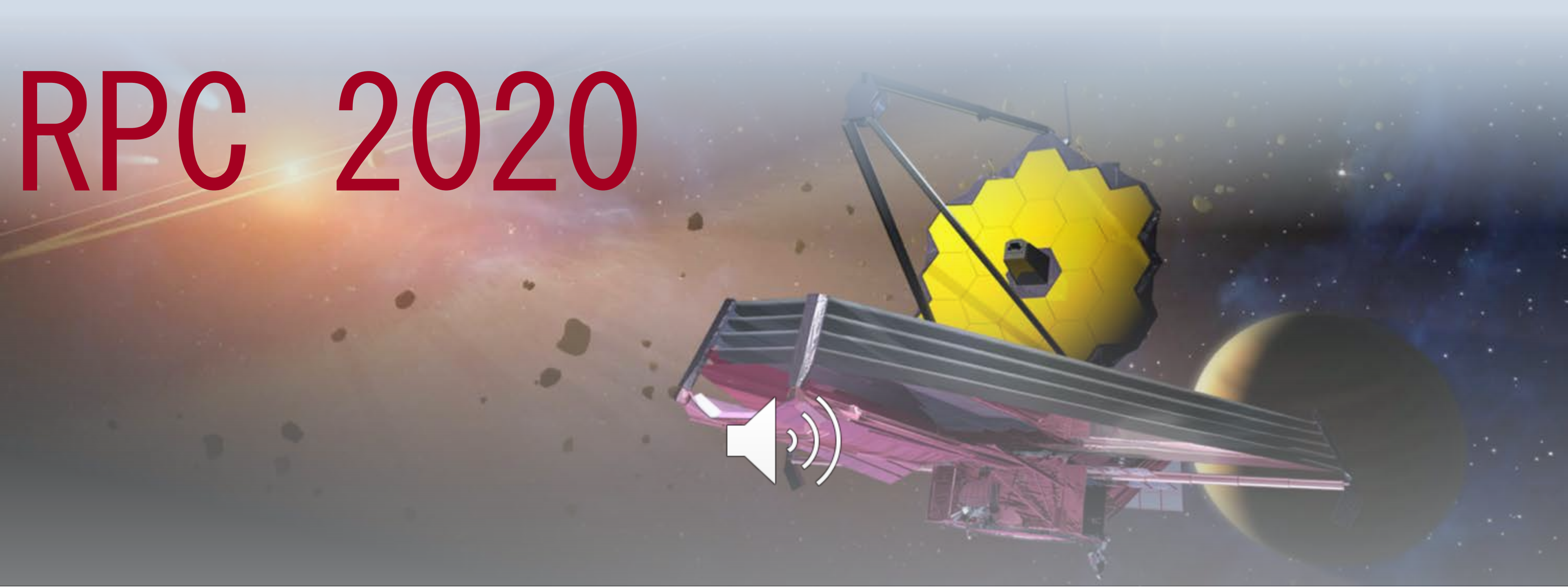

Virtual Research Presentation Conference

Speckle Suppression for Coronagraphic Observations with JWST

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Tutorial Introduction

Abstract

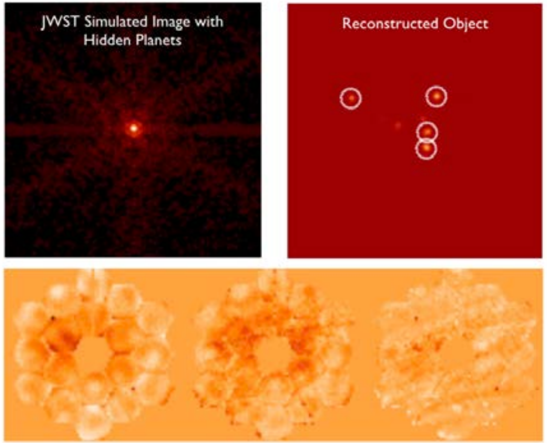
Goal: To develop a new approach to model High Contrast Imaging (HCI) instruments that takes advantage of information, such as Wavefront Sensing and Control (WFSC) data on the James Webb Space Telescope (JWST), to estimate simultaneously instrumental aberrations and the object scene (*Medusae* Approach, Ygouf et al. 2013) and provide a more robust determination of faint astrophysical structures around a bright source.

This approach will enable us to further improve the contrast ga[illegible]ver the achievable contrast with NIRCam imaging and coronagraphic imaging.

How: Implement technique within a Bayesian vein which will allow us to:

(1) quantify uncertainties in the instrument model and obtain a robust, photon-limited performance; (2) build and incorporate knowledge from the observatory (WFSC, thermal evolution models, etc) to infer our post-processing technique; and 3) build a software package tool to simultaneously reconstruct the astronomical scene (e.g. planets) and instrument aberrations using the instrument model and data.

Significance: Our software will be tested at the early stages of the mission and used as early as Cycle 1. We will integrate knowledge in advanced information retrieval into exoplanet studies. This work will pave the way for the future space-based HCI instruments starting with the Roman (formerly WFIRST)/CGI. This technique will be crucial to make the best use of the telemetry data that will be collected during the CGI operations.



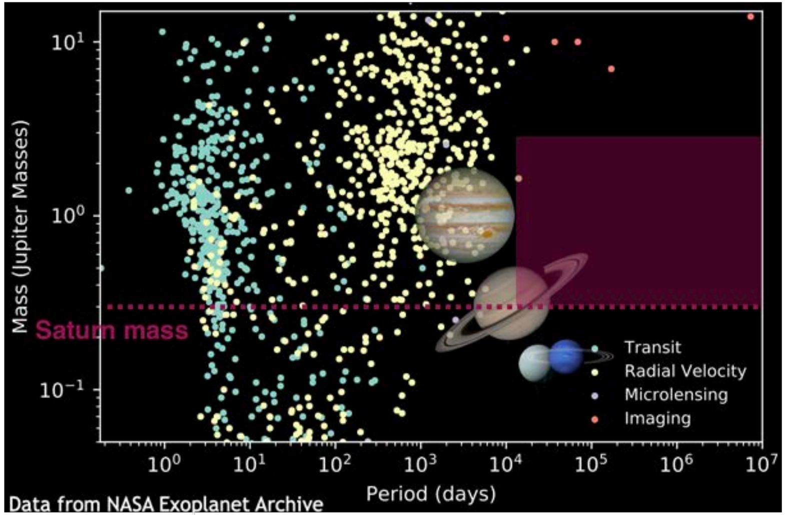
Simulated phase Estimated phase Residuals

Ygouf et al. 2017

Problem Description

a) <u>Context (Why this problem and why now).</u>

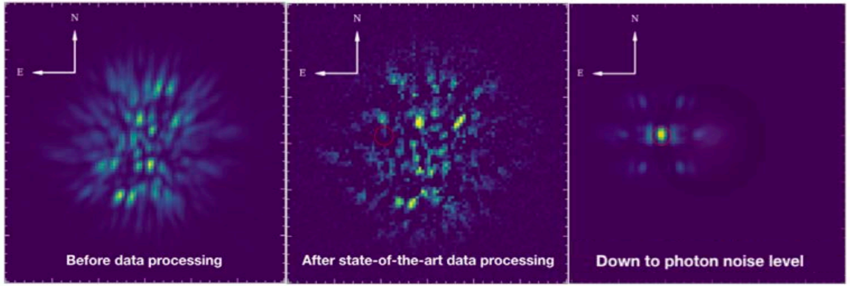
- JWST will probe circumstellar environments at an unprecedented sensitivity
- However, sensitivity dominated by residual light from the star, which considerably limit the sensitivity at close separation to the star (<0.5”)
- Currently no solution to get rid of the speckles down to the photon noise level at those separations, which may prevent some crucial discoveries
- JWST launch is planned for October 2021 and its baseline mission lifetime is only 5 years so it is crucial to find a solution to this problem before its launch
- Further advances in post-processing techniques are required to enhance the detectability of planets hidden in the instrumental noise as well as to improve their characterization



Problem Description

b) SOA (Comparison or advancement over current state-of-the-art).

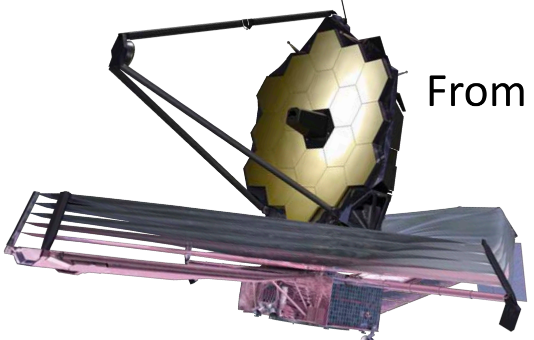
- SOA PSF subtraction techniques have not yet achieved the contrast gain needed to reach the photon-noise limit of HCI observations at those separations
- SOA PSF subtraction techniques operate in the focal plane with little flexibility to use our knowledge about the observatory
- In particular, no program exists to take advantage of observatory telemetry to improve HCI post-processing
- JWST will provide bidiurnal instrumental aberrations measurements thanks to its wavefront sensing and control (WFSC) system. Those measurements can be used to build a good description of the instrument model that will be crucial to inform post-processing in the mitigation of residual speckles



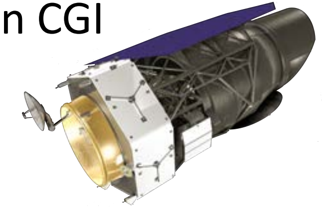
Problem Description

c) <u>Relevance to NASA and JPL (Impact on current or future programs).</u>

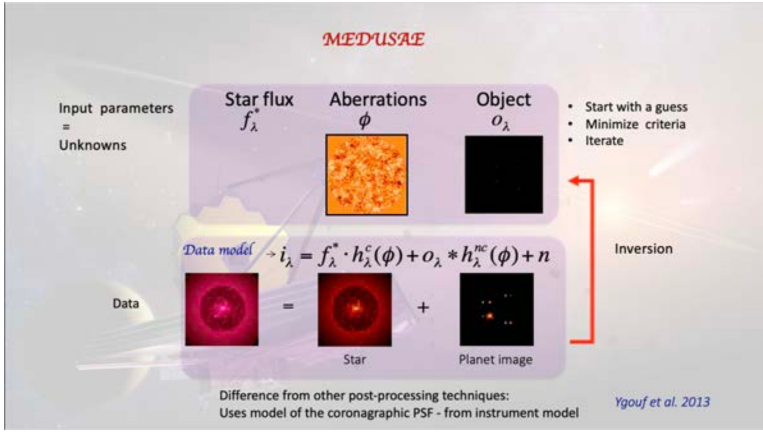
- This study provides the JPL teams with an innovative method to tackle the issue of detectability and characterization of faint planets via direct imaging with the James Webb Space Telescope, helping to address questions about planet formation (constraining orbital motions with astrometry and understanding planet-disk interactions) and planet atmospheric composition (through spectro-photometry)
- This effort strengthened ties with campus via collaboration with two of the Co-Is of this proposal
- In the long-term the methodology developed during this program will help in forecasting performance of HCI technologies as well as to analyze the data from ongoing and prospective experiments including Roman/CGI. Hence this work will support JPL's competitive position in new missions with exoplanet science potential



From JWST to Roman CGI



Methodology



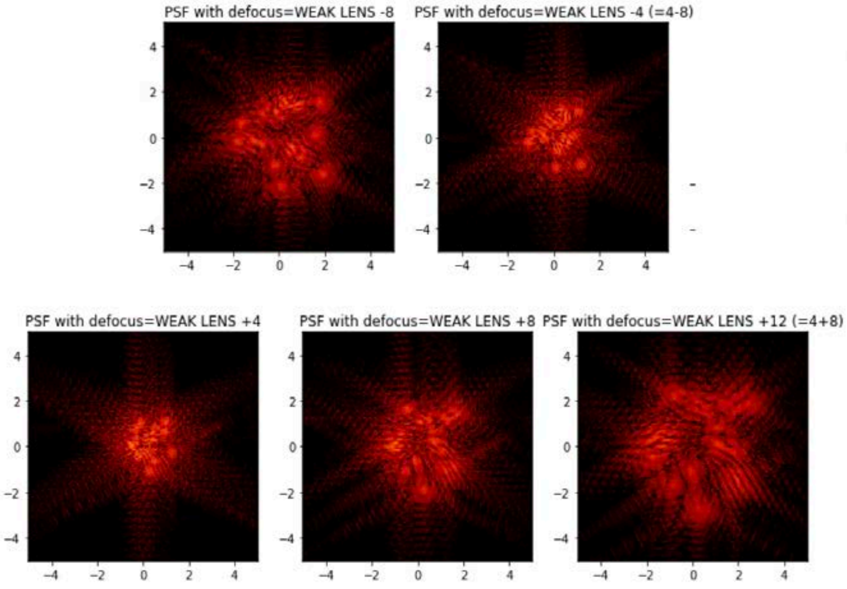
a) <u>Formulation, theory or experiment description.</u>

- Our approach is to implement a model-based technique in a Bayesian framework (Ygouf et al. 2013) for the wavefront reconstruction of NIRCam and NIRISS images
- We first had to assess the data that we will have access to after the launch of JWST that we could possibly use for the validation of our technique once the telescope starts its operations. Wavefront sensing data from the fine phase phasing operations and both NIRISS-AMI and NIRCam coronagraphic data from commissioning, GTO and ERS programs.
  - We identified NIRISS data that fit our needs in the NIRISS-AMI Commissioning Program (JWST Proposal 1093)
  - There is the need for specific NIRCam calibration data that will not be available from commissioning data or GTO/ERS programs. Thus we undertook the task of preparing a JWST GO-calibration proposal to request the required NIRCam data.
- For testing and validation we had to:
  - Simulate NIRCam and NIRISS images with available python software, namely WebbPSF [3] and pynrc [4], and
  - Implement this optimization scheme on those simulated images

Methodology

b) <u>Innovation, advancement.</u>

- The Bayesian framework that we are implementing offers the possibility to make use of the library of wavefront maps from the JWST wavefront sensing operations that will be publicly available
- In particular, we reconstruct the wavefront by minimizing a metric that is based on the model of instrument
- This process is degenerate and thus any prior information to help constraining the optimization algorithm is useful
- The library of wavefront maps can be used to obtain such prior information



JWST wavefront sensing data simulated with WebbPSF

Results

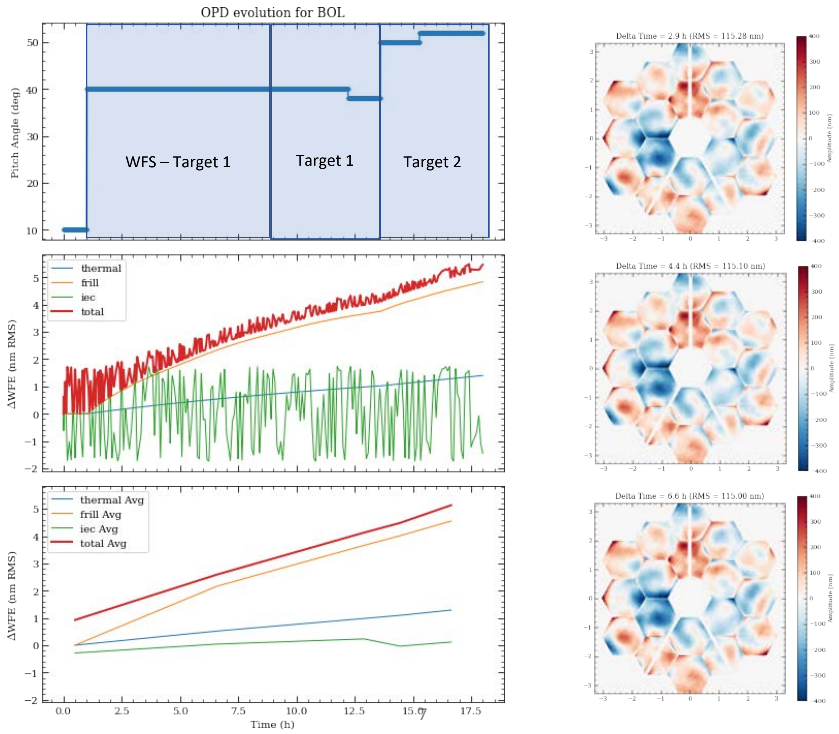
a) <u>Accomplishments versus goals</u>.

We were able to achieve important milestones:

1. We have now a complete python framework to simulate JWST NIRISS-AMI and NIRCam images and estimate wavefront maps from those images

2. We have now a plan to further test and validate our technique on both simulated and real data from JWST, in particular we designed a complete observing scenario for the simulation of NIRCam and we simulated realistic wavefront maps for this scenario

3. We demonstrated that making use of a prior information gathered from WFS to inform post-processing improves the wavefront reconstruction from NIRCam simulated images (see next slide)

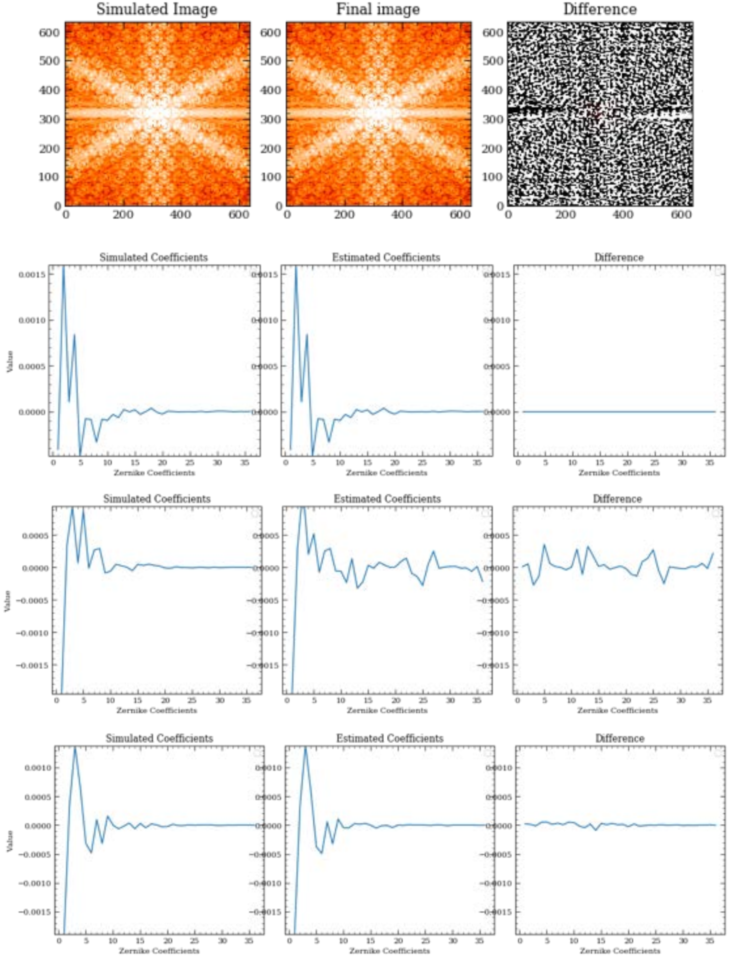


We simulated realistic wavefronts for the NIRCam observing scenario using latest knowledge about wavefront evolution from ground-based commissioning, using real data from ground-based commissioning (Perrin et al 2018).

Results

b) <u>Significance.</u>

- Our reconstruction of the wavefront from NIRCam-like images considering 35 first Zernike coefficients.
- We show that the reconstruction is greatly improved by adding prior information about the wavefront error.
- This means that we will be able to optimally reconstruct the object scene (sources) and enable its detectability and unbiased characterization.
- Figure shows our estimation of the 35 first Zernike coefficients for three different cases: noiseless data (second row), noisy data without prior knowledge on the wavefront error (third row) and noisy data with prior knowledge on the wavefront error (fourth row). As a prior knowledge, we assumed that we were able to estimate the wavefront error budget for those 35 first Zernike coefficients (from publicly available data from WFS) and we used this error budget as an input of our estimation. Doing so greatly improves the estimation of the Zernike coefficients and demonstrates the benefit of using prior information for wavefront reconstruction.
- This result is significant because this is the first time that some knowledge about the wavefront is used to inform and improve data processing.



Results

c) Next steps.

- Implement full approach to estimate jointly the instrumental aberrations and the object scene (for example if a planet is present in the data).
- Two possible paths:
    1. Evidence-based approach to decide whether a given detection is a real planet or just noise (Golomb , Rocha et al. 2019)
    2. Alternative algorithm in the form of iterations between wavefront estimation and object deconvolution (Ygouf et al 2013)
- In FY21, through SURP program support, we will investigate how the estimation of the wavefront error will contribute to the performance of our recovery analysis with NRM simulated sources. We will compare the performance of full pupil analysis to that of NRM for various astrophysical scenes as well as explore any additional recovery enhancements using information from both full pupil and NRM data of the same scene.
- JWST proposal to be submitted in FY21

Publications and References

PUBLICATIONS

Ygouf et al, "Speckle Suppression for high contrast imaging for JWST ", SPIE, *in prep* (2020)

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