Non-Contact Vibration Isolation and Precision Pointing for Large Optical Telescopes

Enabling breakthrough astronomy and astrophysics with ultra-stable optical systems

A White Paper Submitted to the Astro2020 Decadal Survey
Thematic Area: Activity or Project

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July 10, 2019
Key Science Goals and Objectives

Optical coronagraphs enable detection and characterization of exoplanets in the close angular proximity of their parent star by effectively removing the central core of the stellar Point Spread Function, leaving an annular “dark hole,” whose inner and outer angular limits are defined by the telescope and coronagraph instrument performance. A key performance metric of coronagraphs is defined by the contrast ratio that measures the effectiveness of the coronagraph in suppressing the starlight near the planet. For the system architectures being considered by NASA, contrast ratios on the order of $10^{-10}$ are required, and this contrast performance level must be sustained over long time intervals (typically on the order of 10s of minutes) between wavefront error (WFE) sensing and control sample times. Over these intervals, contrast stability is degraded by uncompensated optical WFE due to dynamic vibration of telescope optics arising from disturbances originating on the spacecraft (such as control moment gyroscopes or thrusters).

The performance of large-aperture optical telescopes is always heavily dependent on the degree of dynamic excitation of the telescope structure due to disturbances. Launch vehicles impose limits to system mass for space-based telescopes, and together with deployable structures, drive structural dynamics to lower frequency with lower modal damping. Once excited by vibrational disturbances, the resulting WFE is difficult or impossible to reject by active control (such as fast steering mirrors, or deformable mirrors). A compelling design approach, therefore, is to prevent disturbances from exciting the telescope structure to the maximum extent possible.

The current state-of-the-art in passive vibration isolation does not provide sufficient disturbance isolation to enable coronography, in the presence of significant spacecraft disturbance sources, such as the exported loads from reaction wheels or control moment gyro. Moreover, traditional passive vibration isolation or active vibration cancellation approaches do not scale well to the levels of dynamic stability needed for future large space telescopes, and inevitably lead to complex, brittle, and coupled designs that carry high program cost, technical and schedule risk, and are difficult to test and verify. In a study of the Terrestrial Planet Finder Coronagraph (TPF-C) [1], passive isolation designs were considered for achieving the required total system contrast in the presence of reaction wheel induced vibration. The resulting design, consisting of two passive isolation stages combined with two levels of active vibration cancellation were still insufficient to meet requirements without the addition of engineered modal damping on the Secondary Mirror tower structure.

The above-reference case study illustrates the larger issue that traditional approaches to achieving telescope dynamic stability are not well suited to large optical systems technology roadmaps, such as LUVOIR, as summarized in Table 1. In addition to the already-mentioned limitations of passive isolation stages, active vibration cancellation is
problematic. Even if optical performance were measured only by LOS pointing error, achieving stabilization by means of a FSM alone requires high samples rates from a Fine Guidance Camera, which places requirements on an optical system already operating in a signal-starved environment. For systems whose sensitivity is limited by WFE, a high-bandwidth wavefront sensing and control system, with the associated payload metrology, is needed. This drives system cost and complexity, and increases risk.

The highest possible degree of isolation of a sensitive payload structure from spacecraft disturbances is realized through no physical contact between the two bodies. A parallel study of the same TPF-C architecture with a non-contact pointing and isolation system [2] showed compliance to system-level contrast with margin with a single non-contact isolation stage. An integrated non-contact pointing and vibration isolation system called the Disturbance Free Payload (DFP) has been developed by Lockheed Martin Space over two decades of research and development. This system, applied to the LUVOIR architecture, achieves the ideal non-contact state (with only residual coupling from power and data cables and actuator effects) while allowing for the necessary degree of rigid body payload control to meet required telescope pointing and system line-of-sight (LOS) agility. The Lockheed Martin Space DFP technology is the basis for the non-contact Vibration Isolation and Precision Pointing System (VIPPS), which is baselined for the LUVOIR mission architecture, as illustrated in Fig. 1.

Lockheed Martin Space has tested and demonstrated DFP system pointing, vibration isolation and agility extensively in both three degrees of freedom (using subscale spacecraft and payload emulators suspended with air bearings on a granite table) and five degrees of freedom (with a large-scale mass simulated spacecraft and payload suspended from the laboratory ceiling, as illustrated in Fig. 1). Ultimately, the remaining risk of the DFP architecture can only be retired, and full system TRL advanced, in the gravity-free environment of space, where all 6 rigid-body degrees of freedom are unconstrained. To do this, we propose to fly a subscale demonstration of the DFP technology on a CubeSat, ultimately achieving TRL 6 through this flight test before 2025.

Technical Overview

The VIPPS identified in the LUVOIR architecture is based on the DFP concept (see Fig. 3) for pointing and vibration isolation [3]. DFP was patented [4] by Lockheed Martin Space and matured through years of Internal Research and Development (IRAD) funding to TRL 4. A DFP-configured system is actually two spacecraft flying in close formation. Lockheed Martin Space has demonstrated the DFP technology as a revolutionary concept for isolation of sensitive science payloads from disturbances generated by the supporting spacecraft. DFP allows payload and spacecraft to fly in close proximity without physical

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Table 1: State-of-Art approaches to achieving dynamic stability are poorly suited for the LUVOIR Roadmap.
contact, using custom-designed, large-gap non-contact actuators. This technology enables precision payload pointing and isolation from spacecraft vibration. To control its attitude, the payload pushes against the spacecraft using a set of six non-contact linear-motion, electro-mechanical Lorentz force actuators. Attitude is determined using a Fine Guidance Sensor or other LOS sensor on the payload, and the error signal garnered from six non-contact position sensors is used to drive reaction wheels and thrusters on the supporting spacecraft.

There are several advantages to the DFP control scheme over existing approaches. In addition to allowing for precise pointing control, no additional high-frequency dynamics are introduced because the interface is non-contact. The control architecture does not require high instrument or sensor sample rates and it ensures that isolation performance is not limited by the performance of gyros or position sensors. Notably, the system Integration and Test approach is simplified with decoupled spacecraft and payload precision requirements, and requirements for jitter-producing precision spacecraft components (mechanisms, reaction wheels, solar array drives, or other disturbance sources) become achievable with available hardware.

The LUVOIR 15-meter Primary Mirror architecture [5] presents particular challenges that call for vibration isolation technologies that are beyond the current state-of-the-art. For this system, the line-of-sight (LOS) must be inertially stable to within 0.3 milli-arcseconds (in a root-mean-square, or RMS, sense), and the wavefront error (WFE) must be stable to less than 10 picometers RMS over very long time intervals (on the order of 10 minutes). These requirements must be met for a system that exhibits very low-frequency modes, due to its physical size and system deployment features: the lowest natural frequency of the spacecraft sunshade is 0.1 Hz, and the lowest frequency mode of optical telescope assembly is 0.74 Hz (associated with bending of the secondary mirror tower). Despite these challenges, an integrated model of this system with a non-contact pointing and vibration isolation system developed by LM under NASA funding [6] showed that these requirements could be met, even under conservative assumptions on structural dynamics, spacecraft-payload residual coupling and disturbances arising from both actuator exported loads and sensor noise [7]. Figure 3 shows a plot from this study of
reverse-cumulative RMS WFE between 0.05-200 Hz, broken out by four principal disturbance sources (Control Moment Gyro exported loads in green, Fast Steering Mirror sensor noise and exported loads in red, non-contact interface actuator and sensor noise in cyan, and Fine Guidance Sensor noise in pink). As this plot shows, LUVOIR meets the RMS WFE performance goal of 10 picometers over the 0.05-200 Hz band; the actual predicted RMS WFE performance in Figure 3 is 5.1 picometers. Perhaps most notably, this study showed that the LOS and WFE stability requirements can be met without a Fast Steering Mirror participating in overall LOS control, which provides a significant potential design simplification opportunity. An extensive discussion of the integrated modeling results is described in [7].

Technology Drivers
Lockheed Martin Space has developed a five-pronged approach to mature the DFP technology to TRL 6 by 2024. The approach is described in more detail in subsequent sections. The main risk for vibration isolation systems for large segmented telescopes is the inability to perform system-level tests that follow a Test Like You Fly (TLYF) strategy, because it is almost impossible to recreate the relevant environment on the ground for a full-scale observatory. Subscale ground-based testbeds are limited to 5 Degrees of Freedom (DOF), while a full-scale on-orbit testbed would be cost-prohibitive. Therefore, our technology maturation plan includes a combination of subscale ground-based testbeds, vacuum tests, a 6-DOF flight demonstration and structural dynamics modeling. These efforts will help buy down the risk of individual portions of the DFP system in order to advance the maturity of the system as a whole to TRL 6, using integrated modeling to bridge the gap between subscale and full-scale systems.

The five-pronged approach to maturing DFP is illustrated in Figure 4. Figure 5 details the current stages and planned future work for each parallel step in the technology maturation, differentiating between completed, ongoing, and future work.

**DFP Pillar 1: Upgrade 3D testbed software and processor for flight traceability**—A third-scale demonstration of a segmented telescope with DFP was built in 2001 under Lockheed Martin IRAD. This testbed is composed of separated payload and spacecraft bodies hanging by cables attached to their respective centers of gravity. The isolated segment has an external laser-based metrology system that mimics an inertial attitude reference system. The non-isolated side has reaction wheels and the electronics used to drive the testbed. The testbed currently implements a laboratory version of real time software but does not use flight-like real time processes and tools. The external referencing and pointing system used are also not flight-traceable. An effort to upgrade the electronics and sensors on this subscale demonstration is part of a planned Lockheed Martin Space testbed upgrade. This effort results in a flight-traceable testbed that operates in a manner similar to an on-orbit DFP system and will increase the software and firmware maturity to TRL 5.
DFP Pillar 2: Mature electronics for flight—A parallel effort is planned to mature the TRL of the electronics required for a DFP interface to TRL 5 for the DFP system. Maturation is done through thermal vacuum testing of flight-traceable components, including an integrated subassembly with a real-time processor and flight-like software and/or firmware, non-contact actuators and non-contact position sensors. The electronics architecture is fully traceable in design to the full flight DFP interface, although environmental testing may only exercise a subset of the available drive channels.

DFP Pillar 3: Flight-traceable interface cable stiffness testing—Characterization of the stiffness of flight-like cable harnesses was completed in 2018 under IRAD. This work involved the development of a testbed that actuates one side of the cable harness at a known frequency and amplitude and measures loads on the other end. The testbed allows for actuation and measurement in all six degrees of freedom. A set of tests was conducted on different lengths, geometries and configurations of the cable harness in order to derive trends that can be used to model this interface. Linearity and repeatability of the measurements were also studied. Data from these tests was used to compute transmissibility and stiffness as a function of frequency. The cable stiffness testbed is used to inform and validate the flight harness design for the CubeSat demonstration in DFP Pillar 4.

Fig. 4: The five focus areas for DFP technology maturation
DFP Pillar 4: 6-DOF CubeSat subscale flight demonstration—A subscale flight demonstration of the DFP system helps retire the technology acceptance risk associated with DFP through a 6-DOF validation in the space environment of the critical control architecture underlying DFP. Additionally, this demonstration addresses safety and robustness concerns by showing proper recovery from out-of-range actuation events. On the ground, transmissibility of rotational and translational disturbances between the imaging platform and spacecraft structure are limited to 5-DOF with the 3D testbed described in DFP Pillar 1. The ground-based testbed also relies on attitude sensors that are not flight-traceable and on ground support equipment for data acquisition, sensor fusion, and processing. A self-contained flight demonstration can be accomplished with a relatively low-cost CubeSat mission to gather transmissibility measurements on orbit in 6-DOF with integrated real-time sensing, actuation, and processing. While flexible body dynamics of a full-scale observatory are addressed through the integrated modeling efforts in DFP Pillar 2, a CubeSat demonstration also validates the rigid-body portion of the integrated control-structure-dynamics modeling and matures some components of the DFP interface design to flight maturity.

Lockheed Martin Space has extensive experience designing, building and delivering CubeSat payloads for science missions as well as technology demonstrations. In previous efforts, we partnered with CubeSat bus vendors to develop high quality payloads and to
streamline testing and integration of these satellites. With the goal of maturing DFP technology, we performed a preliminary CubeSat payload concept design for a 6-DOF DFP demonstration. This design effort began in early 2019 and will continue to be refined on Lockheed Martin Space IRAD funds through August 2019. Future development of the DFP CubeSat requires outside funding. Technology maturation programs such as ROSES could enable this effort if supported at sufficient funding levels.

**DFP Pillar 5: Anchored control-structure-dynamics integrated modeling**—Under SLSTD Phase I and IRAD funding, we developed a comprehensive and end-to-end integrated model for segmented optical telescopes that includes a detailed model of the DFP non-contact vibration isolation system, realistic disturbance models, and linear optical models. The integrated modeling effort, graphically depicted in Figure 6, focuses on development and maturation of a rigorous end-to-end integrated model that allows for accurate prediction of dynamic LOS and WFE stability performance of large space telescopes. Such an integrated model is crucial as verification via ground-based test of system-level dynamic optical stability requirements of large space telescopes is extremely challenging and not realistic once these observatories are integrated. Additionally, subsystem-level error budgets are computed to high fidelity as part of this integrated modeling effort without a need for flight-scale subsystem build and testing, allowing for risk mitigation and cost reduction.

**Organization, Partnerships and Current Status**

All technology development efforts for non-contact vibration isolation and DFP are led by the Lockheed Martin Space Advanced Technology Center (ATC) [5]. As the Research and Development laboratory for Lockheed Martin Space, the ATC has a strategic focus area in Space Science and Instrumentation, and technologies to enable missions of relevance to Astro2020, such as large astrophysics missions, fall within this focus area. The ATC regularly collaborates internally across Lockheed Martin Space to support TRL advancement in technologies of mutual applicability to both NASA as well as our commercial and national customers. In addition to our internal collaborations across Lockheed Martin, the ATC regularly engages with external partners and suppliers to achieve its technology maturation objectives. The following
paragraphs briefly summarize the current collaborative relationships and status across the five pillars of DFP TRL advancement that were summarized in Figure 4.

**DFP CubeSat Subscale Flight Demonstration** — A payload conceptual design, as well as preliminary sizing and packaging analysis, was initiated in early 2019 under internal R&D funding. This initial seedling funding has allowed ATC staff to develop a payload experiment design sufficient to develop mature cost estimates and project schedules in support of a proposal to the recent NASA D.13 Amendment to the 2019 Research Opportunities in Earth and Space Science (ROSES) [6]. If the ATC is awarded funding under the ROSES D.13 Amendment, the DFP CubeSat payload design will be matured to a Critical Design Review (CDR) level of maturity, Engineering Development Unit (EDU) and flight hardware procurements will take place, and risk reduction tests will be executed. However, this level of ROSES D.13 funding will be insufficient to complete the flight demonstration in this phase.

**Non-Contact Interface Full-Scale Flight Electronics Design** — Under internal LM 2019 R&D funding, work has begun on defining electronics box performance and environmental requirements, command and data interfaces and concept of operation. The goal of the 2019 R&D efforts is to mature the design to an overall board layout level, sufficient to identify flight parts and specify overall electronic enclosure mass, power and volume. Additional funding beyond these narrow 2019 design objectives is needed to meet the electronics TRL-5 objective shown in Figure 4.

**Cable Interface Stiffness Testbed** — Under internal LM 2018 R&D funding, a testbed was developed (a photo is shown in Figure 4) and test results obtained for a variety of cable geometries and configurations. The testbed is a testing resource that is available to support future DFP technology maturation activities, should funding be secured.

**Cable Interface Stiffness Testbed** — The 3D testbed illustrated in Figure 4 is currently fully developed in ATC’s Palo Alto laboratories. Upgrades to support flight-traceable real-time flight software and processors have not yet been initiated, pending funding availability.

**Control-Dynamics-Optics-Structure Integrated Modeling** — Under internal LM 2018 R&D funding, a generic toolset for integrated controls, optics and structural dynamics were developed and customized for studying the performance of non-contact isolation systems in large space telescopes. These integrated modeling tools were employed in the study of the LUVOIR 15-meter architecture during SLSTD Phase I funding. These tools are available to support future integrated modeling activities in support of DFP technology maturation.

**Schedule**

A top-level schedule of the technology maturation activities for DFP is illustrated graphically in Figure 5. As the legend indicates, while a solid foundation has already been established, much of the work is planned in the future, with its execution dependent on the availability of funding. The maturation activities that have already completed have been accomplished through a combination of LM internal R&D investment, as well as NASA funding through the ROSES SLSTD funding mechanism. It is anticipated that, with elevated funding beyond those sources anticipated through
internal R&D funds and ROSES SLSTD investment, the TRL-6 milestone could be completed in about 3 years.

**Cost Estimates**

As this white paper describes, the overall technology maturation for DFP to TRL-6 involves a combination of ground- and space-based testing, as well as integrated modeling. The portion of costs that are within the scope of the SLSTD Phase II proposal have been developed and submitted to NASA; however, a total integrated cost estimate for the overall effort is still in development. However, it is estimated that the total effort will be less than the $20M limit associated with Small Ground-based projects as defined in the Astro2020 white paper call.

**Conclusions**

Early investment in enabling technologies is essential to build a solid technical foundation for NASA’s future flagship mission [10]. Systems that deliver extreme dynamic stability to precision optical payloads consisting of large optics are a key to achieving NASA’s vision to “explore the nature of the universe at its largest scales, its earliest moments, and its most extreme conditions”. Indeed, dynamic stability is an over-arching technology need for The Large UV Optical Infrared (LUVOIR) Telescope family, since all other technology advances (in lightweight optics, efficient coating and filters, and sensitive detectors) cannot achieve their promise without a dynamically-stable optical system. Traditional passive vibration isolation or active vibration cancellation approaches do not scale well to the levels of dynamic stability needed for future large space telescopes, and inevitably lead to complex, brittle, and coupled designs that carry high program cost, technical and schedule risk, and are difficult to test and verify. Therefore, a fundamentally new approach to achieving dynamic stability is needed, that opens up new levels of performance in dynamic stability of large optical system.

Lockheed Martin Space has developed a non-contact vibration isolation technology called Disturbance Free Payload (DFP) over 20 years specifically to address this dynamic stability challenge for large optical systems, and we have successfully completed a NASA Phase 1 Study to apply this technology to the LUVOIR 15-meter reference design, for which the technology is baselined. In this study, we showed that DFP can be effectively utilized on the LUVOIR-A 15m design to enable stability of WFE and LOS over long time durations (10s of minutes), making high contrast coronography possible. In this paper, we have described a comprehensive path to achieve TRL 6 for DFP within 5 years for less than $20M total investment. With this investment, we will execute a flight CubeSat demonstration of the technology, allowing for testing in a full Test-Like-You-Fly environment, with no constraints associated with gravity offload. Maturing non-contact vibration isolation technology is a key enabler to future flagship astronomy missions like LUVOIR, and provide a new architecture paradigm to enable the ever-expanding physical scales in large space-based telescopes.
References


