The Extrasolar Planetary Imaging Coronagraph: Architectures of Extrasolar Systems

ASMC Study Report

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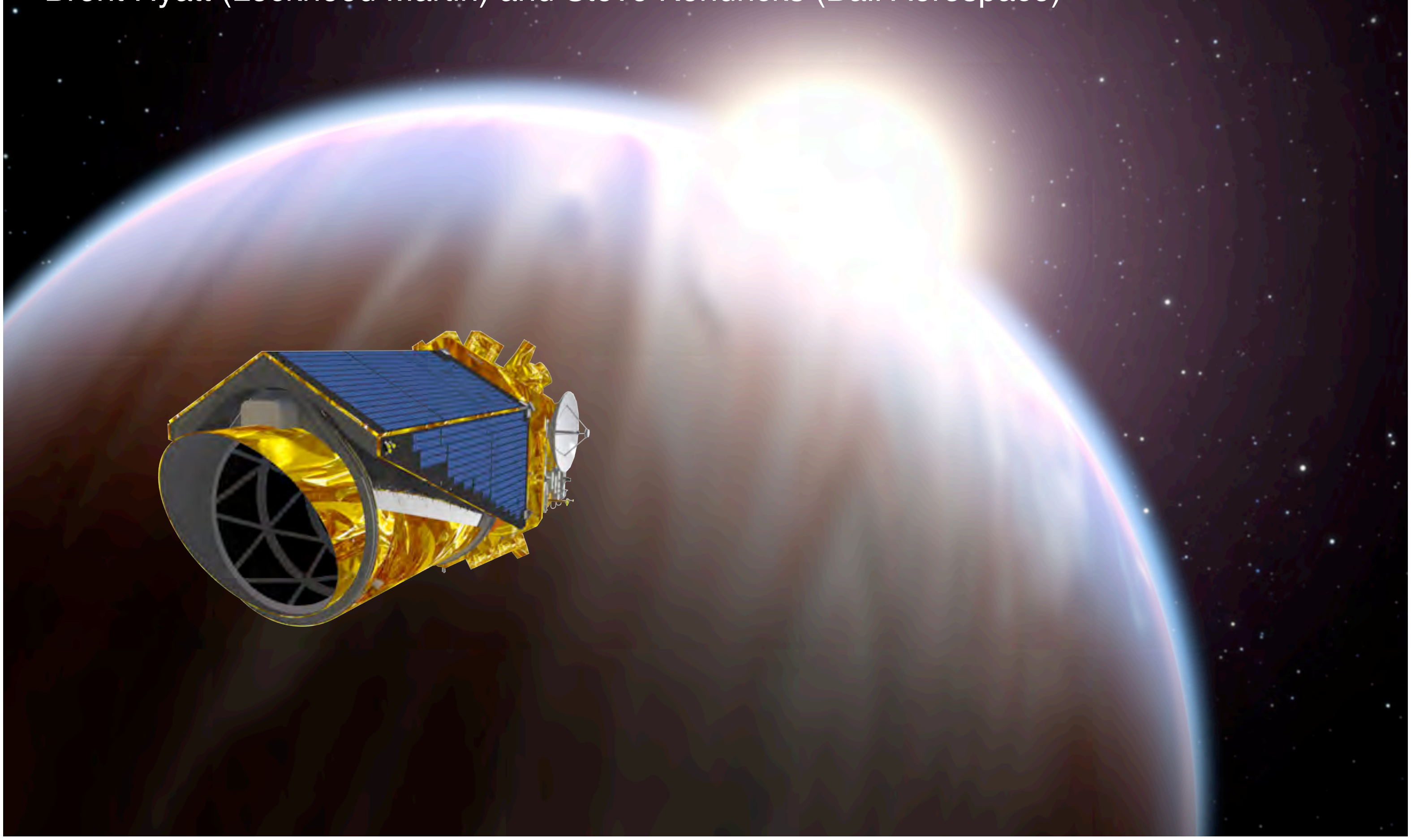
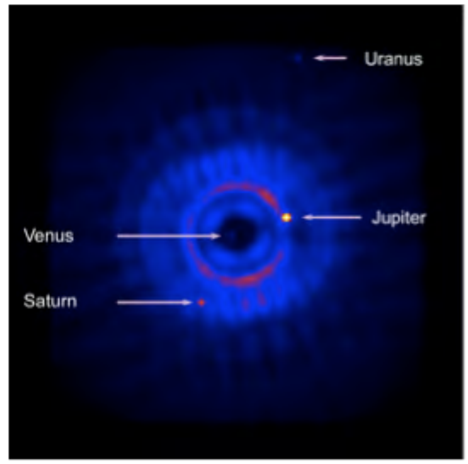
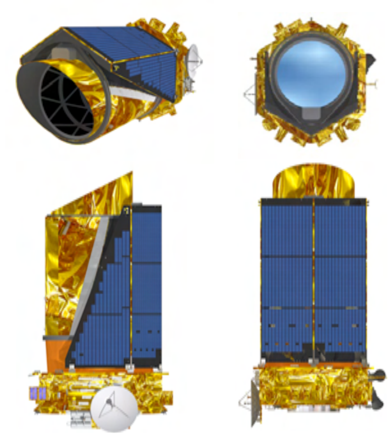


Executive Summary

The Extrasolar Imaging Planetary Coronagraph (EPIC) is a 1.65-m telescope employing a visible nulling coronagraph (VNC) to deliver high-contrast images of extrasolar system architectures. EPIC will survey the architectures of exosolar systems, and investigate the physical nature of planets in these solar systems. In particular, EPIC will focus on star systems possessing architectures similar to our solar system. EPIC will initially focus on imaging and characterizing fifteen RV detected exoplanet systems that currently lie within the discovery space of EPIC. By imaging the giant planets and measuring the zodi-like dust at a few AU, we can estimate the dust in the habitable zone based on dynamical arguments. Mapping the locations of dust islands will constrain the planetary dynamics and suggest locations where terrestrial planets might stably reside. EPIC's high level mission characteristics are shown below. The VNC features an inner working angle of 2λ/D (125 mas), and offers the ideal balance between performance and feasibility of implementation, while not sacrificing science return. The VNC does not demand unrealistic thermal stability from its telescope optics, achieving its primary mirror surface figure requires no new technology, and pointing stability is within state of the art. The science payload mounts on a heritage Kepler spacecraft bus that can accommodate the 1.65-m telescope, while meeting pointing requirements without a redesign, providing significant cost savings. The EPIC mission will be launched into a drift-away orbit with a five-year mission lifetime. EPIC's Astrophysics Strategic Mission Concept (ASMC) study that has focused on maturing a 1.65-m Probe mission concept, developing detailed system error budgets, via Structural/Thermal/Optical (STOP) analysis, to evaluate feasibility, and maturing cost estimates.

EPIC will investigate the architectures of nearby solar systems: *A simulated 48,000 sec EPIC observation of our solar system as viewed at 10 pc. The image is 5"x5" with 31.25 mas sampling. The dust disk model was provided by C. Stark (GSFC). Jupiter, Saturn, Uranus and Venus are detected in this observation .*



EPIC Mission Overview		
Parameter	**Performance**	**Spacecraft**
Telescope Optics	**1.65 meter aperture off-axis primary**	
Coronagraph	**Visible Nulling Coronagraph**	
Science modes	**≥10^9 contrast @ 2λ/D: 4.5"x 4.5" FOV** **≥10^7 contrast 2λ/D: 10"x10" FOV** **R = 20 – 50 spectroscopy**	
Pointing Stability	**4 mas (3 σ)**	
S/C Pointing	**2.5 arcsec**	
Power	**785 W**	
Mass	**1356 kg wet mass**	
Orbit	**Heliocentric, trailing Earth's orbit**	
Launcher	**Evolved Expendable Launch Vehicle (EELV)**	
Mission Lifetime	**5 years (7 year goal)**	
Cost	**$ 842 Million (70% Confidence limit)**	

1. Introduction and Background

The Extrasolar Planetary Imaging Coronagraph (EPIC) is a medium-class mission designed to survey the architectures of exosolar systems, and investigate the physical nature of planets in these solar systems. Addressing these science goals is an important precursor to future large-scale missions that will image and characterize terrestrial planets. EPIC also addresses the wider scientific questions regarding the diversity of extrasolar systems, and the nature of their gas giant planets. EPIC's approach is unique in that its strategy is to focus initially on the detection and characterization of planetary systems identified from radial velocity surveys. This is followed by a broader survey of nearby stellar systems, including binaries, mapping the architecture of these extrasolar systems by surveying their exozodiacal structures and identifying extrasolar planets directly, and indirectly via their interaction with dust debris. EPIC will focus on star systems possessing architectures more similar to that of the solar system, where the giant planets are in longer period orbits, as opposed to planets that have orbits on timescales of days. A key design feature is our team's decision to set the contrast requirement as $\leq 10^{9}$ at $2\lambda/D$ to insure that the mission is within the Exoplanet Probe scope, since our analysis finds contrast levels of $\leq 10^{10}$ drive observatory system stability outside the medium class mission cost environment (note $\textit{Contrast} \propto \textit{Wavefront Error}^{3}$). EPIC's science goals are fully aligned with NASA's Science plan, and will make significant progress towards the long-term goal of detecting life on other worlds.

EPIC employs a Visible Nulling Coronagraph (VNC) to detect and characterize extrasolar planets. The VNC features an inner working angle of $2\lambda/D$ (125 mas @ 500 nm) that takes full advantage of EPIC's 1.65-m telescope aperture to maximize the discovery space for extrasolar planets. EPIC delivers high-contrast images of extrasolar system architectures with a low-risk design that offers a realistic balance between performance and ease of implementation. In Foldout-1 we describe how the VNC operates works.

2. Objectives and Requirement

2.1 Science Objectives

EPIC is a medium class mission concept designed to address exoplanet exploration. It will survey the architectures of exosolar systems, conducting a census of planets in these systems and setting limits on the zodiacal dust emission. EPIC will investigate the physical nature of planets detected in these solar systems. EPIC's science objectives and their relationship both to the science goals in NASA's Science Plan are summarized in Table-1. EPIC's science goals can be divided into two areas of focus, the detection and characterization of extrasolar planets, and the characterization of zodiacal dust structures within extrasolar planetary systems.

2.1.1 Architectures of extrasolar systems: Extrasolar RV Planet Characterization

Fifteen exoplanets detected by radial velocity surveys currently lie within the discovery space of EPIC given its $2\lambda/D$ inner working angle (IWA) of 125 mas. Figure-1 illustrates the parameters of the RV selected stars currently available for study with EPIC and Table-2 summarizes their properties. EPIC will conduct its science investigations using two functional modes: (1) *discovery* and (2) *characterization*. The suite of investigations and measurements that will be performed are summarized in Table-1. In *discovery* mode, a high contrast image of the entire field of view surrounding the nulled starlight is built from a sequence of observations (Foldout-1). This survey mode is used to locate and track any possible planets in the stellar

Table -1: *EPIC's Science Goals well defined and map to NASA's science plan*

NASA Science Plan	EPIC Science Goals	Science Investigation
Area: Search for earth-like planets **Question:** Is there life elsewhere? **Research Objective #4**: Create a census of extrasolar planets and measuring their properties **Targeted Outcomes**: Determine the frequency with which planets are found within the habitable zones of other stars and characterize their physical properties, such as mass, diameter and orbital parameters	Determine the properties of RV selected gas giant planets and characterize their atmospheres	Directly image extrasolar planets in systems with known RV detected planets,
		- Characterize the atmospheres of extrasolar planets detected in systems with known RV detected planets,
		- Determine the orbital inclinations and masses of planets in these systems
		- Map and characterize the exozodiacal structures in these systems to detect unseen planets and determine the exozodiacal dust emission in their habitable zones
	Investigate the diversity of planetary system architectures	Survey nearby exosolar systems to search for extrasolar planets and characterize zodi dust structures.
		- Characterize the atmospheres of extrasolar planets detected in systems
		- Determine the orbital inclinations and masses of planets in these systems
		- Map and characterize the exozodiacal structures in these systems to detect unseen planets and determine the exozodiacal dust emission in their habitable zones

system if their location(s) are unknown. Once a planet is unambiguously located (5σ detection), spectroscopic *characterization of* the planet's atmosphere can be conducted efficiently without the mapping sequence. For the most interesting planets, EPIC will revisit them during their orbit to study the variation of their properties.

Figure-1: *EPIC's discovery space. The contours show the planet orbit semi-major axis versus planetary mass in which Jovian planets can be detected for distances of 5 pc, 10 pc, 20 pc, and 30 pc. The planetary mass is given in M_{Jup} and in M_{Earth}. The semimajor axis is given in mas and AU for a host star at 10-pc distance (the axis changes for other stars according to their distance). The open circles are stars with planets detected in radial velocity surveys and closed circles mark the planets that can be observed with EPIC. The diamonds mark planets detected with coronagraphs.*

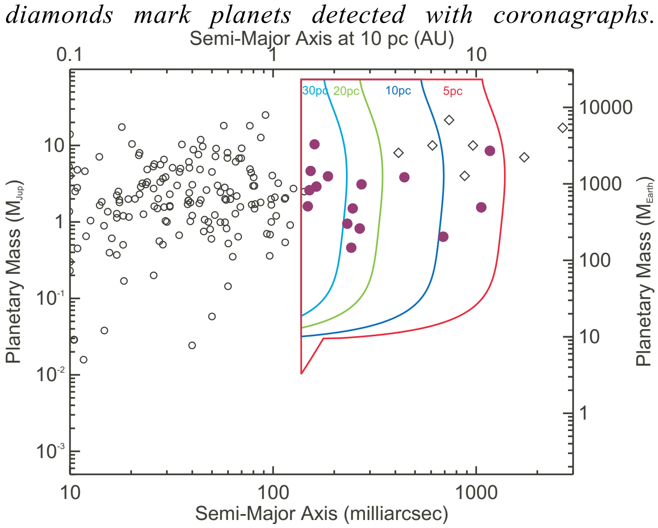


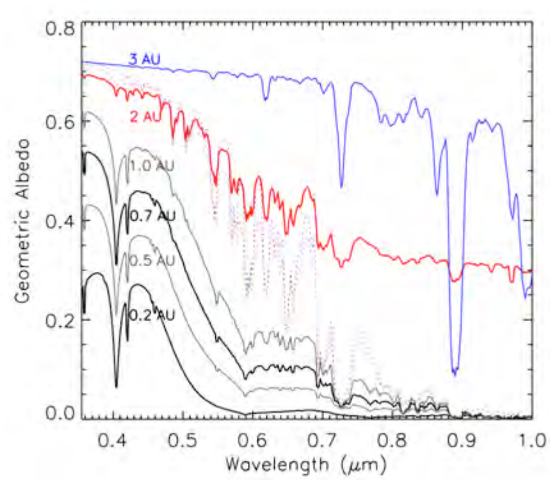
Table-2: *EPIC's inner working angle permits the direct imaging of 15 RV Detected Exoplanets*

Name	Msini	SMA (au)	SMA (asec)	Dist. (pc)	Spectral Type
14 Her b	4.64	2.77	0.153	18.1	K0V
47 Uma b	2.6	2.11	0.151	13.97	G0V
47 Uma c	0.46	3.39	0.243	13.97	G0V
55 Cnc d	3.84	5.77	0.443	13.02	G8V
ε Eridani b	1.55	3.39	1.059	3.2	K2V
γ Cephei b	1.6	2.044	0.148	13.79	K2
GJ 832 b	0.64	3.40	0.688	4.94	K2V
GJ 849 b	0.82	2.35	0.267	8.8	M1.5V
HD 154345 b	0.95	4.19	0.232	18.06	M3.5V
HD 160691 c	3.1	4.17	0.273	15.30	G8V
HD 190360 b	1.5	3.92	0.247	15.89	G3 IV-V
HD39091 b	10.35	3.29	0.160	20.55	G6 IV
HD 62509 b	2.9	1.69	0.163	10.34	KIIIb
Ups And d	3.95	2.51	0.186	13.47	F8V
SCR 1845 b	4.5	4.5	1.17	3.85	M8.5

Spectra and images of extrasolar giant planets help to constrain their masses, atmospheric composition, and particularly their cloud decks. Because the atmospheric temperature of a giant planet depends on a combination of its age, mass, composition, photochemistry, and the incident flux, the EPIC mission will measure an illuminating assortment of planetary spectra and albedos. EPIC will image RV planets with masses (*M*sin *i*) ranging from 0.4 to 10.35 M_J and orbital semimajor axes from 1.7 to 5.8 AU (Table-2). Assuming a typical stellar age of 2 Gyr this collection of planets encompasses effective temperatures ranging from 100 to over 400 K, which includes a wide variety of atmospheres, from cold, ammonia-cloud dominated planets to planets with water clouds, to cloudless worlds. Certainly there will be more long-period RV planets known by the time of launch and EPIC will discover more as well that will add further diversity.

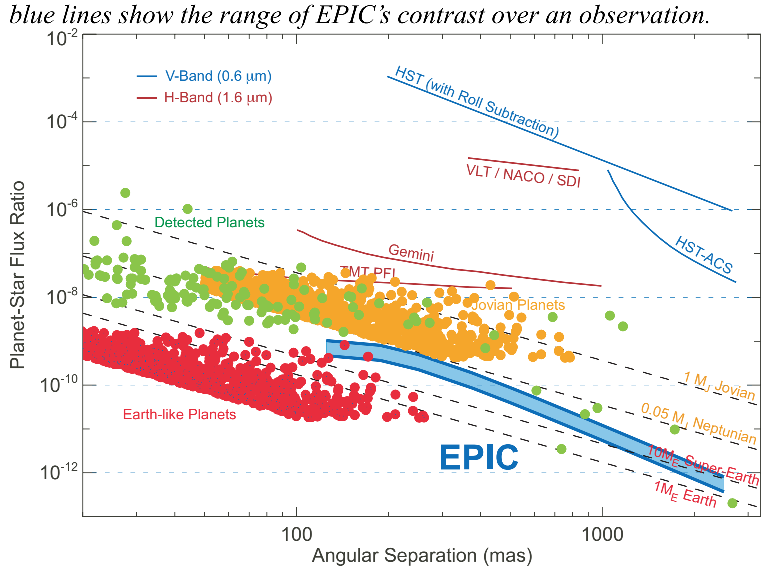
Over this range of planetary properties there will be a great diversity of spectra (Figure-2). While Jupiter's internal heatflow makes only a modest contribution to its atmospheric thermal structure, this will not be true for younger or more massive planets, which will be warmer because of their greater internal heatflows. Likewise a Jupiter found closer or farther from its primary will be warmer or colder than Jupiter itself. Such considerations are important because atmospheric temperature controls which condensates are found in the atmosphere and clouds control the reflectance spectra of giant planets, particularly in the red. The ammonia cloud decks which today control Jupiter's appearance in reflected light evaporate in the atmosphere of a warmer planet, revealing the much thicker and brighter water clouds that lie beneath. An even warmer Jupiter will lack water clouds and consequently be bright in the blue, from Rayleigh scattering, and dark in the red, from methane absorption. Extrasolar Neptunes that are highly enriched in C-N-O species will also have distinctive spectra. Because of this great diversity in spectra, much can be learned even from broadband albedo measurements obtainable from filter photometry. Low resolution spectra, at R~20 to 50, will constrain the abundance of methane, and thus determine atmospheric metallicity as a function of mass and orbit as well as stellar type. In our own solar system giant planet atmospheric metallicity increases with orbital radii and decreases with mass, which is a fingerprint of the planet formation process. Understanding how these trends vary among other stellar systems is a top priority for improving our knowledge of the planet formation process. For the known RV planets two EPIC images spaced over the planetary orbit will constrain the inclination of the orbit and thus the mass. Since the mass of these objects will be known, EPIC albedos and spectra will

Figure-2*: Model geometric albedo spectra for a Jupiter-mass planet at various distances from a solar type star. Dotted lines are models for the 3 and 2 AU planets but without cloud opacity. While these spectra are cast as a function of orbital radius, the same sequence would result for a giant planet kept at a fixed distance and modeled with progressively younger ages, higher masses, or earlier type stellar spectral types, all of which would produce warmer effective temperatures, all else being equal. For example an 8M_J planet at an age of about 1 Gyr would have a similar spectrum to the planet at 1.0 AU. A 4M_J at the same age would be similar to a cloudless planet (dotted line) at 2 AU.*



constrain surface gravity through comparison to models and thus radius and consequently bulk density and composition. EPIC spectra will also determine the thickness and altitude of cloud layers and the abundance of methane. Taken together these constraints will open new windows into our understanding of giant planet atmospheric structure, composition, and energetics as well as planetary composition and formation. For newly discovered planets, lacking RV data, EPIC spectra will constrain surface gravity and atmospheric temperature and thus still place constraints on the nature of the planets and their mass. Comparisons to the RV detected planets will greatly aid in this interpretation.

Figure 3*: EPIC's nominal contrast range allows it to detect gas giants and intermediate gas giant planets. EPIC can potentially detect superearths and terrestrial planets when null phasing is done on shorter timescales. The orange dots show $1M_J$ Jupiters at 3 AU (luminosity corrected) around any of the potential EPIC survey targets. Red dots show earths in the habitable zone (luminosity corrected), and green shows all currently detected planets (RV, Imaging, transit). The blue lines show the range of EPIC's contrast over an observation.*

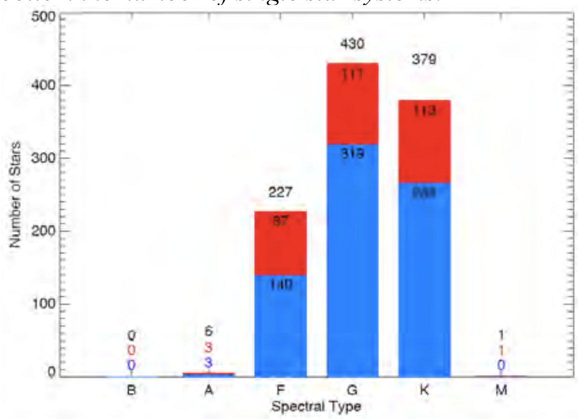


2.1.2 Architectures of extrasolar systems: Extrasolar planet survey

The discovery space enabled by an EPIC survey of nearby stars is shown in Figure-3 and demonstrates the contrast range during a 7,000 sec exposure. It illustrates that EPIC can readily detect gas giant and intermediate mass planets in extrasolar systems in our target list. The achievable contrast ratio depends on the system's stability level (see Section 3). Null phasing is repeated every 7,000 secs to prevent contrast falling below 10^{9}. *However, EPIC can reach ~5x10^{10} for specific targets by null phasing on a shorter timescales (~2000 secs) allowing the detection of some superearths or terrestrial planets.* Due to an abundance of candidate stars, EPIC could potentially detect Jupiter analogs around >300 stars. The candidate list developed for the TPF-SWG is comprised of all Hipparcos stars within 30 pc. The EPIC target list is that subset of these stars for which a jovian planet with a 1-10 AU orbital separation can be detected at 5σ in less than 20 hours of integration using EPIC's broad discovery filter, F560W, and assuming a typical value of the planetary albedo of 0.5. The distribution of stars selected for our survey is shown in Figure-4, and includes binary stars.

EPIC has the unique capability to observe binary and to a limited extend multiple star systems with three and more companions. This is important since approximately 50% of the nearby star systems have multiple companions (Duquennoy and Mayor 1991). Possible planetary orbits in binary systems are S-type orbits, the planet orbits one star, or P-type orbits where the planet orbits all stars. The EPIC target list of 1044 targets includes 315 multiple star systems. Since not all orbital parameters for these targets are known, Our initial analysis of characterized binary systems indicates that 56 systems allow P-type orbits and 75 systems S-type orbits

***Figure-4**: Distribution of spectral type of EPIC targets for the primary target list. The numbers on top the columns are the total number of stars of the particular spectral type. The number below is the number of binary star systems and the number at the bottom the number of single star systems.*



observable with EPIC. For most of the remaining systems with unknown orbital parameters and unresolved companions we can assume that EPIC can also observe planets in P-type orbits. Epic's ability to observe binary system is important because it increases the number of nearby targets with large discovery space (EPIC's target list includes 17 binary star systems within 10 pc and 109 within 20 pc). The statistical frequency of planets in these systems is about the same as for single stars (Bonavita and Desidera 2007).

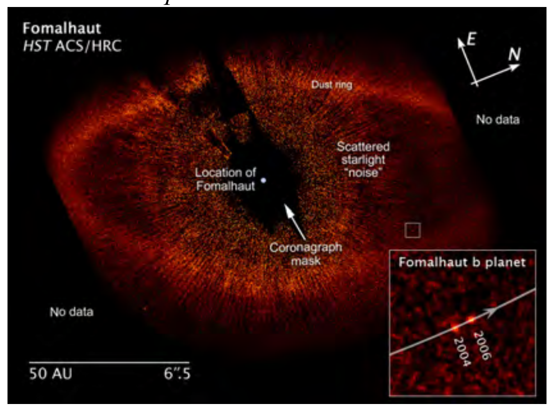
2.1.3 Architectures of extrasolar systems: Debris Disks

EPIC will also study planetary systems by observing circumstellar disks. Debris dust around stars, generated by the collisions and evaporation of planetesimals, is both a source of noise against which planets must be detected and a signal of the architecture of planetary systems. Our Solar System contains only one reservoir of bodies producing significant amounts of dust at present. The asteroid belt has survived 4.5 Gyr and has its current structure because of the dynamical influences of the planets, primarily resonances with Jupiter and the migration of Jupiter and Saturn (Minton & Malhotra 2009). The dust created in the asteroid belt is observed in the inner solar system as the Zodiacal dust. The surface density of planetesimals beyond the asteroid belt is much lower and so is the dust production rate. The Kuiper Belt is actually quite sparse, having been cleared by the migrations of the giant planets, so much so, that dust from the Kuiper Belt has not been detected optically. By analogy, the location and structure of dust bands around other stars will reflect their planetary system architectures.

In its 2008 report the Exoplanet Task Force found that measuring the dust around other stars to the level of 10 zodis and below was essential for assessing the potential for direct imaging of an Earth-like planet around that star. The zodi has a surface brightness of 21.75 mag/arcsec^2 at 1 AU at V-band, as observed pole-on from outside the system. By imaging the giant planets and measuring the zodi-like dust at a few AU, we can estimate the dust in the habitable zone based on dynamical arguments. EPIC can detect at $S/N > 5$ the surface brightness of 1 Zodi (21.75 mag/sq. arcsec) at <4 AU for every star in which it searches for planets.

The dust beyond the habitable zone is of great interest for what it says about the overall planetary architecture. The ExoPTF further found that studying the distribution of dust was "an essential complement" to the studies of planets themselves. Structure within the dust disk may indicate regions where stable orbits exist, i.e., where the resonances of large planets allow planetesimals to orbit for many millions of years. Within our Solar System, the asteroid and Kuiper Belts and the asteroids trapped in Jupiter and Neptune's planet-sun L4 and L5 points are such examples. For systems in which planets cannot be imaged directly, knowing the locations of dust islands will constrain the planetary architectures and suggest locations where terrestrial planets might stably reside. If close-in clumps and asymmetries can be observed in a time-resolved manner, they will reveal the unseen planet's orbit. Dynamical sculpting of the nearby debris disk around Fomalhaut is a good example (see Figure-5), and the dynamics of the dust disk permitted additional mass constraints to be placed on the planet.

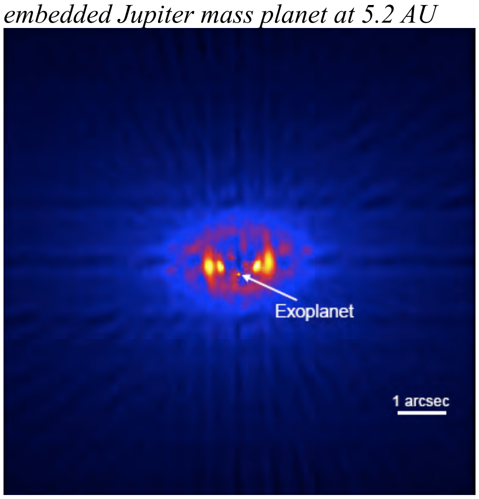
__Figure-5__: Optical image of the Fomalhaut dust belt and its recently detected (Kalas et al. 2008) planet. EPIC will probe the inner circumstellar environment around Fomalhaut for zodiacal dust structures and planets.



Another example, the nearby star Epsilon Eridani has an extended cold disk with structure probably caused by a giant planet at 40 AU (Quillen & Thorndike 2002) as well as perhaps an inner planet at 3.4 AU detected by RV. EPIC will be sensitive to 2 zodi of dust in its habitable zone in 8 hours of integration. If structures such as that seen around Eps Eri are present in the inner (1 – 5 AU) regions around other stars, EPIC will image them, even if they are created by much lower mass planets (Stark & Kuchner 2008). The simulation shown in Figure-6 shows what a resolved disk due to a 10 M_earth planet might look like. The planet carves a hole and generates clumps, both of which will orbit with it.

For young stars farther away, EPIC will measure the dust content and structure in regions analogous to our giant planet region. Mapping disks in different filters to determine the wavelength-dependent dust albedo will constrain the dust composition and production rate. The Zodiacal light is slightly red, and scattered light from the debris disk around HR 4796A is very red (Debes et al. 2008). As for the red slope at the 400-500 nm region of giant planet spectra, dust reddishness probably indicates the presence of organics. In disks, these may be created during cosmic ray bombardment of ices. This could provide an important source of organic material to forming terrestrial planets.

__Figure-6:__ EPIC will image extrasolar planets, and zodiacal dust structures. A simulated 48,000 second, V-band EPIC observation of a 60^0 inclined debris disk at 10 pc, dynamically sculpted by an embedded Jupiter mass planet at 5.2 AU



2.2 Expected Significance

EPIC will provide our first view of the architecture of solar systems similar to our own. It will advance the field of exoplanet science by providing the first detailed characterization of mature gas giants similar to those in our own solar system, rather than the hot systems characterized by transit observations, and young systems detected from the ground. EPIC will complement the recent observations of young exoplanets by HST (Kalas et al. 2008; Marois et al. 2008) with observations of the inner regions of systems not accessible to HST. EPIC will also complement JWST, which will focus on imaging exoplanets around late type stars where its infrared capabilities are at a premium.

2.3 Relevance to NASA Programs

The EPIC science goals are fully aligned with NASA's science goals (See Table-1). EPIC will contribute to the search for earth-like planets. Specifically, its science goals will contribute to the question is there life elsewhere, by trying to measure the properties of solar systems where future searches for terrestrial planets will be undertaken. It is also possible that EPIC may actually image superearths, either directly or indirectly, via analysis of the zodiacal dust distribution in these systems. EPIC will also create a census of planets and their properties both in known RV detected systems and from a survey of nearby stellar systems.

2.4 Precursor Science

The major precursor science programs for EPIC are radial velocity surveys of nearby systems. It is expected that the number of extrasolar planets detected in EPIC's discovery space (Figure-1) will increase with time as longer period systems are detected.

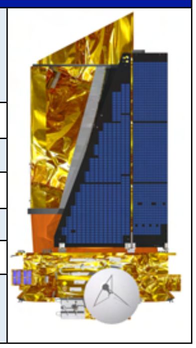
3. Technical Approach and Methodology

EPIC has a mature set of requirements flowed down from its science goals. A science traceability matrix is presented in Foldout-1. For the ASMC study of EPIC, the science team worked with NASA/GSFC, LMCO, BATC, and SAO/CfA to develop a realistic, and realizable mission concept with carefully assigned risks. For a Probe class mission we chose to implement our science requirements by means of a modestly sized (1.65-m) telescope feeding a Visible Nulling Coronagraph, and set our contrast requirement at $\geq 10^9$. EPIC delivers high-contrast images of extrasolar system architectures with a low-risk Visible Nulling Coronagraph (VNC) design that offers a realistic balance between performance and ease of implementation. The VNC features an inner working angle of $2\lambda/D$ (125 mas @ 500 nm) that takes full advantage of the 1.65-m telescope aperture to maximize the discovery space for extrasolar planets (see Figure-3). In selecting a coronagraph design for EPIC, the Science Team has embraced a design philosophy that sets an achievable contrast level, and focuses on the system-level requirements that are specifically driven by the coronagraph e.g. pointing, thermal stability and telescope wavefront error (WFE). EPIC employs a heritage Kepler spacecraft bus, since it can accommodate the 1.65-m telescope without redesign, and already meets the spacecraft pointing requirements, providing a real cost saving.

3.1 Mission Description

EPIC will be launched into a drift-away orbit to make high contrast observations of extrasolar planetary systems. A summary of the mission is shown in Table-3. The spacecraft comprises a 1.65-m telescope, feeding a visible nulling coronagraph, mounted on a Kepler heritage bus. The Kepler bus already meets the mission-level requirements for EPIC and does not require a redesign to accommodate the 1.65-m primary mirror. The Kepler bus, in combination with a fine steering mirror in the optical chain, can also meet the pointing requirements imposed by the EPIC optical error budget. The EPIC payload will be launched into a heliocentric earth trailing orbit, similar to Spitzer, which provides excellent sky coverage, combined with thermal stability. Since EPIC has a very modest data rate requirement (0.5 Gbits/day) the "drift-away" orbit does not drive communications costs. EPIC is designed to be a Class-B mission with redundancy on all major systems. We have designated a nominal mission lifetime of 5 years. EPIC's Science Operations center will be located at the Smithsonian Astrophysical

***Table-3**: Epic's Key Mission Parameters*

Science Payload	**Performance**	
Telescope Optics	1.65 meter aperture off-axis primary	
Coronagraph Design	Visible Nulling Coronagraph - Instrument throughput: 18% - Instantaneous Bandpass: >20%	
Science modes - Discovery - Discovery - Characterization	 $\geq 10^9$ contrast @ 2λ/D: 4.5"x4.5" FOV $\geq 10^7$ contrast @ 2λ/D: 10"x10" FOV (w/o SFA) R=20 – 50 spectroscopy	
- Discovery mode	Photon counting, 512x512 CCD detectors Readnoise: zero in photon counting mode Quantum Efficiency: 85% @ 700 nm	
Spacecraft	**Performance**	
Pointing - Via Spacecraft & fast steering mirror	Pointing Stability: 4 mas (3 σ) Coarse Pointing: 2.5" (3 σ) Abs. Pointing Knowledge: 5"	
Power	785 W	
Mass	1356 kg wet mass	
Orbit	Heliocentric, trailing Earth's orbit	
Launcher	EELV	
Mission Lifetime	5 years	
Communications	Ka-Band via HGA, <0.5 Gb/Day X-Band via Omni	

Observatory(SAO), and its science data archive will be located at the Space Telescope Science Institute (STScI).

3.2 Operations Description

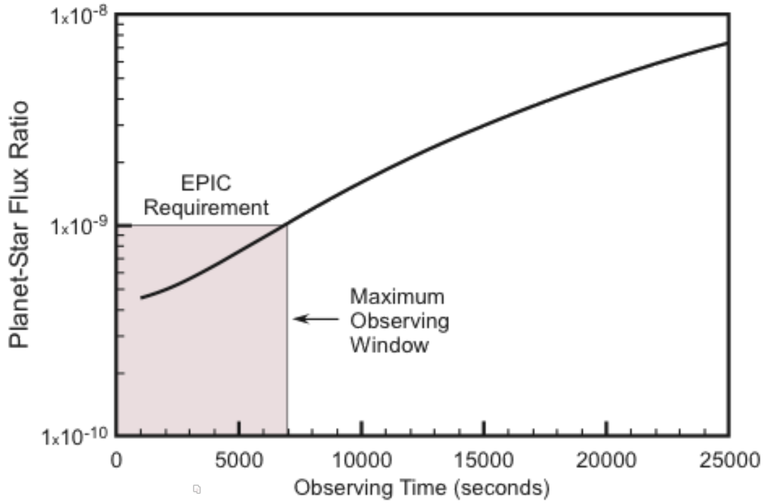
EPIC's Mission Operations Center (MOC) and Science Operations Center (SOC) will be based at GSFC. The MOC/SOC will be responsible for all aspects of observatory planning and scheduling, together with health and safety monitoring, data capture and level-0 data processing. The Smithsonian Astrophysical Observatory (SAO) will act as the science data processing facility and will operate data analysis pipelines that generate Level 1-3 data products. SAO will also be responsible for science performance evaluation of the data and setting long term science priorities. All data products will be delivered to STScI for data arching in the MAST archive.

3.3 Technical Feasibility

We believe that the VNC offers the optimum balance between performance and systems-level complexity. Much of dialogue in coronagraph design thus far has been focused on achieving the optimum throughput, or the best inner working angle. However, the EPIC team's experience has led us to focus on how the coronagraph works within a system, since the requirements the coronagraph imposes on the telescope and the spacecraft bus *present the true challenges, and represent the real cost drivers*.

EPIC's contrast requirement at $\geq 10^9$, represents a good balance between science return and technical challenges. Within the Probe cost cap, the detailed study of terrestrial planets is constrained by aperture size limitations, which restrict collecting area and inner working angle, so we choose to focus *primarily* on gas giant planets and exozodiacal dust. Our requirements analysis shows that to maintain contrast $\geq 10^{10}$ requires overall observatory stability to be held at $\geq 10^{11}$. This drives observatory stability requirements to levels that are challenging and hard to verify, presenting an unacceptable cost risk, that requires mitigations such as costly laser metrology. In Table-4 we illustrate the WFE and WFE-stability requirements for three cases that summarize the challenges for different contrast levels (note that contrast varies as WFE^3). In order to assess the feasibility of our design we have assembled detailed error budgets and Structural/Thermal/Optical (STOP) analyses that show it will meet requirements. Detailed STOP modeling of our observatory system, shown in Figure-7 demonstrates that EPIC will hold

Figure 7: *EPIC's null and contrast stability has been modeled using inputs from end-to-end STOP modeling of the instrument. The planet-star flux ratio is shown as a function of observing time. Following a nulling setup procedure, the contrast is better than 10^9, and drifts up to EPIC's requirement of 10^9 in 7000 seconds. The drift is due to thermally induced changes in the telescope optics and their support structure. Note that the first 2000 seconds yield flux ratios of $<5x10^{10}$.*



contrast at ≥10^9 for 7000 seconds before effects such as residual mirror thermal gradients and secondary mirror motions lead to null drift. Note that these crucial drifts are often ignored, but occur even with active thermal control of the system.

The EPIC science plan has been flowed into science payload and spacecraft requirements and high-level mission requirements EPIC's design requirements are mature since they are based on analyses and performance trades conducted during the ASMC study and two previous Discovery mission proposals. This analysis has also been flowed into our costing. An example is the optical error budget for the science payload (see Appendix). The optical error budget combines static and dynamic wavefront error allocations for each optical element in the system. It flows structural and thermal requirements to the payload and spacecraft systems. Consequently, we are able to place precise specifications on the telescope mirrors in order to facilitate accurate costing.

Table 4*: EPIC's WFE and stability analyses demonstrate the challenge of high contrast imaging. The red column denotes the requirements flowed down from the ≥10^9 contrast requirement.*

Contrast @ 125 mas	Units	Disks 10^8	Jovians 10^9	Earths 10^{10}
Residual WFE	nm RMS WFE	0.038	0.012	0.004
WFE drift per control step	nm RMS WFE	0.070	0.022	0.007
RMS Reflectivity error	%	0.158	0.050	0.016
Polarization Error	degrees	0.032	0.010	0.003
Pointing precision (LOS jitter)	mas (3σ)	7.310	4.100	2.245
Beam Walk per WF control step	mas (3σ)	7.310	4.100	2.245
Pupil Plane Null Depth =		**9.80E-07**	**9.84E-08**	**9.82E-09**
Contrast at 125 mas (2 λ/D) =		**1.00E+08**	**1.00E+09**	**1.00E+10**

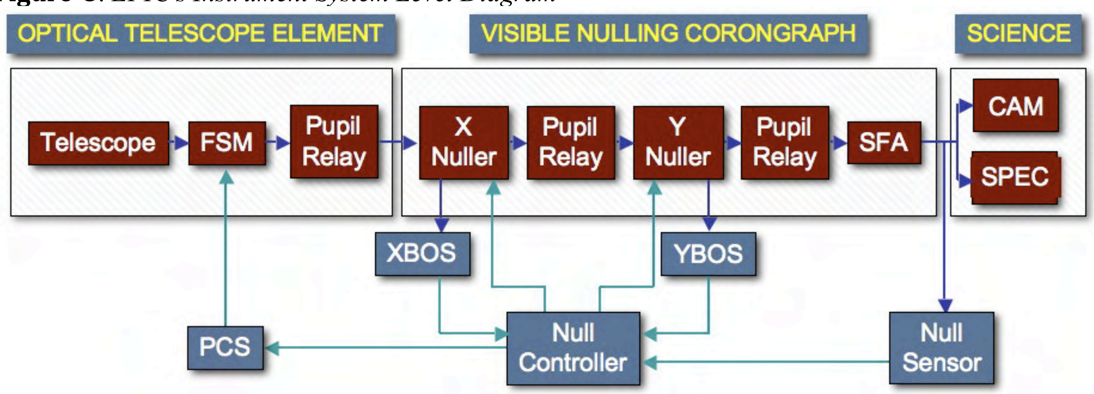
The VNC has been demonstrated with a single fiber in white light by M. Shao (JPL) to achieve the equivalent of 10^8 contrast. The EPIC team has demonstrated the equivalent of 10^7 with the GSFC testbed operating in air, and are just transiting to vacuum tank operations. Our team has a robust technology integration plan to mature the VNC to TRL-6. The current Technology Readiness Levels (TRLs) are summarized in section-6, with many of the technologies already mature (≥ TRL-6). The flight requirements for the VNC are succinctly stated as ≥10^9 contrast, with 20% passband, for ≥ 7000 seconds. In order to demonstrate 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. Currently, VNC testbeds are under development at both GSFC and JPL.

3.4 System Description

3.4.1 Science Payload

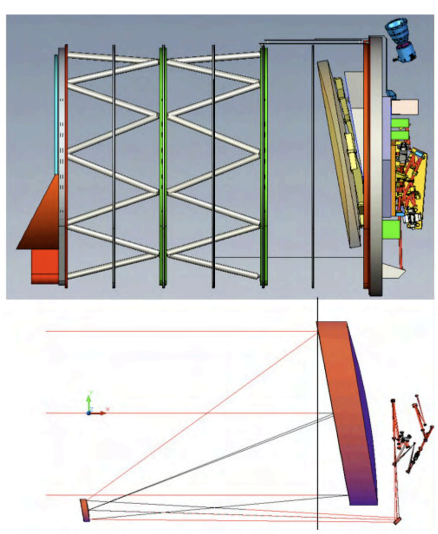
The science payload consists of three primary systems: (1) optical telescope element (OTE), (2) visible nulling coronagraph (VNC), and (3) science instruments; as shown in Figure-8. These systems are coupled to the spacecraft bus that provides guidance, navigation, fine pointing, power, communications, C&DH and telemetry. The EPIC design uses an off-axis OTE, yielding an unobscured collecting aperture. The OTE feeds light to the VNC and subsequently to the science instruments to observe and characterize planets and dust disks, at small angular separations, around nearby stars.

Figure-8: *EPIC's Instrument System Level Diagram*



The OTE is an unobscured two-mirror cassegrain telescope with metering truss, support structure, pupil relay and fine steering mirror (FSM); the pupil relay and FSM physically reside within the VNC enclosure to insure stability but are considered as part of the OTE. The VNC contains fore optics which relays the OTE entrance pupil onto the fine steering mirror (FSM) and a pupil relay to relay the pupil at the into the VNC. The VNC performs starlight suppression to increase the contrast of the dim planet with respect to the bright star. The VNC consists of both an X- and Y-nuller with a pupil relay between them. The pupil relay in the OTE relays the telescope exit pupil onto a multiple mirror array (MMA) within the X-nuller and the pupil relay between the X- and Y-nullers relays the exit pupil to a 2nd MMA within the Y-nuller. A subsequent pupil relay relays the pupil image onto the spatial filter array (SFA). The VNC has three output ports (Figure-9 bottom) which function as part of the control system, these are: (i) the X-bright object sensor (XBOS), (ii) Y-bright object sensor (YBOS) and (iii) nulled beam which feeds into the science instruments. The XBOS is used during coarse phasing of the system and continually in closed-loop to feedback to the pointing control system (PCS). It sees an image of the bright star and performs rapid centroiding and feeds back pointing offsets to the PCS to drive both the spacecraft pointing and FSM. The two MMAs

Figure-9*: EPIC's OTE design*



and the SFA work in concert with feedback from the three output ports of the two nullers to, both passively and actively, correct amplitude and wavefront errors. The YBOS operates as part of the null control system to monitor and control the MMAs during science operations. In addition during the setup for each new target a pupil plane null sensor is used to fine-tune the MMAs to achieve the contrast of 10^9 or better. The two science instruments are the imaging camera and a dispersing spectrometer and are physically mounted to the VNC enclosure. The imaging camera operates in two modes: narrow field-of-view (FOV) with the SFA and wide FOV-field of view without the SFA.

The OTE consists of a Primary Mirror (PM) assembly (with entrance pupil at PM), a Secondary Mirror (SM) assembly, the metering structure between these assemblies, a SM alignment mechanism, VNC interface mounting features, OTE baffles, supporting electronics, and thermal control. The OTE metering truss, support structure, PM, SM, mounting plate, VNC and science instruments are shown in Figure-9 (top). The VNC and science instruments are within the yellow region on the back-side of the mounting plate. The optical design (raytrace) is shown in Figure-8 (bottom). EPIC's approach permits the PM and SM to have benign (λ/9 rms wavefront error) optical tolerances, circumventing the need for highly demanding figure tolerances using undemonstrated technology.

EPIC is relatively insensitive to thermal gradients in the PM, yielding thermal stability requirements that are readily achievable and mitigate risk. Our thermal, structural, and optical analysis indicates PM WFE sensitivities of 0.8 nm/K and 1.4 nm/K for radial and axial gradients respectively. This implies that to meet the dynamic wavefront error stability requirements EPIC needs to hold temperature gradients to only Δ1.6 K radially and ΔT=0.9 K axially. A relatively benign, and easily implemented, thermal design will meet these requirements. Room temperature operation is essential to minimizing mirror figuring costs and mirror test risks and ensuring simple integration and testing (I&T). EPIC's optical train is both tested and flown at laboratory temperatures.

***Table-5**: EPIC's OTE Wavefront Contributors have been analyzed*

Contributor	Static Wavefront Error (nm RMS)				Stability
	Low 0-1 cpa	Mid 1 - 16 cpa	High >16 cpa	Total All cpa	nm (RMS) All cpa
PM	27.8	40.0	11.4	50.0	6.0
SM	3.3	4.8	1.4	6.0	6.0
Fold Mirror	3.3	4.8	1.4	6.0	6.0
OTA Alignment	11.1	16.0	4.5	20.0	6.0
Coatings	-	-	-	1.0%	-
Total OTA	30.3	43.6	12.4	54.5	12.0
Total (static + dynamic)					**55.8**

The VNC has capability to sense and correct OTE wavefront errors (WFE) at the outset of a science observation. During an observation these errors drift and are continually sensed and corrected and the contrast becomes limited by the drift between successive null control steps an correctable range and resolution of the DMs. The OTE wavefront errors are allocated among low, mid and high spatial frequencies and stability per Table-5 and represent the integrals of the wavefront power spectral densities in the bands from 0-1 cycle per aperture (cpa), 1-16 cpa and 16-Infinity cpa; the stability is integrated over all spatial frequencies. These allocations were developed form the system level error budgeting based on sensitivity analysis for EPIC as described in the Appendix.

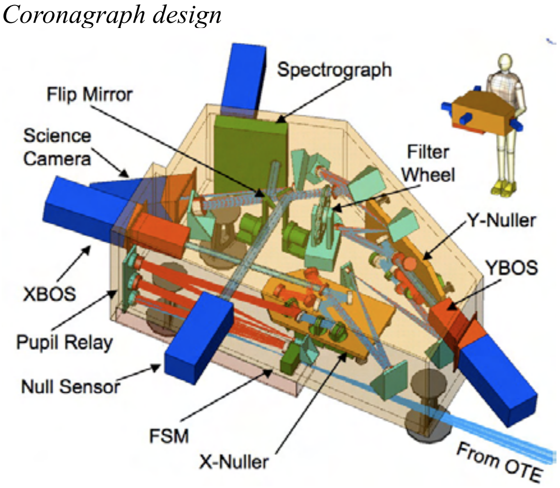
Table 6: Key Features of the Visible Nulling Coronagraph

Key VNC Features	Benefits
2 λ/D inner working angle	- Provides access to a wide range of planet semi-major axes
Integrated control signals	- Bright output channels from nullers provide signals for diversity-based null control and fine jitter sensing - Rapid convergence of wavefront sensing mitigates need for additional instruments (2 pm WFE in <100 sec is << OTA drift timescale)
Achromatic Phase Shifters yield broad bandpass (480 - 960 nm)	- Provides larger signal for null control - Broadband detection mode for direct imaging - Spectroscopic observations cover full passband
Lower sensitivity to OTA drift	- Manageable OTA stability requirements

The VNC is a differential approach, and less driven by absolute tolerances on the optics. It employs a direct approach which senses and controls only that which is important to the science, i.e., null depth, and directly controls it both passively (via the SFA), and actively (via the MMAs), rather than directly sensing and controlling the wavefront and amplitude errors. The key features of the VNC and their benefits are summarized in Table-6.

Foldout-1 shows a schematic outlining how the VNC works, and how it is used to make science observations. The VNC design with science instruments is shown in Figure-10. The VNC suppresses the starlight to increase the contrast of the planet light and consists of a modular box mounted on the back of the OTE mounting plate. Light from the OTE passes into the VNC (Figure-8) through a pupil relay and through an X-nuller and a Y-nuller (orange flats within VNC) which separate on-axis starlight from off-axis planet light. The starlight is used to drive the fine pointing system and the off-axis light is the science light containing the planet light and dust/debris disk. The science channels consist of an imager with spectral filters and a dispersing slit spectrograph. *The flight requirements for the VNC are succinctly stated as >10⁹ contrast in a >23% passband for greater than 1000 seconds*. 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. Lab demonstrations have achieved ~10^7 contrast and efforts are underway at both GSFC and JPL to advance this to $>10^9$. Advances have occurred at GSFC in the development of null control algorithms resulting in stable closed-loop control in a noisy lab environment at 6.7 Hz and with disturbances deliberately introduced.

Figure-10: Packaging of the EPIC *Visible Nulling Coronagraph design*



Achromatic phase shifters (APS) within the VNC are to insure that the relative phase difference between the nuller arms is independent of wavelength. The APS consist of a set of flat glass plates of different glasses with different indices of refraction that vary with wavelength. Optimization techniques are used to select the glass materials, thickness and angles of the plates by minimizing a metric. Past APS designs only gave good correction only over an instantaneous ~ passband of ~20%, thus mandating tuning, via mechanisms, to encompass the entire science passband. During the ASMC study a new and more optimal solution has been developed for the GSFC VNC testbed, that allows the spectral passband to approach 100%, and without the use of mechanisms. Using this approach allows the plates to be mounted and aligned and fixed in place. More importantly, use of this design allows the null control to be achromatic. *The implication is that 10^9 contrast is achievable over the entire spectral passband allowed by the APS (480-960 nm)*. With the larger passband 4 - 5 times as many photons are available for each null control step which allows either more accurate null control implying contrasts $>10^9$ or, less time per null control step.

The EPIC approach lends itself well to modular integration and test since each of the nullers will be developed in parallel and tested as modular units prior to integration within the VNC. The VNC will then be tested as an end-to-end subsystem with the science instruments and null control. The EPIC telescope will be independently tested by injecting light from its cassegrain focus and back out to a fold flat and back through to interferometrically test it in a 1-g environment. Following this test the VNC will be integrated and tested with the same test optical train such that the light from the OTE passes through to the science focal plane.

3.4.2 Flight System

EPIC's spacecraft is a Deep Impact/Kepler heritage bus. The EPIC payload accommodation requirements are very similar to those of the Kepler payload, allowing EPIC to reuse Kepler designs and heritage hardware and software. The EPIC spacecraft has a high degree of design and flight heritage and requires no new technology. The maturity of the EPIC Kepler spacecraft design is presented in the Appendix. The spacecraft can be launched on an EELV into a heliocentric Earth-trailing drift-away orbit. The orbital characteristics and spacecraft bus design with its rigid solar arrays, sunshade, Jitter Isolation Mounts (JIMs) and fixed HGA combine to provide a very low disturbance environment to optimize EPIC's planet detection capability. The Kepler bus design and flight heritage allows for lower contingency and margin requirements. The EPIC spacecraft, like its Kepler predecessor, is fully redundant, with no credible single-point failures.

3.4.4 Launch System

The EPIC exoplanet probe concept has been designed and costed for an EELV launcher.

4.1 Management Approach

The EPIC science and technical team is uniquely qualified to build EPIC and execute its science mission. The science team (Table-7) encompasses a broad range of exoplanet expertise and modeling skills drawn from the astronomical community across the United States. We also have a collaboration with the Observatoire de Paris. The EPIC team has extensive experience with Science Mission Directorate (SMD) missions, including ACS, SWAS, STIS, FOS, COSTAR, JWST, Herschel and Spizter/IRAC. The science and engineering team will oversee technical development of the instrument and spacecraft, including all test and verification.

The EPIC mission comprises five partnerships, summarized in Table-8. Our industry partners, Lockheed Martin, and Ball Aerospace were selected competitively through the GSFC

Partnership Opportunity Document (POD) process to support our Discovery proposals, and more recently the ASMC study. Lockheed Martin will build the science payload with GSFC, leveraging their experience with interferometer optics. BATC is responsible for the spacecraft bus, which is based on the heritage Kepler platform. GSFC will be responsible for the EPIC's program management and mission operations. The Smithsonian Astrophysical Observatory (SAO) will reduce and analyze science data. The Space Telescope Science Institute (STScI) will manage the final mission archive and implement the E/PO effort. The EPIC team plans to continue maturing key mission technologies at GSFC, and the facility under development at JPL. EPIC will be proposed as an Exoplanet Probe.

Table-7: *EPIC's science team members are leaders in exoplanet science and space instrumentation*

Name	Affiliation	Responsibility
M. Clampin	GSFC	P.I.
G. Melnick	CfA	Deputy P.I.
R. Lyon	GSFC	Project Scientist
H. Ford	JHU	Science Chair
G. Hartig	STScI	Payload I&T
L. Petro	STScI	VNC Operations
M. Shao	JPL	VNC Design
V. Tolls	CfA	I&T
R. Woodruff	LM	Optical design
J. Ge	U. Florida	Fiber Array
M. Levine	JPL	VNC Design

Name	Affiliation	Responsibility
D. Golimowski	JHU	Brown Dwarfs
M. Harwit	Cornell	Ancillary Science
M. Marley	ARC	Exoplanet theory
G. Illingworth	UCO/Lick	Mission design
S. Kenyon	CfA	Disk evolution
D. Sasselov	CfA	Exoplanet theory
D. Lin	UCO/Lick	Disk models
J. Schneider	Obs-PM	Target Selection
S. Seager	MIT	Exoplanet theory
W. Sparks	STScI	Polarimetry
A. Weinberger	CIW-DTM	Disk Observations

Table 8: *Key EPIC Partnerships*

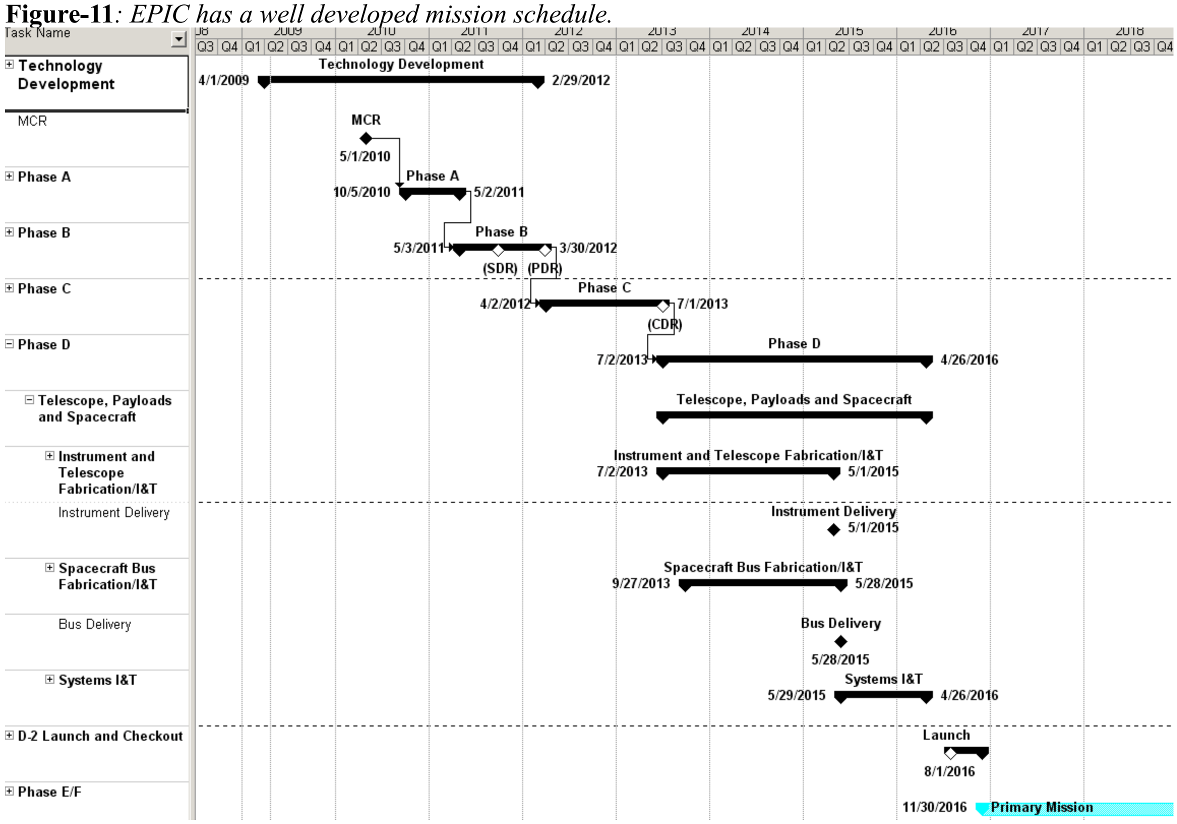
Institution	Responsibilities	Relevant Experience
GSFC	PI Organization; Project management; Mission systems engineering	HST, ACS, GRO, MAP, Swift, JWST, Chandra, GOES/POSE, XTE/TRMM, AQUA, SORCE, AURA
Lockheed Martin	Provide integrated and flight qualified science payload	HST, SST, SIM, Lunar Prospector, Gravity Probe B, IKONOS, NIRCam
Ball Aerospace	Provide integrated and flight qualified spacecraft and perform Observatory I&T	Deep Impact, Kepler, ESAT, Quick-Scat, Orbital Express, WISE
SAO	Data analysis and reduction	SWAS, Spitzer, JWST, Chandra
STScI	Data archive, E/PO	HST, JWST, Kepler, MAST archive

4.3 EPIC Activity Schedule

The activity schedule for EPIC is shown in Figure-11, with the assumption that funding commences in the fourth quarter of 2010 (FY2011). In practice the schedule for the mission would be tied to the date of the AO, which as yet has not been announced. The schedule is based on the standard NASA mission development phases A though F. Figure 9 shows Phases A though the start of phase E, mission science operations. The mission we have studied currently baselines a 5-year schedule of science operations (Phase E), with a goal of 2 additional years that would be available for GO programs.

Phase C-D, integration and test is an important component of the EPIC schedule. EPIC plans to follow "test as you fly principles". The VNC is especially suited to conducting component

Figure-11: *EPIC has a well developed mission schedule.*



level through a complete "end-to-end" test. The EPIC team has developed a baseline plan for tests to verify and characterize each component in the science payload. The science payload is integrated, tested, verified and environmentally qualified at the LM facility prior to delivery to BATC in Boulder. The observatory I&T follows I&T of the spacecraft. The integrated observatory completes all environmental testing, in accordance with specifications in the Goddard's General Environmental Verification System (GEVS). This includes a total of 12 cycles on each component in thermal vacuum; eight cycles at the component level and four cycles at the observatory level.

5. Funding Requirements

5.1 Cost Estimation Methodology

EPIC's 70% confidence limit cost with launcher is $842 million dollars, and is consistent with the expected cost cap for an Exoplanet Probe. EPIC is unique among the ASMC medium-class exoplanet mission studies in having been identified by NASA-HQ to be costed by both the GSFC Integrated Design Center (IDC) and JPL's TEAM-X to assess center-to-center cost variation. A separate report will be submitted with a complete comparision of the IDL and Team-X studies. EPIC was previously costed for the submission of Discovery-class mission proposals during the 2004 and 2006 AO opportunities. Our science team has extensive experience in flight programs, and the complexities of mission cost estimation. We baselined a telescope with 1.65-m aperture for our ASMC study. We also looked at an IDC spacecraft bus for costing, as well as the BATC heritage Kepler bus in our baseline design. We adopted the Kepler bus as it meets our requirements without the need for a re--design or technology development. Finally, for the ASMC study we looked at the addition of a spectrographic channel.

5.2 Cost Study Dates/Key Assumptions

The EPIC team has conducted a very thorough costing of the mission. A number of key inputs and assumptions went into our cost exercise:

Realistic Primary Mirror (PM) Costing: During our ASMC study we developed a detailed wavefront error budget for EPIC, and flowed it into wavefront error and PSD requirements for the primary (off-axis), and secondary mirrors. We obtained quotes for these mirrors based on the derived requirements. EPIC's PM has relatively modest requirements ($\lambda/9$), compared to traditional coronagraphs ($\geq\lambda/100$). Telescope optics for exoplanet imaging missions cannot be costed simply by mirror aperture and mass.

Heritage Flight Hardware: The EPIC mission concept has always been baselined with the heritage Ball Aerospace spacecraft bus employed for Kepler. The Kepler bus can demonstrably meet the pointing requirements we have levied on it and can support a 1.65 meter aperture without a re-design.

Launch Vehicle: NASA-HQ has directed medium class ASMC studies to assume an EELV for the purposes of costing our mission.

Intermediate Class Mission: The costing for this mission has assumed a PI-led science and engineering team. We have not costed a NASA Phase-F GO science program.

5.3 Cost Estimate

Cost estimates for the Payload and Spacecraft were developed by the IDC. The IDC's Mission Design Laboratory (MDL) developed a point estimate and a 70% Confidence Level estimate for the spacecraft bus. The IDC's Instrument Design Laboratory (IDL) developed a WBS point estimate and a 70% Confidence Level estimate for the payload. Following the IDL study, the EPIC team obtained a vendor quote for the specific Optical Telescope Assembly (OTA) requirements. GSFC's Science Proposal Support Office (SPSO) integrated the OTA quote into the IDL parametric model. Following the MDL study, the EPIC team obtained a BATC quote for a Kepler heritage SC Bus. The total mission cost estimate for EPIC, using the most recent EPIC team estimates, is shown in Table 9, and is \$680 million, without the launcher. The WBS point estimate costs (with reserves) are shown broken out by major development phase in Table-10.

Table 9: Total mission cost for EPIC, showing the WBS Point Estimate with reserves, the 50% confidence limit cost, and the 70% confidence limit cost.

Line Item	Top-Level WBS (per NASA Cost Analysis Working Group Cost Analysis Data Requirement)	WBS Point Estimate (with Reserves)	WBS Cost Risk (w/Mass Reserve) 50% CL	WBS Cost Risk (w/Mass Reserve) 70% CL
1.0	Project Management	\$38.0	\$38.4	\$42.7
2.0	Systems Engineering	38.0	38.4	42.7
3.0	Safety and Mission Assurance	23.8	24.0	26.7
4.0	Science/Technology	30.9	31.2	34.7
5.0	Payload(s) (1.65M OTA)	371.6	353.7	386.3
6.0	Spacecraft(s)	103.8	114.1	130.1
7.0	Mission Operations System (MOS)	42.0	42.3	47.1
9.0	Ground System(s)	8.5	8.5	9.5
10.0	Systems Integration and Test	19.0	19.1	21.3
11.0	Education & Public Outreach	4.8	4.9	5.4
	Total w/o Launch Vehicle Services	**\$680.4**	**\$672.8**	**\$712.4**
8.0	Launch Vehicle/Services	130.0	130.0	130.0
	Total NASA Phase A-E	**\$810.4**	**\$802.8**	**\$842.4**

In compliance with the request by NASA-HQ to generate the 70% S-Curve

Table: 10: *EPIC Development costs by Mission Phase*

WBS	Name	Phase A	Phase B	Phase C	Phase D	Phase E	Mission
1	Project Management	$ 3.8	$ 9.5	$ 13.3	$ 11.4	$ -	$ 38.0
2	Systems Engineering	$ 3.8	$ 9.5	$ 13.3	$ 11.4	$ -	$ 38.0
3	Safety and Mission Assurance	$ 1.2	$ 6.0	$ 8.3	$ 8.3	$ -	$ 23.8
4	Science/Technology	$ 9.3	$ 17.0	$ 4.6	$ -	$ -	$ 30.9
5	Payload	$ 37.2	$ 92.9	$ 148.6	$ 92.9	$ -	$ 371.6
6	Spacecraft	$ 15.6	$ 26.0	$ 36.3	$ 26.0	$ -	$ 103.8
7	Mission Operations	$ 0.4	$ 1.3	$ 2.1	$ 8.4	$ 29.8	$ 42.0
8	Launch Services	$ 0.7	$ 6.5	$ 78.0	$ 44.9	$ -	$ 130.0
9	Ground Development	$ 0.9	$ 1.1	$ 3.5	$ 3.0	$ -	$ 8.5
10	System Integration and Test	$ 1.0	$ 1.0	$ 4.8	$ 12.4	$ -	$ 19.0
11	Education/Public Outreach	$ -	$ 0.9	$ 0.9	$ 2.2	$ 0.9	$ 4.4
	Mission Cost Subtotal	**$ 73.7**	**$171.5**	**$313.8**	**$ 220.8**	**$ 30.7**	**$ 810.4**

confidence-limit cost figures, a mission level cost risk analysis was performed with ACEIT using statistical information available from a PRICE H risk analysis. PRICE-H Monte Carlo risk simulations were run for the spacecraft bus and instrument payload. ACEIT mean and standard deviation risk parameters were set using statistics obtained from the spacecraft bus and instrument payload risk analyses. Percentages were calculated for the spacecraft bus mean and standard deviation relative to the spacecraft bus point estimate. These percentages were entered into ACEIT. Other WBS risk parameters were set to a weighted mean and standard deviation (weighting based on relative contribution of spacecraft bus and instrument payload to total of spacecraft bus plus payload point estimate). This approach captures the inherent risk of the flight hardware, as modeled with PRICE H, and applies it to the other WBS elements effectively tying overall mission risk to flight hardware risk. The statistics derived from the MDL cost risk analysis of the spacecraft bus were applied to the EPIC team spacecraft bus point estimate to derive a mission level S-Curve and 70% confidence level shown in yellow in Table 9.

5.4 *Cost Flexibility*

During our ASMC study the EPIC team studied the cost impact of varying the telescope aperture from the 1.45-m used in our previous Discovery proposals to a larger 2.0-m. We have identified three initial descope options:

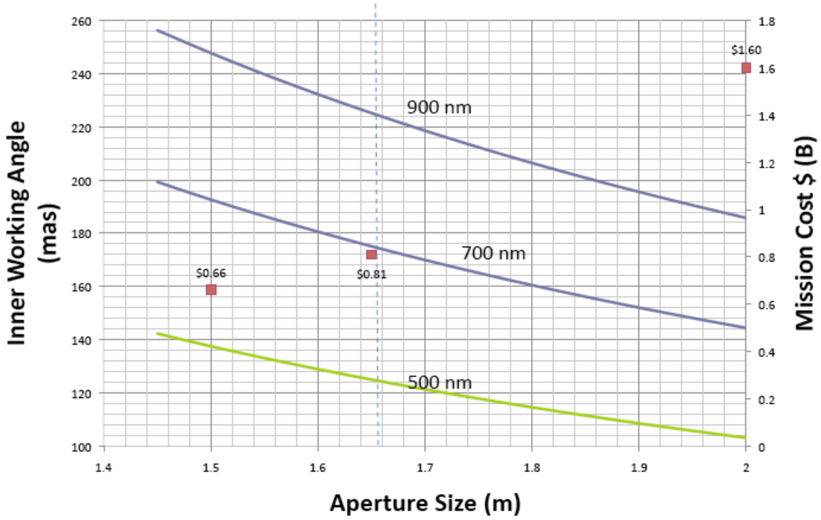
1) Reduction to a 1.45-m aperture telescope, which incurs a significant science impact due to the loss of inner working angle. Our cost analysis suggests that there is little difference in cost between 1.65-m and 1.45-m, as shown in Figure 12.
2) Removal of the spectrograph component of the VNC option. The spectroscopic capability would be replaced by a simpler fold-in mechanism with a long slit. It would incur higher operational complexity.
3) Reduction of mission duration to a phase E of 3 years.

6.0 Technology Development Requirements

6.1 Mission Critical Technologies

The flight requirements for the VNC are succinctly stated as stable $\geq 10^9$ contrast, with >20% passband, for $\geq$ 7000 seconds. The critical technologies to meet this are all associated with the VNC and those below TRL-6 are the multiple mirror array (MMA), spatial filter array (SFA) and its lenslets, achromatic phase shifter (APS), null control approach and photon counting CCDs. Each is briefly described below. In order to meet this requirement, deformable mirrors, spatial

Figure 12: EPIC's aperture versus cost breakpoint occurs at ~1.7-m where a new spacecraft bus is required to accomodate the primary mirror aperture. WBS point estimates with reserve are shown.



filter arrays and null control algorithms must act together in a stable environment within a vacuum tank and the development plan calls for three years to complete the end-to-end testing and validation of the VNC to TRL-6. Further details are given in the appendix material.

EPIC requires two 1027 segment hexagonal pack MEMS based deformable mirror within the VNC which are used for null control. Each individual segment is actuated in piston, tip and tilt control (3 DOF) and the segments and backplane structure are fabricated from silicon with the segments coated with aluminum.

The SFA consists of an array of 1027 single mode fibers with lenslet arrays on front and backsides, one input and one output lenslet per fiber. The input beam is decimated into an array of sub-beams, one per fiber, and light not matched to the fiber mode is not coupled in resulting in passive filtering of higher spatial frequency amplitude and wavefront errors.

The VNC consists of an X- and Y-nuller each with an achromatic phase shifter which effectively achromatizes the path length delay to accomplish a wavelength independent π-phase shift. Each APS consists of a set of 10 glass plates of 5 different materials and thickness with surface requirements of < 1.0 nm rms and each of diameter 2 cm.

The VNC requires starlight suppression by 9 orders of magnitude and thus requires sensing and control the rms wavefront error to 0.012 nm rms. The sensing is accomplished by the two bright object sensors and the null sensor outputs which give the optimal photon yield for sensing. An algorithm is used to convert the senses photons to commandable actuator voltages on the two MMAs and working through the SFA gives, in principal, control to < 0.012 nm rms. This approach has been partially demonstrated on the GSFC testbed (see Appendix), but requires an end-to-end demonstration in closed-loop with the spectral bandpass from 480 – 960 nm.

EMCCD photon counting detectors are already available from E2V but have yet to be calibrated and measured for the EPIC spectral response, dark current noise and photometric response from pixel to pixel. Efforts are underway to perform these tasks and a COTS version has been obtained from Princeton Instruments for laboratory useage.

6.2 Technology Readiness Levels

Of the 8 EPIC mission critical technologies listed in Table-11, five are below TRL-6 and these include the MMA, SFA, APS, null control approach and photon counting CCDs. Our team has a robust technology development plan to mature these to TRL-6. The TRL rational is based upon flight heritage from missions and/or development efforts summarized in Table-11.

Table-11: *EPIC Heritage and Technology Readiness Levels*

Component/ Subsystem	Heritage	TRL	Comments
Multiple Mirror Arrays	Boston Micromachines, TPF-C , Boston U/JPL PICTURE, Multiple SBIRs	4	Refer to Section C.1.
Spatial Filter Array (SFA)	Fiber optics flown on ISS, WMAP, EO1, GLAST, FiberGuide development and SBIR	4	Refer to Section C.2. Commercial alignment tolerances already exceed EPIC needs and vendors such as Fiberguide can build fiber arrays.
Beamsplitter Substrate & coatings	MDI, HMI, HST, GSFC/ LMCO VNC Testbed	8	Commercially available material, SiO_2 and processing, process as matched pairs.
Achromatic Phase Shifter	MDI, HMI, HST, GSFC/ LMCO VNC Testbed	5	Commercially standard materials, SiO_2 and BK7 and processing well understood, use as APS in VNC is new application
Nuller Structure	GP-B, LISA	6	Optically contacted stable structure.
Shear Mechanism	JWST NIRCam, MRO, HST, Spitzer	6	Modification of linear actuator using harmonic drive and ball screw
Null Control Strategy	BU/JPL PICTURE Mission, GSFC/LMCO VNC Testbed	4	Passive null control with SFA, active null control with MMA coupling to SFA.
E2V-L3 CCD	GSFC qualifying E2V-L3	5	Photon counting CCD.

6.4 Technology Development Plan

The EPIC technology development schedule for pre-Phase-A, Phase-A and Phase-B is shown in the appendix. Pre-Phase-A development is ongoing and consists of validation of the VNC approach within vacuum to achieve stable 10^9 contrast, but with smaller MMAs and SFA than needed for flight. Pre-phase-A work require further funding to develop the full scale SFA, MMA and 16-bit electronics.

6.5 Technology Development Plan Costs

The pre-Phase-A technology development costs are estimated at $679,500 and procurement costs at $3,858,897 for an aggregate total of $4,538,397 to complete the 18-month effort shown in Table 12. The costs for the personnel are at the standard rate for senior level engineers and the procurement costs are rough order of magnitude estimates supplied by the vendors, namely Boston Micromachines, Fiberguide Industries and JPL for recent APRA proposal costing exercises. The Phase A/B costs are summarized in Table-10 for the full development of the ETU VNC. The Phase A/B cost estimate is from the GSFC Integrated Design Center costing exercise.

FO2: Science Traceability Matrix

Science Goals

- ➦ Determine the properties of gas giant planets and characterize their atmospheres
- ➦ Investigate the diversity of planetary system architectures

Science Investigation

- ➦ **Directly image extrasolar in systems with known RV detected planets**
  - Characterize the atmospheres of planets in systems with known RV detected planets
  - Determine the orbital inclinations and masses of planets in these systems
  - Map and characterize the exozodiacal structures in these systems
- ➦ **Survey nearby exosolar systems to search for extrasolar planets and debris disk structures.**
  - Characterize the atmospheres of extrasolar planets detected in systems
  - Determine the orbital inclinations and masses of planets in these systems
  - Map and characterize the exozodiacal structures in these systems

Mission Requirements

Contrast
- $\geq 10^9$ contrast @ $2\lambda/D$: 4.5"x4.5" FOV
- $\geq 10^7$ contrast @ $2\lambda/D$: 10"x10" FOV

Spectroscopy: R=20 – 50 spectroscopy
Inner Working Angle: ≥125 mas
Collecting area: ≥2.5 m^2
All sky access
Drift-away earth trailing orbit
Five year mission life
EELV launch vehicle accommodation

Spacecraft Requirements

- Mass: Specific to EELV launcher
- Drift away orbit: C3 = 0.3 – 0.4 km^2s^{-2}
- Class-B mission: Fully redundant
- Three-Axis stabilized, inertial pointing
  - X-axis ➔ Sun: Z-axis ➔ science target
  - ±15º roll around Z axis
- Coarse Pointing: 2.5: (3σ)
- Pointing Accuracy: 9.1 mas (3σ)
- Pointing Stability (jitter): 4.1 mas (3σ)
- Fully cross-strapped and redundant
- Ka-Band downlink via 1-m High Gain Antenna
- 48 Gbit mass memory module
- Jitter isolation mount (JIM)

Ground System Requirements

Science & Mission Operations Center
- Observatory health and safety monitoring
- Observatory/Science planning and scheduling
- DSN station scheduling
- Data capture and Level zero data processing
- Science command generation & operations
- Science Payload health, safety, and performance

Smithsonian Astrophysical Observatory (SAO)
- Level 1-3 data product generation and delivery
- Science Payload performance evaluation

Multi-mission Archive Space Telescope (MAST)
- Level 0-3 data archive and distribution

Science Payload Requirements

Optical Telescope Assembly (OTA)
- Off-axis, unobscured Cassegrain
- Aperture: 1.65 m
- WFE: < 55.8 nm rms
  - Static: < 54.5 nm rms
  - Stability: < 12 nm rms

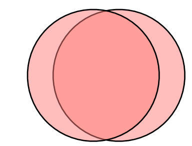
Visible Nulling Coronagraph
- Inner Working Angle: 125 mas
- WFE: < 12 pm rms
- WF drift: <22 pm rms / ≤7000 secs
- Amplitude stability: 0.158%/≤7000 sec
- Polarization stability: 0.03 deg rms
- Beamwalk/WF control step: 4.1 mas (3s)
- Pixel Sampling: 22.4 milli-arcseconds
- Nulled FOV: +/- 2.4 arcsec @ l = 560 nm
- Overall throughput: ≥18%
- Instrument spectral range: 440 - 960 nm
- Spectral resolution: R = 6 - 172
- Instantaneous bandpasses: ≥20%
- Photometric accuracy: < 5%
- Three Multiple Mirror Arrays
  - 1027 hexagonal pack mirrorlets
- 1027 Fiber Spatial Filter Array
- Five 512x512 Photon Counting CCDs

FO1: Visible Nulling Coronagraph: How it Works

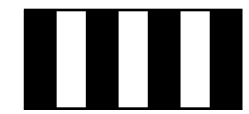
Optical Outputs	VNC stage	Comments

Optical Outputs: Pupils sheared in X

Pupils sheared in X

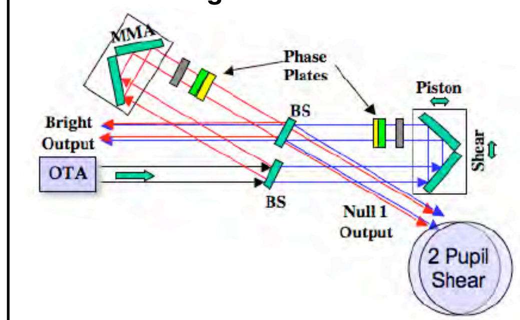


X axis contrast nulls



VNC stage: First nuller stage

First nuller stage



Comments: First Nuller Stage

First Nuller Stage

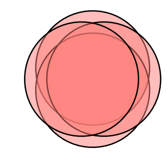
•The first stage of the VNC shears the telescope pupil in the X axis by means of a shearing interferometer arm

• The output is fed to the second nulling stage

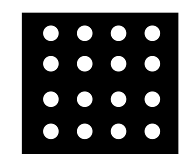
• The bright output (BS) is used for pointing and WFSC

Optical Outputs: Pupils sheared in Y

Pupils sheared in Y

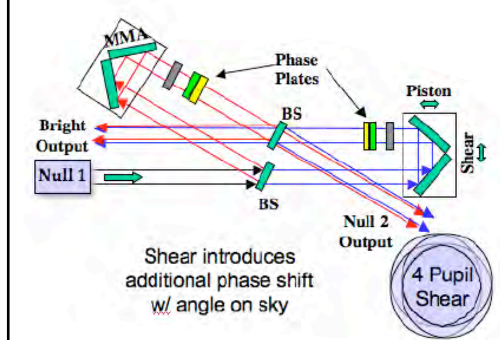


Combined X & Y shear contrast nulls



VNC stage: Second nuller stage

Second nuller stage



Comments: Second Nuller Stage

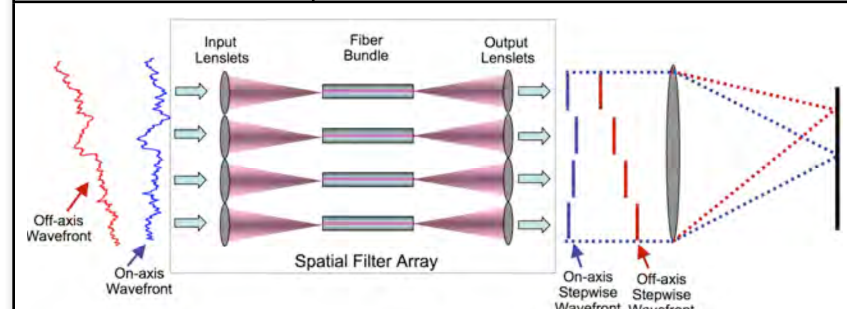
Second Nuller Stage

•The second stage of the VNC shears the input from the first nuller stage in the Y axis by means of a shearing interferometer arm

• The output is fed to the spatial filter array

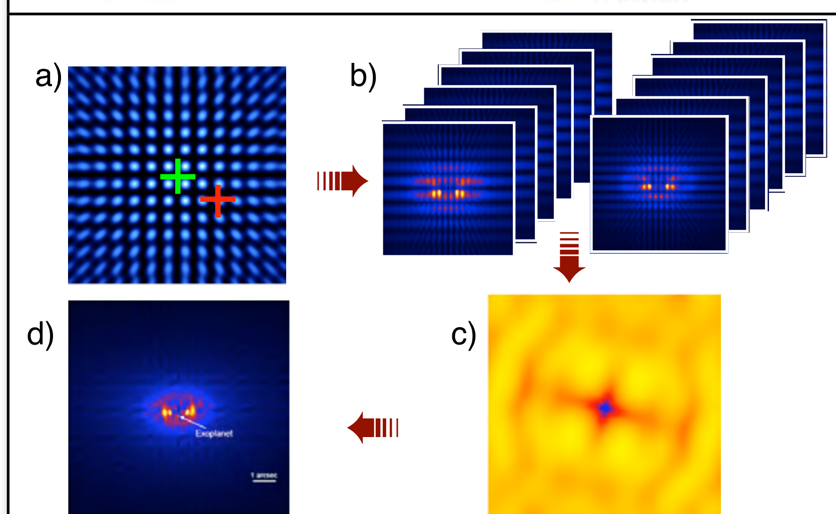
• The bright output (BS) is used for WFSC

Spatial Filter Array



Spatial Filter Array (SFA)
The SFA removes high frequency components from the nulled wavefront and comprises an array of fibers interfaced to a lenslet array at each end.

VNC discovery observation sequence



VNC discovery observation sequence:
a) Pattern of contrast nulls projected on the sky. The green cross shows the location of the star at a null.
b) Observation sequence builds the null on the sky by combining 12 images obtained at 4 shears and 3 telescope rolls
c) Effective null pattern pattern on the sky produced by sequence (b)
d) Actual science image when the parent star is nulled to reveal an exoplanet.
VNC characterization mode simply places planet so it falls in a contrast maximum [red cross in (a)]
Note: binaries are observed by placing both stars in a null minimum