



Technology Milestone Whitepaper

# EXCEDE Technology Milestone #1: Monochromatic Contrast Demonstration

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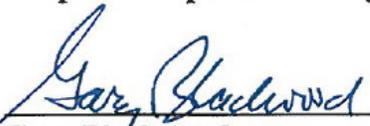
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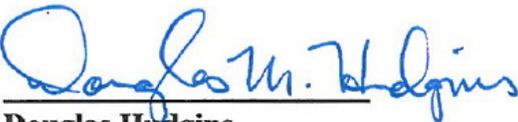
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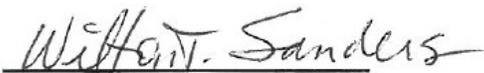
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# 1. Objective

The Exoplanetary Circumstellar Environments and Disk Explorer (EXCEDE) [1] is an EXPLORER EX-class mission proposed to NASA. EXCEDE uses a 0.7-m diameter telescope to perform high contrast imaging of the circumstellar environments of nearby stars, and was selected by NASA as a Category III investigation for technology development and maturation. EXCEDE will study the formation, evolution and architectures of exoplanetary systems, and characterize circumstellar environments into stellar habitable zones (HZs). EXCEDE provides contrast-limited scattered-light detection sensitivities currently estimated to be  $\sim 1000\times$  greater than HST performance and expectations for coronagraphy at a much smaller effective inner working angle (IWA), thus enabling the exploration and characterization of exoplanetary circumstellar disks in currently inaccessible domains. EXCEDE will utilize a laboratory demonstrated Phase Induced Amplitude Apodized Coronagraph (PIAA-C) integrated with a 70 cm diameter unobscured aperture visible light telescope. EXCEDE is a science-driven technology pathfinder that will advance our understanding of the formation and evolution of exoplanetary systems, placing our solar system in broader astrophysical context. Concomitantly, EXCEDE will demonstrate the high contrast technologies required for larger-scale space-based follow-on and multi-wavelength investigations on the road to finding and characterizing exo-Earths in the years ahead.

The EXCEDE Category III-funded technology development effort is focused on its starlight suppression system, and includes two milestones:

- Milestone 1: reaching  $10^{-6}$  raw contrast between  $1.2$  and  $2 \lambda/D$  in monochromatic light, *simultaneously* with  $10^{-7}$  raw contrast between  $2$  and  $4 \lambda/D$
- Milestone 2: polychromatic light test, reaching the same contrast values as Milestone 1 in a 10% wide spectral band

The current whitepaper describes milestone 1 only, with the expectation that milestone 2 will be formulated upon completion of milestone 1.

These advances are significant because:

- (a) in both cases these milestones require a similar improvement in stability;
- (b) the published results achieved to date have not yet been verified to be repeatable in the sense this milestone requires them to be;
- (c) these milestones call for a simultaneous demonstration of two contrasts, whereas in the past they have been demonstrated separately -- it is more challenging to achieve  $1e-7$  contrast between  $2$  and  $4 \lambda /D$  in a coronagraph that has an IWA of  $1.2 \lambda /D$  than in a coronagraph that has an IWA of  $2 \lambda /D$ , because the former is more sensitive to low-order instabilities;
- (d) unlike many previous white papers, these milestones are associated with a specific flight mission, and are therefore more conservative than would be in a pure technology demonstration.

The milestone 1 objective described in this white paper is complementary with the high contrast inner working angle milestone formulated for the PIAA Technology Demonstration for Exoplanet Missions (TDEM) effort at larger IWA, which aims at demonstrating  $10^{-9}$  contrast at  $\geq 2 \lambda/D$  using a similar approach for starlight suppression. The  $10^{-6}$  raw contrast at  $1.2 \lambda/D$  is representative of the required performance for small ( $< 1$  meter diameter) telescopes characterizing planet-hosting environments in dusty exoplanetary systems. The photon noise that fundamentally re-

stricts raw sensitivity for most targets on estimated on-orbit integration timescales is commensurate with the achievable image contrast and science goals when IWA is pushed below  $2 \lambda/D$  to overcome the limitations of the small telescope aperture size.

### 1.1. EXCEDE Technology Maturation and Demonstration

We undertake the EXCEDE technology demonstration program as part of a broader effort to advance the instrument system TRL in the context of NPR 7120.8 Appendix J. The UofA lead NASA/Category III funded EXCEDE technology development/maturation investigation comprises a part of larger and longer duration effort to demonstrate a fully integrated Starlight Suppression System (SSS) to EXCEDE specifications (per our response to the ROSES 2010/EXPLORER 2011 AO) in vacuum in advance of the next EXPLORER opportunity now anticipated circa 2015.

Our overall (3-year) plan, of which this Category III investigation is an integral part (see Figure 1), is designed to:

- (1) demonstrate the performance of the Starlight Suppression System in an air testbed at the Ames Coronagraph Experiment laboratory (~1.5 year effort) while,
- (2) in parallel, building up a vacuum testbed at the Lockheed Martin facility in Sunnyvale, and using these facilities to
- (3) test key components, subsystems, and operating methodologies for the SSS, and
- (4) test a fully integrated EXCEDE SSS prototype in vacuum

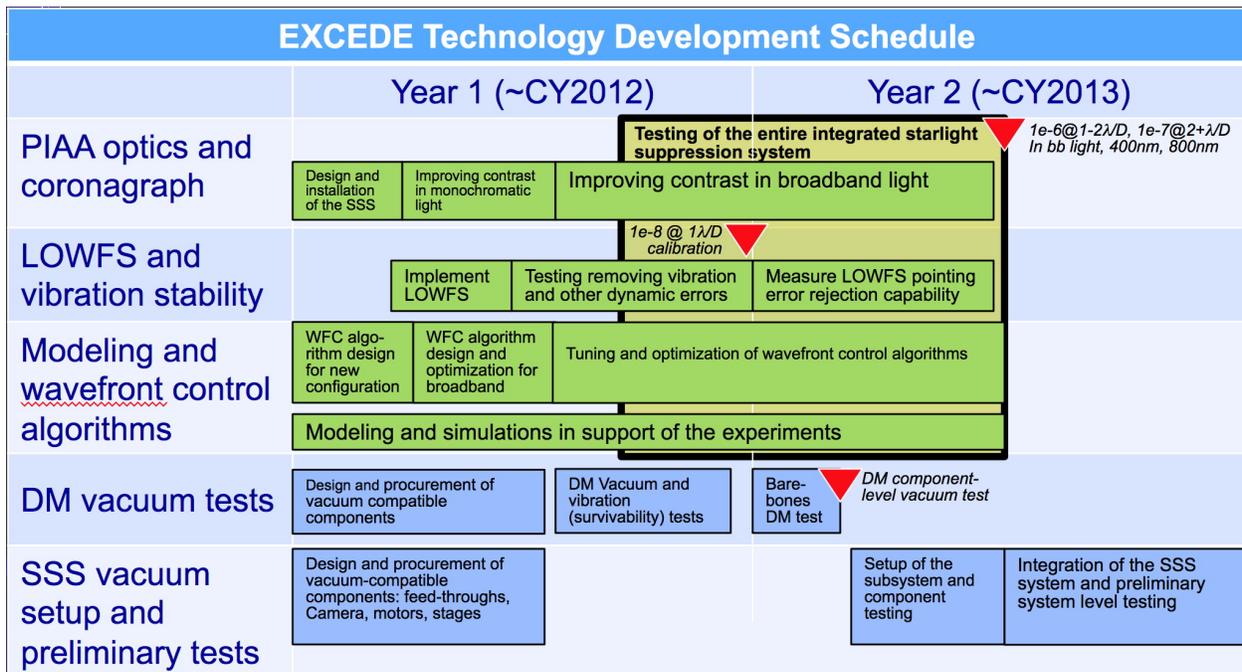


Figure 1. High-level EXCEDE technology maturation and demonstration schedule. Green boxes indicate work to be carried out in air at the NASA/Ames Coronagraph Experiment laboratory. Blue boxes indicate work to be carried out at Lockheed-Martin facilities in vacuum.

Details of these project elements are discussed in our February 02, 2012 project plan as provided to NASA HQ as predicated upon the EXCEDE proposal following the EXPLORER 2011 Category III award.

## ***1.2. Traceability to EXCEDE Science Objectives and Mission Goals***

The EXCEDE mission concept encompasses six symbiotic science objectives to study the formation, evolution, and architectures of exoplanetary systems and characterizing circumstellar environments in HZs (see [1]). The mission will survey four target classes to meet these objectives using optical coronagraphy with two-band imaging polarimetry [2]. To reach into stellar HZs for debris-disk hosting stars with statistical significance in a proposed three-year mission DRM, we identified appx 230 IR detected debris systems to be observed with high priority by EXCEDE. To directly reach into HZs for appx 25% of the debris target sample (a science program goal) requires an IWA of appx 120 mas and is achievable at 0.4 microns with a 0.7 meter telescope. To convey sufficient information on debris disk sub-structure to inform on planetary system architectures, the EXCEDE mission will provide spatially resolved imaging on the sample ensemble at stellocentric distances to a factor of appx 20x the distance of the HZs (e.g., appx 1 – 20 AU at 10 pc, where Neptune resides (at 20 AU) in our solar system), thus an OWA of appx  $24 \lambda/D$  (though this OWA is not a hard requirement). To break degeneracies in dust grain properties, EXCEDE importantly uses two-band optical polarimetry with a wavelength ratio in the optical of appx x2 that, for compliance with the IWA, informs the bands be centered at appx 0.4 and 0.8 microns. The above capabilities enable protoplanetary disk evolutionary studies with disk/halo interactions and central disk. Current space-based technologies, e.g., as implemented with HST coronagraphy with smallest possible (with no-longer operating NICMOS, and STIS but often not achieved) IWA at least 2.5x larger than EXCEDE are contrast-limited at their inferior IWAs with  $\sim$  raw  $10^{-3}$  per resolution element contrast, corresponding to dust fractions of many thousands of zodis in CS disks with uniform dust density distributions. IR excesses observed in, and theoretical models of, debris disk systems strongly suggest warm dust close to their host stars orders of magnitude fainter (in contrast) than in most cases are currently observable (N.B.: Disk surface brightness are direct proxies for surface density distributions, from which exoplanetary system architectures can be derived or constrained). These are the drivers for EXCEDE  $10^{-6}$  to  $10^{-7}$  raw contrast sensitivity to spatially extended CS dust at sub-arcsecond stellocentric angles.

## **2. Introduction**

Technology Milestones serve to gauge the developmental progress of integrating technologies for a space-based mission, such as EXCEDE, that will perform high contrast observations of exoplanetary systems. These sensing and control method performance milestones, along with all the complimentary hardware technology maturation required by NPR 7120.8 Appendix J, will inform on the mission's readiness to proceed from pre-Phase A to Phase A. Completion of a milestone is to be documented in a report by the Principal Investigator and reviewed by NASA HQ.

EXCEDE milestone #1 addresses narrowband starlight suppression at small inner working angles with a PIAA coronagraph, a high-efficiency coronagraphy technique enabling high-contrast

imaging at a small inner working angle ( $1.2 \lambda/D$  for the configuration to be tested) [3-12]. The approach for accomplishing this milestone is similar to the one implemented for TPF-C milestone #1, that demonstrated narrow band starlight suppression at larger IWA on the JPL High Contrast Imaging Testbed (HCIT), and recently formulated milestones for the TDEM program. For EXCEDE milestone #1, a PIAA type coronagraph is used at NASA Ames on an optical breadboard, including wavefront control and data processing algorithms. This demonstration will be performed in air. A future milestone, not described in this document, will address starlight suppression for the EXCEDE mission in polychromatic light.

### ***2.1. Phase-Induced Amplitude Apodization***

PIAA is a lossless beam apodization technique. Beam apodization is very useful in coronagraphy: a properly apodized pupil produces a high contrast image free of Airy rings. The conventional method to apodize the pupil is to introduce a mask into the beam that is fully transmissive in the center and becomes opaque at the edge of the pupil. With PIAA, the same apodized pupil is created by geometric redistribution of the light rather than by selective absorption. This is achieved by aspheric optics (mirrors or lenses), as illustrated in Figure 2.

The Airy rings produced with a conventional imaging telescope are due to diffraction from the sharp edges of the pupil. Pupil apodization creates a soft-edged pupil that greatly reduces the amplitude of the rings. Pupil apodization can be used either by itself or in combination with other coronagraph techniques (for example, the apodized pupil Lyot coronagraph combines pupil apodization with Lyot coronagraphy). The conventional technique used to apodize the telescope beam is with an amplitude mask (continuous or binary) with variable transmission from the center to the edge of the pupil. This leads to a difficult compromise between reaching high contrast (which requires a strong apodization) and achieving high coronagraph throughput with good angular resolution (which both favor a weak apodization). In a conventional apodized pupil coronagraph, for example, reaching  $10^{-10}$  raw contrast (e.g., for Exo-Earth detection and characterization, beyond the domain required for EXCEDE) needs strong apodization with a resulting throughput of only 10% that degrades the telescope's angular resolution to approximately  $2.5 \lambda/D$  (instead of  $1 \lambda/D$ ) and does not allow high contrast imaging within approximately  $4 \lambda/D$ . PIAA obviates this particular deficiency in conventional coronagraphy.

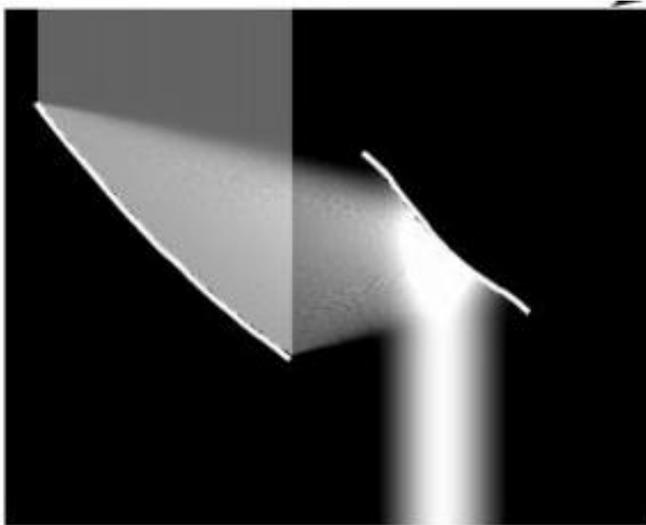


Figure 2: PIAA uses aspheric optics to apodize a beam.

With PIAA optics, strong apodizations can be achieved with no loss in throughput or angular resolution, thus enabling high contrast imaging at small off-axis angles with almost no loss in efficiency. The PIAA's IWA design value at high contrast ranges from  $0.64 \lambda/D$  for an aggressive PIAA Complex Mask Coronagraph (PIAACMC) design [12] to  $1.2$  and  $2 \lambda/D$  for a more conventional PIAA design respectively providing  $10^{-6}$  and  $10^{-10}$  raw contrast (the design choice depends on the goal contrast, manufac-

turing capabilities, ability to mitigate chromatic issues and angular size of the central source). We define the IWA as the off-axis angle at which the coronagraphic throughput (partially occulted PSF energy) declines with decreasing stellocentric distance to 50% compared to an unocculted PSF; for EXCEDE  $1.2 \lambda/D$ . PIAA optics do not absorb light, and therefore preserve the sensitivity and angular resolution of the telescope system. When implemented with mirrors, PIAA can be made to operate at high contrast over a wide spectral band.

The performance gain offered by PIAA over other coronagraphs is quantified in [10]. Compared to more conventional coronagraphs, which were considered for TPF-C, adopting the PIAA is equivalent to a 2x to 3x gain in telescope diameter. Recent improvements on the PIAA concept may allow even higher performance, with high contrast detection of dust-scattered and exoplanet-reflected starlight at stellocentric angles smaller than  $2 \lambda/D$  [12] that is of key importance to EXCEDE. EXCEDE will operate at a more moderate raw contrast level ( $10^{-6}$  to  $10^{-7}$ ), suitable for direct imaging of circumstellar protoplanetary and debris disks. The benefits of the PIAA approach extend to this more moderate contrast level and are key to EXCEDE's scientific success.

## ***2.2. Current status of PIAA coronagraph technology***

The EXCEDE science mission objectives are defined to address key questions in advancing our understanding of the formation, evolution, and architectures of exoplanetary systems by characterizing circumstellar environments into stellar HZs. E.g., What are the levels of dust in HZ of exoplanetary/debris systems? Will dust in HZs interfere with future planet finding/characterization missions? See [1] for additional details. The EXCEDE proposal mission concept defined a DRM capable of imaging starlight-scattering debris, at  $10^{-6}$  to  $10^{-7}$  contrast per resolution element, from appx 25% of a sample of  $\sim 250$  debris disk hosting stars (known from their thermal IR excesses) in their HZs, thus requiring an IWD reach of  $1.2 \lambda/D$  at 0.4 microns with a proposed 0.7 m telescope. These science-driven metrical requirements push the current state-of-the-art in IWA contrast.

PIAA technologies have been developed through laboratory demonstrations and modeling since late 2002. A PIAA coronagraph testbed effort was initiated at Subaru Telescope / Research Corporation of the University of Hawaii. This monochromatic testbed, in air, included reflective PIAA optics, a 32x32 MEMS deformable mirror for wavefront control, and a coronagraphic low order wavefront sensor (CLOWFS) for accurate pointing/focus measurement. This testbed demonstrated  $2 \times 10^{-7}$  raw contrast in monochromatic light at  $1.65 \lambda/D$  in air [13], and  $10^{-3} \lambda/D$  closed loop pointing control [14] corresponding to 0.2 mas on a 0.7 meter diameter telescope at visible wavelengths. Raw contrast performance was limited by incoherent ghosts in the system, which used several lenses without anti-reflection coatings. The testbed, however, demonstrated control of static coherent light at the  $3.5 \times 10^{-9}$  contrast level over a few hours of testbed operation (the time-averaged complex amplitude in the focal plane corresponds to a  $3.5 \times 10^{-9}$  contrast). The Subaru testbed effort was discontinued in early 2009 and its final results have been compiled in a publication [13].

The Ames Coronagraph Experiment (ACE) Testbed (Figure 3) is the successor to the Subaru testbed and is designed for flexible and rapid testing of coronagraph technologies prior to full performance verification in vacuum. ACE began operations in March 2008 and has so far achieved

performance of  $2 \times 10^{-8}$  raw contrast between 2.0 and 3.4  $\lambda/D$  and  $1.3 \times 10^{-6}$  between 1.4 and 2.5  $\lambda/D$  in 655nm monochromatic light with the PIAA coronagraph [15], approaching, but not yet meeting, EXCEDE's milestone requirement #1. In particular, Guyon's PIAA/TDEM milestone addresses high contrast, but ONLY outward from 2  $\lambda/D$ . Results quoted above were obtained at ACE during tests that were not part of the work funded by that TDEM effort, no TDEM milestone was quoted for contrast goals at  $< 2 \lambda/D$ , and no rigorous demonstration of repeatability was performed, as we plan for EXCEDE Milestone #1. The most significant technical hurdle, for the context of this EXCEDE milestone, is in reducing the IWA, repeatably, to 1.2  $\lambda/D$ . This requires an improvement in system stability equivalent to one that would improve contrast by a factor of 10 at a fixed IWA; in a tip-tilt instability-limited regime, an improvement from 1.5 to 1.2  $\lambda/D$  is about as challenging as an improvement of contrast by a factor of 10 at 1.5  $\lambda/D$ .

ACE is designed with several improvements from lessons learned at Subaru, in particular with regard to stability and flexibility. It is operated in a (thermally stabilized) air environment as opposed to vacuum, in order to make accessing and reconfiguring the layout easier and cheaper, complementing vacuum facilities such as the high contrast testing in vacuum at JPL, as well as an existing vacuum facility being adapted for further EXCEDE technology development at Lockheed-Martin.

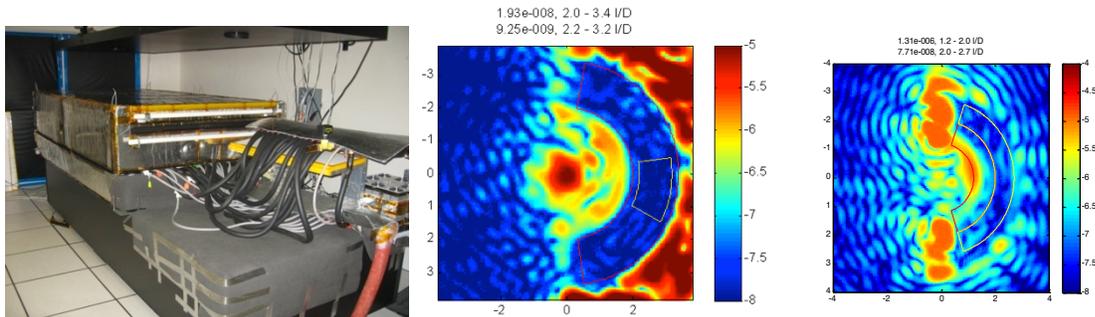


Figure 3. left: Actively stabilized thermal enclosure of the NASA Ames Coronagraph Testbed. Center and right: High contrast image taken at the Ames testbed, showing, respectively,  $2 \times 10^{-8}$  contrast between 2.0 and 3.4  $\lambda/D$  in the dark zone and  $1.3 \times 10^{-6}$  contrast between 1.4 and 2.5  $\lambda/D$  (dark zones are shown by red outlines).

The tests at JPL/HCIT and NASA Ames/ACE have been performed using two prototype sets of PIAA mirrors:

- Set 1: PIAA mirrors fabricated by Axsys Imaging Technologies under contract with NOAO (funded by a NASA JPL grant for development of technologies for TPF), and delivered in mid 2006. These nickel-plated aluminum mirrors are suitable for monochromatic work, but their design is not suitable for contrast in broadband light (raw contrast limited to  $10^{-7}$  in a 20% wide band with perfect optics but no wavefront correction). At the time the mirrors were designed, chromatic effects due to diffractive propagation through the PIAA system were not understood, and compensation of chromatic errors through mirror shape design was not implemented. These mirrors are currently (June 2012) under testing at HCIT, and a  $\sim 4 \times 10^{-9}$  raw contrast has been so far achieved in a 2 to 4  $\lambda/D$  dark zone in monochromatic light.
- Set 2: PIAA mirrors fabricated by Tinsley/L-3 under contract with NASA Ames, and delivered in April 2009. One of the mirrors in this set is shown in Figure 4. This set of Zerodur mirrors

was designed to deliver  $10^{-10}$  raw contrast in a 20% wide band in the absence of wavefront or coating errors, using a design optimization scheme that takes into account chromatic effects due to diffractive propagation between the mirrors. In the first 2-month-long PIAA test run at HCIT,  $4 \times 10^{-7}$  raw contrast was reached at  $2.5 \lambda/D$ . These preliminary tests exposed an unexpected system wavefront error that was not in agreement with the surface figure measurements performed at Tinsley. The mirrors were sent back to Tinsley to for re-figuring with narrow-beam ion beam figuring [16]. These mirrors are now in use at the NASA Ames testbed.

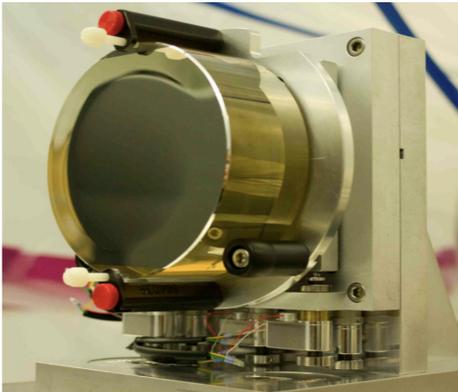


Figure 4: Zerodur PIAA M1 mirror (one of two in the PIAA M1/M2 mirror pair) fabricated by Tinsley. The mirror substrate size is 120 mm diameter, while the clear aperture is 90 mm diameter. The rapid change in radius of curvature at the edge of the clear aperture is visually apparent in this picture, and is the most challenging feature of the mirror for manufacturing, testing and alignment. This mirror has undergone ion beam figuring to compensate for a figure error due to a misalignment during optical testing.

- Either set of PIAA mirrors is suitable for the milestone described in this whitepaper. The surface quality of the Tinsley and Axys mirrors are sufficient for the monochromatic Milestone #1 experiment; in each case the mirrors are unlikely to be a limiting factor in the experiment.

### 2.3. EXCEDE PIAA architecture

Direct imaging and characterization of the constituent material in the planet-hosting environments of exoplanetary systems strongly benefit from the use of a high performance PIAA coronagraph. Most of the technology development efforts for the PIAA technique have thus far been focused on imaging potentially habitable exoplanets themselves with a medium-size space telescope at optical wavelength. This was explored by two of the NASA-funded medium class Astrophysics Strategic Missions Concept Studies (PECO and ACCESS). PIAA is also a candidate for a larger  $\sim 4$ -m diameter Terrestrial Planet Finder Coronagraph mission [17].

The PIAA technique is also highly valuable for imaging and studying the dust content in exoplanetary systems at more modest contrast levels than required for exoEarth imaging, but still with stellocentric reach into the HZs of nearby disk-hosting stars utilizing a smaller telescope. This capability enables the primary science objectives of the EXCEDE mission [1].

The EXCEDE PIAA coronagraph is designed for delivering  $10^{-6}$  raw contrast with a  $1.2 \lambda/D$  inner working angle. The EXCEDE starlight suppression system includes a low order wavefront sensor (LOWFS) to maintain the pointing accuracy required for this IWA, and a deformable mirror to actively suppress diffracted starlight. An inverse PIAA system is used downstream of the coronagraphic image-plane mask to recover a sharp image over a wide field of view. While the current milestone is focused on the contrast and IWA performance, it is planned that the PIAA testbed used for this milestone will also include the LOWFS and inverse PIAA, consistent with the EXCEDE flight instrument concept.

The PIAA coronagraph design for EXCEDE differs in some key details from PIAA designs aimed at more ambitious contrasts. In EXCEDE, the focal plane mask is, by design, slightly undersized, allowing some light to propagate to the Lyot plane (pupil plane after the coronagraph focal plane mask). The size of the focal plane mask and PIAA apodization function are co-optimized to diffract most of the light that passed around the focal plane mask outside the geometric pupil in the Lyot plane. A Lyot stop thus further enhances the coronagraph contrast. This optimization is similar to the Apodized Pupil Lyot Coronagraph (APLC) technique [19], the main difference being that the pupil apodization is performed without loss of throughput or inner working angle.

### 3. Milestone description: PIAA Monochromatic Contrast Demonstration

#### 3.1. Milestone definition

**“Demonstrate using Phase-Induced Amplitude Apodization a raw contrast median level  $10^{-6}$  between a  $1.2 \lambda/D$  inner working angle and  $2 \lambda/D$ , simultaneously with a median level of  $10^{-7}$  between  $2 \lambda/D$  and  $4 \lambda/D$ , in monochromatic light at any single wavelength in the range of  $400 \text{ nm} \leq \lambda \leq 900 \text{ nm}$  over a single-sided dark zone.”**

This milestone addresses several key aspects of the EXCEDE performance error budget. EXCEDE is required to form a high contrast “dark zone” over a working angle range from  $1.2 \lambda/D$  or less to approximately  $25 \lambda/D$  or greater and a bandwidth of 20% over a wavelength range in the optical of  $\sim \times 2$ ; EXCEDE baseline:  $\lambda_{\text{central}} \simeq 400 \text{ nm}$  and  $\lambda_{\text{central}} \simeq 800 \text{ nm}$ . The Ames testbed is addressing the most challenging location in the image plane, near the inner working angle, at the same location required by EXCEDE. The outer working angle for the flight mission is achieved using a large actuator count with a 2000 element centrally actuated deformable mirror (DM) for  $15 \lambda/D$  outer working angle located ahead of PIAA optics. The testbed environment will use an existing  $32 \times 32$  actuator heritage device more than sufficient for the Milestone #1 demonstration. The  $1.2 \lambda/D$  to  $4 \lambda/D$  dark zone to be tested in milestone #1 is of sufficiently large size that the physics of the wave front control problem can be demonstrated with high expectation of applying the same approach to a larger dark zone at a later date with a more capable (and flight-like) optical design.

Existing analytical and numerical models demonstrate that under ideal conditions the raw image contrasts required for EXCEDE are achievable at the performance level of this milestone demonstration. However, a complete error budget has yet to be validated with realistic error terms. While our milestone does not aim at developing such an error budget, this will be required for advancing the TRL for the PIAA mirrors as a component of a larger system. A complete error budget will require a thorough understanding of the environment provided by the NASA Ames testbed (including wavefront stability in time and spatial coherence of the source). While a complete error budget analysis is beyond the scope of the effort described in this white paper, the latter represents an important step towards accurate empirical estimates of certain error budget terms. These include in particular, (a) wavefront errors on the PIAA mirrors, support optics, and

the DM; (b) chromaticity of the system; (c) level of low-order wavefront suppression by the LOWFS (under simulated flight-like disturbances).

### 3.2. Description of Ames PIAA laboratory configuration

The light source for our testbed can be one of several lasers that are available for our use, such as a long-coherence-length 655nm laser (Newport SWL-7505 which we baseline), a green HeNe or a diode laser at 532nm, or a supercontinuum light source, coupled into a single mode fiber. We use a single-mode fiber output as a reasonable approximation to a star image delivered by a telescope. For this milestone demonstration, the fiber tip will be  $\sim 5$  microns in diameter (depending upon wavelength, exactly  $1 \lambda/D$  at 500 nm); though the actual size of the spot on the fiber depends not only on the fiber tip diameter, but also on the refractive indices in the core and cladding of the fiber. This light then passes through our Starlight Suppression System shown in Figure 5. Many components are on motorized stages, and in particular the source can be moved by calibrated amounts corresponding to desired off-axis displacements of the target. The primary characteristics of the ACE and anticipated LM test configurations are summarized in Table 1.

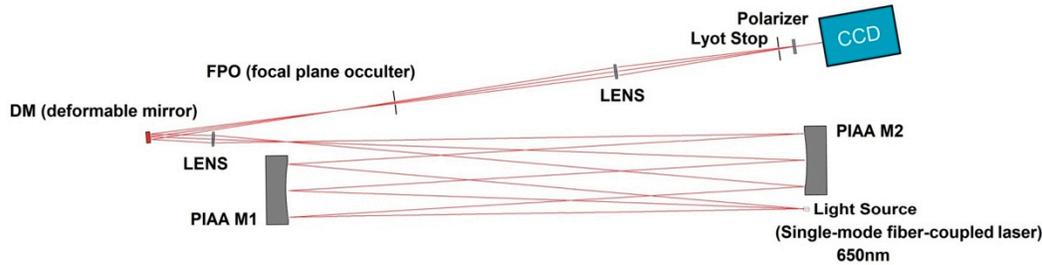


Figure 5. Current configuration of the coronagraph testbed at NASA Ames using a PIAA M1/M2 mirror set (pair of mirrors), DM conjugated to PIAA mirror M2, and without an inverse (second) PIAA mirror set.

Our layout is located inside an active thermal enclosure that provides excellent stability of  $<1\text{mK}$  rms over  $\sim 30$  minutes and is designed to stabilize temperature-induced dynamic tip/tilt errors and air motion to enable EXCEDE performance without resorting to vacuum.

TABLE 1 – PIAA TEST CONFIGURATIONS			
COMPONENT CONFIGURTION	ACE	LM	FLIGHT
PIAA M1 diameter (D1)	90 mm	75 mm	TBD
PIAA M2 diameter (D2)	90 mm	75 mm	TBD
Distance between M1 and M2 (z)	900 mm	1125 mm	TBD
Central Wavelength ( $\lambda_c$ )	in range 400–900 nm, default 655 nm	$\sim 450$ nm	400 & 800 nm
Bandpass ( $\Delta\lambda$ )	default mono-chromatic & 10%	10%	20%
Central magnification of M2:M1 map with DM placed after M2, conjugate to it	7.8	4.92	TBD
Edge magnification of M2:M1 map with DM placed prior to M1, conjugate to it	6.6	9.67	TBD
Apodizer location	none	TBD	TBD
Apodizer-edge transmission (complex amplitude multiplier)	N/A	TBD	TBD
# of DM actuators across conjugated mirror	$\sim 29$ (varies)	$\sim 30$	$\sim 50$

## Wavefront control

*Hardware:* The input wavefront to the PIAA optics is corrected by a single 32x32 MEMS type actuator deformable mirror, located before the focal plane mask (as illustrated schematically in Figure 5), with the DM conjugated to PIAA Mirror M2. A visualization of the remapping between two PIAA mirrors, illustrating how the DM actuators map from PIAA M2 to PIAA M1 is shown in Figure 6. The DM is manufactured by Boston Micromachines and converts voltages into displacement of individual actuators.

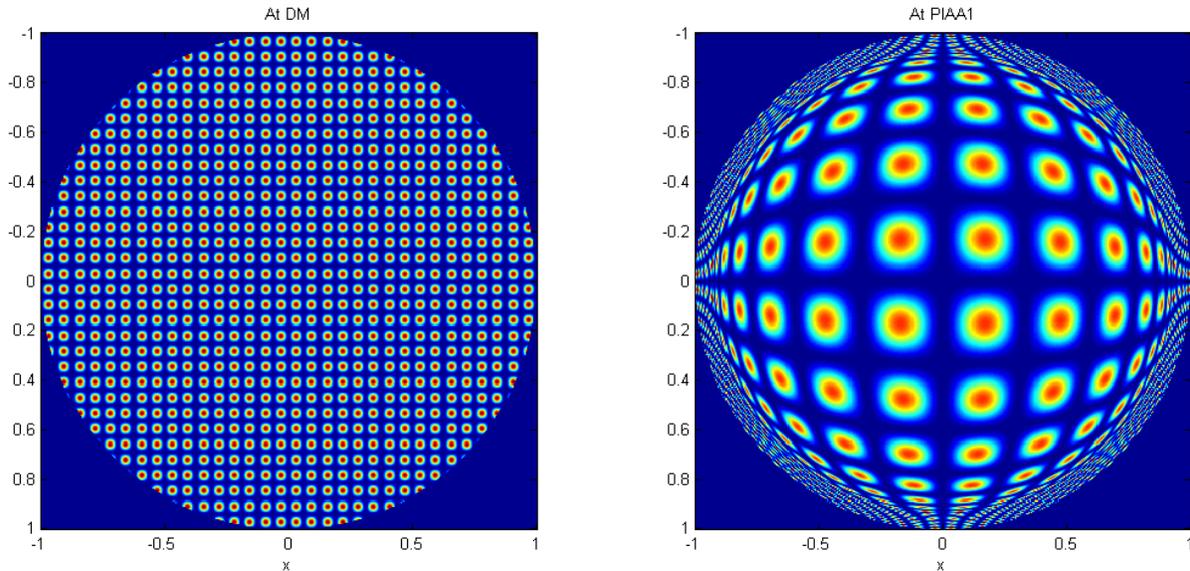


Figure 6. Actuator geometrical re-mapping from PIAA M2 (left; conjugated to the DM) to PIAA M1 (right). Each DM actuator is represented by a spot. While the density of DM actuators is uniform in the plane of PIAA M2, it can be seen that in the plane of PIAA M1 the actuator density is sparse in the middle and high at the edges (so that the correction emphasizes the edge errors much more than the center of the mirror). (Conversely, if the DM was conjugated to PIAA M1, the density of DM actuators would be uniform in the plane of M1, high in the center of PIAA M2, and low on the edges of M2.)

*Wavefront measurement:* The wavefront errors in the coronagraph are measured as a complex amplitude field in the focal plane of the camera. The steps to perform this measurement are as follows:

- (a) Acquire a focal plane image and measure the speckle field intensity in each pixel of the dark zone in the focal plane.
- (b) Compute a set of DM voltage settings that will modulate the speckles in the dark zone by an amplitude comparable to their measured amplitude, and will produce sufficient diversity to solve for the coherent complex amplitude and incoherent light contribution on each pixel of the dark zone. The DM settings will therefore be a function of the speckle field intensity measured in (a), as there is a direct relationship between DM actuator stroke and amount of light introduced in the focal plane for the modulation. We note that several approaches are possible. For example, the algorithm currently used on HCIT aims at adding a nearly constant level of light over the dark zone, with this level adjusted to the mean speckle intensity in the

dark zone. The algorithm previously in use at the Subaru testbed produced a modulation that matched for each pixel the intensity measured in (a).

- (c) Apply this sequence of DM settings and measure for each the resulting speckle field.
- (d) Using measurements obtained in (a) and (c), and the knowledge of the DM settings computed in (b), estimate, for each pixel of the dark field, the coherent and incoherent light contribution. Coherent light originates from residual wavefront errors, amplitude errors, and some coronagraph defects such as errors in the shape of the PIAA optics or apodizer. Incoherent light can be caused by ghosts, polarization effects, and chromatic effects. Since the distinction between incoherent and coherent light is based on measuring if the light interferes with light added in the dark zone with the DM settings, we note that some coherent light may behave as incoherent light, and will therefore be considered incoherent in the experiment: coherent light that varies in phase or amplitude on timescales shorter than our measurement, or coherent light that varies in phase or amplitude within a single pixel of the detector.

*Wavefront correction:* Once the wavefront has been measured, a new DM setting is computed to minimize the coherent portion of the light in the dark field. The computation is based on inversion of the relationship between DM actuator displacements and complex amplitude in the dark zone. Variations on this scheme include Electric Field Conjugation (EFC) [18] and speckle nulling. We will employ wavefront control algorithms combined to find a DM setting that achieves the required contrast.

### ***3.3. Differences between Laboratory Demonstration and Flight***

#### **Environment**

Our milestone will be achieved in a laboratory environment with a test/calibration light source rather than the focal plane of a telescope looking at a star at the input of the instrument. Stability issues associated with the laboratory testbed environment may not be representative of the on-orbit stability of the EXCEDE flight system. This anticipated disparity can be mitigated in the laboratory by increasing the source brightness to commensurately reduce the system response time.

#### **Coronagraph system architecture**

The coronagraph system architecture adopted for our milestone is similar, but not identical to, the flight instrument design. The primary differences in achieving milestone #1 are:

- (1) we will use a single monochromatic coronagraph channel. The flight instrument concept includes two (non-multiplexed) polychromatic bands centered at about 400 nm and 800 nm, each about 20% wide in spectral bandwidth.
- (2) an inverse PIAA is not required (but may be added if possible without jeopardizing or unduly complicating the test) for this milestone demonstration, though will be required in the flight system to optimize the use of the full field of DM actuators and offer an outer working angle with a radius up to  $0.5 \times N \lambda/D$  ( $N$  is the linear number of actuators across the beam). Since the inverse PIAA is not essential to the goals of achieving milestone #1, we may adopt a simpler configuration with no inverse PIAA and only a single DM downstream of the PIAA optics. This configuration will deliver a dark zone on one side of the focal plane only, and a small outer working angle ( $\sim 4 \lambda/D$ , which is fully compatible with this milestone).

Our baseline configuration for this milestone demonstration is a single DM located after the PIAA optics, with no inverse PIAA optics. This is the simplest configuration for reaching the milestone goals. The EXCEDE mission configuration (DM  $\rightarrow$  PIAA  $\rightarrow$  inverse PIAA) will be separately implemented as part of our technology validation effort, but is not required for this milestone. The difference between the two configurations is not believed to be relevant to achieving the milestone goals (it would be relevant in polychromatic light, or if OWA were to be demonstrated).

## 4. Definition and computation of the Performance Goal Metric

### 4.1. Definitions

The demonstration of the attainment of the requisite coronagraphic contrast commensurate with milestone #1 requires a measurement of the intensity of speckles appearing within the dark field, relative to the intensity of test source as a surrogate to a star. In the following paragraphs we define the nomenclature involved in detailing the measurement process, spell out the measurement steps themselves, and specify the data products that will be produced in the conduction of the laboratory demonstration.

4.1.1. “Raw” Image and “Calibrated” Images. Standard techniques for the acquisition of camera images are used. We define a “raw” image to be the 2D array of digitally quantized pixel values obtained by reading the charge from each pixel of the camera detector, amplifying and sending those charge packets to an analog-to-digital converter. We define a “calibrated” image to be the result of processing a raw image by subtracting the background bias and correcting for pixel-to-pixel variations in the detector responsivity by dividing by an intensity (unity) normalized flat-field image. Saturated images are avoided by choosing appropriate settings for the exposure time, camera gain (if selectable) and source brightness in order to avoid the confusion of camera detector blooming and other potential camera detector nonlinearities. All raw, and calibrated, images are permanently archived and available for later analysis.

4.1.2. We define “scratch” to be a DM setting in which actuators are set to a predetermined surface figure that is approximately flat.

4.1.3. “Star”. We define the “star” to be a bare fiber tip, with narrowband light relayed via the optical fiber into the testbed optical path. This “star” is the only source of light in the optical path. It is a stand-in for the star image that would have been formed by a telescope system.

4.1.4. "Wavefront control iteration". We define in this document "wavefront control iteration" to be a measurement of the complex amplitude in the dark zone followed by a DM correction aimed at removing coherent light in the dark zone, as detailed in section 3.2. Such iterations will be repeated for as many cycles as are needed to reach a desired level of speckle suppression.

4.1.5. The “Contrast field” is a dimensionless map representing each pixel of the detector, and is the ratio of all off-axis pixels to peak intensity in the central pixel of the PSF (if unobstructed) that would be measured in the same conditions (camera setting, exposure time, central source illumination at the input of the instrument) if the coronagraph focal plane mask were removed. Measurement of the contrast field is detailed in sec. 4.4.

4.1.6. The “Contrast value” is a dimensionless quantity that is the median value of the contrast field over the dark zone adopted for the experiment. Its measurement is detailed in sec. 4.5.

4.1.7 The “Inner Working Angle” is the off-axis angle at which the coronagraphic throughput (partially occulted PSF energy) declines with decreasing stellocentric distance to 50% compared to an unocculted PSF

## ***4.2. Measurement of the Star Brightness***

The brightness in the central pixel of the stellar (fiber surrogate) PSF is required to compute contrast, and is measured with the following steps:

4.2.1. The occulting mask is laterally offset by at least  $10 \lambda/D$ , so as to eliminate the effect of the occulting mask at the location of the on-axis star image.

4.2.2. A deep, but non-saturated, image of the star is obtained by co-adding many unsaturated frames, with all coronagraph optics other than the focal plane mask in place (PIAA optics, binary apodizer, focal plane mask substrate).

4.2.3. In this deep image, the peak intensity of the PSF core is scalable in ratio to the intensity average over a part of the PSF halo at many  $\lambda/D$  that is not covered up by the occulter and is not significantly affected by the presence of the DM (e.g., far out in the DM transfer function). This PSF core-to-halo intensity ratio is then computed.

4.2.4. This (4.2.3) PSF core-to-halo intensity ratio is then applied to any subsequent measurement of the speckle field, by multiplying the image by a constant to produce speckle intensities on a relative scale where the star image would have a peak value of unity.

## ***4.3. Measurement of the focal plane scale***

Milestone #1 may be achieved with (EXCEDE baseline configuration) or without inverse PIAA optics.

Without inverse-PIAA optics, the off-axis PSF will be highly distorted. As a result, the focal plane scale (camera pixels per  $\lambda/D$ ) estimation cannot use the translation invariance of the PSF. In that case, the following definition should be adopted: The focal plane scale is defined by the displacement (pixels) of the PSF’s photocenter in the absence of a focal plane mask in the system for a physical displacement of the light source by  $f\lambda/D$ , where  $f$  and  $D$  are respectively the focal length and diameter of beam at the input of the system (before PIAA optics). We note that this

definition *also* applies to the EXCEDE baseline (PIAA + inverse PIAA configuration), for which there is PSF translation invariance.

All off-axis angular distances given in this document adopt this definition. The PSF photocenter is defined as the intensity-weighted center of the PSF, and it is a linear function of the source position at the input of the system. With the above definition, the focal plane scale value obtained is independent of the source offset used in the measurement. We will empirically measure the focal plane scale by moving the light source by a known amplitude and measuring its photocenter, and verifying that the obtained scale matches the value expected from the optical design of the PIAA mirrors and re-imaging optics.

#### ***4.4. Measurement of the Coronagraph Contrast Field***

Each “coronagraph contrast field” is obtained as follows:

4.4.1. The occulting mask is placed (centered) on the star image.

4.4.2. A sufficiently-deep image is taken of the circumscribing coronagraph field (i.e. the suppressed star plus surrounding speckle field) with the coronagraph focal plane mask in place. The dimensions of the dark zone target areas are defined as follows:

- (a) An inner dark zone extending from 1.2 to 2.0  $\lambda/D$ , is bounded by a line that passes 0.5  $\lambda/D$  from the star at its closest point (see Figure 7).
- (b) An outer dark zone extending from 2.0 to 4.0  $\lambda/D$ , also bounded by a line that passes 0.5  $\lambda/D$  from the star at its closest point (see Figure 7).

4.4.3. The resulting image is divided by the central-pixel peak value of the reference star to produce a “contrast field” image, as discussed in Sec. 4.2.

#### ***4.5. Contrast value as a single metric (for each zone)***

The contrast value metrics we adopt for the inner ( $1.2 \leq r \leq 2.0 \lambda/D$ ), and outer ( $2.0 \leq r \leq 4.0 \lambda/D$ ), dark zones are the medians of the per-pixel raw contrast values within those zones (as shown in Figure 7; red and blue regions, respectively). In each case, the median values in the inner and outer dark zones are computed from a single image (that may consist of a co-addition of consecutive camera frames, with no DM shape update between consecutive frames). No statistical filtering other than removal of detector defects (bad pixels, cosmic rays) will be applied.

The shape of the contrast field is motivated by the use of a single DM for the experiment, allowing independent control of only one side of the focal plane within the DM control radius. The inner edge of the contrast field is chosen to match our IWA value for this demonstration. The outer edge is chosen at several times the IWA, and is a compromise between having a statistically large sample of speckles within the contrast area (which favors a large outer radius) and avoiding biasing the median contrast to the possibly more favorable outer part of the high contrast field (which favors keeping the outer radius small). Since the area chosen for the inner zone is only 0.8  $\lambda/D$  wide (similar to the PSF size), there is little need to further complicate the mile-

stone contrast definition to avoid situations where the outer part of the contrast field favorably biases the measurement.

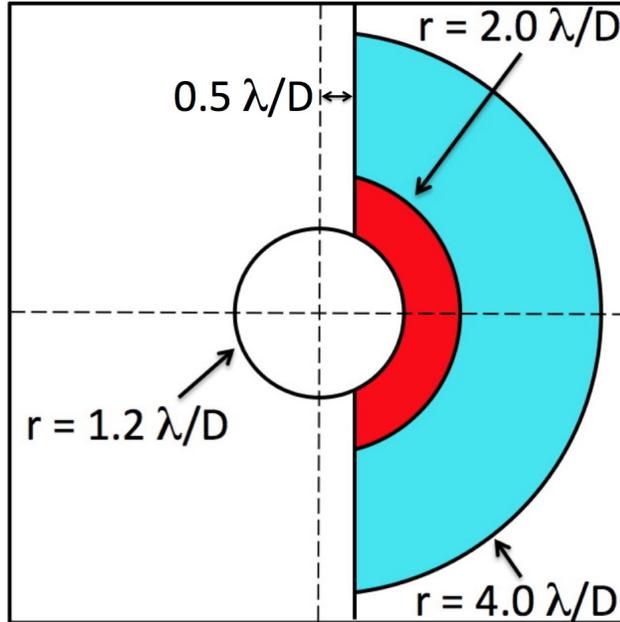


Figure 7: Inner (red) and outer (blue) high-contrast dark zone geometries.

#### 4.6. Milestone Validation Demonstration Procedure

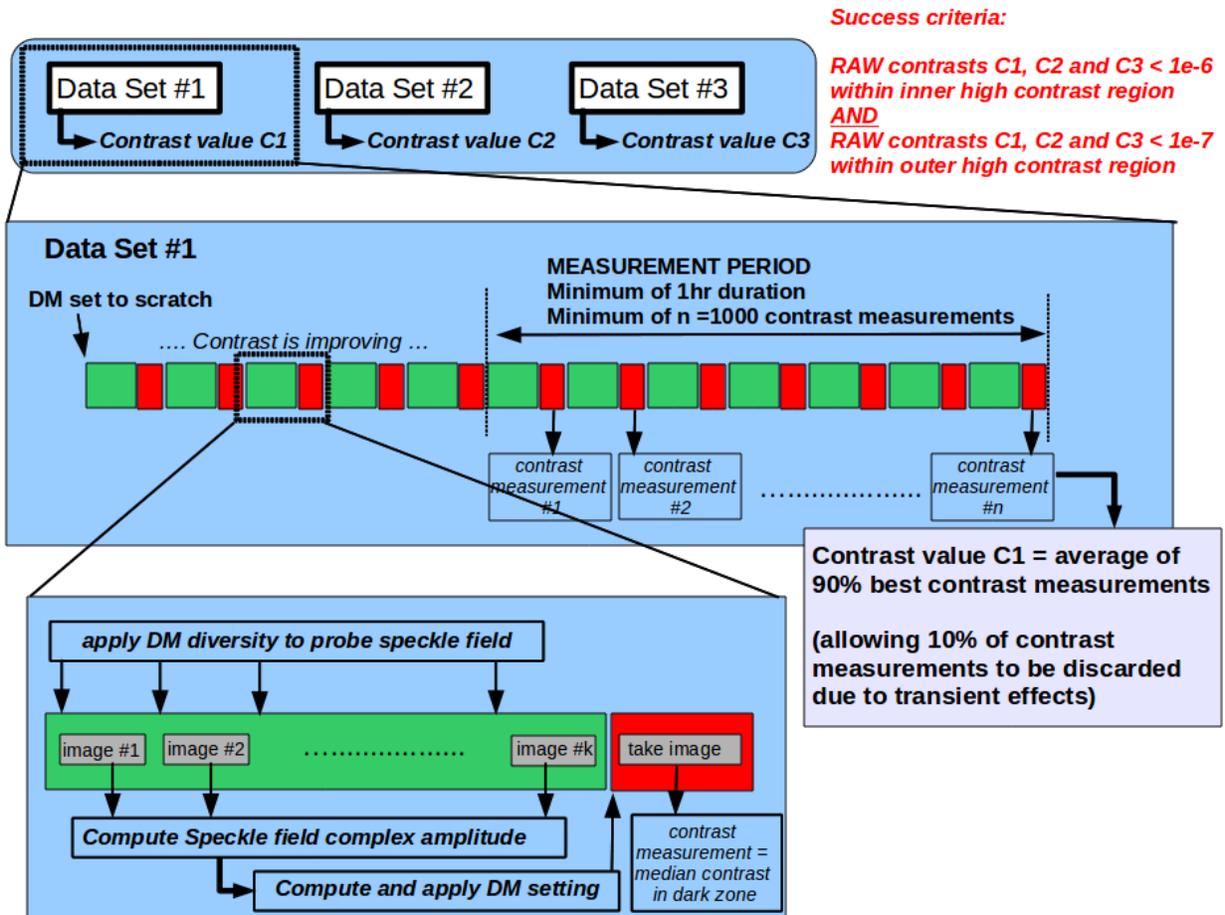


Figure 8: Data acquisition sequence. The success criteria is met when three data sets each meet simultaneously the  $10^{-6}$  (inner dark zone) and the  $10^{-7}$  (outer dark zone) contrast criteria. Data acquisition is detailed for one set in the central part of the figure. A set consists of a succession of wavefront control iterations and contrast measurements. One such wavefront control iteration is shown in the lower part of the figure.

The Milestone #1 validation demonstration procedure, shown in Figure 8, is as follows:

4.6.1. The DM is set to scratch with a reset of the wavefront control system software.

4.6.2. Wavefront control iterations (sec 4.1.4) are performed to converge to settings of the DM actuator driver voltages that simultaneously give an acceptable high-contrast wavefront solution for the target dark zone(s). The expectation is that this typically will take from one to several hours, starting from scratch, if no prior information is used to establish the initial conditions.

4.6.3. When contrast in the inner and outer dark zones stops improving, the high-contrast measurement begins while the wavefront control iterations are being performed, as described below:

- Wavefront control iterations are continuously performed at a speed that optimizes contrast in the target inner and outer dark zones (typically one wavefront control iteration every few minutes).
- As described in Sec. 4.1.4, for each wavefront control iteration, one measurement is acquired (in each zone) with the best DM shape for high-contrast (no additional deformation on the DM to probe speckles). This measurement is used toward contrast measurement, and is referred to as the contrast field image.

4.6.4. Contrast field images are acquired by repeating step 4.6.3. The contrast metric is measured for each of the contrast field images on each pixel within the inner and outer dark zones.

4.6.5. The following images and data are to be archived for future reference: raw and calibrated coronagraphic images, all DM voltage commands, coronagraph transmittance profile (radial function derived from the as-built coronagraph design or laboratory measurement of total intensity vs. off-axis distance for the testbed fiber source)

4.6.6. The following images or data are to be presented in a final report:

- calibrated images of the reference star,
- the coronagraph transmittance profile and focal plane scale
- a set of contrast field images
- a contrast metric value for the target area in each of the contrast field images
- a histogram of the brightness distribution of pixels in the dark field for each of the high contrast images in the data set, and for the combined data acquired in each data set.

## 5. Success Criteria

The following are the required elements of the milestone demonstration. Each element includes a brief rationale.

**5.1.** Illumination is monochromatic light at a wavelength in the range of  $400 \text{ nm} < \lambda < 900 \text{ nm}$ .

*Rationale: This milestone is a monochromatic experiment to demonstrate feasibility of the approach at a wavelength close to or within the spectral range of the EXCEDE science requirements.*

**5.2.** The median contrast metrics shall be measured in a  $1.2$  to  $2.0 \lambda/D$  dark zone, and in a  $2.0$  to  $4.0 \lambda/D$  dark zone, as defined in Sec. 4.4.

**5.3.** The contrast values, as computed in element 5.2., shall be measured over  $n > 1000$  consecutive wavefront control iterations. The average of the 90% best contrast values in this set of  $n$  values shall simultaneously be  $1 \times 10^{-6}$  or smaller for the inner dark zone and  $1 \times 10^{-7}$  or smaller for the outer dark zone.

*Rationale (5.2 + 5.3): This provides evidence that the high contrast field is sufficiently dark for the EXCEDE science goals (detection and characterization of circumstellar disks), and test whether there is a fundamental limitation at the inner working angle. Allowing for 10% of the data to be discarded in the averaging accommodates for transient events that may occur in the lab, and corresponds to a moderate loss in science efficiency.*

**5.4.** Elements 5.1 – 5.3 must be satisfied on three separate occasions with a reset of the wavefront control system software (DM set to scratch) between each demonstration.

*Rationale: This provides evidence of the repeatability of the contrast demonstration. The wavefront control system software reset between data sets ensures that the three data sets can be considered as independent and do not represent an unusually good configuration that cannot be reproduced.*

*N.B.:* For each demonstration (5.4), the DM will begin from a "scratch" setting and the algorithm used to converge will have no memory of settings used for prior demonstrations. There is no time requirement for the demonstrations, other than the time required to meet the statistics stipulated in the success criteria. There is no required interval between demonstrations; subsequent demonstrations can begin as soon as prior demonstrations have ended. There is also no requirement to turn off power, or delete data relevant for the calibration of the DM influence function.

## **6. Certification Process**

The Principal Investigator will assemble a milestone certification data package for review by the Exoplanet Exploration Program and its Technology Advisory Committee. In the event of a consensus determination that the success criteria have been met, the Program will submit the findings of the TAC, together with the certification data package, to NASA HQ for official certification of milestone compliance. In the event of a disagreement between the Program and the TAC, NASA HQ will determine whether to accept the data package and certify compliance or request additional work.

### ***Milestone Certification Data Package***

The milestone certification data package will contain the following explanations, charts, and data products:

6.1.1. A narrative report, including a discussion of how each element of the milestone was met, an explanation of each image or group of images, appropriate tables and summary charts, and a narrative summary of the overall milestone achievement.

6.1.2. Calibrated images of the coronagraph transmittance profile.

6.1.3. Calibrated images of the (minimum) 3 sets of data, with appropriate numerical or color-coded or grey-scale coded contrast values indicated, and with coordinate scales indicated in units of Airy distance ( $\lambda/D$ ), all in demonstration of achieving the milestone elements.

6.1.4. A histogram of the brightness distribution of pixels in the inner and outer dark field for each of the high contrast images in the data set, and for the combined data acquired in each data set.

6.1.5. A set of contrast measurement values for each of the 3 data sets.

6.1.6. A description of the residual components of the residual light in the dark zone: static coherent light, dynamic coherent light (due to time-variable pointing errors and wavefront changes too rapid to be fully corrected by the wavefront control loop) and incoherent light (ghosts, polarization leaks).

6.1.7. A step by step description of all data processing and analysis performed, along with source code and algorithm description. This will be provided in sufficient detail so an independent analysis of the raw data can be applied outside our team.

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## **APPENDIX – ACRONYM LIST**

AACMC	Amplitude Apodized Complex Mask Coronagraph
ACCESS	Actively-Corrected Coronagraph for Exoplanet System Studies
ACE	Ames Coronagraph Experiment
APLC	Apodized Pupil Lyot Coronagraph
AU	Astronomical Unit
CLOWFS	Coronagraphic Low Order Wave Front Sensor
DM	Deformable Mirror
DRM	Design Reference Mission
EFC	Electric Field Conjugation
EXCEDE	Exoplanetary Circumstellar Environments & Disk Explorer
HCIT	High Contrast Imaging Testbed
HST	Hubble Space Telescope
IWA	Inner Working Angle (in L/D, arcseconds, or milliarcseconds)
IWD	Inner Working Distance (in Astronomical Units)
JPL	Jet Propulsion Laboratory
JWST	James Webb Space Telescope
mK	milli-Kelvin
LM	Lockheed-Martin
LOWFS	Low Order Wave Front Sensor
M1 / M2	Mirror 1 or 2: referring to PIAA mirrors used in pairs
MAS	milli-arcseconds (or lower case: mas)
MEMS	Micro Electro-Mechanical Systems
NASA	National Aeronautics and Space Administration
NOAO	National Optical Astronomy Observatory
PECO	Pupil-Mapping Coronagraphic Observer
PI	Principal Investigator
PIAA	Phase Induced Amplitude Apodized
PIAA-C	PIAA Coronagraph
PSF	Point Spread Function
TDEM	Technology Demonstration for Exoplanet Missions
TPF-C	Terrestrial Planet Finder – Coronagraph
TRL	Technology Readiness Level