ExoSpec Project: An exoplanet spectroscopy technology research collaboration based at NASA’s Goddard Space Flight Center and Ames Research Center

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ABSTRACT

The exoplanet atmosphere characterization goals of future UV/Optical/Infrared flagship space missions will drive challenging design requirements for instrument wavefront controls, spatial and spectral sampling, spectral bandwidth, and detector performance. The new ExoSpec Project links four previously distinct research efforts at Goddard and Ames for enabling and enhancing the characterization of directly-imaged exoplanets. ExoSpec is comprised of three laboratory subsystem demonstrations: high-contrast integral field spectrographs, p-channel CCDs, and parabolic deformable mirrors. A fourth component, exoplanet spectral retrieval, is an iterative data simulation activity driven by the goal of optimizing the system-level instrument design for atmosphere retrieval metrics. The ExoSpec Project’s emphasis on system-level spectroscopy performance complements the objectives of other technology demonstrations supported by NASA.

Keywords: exoplanets, spectroscopy, high-contrast imaging, deformable mirror, wavefront control, detectors, integral field spectrograph

1. INTRODUCTION

High-contrast spectroscopic imaging holds immense promise to unveil diverse populations of rocky exoplanets and to establish the cosmic context of the Solar System and Earth.\textsuperscript{1,2} The Coronagraph Instrument (CGI) on NASA’s Nancy Grace Roman Space Telescope will mature several of the key technological elements needed to characterize habitable worlds with a future flagship space telescope.\textsuperscript{3} The Roman Coronagraph, however, is primarily an imaging tech demo, with limited spectroscopic functionality.\textsuperscript{4} Therefore, in parallel to the Roman CGI technology demonstration, a dedicated spectroscopy instrumentation research effort can help to bridge present-day capabilities with the exoplanet characterization goals of future missions.

Detecting atmospheric absorption features of rocky exoplanets observed in reflected starlight is one of the few means available to remotely assess their habitability. Using Earth as a template, we expect the atmosphere of a terrestrial analog to show an O\textsubscript{2} absorption feature at 760 nm, requiring a spectral resolving power of R\textasciitilde140 to detect.\textsuperscript{5} At longer wavelengths, a spectral resolving power of R\textasciitilde70 would be needed to detect a water vapor absorption feature at 940 nm.\textsuperscript{6} Additional features from water, CH\textsubscript{4}, and CO\textsubscript{2} between 1.0–2.0 \(\mu\)m motivate a dedicated near-infrared channel. This broad wavelength span, together with the reduced signal-to-noise ratio of the spectrally dispersed exoplanet light, lead to characterization observations that require orders of magnitude more integration time than broadband imaging detections. Therefore, the spectroscopic characterization goals of future exoplanet imaging missions will drive instrument requirements for spectral bandwidth (both instantaneous bandpass and overall range), spectrograph optical efficiency, and detector performance.

The Exoplanet Spectroscopy Technologies Project (abbreviated ExoSpec) is a new collaboration dedicated to maturing three subsystem technologies related to enabling spectroscopy of directly imaged exoplanets: integral...
field spectrographs, photon counting CCD detectors, and parabolic deformable mirrors. While we advance these subsystem technologies through separate laboratory prototype demonstrations, we are also assessing their impact in terms of scientific yield at the system level through integrated modeling and spectral retrieval simulations. This modeling pipeline provides a framework for guiding subsystem-level engineering trades, as illustrated in Figure 1.

Figure 1: By developing several strategic technology enhancements and simulating the combined impact on scientific yields, the ExoSpec project helps to create a new framework for science-driven systems level mission requirements for a future flagship observatory capable of characterizing Earth-like exoplanets.

2. INTEGRAL FIELD SPECTROSCOPY

Lenslet-based integral field spectrographs have been deployed in several ground-based high-contrast instruments. A lenslet integral field spectrograph (IFS) preserves the spatial context of the source signal, which is essential for calibration and data post-processing. At the same time, a lenslet IFS minimizes optical losses and distortions before the detector, enabling accurate reconstruction of the 3-D spectral image cube (Figure 2). For these reasons, a lenslet IFS was part of the original Phase-A architecture of Roman CGI, until it was descoped due to mass and power concerns.

Due to the very low irradiances of rocky exoplanets observed in reflected starlight, spectroscopic characterization goals will place extraordinary demands on per-target integration times. The ExoSpec project is investigating two paths to improving the efficiency of a lenslet-based integral field spectrograph (IFS): pinhole filtering to enhance starlight suppression, and novel off-axis lenslet array designs to more efficiently pack dispersed spectra on the detector array. Our prototype demos of improved IFS designs will make use of spare optics from the Prototype Imaging Spectrograph for Coronagraphic Exoplanet Studies (PISCES) project.

To implement a novel approach to more efficiently pack prism-dispersed spectra on the detector, we designed a prototype off-axis lenslet array with 78 micron lenslet pitch (equivalent to the spatial sampling in the image plane). This optical prescription places the focal points in groups of 4 lenslets (left-hand side of Figure 3). We are iterating on this design to address a fabrication problem before further testing with PISCES optics.

3. PHOTON-COUNTING DETECTORS

ExoSpec will advance the technological readiness of photon-counting, radiation tolerant, visible and near-IR detectors. Our research efforts have concentrated on adding photon counting outputs to Lawrence Berkeley National Laboratory’s (LBNL) thick, fully depleted, p-channel CCDs (Figure 4). The underlying p-channel CCDs are known to be radiation tolerant from previous demonstrations for the SuperNova Acceleration Probe (SNAP) dark energy mission concept. We are investigating two paths to achieving sub-electron read noise with...
Figure 2: Conceptual diagram of a lenslet-based integral field spectrograph for high-contrast imaging: A lenslet array partitions the coronagraph image into a grid of spatial elements which are each dispersed by a prism. The spectra are reconstructed to form a multi-wavelength data cube.

Figure 3: Left: Diagram of grouped focal points specified by the off-axis lenslet array optical prescription. Each group of 4 lenslets will produce a corresponding group of spectra on the detector, aligned along the dispersion axis. Right: Testbed setup at Goddard for characterizing the newly procured lenslet array, mounted on the post in the right-hand side of the photo.

these p-channel CCDs: hole multiplication (analogous to electron multiplication) and non-destructive reads to average down the read noise.\textsuperscript{12}

Figure 4: The a) Goddard Detector Characterization Lab’s HMCCD test system is based on a Gen-II Leach Controller (here labeled ”CCD Controller”). Panel b) shows most components, with the dewar faceplate removed so that the HMCCD is visible.
4. PARABOLIC DEFORMABLE MIRRORS

In a space coronagraph, the bandwidth and depth of contrast are strongly coupled to the performance of the wavefront control system. Conventionally, space coronagraph designs use two deformable mirrors (DMs) in series. The ExoSpec project is exploring an alternative design architecture to the two-DM approach in which the reimaging optics for the coronagraph are also deformable. Only one high-order pupil DM is retained. With these off-axis parabolic elements being made deformable, the long propagation distance between the two DMs is eliminated. The performance gains enabled by parabolic deformable mirrors (DMs) may include expanded spectroscopy bandpasses, and system-level optimizations such as relaxed requirements on the number and size of actuators on each DM.\textsuperscript{13}

Starting from numerical simulations (Figure 5) we have worked with a vendor to fabricate an off-axis parabolic DM prototype. We are preparing a laboratory testbed to test the functionality at Goddard with a shaped pupil coronagraph and a pupil-plane MEMS DM (Figure 6). The testbed has low-order wavefront sensing capability, allowing for integrated testing of a dynamic environment with multiple estimation and control loops. Numerical simulations of the concept are shown in Figure 5.

Figure 5: Simulations of correction using a single parabolic DM and a BMC kilo-DM at a pupil plane. a) Phase error at the pupil plane, b) contrast improvement at each EFC control iteration, c) parabolic DM voltage map solution, and d) final dark zone after wavefront control.

Figure 6: Left: Optical layout for testing an off-axis parabolic DM with a shaped pupil coronagraph and one BMC Kilo-DM in a pupil plane. Right: Photo of the parabolic DM testbed under assembly at Goddard.

5. INTEGRATED MODELING AND SPECTRAL RETRIEVAL

To guide the development of these technologies, the ExoSpec project is creating astrophysical data simulations that integrate the subsystems described above (DM control architecture, integral field spectrograph, and detector), and then applying spectral retrieval tools to the resulting spectroscopic data products (Figure 7. The assessments of inferred exoplanet properties will then be used to improve our definition of mission requirements...
and our understanding of the sensitivity of scientific capabilities to individual technology investments. Several tasks are underway to prepare these models:

- Generalize the spectral retrieval tools that team members based at Ames Research Center previously developed for Roman CGI data so that they can be applied to future instruments with different design parameters and wavelength bandpasses.
- Integrate astrophysical scenes, coronagraph models with DM control, IFS model, and detector model in one pipeline for simulating spectroscopic data products for directly imaged exoplanets. 
- Apply radiative transfer algorithms to construct forward model atmospheres of various planet types.

Where practical, these ExoSpec modeling efforts will be community-facing. Team members will release source code to the public (for example, a new code for modeling clouds and their effects on planetary albedo spectra). We will integrate new spectral retrieval methods into the public Planetary Spectrum Generator server. We will also organize simulated spectroscopic data products, both with and without instrument noise, in a library for access by the exoplanet research community.

Figure 7: Simulated posterior distributions of retrieved atmospheric parameters for an Earth-like exoplanet observed at a spectral resolving power R=140 in visible wavelengths.

REFERENCES


