Evaluation of Internal Coronagraphic Techniques
For a Segmented Space Telescope

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Introduction

The ATLAST mission concept study will identify technologies needing development in the upcoming decade that will allow the construction and operation of an 8-16 meter UV/optical space telescope, taking advantage of the large capacity of the planned Ares V heavy lift booster. A primary science goal of such a telescope would be the spectral characterization of extrasolar planets. The planet/star integrated brightness contrast ratio for a terrestrial planet is about $10^{-10}$ (the Earth/Sun ratio), and it will appear at small angles from the star (down to $<0.05$ arcsec). The optically diffraction and scattered light that surrounds the telescope's image of a star must be suppressed in order to extract a planet's spectrum. A coronagraph can be used to suppress the diffraction light while wavefront control using deformable mirrors (DMs) can suppress the scattered light and light from imperfect optics. A large variety of coronagraphic techniques exist, but nearly all of them are unsuitable for use at the required contrast levels on a segmented optical system that would inevitably be required for a 16 m space telescope. Here we discuss why and identify one method, visible nulling, that theoretically can achieve the desired contrasts.

Goal: A Terrestrial Planet Spectrum

The plot below shows the spectrum of the Earth at a resolution of 70 between 650-900 nm. ATLAST's primary wavelength range of interest in regards to exoplanets. The O2 line at ~760 nm has a depth, in terms of contrast, of 2×10$^{-11}$. Using a combination of optical suppression (coronagraph), wavefront control (deformable mirrors), and postprocessing (PSF subtraction), the background noise must be reduced to <10$^{-11}$ in contrast to allow spectral features to be measured.

ATLAST 16m Configuration

The baseline configuration for the 16 m ATLAST telescope is a primary with 36 segments with a separate on-axis Cassegrain focus for coronagraphy and UV imaging/spectroscopy and an off-axis TMA focus for wide-field imaging and spectroscopy. The telescope is centrally obscured by the secondary mirror, which is supported by struts (configuration TBD). These obscurations and the segment gaps produce a diffraction pattern with significant power in the wings.

Lyot Coronagraphs Won’t Work

Lyot coronagraphs (ones with image-plane amplitude or phase masks followed by pupil-plane aperture masks) have achieved $<10^{-9}$ contrast in laboratory conditions. They are optically rather simple to implement, and some (e.g. 8th order occulters) can tolerate significant low-order aberrations. However, image plane masks alter the wavefront so that any telescope obscurations will spread out the remaining starlight inside the reimaged pupil, rather than concentrating it where it can be masked by a Lyot stop. No Lyot coronagraph can provide the necessary $10^{-10}$ contrast at the required inner working angle in a segmented, obscured system.

A Visible Nuller Might Work

A visible nulling coronagraph (VNC) is essentially a nulling interferometer. The collimated beam from the telescope is split into two identical, laterally-shifted ones, a phase difference of 2λ/2 waves is applied between the two, and then they are recombined, resulting in cancellation of the on-axis starlight. The nulled output is then rotated and sent through another nuller, further reducing any leakage due to resolution of the star or small low-order aberrations. Because it operates directly on the pupil without altering the spatial distribution of light within it, the VNC can handle obscured and segmented systems. In the case of the 16m ATLAST, the beam shears are in segment-sized steps so that segments appear to stack on top of each other.

For wavefront sensing, the bright output beam and a fraction of the nullled output from the 1st stage nuller are interfered with each other and the resulting intensity pattern measured. With modulations of phase, the wavefront can be derived. Two DMs in sequence in one arm of the 1st nuller are used to correct phase and amplitude wavefront errors (another pair of DMs are in the other nuller arm for backup).

Advantages of the VNC

The diffraction pattern of a segmented, obscured, unaberrated telescope can be fully suppressed. It provides a 3λ/D (25 mas @ 680 nm) inner working angle (this is defined by the amount of pupil shear). It can tolerate most of the top 100 TPF-C target star diameters.

Disadvantages of the VNC

VNC is complex with many reflections (~19) and transmissions (~14). It’s not as tolerant of low-order aberrations as 8th order Lyot coronagraphs (VNC is 4th order), resulting in tighter optical and pointing requirements. Star offsets must be <0.01 mas (via body pointing and fine steering mirror), which may require a dedicated low-order wavefront sensor. It produces limited regions of high sky throughput, making it suitable only for spectroscopy of known planets (the telescope is orientated to place planet in a high throughput region).

Needed Technology Development

The VNC requires high-density DMs. More development is needed for segmented MEMs DMs (optical surface smoothness, stability) and continuous ones (higher density). Optical fibers might improve wavefront control but need analysis of both end fiber coupling effects and fiber array fabrication. Broadband phase shifters that work at $10^{-10}$ contrast also need to be developed.