Ultra-Stable Telescope Research and Analysis (ULTRA)

Thematic Areas: Large, Stable Optical System Architectures, Technology Development

Relevant Missions: LUVOIR, HabEx

Laura Coyle, Ball Aerospace, lecoyle@ball.com, 303-939-4291

Scott Knight, Allison Barto, Cody Allard, Sarah Lipscy (Ball Aerospace)

Matthew East, Conrad Wells, Keith Havey, Chris Sullivan, Lynn Allen (L3 Harris Technologies)

Jonathan Arenberg (Northrop Grumman Corporation Aerospace Systems)

Todd Lawton, Kevin Patton, Bob Hellekson, Austin Van Otten (Northrop Grumman Corporation Innovation Systems)

Marcel Bluth, Matthew Nielsen (SGT, a KBR Wyle Business Unit, now at Intuitive Machines)

Laurent Pueyo, Remi Soummer (Space Telescope Science Institute)

Abstract:

To meet the ambitious science goal of characterizing exo-Earths via direct imaging and spectroscopy, future space-based astronomical telescopes will have requirements for optical stability at least several orders of magnitude beyond the current state of the art. Mission concepts requiring stability on the order of picometers include LUVOIR and HabEx, which use large primary mirrors and internal coronagraphs to perform high contrast imaging. The Ultra-Stable Large Telescope Research and Analysis Program (ULTRA) is a system study performed by an industry consortium led by Ball Aerospace to evaluate potential architectures, perform trade studies, and identify technology gaps that must be addressed to enable picometer-level optical stability in space. This white paper will describe the high-level results of the study, including the identification and prioritization of technology gaps and a corresponding development roadmap to raise the TRL of key enabling/enhancing technologies.

Key Science Goals and Objectives:

One of the highest priorities in NASA's "Enduring Quests, Daring Visions" 30 Year Roadmap and a recurring theme in the science white papers submitted to the Astro2020 Decadal Survey (Sembach and Hammel 2019; Plavchan 2019) is the study of extra-solar, Earth-like planets to answer the question: "Are we alone?" To support this ambitious science goal, the ULTRA study performed a system-level engineering assessment to evaluate current methods for achieving stable telescopes and to identify areas where further technology development is required.

Two of the large mission concepts currently in development for the 2020 Astronomy and Astrophysics Decadal Survey – the Large UV/Optical/Infrared (LUVOIR) Surveyor and the Habitable Exoplanet (HabEx) Observatory – aim to perform direct imaging and spectroscopy of exo-Earth candidates with high-contrast coronagraphs (Bolcar et al. 2017; Bolcar et al., 2018; Stahl 2017; Stahl, 2018). Meeting this ambitious science goal will require architectures with large-area primary mirrors (PMs) to achieve the high resolution and greater photon flux needed to detect faint objects, as well as instrumentation to suppress light from a host star ~10 billion times brighter than the Earth-like exoplanet of interest (Stark et al. 2015; Stark et al. 2019; Bolcar et al. 2016; Morgan et al. 2018). Achieving contrast of 10^{-10} at visible wavelengths using a coronagraph ushers in a new regime of "ultra-stable optical systems" where the corresponding wavefront stability is expressed in units of picometers (pm) rather than nanometers (nm) for certain modes (Lyon & Clampin 2012; Nemati et al. 2017; Nemati et al. 2018). <u>Some additional, active wavefront sensing and control (WFSC) and thermal sensing and control capability will be required beyond traditional passive approaches (Acton et al. 2012; Krist 2004) to achieve picometer-level stability</u>. These types of active controls will be needed for both monolithic and segmented primary mirrors, though the segmented architecture will be more complex due to the larger number of degrees of freedom that must be controlled.

To support these mission concepts and enable ground-breaking science, an industry coalition led by Ball Aerospace (including Harris Corp., Northrop Grumman Corp. Aerospace Systems, Northrop Grumman Corp. Innovation Systems, SGT and the Space Telescope Science Institute) has been working together to address technology development needs. A contract was awarded to this industry team through the NASA ROSES-17 solicitation, element D.15 – which called for a one-year system-level engineering design and modeling study for a >10-m class UV/optical/IR segmented-aperture telescope with sub-nanometer wavefront stability. The ULTRA study was completed in July of 2019 and includes a final report (Coyle et al. 2019) that documents the results.

Technical Overview & Technology Drivers:

The team completed a holistic systems study guided via the formalism of error budgets, where sub-system allocations were compared to current capabilities to identify technology gaps across the telescope architecture. These gaps were prioritized by urgency/impact and laid out in a proposed development roadmap culminating in a TRL6 ultra-stable payload demonstration.

The approach was a systems architecture study treating the observatory, telescope, and coronagraph as a complete system and considering the impacts of instability in both the temporal and spatial domains. It was guided via the formalism of error budgets, where top level contrast/wavefront requirements in various spatial/temporal domains were set by the modeled coronagraph performance (Coyle et al. 2019; Pueyo et al. APC White Paper) and flowed down to various sub-systems. Then the sub-system allocations were compared to current capabilities, often including trade studies of potential technologies or approaches. Technology gaps were identified where current capabilities would not meet allocations. The resulting technology gap list and gap classification are shown in **Figure 1** and **Table 1**, respectively.

Area	Active Sensing & Control				Low Disturbance			Structures			Mirrors and Mirror Mounting					
Technology	Segment Dynamic Sensing & Control	Laser Metrology	System Control Methodology	Thermal Sensing & Control	LOS Stability	Payload Isolation	Low Disturbance Mechanisms	Stable Composite Structures	Microdynamics	Stable Joining (Hinges/Latches)	Stable Mirrors	Mirror Mounting	PMSA Figure Actuation (if needed)	Coronagraph Design (LOWFS/HOWFS)	Infrastructure/ External Metrology	Path Forward for TRL Advancement
Current TRL	3	5	2	4	3	5	2	5	2	4	5	4	3	4/5	-	
Knowledge Gap	X		X	X	X		X		X	X		X	(X)			Analysis/ Measurements
Low-TRL Gap	X		X		X								(X)			Component-Level Demo
Mid-TRL Gap				X						X		X				Analysis/ Subsystem Demo
Engineering Gap		X				X		X			X				X	Analysis
System-Level Gap	X				X			X			X					System/ Subsystem Demos
Showstopper																Unknown

***Figure 1**: ULTRA Study Technology Gap List. Includes current TRL, gap classification (see Table 1 for definitions), and suggested path forward for TRL advancement. Technology gaps were identified using the LUVOIR Architecture A as the baseline design. Low TRL gaps are the highest priority for development.*

***Table 1**: Classification of technology gaps. The type of gap determines the maturation path, with Knowledge, Low-TRL and Mid-TRL types carrying the most risk.*

Knowledge Gap	Do not have measurements or knowledge of performance at the picometer level, but do not know of anything yet that will cause an issue. May transition to Low- or Mid-TRL gap as knowledge is gained.
Low-TRL Gap	Technologies are identified but need development to show they are feasible.
Mid-TRL Gap	Current technologies appear feasible but need to be proved in flight-like ways through brassboards.
Engineering / Manufacturing Gap	A solution is available, but it takes engineering and process work to make sure it can be built to cost and schedule.
System-Level Gap	Components or subsystems have been proven but need to be integrated into a larger system to characterize interactions.
Architectural Show Stopper	No known technologies can provide a solution.

Given these technology gaps, a development roadmap was created to prioritize and propose a path forward for development of the most urgent technologies, as shown in **Figure 2**. The general approach for maturing key technologies is to demonstrate them at the component level, then combine them in sub-system testbeds to gain an understanding of the interactions early in the development process, then continue to build up higher fidelity testbeds.

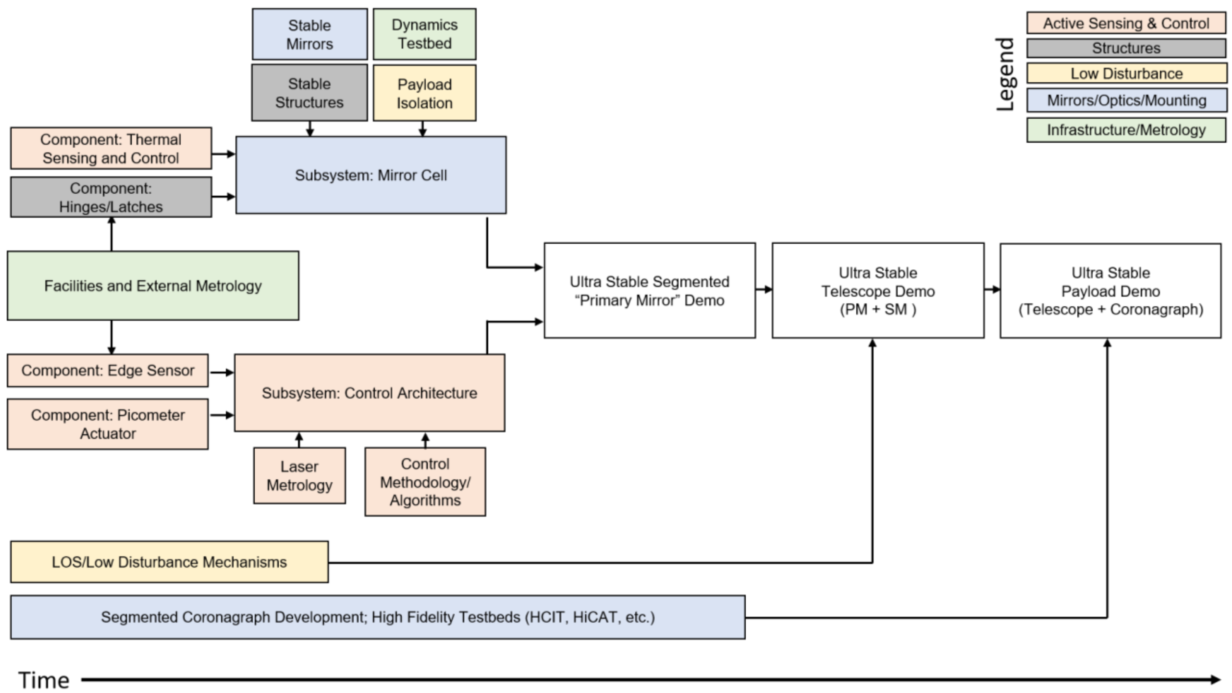

***Figure 2**: Roadmap for component and subscale, subsystem demonstrations for ultra-stable optical systems with segmented primary mirrors. This roadmap leverages work being done at NASA centers, universities and industry through a variety of programs (NASA ROSES, internal research and development, etc.).*

There is a need to balance the most promising technologies with the existing cost and schedule resources. The full development path in **Figure 2** will take a significant amount of time and funding, so the ULTRA study team has identified several areas for near-term investment to understand and substantiate the technical and fiscal feasibility of LUVOIR/HabEx:

- The ULTRA results corroborate previous analysis that mid spatial frequencies (especially segment-level piston-tip-tilt) will be most damaging to contrast stability in the coronagraph. Thus, low-TRL active sensing and control technologies at the segment level should be given highest priority as it is enabling for LUVOIR.

- Active thermal sensing and control at the milli-Kelvin level will be necessary to limit structural/optical perturbations for both monoliths and segmented telescopes, which only have only segment piston, tip, tilt correction as a baseline. This level of control over a large, complex structure has not been demonstrated and is enabling for LUVOIR and HabEx.
- An assessment of the structural stability due to microdynamics and other non-linear impulses as well as the line-of-sight stability using payload isolation should also be investigated as soon as possible. If the results reveal state of the art techniques are not sufficient, other solutions are currently low-TRL.

<u>These priorities will tackle the most difficult parts of the stability problem with the longest lead times first and provide a solid foundation for additional demonstrations and testbeds.</u>

Error budgeting is a key component of the ULTRA study as it is used to identify technology gaps. Power Spectral Density (PSD) based error budgets can provide relief in certain allocations by considering the spatial distribution of energy in the coronagraph focal plane, rather than just calculating the total wavefront error.

While the traditional branching error tree budget approach works well for many optical systems (Lightsey et al. 2018), just breaking the spatial content into bins that root-sum-square (RSS) together may still prove overly conservative for a coronagraph. Ball explored a PSD-based approach during the ULTRA study, where the PSD of a surface can be used to predict how energy will be distributed in the coronagraph dark hole (Lyon et al. 2012). In this approach, coronagraph simulations calculate the maximum energy density in any part of the coronagraph dark hole that decreases contrast to 10^{-10}, which sets an upper limit for the region (the limit varies in the different temporal regimes based on the coronagraph sensitivity). Additional error terms can be budgeted using "PSD sensitivities" and ensuring the combined PSD does not exceed that limit. **Figure 3** demonstrates this concept for three important terms in for LUVOIR Architecture A – primary mirror segment-level random piston, random tilt, and bulk temperature change.

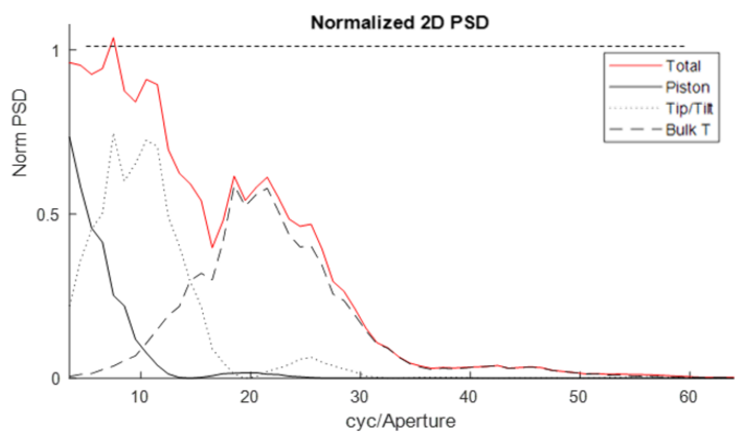

Figure 3*: Example of a PSD-based stability budget for simulated LUVOIR primary mirror segment random piston, random tilt and bulk temperature change (trefoil at the segment level) from the ULTRA study. While there is overlap in the sensitivity PSDs, the peaks are shifted slightly, which means there is some relief in budgeting those terms.*

Each PSD can be scaled such that the sum is below the normalization limit (allowable wavefront error ~ SQRT(PSD ratio)). The important result is that errors that distribute energy into different parts of the dark hole do not need to share allocations. If the PSDs do not spatially overlap, each perturbation can consume the full allocation. For the example shown in **Figure 3**, each term gets ~80% of the allocation due to the shifted peaks, whereas in a RSS WFE approach, each term would get 58% of the allocation (1/SQRT(3)). In addition, terms that create high spatial frequency errors, like trefoil from mounting effects, will not have significant overlap with piston/tip/tilt and can consume much of the allocation. Based on these results, parts of the system architecture (such as mirror mounting) may be adjusted to put energy into regions of the dark hole that do not have other sources, providing additional relief on the allowable perturbations for those terms or performance of the active control systems. Our team recommends this approach be carried forward to avoid over specifying systems/components that are already pushing beyond current state-of-the-art.

Picometer-level active sensing and control at the segment level is an enabling technology for LUVOIR. To support the development of picometer-capable edge sensors and actuators for the mirror segments, Ball and others have been investing in metrology and motion solutions to prove sensing and control in this regime is possible (Lou et al. 2018, Kaplan et al. 2018).

Ball has acquired a commercial system that is capable of measuring displacements over a large range of working distances (millimeters to meters) to 10s of picometers in select bandwidths. To characterize the sensing noise independent of environmental conditions, a fixed mirror was measured with two sensor heads and the differential signal was analyzed. The PSDs of the single and differential measurement are shown in **Figure 4**. The differential signal removes the environmental (common) motions, which results in an integrated noise of 31 pm RMS from 1-10 Hz (~ 22 pm RMS in a single channel assuming random statistics). While measurements will likely be limited by thermal drift at low frequencies, the distance being measured (e.g. displacement of an actuator) could be actuated at a specific frequency above expected thermal disturbances and detected over a small bandwidth for reduced noise (similar to a lock-in amplifier). In the cumulative noise plot shown in **Figure 4**, the integrated noise from 9.95-10 Hz is only 1.4 pm RMS (~ 1 pm RMS in a single channel).

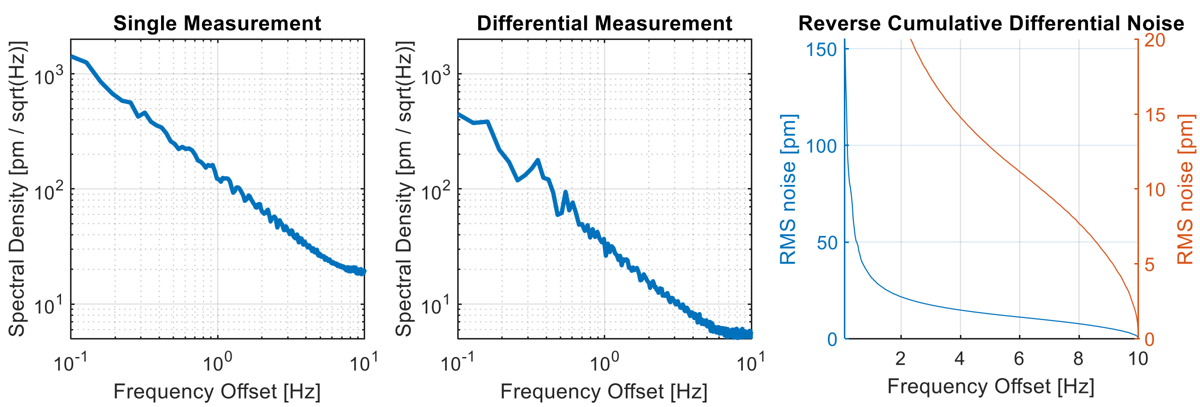

Figure 4*: Left: Measured PSD of stationary mirror with single sensor. Center: PSD of differential measurement, which shows reduced noise from bulk removal of environmental effects. Right: The reverse integrated noise for a single channel demonstrates a measurement bandwidth of 0.05 Hz around a frequency of 10 Hz results in picometer-level RMS noise and a bandwidth of 1.7 Hz produces 5 pm RMS noise.*

While this system may not provide the ultimate performance verification for various technologies, which will likely take place in thermally controlled vacuum chambers over wider bandwidths, it can serve as an independent metrology tool and provide measurements of fundamental sensitivities in ambient lab environments. These measurements are within an order of magnitude or better of the desired performance and allow for cost- and time- efficient technology development.

Ball has also demonstrated a closed-loop system that uses picometer-capable capacitive sensors and piezoelectric (PZT) actuators (Coyle, Knight, & Adkins 2018) to stabilize an etalon gap, which can be adapted for segment edge sensing. Custom electronics enable very low noise operation and recent experiments demonstrate capacitive sensing approaching the picometer-level an ambient lab environment (the system does have thermal control, but it was not enabled). The measured noise in each of the system's three capacitive sensors (Ch 0, 1 and 2 respectively) for open loop operation was <11 pm RMS in a 0-60 Hz bandwidth, as shown in **Figure 5**. Closed loop operation (**Figure 6**) is achieved by compensating measured changes in the capacitive sensors, and thus the etalon gap, with PZT motion, which reduces the noise at low frequencies as expected. The measured noise in Channels 0 and 1 decreases to < 5.5 pm RMS, though the noise in Channel 2 is similar to the open loop noise level at 9.8 pm RMS. The offset between channels is suspected to be from the PZT drive electronics, which will be investigated in future work. <u>The closed loop noise/motion residual in the etalon piston, or the average of the three channels, is 4.3 pm RMS.</u>

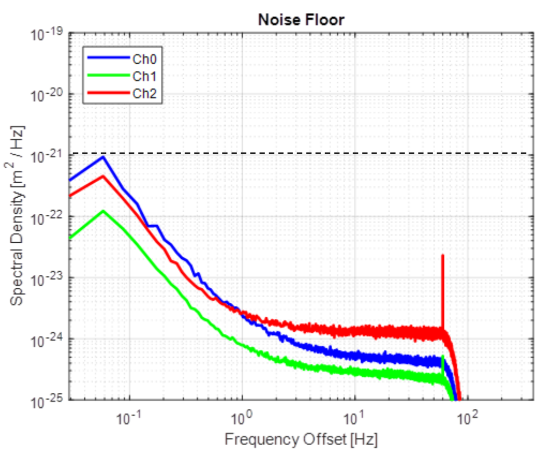

***Figure 5**: The open loop measured PSD of the three capacitive sensors results in an integrated error of <11 pm RMS over a 0 to 60 Hz bandwidth.*

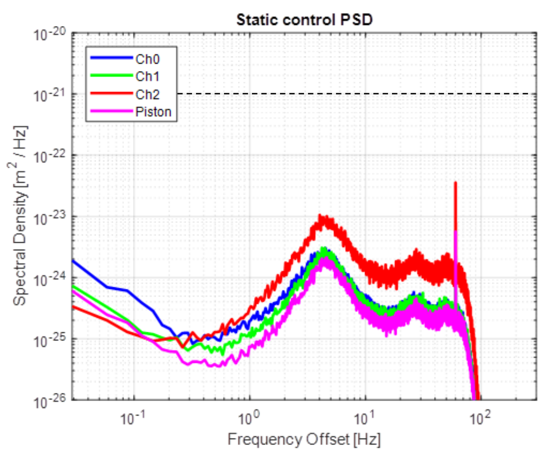

***Figure 6**: The closed loop measured PSD of the three capacitive sensors results in an integrated error of <10 pm RMS over a 0 to 60 Hz bandwidth. Channels 0, Channel 1 and the average (piston) have errors of <5.5 pm RMS.*

Much of the optical, electrical, and mechanical engineering work is directly applicable to edge sensing for segmented telescopes. The measured performance can inform the design of a scaled-up sensor head with a larger gap suitable for the LUVOIR geometry. In addition, engineers at Ball have identified several specific changes to the electronics to decrease noise and optimize performance for the required operating bandwidth, if different from the above.

Organization, Partnerships, and Current Status:

Our ULTRA industry team is collaborative and interdisciplinary, with experienced engineers in the components and systems that comprise ultra-stable space-based observatories. The team regularly engages with the astronomical community to ensure traceability of technology development efforts to the overall science goals to produce credible system architectures.

The ULTRA team is comprised of industry-leading members with experience and skills in architecting, developing, and delivering technically demanding space-based observatories, often for NASA astrophysics. Ball Aerospace leads the team and relies on the partners to bring their internally and externally developed technologies and knowledge to the study. Our team has worked together to play large roles in technology development for the Chandra Observatory, the James Webb Space Telescope (JWST), and other non-NASA missions (Arenberg et al. 2014; Michaels & Speed 2004; Mooney et al. 2015, Matthews et al. 2015; Atkinson, Gilman, & Reynolds 2003; Dean et al. 2006; Acton et al. 2004; Feinberg et al. 2007; Bronowicki 2006; Saif, Bluth, & Feinberg 2015; Warden 2016; Stahl, Feinberg, & Texter 2004; Arenberg et al. 2006; Eisenhower et al. 2015). For the ULTRA study, each partner's primary contribution is analysis in their demonstrated areas of expertise – Ball in systems engineering and wavefront sensing and control, Harris in stable mirrors and mirror mounting, Northrop Grumman and SGT in stable composite structures, and the Space Telescope Science Institute in coronagraph modeling – though the team works collaboratively through regular technical meetings and provides feedbacks in all areas to the other partners. This industry collaboration is intended to leverage expertise across multiple companies and provide maximum benefit to NASA.

The team has been engaged with the Large Mission Concept Science and Technology Definition Teams (STDTs) and NASA engineering teams over the last few years to understand the specific science goals and engineering needs of LUVOIR/HabEx. Select team members have also performed initial architecture assessments for the STDTs.[1,2] Additionally, our individual organizations have performed internal research and development (IRAD) work that is germane to ultra-stability and can be leveraged in future technology development efforts (Coyle, Knight, & Adkins 2018; Barnes et al. 2017; Wachs et al. 2016).

The ULTRA study for the ROSES D.15 element completed in July of 2019 and the team has submitted a proposal to the follow-on D.13 element. Awards for this solicitation are expected to be announced in August 2019 with a two-year period of performance. <u>The focus of this team's proposed work is to advance the TRL for the most pressing Low/Mid-TRL gaps identified in the ULTRA study through component-level hardware demonstrations and to retire knowledge gaps through improved modeling and metrology</u>. The proposed effort maps directly to the left side of the roadmap (near-term) pictured in **Figure 2**.

Though a significant technology development effort remains to demonstrate a sub-scale version of LUVOIR/HabEx to TRL6, the ULTRA study has determined that a credible path forward exists to achieve the contrast stability required for direct imaging of Earth-like exoplanets with a large, space-based observatory.

[1] Cooperative Agreement Notice (CAN) FY2017 NNG16401001C 2020 Astrophysics Decadal Large Mission Concept Large Ultraviolet Optical Infrared (LUVOIR) Systems Studies at NASA Goddard Space Flight Center

[2] Work performed as a sub-tier contractor under JPL Contract 1531172.

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