

pendent optical path in one or both of the arms of the interferometer. By intelligently choosing the number, material and thickness of a series of glass plates, a nearly uniform, arbitrary phase shift can be introduced between two arms of an interferometer.

There are several constraints that make choosing the number, type, and thickness of materials a difficult problem, such as the size of the bandwidth to be nulled. Several solutions have been found for bandwidths on the order of 20 to 30 percent ( $\Delta\lambda/\lambda_c$ ) in the mid-infrared region. However, uniform phase shifts over a larger bandwidth in the visible regime between 480 to 960 nm (67 percent) remain difficult to obtain at the tolerances necessary for exoplanet detection.

A configuration of 10 dispersive glass plates was developed to be used as an achromatic phase shifter in nulling interferometry. Five glass plates were placed in each arm of the interferometer and an additional vacuum distance was also included in the second arm of

the interferometer. This configuration creates a phase shift of  $\pi$  radians with an average error of  $5.97 \times 10^{-8}$  radians and standard deviation of  $3.07 \times 10^{-4}$  radians. To reduce ghost reflections and interference effects from neighboring elements, the glass plates are tilted such that the beam does not strike each plate at normal incidence. Reflections will therefore walk out of the system and not contribute to the intensity when the beams are recombined.

Tilting the glass plates, however, introduces several other problems that must be mitigated: (1) the polarization of a beam changes when refracted at an interface at non-normal incidence; (2) the beam experiences lateral chromatic spread as it traverses multiple glass plates; (3) at each surface, wavelength-dependent intensity losses will occur due to reflection. For a fixed angle of incidence, each of these effects must be balanced between each arm of the interferometer in order to ensure a deep null.

The solution was found using a nonlinear optimization routine that minimized an objective function relating phase shift, intensity difference, chromatic beam spread, and polarization difference to the desired parameters: glass plate material and thickness. In addition to providing a uniform, broadband phase shift, the configuration achieves an average difference in intensity transmission between the two arms of the interferometer of 0.016 percent with a standard deviation of  $3.64 \times 10^{-4}$  percent, an average difference in polarization between the two arms of the interferometer of  $5.47 \times 10^{-5}$  percent with a standard deviation of  $1.57 \times 10^{-6}$  percent, and an average chromatic beam shift between the two arms of the interferometer of  $-47.53$  microns with a wavelength-by-wavelength spread of 0.389 microns.

*This work was done by Matthew R. Bolcar and Richard G. Lyon of Goddard Space Flight Center. Further information is contained in a TSP (see page 1). GSC-15830-1*

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## Super Dwarf Wheat for Growth in Confined Spaces

*Lyndon B. Johnson Space Center, Houston, Texas*

USU-Perigee is a dwarf red spring wheat that is a hybrid of a high-yield early tall wheat (USU-Apogee) and a low-yield, extremely short wheat that has poor agronomic characteristics. USU-Perigee was selected for its extremely short height ( $\approx 0.3$  m) and high yield — characteristics that make it suitable for growth in confined spaces in controlled environments. Other desirable characteristics include rapid development and resistance to a

leaf-tip necrosis, associated with calcium deficiency, that occurs in other wheat cultivars under rapid-growth conditions (particularly, continuous light).

Heads emerge after only 21 days of growth in continuous light at a constant temperature of 25 °C. In tests, USU-Perigee was found to outyield other full dwarf (defined as  $< 0.4$  m tall) wheat cultivars: The yield advantage at a constant temperature of 23 °C was found to be

about 30 percent. Originally intended as a candidate food crop to be grown aboard spacecraft on long missions, this cultivar could also be grown in terrestrial growth chambers and could be useful for plant-physiology and -pathology studies.

*This work was done by Bruce Bugbee of Utah State University for Johnson Space Center. For more information, see [www.usu.edu/cpl/Progression.pdf](http://www.usu.edu/cpl/Progression.pdf). MSC-24200-1*

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## Fine Guidance Sensing for Coronagraphic Observatories

*NASA's Jet Propulsion Laboratory, Pasadena, California*

Three options have been developed for Fine Guidance Sensing (FGS) for coronagraphic observatories using a Fine Guidance Camera within a coronagraphic instrument. Coronagraphic observatories require very fine precision pointing in order to image faint objects at very small distances from a target star. The Fine Guidance Camera measures the direction to the target star.

The first option, referred to as Spot, was to collect all of the light reflected from a coronagraph occulter onto a focal plane, producing an Airy-type point spread function (PSF). This would allow almost all of the starlight from the central star to be used for centroiding. The second approach, referred to as Punctured Disk, collects the light that bypasses a central obscuration, producing a PSF with a punctured

central disk. The final approach, referred to as Lyot, collects light after passing through the occulter at the Lyot stop.

The study includes generation of representative images for each option by the science team, followed by an engineering evaluation of a centroiding or a photometric algorithm for each option. After the alignment of the coronagraph to the fine guidance sys-