

Astro2020 APC White Paper

Exo-C: A Dedicated Probe-scale Space Mission for Coronagraphic Imaging and Spectroscopy of Exoplanetary Systems

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"Exo-C", the Exoplanet Coronagraph, is a concept for a dedicated probe-scale (< \$1B) space mission optimized for direct imaging of exoplanetary systems. It was the product of a detailed mission study carried in 2013-2015 under the sponsorship of the NASA Astrophysics Division. Exo-C was designed to be capable of spectrally characterizing 1-2 dozen nearby exoplanets in reflected visible light, discovering previously undetected planets, and imaging structure in hundreds of circumstellar disks. It would obtain unique science results on planets down to super-Earth size and serve as a technology pathfinder toward an eventual flagship-class mission to find and characterize habitable Earth-like exoplanets. Key design elements are an unobscured telescope aperture, an internal coronagraph with deformable mirrors for precise wavefront control, and an orbit and observatory design chosen for high thermal stability. Exo-C's telescope aperture, orbit, mission lifetime, and spacecraft bus are all comparable to those of the highly successful Kepler mission. Much of the needed technology development (precision pointing, wavefront sensing and correction, high contrast integral field spectroscopy, detector flight readiness) has been advanced by the WFIRST Coronagraph Instrument (CGI) project over the past several years. Mission performance, mass, power, and cost estimates have also benefited from detailed work by the WFIRST CGI team. A Cost and Technical Evaluation (CATE) was performed in 2015 by the Aerospace Corporation. Today Exo-C is a backup option to WFIRST CGI. It could nominally be implemented within seven years from project start. This white paper summarizes the study final report, with updates on performance and technical readiness as of spring 2019.

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INTRODUCTION

The key enabling technology for space coronagraphy is precise wavefront control using deformable mirrors (DMs) capable of being commanded and maintained at sub-angstrom accuracy. In conjunction with additional coronagraph elements to suppress diffraction, the DM is used to clear a high-contrast dark hole around the target star out to a maximum radius of $N\lambda/2D$, where N is the linear DM actuator count, λ is the wavelength, and D is the telescope aperture diameter. Laboratory demonstrations to date show that the needed level of 10^{-9} contrast can be achieved for unobscured pupils in a static system with optical bandwidths up to 20%. Past exoplanet direct imaging mission concept studies utilizing this approach include ACCESS, EPIC, and PECO (Trauger et al. 2010; Clampin et al. 2010; Guyon et al. 2010). During 2013-2015, Exo-C brought these previously competing groups together in a single Science and Technology Definition Team supported by an Engineering Design Team at NASA/JPL.

SCIENCE GOALS & REQUIREMENTS

The Exo-C mission was specifically designed to perform direct imaging and spectroscopy of nearby extrasolar planets. Exo-C would open a new observational domain - imaging at very high contrast and very small angular separation - enabling the first detailed exploration of planetary systems around stars like our Sun. Exo-C's prime science targets are planetary systems within 20 pc of the sun. By the late 2020s when Exo-C would launch, ground and space telescopes will have identified stars hosting short-period transiting planets and gas giant planets on orbits $\sim < 7$ AU. The atmospheric properties of hot, close-in planets will have been probed in the near-infrared by transit spectroscopy; and for hot, young planets

Primary mirror diameter	1.4 m
Raw speckle contrast	10^{-9} at the IWA
Contrast stability after control	10^{-10} or better at the IWA
Spectral coverage	450-1000 nm
Inner Working Angle (IWA)	$2 \lambda/D = 0.16''$ @ 550 nm
Outer Working Angle (OWA)	$> 20 \lambda/D = 2.6''$ @ 800 nm
Binary spillover light	3×10^{-8} contrast @ $8''$
Spectral resolution, $\lambda > 500$ nm	$R = 70$
Astrometric precision	< 30 milliarcsec
Imaging camera field of view	$42''$
Imaging spectrograph field of view	$2.2''$
Mission lifetime	3 year prime mission

Table 1: Exo-C Instrument Specifications

by near-infrared adaptive optics imaging.

While these advances will be remarkable scientific milestones, they will fall well short of the goal of obtaining images and spectra of planetary systems like our own. Exo-C would study cool planets in reflected light at visible wavelengths, ranging from gas giants down to super Earths, at separations from 1-9 AU, around nearby stars like the Sun. The mission design parameters needed to achieve this science goal are given in Table 1, and the performance illustrated in Fig. 1.

Exo-C's direct imaging will detect and characterize planets in Earth-like to Saturn-like orbits, and from Jupiter down to super-Earth sizes, complementing transit-based exoplanet observations, which are limited to planets that are much closer to the parent star.

Exoplanet Direct Imaging in the Optical and Near-infrared

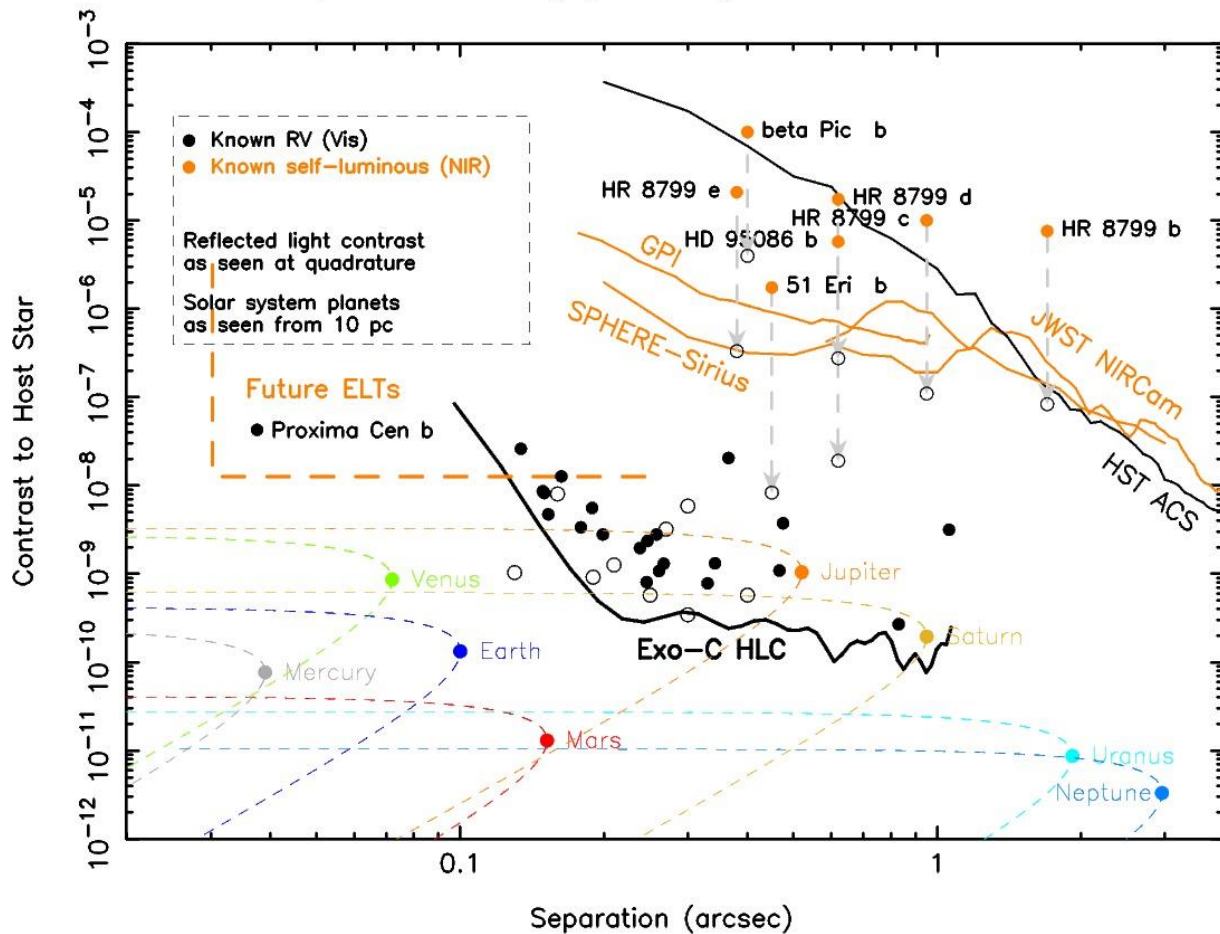


Figure 1: The star-planet contrast and separation for known planetary systems (solid dots) and the performance of existing and future high-contrast imaging instruments (lines). Orange dots show the near-infrared contrast of known self-luminous directly-imaged planets, with arrows pointing to their theoretical I-band contrast. Open circles show a representative set of new planet discoveries. The black dots show the theoretical V-band contrast of planets detected by the RV method. The solar-system planets at maximum elongation are shown as colored dots; the dashed lines from these show their brightness variation with orbital phase as seen from 30° inclination to the ecliptic. The JWST NIRC2 and HST ACS curves are from Lawson et al. (2012). The GPI H band curve was provided by Bruce Macintosh (personal communication); the SPHERE-Sirius K band curve is from Vigan et al. (2015) Fig. 2. The projected Exo-C performance curve is for V band.

Exo-C's exoplanetary "Grand Tour" of our nearest bright stellar neighbors will provide a comprehensive survey of planetary systems more like our own, enabling a new era of comparative planetology. The high-contrast direct imaging capabilities of Exo-C also have the potential to advance other fields of astronomy. In the course of its 3-year mission, Exo-C would address four key science goals:

Spectroscopy of known exoplanets: Exo-C will obtain photometry, astrometry and spectroscopy of about a dozen giant planets detected by radial velocity (Figure 2) and orbiting nearby stars. These will be the first "cool Jupiters" like our own, for which true masses and atmospheric composition will be measured. Exo-C's spectra will be sensitive to features of methane and water in their planetary

atmospheres, and spectral detections will be used to constrain relative abundances, metallicity and the depth of any cloud decks (Figure 3; see also Cahoy et al. 2010, Lupu et al. 2016, and Marley et al. 2019).

Discovery and characterization of new planets in the solar neighborhood: Exo-C's multi-epoch imaging has the capability to discover nearby planets beyond the limits of the radial velocity and transit detection techniques around at least 100 nearby stars, including the nearby prime targets α Centauri A and B. A possible search result appears in Figure 4, while the discovery potential around nearby stars is shown in Figure 5. Searches will be made at multiple epochs for planets at contrasts down to a few $\times 10^{-10}$. Exo-C's contrast capability will permit detection of Jupiter-like planets with semi-major axes out to 9 AU, Neptune-like planets out to 3 AU and super-Earths out to 1 AU. If excellent telescope stability is achieved and exo-zodi is low, Earth-twins might be detected around a few of the nearest stars. Spectral characterization of the brightest planet discoveries—from exo-Jupiters to any nearby Earths—will be obtained. Spectrally searching for biosignatures in the atmospheres and surfaces of Earth-like planets around the closest stars may be possible, if suitable candidate planets are found.

Structure and evolution of circumstellar disks: Exo-C, with contrast 1,000 times better than that achievable with the Hubble Space Telescope (HST), will resolve dust structures, tracing the gravitational effect of planets too small or remote to detect by any other means, and measure dust properties in a large sample of exo-Kuiper belts. Exo-C will survey several hundred debris disk targets and will be capable of resolving rings, gaps, warps and asymmetries driven by planetary perturbations of circumstellar debris disks. Exo-C will be able to detect disks as tenuous as the Kuiper belt, enabling comparative studies of dust

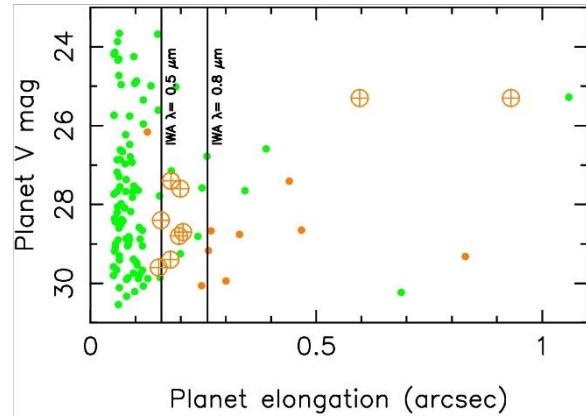


Figure 2. Separation and expected brightness for known RV planets (points) and putative HZ Earth analogs ($\oplus$) accessible to Exo-C. Color codes for contrast difficulty.

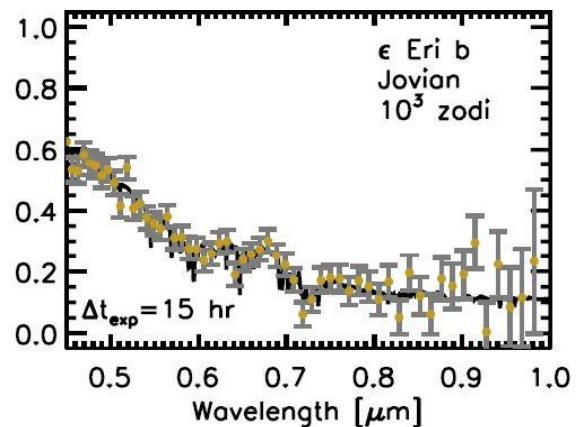


Figure 3. Simulated Exo-C spectrum of ϵ Eridani b, the nearest Jovian planet to the Sun found by RV. Figure by Ty Robinson.



Figure 4. Hypothetical planetary system around the bright star Altair detected by Exo-C in a simulated 12 hour exposure in V, R, and I bands. Shown are Jupiter and Saturn analogs in 5 and 10 AU orbits, and a 1 zodi dust ring between 2-4 AU.

inventory and properties across stellar ages and spectral types.

Survey of dust in habitable zones: Exo-C's inner working angle of $0.16''$ at 550 nm will spatially resolve the habitable zones of dozens of nearby

stars, enabling the search for dust down to levels a few times that found in our Solar System. These observations will provide crucial constraints on the background levels against which future missions will observe Earth-like exoplanets.

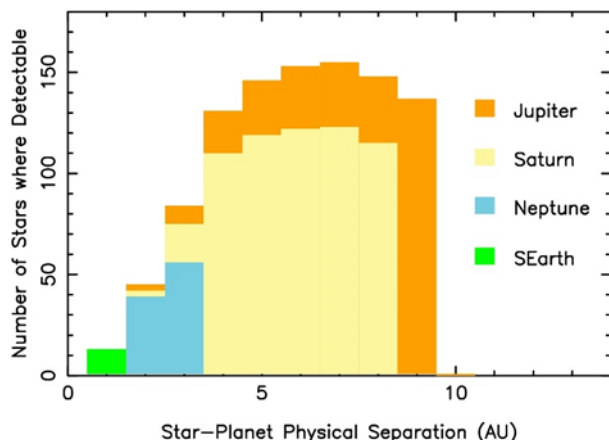


Figure 5. Exo-C exoplanetary search space in 48 hour broadband integrations for nearby stars, as a function of planet size and orbit.

In the event that WFIRST’s coronagraph instrument was descoped from the mission, Exo-C offers an alternative next step on NASA’s exoplanet exploration path. The basic mission concept of a dedicated 1-1.5 m class coronagraphic observatory was endorsed by the Astro2010 Electromagnetic Observations from Space (EOS) panel. Exo-C will image and spectrally characterize planets and disks in reflected light. It will achieve image contrast levels that surpass those of currently operating space telescopes, the *James Webb Space Telescope (JWST)*, and what can be done by groundbased Extremely Large Telescopes (ELTs) equipped with extreme adaptive optics. Exo-C will characterize cool planets in orbits at or beyond 1 AU irrespective of their orbit inclination to the line of sight, allowing equal access to all nearby stellar hosts and probing a different population than the set of hot, short period planets that may be characterized by transit spectroscopy. In addition to its compelling and unique science, Exo-C can be

the technology pathfinder to demonstrate precision wavefront control in space for potential future missions to characterize Earth-like planets in the habitable zones of nearby Sun-like stars.

As a dedicated and self-contained observatory for direct imaging of exoplanetary systems, Exo-C will have the mission time and pointing agility to revisit targets as often as needed. Revisits enable candidate exoplanets to be verified by establishing common proper motion with their host star. Revisits also provide astrometric measurements needed for orbit determinations, photometric measurements of planetary phase curves, and the additional search completeness needed to maximize discovery of new planets. The Exo-C mission design will allow revisits to be scheduled as soon as a month after a previous observation. This flexibility allows quick return to a planet that proves exceptionally interesting or that requires further integration time to constrain a promising spectral feature.

MISSION ARCHITECTURE

The baseline Exo-C design is an unobscured Cassegrain telescope with a 1.4-m clear aperture, in a highly stable Earth-trailing orbit, and designed for a 3-year science mission lifetime. It carries a starlight suppression system (SSS) consisting of the following elements (in optical train order): fine-guidance and low-order wavefront sensor (FGS/LOWFS), wavefront control (WFC) system based on two large-format deformable mirrors, and a coronagraph. Two backend instruments, an imaging camera and an integral field spectrometer (IFS), receive the SSS output beam. The science instrument bench is mounted laterally on the anti-Sun side of the telescope, obviating the need for high incidence reflections that induce unwanted polarization effects and providing better isolation from spacecraft disturbances. The instrument creates a dark field with 10^{-9} raw contrast between radii of 2-20 λ/D from the star. The imager fully covers

this field with bandpass filters over the wavelength range 450–1000 nm. A smaller field 1.2" in radius is covered by the IFS at spectral resolution $R=70$ over $\lambda=495\text{--}1000$ nm.

The telescope is designed for precision pointing and high stability. Two stages of vibration isolation are used between the reaction wheels and the science payload. The solar arrays and high-gain antenna are body-fixed, and a stiff barrel assembly is used as the telescope metering structure (Figure 6).

Telescope pointing is updated at a high rate using the bright science target star as a reference to drive a fine steering mirror. Spacecraft body pointing requirements are comparable to those of Kepler. Active thermal control is used for the telescope, instrument, and telescope barrel assembly—all of which are shielded from direct sunlight by a large solar panel. Modeling of the structural, thermal, and optical performance shows that the telescope in its Earth-trailing orbit will have the high wavefront stability needed to meet Exo-C's science goals (Figure 7).

Exo-C builds on more than a decade of NASA technology investments and laboratory demonstrations for high contrast imaging with unobscured apertures. The WFIRST CGI continues to mature the technologies needed for

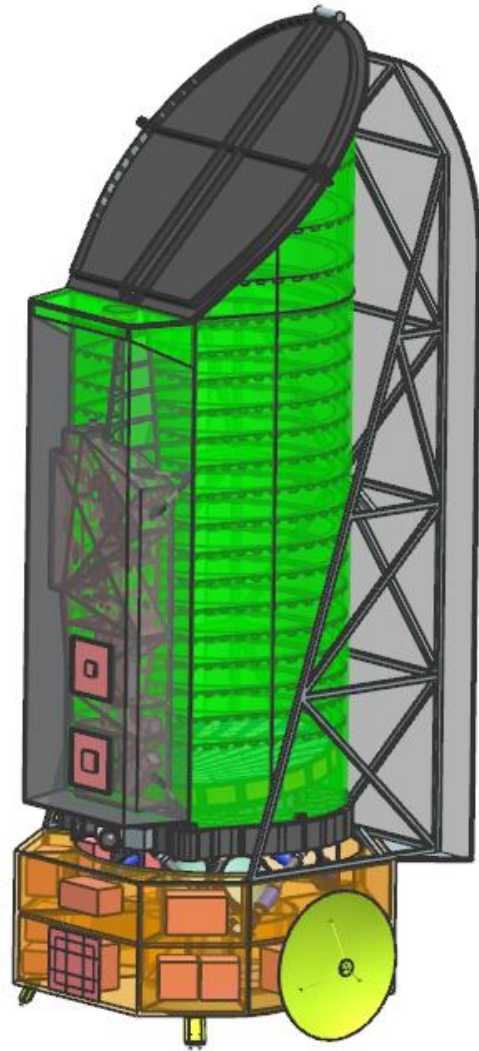


Figure 6. Visualization of the final Exo-C observatory design. A Kepler-like spacecraft hosts a telescope aperture the same as Kepler's, launched into the same orbit and with the same prime mission lifetime as Kepler. The coronagraph instrument is accommodated on a lateral optical bench on the anti-Sun side of the telescope. The Exo-C design was later adopted for the larger HabEx telescope and coronagraph (Gaudi et al. 2019)

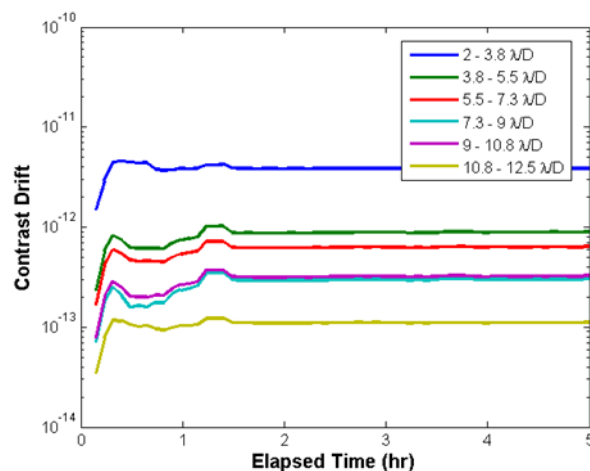


Figure 7 Modeled contrast evolution in six radial zones in the coronagraphic image plane after the telescope was rolled by 30° about the line of sight. Even at the inner working angle of $2 \lambda/D$, the contrast drift is below the 10^{-11} level, showing that the Exo-C design meets its stringent wavefront stability requirements.

Exo-C. CGI efforts directly beneficial to Exo-C include flight qualification of deformable mirrors and low-noise detectors, development of coronagraphic masks, LOWFS design and testing, and the development of a dynamic high-contrast testbed to demonstrate coronagraph contrast performance in the presence of flight-like pointing and wavefront disturbances. A prototype high contrast IFS (McElwain et al. 2013) has now been tested with a coronagraph in a simulated space environment. Exo-C's remaining technology requirements beyond

CGI efforts are 1) testbed time with an unobscured pupil and 2) coronagraph-specific mask or beamshaping technology developments to demonstrate 10^{-9} contrast in 20% bandwidth at $2\lambda/D$ inner working angle.

Five coronagraph options were evaluated for use on the mission: hybrid Lyot, phase-induced amplitude apodization (PIAA), shaped pupil, vector vortex, and the visible nuller. The original 2015 evaluations resulted in the selection of the hybrid Lyot as the baseline, primarily on the basis of its greater technical readiness. The vector vortex and PIAA coronagraphs have the potential for even better science performance and should continue to be developed as options for a later mission start. All three coronagraphs have already demonstrated performance in the laboratory that is closing in on Exo-C's requirements; they differ primarily in which of three key performance parameters (inner working angle, contrast, and spectral bandwidth) still needs to be improved.

Possible mission enhancements that would increase science performance include the use of larger format detectors and deformable mirrors, a redesign of the pointing system to enable a broader range of general astrophysics, the addition of a general astrophysics auxiliary instrument on the existing optical bench, operating the mission to its full design lifetime of 5 years, and a starshade rendezvous with Exo-C. Additional study would be needed to evaluate the costs and benefits associated with each of these options.

In the original Exo-C CATE, The Aerospace Corporation identified reaching the coronagraph's required contrast of 10^{-9} as their primary technical concern. Pointing control, wavefront correction, and space qualification of the Integral Field Spectrograph (IFS) and the coronagraph were seen as major components of this risk. Since then, the WFIRST CGI development effort has demonstrated the required pointing control, detector and IFS performance, and has made significant progress toward meeting the Exo-C contrast requirement in a dynamic environment. All these risks to the

original Exo-C architecture have therefore been reduced for a 2021 realization of the mission.

During development the WFIRST CGI team found their detector system had lower effective quantum efficiency than hoped. If the same was true for the Exo-C detector, mission yields would be reduced by roughly 30%.

MISSION COST ESTIMATES

The past four years of work by WFIRST CGI have bought down a significant fraction of needed Exo-C technical development cost and risk. Conversely, CGI's design experience has led to increases in estimated mass and cost that have been propagated into the 2017 estimates shown below for the Exo-C coronagraph instrument. The two cost changes roughly cancel each other out, leaving the estimated cost of the mission about the same as estimated in 2015. A cost estimate breakdown performed by JPL Team X and the ExEP Chief Engineer is shown Table 2. These are in units of FY 15 dollars, which must be inflated by roughly a factor of 1.1 to convert to FY 20 dollars. Aerospace's total cost estimate was only modestly higher than shown here. The cost information shown below is of a budgetary and planning nature and is intended for informational purposes only. It does not constitute a commitment on the part of JPL and/or Caltech.

Element	FY15 cost Estimate	Basis of Estimate
Total Project	\$972 M	
Tech development	\$ 5 M	Expert judgement
Payload system	\$288 M	NICM & Stahl 2013
Spacecraft	\$187 M	Adjusted Kepler actuals
Launch vehicle	\$110 M	NASA HQ guidelines
Mission ops	\$ 93 M	60% Kepler costs
Other	\$ 91 M	JPL Team X
Reserves	\$198 M	30% less LV

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