ground Data System	58	
Launch vehicle	170	Atlas V 521
Assembly, Test, Launch Operations	23	
Science	40	
Education and Public Outreach	8	
Mission Design	7	
Reserves	230	
Total Project Cost	1200	

Notes

* Individual WBS elements have been rounded to 2 significant digits.

1. Payload system includes instrument.
2. 4 telescopes, metrology package, thermal shield, mounting structure

Phase Cost Table

Phase A	Phase B	Phase C/D	Phase E/F	Total
10	86	1030	70	1200

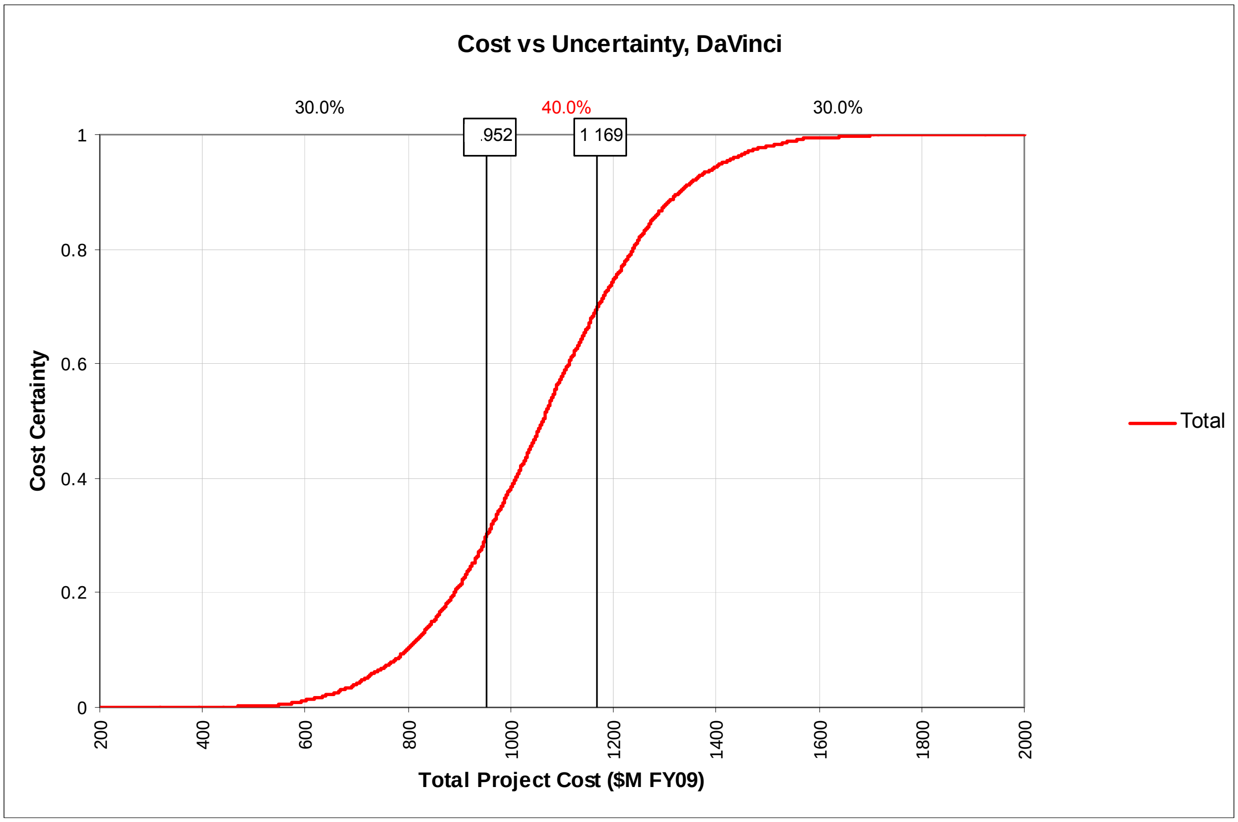
Technology Costing

Team X does not provide technology development costing. Models are based on assuming TRL 6 by the end of Phase B.

The DAViNCI mission cost curve with appropriate confidence levels is shown on the next page.

8.2 DAViNCI Mission Cost vs. Uncertainty Curve

The Team X Cost Confidence Curve is calculated by stochastically adding the distribution of each WBS element in the cost estimate through Monte Carlo simulation. Each WBS element estimated cost represents the 50% estimate for that element. The WBS element variances are derived from the error observed during that WBS's model validation, and an additional contribution from the uncertainty as shown by the assigned contingencies in the Master Equipment List. No reserve is used in the simulation of the of the total mission cost distribution. When compared to the cost estimate the CBE costs fall roughly at 40% on the curve due to adding asymmetric distributions; with the JPL Design Principle guideline of CBE plus 30% (PBE cost estimate) the costs fall around 70%. This shows that the Team X practice of adding 30% reserve to CBE is roughly equal to the 70% cost risk estimate when risks are directly represented as variances in the lower level WBS element distributions.



.Note: This information is *JPL Proprietary: it contains proposal sensitive information, and is not to be released without approval of the study lead*

8.3 DAViNCI Operations Concept

In addition to the two main phases already mentioned, there are multiple mission phases and sub-phases that are part of the concept of operations. The main chronological mission phases include launch, spacecraft and instrument checkout, discovery, and characterization. The operations concept plan also includes a telecommunications phase, a science with telecommunications phase, and a safe mode. If the schedule permits, optional phases can include giant planet detection as well as simultaneous discovery and characterization.

Launch will occur on an Atlas V 521 into Earth trailing orbit. The hyperbolic escape velocity, or C3, of the launch vehicle is 0.4 km2/s2 in order to safeguard against launch dispersions so that the spacecraft can achieve its drift-away orbit.

Spacecraft and instrument checkout will occur once the drift away orbit is achieved. The antenna and solar panels will be deployed in the first hours after launch. Then, spacecraft checkout procedures will verify all subsystems are working correctly. After spacecraft checkout, a two month instrument commissioning will ensure payload functionality. The instrument checkout will overlap with the discovery phase to confirm instruments are functioning properly. If desired, this instrument checkout can be followed by giant planet detection in order to verify instrument functionality on objects that are easier to detect than Earthlike exoplanets. The telescopes will be moved along the variable baseline after initial observations are completed in the minimum baseline. Once the telescopes have been moved, checkout of the baseline and its stability will be performed prior to further observation.

For the discovery and characterization phases (which will be explained further below), there are three sub-phases: telescope pupil alignment, target acquisition, and instrument calibration and alignment. In telescope pupil alignment, the telescope pupils will be aligned to overlap the telescope output in the camera focal plane, which will be maintained using pupil camera feedback. Alignment can be held throughout slews, so pupil alignment does not need to be performed for every target acquisition. However, alignment must be performed before the first science observation, after the telescope baseline has been changed, and after coming out of safe mode.

Target acquisition will be performed for each new target. First, coarse bus pointing (to 15 arcsec) will bring the target into the telescope field of view using the star tracker and the spacecraft reaction wheels in a closed loop. If necessary, the telescope pointing will be re-aligned such that the same section of the field of view is being collected in all four telescopes. However, telescope pointing can be held throughout observation periods and slews and therefore does not need to be performed for every target acquisition. To finish target acquisition, fine bus pointing (0.1 arcsec) will be obtained using the spacecraft bus reaction wheels in a closed loop with the telescope ACS camera (which outputs the spacecraft / telescope pointing offset).

The third and final sub-phase is instrument calibration and alignment. The telescope amplitudes are equalized using the wave front sensor (WFS) camera. Then, the telescope phases are equalized using the WFS camera error signals, which equalize phases with the deformable mirror in order to obtain a coarse null. A deep null is obtained using the three nullers, and this null is maintained using the deformable mirrors in closed loop with the WFS camera.

In the discovery phase, the first task is to set the telescope baseline to either the small or large setting depending on the parameters of the target star. Next, two of the sub-phases are performed: telescope pupil alignment and target acquisition. The rest of the steps in this phase depend on whether it is a blind search or if there is prior knowledge of the planet's location. For the blind search, instrument calibration and alignment will be performed, and data from the science and WFS cameras will be recorded (for two to four hours). To explore the entire area around the star, the spacecraft will roll 45 degrees about the telescope array axis (~30 minutes), re-acquire the deep null, and record the data again. This maneuver will be performed four times to collect data over the entire area around the star for a total integration time on the order of eight to 16 hours.

For discovery with prior knowledge, the same first two sub-phases are performed, and then the spacecraft is rolled to the exoplanet's position such that the null fringes do not obscure the known position of the target exoplanet. Then, instrument calibration and alignment is performed, and the data from the science and WFS cameras are read.

The last main chronological mission phase is characterization. After the proper telescope baseline is set, the sub-phases of telescope pupil alignment and target acquisition will be performed. The spacecraft will then roll to the exoplanet position and activate the desired band filter. Next, the instrument is calibrated and aligned, and data are recorded from the spectrograph and WFS cameras. The total integration time depends on the target star and planet, but on average, it is expected to be three months per target.

As the schedule requires, a combined discovery/characterization phase could be included. This phase would be used if there is a planet that needs to be characterized immediately due to its orbit, or spectroscopy could be put on hold if there is a suspected planet that needs to be verified.

Telecommunications with Earth will be performed at the same time as the science investigations. Communications with the DSN will occur two times per week for one hour for the first three years, and 1.8 hours for the last two years. For more information on telecommunications, see the MOS and GDS sections. As necessary, the spacecraft can perform communications separately from science.

The spacecraft has a safe or standby mode that will be utilized as needed to prevent the observatory from becoming stuck in a specific mode. This will be employed to recover the spacecraft from errors.