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The Roman exoplanet imaging data challenge: A major community engagement effort

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ABSTRACT

Organized by the Turnbull Science Investigation Team (SIT), the 2019-2020 Roman Exoplanet Imaging Data Challenge[*] (EIDC) launched in mid October 2019 and ran for eight months. This data challenge was a unique opportunity for exoplanet scientists of all backgrounds and experience levels to get acquainted with realistic Roman CGI (coronagraphic) simulated data with a new contrast regimes at 10^{-8} to 10^{-9} enabling to unveil planets down to the Neptune-mass in reflected light. Participating teamshad to recover the astrometry of an exoplanetary system combining precursor radial velocity data (also simulated across 15 years) with two to six coronagraphic imaging epochs (HLC and Star Shade). They had to perform accurate orbital fitting and determine the mass of any planet hidden in the data. It involved PSF subtraction techniques, post-processing and other astrophysics hurdles to overcome such as contamination sources (stellar, extragalactic and exozodiacal light). We organized four tutorial "hack-a-thon" eventsto get as many people on-board. The EIDC proved to be an excellent way to engage with the intricacies of the first mission to perform wavefront control in space, as a pathfinder to future flagship missions. It also generated a lot of positive interactions between open source package owners and a whole new set of young exoplanet scientists running them. As a community we are a few steps closer to being ready to analyze real CGI data!

Keywords: High Contrast Imaging, Exoplanets, Nancy Grace Roman Space Telescope, Data Challenge, Coronagraphs, Community Engagement, Astrometry, Star Shade

1. INTRODUCTION

1.1 The Roman Mission

The Nancy Grace Roman Telescope (Roman, formerly the Wide Field Infrared Survey Telescope,WFIRST) is a NASA mission set to launch in the mid-2020s. It is primarily a super wide field telescope with a field of view, ≃100 times that of the Hubble Space Telescope (HST) yet with the same sharp vision thanks to its equal size (2.4-meter) primary mirror. Most of its time will be dedicated to the Wide Field Instrument (WFI). But Roman also has a Coronagraph Instrument (CGI)[1] onboard. CGI is a Technology Demonstrator towards future flagship missions like the Habitable Exoplanet Observatory (HabEx)[2] or the Large Ultraviolet Optical Infrared Surveyor

[*]Visit the Roman Exoplanet Imaging Data Challenge website: www.exoplanetdatachallenge.com

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(LUVOIR)[3] †. Roman CGI is our best shot as a community, to achieve wavefront control in space in the coming 5-10 years and thus access the contrasts enabling direct imaging of exoplanets in reflected light in the 2020s.

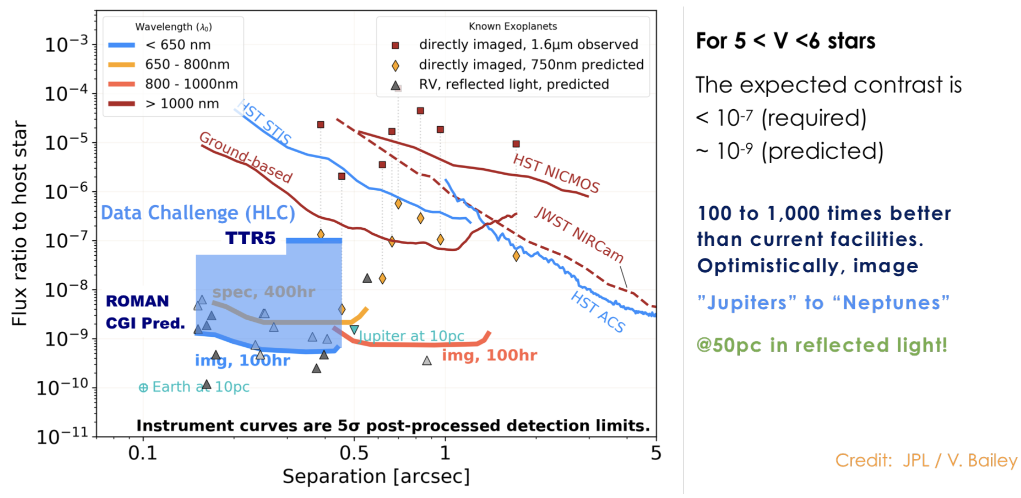

Figure 1. The Roman CGI contrast regime (bottom of the plot) in contrast against angular separation versus the achieved contrasts by current ground and space facilities, including JWST. For nearby, bright stars, it will be 100 to 1,000 better. The area shaded in blue is the band 1 regime covered by the EIDC.

As shown in figure 1‡, contrasts of the order of 10^{-7} (minimum requirement) to 10^{-9} (predicted assuming all systems perform as planned) for nearby bright ($5 < V < 6$) stars and opens a whole new science:reflected light planets down to Neptune masses. Roman will operate at the second Sun-Earth Lagrange point (SEL2). The mission has passed recently the critical (and final) design review and is entering the construction phase.

1.2 The Coronagraph Instrument (CGI)

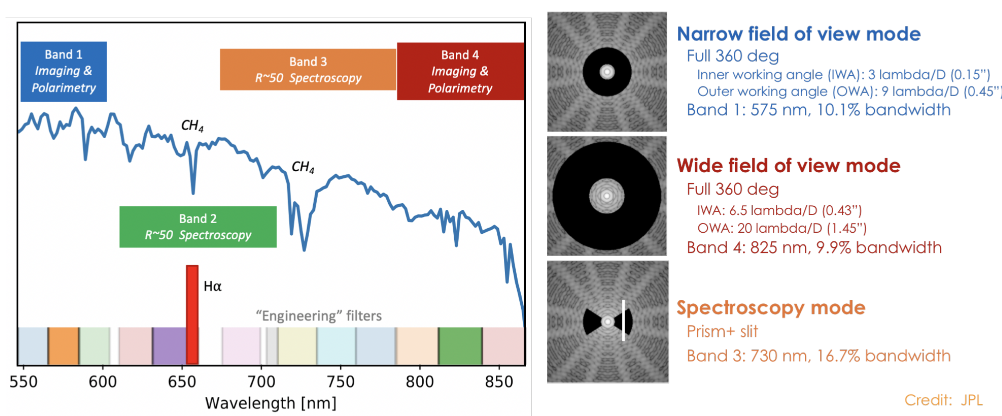

Figure 2. The three main Hybrid Lyod Coronagraph (HLC) modes and spectral bands. For this DC, only the Band 1 and the narrow field mode are considered. It is a 360°mode with the smallest inner-working angle, ≃0.15″.

The Data Challenge makes use of of the narrow field mode of the HLC coronagraph at the shortest wavelength (575nm). Figure 2 shows the main three modes of CGI (not displaying polarimetry nor engineering modes).

†For more information about HabEx and LUVOIR, visit the website of the four "Great Observatories" proposed to the 2020 Decadal Survey (with final reports): www.greatobservatories.org

‡For an up-to-date version of this plot, maintained by V. Bailey (JPL), please visit: github.com/nasavbailey/DI-flux-ratio-plot

Highlighted in blue is the contrast regime of band 1 with the HLC. The DC regime is rather optimistic, close to the CGI prediction line (bottom).

CGI's Science, beyond the "Tech Demo" phase is articulated around the following themes (in **bold**, the ones tackled by the challenge):

- **Mature Jupiter Analogues in reflected light: Blind search for exoplanets; Orbital solution, mass measurements**; Atmospheric properties
- Self-luminous, Young Super Jupiters
- Circumstellar disks: Protoplanetary (young); Debris (mature), **Exozodi** (mature, HZ)

2. THE 2019-2020 ROMAN EXOPLANET IMAGING DATA CHALLENGE

2.1 Motivations

Data challenges and this one in particular aim at broadening and deepening our knowledge as a community. The goals of the Roman Exoplanet Imaging Data Challenge include:

- Familiarize the exoplanet community with the CGI data products, and with working in a new contrast regime that enables the detection of mature giant planets in reflected starlight.
- Develop, use, and improve data simulation and analysis tools, including combining RV and imaging data and using a variety of post-processing and PSF subtraction techniques.
- Explore the detection space enabled or enhanced by combining precursor RV and late-mission starshade observations with the CGI data.
- Train and foster collaborations between future leaders of exoplanet science.

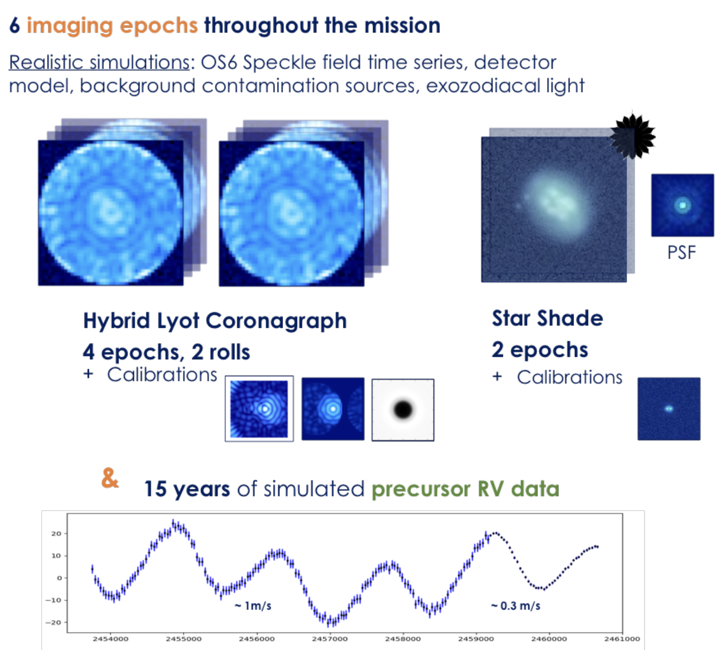

Figure 3. Input data for the data challenge: 6 imaging epochs (4 HLC and 2 star shade) and their calibration files (coronagraph throughput, off-axis PSF) as well as 15 years of precursor radial velocity data (in this case, this RV data is the one use for one of our rehearsal data sets).

2.2 Scope: blind search and astrometry

The scope of the challenge is tounveil an exoplanetary system of at least one planet hidden in realistic CGI data which includes wavefront control residuals, detector modeling and astrophysical contamination. Participating teams are given6 imaging epochsof the same target throughout mission, thenearby star 47 UMa.They are also given calibration files corresponding to the Observing Senario 6 (OS6, described in section 3.1) as well as 15 years of simulated precursor radial velocity data. There are 4 imaging epochs 4 with the Hybrid Lyot Coronagraph (HLC) and 2 epochs with the Star Shade assuming a rendezvous occurs down the road. They had toperform accurate astrometry and orbital fittinganddetermine the mass, radius and albedoof any planet hidden in the data. It also involvedPSF (Point Spread Function) subtraction techniques and post-processingand other astrophysics hurdles to overcome such as contamination sources (stellar, extragalactic and exozodiacal light).

2.3 Four steps to unravel a hidden exoplanetary system

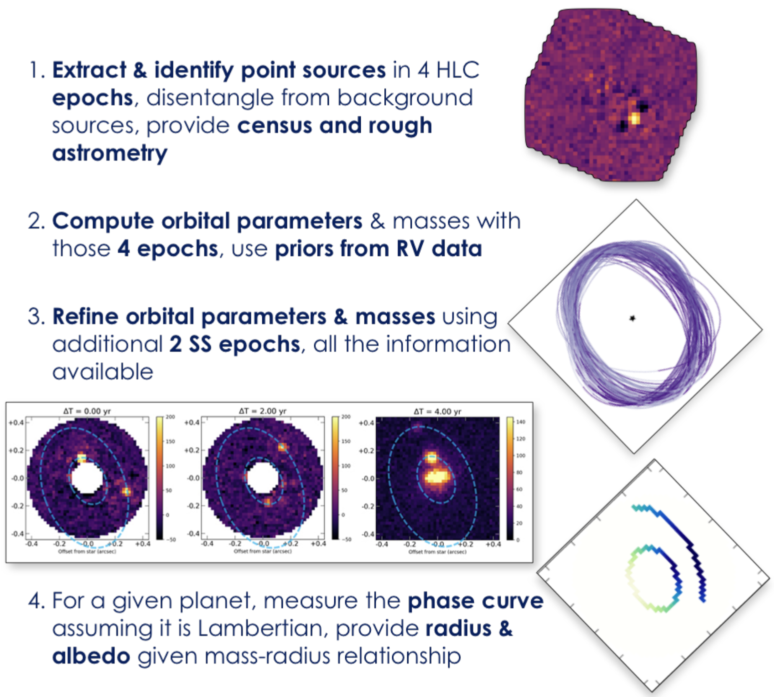

Figure 4. The challenge is broken down in four steps which should help participants perform tasks in a logical order and which are gradually more difficult.

The EIDC was rolled out in four increasingly difficult steps as shown in 4, to help participants work in a logical manner and avoid overwhelming the teams. Participants submitted the results of each step in order to receive the next package of simulated data:

- Step 1: HLC only. Identify all the point sources in 4 HLC epochs, disentangle planets from any background sources, provide system census and astrometry.
- Step 2: HLC + RV priors. Compute orbital parameters and masses using the above 4 HLC epochs plus priors from RV data.
- Step 3: HLC + RV + starshade (SS). Refine the orbital parameters and masses of all detected planets using two additional SS epochs.
- Step 4: For each planet, measure the phase curve (assuming a Lambertian reflectance function), and derive the radius and albedo from a provided mass-radius relationship.

Importantly, the SS images were not provided until Step 3, because these data would have undermined the blind analyses of the prior epochs by clearly revealing planets that are only marginally detected with the HLC. Figure 5 shows the science grade data products (post PSF subtraction) for the HLC and SS, respectively.

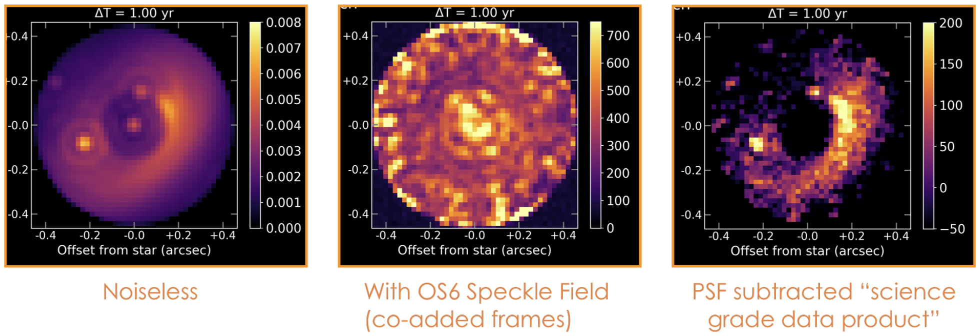

Figure 5. HLC epoch 4 at $\Delta_t = 1$ yr. Left: injected diffraction limited scene. Middle: co-added raw data. Right: RDI subtracted "science grade product"

3. DESIGN OF THE CHALLENGE

Our team designed the challenge in such a way that the most could be learned, to prepare as a community for when the CGI data will be available. Will we be able to discriminate planets from speckle or contaminants? How many epochs are needed to derive a meaningful mass? Can we cope with the exozodiacal light? In fact, we wanted to really imagine we already had on-sky CGI data, a few imaging epochs (HLC and then SS) and the tasks to dig for exoplanet signal. The three planets b, c and d that we injected in the real challenge covered a range of contrast and angular separations which are particularly interesting. Planet b, the inner-most one is at the limit of the inner-working angle of the CGI HLC narrow-field mode. Planet c is the easiest one as it is bright and lies in the ∼middle Details of the `EIDC` design and our "in-house" analysis of planet c will be given in a subsequent publication[4] which will also announce the release of a software package to create such a "scene" and our legacy tutorial suite to complete all the steps described in figure 4 on planet c. In figure 2.1 we summarize all the main input data provided to the participants (challenge and/or tutorial "hack-a-thon" data sets). For the orbital analysis, we used the *orbitize!* package.[?]

3.1 HLC simulations

The baseline imaging mode of CGI is a Hybrid Lyot Coronagraph (HLC) operating in a bandpass centered at 575 nm (the 546-604 nm "Band 1" filter of CGI). This configuration provides the smallest inner working angle of the available coronagraph modes, approximately 150 mas, which results in the best overall sensitivity for detecting exoplanets in reflected starlight. The data challenge files include four epochs of simulated HLC images of the scientific target at time intervals T= 0.0, 0.15, 1.0, and 2.0 years from an initial observation on 2026 Nov 1. The time-varying residual starlight pattern, including speckles and pointing jitter effects, is based on the "Observing Scenario 6" (OS6) PSF time series prepared by the CGI project?s integrated modeling team in 2018.[5] The OS6 PSF time series includes alternating observatory roll angles, to assist in discriminating astrophysical signals from quasi-static speckles. Therefore, the simulated HLC images are provided as co-added images with total integration time 66000 seconds (approximately 18 hours) in each of two roll angles 26°apart. Along with the science target observation, at each epoch there is a corresponding bright reference star observation to enable reference differential imaging (RDI) to partly subtract the residual starlight pattern.

To the raw "speckle field" co-added images from OS6, we injected astrophysical signals: the three planets, an epoch-varying exozodiacal disk,[6] a background star asuming a realistic galactic density (to be discriminated through multi-epoch, proper motion analysis), an extragalactic background from the Haystacl Project.[7]

3.2 Star shade simulations

The starshade (SS) images were generated with SISTER,[8] a source free software capable of performing SS simulations with high optical fidelity. We chose the 425-552 nm band of the Starshade rendezvous Probe (SRP)[9] because it is the closest channel to the HLC simulated images. The simulation uses nominal instrument parameters consistent with Roman end-of-life (EOL) operation.

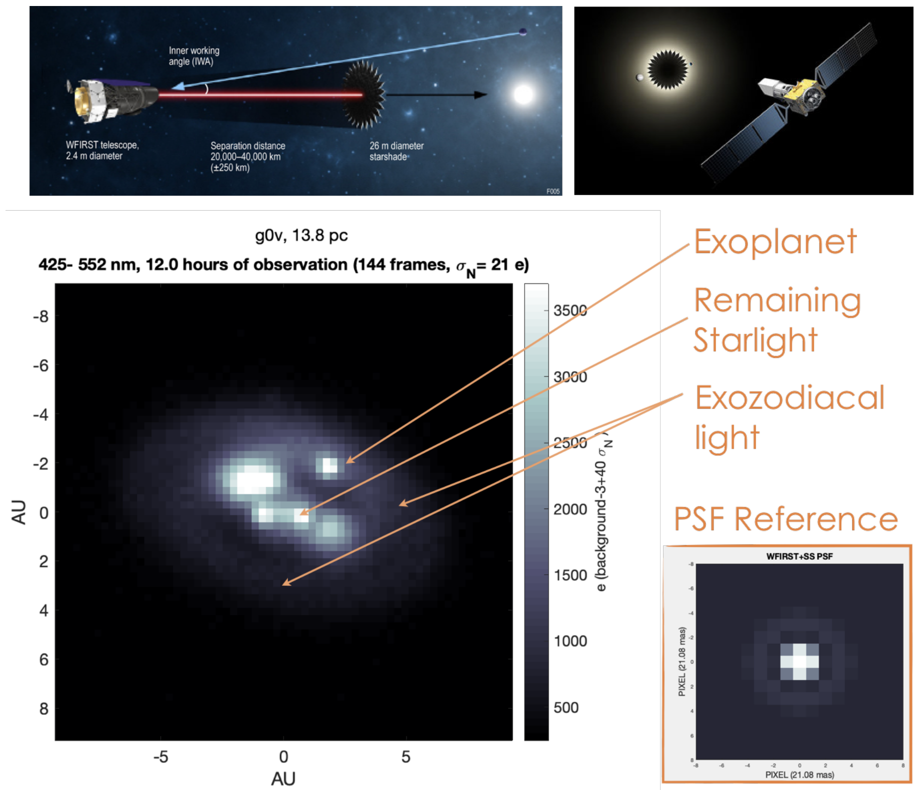

Figure 6. The geometry of the starshade and Roman telescope in the SRP mission concept. The starshade?s inner working angle (IWA) is the apparent size of the starshade?s radius as seen by the Roman telescope. In the 425-552 nm passband, the IWA is 72 mas.

Telescope and Detector. The telescope pupil includes the secondary mirror central obscuration and struts, and is 2.36 m in diameter. The detector noise follows the expected Roman EMCCD model at its EOL. The particular values of the different parameters come from online Roman parameters [§].

The readout noise is 100 e^- per frame, EM gain is 1,000, dark current at EOL is 0.77 e^-/pix/hour, and clock induced charge noise is 0.02 e^-/pix/frame. In order to be able to compare the contribution of starshade data to the CGI data more easily, the total integration time set for both epochs with starshade data was 1.5 days, the same as for the CGI HLC epochs. The detector Quantum Efficiency is based on laboratory measurements of Roman's EMCCD detector. The effective QE across the 425-552 nm is 0.45 and it is the result of the actual QE and further losses due to cosmic rays, charge transfer efficiency, and hot pixels. The pixel scale in the Roman coronagraph instrument is 21.85 mas/pixel. We have assumed that all the pixels are identical without any hot pixels. The simulation does not include contamination from cosmic rays or sources of noise not intrinsic to the detector electronics. The end-to-end optical throughput is the product of reflection losses in the telescope (0.81), the coronagraph instrument (0.60, exclusive of coronagraph masks which are not used), and the starshade dichroic filter (0.9) for a net throughput of 0.44.

[§] see https://wfirst.ipac.caltech.edu/sims/Param_db.html

The SS has 24 petals and is 26 m in diameter. The starshade's geometric inner working angle (IWA) is the apparent size of the starshade's radius as seen by the Roman telescope and in the 425-552 nm passband is 72 mas. For sources located far from the starshade's IWA, the optical response (PSF FWHM = 40.6 mas at mid-band) is that of the Roman telescope, including the secondary mirror and 6 supporting struts. Figure 6 shows a summary our of starshade simulations.

The simulations include the astrophysical components (the three-planet system), residual starlight from an imperfect starshade, the solar glint due to sun?s light scattered through the starshade petals, local zodiacal light, exozodiacal dust light, and a background galaxy.

3.3 Precursor radial velocity (RV) data

Synthetic RV data points were created spanning 15 years, first 10 years with RV instrumental precision of 1 m/s similar to instruments such as Keck HIRES, and additional five years with 0.3 m/s taking into account the emerging extreme precision RV instruments such as WIYN NEID. A total of 200 data points were created by solving Kepler?s equation and superposing individual signals from each planet. To mimic different sources of noises, each RV data point was passed through a Gaussian filter to randomize the velocity measurements, with the sigma calculated from the quadrature sum of instrumental error and stellar jitter. The jitter value of around 2.1 m/s was estimated using the method from[10] assuming the stellar mass and S-index values of 47 UMa host star. The total RV as well as individual phase-folded RV for each planet is shown below. The figure is generated using RV modeling toolkit RadVel[11] with all the parameters fixed so that the outermost planet can be properly displayed. Parameters for each planet such as the orbital period (P), semi-amplitude (K), and eccentricity (e) are shown in the upper right corner of each phase-folded panel.

4. RUNNING THE CHALLENGE

Figure 7. A few pictures taken during our four "hack-a-thon" tutorial events in Baltimore (STScI), Pasadena (IPAC), New York (Flatiron Institute) and Tokyo (In the Spirit of Lyot Conference). More pictures are available on the EIDC website.

To engage the community prior to launching the EIDC, we organized four tutorial "hack-a-thon" events in Baltimore, Los Angeles, New York and Tokyo. Hack-a-thon participants were given two rehearsal data sets as well as a suite of Jupyter notebooks (mainly written in Python) for the participants to begin working with the data. This training material was developed and improved over the duration of the challenge, and is now available for public use[¶]). Altogether, a diverse group of over 70 people (figure 7) attended the hack-a-thons, a subset of

¶To access our legacy tutorial, please visit github.com/wfirst-cgi/Roman-CGI-Data-Challenge-Tutorials whom ultimately participated in the full data challenge either individually or in teams. In an upcoming paper,[12] we will report on the EIDC results in detail. We also answered questions through emails and a Slack channel dedicated to EIDC. In the context of the COVID19 pandemic, we adapted our schedule and moved the final deadline several time to keep teams on-board. In the end, the challenge was opened for 8 months and closed in June 2020. Seven teams entered the EIDC.

4.1 Results

We are currently finalizing the analysis of the participating teams' data. We elaborated metrics to rank the teams quantitatively taking into account completeness and accuracy (photometry, astrometry, physical parameters). We will organize a dedicated virtual event in early 2021 to announce the winner(s) and prizes (will be announced on our website). The detailed analysis will be published in Girard et al. (in prep).[12]

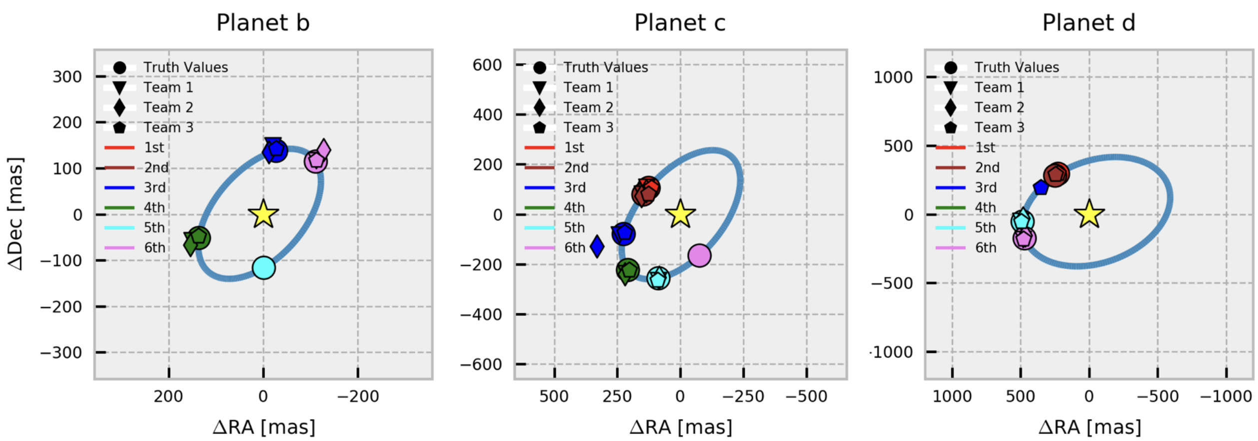

Figure 8. Preliminary results: astrometry on planets b, c and d for the best teams.

4.2 Lessons Learned

The Roman CGI data, combined with precursor RV data and late-mission SS imaging in detecting exoplanets and determining their masses, albedos, and system configurations. While the CGI is more nimble than a starshade and can more readily target specific epochs to reduce uncertainty in planet orbits, the higher throughput of the starshade enables detection and study of planets much farther out in the system and resonant exozodiacal dust structures. Roman CGI is expected to break new ground with direct detection of giant exoplanets within ∼5 AU of V∼5 and brighter stars, a Roman Starshade rendezvous mission would additionally enable the detection and characterization of planets out to ∼8 AU in those systems. A Starshade specific analysis will be reported in.[13]

The EIDC proved to be an excellent way to engage with the intricacies of the first mission to perform wavefront control in space, as a pathfinder to future flagship missions with high contrast. It also generated a lot of positive interactions between open source package owners and a diverse crowd of young exoplanet scientists running them. Five teams performed orbital fitting anf found good astrometric solutionsfor at least one planet with or without the priors from RV precursor data. Three teams did a very compelling analysis of the three planets. Only one team completed Step 4 which is one of the novel aspects of future reflected starlight direct imaging will be the ability to observe the photometric variation over the course of the orbit due to the changing star-planet-observer phase angle. Combined knowledge of the orbit, along with an inferred planet radius, will enable observers to estimate the bulk geometric albedo from a flux ratio time series. One team has been able to recover a challenging planetin some epochs for which we thought it was not possible! Post-processing and experience on precursor data helps. Allstruggled with calibrating photometry. Some participantsdeveloped their own toolsrather than use the publicly available packages (potential added value). We have two main papers in preparation:

- Paper I:[4] DC design/concept/in-house analysis of planet c.
- Paper II:[12] DC organization and results with participants? contributions, discussions of lessons learned and future Data Challenges / Community Engagement.

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