Technology Milestone Whitepaper

EXCEDE Technology Milestone #2: Broadband Contrast Demonstration

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0. Preamble

This EXCEDE technology milestone (MS) #2 whitepaper ("Broadband Contrast Demonstration"), is predicated upon the technology maturation & demonstration (TM&D) goals for the NASA/Explorer program sponsored EXCEDE category III investigation as described in its predecessor document:

"EXCEDE Technology Milestone #1: Monochromatic Contrast Demonstration" (JPL Document D-75789[3]) [Sch12a]; henceforth: whitepaper (WP) #1.

For brevity, and obviation of redundancy in this WP (#2), our previous WP #1 along with the:

"EXCEDE Technology Milestone #1 Monochromatic Contrast Demonstration Closure Report" (JPL Document D-81732[4]) [Sch13],

should be consulted as the primary references to gain a detailed understanding of:

(a) the overall objectives of the EXCEDE TM&D program including traceability to science requirements and mission goals,
(b) an introduction to Phase Induced Amplitude Apodization (PIAA) coronagraphy and its applicability with wavefront error (WFE) sensing and control to the EXCEDE measurement and instrument requirements,
(c) a description of the overall TM&D plan,
(d) further rationale, definitions, and computations for ascertaining performance metrics,
(e) S/W tools and processes developed for MS #1 testing applicable for MS #2, and
(f) criteria for evaluating, and procedures for documenting, success.

The laboratory TM&D program for EXCEDE MS #1 was conducted using facilities of the NASA/Ames Research Center's (ARC) Coronagraph Experiment (ACE) Laboratory, under the programmatic direction of Glenn Schneider (PI, UofA) and technical leadership of Ruslan Belikov (NASA/ARC). The laboratory TM&D program and performance analysis for MS #1 was carried out from April 2012 – December 2013 in a thermally stabilized air environment. TM&D MS #1 was fully realized, with technical review and approval by the NASA Exoplanet Exploration Office, as a result of that first (of two phases) of the EXCEDE TM&D program.

The laboratory TM&D program in lead-up to our MS #2 (broadband) demonstration has been on-going, and will be carried out and completed as described in this whitepaper. For MS #2 we are using facilities at the Lockheed Martin (LM) Advanced Technology Center (ATC), in particular LM's vacuum environment Metrology ("MET") test chamber. In advancing from MS #1 to MS #2, per our TM&D plan, the EXCEDE starlight suppression system (SSS) test bench was reconfigured for **exploring broadband (up to $\Delta\lambda/\lambda = 10\%$), rather than monochromatic, contrast/working angle performance** as the prior stated and continuing primary goal of the MS #2 phase of the investigation. In this phase, though not a MS #2 requirement, the EXCEDE instrument concept maturation benefits greatly from: (a) testing and verifying SSS operability and performance in a space-like vacuum environment and, (b) moving to a more "flight-like" optical configuration including: (1) the placement of the

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[3] http://exep.jpl.nasa.gov/files/exep/EXCEDE_Milestone_1_01DEC2012_GS09.pdf
[4] http://exep.jpl.nasa.gov/files/exep/EXCEDE_MILESTONE1_CLOSURE_REPORT_02DEC2013_V06.pdf

deformable mirror (DM) at the front-end of the optical path and, (2) the incorporation of inverse PIAA optics - both per the EXCEDE concept SSS/coronagraph flight configuration.

Herein, with only brief restatements of key elements of the overall investigation plan in the context of the EXCEDE mission concept and flow-down technical requirements (see JPL Documents D-75789 and D-81732 for additional details of both), we focus on the TM&D program test plan unique to the MS #2 investigation and closure.

1. Introduction and Technology Milestones/Objectives

1.1. Background

The Exoplanetary Circumstellar Environments and Disk Explorer (EXCEDE) [Guy012a, Sch12b] is an EX-class mission concept that was proposed to NASA's Explorer program under the ROSES 2011 AO. EXCEDE was selected and funded for technology maturation as an Explorer category III program to close TRL gaps identified in its proposal review associated with its starlight suppression system (SSS).

The EXCEDE flight concept uses a 0.7-m diameter telescope to perform high contrast coronagraphic imaging of the circumstellar environments of nearby stars. By imaging light-scattering material in planet-hosting environments, EXCEDE will study the formation, evolution, architectures, and diversity of exoplanetary systems, and characterize those environments into stellar habitable zones (HZs). EXCEDE, with inner working angle (IWA) reach smaller than HST, provides contrast-limited scattered-light detection sensitivities currently estimated to be ~ 1000x greater than HST coronagraphy's smallest IWAs, thus enabling the exploration and characterization of exoplanetary debris systems in currently inaccessible domains [Sch14a].
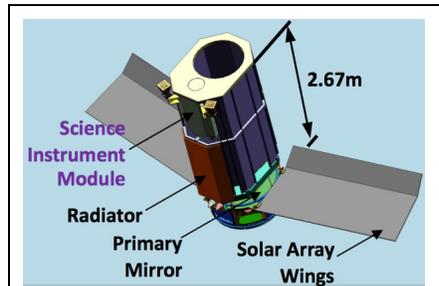
Fig. 1. The EXCEDE space-craft and its off-axis (un-obscured) telescope with SSS and science camera in its Science Instrument Module.

EXCEDE will utilize a laboratory-demonstrated Phase-Induced Amplitude Apodization (PIAA) coronagraph [Bel12a,b] integrated with a 70 cm diameter unobscured aperture visible light telescope (Fig. 1). 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.

1.2. Technology Milestones (Programmatic)

Technology Milestones serve to gauge the developmental progress of integrating technologies for a space-based mission, such as EXCEDE, in this case to perform high contrast observations of circumstellar material in exoplanetary systems. These sensing and control method performance milestones, along with all the complementary hardware technology

maturation required by NPR 7120.8 [NAS08], will inform on a mission's readiness to proceed from pre-Phase A to Phase A. Completion of a milestone is documented through a report (i.e., this document for EXCEDE MS #2, and its later closure report) by the Principal Investigator and reviewed by NASA HQ.

1.3 EXCEDE's Technology Milestone Objectives

The EXCEDE Category III-funded TM&D effort is focused (by direction) on its SSS, and includes two technology milestones:

• Milestone 1: reaching 10^{-6} median raw contrast between 1.2 and 2 λ/D in monochromatic light, *simultaneously* with 10^{-7} median raw contrast between 2.0 and 4 λ/D.
• Milestone 2: broadband light test, reaching similar contrast values as Milestone 1 in a nominally 10% wide spectral band.

This whitepaper specifically describes the EXCEDE TM&D MS #2 definition and laboratory demonstration program. JPL Document D-75789 should be consulted for broader context and relation to MS #1 (as demonstrated per JPL Document D-81732).

EXCEDE MS #2 addresses broadband starlight suppression at small inner working angles with a PIAA coronagraph (see JPL Document D-75789 for background, and [Guy03, Tra03, Van05, Guy05, Mar06, Van06. Plu06, Guy06, Loz09, Guy10] for details of PIAA technology). PIAA is a high-efficiency coronagraphy technique enabling high-contrast imaging at a small inner working angle (1.2 λ/D for EXCEDE). The approach for accomplishing this milestone is similar to the one previously implemented for TPF-C MS #2, that demonstrated broadband starlight suppression at larger IWA on the JPL High Contrast Imaging Testbed (HCIT), and subsequently formulated milestones for NASA's TDEM program. For EXCEDE MS #2, a PIAA type coronagraph is used at LM on an optical breadboard in a vacuum chamber. The MS #2 breadboard configuration is close to the EXCEDE optical flight design, and in operation (as for MS #1) includes real-time data processing algorithms for wavefront error control.

Both MS #1 and MS #2 represent important advances in technology-enabled performance:

(a) In both cases these milestones require a similar improvements in system stability.
(b) The published results achieved prior to our MS #1 closure report had not yet been verified to be repeatable as required by our milestone demonstration criteria.
(c) These milestones call for a *simultaneous* demonstration of two contrasts domains (driven by science needs) whereas, in the past, stellocentric contrasts have been demonstrated separately in different annular zones; N.B., it is more challenging to achieve a few x 10^{-7} contrast between 2 and 4 λ/D in a coronagraph that has an IWA of 1.2 λ/D than in a coronagraph that has an IWA of 2 λ/D, because the former is more sensitive to low-order instabilities[5].
(d) Unlike many previous TDEM white papers, these Explorer-program derived milestones are associated with a specific flight mission concept and requirements, and are therefore more conservative than they would be in a pure (mission-independent) technology demonstration.

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[5] A decrease by a factor of x2 in stellocentric angle (IWA in λ/D) represents an ~ order of magnitude greater challenge in achievable image contrast.

Regarding (c) and (d) in particular, the EXCEDE MS #2 objective described in this WP is *complementary* to higher (e.g., $\geq 10^{-9}$ *augmented*) contrast performance at ≥ 2 λ/D (exclusively) using similar or alternate approaches for starlight suppression pursued through independent PIAA SAT/TDEM investigations. The EXCEDE 10^{-6} *raw* contrast at 1.2 λ/D is representative of the required performance for small (< 1 m diameter) telescopes characterizing interplanetary dust in exoplanetary system environments. The photon noise that fundamentally restricts raw sensitivity for most targets on estimated on-orbit integration timescales is commensurate with the achievable image contrast science goals when IWA is pushed below 2 λ/D to overcome the limitations of the small telescope aperture size. (To read more about the traceability to EXCEDE science objectives and mission goals, see Sec. 1.2. of WP #1).

2. A Brief Review of the EXCEDE Concept

2.1. Overview

EXCEDE was proposed to NASA in response to the Explorer AO in February 2011 by a team led by Dr. Glenn Schneider of University of Arizona (UofA) and is a partnership between UofA, Lockheed-Martin (LM) Corporation, and the NASA Ames Research Center (ARC). EXCEDE was selected as an Explorer Category III investigation ("Scientifically sound investigation requiring further technical development"), receiving technology development funding to mature specific elements of its proposed SSS to early TRL 5 (or beyond).

EXCEDE is a science-driven technology-pathfinder EX-class Explorer mission concept [Sch14a, Guy012a]. It consists of a 0.7 m coronagraphic space telescope (see Fig. 1) with an unobscured pupil. The EXCEDE science instrument is a two-band Nyquist-sampled imaging polarimeter[6] operating non-simultaneously in two ($\Delta\lambda/\lambda \leq 20\%$) spectral bands at 0.4 and 0.8 μm. The EXCEDE flight design uses a SSS with a deformable mirror (DM) and PIAA coronagraphic optics (forward and inverse) to simultaneously suppress starlight to 10^{-6} median *raw* contrast from 1.2 to 2 λ/D, and 10^{-7} median *raw* contrast from 2 to ~ 22 λ/D. With speckle subtraction and polarimetric PSF nulling [Sch14b] combined in post-processing EXCEDE is capable of imaging intrinsically polarized circumstellar debris dust with augmented contrast of 10^{-9} (for sufficiently bright targets) in concert with the main EXCEDE mission goals:

- To characterize the circumstellar environments into habitable zones and assess the potential for habitable planets.
- To understand the formation, evolution, architectures, and diversity of planetary systems.
- To develop and demonstrate advanced coronagraphy in space, enabling future exoplanet imaging and characterization missions.

2.2. EXCEDE's Starlight Suppression System

The EXCEDE flight concept SSS is schematically illustrated in Fig. 2 (described more fully in [Guy12]) with anticipated performance as shown in Figure 3. Stellocentric angle/raw contrast

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[6] The EXCEDE TM&D program is designed to demonstrate the stellocentric angle/contrast performance of the SSS (as directed to us from NASA HQ), and with demonstration sufficiency (and for cost containment) does not implement the flight-design back-end polarimeter. See Appendix A.

performance in compliance with expectations, simultaneously in the most challenging 1.2 –2.0 λ/D and 2 – 4 λ/D zones has been demonstrated (in 0.6 μm monochromatic light) with the in-air EXCEDE test bed configuration per the MS #1 closure report (JPL Document D-81732).
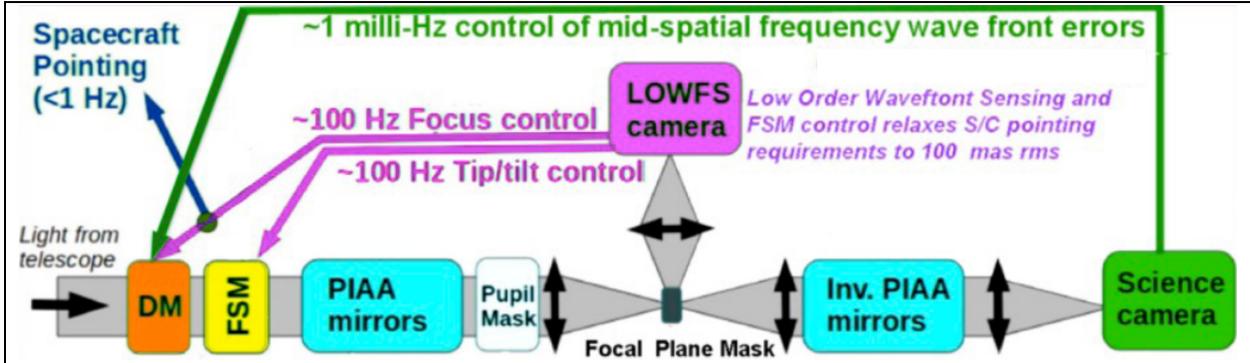

Fig. 2. Schematic of EXCEDE flight SSS. DM: Deformable mirror; FSM: Fine Steering Mirror; LOWFS: Low Order Wavefront Sensor; PIAA: Phase Induced Amplitude Apodization.

Fig. 3. Red curve: Simulated 0.4 μm raw coronagraphic contrast with wavefront control taking into account expected chromatic aberrations, low order instabilities, and known static errors. Green curve: anticipated order of magnitude augmented median contrast per resolution element after post-processing with speckle calibration (subtraction). Blue curve: Further contrast enhancement from polarimetric PSF nulling (PPN; see [Sch14b] *c.f.* § 8.9, and Appendix A) of residual "speckles" with full linear-Stokes polarized intensity (p*i) imaging for sufficiently bright unpolarized stellar targets with disk polarized surface brightnesses not in the photon noise dominated regime. Here, the OWA is defined / limited by the number of actuators on the DM and their mapping across the telescope pupil.
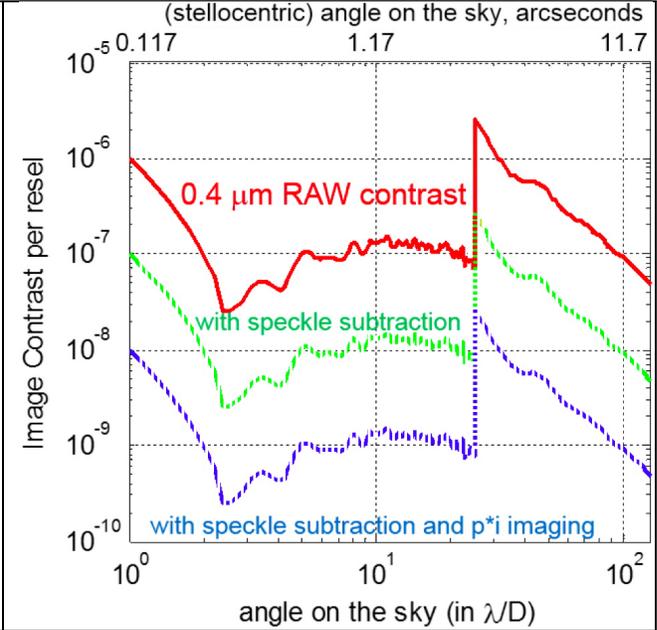
The EXCEDE SSS contains three critical components that suppress stellar light arising from three different, but equally important, sources:

(1) Fundamental physics, specifically diffraction that is removed by the coronagraph (blue in Fig. 2). The EXCEDE SSS is based on the highly efficient Phase Induced Amplitude Apodization coronagraph that allows it to take full advantage of the smaller aperture, enabling performance of a much larger telescope utilizing other coronagraph architectures.

(2) Manufacturing limitations such as static and quasi-static WFEs, as well as alignment errors, which are removed by the WFE control system (green and orange in Fig. 2). EXCEDE relies on a WF control system based on focal-plane-based sensing such as the Electric Field Conjugation and Speckle Nulling [Giv07], demonstrated monochromatically with MS #1.

(3) Environmental disturbances and instabilities such as fast low order errors (e.g. tip/tilt), which are sensed by the Low-Order Wavefront Sensor (LOWFS, purple, orange, and yellow in Fig. 2) [Loz13] and, corrected in the flight configuration also with a fast steering mirror.

A fourth critical component is the science camera which is a two-band Nyquist sampled imaging polarimeter, green in Figure 2, replaced by only a CCD detector and fixed linear polarizer in the ground-test (MS#1 and MS #2) configurations.

2.3. Summary of Progress to Date

In addition to the MS #1 closure report, we have presented and published many of the technical details of our test bed configuration and TM&D program leading to the final (MS #1) summary results; e.g., principal results may be found in papers [Bel12b, Bel13a, Bel13b, Loz13, Sch13, Bel14, Ben14, Sch14a] that we do not reproduce in this whitepaper.

Preliminary findings in preparation for our broadband MS #2 vacuum demonstrations include:

(a) successful integration and demonstration of the Low Order Wavefront Sensor [Bel12,14].
(b) 1.8×10^{-7} in-air median contrast between 1.2 and 2.0 λ/D, simultaneously with,
(c) 6.5×10^{-8} in-air median contrast between 2.0 and 4.0 λ/D, in monochromatic light, and,
(d) monochromatic and *preliminary* broadband results (Fig. 4) with the vacuum testbed at LM.
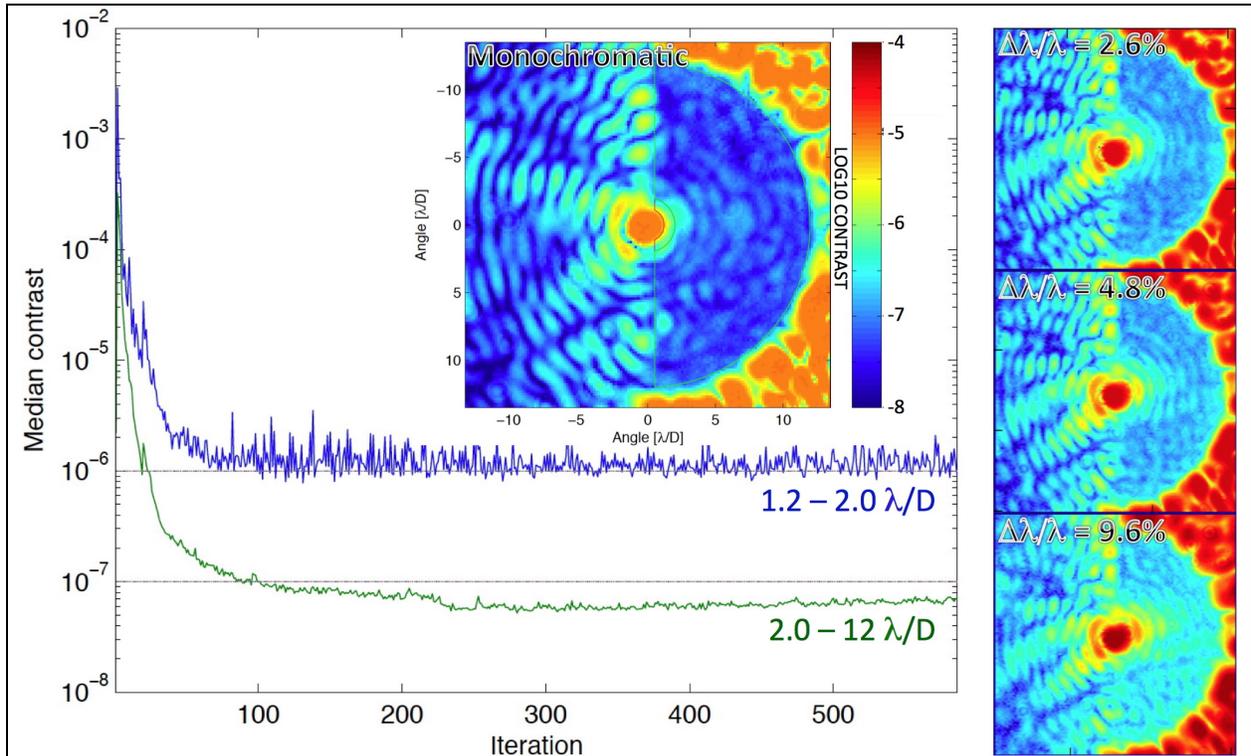
Fig. 4. *Preliminary* vacuum monochromatic and broadband results through October 2014 with the EXCEDE MS #2 configuration build-up, from 1.2 − 12 λ/D (655 nm light). Left: Representative monochromatic image and repeatability after WFE control stabilization. Median contrasts are derived for C-shaped regions (e.g., Fig 7) in "right size" dark zone (as in image inset). Right: *Initial* representative contrasts (to be improved) in $\Delta\lambda/\lambda$ = 2.6%, 4.8%, and 9.6% broadband light.

(a) – (c), above, were obtained with the in-air (ACE) test bed, with a "simplified" layout that did not contain inverse PIAA mirrors and where the DM was downstream instead of upstream of the (forward) PIAA mirror set. See [Sch13], *c.f.*, Fig 9 for representative additional, and discussions of, in-air monochromatic performance results. (d) is relevant to MS #2 and implements a more flight-like layout (see Fig. 5) in a vacuum environment; *preliminary* performance of the vacuum test bench during vacuum operability/functionality testing is shown Fig 4.

3. MS #2 description: Broadband Contrast Demonstration

3.1. Milestone #2 Definition[7]

"Demonstrate, using a PIAA coronagraph with an inner working angle of 1.2 λ/D, a raw contrast median level of 10^{-6} between 1.2 and 2 λ/D, simultaneously with a median level of ≤ 3 x 10^{-7} between 2 and ≥ 4 λ/D, in broadband light at a central wavelength in the range 400 - 900 nm and a spectral bandwidth Δλ/λ of 10% over a single-sided dark zone."

Rational for 2 to ≥ 4 λ / D Contrast

After having attained the MS #1 goal in monochromatic light [Sch13], the MS #2 goal is to obtain similar levels of contrast with Δλ/λ = 10% broadband light, demonstrated with an optical design, configuration [Ben14], and test environment closer to the EXCEDE flight configuration. Herein we define the MS #2 contrast metric in the 2 to ≥ 4 λ / D region to conform to (and *exceed by a factor of 3*) the EXCEDE instrument functional requirement (IFR) to carry out the most demanding of the baseline mission objectives and science goals as given in the EXCEDE flight proposal (11-EXPLORER11-0011, from which this investigation is charged) in its Science Traceability Matrix (STM; Table B-2) as 10^{-6} resel^{-1}. Meeting this IFR contrast in broadband light (10% spectral bandwidth also per the STM IFRs) would satisfy all of the related EXCEDE science requirements. Based on our *preliminary* testing to date we believe with high confidence we can exceed this IFR with ~ 3x better ≥ 2 λ/D contrast, and so we have adopted this for our MS #2 definition.

Uniqueness of EXCEDE MS #2 and Difference from Guyon TDEM MS #3

The EXCEDE mission is *not* designed to meet the requirements for exoplanet imaging, but rather to enable the imaging of light-scattering circumstellar debris in *both* the zodiacal (inner) and Edgeworth-Kuiper belt (outer) analog regions of a sufficient number of exoplanetary debris systems (as defined in the EXCEDE flight proposal and its two-year DRM and science requirements), and to do so with a small (0.7m) telescope. This drives the EXCEDE design, from astrophysical necessity, to an IWA of 1.2 λ/D. This is not within the larger stellocentric angle of the Guyon TDEM investigation MS #3 [Guy14]. Moreover, EXCEDE circumstellar disk science requires a high contrast stellocentric field *simultaneously* in two zones: at 2.0 -

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[7] For MS #1 we established an outer working angle (OWA) benchmark limited to a 4 λ/D configuration for our (now monochromatically demonstrated) in-air testing to allow for timely maturation using then existing, compatible, coronagraphic optics. We have subsequently reconfigured the test bench with (in particular) a new focal plane occulter and inverse PIAA optics that, together, will allow exploration to an OWA of ~12 λ/D, advantageously closer to the larger proposed final, flight DM limited, configuration.

4.0 λ/D (and beyond) with an IFR of 10^{-6} resel^{-1} median raw contrast (with a projected performance goal ~ 10x better), and at 1.2 - 2.0 λ/D at ~ 10^{-6} resel^{-1} median raw contrast. *N.B.*: This capability, different from those needed for exoplanet imaging, will enable EXCEDE to measure and map debris dust surface brightnesses, and characterize material composition in debris systems, ~ 2 - 3 orders of magnitude fainter than have been observable with HST (or anticipated with JWST) coronagraphy, and (at least) 3x closer to their host stars.

By excluding the 1.2 - 2.0 λ/D region (required for EXCEDE), the Guyon TDEM milestone #3 worked with a coronagraph with a larger IWA that is much more forgiving of low-order aberrations. One (unfortunately) cannot assume that the Guyon TDEM results validate the 2.0 - 4.0 λ/D contrast goal for EXCEDE, since EXCEDE with 1.2 λ/D IWA is much more sensitive to these low-order aberrations. *At equal angular distances, contrast values cannot be directly compared if the coronagraph IWA also changes*. These systems are very different. Obtaining ~ few x 10^{-7} resel^{-1} median raw contrast at 2.0 - 4.0 λ/D would be *much* easier if EXCEDE could block the 1.2 - 2.0 λ/D region, which cannot be done. Conversely, to drop the 2 - 4 λ/D region from the MS #2 demonstration plan, with a claim that had been done with the Guyon TDEM MS #3, also cannot be done; Using a larger IWA contrast to justify what might be obtained on a smaller IWA system is invalid. What makes this milestone unique, and distinct from the Guyon TDEM milestone 3, is to get the requisite contrast in the 2 - 4 λ/D region while also retaining access to the 1.2 - 2.0 λ/D region.

3.2. Description of the LM PIAA Vacuum Laboratory Configuration
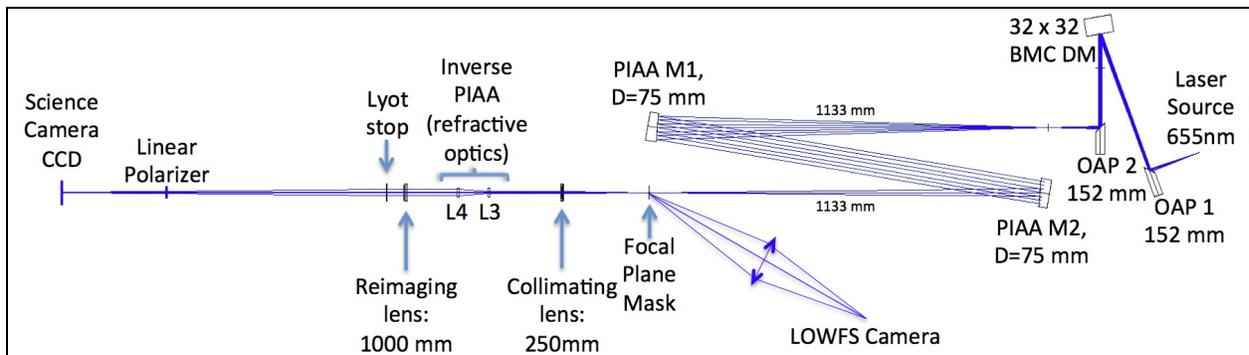
Figure 5. Optical layout used for MS #2 broadband testing and demonstration in vacuum.

Unlike the optical and environmental configuration of the EXCEDE test bench employed in our MS #1 demonstration, for MS #2 the EXCEDE test bench has been re-configured for a closer to flight-like architecture and for vacuum operation conditions [Ben14]. The most significant changes are: (a) the deformable mirror is now upstream, rather than downstream of the PIAA system; and (b) an inverse PIAA system is used. This combination enables a much wider, and off-axis unaberrated, stellocentric field and outer working angle, but it is more challenging to align and perform wavefront control; See section 3.4. Preliminary in-vacuum functionality and operability (but not yet final performance) testing of the reconfigured test bench in the LM vacuum environment test chamber has been successfully completed [Bel13a, Bel13b], and an example of current performance is shown in Fig. 4.

Fig. 5 presents a schematic representation of the optical layout of the test bench used in our vacuum environment testing with the PIAA configuration (compared to MS #1) given in Table 1. The input to our system is a fiber fed by a laser into the vacuum chamber. (We have a number of fibers in a bundle, thus allowing flexibility to test different kinds of fibers at the source, to match the fiber to the wavelength range used, and to experiment with polarization-maintaining vs. non-maintaining fibers).

TABLE 1 - MS #1 and MS #2 PIAA TEST CONFIGURATIONS		
COMPONENT / CONFIGURATION	ACE (MS #1)	LM (MS #2)
DM Placement	After PIAA M2	Ahead of 2nd OAP and PIAA M1
Central Wavelength (λc)	in range 400–900 nm, default 655 nm	
Bandpass ($\Delta\lambda/\lambda$)	monochromatic	$\leq 10\%$
PIAA M1 active optical diameter	90 mm	75 mm
PIAA M2 active optical diameter	90 mm	75 mm
Distance between M1 and M2	900 mm	1125 mm
Inverse PIAA L3 active optical diameter[a]	N/A	16 mm
Focal Plane Mask[b]: binary (opaque/transmissive) optic	circular opaque center	C-shape (e.g. Fig 7) matched to (or slightly larger than) the high contrast zone
Inverse PIAA L4 active optical diameter[a]	N/A	16 mm
Distance between L3 and L4	N/A	100 mm
Central magnification of M2:M1 map with DM placed after M2, conjugate to it	5.5	3.5
Edge compression factor of PIAA remapping (values <1 represent stretching rather than compression)	1/6.6	1/9.67
# of DM actuators across conjugated mirror	~ 29 (varies)	~ 30

[a]Diameter of the pupil on inverse PIAA lenses is 16 mm; a 15 mm Lyot stop is located downstream of PIAA L4.
[b]For MS #2 C-shape baseline, but one of a number of selectable circular/C-shaped masks of different sizes

As in the EXCEDE flight design, the DM is conjugated to the PIAA system. For both cost-containment and demonstration sufficiency, our MS #1 and MS #2 test bench configurations each use a (different) existing and available 1K square footprint BMC DM. The flight implementation calls for a 2000-element "circular" footprint BMC device with a common heritage design to the 1K devices. This is not an important difference for our current TM&D goals, to demonstrate high contrast in broadband light primarily in the vicinity of the inner working angle which is the most challenging part of the science image focal plane.

Our MS #2 forward PIAA system consists of two 75 mm active diameter mirrors made by Axsys, and our reverse system consists of two 16 mm active diameter lenses. Both sets of optics convert from a top-hat illumination profile to a prolate spheroidal (or vice versa) in the center of the beam. These mirrors have different beam edge profiles than the PIAA mirrors used in the in-air test bench (because they were designed for different systems; but both were sufficient for our TM&D needs without incurring additional procurement costs). Though the edge profiles are different, the degradation in Strehl ratio is negligible. Because very little (laser-simulated) starlight illuminates the inverse PIAA system (most of which is blocked by the focal plane occulter), high quality mirrors are not required for the inverse PIAA system. Thus, for our MS #2 testing and demonstration we used lenses both for ease of alignment and to save physical space on

the test bench. (The viability of this decision is evidence by the sharpness of the speckles in the preliminary $\Delta\lambda/\lambda \approx 10\%$ image presented in Fig. 4, lower right panel).

As with the in-air test bench configuration, we are using a fixed linear polarizer immediately in front of the CCD camera. In the EXCEDE flight layout, the linear polarizer is "replaced" by selectable Wollaston prism polarizers in a mechanism located in a collimated beam ahead of the science camera reimaging optics. This difference is not consequential for our MS #2 testing.
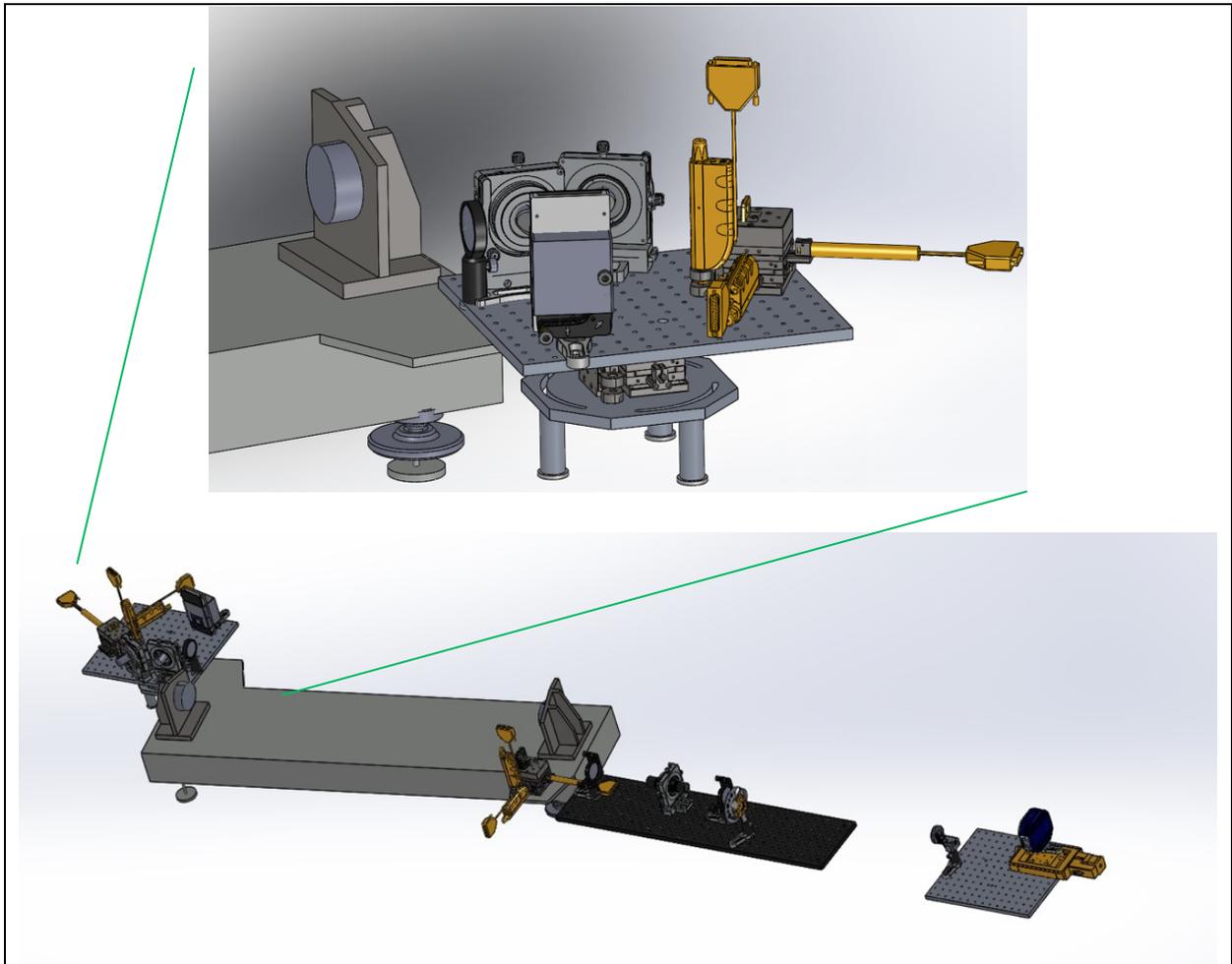
Figure 6. CAD layout of the vacuum system

Fig. 6 shows a CAD layout of our vacuum system test bench, implementing the optical layout from Fig. 5, and illustrates the opto-mechanical configuration of our MS #2 hardware. The top of the figure shows our "front end" which is placed on a separate plate on a stage for ease of alignment and better stability. The PIAA mirrors are mounted on their own separate bench aligned to the front end, followed by the rest of the system.

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3.3. Primary Differences in MS #2 Demonstration w.r.t. MS #1 and Flight

Environment

Like MS #1, MS #2 will be achieved in a laboratory environment with a test/calibration light source rather than with 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. The MS #2 test bed in vacuum, however, is closer to flight conditions then the ACE test bed in thermally stabilized air.

The coronagraph and wavefront control system architectures adopted for the MS #2 TM&D are closer to the flight instrument design than the one adopted for MS #1. The primary differences in our MS #2 configuration from the flight design are as follows:

Coronagraph system architecture

(1) In ground testing we will use a single broadband coronagraph spectral channel, nominally centered at 655 nm, with one or more bandwidths up to 10% (EXCEDE's instrument functional requirement). The flight instrument concept includes two (non-multiplexed) $\Delta\lambda/\lambda = 20\%$ spectral bands centered at ~ 400 nm and 800 nm. Upon meeting the milestone, we will use any remaining resources to test $\Delta\lambda/\lambda = 20\%$ performance.

(2) The inverse PIAA system is made of lenses for this milestone demonstration, though the flight system will have mirrors.

(3) Our MS #2 baseline is to demonstrate the contrast for an OWA of $\geq 4 \lambda/D$. In our vacuum test configuration we have the ability to optionally evaluate performance at larger than $4 \lambda/D$ OWA but smaller than the flight configuration ($\sim 22 \lambda/D$); optional use of the full field of DM actuators with an outer working angle radius closely approaching $0.5 \mathrm{x} N \lambda/D$ (N is the linear number of actuators across the beam) is an option we will evaluate based upon interim testing results; preliminary tests with OWA $\leq 12 \lambda/D$ have been made (e.g., Fig 4).

Starlight Suppression System

(4) In flight, a fast-steering mirror is employed for fast tip-tilt (beam centering) correction in response to the LOWFS error signal.

(5) In flight, a 2000 element circular footprint DM will be used rather than a 1K square device.

3.4. MS #1 to MS #2 Differences in Optical Alignments and DM Configuration

Optical Alignments

In our MS #2 test bed configuration, the input point source image is formed with the DM in a collimated beam between the two OAPs and with the DM optically conjugated with the PIAA M1 mirror. The procedure for aligning the position of the input point source to the PIAA mirrors remains basically the same as for the MS #1 test bed demonstration configuration, but

the source itself for the MS #2 demonstration is somewhat more complicated, and required (with explanation) the following revisions/augmentations:

(1) Co-alignment of: (a) the input fiber source, (b) the two OAPs, and (c) the DM was done with these optical elements co-mounted on the top of a separate "front-end" platform (illustrated schematically in Fig 6, top); We used the Zygo interferometer to align the OAPs and DM, and focal plane PSF analyses to align the fiber.

(2) This front-end platform is mounted on a XYZ-axis stage that makes it possible to match the source position to the first PIAA focus by the same procedure used in the MS #1 demonstration.

(3) With the addition in MS #2 of inverse PIAA optics, to match the inverse PIAA focus with the second PIAA focus, the collimating lens after PIAA M2 mirror (see Fig. 5) was aligned (relative to PIAA mirrors) with the Zygo interferometer.

(4) A preliminary alignment of the inverse PIAA lenses inside of a centering tube mounted on a 4 axis stage (also using a Zygo interferometer) that makes it possible to co-align the optical axes of the main and inverse PIAA systems. Optical axis adjustment is then performed by analyzing the sharpness of the focal plane image.

DM Configuration

The layout change from "DM after PIAA" in the MS #1 configuration to "DM before PIAA" in the MS #2 configuration also affects the coronagraph performance. Specifically, it is known that the optimum coronagraph performance can be reached if the light outside of the created dark zone is completely blocked by the occulter. However, it is impossible to fully block this light when an inverse PIAA system (added in the MS #2 configuration) is used.

The inverse PIAA system behaves exactly in the same way the main (forward) PIAA system does; It redistributes light from off-axis sources in the PIAA focal plane to a coma-like ("pineapple") structure in the inverse PIAA focal plane (e.g., see Guyon et al. 2005, ApJ 622 744; *c.f.* Fig 5.) A speckle next to the edge of the occulter in the forward PIAA focal plane whose "pineapple" wings are blocked with the occulter, is converted into a "pineapple" feature after the inverse PIAA that is much larger then the expected speckle size. This can expand beyond the dark zone and thus affect the system performance.

The second effect, vis-à-vis wavefront control is the number of degrees of freedom that should be corrected - this number larger in the "DM before PIAA" to achieve convergence of the wavefront control algorithms.

4. Performance Goal Metric: Definition and Computation

The attainment of the requisite coronagraphic contrasts, in the stellocentric annuli of merit commensurate with MS #2, are demonstrated through the measurement of the final image-plane brightness (i.e., intensity of "speckles") in the high-contrast dark-zone region relative to

the intensity of the test source as a surrogate to a star. In §§ 4.1 - 4.6 of this whitepaper we note differences in details of the measurement procedures and processes from those defined in JPL Document D-75789 for MS #1, spell out the measurement steps themselves, and specify the data products that will be produced in the conduction and documentation of the MS #2 laboratory demonstration.

4.1. Definitions

4.1.1a. "Raw" Images: We defined "raw" images as in the MS #1 whitepaper.

4.1.1.b. "Calibrated" Images. Here we clarify the definition of a photometrically "calibrated" image, in dimensionless contrast units, relative to the unobscured stellar (test source) PSF. Such PSF-intensity normalized calibrated images result from processing a raw image by subtracting the background bias and multiplying by a calibrated constant that converts raw pixel (instrumental count) values into contrast units (process detailed in §§ 4.2 and 4.4). In the MS #1 whitepaper we spoke additionally of flat-fielding, but that was found to be unnecessary to produce unbiased median contrast measurements. We now removed this from the *definition* of a calibrated image, but retain that processing step option if found necessary for our MS #2 demonstration. We archive permanently all the calibrated images, as well as the subtracted background bias. Each calibrated image (in FITS format) also contains a header with the acquisition and calibration parameters, including the linear contrast-gain constant that provides invertible traceability to the raw images.

4.1.2. Definition: "Scratch": see WP #1.

4.1.3. Definition: "Star": see WP #1.

4.1.4. "Wavefront control iteration": see WP #1.

4.1.5. Definition: "Contrast field": see WP #1, and how it is measured in Sec. 4.4.

4.1.6. Definition: "Contrast value": see WP #1, and how it is measured 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 unoccluted PSF. In detail we measure the IWA along the final image plane X (horizontal) axis per the geometry illustrated in Fig. 7 with the assumption of IWA symmetry at other stellocentric azimuthal angles within the region defined by the occulting mask.

4.2. Measurement of the (Simulated) Star Brightness

The brightness in the central pixel of the stellar (laser/fiber surrogate source) PSF is required to compute contrast, and is measured with the following steps. This procedure, in part, was updated during the course, and as a result, of our MS #1 investigation and here in concert with changes in configuration between the in-air and vacuum test benches.

4.2.1. The occulting mask is laterally offset by at least 10 λ/D (same as WP#1), to allow the star image to imping upon a transparent area of the focal plane mask.

4.2.2. A deep, but non-saturated, image of the star is obtained by co-adding a few unsaturated frames, with all coronagraph optics other than the focal plane mask in place (this now includes the inverse PIAA system).

4.2.3. The maximum intensity in the PSF core is then measured. (This intensity is then used later to calculate/calibrate the contrast field in concert with 4.1.1b.)

4.3. Measurement of the Focal Plane Scale

In the MS #1 whitepaper, we spoke to establishing the focal plane scale of our in-air test bench in the absence of inverse PIAA optics. This is not germane (and simplified) for the more flight-like configuration of the vacuum test-bench now using both forward and inverse PIAA optics. For MS #2 the focal plane scale is easily measured using the DM as follows:

4.3.1. A sine wave shape is sent to modulate the surface of the DM, with N_{DM} cycles across the 32 actuators along one axis of the DM (but see also 4.3.4), i.e. with a period of $32/N_{DM}$ actuators.

4.3.2. The footprint of the pupil on the DM, of diameter D, is actually a bit smaller than the biggest circle inscribed by the DM itself, of diameter D_{DM}, corresponding to 32 times the distance between actuators. D is known by measuring the physical aperture that defines the pupil. So the number of cycles N across the pupil is given by $N = N_{DM}*D/D_{DM}$.

4.3.3. This sine wave creates a set of two speckles that are known to have an angular distance of $\pm N$ λ/D around the on-axis PSF. So the position of these speckles is measured in the focal plane image scale, in units of pixels on the camera.

4.3.4. We perform the same focal plane image scale calibration on both the image x and y axes, as well as along a 45° "diagonal". With the measured positions, we derive three parameters: the position of the on-axis PSF center, the rotation angle between the DM and the detector x/y pixel grid, and the focal plane scale, in pixels per λ/D.

4.4. Measurement of the Coronagraph Contrast Field

This procedure was also slightly updated from our MS #1 whitepaper, based on our experience from MS #1 testing and demonstration.

4.4.1. The flux of the unobscured on-axis PSF is measured as in 4.2, with an exposure time optimized to maximize the SNR without saturating any image pixels.

4.4.2. The focal plane occulting mask is put in place, with an IWA obscuration at 1.2 λ/D.

4.4.3. The flux of the source is incrementally increased as needed, to avoid very long exposures when the contrast is deep. The ratio between two (low and high) source fluxes is characterized either with a calibration procedure if the flux is controlled by the computer, or using the LOWFS camera if the flux is modified manually.

4.4.4. 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 λ/D (red region in Fig. 5) that is bounded by a line that passes 0.5 λ/D from the star at its closest point.
   (b) An outer dark zone extending from 2.0 λ/D to the OWA (blue region in Fig 5.); this OWA being *at least* 4.0 λ/D, also bounded by a line that passes 0.5 λ/D from the star at its closest point.
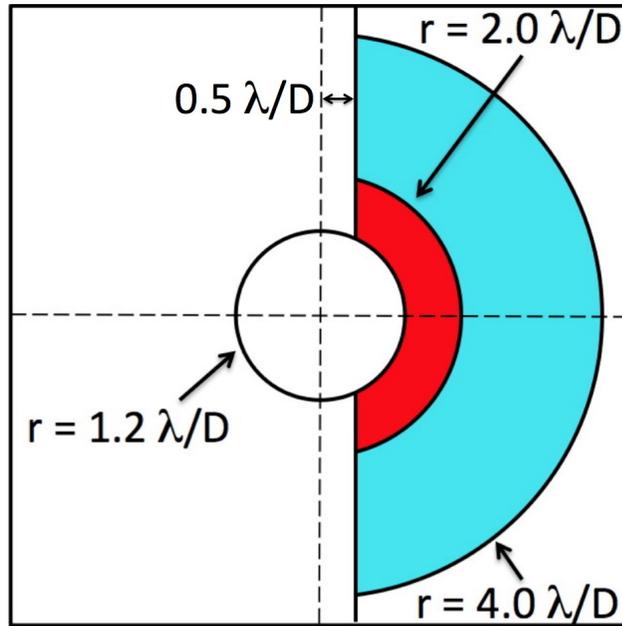

Figure 7: Inner (red) and outer (blue, to a *minimum* 4λ/D) high-contrast dark zone geometries.

4.4.5   This image is divided by a constant, defined as the multiplicative product of:
   (a) The flux of the unobscured PSF,
   (b) The ratio between the exposure time of the obscured PSF to the unobscured PSF,
   (c) The calibration constant for the two levels of flux used, measured in step 4.4.3.

The resulting image is calibrated in dimensionless contrast units; this is the contrast field as described in § 4.1.

N.B: A similar procedure may be followed, but to a larger OWA than the minimum 4λ/D to explore the contrast to a larger stellocentric angle.

4.5. Contrast Value as a Single Metric (for Each Zone)

See WP #1 (unchanged).

4.6. Milestone Validation Demonstration Procedure

The MS #2 validation demonstration procedure is essentially unchanged from MS #1. Steps 4.6.1 – 4.6.4 (same enumeration in JPL Document D-75789) are identical. Here we modify slightly steps 4.6.5 and 4.6.6.

4.6.1 – 4.6.4. See MS # 1 whitepaper (JPL Document D-75789)

4.6.5. The following images and data are to be archived for future reference: raw and calibrated coronagraphic images delivered as part of the Certification Data Package used to demonstrate the milestone - including headers containing all the parameters of the acquisition, darks, all DM voltage commands, and images used for the different calibrations.

4.6.6. The following images or data are to be presented in a final report (consistent with the as-approved MS #1 closure report; JPL Document D-81732):

    (a) calibrated images of the laser-simulated reference star (per 4.2),
    (b) the focal plane scale (per 4.3),
    (c) a set of contrast field images (per 4.4),
    (d) a contrast metric value for the target area in each of the contrast field images, and
        for the combined data acquired in each data set.

5. Success Criteria

The following are the required elements of the MS #2 demonstration. Each element includes a brief rationale. Elements 5.1 – 5.3 are very similar to those for MS#1, but for a broadband experiment. Element 5.4 is identical to that for MS #1.

5.1. Illumination in broadband light at a central wavelength in the range of 400 nm $< \lambda <$ 900 nm, and a spectral bandwidth of 10%.

Rationale: *This milestone is for a broadband experiment to demonstrate feasibility of the approach at a wavelength and optical bandwidth within or the spectral range of the EXCEDE flight mission science requirements.*

5.2. The median contrast metrics shall be measured in a 1.2 to 2.0 λ/D dark zone, and in a 2.0 to $\geq$ 4.0 λ/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 $\geq$ 1000 consecutive wavefront control iterations. The average of the 90% best contrast values in this set of n values shall simultaneously be 1 x 10^{-6} or smaller for the inner dark zone and 3 x 10^{-7} or smaller for the outer dark zone. See Fig. 8 that is reproduced in identical context from WP #1.

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 tests 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. See Fig. 8.

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.*
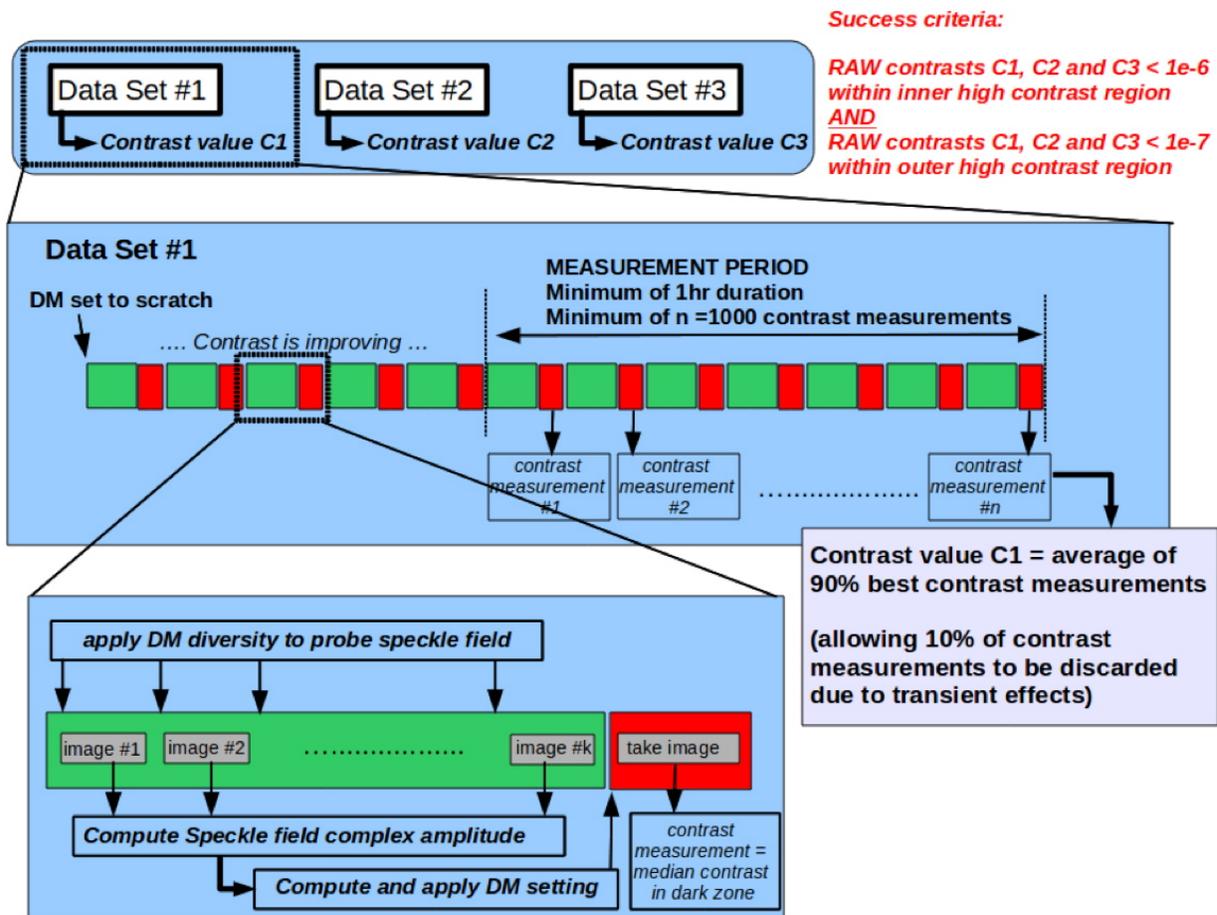

Figure 8: Schematic representation of data acquisition sequence. The success criteria is met when three data sets each meet simultaneously the 10^{-6} (inner dark zone) and 3×10^{-7} (outer dark zone) contrast criteria. Data acquisition is detailed (bottom) for one set in the central part of the figure. 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.

N.B.: For each demonstration (element 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

As for Milestone #1, 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.

6.1 Milestone Certification Data Package

As in WP #1, 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 (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 (λ/D), all in demonstration of achieving the milestone elements.

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

6.1.4. 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 (e.g., ghosts, polarization leaks, model errors).

6.1.5. 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 A – Some Comments on EXCEDE Polarimetry
Beyond the Scope of this Milestone Demonstration

The advancement, testing, and demonstration of high-contrast full linear-Stokes imaging polarimetry (FLSIP), although integral to the EXCEDE flight mission concept, is *NOT* within the charge given to us from NASA HQ that is sponsoring this EXPLORER Category 3 investigation. Within the scope of this investigation we have been directed to "further mature the appropriate elements of the EXCEDE technologies as outlined in Table F-5 of your {EXPLORER-11 flight mission} proposal", wherein those elements comprise the (when integrated) starlight suppression system (SSS) only: PIAA optics (mirrors, focal plane occulter, optional apodizer), Deformable Mirror, Low Order Wavefront Sensor, and Wavefront Control Algorithms. Though in the future we separately hope to advance the back-end polarimeter integrated with the EXCEDE SSS, this is not an element of the current investigation. This (limited scope of the current investigation) is what we convey in footnote 6 of this white paper, though here (at the request of the ExEP TAC), for broader context, we include some commentary vis-à-vis EXCEDE polarimetry that is beyond the scope of our current investigation.

The EXCEDE back-end instrument design concept, as detailed in our EXPLORER mission proposal, is a full-linear (only) Stokes imaging polarimeter, designed to measure Stokes I, Q, and U (but not V; circular polarization component) from which the total intensity (i), polarization fraction (p), and polarization pseudo-vector orientation (theta) are derived through polarimetric analysis. This was an early design decision informed astrophysically by the understanding that starlight scattered by micron sized circumstellar particles (to which EXCEDE is sensitive in its optical passband), in an optically thin medium (i.e., a debris disk), will be linearly polarized (only), and the starlight will be unpolarized (or very approximately so for nearly all targets). Hence, there is no astrophysical circular polarization signal that would be germane in the case of some other (e.g., synchrotron) sources we do not study. This same design decision was made, for the same reasons (though operating in different contrast/IWA regimes), with NASA's flagship HST coronagraphic instruments with FLSIP imaging capabilities: ACS and NICMOS, both fully validating this design architecture decision through on-orbit use and producing some remarkable results (e.g., AU Mic [Gra07], HD 61005 [Man09], and others). This need (and lack of need for Stokes V) for circumstellar disk science in general (and fully applicable to EXCEDE) is discussed in detail in [Sch14b] in the context of high contrast, coronagraphic, polarimetry. The EXCEDE FLSIP provides the requisite key diagnostic measures to constrain the physical properties of circumstellar material, while also delivering a value-added a mode of image contrast augmentation with polarization PSF nulling (PPN); e.g., see [Sch14b].

Unlike some future exoplanet detection/characterization mission concepts, to achieve the EXCEDE science and mission goals, it is not necessary for the EXCEDE FLSIP instrument to reach the photon noise limit[8], although for sufficiently bright target with speckle calibration (SC) and PPN this could be achieved. While this would present a value-added capability, the EXCEDE science program does not demand, and is not predicated upon, on this assumption. This is the intent of what is conveyed in § 2.1 of this white paper in saying that both SC and

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[8] The photon noise limited regime is not the expected regime of operation for the significant majority of EXCEDE targets in its science sample of both dust-rich protoplanetary and debris disks (~50 and 250, respectively for a two-year DRM [Guy12]; and see: https://soweb.as.arizona.edu/~gschneider/EXCEDE_OVERVIEW.html).

PPN (intrinsically enabled with EXCEDE's requisite FLSIP capability) in post-processing provide independent (but combinable) pathways to augment EXCEDE's contrast incrementally below its IFRs and projected (raw) performance baselines, each by about an order of magnitude or greater (see examples cited below) as shown notionally with the EXCEDE SSS raw projected performance (currently closely demonstrated for small IWAs in monochromatic light through EXCEDE MS #1) in Fig. 2.

SC methods, e.g., as is done in space with HST coronagraphy via PSF template subtracted coronagraphy (see [Sch14c] and [Sch14d]) or other speckle calibration techniques (e.g., [Sou12], [Fer14]) that are being perused by independent investigations, are pathways to speckle suppression other than PPN before hitting the photon noise limit.

Order of magnitude contrast enhancement in circumstellar dust structures (that are polarized with with P%$_{max}$ of tens of percent; e.g. see [Sch14b], *c.f.* § 8) in the presence of residual unpolarized starlight has been demonstrated with PPN in space using HST coronagraphy (when not in the photon noise limited regime). For example, GM Aur (H = 8.6, spec: K5V) as discussed in [Hin07] and and reproduced from [Per14] (c.f., Fig 7.11) in Fig. 9 illustrates this point.
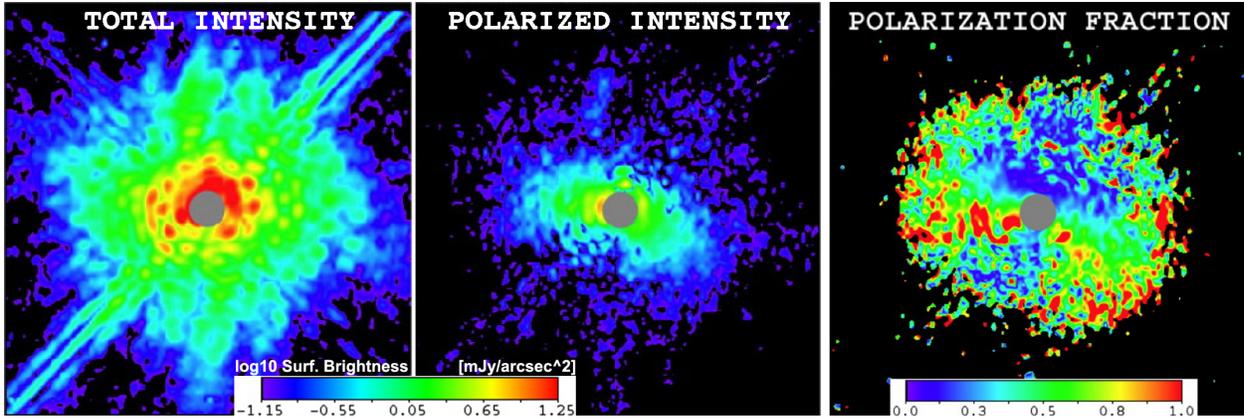

Fig 9. HST/NICMOS 2-μm coronagraphy of GM Aurigae. Left: Total intensity image wherein starlight-scattering dust from the host-star CS disk is coronagraphically undetected due to the residual light from the stellar PSF halo ("speckles" and other structures not fully suppressed by the coronagraph). Middle: Polarized Intensity (p*i) imaging with PPN (Polarization PSF Nulling) after coronagraphy of the largely unpolarized starlight in the PSF halo reveals the underlying CS disk that has P%$_{max}$ polarization ~ 50% along the disk mid-plane (see right panel, polarization fraction determined from full linear-Stokes polarimetric analysis), an order of magnitude (or more) fainter than the residual unpolarized starlight. Reproduced from [Per14].

Ultimately, the performance of the EXCEDE FLSIP (and indeed any polarimeter) may be limited by instrumental polarizations, in particular with optical systems comprised of multiple mirrors and high reflective angles of incidence. This is a potential issue not unique to PIAA mirrors. Other space-based imaging polarimeters have faced (and overcome) these and similar concerns of instrumental polarizations (e.g., for HST ACS and NICMOS as noted earlier, both off-axis instruments with multiple, internal high-incidence angle mirrors) through suitable calibrations. In EXCEDE ground calibration (if later proposed and selected for flight) or in

future flight-system advancements for EXCEDE, the optical system buildup with then a back-end polarimeter integral to the SSS, would be designed, tested and calibrated against instrumental polarizations in concert with the polarization requirements in a contrast error budget[9]. In ground test/calibration of an EXCEDE flight build-up unit, we can explore (and if found seek to mitigate or calibrate) any instrumental polarizations of consequence (including circular, e.g., by the inclusion of a rotatable quarter waveplate in a ground calibration/test configuration). Indeed this, specifically, likely warrants future investigation. Such an exploration, however, is beyond the scope of the current EXPLORER-directed MS #2 investigation.

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[9] Fig E.1.2 in the EXCEDE flight mission proposal.

APPENDIX B – ACRONYM LIST

ACE	Ames Coronagraph Experiment
ACS	Advanced Camera for Surveys
AO	Announcement of Opportunity
BMC	Boston Micromachines Corporation
CAD	Computer Aided Design
DM	Deformable Mirror
DRM	Design Reference Mission
EFC	Electric Field Conjugation
EXCEDE	EXoplanetary Circumstellar Environments & Disk Explorer
FLSIP	Full Liner-Stokes Imaging Polarimetery
FMS	{Fine|Fast} Steering Mirror
HCIT	High Contrast Imaging Testbed
HST	Hubble Space Telescope
HZ	Habitable Zone
IFR	Instrument Functional Requirement
IWA	Inner Working Angle (in λ/D, arcseconds, or milliacrseconds)
IWD	Inner Working Distance (in Astronomical Units)
JPL	Jet Propulsion Laboratory
L3 / L4	(inverse PIAA) Lens 3 or Lens 4
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
NICMOS	Near Infrared Camera and Multi-Object Spectrometer
MS	Milestone
NASA	National Aeronautics and Space Administration
OAP	Off-Axis Paraboloid
OWA	Outer Working Angle (in λ/D, arcseconds, or milliacrseconds)
PI	Principal Investigator
PIAA	Phase Induced Amplitude Apodized
PPN	Polarimetric PSF Nulling
PSF	Point Spread Function
SAT	Strategic Astrophysics Technology
SSS	Starlight Suppression System
TDEM	Technology Demonstration for Exoplanet Missions
TM&D	Technology Maturation and Demonstration
TPF-C	Terrestrial Planet Finder – Coronagraph
TRL	Technology Readiness Level
WF	Wavefront
WFE	Wavefront Error
WP	Whitepaper