Ultra-Stable Wavefront Sensing and Control for Space-Based Exoplanet Coronagraph Imaging

by

Rachel Turner

A Master's Report Submitted to the Faculty of the

WYANT COLLEGE OF OPTICAL SCIENCES

In Partial Fulfillment of the Requirements

For the Degree of

MASTER OF SCIENCE

In the Graduate College

THE UNIVERSITY OF ARIZONA

2024

Table of Conter

List of Figures
Abstract
Chapter 1: Introduction
Chapter 2: Key Concepts
2.1. Coronagraph
2.2. Segmented-Aperture Telescope
2.3. Wavefront Sensing and Control10
Chapter 3: Coronagraph Design for Segmented-Aperture Telescopes 12
3.1. Coronagraph Design12
3.2. Electric Field Conjugation Algorithm
3.3. Auxiliary Field Optimization Algorithm13
3.4. Application to Segmented Telescope Aperture Designs
Chapter 4: Important Subsystems in Ultra-Stable Architecture 19
4.1. Active Stabilization 19 4.1.1. Segment Sensing and Control 19 4.1.2. Thermal Sensing and Control 21
4.2. Passive Stabilization234.2.1. Stable Structures234.2.2. Low Disturbance Architecture244.2.3. Stable Mirror Mounting26
Chapter 5: Case Studies in Stable Spacecraft
5.1. James Webb Space Telescope
5.2. Hubble Space Telescope 31 5.2.1. Stability Challenges 31 5.2.2. PSF Subtraction Success 33
5.3. Nancy Grace Roman Space Telescope34
Chapter 6: Challenges and Solutions in Ultra-Stable Wavefront Sensing and Control
Conclusion
References

List of Figures

Figure 1. Exoplanet in different bands of infrared light as seen from the James Webb Space Telescope⁴.

Figure 2. Basic design and principles of a Lyot coronagraph⁵.

Figure 3. Illustration of the James Webb Space Telescope primary mirror⁶.

Figure 4. Demonstration of the basic function of a deformable mirror⁸.

Figure 5. Demonstration of a basic open loop control system⁸.

Figure 6. Demonstration of a basic closed loop control system⁸.

Figure 7. Lyot coronagraph design¹⁰.

Figure 8. Vortex coronagraph design⁹.

Figure 9. Results for the SPLC for LUVOIR A with DM-assisted apodization.

(a)-(c) show the 1-D radial solution. (d) shows the LUVOIR A pupil. (e)-(f) show the two DM surfaces that are used for apodization. (g) shows the reshaped pupil before apodization. (h) shows the pupil before the Lyot stop. (i) shows the stellar irradiance at the final image plane¹⁰.

Figure 10. Results for the vortex coronagraph for LUVOIR A with DM-assisted apodization. (a)-(c) show the 1-D radial solution. (d) shows the LUVOIR A pupil. (e)-(f) show the two DM surfaces that are used for apodization. (g) shows the reshaped pupil before apodization. (h) shows the pupil before the Lyot stop. (i) shows the stellar irradiance at the final image plane¹⁰.

Figure 11. Example apertures used in the SCDA study⁹.

Figure 12. "Ideal DM" solutions for the LUVOIR "A" architecture, achieving 10⁻¹⁰ suppression⁹.

Figure 13. Model of the active control geometry of a segmented mirror¹³.

Figure 14. GMT and TMT edge sensor designs^{14,15}.

Figure 15. Direct heating control cycle¹⁶.

Figure 16. Proportional control cycle¹⁶.

Figure 17. James Webb Space Telescope backplane demonstrates stable support structure capabilities¹⁸.

Figure 18. Dynamic model of wheel isolation¹⁹.

Table 1. Precession frequency and decay time for a rotor speed of 6000 rpm¹⁹.

Figure 19. Schematic of LUVOIR primary segmented mirror assembly baseline design¹.

Figure 20. Illustration of the struts used in the James Webb Space Telescope²⁰.

Figure 21. High precision hexapod used in the James Webb Space Telescope²².

Figure 22. Schematic of the overall OTE commissioning process²³.

Figure 23. Schematic of Hubble's instruments including control and support systems²⁵.

Figure 24. Hubble Space Telescope direct image of the GG Tauri circumbinary disk before (left) and after (right) PSF subtraction²⁴.

Figure 25. Nancy Grace Roman Space Telescope²⁷.

Figure 26. Schematic optical layout of the Roman Coronagraph²⁶.

Figure 27. Roman Coronagraph flight deformable mirrors. DM1 with thermal cover on (left) and DM2 with thermal cover off (right)²⁶.

Figure 28. LUVOIR Telescope's major features²⁹.

Abstract

Advancements in high-contrast imaging coronagraphs for large segmented-aperture space telescopes are necessary for the science goal of directly imaging faint exoplanets orbiting bright stars. Achieving a high enough contrast for imaging and spectroscopy of dim celestial bodies necessitates ultra-stable optical systems with picometer-level wavefront stability, challenging current technological limits. Wavefront sensing and control systems, which incorporate both active and passive stabilization, play a critical role in maintaining the wavefront stability needed to achieve high contrast levels. Through the analysis of current technological capabilities and case studies of notable telescopes, we explore the successes, challenges, and future directions in achieving ultra-stable wavefront sensing and control for space-based exoplanet coronagraph imaging.

Chapter 1: Introduction

At the forefront of astronomical research is the advancement of high-contrast imaging coronagraphs for large segmented-aperture space telescopes. The detection of faint extra-solar planets using high-contrast coronagraphs is a current mission concept of interest in the optical engineering industry¹. In order to achieve a high enough contrast to perform imaging and spectroscopy of very dim celestial bodies, ultra-stable optical systems require wavefront stability on the order of picometers². The development of new technology and methods is necessary to achieve stability levels beyond the current state-of-the-art.

Segmented telescopes with internal coronagraphs offer many advantages in the detection of faint objects in space. Coronagraphs aim to block the light of a bright star so that fainter objects close to the star can be observed. In order to directly image Earth-like exoplanets orbiting Sun-like stars, a coronagraph that enables a 10⁻¹⁰ contrast sensitivity is needed³. To achieve this high level of contrast, a large telescope aperture must be implemented. The use of segmented mirrors in a telescope allows for the fulfillment of large aperture requirements while also achieving diffraction-limited imaging.

Wavefront sensing and control are a critical system requirements of these telescopes, needed to mitigate degradation in performance caused by wavefront aberrations. Large segmented space telescopes require a high level of wavefront stability to achieve 10⁻¹⁰ contrast. Establishing wavefront stability on the order of picometers requires the implementation of ultra-stable wavefront sensing and control techniques.

Ultra-stable optical systems implement both active and passive stabilization to maximize wavefront stability. Active wavefront sensing and control is critical for the correction of wavefront aberrations. Key technology areas in the active stabilization of segmented telescopes include segment sensing and control and thermal sensing and control. Passive stabilization is essential for minimizing input wavefront disturbances. Stable structures, low disturbance architecture, and stable mirror mounting are important subsystems in the passive stabilization of a telescope.

This report explores the crucial role of ultra-stable wavefront sensing and control techniques, along with the optimization of coronagraph designs, in achieving the high contrast sensitivity necessary for future space telescopes. It explores various challenges and achievements in this field, drawing examples from renowned telescopes like the James Webb Space Telescope, the Hubble Space Telescope, and the forthcoming Nancy Grace Roman Space Telescope.

The development and optimization of wavefront sensing and control systems, alongside the advancement of high-contrast imaging coronagraphs, promise not only to expand our understanding of the universe but also to pave the way for groundbreaking discoveries in exoplanet exploration and beyond.



Figure 1. Exoplanet in different bands of infrared light as seen from the James Webb Space Telescope⁴.

Chapter 2: Key Concepts

2.1. Coronagraph

Coronagraphs are specialized instruments designed to block light from a bright solar object like a star so that nearby dim objects can be seen. The Lyot coronagraph, named after the French astronomer and inventor of the coronagraph, operates as follows. An evenly-illuminated light source enters the telescope aperture, and the center of the source is blocked by a secondary mirror. A lens then images the light and an occulting spot is placed at its focus. The pupil is reimaged by another lens and, with most of the light from the center of the field of view blocked by the occulting spot, the remaining light is concentrated around the edges of the pupil. The Lyot stop blocks out the remaining rings of light from the central source and allows the light from the surrounding sources to pass through to the lens that creates the final image.



Figure 2. Basic design and principles of a Lyot coronagraph⁵.

The design of a Lyot coronagraph demonstrates the basic operating principle of a coronagraph: to block the light from a star while allowing light from dimmer surrounding sources to pass through undisturbed.

2.2. Segmented-Aperture Telescope

In order to achieve a high spatial resolution and contrast in the detection of very faint objects in space, a large telescope aperture must be implemented. The use of segmented primary mirrors in place of monoliths is one solution to fulfill these large aperture requirements while also achieving diffraction-limited imaging. The James Webb Space Telescope employs a segmented mirror as the primary mirror and demonstrates the success of this solution in the application of a large aperture telescope.



Figure 3. Illustration of the James Webb Space Telescope primary mirror⁶.

Another benefit of using a segmented mirror instead of a monolith as the primary mirror is that the use of segments reduces the mass of the mirror and therefore relaxes the requirements on the mirror's support structure.

Segmented mirrors add complexity into the system as they require precision in their fabrication and alignment and introduce a large number of degrees of freedom that must be controlled. While mirror segments will be adjusted in six degrees of freedom, piston, tip, and tilt movements have the greatest effect on wavefront error. Therefore, the piston, tip, and tilt (PTT) degrees of freedom must be given great attention in the design of ultra-stable optical systems that have high stability requirements⁷.

2.3. Wavefront Sensing and Control

Wavefront sensing and control systems measure the shape of an incoming wavefront and correct its deviation from an ideal reference. Wavefront sensing provides a direct measurement of the amplitude and phase of a wavefront and therefore information about how the wavefront is aberrated. Using this information, wavefront correction is often performed by a deformable mirror, whose surface is deformed in such a manner to correct a distorted input wavefront.



Figure 4. Demonstration of the basic function of a deformable mirror⁸.

The wavefront sensing and control can operate in either an open or closed loop system. An open loop control system operates by controlling the mirror shape based on pre-calculated values.



Figure 5. Demonstration of a basic open loop control system⁸.

A closed loop control system operates using a wavefront sensor that measures the shape of the incoming wavefront and controls the deformable mirror shape based on these data. In a basic closed loop control system as seen in Figure 6, a beamsplitter is placed in the optical path to reflect light onto the wavefront sensor that is used to characterize the incoming wavefront shape.



Figure 6. Demonstration of a basic closed loop control system⁸.

A wavefront sensing and control system incorporated into a segmented telescope requires greater complexity due to the adjustment of multiple segments and a larger number of degrees of freedom. Despite these challenges, active wavefront sensing and control is essential for achieving high levels of wavefront stability in an optical system.

Chapter 3: Coronagraph Design for Segmented-Aperture Telescopes **3.1. Coronagraph Design**

The design of high-contrast imaging coronagraphs for use with large segmented-aperture space telescopes has been motivated by the scientific goal of directly imaging faint extra-solar planets residing in the habitable zones of bright stars. In order to meet this science goal, coronagraph designs need to be optimized to a contrast capability of 10⁻¹⁰. Coronagraph designs must balance between ensuring sufficient light throughput from the planet and suppressing diffracted starlight⁹.

The Lyot coronagraph and the vortex coronagraph are two types of coronagraphs commonly used in space telescopes. These designs can be optimized for high contrast exoplanet imaging using different active control algorithms.



Figure 7. Lyot coronagraph design¹⁰.



Figure 8. Vortex coronagraph design⁹.

3.2. Electric Field Conjugation Algorithm

The Electric Field Conjugation (EFC) algorithm corrects aberrations in imaging systems by adjusting the position of deformable mirrors (DMs) to eliminate aberrations in the electric field at the image plane. To demonstrate the basic principles of the EFC algorithm, consider its application to a general imaging system with a deformable mirror. The algorithm consists of two main phases: estimation and correction.

In the estimation phase, the complex electric field amplitude in the image plane is estimated based on the ideal electric field, aberrations in the system, and DM shape. This estimation is used to determine what the DM's actuator lengths need to be to correct for aberrations¹¹.

The correction phase involves setting the DM's actuator lengths to superpose the negative of the estimated electric field onto the image plane, which should ideally eliminate aberrations¹¹.

The reconstruction stage of the algorithm provides an estimate of the complex electric field in the image plane based on pairs of images taken at the final image plane with different DM configurations. The intensity of light in the final image plane is approximated for each DM configuration, and a relationship between pairs of images is established to recover the desired electric field¹¹.

Since the control vector in the algorithm can be generalized to contain any degrees of freedom, the EFC algorithm can be applied to coronagraph designs. In coronagraphic applications, the EFC algorithm iteratively reduces the intensity in the dark hole of the image plane. The algorithm computes changes in actuator heights that are needed to null the electric field in the image plane. By adjusting control vectors, like the DM actuators and parameters of the focal plane mask, the EFC algorithm can iteratively refine coronagraph designs¹².

3.3. Auxiliary Field Optimization Algorithm

Another approach to coronagraph design optimization is called the "Auxiliary Field Optimization" (AFO) algorithm. This algorithm was developed by engineers at JPL and the Department of Astronomy at Caltech. The AFO algorithm addresses the challenge of optimizing coronagraphs, which involves minimizing energy from the star within a specific region of the science focal plane to detect exoplanets⁹.

In the case of a uniform circular aperture, a vortex coronagraph is a very effective solution in providing suppression of an on-axis point source like a star. However, the drive to larger telescopes for exoplanet imaging requires the use of segmented telescopes. In segmented telescopes, diffraction from the additional structures like segment gaps, the secondary mirror, and the support struts makes the vortex solution unusable. The goal of this coronagraph design optimization is to find design variables that allow the vortex coronagraph solution to work with large segmented-aperture telescopes⁹.

The development of the AFO algorithm started with coronagraphs that already implemented phase control. The central idea of the AFO algorithm is to embed the original optimization problem into a problem with additional degrees of freedom by using fictitious "auxiliary" electric fields that serve as targets to inform the variation of the phase or amplitude parameters. The algorithm essentially alternates between computing target light configurations and adjusting coronagraph parameters to approximate those targets⁹.

3.4. Application to Segmented Telescope Aperture Designs

The Fast Linearized Coronagraph Optimizer (FALCO) is an open-source software tool that implements the EFC algorithm to calculate the surface shapes of deformable mirrors that minimize the presence of starlight within a designated area of the image which is commonly referred to as the dark hole. The results can then be used to compare the performance of different coronagraph designs. A study performed by JPL on coronagraph design for obstructed and segmented apertures discusses the design of shaped pupil Lyot and vortex coronagraphs for the Large UV/Optical/Infrared Surveyor (LUVOIR) 'A' aperture. Both designs aim to achieve a raw contrast of less than 10⁻¹⁰, including considerations for the central obscuration, struts, and segment gaps¹⁰.

The Shaped Pupil Lyot Coronagraph (SPLC) involves a binary apodizer, annular occulting mask, and annular Lyot stop. Optimization is performed for a one-dimensional representation of

LUVOIR A. Analytical models are used to determine optimal values for the inner and outer radii of the focal plane mask and the Lyot stop. DM-assisted apodization is employed to optimize the SPLC design, resulting in the smallest possible stellar irradiance within the focal plane mask opening¹⁰.



(a)-(c) show the 1-D radial solution. (d) shows the LUVOIR A pupil. (e)-(f) show the two DM surfaces that are used for apodization. (g) shows the reshaped pupil before apodization. (h) shows the pupil before the Lyot stop. (i) shows the stellar irradiance at the final image plane¹⁰.

The vortex coronagraph is similar in function to the SPLC but with different coronagraph masks. The coronagraph used in this study is an apodized vortex coronagraph with a grayscale apodizer that suppresses diffraction from the central obscuration. A charge six vortex phase mask is used in the focal plane, along with an annular Lyot stop. Optimization includes deriving analytical and numerical solutions for apodizers and selecting parameters such as the inner and outer radii of the Lyot stop to maximize throughput. DM-assisted apodization is used to reduce diffraction from the struts and gaps between mirror segments in the LUVOIR A¹⁰.



Figure 10. Results for the vortex coronagraph for LUVOIR A with DM-assisted apodization. (a)-(c) show the 1-D radial solution. (d) shows the LUVOIR A pupil. (e)-(f) show the two DM surfaces that are used for apodization. (g) shows the reshaped pupil before apodization. (h) shows the pupil before the Lyot stop. (i) shows the stellar irradiance at the final image plane¹⁰.

In the study using the FALCO software, both designs are initially optimized for annular apertures and demonstrate effective suppression of diffraction over the specified radii, contributing to the goal of achieving high-contrast imaging for LUVOIR A. The AFO algorithm can be applied to various segmented telescope aperture designs explored in the Segmented Coronagraph Design and Analysis (SCDA) study. The AFO algorithm yields solutions for both beam shaping and apodization, which are advantageous when combined with a vortex focal plane mask and a simple Lyot stop, achieving excellent throughput and on-axis source diffracted light suppression⁹.



Figure 11. Example apertures used in the SCDA study⁹.

For the Large UV/Optical/Infrared Surveyor (LUVOIR) 'A' aperture, beam-shaping solutions were shown using an "ideal DM" model with Optical Path Difference (OPD) phase masks in both the entrance pupil and Fresnel Plane. The aperture was left unmodified, and the Lyot stop covered the secondary mirror. No apodization was used, achieving 10⁻¹⁰ contrast purely with phase solutions. These solutions are preliminary and aim to assess the feasibility of using a vortex focal plane mask with a central obscured aperture like that of the LUVOIR 'A' architecture⁹.



Figure 12. "Ideal DM" solutions for the LUVOIR "A" architecture, achieving 10⁻¹⁰ suppression⁹.

In order to achieve the science goal of imaging faint Earth-like planets that reside near bright stars, the use of high-contrast imaging coronagraphs with large segmented-aperture space telescopes must be optimized to a contrast level of 10⁻¹⁰. The use of the EFC and AFO algorithms is promising in the development of concepts like the Large UV/Optical/IR Surveyor. The optimization of high-contrast coronagraphs aligns closely with the advancement of ultrastable architecture, both essential for reaching ambitious science objectives.

Chapter 4: Important Subsystems in Ultra-Stable Architecture

4.1. Active Stabilization

4.1.1. Segment Sensing and Control

An important component of ultra-stable architecture in segmented telescopes is segment sensing and control. Wavefront piston, tip, and tilt due to segment level rigid body motion have a significant impact on contrast stability². The sensing of the optic rigid body motions is important in determining the necessary movement of each segment to correct for instability and misalignment caused by relative segment motion.

To demonstrate a basic overview of the active control geometry of a segmented mirror, the following model from a JPL presentation will be used. Edge sensors report on the relative position of the neighboring segments, and each sensor has a drive half on one segment and a sense half on the other side of the gap between segments¹³. The outputs from these sensors inform the relative movement of each segment to compensate for misalignment and wavefront error. Three actuators move each segment in tip, tilt, and piston, since these rigid body movements have the greatest effect on wavefront error⁷.



Figure 13. Model of the active control geometry of a segmented mirror¹³.

Ground-based segmented-aperture telescopes have a history of controlling mid-order wavefront perturbations through direct measurement of relative segment motion using edge sensors⁷. When relative segment motion causes a change in geometry, capacitors produce electrical signals that can be measured with high precision at large bandwidths². Therefore, capacitive edge sensors can be used to effectively control segment level misalignments.

Conceptual edge sensor designs for the Thirty Meter Telescope (TMT) and Giant Magellan Telescope (GMT) use overlapping capacitor plates to sense individual degrees of freedom to a planned accuracy of 6nm in piston and 10nrad in tilt^{14,15}. This control architecture work that demonstrates a high level of accuracy will inform future segment sensing and control efforts within the field.

Figure 14. GMT and TMT edge sensor designs^{14,15}.

Once the edge sensors have measured the relative segment motion, the perturbations must be corrected with actuators. Piezoelectric and voice coil actuators are suitable for applications requiring high precision and high frequency actuation over small distances¹. For example, these types of actuators would be used during observation on a science instrument requiring high levels of stability to reduce the impact of wavefront error disturbances on instrument performance¹. The selection of the actuator depends on the application as well as the dynamics and frequency characteristics of the system. Piezoelectric actuators, considered "hard" actuators, enable a more stable coupling between the structure and the mirrors, whereas voice coil actuators, considered "soft" actuators, provide more damping to the system¹.

In order to achieve picometer level sensitivity with the actuators, current control architecture work must be adapted and scaled. BAE Systems is working on improving the performance of capacitive and optical edge sensing technology in an effort to advance current capabilities by several orders of magnitude².

4.1.2. Thermal Sensing and Control

In addition to positional sensing and control, thermal sensing and control is critical to the stability of an optical system. Changes in temperature when a telescope moves relative to the Sun lead to thermal expansion, causing thermal wavefront error to occur. Variations in thermal heat load induce expansion and contraction in the mirror's support structures, resulting in changes to the shape of the mirrors. When a wavefront sensing and control subsystem is incorporated into the telescope, longer thermal drift can be corrected by the deformable mirror, and therefore, the primary concern is stability errors shorter than 10 to 120 minutes. The current standard for ambient temperature space telescopes is to adopt a "cold-biased" approach supplemented with heaters¹⁶. This involves insulating the telescope from solar heat such that, regardless of its orientation relative to the Sun, the telescope remains below its designated temperature when the heaters are off¹⁶.

According to preliminary studies, the optical telescope assembly for a telescope with an operating temperature of 270K must achieve a milli-Kelvin level of stability in order to produce picometer level wavefront stability².

Active thermal control can be used to regulate the temperature of the telescope and maintain a stable operating environment. The most widely used method of thermal control is direct heating in which sensors attached to the telescope detect when the temperature drops below a certain point and heaters are employed until another set point is reached. This method is not precise enough for direct imaging of exoplanets.

Figure 15. Direct heating control cycle¹⁶.

Another method of thermal control is proportional integral derivative (PID) control. This method regulates temperature by adjusting the power supplied to heaters or coolers based on the difference between the desired and actual temperature measured by the sensors. Both methods, direct heating and PID control, lack information like when and how much the telescope slews, the power usage of telescope subsystems, and the temperatures of nearby components¹⁶.

Figure 16. Proportional control cycle¹⁶.

Researchers are investigating another approach called model predictive control (MPC). This method uses a physics-based model to predict how the temperature will change and adjusts the heaters accordingly¹⁶. This method is computationally intensive but may be viable for exoplanet imaging if future technology developments improve its capabilities.

4.2. Passive Stabilization

4.2.1. Stable Structures

In order to achieve high levels of wavefront stability, the structures built to support the telescope assembly must be highly stable. Maintaining dimensional stability while the thermal environment fluctuates requires a structure with a low coefficient of thermal expansion (CTE). The balance between stiffness and thermal stability in the design of stable structures is a common challenge on space telescopes. Thermo-elastic changes, moisture desorption, and dynamic perturbations affect structure stability and must be considered in the design of composite structures¹.

The James Webb Space Telescope is a good example of a space-based telescope that employs ultra-stable structures in its design. The backplane was engineered to provide thermal stability on the level of 32 nanometers at temperatures colder than -240 degrees Celsius¹⁷.

Figure 17. James Webb Space Telescope backplane demonstrates stable support structure capabilities¹⁸.

In the ULTRA study and design of the Large UV/Optical/Infrared Surveyor (LUVOIR), the architecture for the primary mirror backplane is derived from the James Webb Space Telescope design¹.

4.2.2. Low Disturbance Architecture

Minimizing input disturbances alleviates stress on the telescope's structure and optics and also contributes to telescope stability. The movement and control of the spacecraft itself can cause disturbances, but the use of different technologies for pointing and keeping the spacecraft stable can be used to mitigate dynamic perturbations¹.

The term "quiet spacecraft" refers to a spacecraft designed to minimize disturbances that interfere with its operations. Precision payloads require a spacecraft platform with an ultra-quiet working environment. The control system of a high precision spacecraft should provide accurate pointing control but also minimize high frequency disturbances caused by movement of its actuators. In order to mitigate disturbances emitted by actuators such as momentum wheels and control moment gyroscopes, vibration isolators are often used. Vibration isolators function as mechanical low pass filters, which can reduce high frequency disturbances. However, vibration isolators introduce flexibility into the system, which affects the spacecraft's dynamic characteristics, control system performance, and stability. Therefore, the interaction between the spacecraft's vibration isolators and its control system should be carefully considered¹⁹.

Momentum wheels and control moment gyroscopes are often used as high speed rotors for attitude control actuation in a spacecraft. When they are mounted through vibration isolators, the gyro effect of the rotor and the structural flexibility of the isolator interact, leading to the phenomena of precession and nutation. Precession is the phenomenon where the axis of rotation of a spinning rotor gradually changes orientation, and nutation is the phenomenon where an oscillatory motion of the rotor axis occurs. Precession decay time refers to the duration it takes for the precession motion of the spinning rotor to slow down and eventually stop. These parameters are important because they determine how long the spinning rotor can maintain its stability¹⁹.

Figure 18. Dynamic model of wheel isolation¹⁹.

As the rotor spins, its movement can be deconstructed into two components: nutation and precession. Nutation is characterized by a lower magnitude and a faster decay rate, inducing less of an effect on the spacecraft attitude. Precession motion is characterized by a lower frequency and a longer decay time, which may cause continual perturbation to the spacecraft attitude. To address this perturbation, precession delay time should be considered in the design of vibration isolators for momentum wheels and control moment gyroscopes. Table 1 shows that the precession decay time extends significantly when the frequency of the isolator is decreased, leading to better mitigation of disturbances¹⁹.

Natural Frequency (Hz)	Precession Frequency (Hz)	Precession decay time (s)
15	1.5	21.2
10	0.67	71.6
5	0.17	573.0
1	0.0067	71620

Table 1. Precession frequency and decay time for a rotor speed of 6000 rpm¹⁹.

Sometimes, relying solely on "quiet spacecraft" methods to attenuate dynamic perturbations may prove insufficient in maintaining the required stability. In such cases, the payload can be isolated from the spacecraft through passive or active methods. Additionally, employing low disturbance payload mechanisms for fine steering mirrors or instrument pupil/filter wheels can help reduce the dynamic disturbances caused by the internal telescope mechanisms and instruments¹.

4.2.3. Stable Mirror Mounting

Maintaining passive stability in the mirror assemblies is crucial for minimizing distortion. Mirror mount pad assemblies connect the substrate to the rest of the telescope and are typically the closest structural component to the optical surface with a high coefficient of thermal expansion (CTE). Therefore, the mount pad assembly has a great effect on wavefront errors from higher-order bending of the mirror surface and must be given great consideration in its design¹.

For example, in the design of the LUVOIR, the major structural components in the primary segmented mirror assembly are the lightweight mirror substrate, kinematic mirror struts and flexures, and kinematic rigid body actuators. Figure 19 displays these components, including the entire load path between the primary mirror backplane support structure and the mirror substrate. Each element of the mirror assembly is important in achieving high levels of stability and minimizing wavefront error caused by movement of the mirror¹.

Figure 19. Schematic of LUVOIR primary segmented mirror assembly baseline design¹.

Struts are another important component in the mirror assembly as they impact the rigid body motion of the segmented primary mirror assembly. Each strut needs a substantial lever arm around the mirror's vertex to uphold the mirror and enhance the natural frequency of the assembly, thus enhancing dynamic stability performance. However, expansion or contraction of the mirror struts will induce considerable rigid body motion in the mirror, a factor that must be considered in the design of ultra-stable mirror mounting systems¹.

Figure 20. Illustration of the struts used in the James Webb Space Telescope²⁰.

Chapter 5: Case Studies in Stable Spacecraft

5.1. James Webb Space Telescope

The James Webb Space Telescope (JWST) is a current example of a space-based telescope employing wavefront sensing and control techniques. JWST employs 7 degrees of freedom for the adjustment of each of the 18 segments of the primary mirror and 6 degrees of freedom for the adjustment of the secondary mirror. In order to achieve diffraction-limited imaging, the optical elements must be positioned within nanometer-level precision. This level of precision necessitates the implementation of wavefront sensing and control techniques²¹.

The wavefront sensing and control system is designed with three high-level principles in mind: correct the largest type of errors present at any given step, consistently improve the alignment of the telescope, and keep large movements of the actuators to a minimum. These guiding principles can be utilized in the development of future wavefront sensing and control systems for large space-based telescopes that require high levels of wavefront stability²¹.

The wavefront sensing and control process developed for JWST includes three general phases of operation: segment location and positioning, segment-level wavefront control, and global phasing. In the segment location and positioning phase, the approximate boresight of the telescope and the rough pointing errors of the primary mirror segments are determined. In the segment-level wavefront control phase, the goal is elimination of wavefront errors local to each segment. Large piston errors between segments, large field-dependent errors, and segment-level power and astigmatism are corrected. During global phasing, the individual segments are co-phased relative to each other and residual field-dependent wavefront error is corrected. After the three-phase operation is complete, the process may loop back to one of the earlier phases depending on error correction²¹.

The observatory does not contain a wavefront sensor and is designed for passive stability, so the wavefront sensing and control is not performed automatically. Exposures taken by the science instruments on the James Webb Space Telescope are sent to the Science and Operations Center (SOC) through the Deep Space Network. After the science and engineering data are processed and assembled into science-quality images, the images are sent to the Wavefront Sensing and

Control Software Subsystem (WSS) for analysis. The WSS is a subsystem of the SOC which allows the scientists to interface with the telescope, perform wavefront analysis, and control the mirror segment positions to correct for wavefront error. Wavefront analysis software is used to perform wavefront processing on the image data and generate new recommended mirror positions. The mirror control software is then used to plan for safe mirror movement and the commands are sent to the observatory. This process repeats as more images are taken and wavefront error is reduced²¹.

High-precision hexapods that allow for six rigid-body motions control each primary mirror segment and the secondary mirror. These rigid-body motions include piston, clocking, x- and y-translation, and x- and y-tilt. The radius of curvature of each segment of the primary mirror can also be adjusted with an actuator. The hexapod actuators have coarse and fine mechanisms, with the coarse mechanisms supporting an adjustment range of several millimeters with steps of 50 nanometers, and the fine mechanisms supporting a range of 8 microns with steps of 7 nanometers²¹.

Figure 21. High precision hexapod used in the James Webb Space Telescope²².

Thermal sensing and control is also important in achieving high levels of wavefront stability. After the telescope is deployed and passively cooled to a temperature of 80 degrees Kelvin, the science instruments can begin to take images. Cooling continues until the telescopes reaches its operating temperature of 40 degrees Kelvin.

After the deployment of the James Webb Space Telescope in December of 2021, high quality images were first achieved on the NIRCam, the main wavefront sensing sensor, about halfway through telescope commissioning. Then, the secondary mirror alignment was adjusted to optimize image quality over all the science instrument capabilities. Figure 22 demonstrates an overview of the optical telescope element (OTE) commissioning process, which lasted several months and was completed in April of 2022. Then, the commissioning of the science instruments was executed, during which the OTE wavefront was measured and corrected. The wavefront sensing and control system plays a crucial role in the performance of the James Webb Space Telescope to capture high quality images of space²³.

Figure 22. Schematic of the overall OTE commissioning process²³.

5.2. Hubble Space Telescope

5.2.1. Stability Challenges

In high-contrast observations with the Hubble Space Telescope (HST), point spread function (PSF) subtraction is employed to obtain images of faint sources against a low background. PSF subtraction involves subtracting the image of another star or the same star observed at a different angle from the original image. The accuracy of this subtraction relies on the optical and mechanical stability of the telescope. Small changes in focus, pointing, or other factors can cause differences between the target and reference PSFs, resulting in incomplete subtraction and lower-quality results. Factors that affect the stability and performance of the telescope include wavefront changes, mechanical changes, color differences, and position changes²⁴.

Figure 23. Schematic of Hubble's instruments including control and support systems²⁵.

In the Hubble Space Telescope, wavefront variations caused by optical and mechanical instabilities result in the largest changes in the point spread function. One significant factor in wavefront instability is thermally-induced focus changes, which can change the distribution of light between the wings and core of the PSF. Additionally, the symmetry of the PSF can change with focus due to other aberrations like astigmatism. As the Hubble Space Telescope orbits, parts of its field of view are blocked by the Earth, causing the telescope to absorb heat and expand, a phenomenon known as "breathing." This cycle occurs every orbit, causing the separation

between the primary and secondary mirrors to change by 3-5 microns, which results in focus changes of up to 1/16th wave RMS (at a wavelength of 0.5 microns). The difference in focus due to breathing between two images of a star taken at different points in the orbit can lead to greater residuals when performing PSF subtraction. Additionally, when HST points away from the Sun for multiple orbits, a shadowing effect occurs that can cause the primary and secondary mirror separation to shrink by up to 10 microns, which results in focus changes of up to 1/8th wave RMS defocus²⁴.

Over time, the alignment of components in the HST cameras shifts due to factors like gravity release and thermal fluctuation. For example, the Advanced Camera for Surveys coronagraphic occulting spots initially shifted by about 1 arcsecond due to launch stresses and gravity release and then another 0.15 inches during the first few months on-orbit. These shifts caused the coronagraph flat fields taken during ground tests to become invalid and unable to be used to calibrate the on-orbit data. The spots continued to move unpredictability, so reference PSF observations had to be taken immediately before or after science exposures to mitigate spot motion. Similarly, in the Near Infrared Camera and Multi-Object Spectrometer, coolant expansion caused internal alignment shifts, which affected the cold stop of each channel and altered the resulting diffraction pattern. The masks also moved over time, altering the PSF shape over short timescales. Even after coolant exhaustion and cryocooler installation, thermal effects continued to cause the masks to fluctuate. These shifts and fluctuations complicated PSF subtraction, leading to significant subtraction residuals²⁴.

When imaging a faint source that is near a much brighter source, small color differences between the target and reference point spread functions can affect the contrast ratio and create subtraction residuals. The Space Telescope Imaging Spectrograph coronagraph is especially sensitive to color differences because of its broad passband. However, the scale change of the PSF with wavelength can be utilized in the spectral deconvolution method to eliminate the PSF itself when searching for faint planets. This method involves taking narrowband images at different wavelengths over a limited range and analyzing intensity changes. This would allow for deviations in the intensity change from the predicted to be extracted, providing spectral information without needing reference PSFs²⁴.

Position changes also affect the point spread functions taken by the Hubble Space Telescope. Internal parts of the HST cameras like secondary mirrors and spiders contribute to the diffraction pattern. Since these structures are not located in the pupil plane, their diffraction pattern shifts relative to the telescope's diffraction pattern depending on field angle. Therefore, the resulting diffraction pattern varies significantly with field angle, and a reference PSF that was observed at a similar position on the detector as the target should be chosen. Off-detector stray light and ghosts are also sensitive to the field position of the source, making it challenging to fully subtract these features due to limitations in the pointing accuracy of HST. Additionally, in coronagraphs, the position of the star in the focal plane can impact the residual PSF, with acquisition exposures taken to precisely locate the target²⁴.

In conclusion, the accuracy of point spread function subtraction relies on the stability of the optical and mechanical telescope assembly. Various factors affect the stability and performance of the HST. Wavefront changes are significant contributors to PSF variations. Additionally, over time, the alignment of internal components in the HST cameras can shift, which complicates PSF subtraction and calibration efforts. Small color differences between target and reference PSFs can also affect contrast ratios, and position changes within the telescope's optics contribute to field-dependence in diffraction patterns.

5.2.2. PSF Subtraction Success

Until NICMOS and STIS were installed in 1997, high contrast imaging on the Hubble Space Telescope primarily relied on direct observations with WFPC2. Despite not being an ideal high contrast camera, WFPC2 was successfully used for tasks like searching for low-mass companions and imaging circumstellar disks, stellar jets, and quasar host galaxies. Its main limitations are its field-dependent PSF and the absence of an occulter or coronagraph. However, by observing a reference PSF at a similar field location and color, PSF subtraction could significantly reduce the PSF wing surface brightness²⁴.

The success of PSF subtraction with WFPC2 led to its adoption on STIS, NICMOS, and ACS. Despite the availability of coronagraphs on these instruments, there are instances where it is

necessary to observe objects closer to the central source or when the object is unsuitable for coronagraph use. For example, the binary star GG Tauri, with a separation of 0.25", was observed directly by WFPC2, NICMOS, and ACS, with both stellar components subtracted using reference star images. These observations revealed reflecting material within 0.3" of one of the stars, which would have been blocked by the smallest available occulters²⁴.

Figure 24. Hubble Space Telescope direct image of the GG Tauri circumbinary disk before (left) and after (right) PSF subtraction²⁴.

5.3. Nancy Grace Roman Space Telescope

The Nancy Grace Roman Space Telescope (NGRST), set to launch in the mid-2020s, will feature a Coronagraph Instrument for high-contrast direct imaging of exoplanets. This instrument will enable the detection and characterization of exoplanets and circumstellar disks with unparalleled precision, achieving a contrast level of approximately 10⁻⁸ or better. The Roman Coronagraph will utilize active wavefront control with large-format deformable mirrors, showcasing key technologies necessary for future exo-Earth direct imaging missions²⁶.

Figure 25. Nancy Grace Roman Space Telescope²⁷.

The active wavefront sensing and control is a critical part of achieving the NGRST mission. In order to achieve the high levels of contrast necessary for exoplanet imaging, advanced wavefront sensing and control must be implemented.

Figure 26. Schematic optical layout of the Roman Coronagraph²⁶.

During observations with the NGRST Coronagraph Instrument, drifts in the wavefront are sensed and rejected by the Low-Order Wavefront Sensing and Control (LOWFSC) system. The LOWSFC system operates independently and concurrently with both the High-Order Wavefront Sensing and Control (HOWFSC) system and exoplanet observations. The LOWFSC system measures a reference wavefront and calibrates the response to maintain the wavefront at its reference state throughout the observation visit. It does not aim to drive the wavefront to a specific state but rather to sustain it at the measured reference level. During science camera exposures, low-order wavefront sensing is provided by an intensity-based Zernike wavefront sensor, which continuously measures drifts in the incoming wavefront coefficients and feeds the error signal to various control mechanisms²⁶.

High-order wavefront sensing in the Roman Coronagraph employs the electric field conjugation technique. Focal plane images are used to estimate the complex electric field of the wavefront, which is combined with a coronagraph model to determine new actuator positions for the deformable mirrors. This process iterates to create a coronagraphic dark hole around the star for better imaging of exoplanets²⁶.

The Roman Coronagraph utilizes two deformable mirrors with electro-strictive lead magnesium niobate ceramic actuators, which have undergone thorough testing and qualification to ensure performance and reliability in space²⁶.

Figure 27. Roman Coronagraph flight deformable mirrors. DM1 with thermal cover on (left) and DM2 with thermal cover off (right)²⁶.

The Roman Coronagraph is anticipated to yield a substantial improvement in coronagraphic performance, with projections indicating a 100-1000x enhancement over current technology across various angular separations. However, despite its advancements, the estimated detection

limit of around 10⁻⁸ still falls short by approximately a factor of 100 compared to the requirements for future exo-Earth imaging missions. A recent whitepaper²⁸ aimed to assess the Roman Coronagraph's readiness for potential future exo-Earth direct imaging missions by comparing its performance estimates and specifications with the needs outlined by representative concepts such as HabEx and LUVOIR. While the cross-analysis was not exhaustive, it found that although there are significant differences in the planet-to-star flux ratio detection limits between the Roman Coronagraph and future missions like HabEx and LUVOIR, many subsystems share similarities. Consequently, the Roman Coronagraph serves as an excellent technology demonstration for future exo-Earth direct characterization missions, especially considering its performance in key technical areas such as pointing jitter control, low-order wavefront control, and detector properties²⁶.

The Roman Coronagraph acts as a crucial intermediary step toward the realization of future infrared/optical/UV missions. Although the Roman telescope's complex entrance pupil imposes limitations on its point source detection capabilities, it demonstrates important technological advancements, with many subsystems required to operate at levels aligned with the requirements of future exo-Earth missions²⁶.

Chapter 6: Challenges and Solutions in Ultra-Stable Wavefront Sensing and Control

Ultra-stable architecture in space-based telescopes involves intricate subsystems designed for maintaining precise control over the optics to minimize wavefront errors. This control is achieved through both active and passive stabilization techniques. However, many challenges arise in the design of ultra-stable optical systems that aim for performance that is beyond state-of-the-art capabilities.

The key challenges in ultra-stable wavefront sensing and control for space-based exoplanet coronagraph imaging are as follows.

- 1. Achieving a 10^{-10} level of contrast.
- 2. Managing a large number of degrees of freedom in the control of the multiple segments of the primary mirror.
- 3. Achieving milli-Kelvin levels of thermal stability.
- 4. Balancing between stiffness and thermal stability in the design of stable structures.
- 5. Minimizing input disturbances to the spacecraft caused by movement of the optics and structural components.

To address the challenge of achieving high levels of contrast in a coronagraph used with a large segmented-aperture space telescope, the coronagraph design must be optimized. The coronagraph must balance between suppressing diffracted starlight and allowing sufficient light throughput from the exoplanet of interest. The Electric Field Conjugation (EFC) and Auxiliary Field Optimization (AFO) algorithms can be utilized in this endeavor. These approaches are promising for achieving the stringent 10⁻¹⁰ contrast levels necessary for ambitious scientific objectives, exemplified by applications to coronagraphs like the Lyot and vortex designs tailored for the LUVOIR 'A' aperture. The optimization of high-contrast coronagraphs is closely linked with the advancement of ultra-stable architecture, both critical for space-based exoplanet imaging.

Active wavefront sensing and control plays a crucial role in achieving ultra-stable architecture in segmented telescopes. The use of a segmented primary mirror introduces a significant number of degrees of freedom to be controlled. Segment sensing and control must be implemented in order to determine the necessary motion of each segment to mitigate misalignments and wavefront errors. Edge sensors provide precise measurements of relative segment motion, enabling effective control of segment-level misalignments. Advancements in control architecture, particularly in edge sensing technology, are essential for achieving picometer-level sensitivity and improving overall performance.

Thermal sensing and control is important for ensuring the stability of space telescopes because temperature changes can lead to thermal expansion and wavefront errors. Achieving picometerlevel wavefront stability requires precise thermal control, as demonstrated by challenges faced by telescopes such as Hubble and James Webb. Active thermal control methods, such as direct heating and proportional integral derivative control, are commonly used to regulate telescope temperature. However, since these methods may not be precise enough for direct imaging of exoplanets, model predictive control should be explored as an alternative. This method uses physics-based models to predict temperature changes and adjust heaters accordingly. To achieve milli-Kelvin levels of thermal stability, active thermal sensing and control methods should be implemented along with passive thermal stabilization.

Stable structures are essential for minimizing wavefront error in telescopes. Structures like the backplane in telescopes, such as the James Webb Space Telescope, provide stability even in extreme temperature conditions. In designs like the LUVOIR telescope, shown in Figure 28, structural materials must be chosen carefully to ensure both dynamic and dimensional stability. Components like mirror mount pad assemblies play a significant role in reducing wavefront errors caused by mirror movement. In the design of the mirror assembly, the material of the struts must also be considered in order to maintain stability while also enhancing dynamic performance. Achieving high levels of stability requires careful consideration of all structural elements to minimize wavefront error effectively.

Figure 28. LUVOIR Telescope's major features²⁹.

Minimizing input disturbances is an important method of relieving stress on the telescope's optics and structures as well as improving telescope stability. The use of vibration isolators and quiet spacecraft design can help mitigate these disturbances. It is important to consider that the interaction between vibration isolators and the control system affects stability. For components like momentum wheels and gyroscopes, precession and nutation phenomena can impact stability, and designing isolators with longer decay times can help mitigate these effects. In cases where quiet spacecraft methods are insufficient, isolating the payload from the spacecraft and using low-disturbance payload mechanisms can further reduce dynamic disturbances.

Achieving picometer-level wavefront stability using ultra-stable architecture in high contrast coronagraphs presents significant challenges. Addressing these challenges involves a multidisciplinary approach, which incorporates advanced sensing technologies, precise actuation mechanisms, and robust structural design. Additionally, the trade-offs between precision, computational complexity, and dynamic stability need careful consideration to achieve optimal performance. As advancements continue, a deeper understanding of these subsystems and their interactions will be crucial for pushing the boundaries of ultra-stable architecture in the future of space-based telescopes.

Conclusion

The advancement of high-contrast imaging coronagraphs for large segmented-aperture space telescopes is a current focus area of astronomical research. Improving the capabilities of ultrastable optical systems is essential for the successful detection and characterization of faint Earthlike exoplanets in the habitable zones of bright stars. The development of ultra-stable wavefront sensing and control techniques, as well as the optimization of coronagraph designs, is crucial to reaching the high contrast sensitivity needed for future space telescopes. Various examples, such as the James Webb Space Telescope, the Hubble Space Telescope, and the upcoming Nancy Grace Roman Space Telescope, highlight the challenges and achievements in this field.

Active and passive stabilization systems play vital roles in achieving ultra-stable wavefront sensing and control. Active stabilization, including segment sensing and control and thermal sensing and control, addresses wavefront aberrations and thermal drift, respectively. Passive stabilization focuses on minimizing input disturbances through stable structures, low disturbance architecture, and stable mirror mounting.

The James Webb Space Telescope has employed wavefront sensing and control to achieve diffraction-limited imaging. Its overall success highlights the significance of precise alignment and control mechanisms in space-based telescopes.

The Hubble Space Telescope has faced and adapted to stability challenges, especially in terms of point spread function (PSF) subtraction. PSF subtraction has successfully enabled high contrast imaging and the observations of various celestial phenomena.

Looking toward the future, the Nancy Grace Roman Space Telescope is set to demonstrate cutting-edge wavefront sensing and control techniques, as well as advanced coronagraph designs. Advancements made by the Roman Coronagraph will not only significantly enhance coronagraphic performance but also serve as a critical stepping stone towards future exo-Earth direct imaging missions.

The development and optimization of wavefront sensing and control systems and the advancement of high-contrast imaging coronagraphs are pivotal to the future of space-based telescopes. These advancements will not only expand our understanding of the universe but also pave the way for the direct imaging and characterization of exoplanets and other celestial bodies, providing invaluable contributions to astronomical research and space exploration.

References

- [1] Coyle, Laura, et al. Ultra-Stable Telescope Research and Analysis (ULTRA) Program Phase *l Report*, <u>www.astrostrategictech.us/pdf/projectfiles/Reports/17-SLSTD17-</u> <u>0003</u> FR Ball 2019_04_Public.pdf.
- [2] Coyle, Laura E., J. S. Knight, Laurent Pueyo, Matthew East, et al. "Achieved technology maturation of key component-level technologies for ultra-stable Optical Systems." *Space Telescopes and Instrumentation 2022: Optical, Infrared, and Millimeter Wave*, 27 Aug. 2022, <u>https://doi.org/10.1117/12.2627057</u>.
- [3] "Exoplanet Program: Segmented Coronagraph Design and Analysis (SCDA)." NASA, NASA, 1 June 2023, <u>https://exoplanets.nasa.gov/exep/technology/SCDA/</u>. (Acton & Bouchez, 2012; Brooks & Stahl, 2022; Coyle et al., 2018; Mast et al., 2006; Qin & Chan, 2020; Ruane et al., 2020)
- [4] Fisher, Alise. "NASA's Webb Takes Its First-Ever Direct Image of Distant World." NASA, NASA, 1 Sept. 2022, <u>https://blogs.nasa.gov/webb/2022/09/01/nasas-webb-takes-its-firstever-direct-image-of-distant-world/</u>.
- [5] "Coronagraphy." *The Lyot Project*, lyot.org/background/coronagraphy.html.
- [6] *Designing the James Webb Space Telescope with Simulation*, <u>https://www.ansys.com/blog/designing-the-james-webb-space-telescope-with-simulation</u>.
- [7] Coyle, Laura E., J. Scott Knight, and Michael Adkins. "Edge sensor concept for segment stabilization." Space Telescopes and Instrumentation 2018: Optical, Infrared, and Millimeter Wave, 12 July 2018, https://doi.org/10.1117/12.2312224.
- [8] Introduction to Adaptive Optics and Deformable Mirrors, www.edmundoptics.com/knowledge-center/application-notes/optics/introduction-toadaptive-optics-and-deformable-mirrors/.
- [9] Jewell, Jeffrey B., et al. "Coronagraph Design Optimization for Segmented Aperture Telescopes." *Techniques and Instrumentation for Detection of Exoplanets VIII*, 13 Sept. 2017, <u>https://doi.org/10.1117/12.2274574</u>.
- [10] Riggs, A.J. Eldorado, et al. "Fast Linearized Coronagraph Optimizer (FALCO)." Space Telescopes and Instrumentation 2018: Optical, Infrared, and Millimeter Wave, 21 Aug. 2018, <u>https://doi.org/10.1117/12.2312973</u>.
- [11] Give'on, Amir, et al. "Broadband wavefront correction algorithm for high-contrast imaging systems." SPIE Proceedings, 13 Sept. 2007, <u>https://doi.org/10.1117/12.733122</u>.

- [12] Llop-Sayson, Jorge, et al. "Coronagraph design with the electric field conjugation algorithm." *Journal of Astronomical Telescopes, Instruments, and Systems*, vol. 8, no. 01, 26 Feb. 2022, <u>https://doi.org/10.1117/1.jatis.8.1.015003</u>.
- [13] Shelton, Chris. Edge Sensors for Segmented Telescopes. January 2017, https://exoplanets.nasa.gov/internal_resources/433/#:~:text=Active%20Control%20Geome try&text=Edge%20sensors%20report%20on%20the,of%20height%20and%20dihedral%20 angle. PowerPoint Presentation.
- [14] Acton, D. Scott, and Antonin Bouchez. "Phasing metrology system for the GMT." SPIE Proceedings, 17 Sept. 2012, <u>https://doi.org/10.1117/12.925012</u>.
- [15] Mast, Terry, et al. "Edge sensor design for the TMT." SPIE Proceedings, 14 June 2006, <u>https://doi.org/10.1117/12.672028</u>.
- [16] Brooks, Thomas E., and H. Philip Stahl. "Precision thermal control technology to enable thermally stable telescopes." *Journal of Astronomical Telescopes, Instruments, and Systems*, vol. 8, no. 02, 22 Apr. 2022, <u>https://doi.org/10.1117/1.jatis.8.2.024001</u>.
- [17] "Backplane Webb/NASA." *NASA*, NASA, <u>https://webb.nasa.gov/content/observatory/ote/backplane.html</u>
- [18] "Composites Stabilize Space-Based Telescope." *CompositesWorld*, www.compositesworld.com/articles/composites-stabilize-space-based-telescope.
- [19] Tang, Liang, et al. "Control design of ultra-quiet Spacecraft Platform." *IFAC Proceedings Volumes*, vol. 46, no. 19, 2013, pp. 266–270, <u>https://doi.org/10.3182/20130902-5-de-2040.00062</u>.
- [20] "Understanding James Webb Images: Color, Curves and Spikes." *The Space Techie*, 18 July 2022, <u>www.thespacetechie.com/understanding-james-webb-images-color-curves-and-spikes/</u>.
- [21] Acton, D. Scott, et al. "Wavefront sensing and controls for the James Webb Space Telescope." Space Telescopes and Instrumentation 2012: Optical, Infrared, and Millimeter Wave, 22 Aug. 2012, <u>https://doi.org/10.1117/12.925015</u>.
- [22] "Hexapod for James Webb Space Telescope." *ESA*, <u>www.esa.int/ESA_Multimedia/Images/2016/07/Hexapod_for_James_Webb_Space_Telescope</u>.
- [23] "JWST User Documentation." *JWST Wavefront Sensing and Control JWST User Documentation*, <u>https://jwst-docs.stsci.edu/jwst-observatory-hardware/jwst-wavefront-sensing-and-control</u>.

- [24] Krist, John E. "High-contrast imaging with the Hubble Space Telescope: Performance and Lessons Learned." *SPIE Proceedings*, 12 Oct. 2004, <u>https://doi.org/10.1117/12.548890</u>.
- [25] Hubble's Instruments Including Control and Support Systems (Cutaway), hubblesite.org/contents/media/images/4521-Image.html?keyword=Infographics.
- [26] Mennesson, Bertrand, et al. "The Roman Space Telescope Coronagraph Technology Demonstration: Current status and relevance to future missions." Space Telescopes and Instrumentation 2022: Optical, Infrared, and Millimeter Wave, 27 Aug. 2022, <u>https://doi.org/10.1117/12.2629176</u>.
- [27] "Nancy Grace Roman Space Telescope at IPAC." *Roman Space Telescope*, <u>https://roman.ipac.caltech.edu/mtgs/Roman_CGI_workshop.html</u>.
- [28] Mennesson, B. et al. 2020, "Paving the way to future missions: the Roman space telescope coronagraph technology demonstration", <u>https://arxiv.org/pdf/2008.05624.pdf</u>.
- [29] Richardmitnick. "From SA: 'NASA Considers Its next Flagship Space Telescope." Sciencesprings, 1 Apr. 2016, <u>https://sciencesprings.wordpress.com/2016/04/01/from-sa-nasa-considers-its-next-flagship-space-telescope/</u>.
- Note: When a citation is placed at the end of a paragraph, this indicates that the paragraph is being cited.