# The EXoplanetary Astrometric-Coronagraphic Telescope (EXACT)
# Astrophysics

## Overview:

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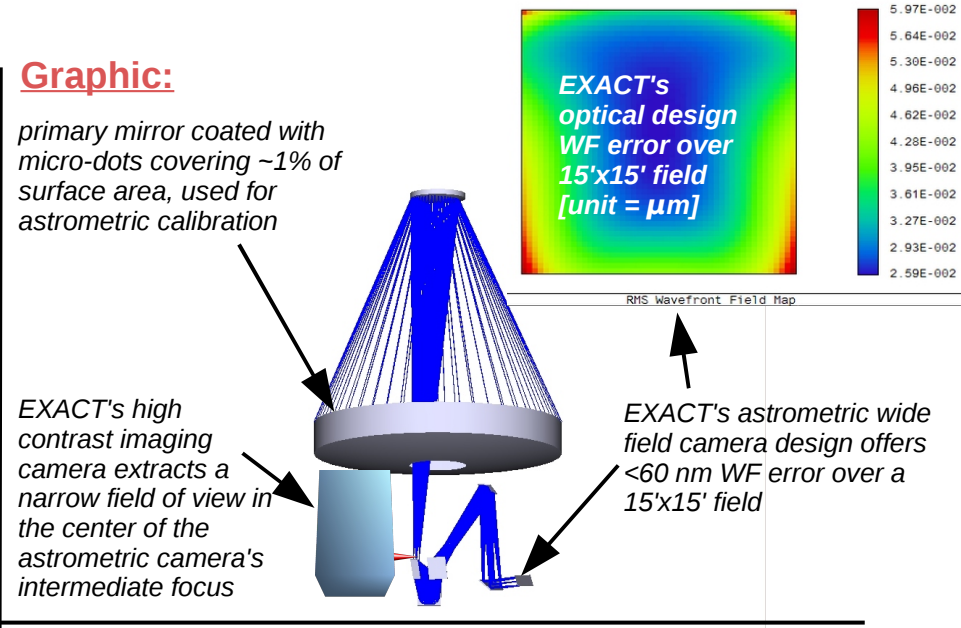
EXACT will allow **comprehensive study of exoplanetary systems** with simultaneous astrometric and coronagraphic observations, using a wide-field telescope design also suitable for deep optical wide field imaging.
EXACT will **study the formation, evolution, diversity, and architectures of exoplanetary systems,** and will **identify and characterize exoplanets, their masses, and their orbits**. EXACT's high efficiency coronagraph enables access into the habitable zone of a well-selected sample of nearby stars, around which it has the sensitvity to observe and characterize (orbit, mass and spectra) potentially habitable exoplanets. Robust and efficient identification is provided by simultaneous astrometry and coronagraphy.

## Graphic:




## Description:

**2.4-m telescope** with new mirror coatings, and addition of a tertiary mirror
**Two instruments**, operating simultaneously:
- a **high contrast multi-band (4 bands from ~0.4µm to 1µm, each feeding a R~100 integral field unit) imaging polarimeter** offering 1 λ/D inner working angle thanks to a high efficiency PIAA type coronagraph. Includes deformable mirrors for wavefront control.
- a **visible light wide field (15'x15') imaging camera** used for sub-µas astrometry and deep wide field imaging, using telescope pupil grid diffraction and focal plane array pattern illumination to calibrate astrometric distortions.

EXACT will **observe few hundred nearby stars** over 5 yrs, produce **spectro-polarimetric maps of exozodiacal dust** within and outside their habitable zones, **identify exoplanets**, measure their **spectra** and **masses.** EXACT's simultaneous astrometry + coronagraphy measurements improves characterization robustness and reduces required number of visits.
EXACT's **key technologies at TRL 4-5:** PIAA coronagraphy, wavefront control (deformable mirror, wavefront sensing), dot deposition on mirror coating for astrometry, large focal plane array.

EXACT's architecture is **well-suited for wide-field applications of the 2.4-m ex-NRO telescope(s)**, which can be done simultaneously with exoplanet and circumstellar disks observations.

## Value to NASA:

**EXACT directly addresses the New World New Horizon 2010 Space medium-scale priority #1 ("Preparation for a planet-imaging mission beyond 2020, including precursor science activities")**
***EXACT follows on from earlier and ongoing NASA sponsored concept studies and is a key-science capable pathfinder mission for a later flagship exoplanet characterization mission***
**Technology**: EXACT's high efficiency starlight suppression concept and its astromety approach enable characterization of potentially habitable planets, both with the 2.4-m ex-NRO telescope (identification, mass determination and early spectral characterization) and with future telescopes (life finding).
**Precursor science**: EXACT will study dust and exoplanets around nearby stars, identifying prime targets for future planet-imaging mission(s) capable of detailed characterization of potentially habitable words. It will map exozodiacal clouds that contain signature of exoplanets but are also a fundamental source of measurement noise.

EXACT's wide field camera will be capable of **mapping the visible sky with an unprecedented combination of depth, angular resolution, PSF stability and astrometric precision,** addressing multiple high priority astrophysics questions, and enabling a rich guest observer (GO) program.

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***EXACT will comprehensively study exoplanetary systems with simultaneous astrometric and coronagraphic observations***

Primary concept category: **Astrophysics**

## Goals & Overview

EXACT simultaneously enables the **robust characterization of extrasolar planetary systems** (exoplanets + circumstellar debris and systemic architectures) via symbiotic high-performance coronagraphy and precise differential astrometry, with **well-calibrated, deep, wide-field imaging**. EXACT provides two duplexed instruments:

- **a narrow-field high-contrast camera** providing polarimetric, diffraction-limited imaging of exoplanets and circumstellar debris, with integral field unit R~100 spectroscopy
- **a dual-use wide field camera** for differential astrometry and deep wide field imaging. High precision astrometry is enabled by EXACT's calibration of distortions using a grid of dots covering ~1% of the telescope primary mirror.

EXACT's simultaneous specto-polarimetric and astrometric imaging capabilities uniquely facilitate **comprehensive and efficient studies of nearby exoplanetary systems**. EXACT's high-efficiency coronagraph provides access to exoplanets and co-orbiting circumstellar (CS) debris with an inner working angle (IWA) reach penetrating into the habitable zones (HZ) of hundreds of stars and with sufficient sensitivity to **identify and characterize Earth analogs around ~ 20 nearby stars**.

The EXACT Wide Field Camera delivers geometrically rectified, diffraction-limited images through high-precision distortion, and PSF, calibrations. While this whitepaper focuses on exoplanet-related observations, EXACT also enables wide-field astrophysics use of the ex-NRO telescope(s). EXACT is particularly beneficial to scientific investigations relying on wide field astrometry and good PSF knowledge, including weak lensing dark matter measurement, Near-Earth Objects orbit determination, and galaxy dynamics.

## *Scientific benefits and expected results*

EXACT will observe a few hundred nearby stars with its combination of astrometry and diffraction-limited spectral imaging polarimetry, enabling EXACT to efficiently and robustly characterize exoplanetary systems.

**EXACT will identify planets by combining astrometric and imaging measurements**. EXACT will have the astrometric sensitivity to detect Earth analogs (~1 Earth mass planets in their stellar habitable zones) around approximately 200 stars, and will also identify more massive planets (Super-Earths, Giants), measure their orbits and masses. EXACT's astrometry+imaging combination allows robust identification of multiple planets in only ~10 observations.

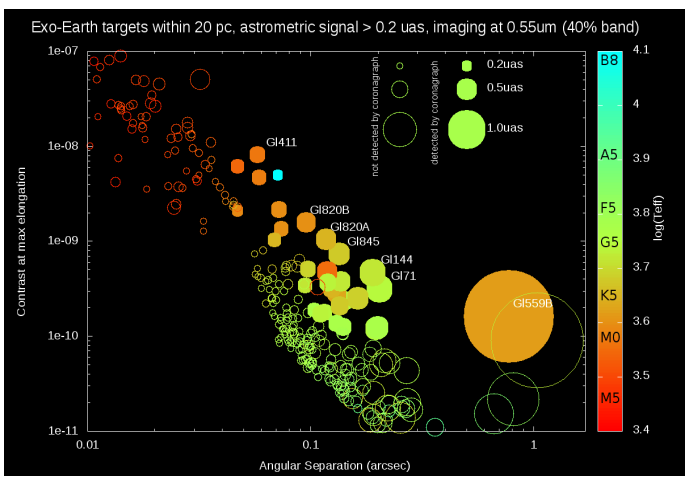
Circumstellar (CS) disks are both the progenitors and outcomes of the planet formation processes. **EXACT's mapping of starlight-scattering CS debris** directly informs on the formation, evolution, architectures, and diversities of exoplanetray systems:

- Dynamical interactions between planets and CS disks play vital roles in generating the architectures of planetary systems and create sub-structures in debris systems. These will be directly, and uniquely, observable with EXACT.
- Dust structures trace the presence of even unseen planets. How many systems possess massive planets on large orbits that can dominate their dynamical evolution? EXACT will elucidate.
- EXACT's spectal imaging polarimetry characterizes and constrains the physical properties of the constituent materials in CS planet-hosting environments reaching into stellar HZs. What veneer is delivered to planets by asteroids and comets? EXACT will arbitrate.

EXACT is ideally suited to **mitigate confusion between exozodiacal dust structures and planets**: both spectro-polarimetric measurements and astrometry will distinguish between dust and planets. EXACT's circumstellar dust observations will thus guide the design of future flagship missions that must overcome the dust/planet confusion issue to

study habitable planets.

**EXACT will have the sensitivity to characterize potentially habitable Earth-size planets around a well-selected sample of ~20 nearby stars**. If such planets exist, their orbit and mass will be constrained by astrometry and imaging, and their atmosphere composition will be constrained by specral and dual-band polarimetry. While this scientific goal was previously thought to require an ~8m telescope, the improvement in coronagraphy efficiency between the TPF-C FB1 concept coronagraph[1] and the proposed PIAACMC architecture offsets the losses due to the use of a smaller telescope (3 λ/D on a 8x2.5m aperture is similar to 1 λ/D on a 2.4m aperture). EXACT can astrometrically detect ~1 Earth mass planets in the habitable zones of 200 stars. Around 34 of these stars, direct imaging of such planets will be possible at 0.55µm. Comprehensive characterization of habitable planets, with spectroscopy from 0.4 to 1µm and astrometric measurement, will be possible around 11 stars. A whitepaper led by team member R. Belikov describes in further detail how the coronagraph enables access to potentially habitable planets.

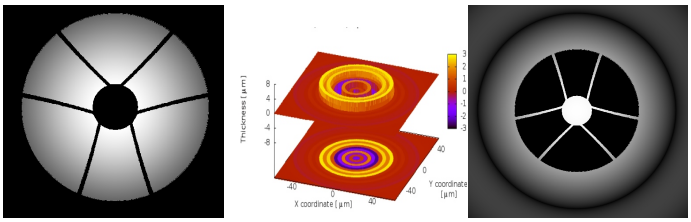



***EXACT has the sensitivity to detect and characterize Earth-sized planets in the habitable zones of their stars. In this simulation, where every star within 20pc is assumed to have a 1 Earth mass habitable planet, open circles represent stars for which the astrometric signature of the exoplanet is within EXACT's reach, and filled circles show show stars around which habitable planets would be observed with both astrometry and direct imaging at 0.55µm.***

## *EXACT's two-instrument Design*

**EXACT's high contrast imaging instrument** is optimized for efficiency[2], maximizing science return and also enabling high contrast at small IWA as wavefront variations from the telescope are measured rapidly. EXACT's high efficiency is achieved by covering the 0.4µm to 1µm spectral range simultaneously with four coronagraph spectral channels, each ~20% wide, fed by dichroics. Within each coronagraph channel, an integral field unit provides a spectral resolution R~100. Wollaston polarization prisms split each spectral channel into two images.

EXACT's baseline coronagraph is a phase-induced amplitude apodization complex mask coronagraph (PIAACMC)[3], offering 1 λ/D IWA, 100% throughput, and full angular resolution. Deformable mirrors are used for wavefront correction. While the coronagraph can conceptually deliver better than 1e-10 raw contrast with 0.65 λ/D IWA on an ex-NRO telescope pupil, EXACT's expected *raw* contrast is approximately 1e-7 from 1 to 2 λ/D (limited by stellar angular size, chromatic residuals and wavefront instability), and 1e-8 to 1e-9 raw contrast @>= 2 λ/D (limited by wavefront instability).

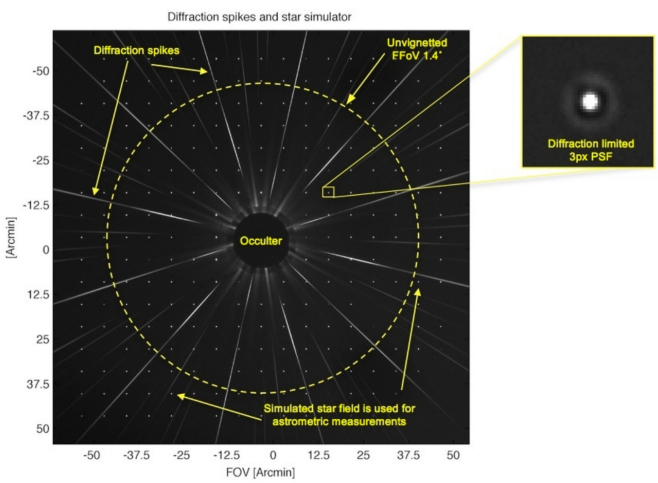


***EXACT's PIAACMC coronagraph design. The telescope pupil is first remapped into a slightly apodized pupil (left) using lossless aspheric optics. A phase focal plane mask (center), optimized for broadband operation, diffracts light outside the pupil (right), which can then be masked by a Lyot stop.***

EXACT's coronagraphic sensitivity is achieved through calibration of PSF-suppression residuals as limited by photon noise and systematics. Pointing and low order aberrations are actively measured with a low-order WF sensor[4] and removed by the deformable mirrors in the closed-loop starlight suppression system. Leaks, primarily due to the stellar angular size but also instrumental chromaticity are removed in post-processing. A PSF library accumulated during the mission is used as a

final calibration step. Thanks to these steps, the detection limit systematics are 100x to 1000x smaller than imposed by the raw PSF. Similar gain augmentation with inferior "raw" PSFs have been demonstrated with coronagraphy plus PSF-calibration with HST and with the addition of Adaptive Optics on ground-based telescopes. EXACT can use both spectral differential, and polarized flux imaging to further improve detection contrast.

**EXACT's wide field camera** images a 15'x15' field centered around the narrow field of the high contrast imaging instrument. A tertiary mirror is required to achieve <60nm wavefront error (excluding optical defects) over the full field. The diffraction-limited focal plane array requires >1 Gpix, and is sensitive from 0.4µm to 1µm.




***EXACT will acquire wide-field images, such as this laboratory image, for astrometry measurement. The central part of the field (labeled "Occulter") is missing, as it is diverted to the high contrast imaging camera. Diffraction spikes from the central bright star are visible in the wide field image, and are used to measure instrumental astrometric distortions. The astrometry measurement is obtained differentially between the background stars (here, pinholes in a plate) and the diffraction spikes.***

**EXACT's approach to high-precision differential astrometry is to calibrate and track distortions during observations instead of relying on telescope and instrument stability**. Temporal variations in optical distortions are measured thanks to a grid of small "dots" deposed on the primary mirror coating. The ~100µm diameter dots, covering approximately 1% of the primary mirror surface, create diffraction spikes that encode distortions[5].

Additionally, the focal plane array can also be independently calibrated by projecting a monochromatic fringe pattern onto it (see whitepaper submitted by M. Shao). The primary mirror dots do not compromise deep wide field observations, as the total area covered is ~1%, which is about 5x less area thanvthe telescope spiders. The faint diffraction spikes can be digitally removed from the image if needed. High contrast imaging is also unaffected, as the diffraction spikes do not extend inward into the coronagraph field of view, as shown in a recent laboratory demonstration. EXACT's single visit astrometric precision is 0.2µas per axis for high galactic latitude targets (worst case), assuming a 2-day observation[5,6].

## EXACT key technologies

Laboratory PIAA type coronagraphs have demonstrated raw contrast at the EXACT level: 1e-7 from 1 to 2 λ/D and <1e-9 in monochromatic light from 2 to 4 λ/D (PIAA TDEM milestone #1). Broadband vacuum performance will be demonstrated as part of the EXCEDE maturation/test program and the ongoing TDEM program. Astrometric calibration with a pupil grid was demonstrated in the laboratory[7], and on-sky.

***References:***


*[1] exep.jpl.nasa.gov/TPF-C/TPFC-MissionAstro2010RFI-Final-2009-04-01.pdf*
*[2] "Theoretical Limits on Extrasolar Terrestrial Planet Detection with Coronagraphs" Guyon et al. ApJ Suppl, 167, 81-99 (2006)*
*[3] "High performance PIAA coronagraphy with complex amplitude focal plane masks" Guyon et al. ApJ Suppl, 190, 220-232 (2010)*
*[4] "Coronagraphic Low-Order Wavefront Sensor: Postprocessing Sensitivity Enhancer for High-Performance Coronagraphs" Vogt et al., PASP, 123, 1434-1441 (2011)*
*[5] "High Precision Astrometry with a Diffractive Pupil Telescope" Guyon et al., ApJ sup, 200 (2012)*
*[6] "Simultaneous Exoplanet Characterization and Deep Wide Field Imaging with a diffractive pupil telescope" Guyon et al., ApJ, (2013)*
*[7] Bendek et al. (2013)*