# Nancy Grace Roman Space Telescope Observatory Implementation and Challenges

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***Abstract*—NASA's Nancy Grace Roman Space Telescope (Roman) is a deep space infrared observatory with a Hubble-sized telescope and wide field of regard with a boresight view greater than 200 times that of the Hubble Wide Field Camera 3 infrared field of view, that will conduct a suite of science surveys to characterize dark energy and expand the census of exoplanets in our galaxy. Roman will also demonstrate exoplanet coronagraphy with active wavefront control technology and provide general investigator opportunities for the science community. Roman is finishing the critical design phase and is planning for launch in 2026. It will operate at the second Sun-Earth-Moon Lagrange for a five-year primary mission life. The Observatory features a telescope with an existing, repurposed 2.4m primary mirror, a Wide Field Instrument with a near-infrared detector focal plane array and optical elements for imaging and spectroscopy, as well as a Coronagraph instrument technology demonstration for direct imaging and spectroscopy of exoplanets. The telescope and instruments are mounted to an Instrument Carrier for optical metering and isolation from Spacecraft-induced disturbances. The Spacecraft includes a Bus, Solar Array Sunshield, Deployable Aperture Cover, Outer Barrel Assembly, and Star Tracker/Inertial Reference Unit Bench. When fully integrated, Roman will be the largest Observatory assembled and tested at NASA's Goddard Space Flight Center. The development of scientific satellites is challenging and pushes engineering boundaries to broaden scientific knowledge. The Roman mission implementation is a prime example and expected challenges have been amplified by the foundational decision to use existing, repurposed telescope components. Other unique aspects of the Roman mission, including its survey nature, large data volume, and Observatory packaging, create constrained design spaces that drive competing requirements across Observatory subsystems. Given these challenges, systems engineering has been a critical discipline in balancing implementation decisions and will continue to play a key role in the development of the Roman mission. This paper will discuss details of the Roman Observatory configuration, systems engineering challenges and the decision-making process used to mature the Roman Space Telescope from preliminary design to implementation.***

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## 1. INTRODUCTION

NASA's Nancy Grace Roman Space Telescope (Roman), previously referred to as the Wide Field Infrared Survey Telescope (WFIRST), has been named after Dr. Nancy Grace Roman, an astronomer and NASA pioneer of modern space-based astronomy who is known as the "mother of the Hubble Space Telescope". Roman is a deep space infrared observatory with a Hubble-sized telescope and wide field instrument with a boresight view greater than 200 times that of the Hubble Wide Field Camera 3 infrared field of view, as shown in Figure 1, that will investigate dark energy and expand the census of exoplanets in our galaxy while allowing a broad range of astrophysics research. Roman will also demonstrate exoplanet coronagraphy and provide general investigator opportunities for the science community.


**Figure 1. Comparison of Instrument Fields of View - Roman, Hubble, and James Webb Space Telescopes**

Roman is finishing the critical design phase and is planning for launch in 2026. Its development, like all scientific satellite developments, is challenging by nature and pushes engineering boundaries. Expected implementation challenges have been amplified by the foundational decision to use existing telescope components, developed in the early 2000s by another Government agency for a different application. Other unique aspects of the Roman mission, such as its survey nature, the vast amount of data required to meet science objectives, and packaging of the Observatory elements around the existing telescope components, create constrained design spaces that drive competing requirements across Observatory subsystems. Given these challenges, systems engineering has been a critical discipline in balancing implementation decisions for the Roman mission and will continue to play a key role going forward.

This paper will discuss details of the Roman Observatory configuration, as well as some of the systems engineering challenges and the decision-making process used to mature the Roman Space Telescope from preliminary design to implementation.

## 2. MISSION DESCRIPTION

The Roman Space Telescope is a five-year, Class A mission which will survey the sky to increase humankind's understanding of dark energy and exoplanets. Dark energy science objectives include determining the cosmic expansion history, investigating the growth history of large-scale structure, and testing theories of accelerated expansion including dark energy and modifications of general relativity. Roman also seeks to expand the census of exoplanets from the outer habitable zone to free-floating planets larger than the mass of Mars. In order to achieve its prime science objectives, Roman will conduct a high latitude time-domain (HLTD) survey, and a high latitude wide area (HLWA) survey (including imaging and spectroscopy in both high ecliptic and Galactic latitudes) to characterize dark energy. A galactic bulge time-domain (GBTD) survey will expand the census of exoplanets in our galaxy. These three surveys will allow a broad range of astrophysics research. In addition to this prime science, Roman has a technology demonstration objective to advance exoplanet coronagraphy using active wavefront control and will host a general investigator program for the broader science community.

The mission is divided into four distinct phases: pre-launch, launch to mission orbit, baseline science mission, and end of mission. The activities associated with each phase are shown in Table 1. In the pre-launch phase, the Observatory is integrated, tested for baseline performance and then put through its paces against thermal and mechanical flight-like environments. Important Mission-level testing occurs between the ground and flight segments, including simulations of operational scenarios, radio frequency compatibility between the Observatory and ground stations, contingency testing and launch rehearsals. After final verification activities are completed, the Observatory is shipped to the launch site for processing and, ultimately, launch. After launching from Kennedy Space Center, the space telescope will transit to and operate in a quasi-halo orbit about the second Sun-Earth-Moon Lagrange point (L2), 1.5 million kilometers from Earth on average, for a five-year baseline mission, with a ten-year goal supported by on-board fuel. The orbit is designed to eliminate eclipses due to the Earth and Moon and has an approximate 6-month period. Roman's field of regard, shown in Figure 2, provides total sky coverage over a year, implemented as a 72° swath with 360° of rotation. It is centered along the ecliptic poles to provide a continuous viewing zone to enable monitoring of supernova every five days over a two-year period. The large pitch range (+/-36°) was set to allow viewing of the galactic bulge for 72 continuous days, providing some scheduling margin for the minimum 60-day viewing required for the GBTD survey. In addition, the Observatory is allowed to roll +/- 15° about the boresight to allow diversity in viewing targets at different angles. The Observatory is designed to maintain pointing within the field of regard.

**Table 1. Roman Mission Phases**

| Phase | Description |
|---|---|
| **Pre-Launch** | Observatory-Level I&T<br>Ship to Launch Site<br>Preparations for Launch |
| **Launch to Mission Orbit** | Launch & Ascent<br>Coast Phase<br>Launch Vehicle Separation<br>Cruise / Commissioning |
| **Baseline Science Mission** | Libration Orbit Insertion<br>Nominal Operations<br>Contingency Operations |
| **End of Mission** | Extended Mission<br>Passivation |

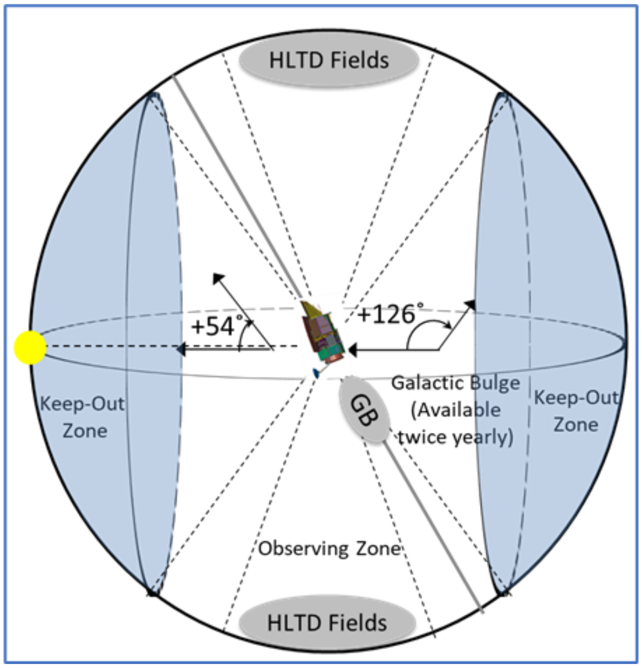


**Figure 2: Roman Field of Regard**

The Roman mission is managed by NASA's Goddard Space Flight Center (GSFC). GSFC is responsible for the development of both the flight and ground segments as well as integration of the mission. The flight segment consists of the Observatory and Launch Vehicle (LV), with prime developers of the LV and Observatory elements spread across the federal government and industry, as noted in Table 2. For the purposes of assigning development responsibility to managers within the Project, the Observatory has been divided into five management elements: the Optical Telescope Assembly (OTA), the Instrument Carrier (IC), the Wide Field Instrument (WFI), the Coronagraph Instrument, and the Spacecraft. The ground segment is focused on ground system development, and, while managed by GSFC, is supported by government and non-government entities across the aerospace industry and the country. It relies on multiple space-to-ground networks, including some international contributions. Notably, the mission operations center is developed by GSFC, where flight operations will be conducted.

**Table 2: Roman Flight Segment Developers**

| Flight Segment Element | | Developer |
|---|---|---|
| **Launch Vehicle** | Launch Vehicle & Services | NASA Launch Services Program |
| **Observatory** | Spacecraft | NASA Goddard Space Flight Center (GSFC) |
| | Optical Telescope Assembly | L3Harris |
| | Wide Field Instrument | NASA GSFC & Ball Aerospace |
| | Coronagraph Instrument | Jet Propulsion Laboratory |
| | Instrument Carrier | NASA GSFC |
| *NASA GSFC (Greenbelt, MD); L3Harris (Rochester, NY); Ball Aerospace (Boulder, CO); NASA JPL (Pasadena, CA)* | | |

## 3. Observatory Description

The Roman Observatory is a dimensionally large and massive space telescope. When fully deployed, it will stand over twelve meters in height and weigh around 10,500kg. It will be the largest Observatory assembled and tested at NASA's GSFC.

The hardware breakdown structure in Figure 3 shows the Observatory, comprised of the Integrated Payload Assembly (IPA) and the Spacecraft. The OTA, the IC, the WFI, and the Coronagraph comprise the optical system, provide the science measurement functions, and are integrated to form the IPA. The Spacecraft element provides the usual bus functions (command and data handling, attitude control, thermal control, etc.) and accommodations (power distribution and analog services) for the Observatory, along with assemblies that provide communications, power generation, thermal and stray light control, and attitude control sensing. These assemblies are the High Gain Antenna System (HGAS), the Lower Instrument Sun Shades (LISS), Outer Barrel Assembly (OBA), the Solar Array Sunshield (SASS), the Deployable Aperture Cover (DAC), and the Star Tracker (ST)/Inertial Reference Unit (IRU) bench. Figure 3 also shows how the management elements are related to the assemblies making up the Observatory. Figure 4 shows the physical layout of the Observatory including the various elements and Spacecraft assemblies.

*Spacecraft Overview*

The Roman Spacecraft consists of an integrated Spacecraft bus (including the HGAS and LISS), an OSD (consisting of the OBA, SASS, and DAC), and an ST/ IRU bench, as shown in Figure 5. The bus is the primary structure for the entire Observatory, while the OBA supports the SASS and DAC. The ST/IRU bench mounts on the instrument carrier.

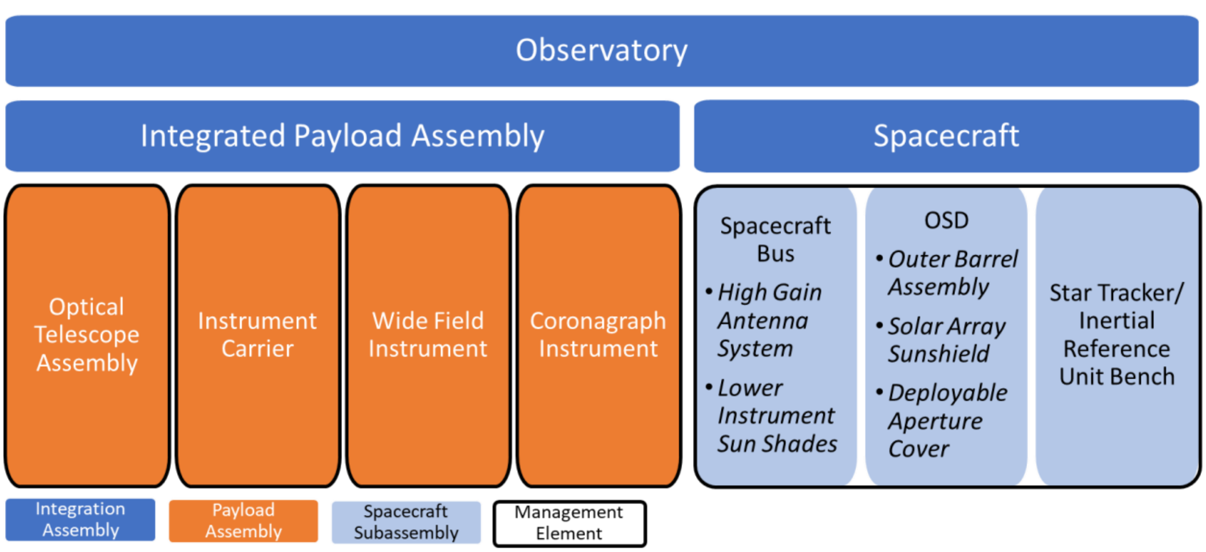


**Figure 3. Roman Observatory Hardware Breakdown Structure**

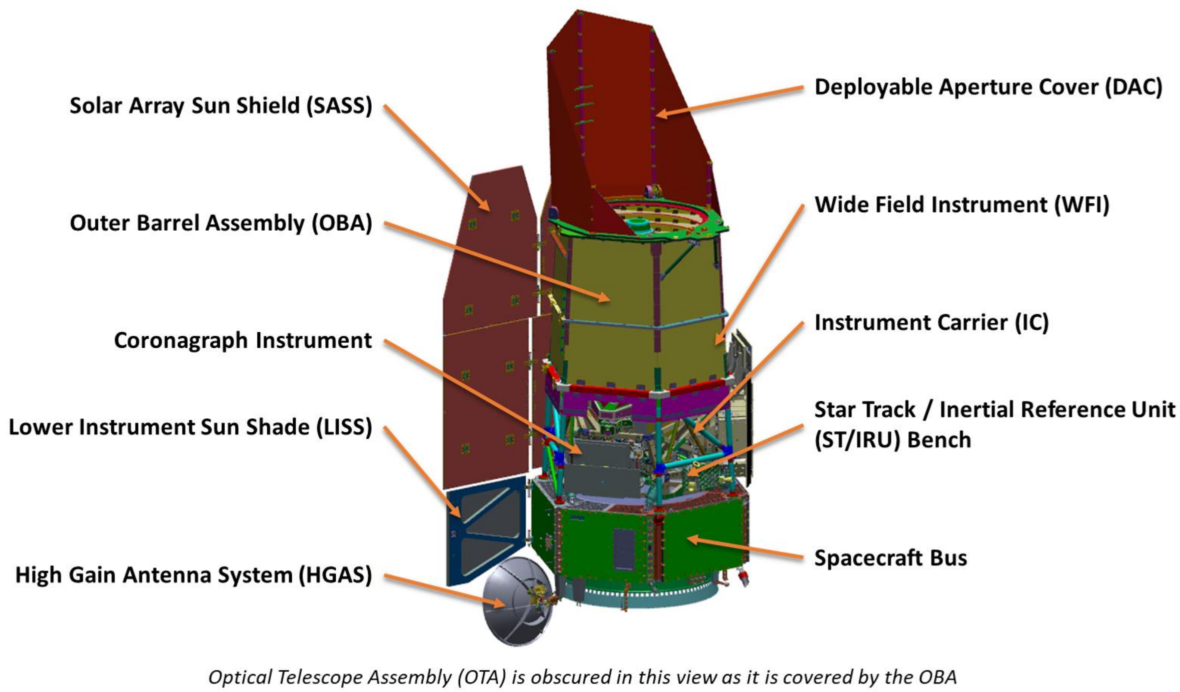


**Figure 4: Roman Observatory Physical Layout**

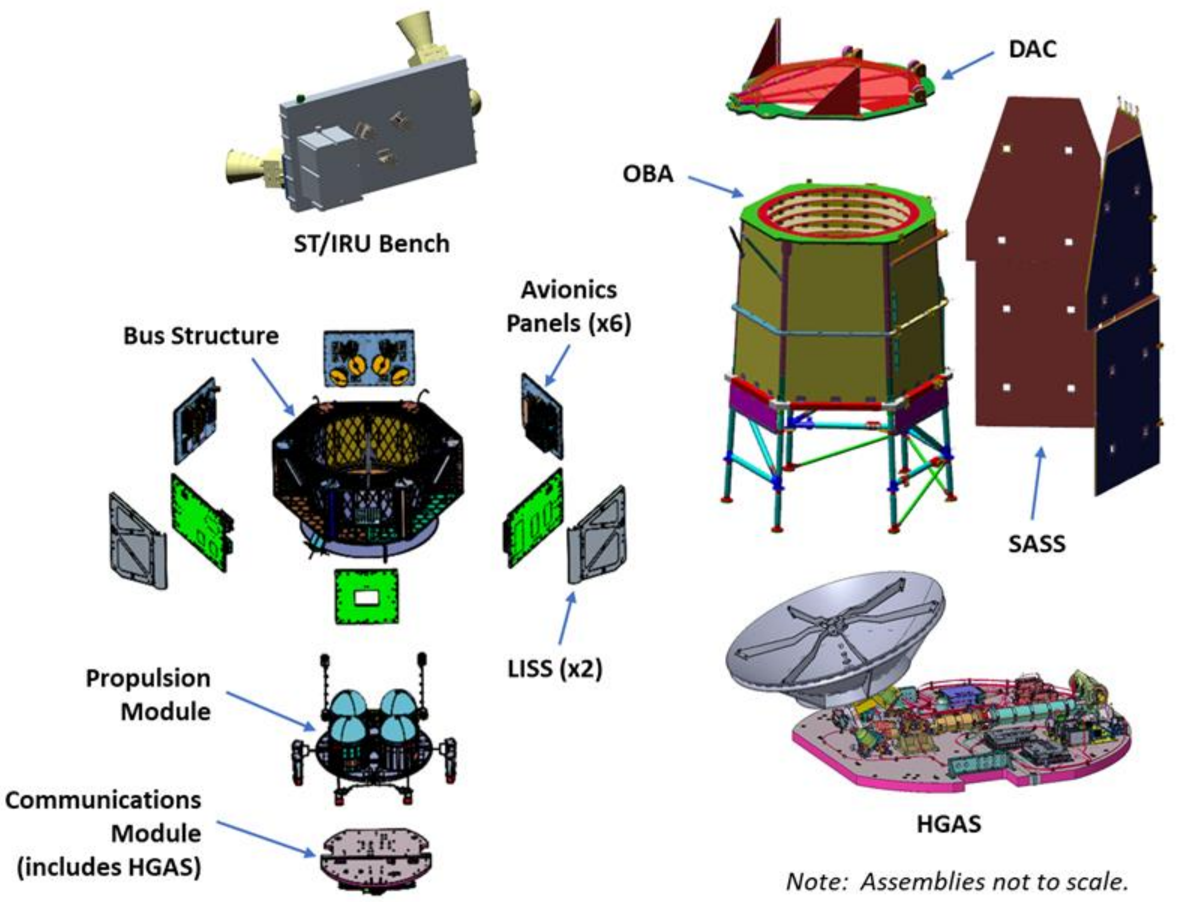


**Figure 5: Expanded View of Spacecraft Assemblies**

The Spacecraft is responsible for providing electrical power, attitude control, space-ground communications, command and data handling, thermal control, propulsion, flight software, post-launch release/deployments, and stray light and thermal protection of the IPA. The following paragraphs give some additional detail on the main components of the Roman Spacecraft.

*Spacecraft Bus*—The Spacecraft bus is an aluminum isogrid hexagonal bus structure with six avionics bays that are hinged for ease of integration and testing. Spacecraft and Instrument avionics boxes mount directly to the panels, which serve as thermal radiators. The components mounted on the avionics panels include the two Spacecraft Command and Data Handling (C&DH) units; the two Science Data Recorders (SDRs); the two Deployment and Propulsion Electronics (DPE) units; the single, internally redundant Power System Electronics (PSE) unit; the single, internally redundant Power Distribution Unit (PDU); the single Battery; and six Reaction Wheel Assemblies (RWA). Each RWA is mounted on a vibration isolation system that serves to prevent RWA disturbances from impacting instrument observations. In addition, the Spacecraft avionics panels house avionics for both the Wide Field Instrument (the two Instrument Command and Data Handling (ICDH) units and the single, internally redundant Mechanism Control Electronics (MCE)) and the Optical Telescope Assembly (the single, internally redundant Telescope Control Electronics (TCE)).

Inside the bus is a centrally mounted mono-propulsion hydrazine propulsion system that includes four propellant tanks, sixteen 5N thrusters, and eight 22N thrusters supported by an aluminum isogrid propulsion deck. The Propulsion system supports the maneuvers necessary to adjust the trajectory to the mission orbit, insert Roman into its mission orbit, and perform the stationkeeping and momentum-unload maneuvers for on-orbit operations. At the end of the Science mission, the Propulsion system will also support disposal maneuvers needed to remove Roman from its L2 orbit.

At the bottom of the bus is the communications module which supports the avionics for the dual-band (Ka- and S-) Radio Frequency Communications subsystem and the deployable, two-axis gimbaled 1.7m dual-band high gain antenna. The S-band system is used for two-way, command uplink and low-rate housekeeping telemetry downlink and ranging between the Spacecraft and ground stations. The Ka-band system is used for high-rate science data downlink to the ground stations. In addition, two omni S-Band antennas are provided for initial post-launch communications (until the High Gain Antenna System (HGAS) is deployed) and contingency communications during the operational mission.

The LISS augment the straylight and thermal isolation functions of the SASS. They are two deployable panels mounted on the outside of the two Spacecraft bus panels directly below the lower deployed SASS panels.

*Outer Barrel Assembly*—The OBA is a hexagonal, composite, panel-construction structure that mounts to the Spacecraft top deck around the IPA. It provides structural support for the SASS and DAC and thermal and straylight protection for the telescope. Mounted inside the OBA are ten composite baffles that prevent far out-of-field light from reflecting off the walls of the OBA and having a direct line-of-sight to the primary mirror.

*Solar Array Sun Shields*—The SASS consists of six panels (two fixed and four deployable) populated with solar cells that provide approximately 4500W of power generation capability at the end of life and at the maximum Observatory pitch and roll angles. The SASS is supported by the OBA, where the two center panels are fixed to the OBA and the outer four panels deploy after launch to assist in providing straylight and thermal isolation for the IPA. In addition, the SASS also provides mounting locations for several of the Coarse Sun Sensors used by the Attitude Control System Safehold control mode.

*Deployable Aperture Cover*—The DAC is a is a one-time deployable soft-structure cover that, when stowed, protects the telescope from direct sunlight during post-launch activities (e.g. initial sun acquisition, mid-course correction maneuver) when the science field-of-regard pointing constraints cannot be maintained. After deployment, the DAC prevents direct sunlight from entering the OBA at the extreme angles of the field of regard. In addition, the DAC also provides mounting locations for several of the Coarse Sun Sensors used by the Attitude Control System Safehold control mode.

*Star Tracker/Inertial Reference Unit Bench*—Three star trackers and a single, internally redundant IRU are used by the Attitude Control System to facilitate transition from coarse to fine attitude pointing and control, where guide stars on each of the WFI detectors serve as the fine guidance sensor. To facilitate optical alignment and stability between the various sensors used by the ACS, the STs and IRU are mounted on a common, thermally stable bench which is, in turn, mounted on the instrument carrier along with the WFI and the Coronagraph instrument.

*Integrated Payload Assembly*

The IPA, as seen in Figure 6, features the OTA with an existing, repurposed 2.4m primary mirror; the WFI for imaging and spectroscopy in support of the prime science; as well as a Coronagraph instrument technology demonstration with starlight suppression technology for direct imaging and spectroscopy of exoplanets. The telescope and instruments are mounted to the IC composite truss structure which also optically meters each instrument and includes a Launch Load and Vibration Isolation System (LLVIS) to provide passive isolation of Spacecraft disturbance sources while also supporting the IPA during launch. The IPA is attached to the Spacecraft Bus.

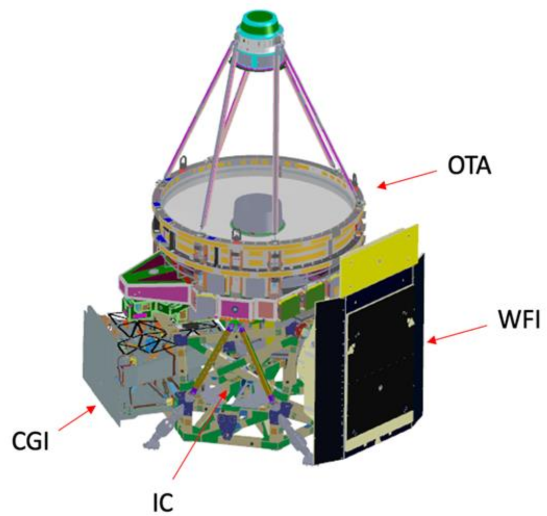


**Figure 6. Integrated Payload Assembly**

*Optical Telescope Assembly*—The OTA is the optical front end of the Observatory and directs light to each instrument. It consists of the Imaging Optics Assembly (IOA) and the TCE as shown in Figure 7. The TCE is mounted to one of the Spacecraft bay panels, while the IOA is mounted to the IC.

The IOA consists of the Forward Optics Assembly (FOA), FOA struts, Aft Optics Module (AOM), and Tertiary Collimator Assembly (TCA). The FOA is mostly inherited hardware, refurbished and repurposed for the Roman mission application and includes the first two optics of a three-mirror Anastigmat imaging system. It is the common optical path for the two instruments. The inherited 2.4-m primary mirror of the FOA was modified and refinished to fit the optical design[1] of the Roman Observatory, as well as

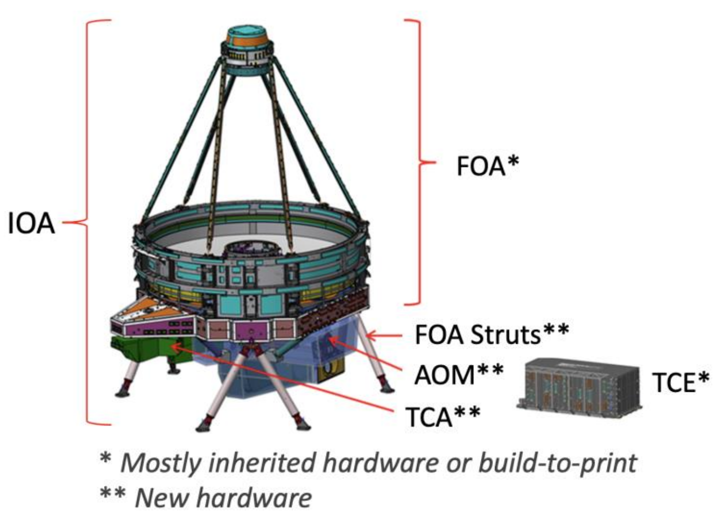


**Figure 7. Imaging Optics Assembly and Telescope Control Electronics**

the secondary mirror, which includes flight alignment compensation for on-orbit commissioning and periodic adjustments. Both mirrors operate at approximately 265 K, well below their original room temperature planned operating point.

The AOM, operating at approximately 220 K, is the relay optics needed to forward the light ray bundle to WFI and includes an actuated mirror, fixed relay mirror, and tertiary mirror. The TCA is the relay optics needed to forward the light ray bundle to the Coronagraph and consists of five mirrors, one of which is actuated, operating at about 293 K. The AOM, TCA, FOA struts, secondary mirror support struts, and baffling to mitigate stray light are new Roman hardware. Overall, the IOA is designed to meet image quality and nanometer-level optical stability requirements for the Observatory.

The TCE is the fully redundant electronics that will control and manage OTA thermal and actuator functions. The TCE provides mechanism control for the secondary mirror alignment and focus actuators, the actuated mirrors in the AOM and TCA described above, as well as monitors OTA telemetry, controls OTA heaters, and communicates with the Spacecraft C&DH.

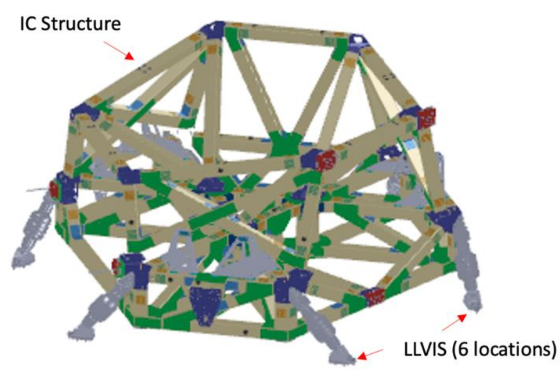


**Figure 8: Instrument Carrier**

*Instrument Carrier*—The IC consists of a truss structure and an isolation system and is the primary load path and optical metering structure for the IPA and ST/IRU bench, providing stiff, stable support. The IC structure is a composite tube frame joined with titanium fittings, clips, and composite gussets, as shown in Figure 8, and operates at approximately 213 K. The structure is derived from the James Webb Space Telescope[2,3], using the same composite laminate and fabrication process. The WFI, CGI and OTA all mount to the IC and the IC mounts to the Spacecraft bus via the LLVIS. The LLVIS is a thermally controlled, passive isolation system that supports the IPA during launch and isolates Spacecraft-generated disturbances on-orbit. The on-orbit isolation is critical for meeting wave-front stability and line-of-sight jitter requirements.

*Wide Field Instrument*—The WFI[4] performs both wide field imaging and spectroscopic science observations, with a focal plane array comprised of 18 4kx4k pixel mercury cadmium telluride (HgCdTe) near-infrared detector arrays, a complement of filters, and grism and prism elements. The WFI detectors are arranged in a six by three mosaic shown in Figure 10. The instrument detectors operate via passive cooling at approximately 95 K and the filters at approximately 180 K. The WFI provides on-board calibration to monitor changes in non-linearities, flat field pattern, and detector persistence. It also provides flexible sampling and compression to tune science data content and volume for each observing program mentioned above, in addition to providing guide sensors for fine guiding. Guide stars for each detector are selected by the ground and adjustable windows are commanded around expected position. WFI then provides attitude correction estimates to the ACS to maintain fine pointing control. The associated optics, focal plane system, relative calibration system, sensor electronics, radiators and other components are in the Cold Sensing Module (CSM), shown in Figure 9 for reference, supported below the OTA and kinematically mounted to the IC by three instrument latches.

Select WFI electronics are located on the Spacecraft bus and consist of the two ICDH units, one of which is a cold back-up, and the internally redundant MCE. These avionics are maintained at a near-room temperature environment by Spacecraft thermal control. The ICDH receives primary bus power from the Spacecraft and provides switched power outputs to internal WFI components, as well as receives commands from and sends telemetry to the Spacecraft C&DH. The ICDH communicates with the MCE and with the focal plane electronics for operation of the instrument

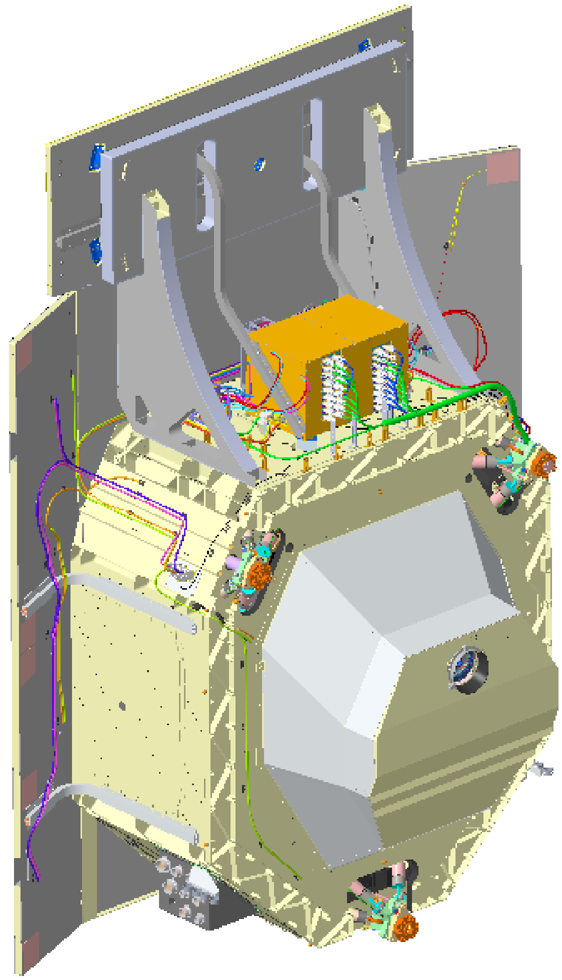

**Figure 9. WFI Cold Sensing Module**

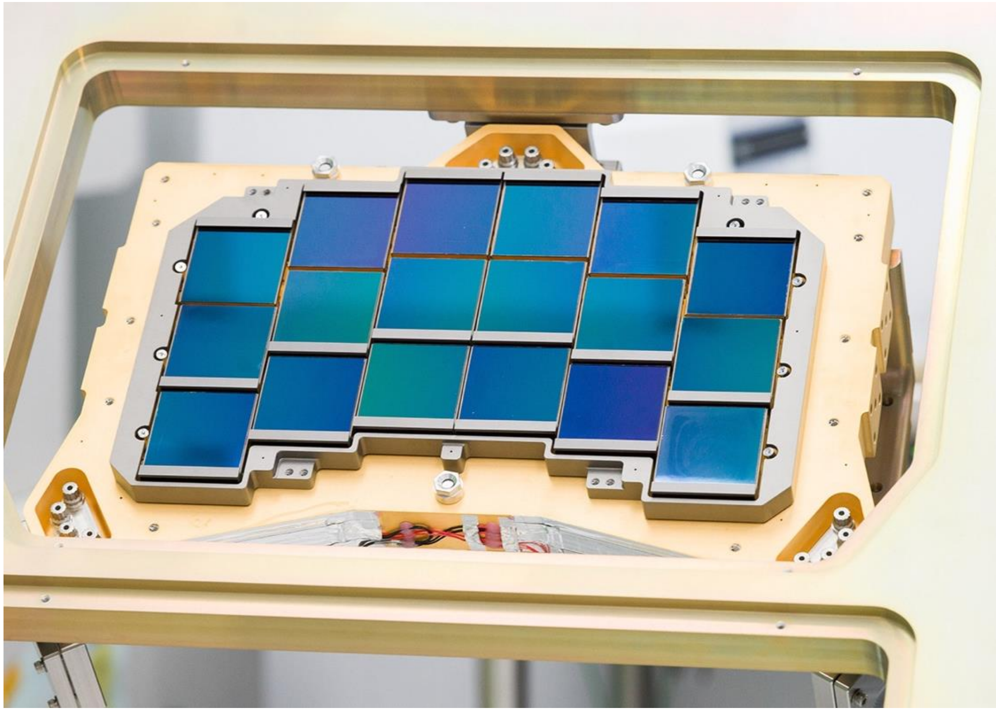

**Figure 10. WFI Engineering Test Unit Detector Focal Plane Array**

detectors and associated electronics. The MCE controls the alignment compensation mechanism, filter element mechanism, and a portion of the instrument heaters, in addition to the electronics, mechanisms, heaters, and light sources within the relative calibration system. Science data from WFI is transmitted directly from the WFI focal plane electronics multiplexer control card to the Spacecraft SDR, which multiplexes the large stream of image data coming from the 18 detector arrays into a single stream over a high speed Serializer/Deserializer (SERDES) link.

*Coronagraph Instrument*—The Coronagraph[5,6] is a technology demonstration that will perform both high contrast broadband imaging and spectroscopy of exoplanets using three different observational modes. The observation modes achieve starlight suppression with interchangeable coronagraphic masks, the Hybrid Lyot Coronagraph masks, and the Shaped Pupil Coronagraph masks. The Coronagraph, including its optical bench, avionics, and thermal subsystem and radiator and shown in Figure 11, is supported below the OTA and kinematically mounted to the IC by three instrument latches.

The actuators and mechanisms, including associated optics, sit atop the optical bench. The wavefront sensing and control system includes low- and high-order wavefront sensor subsystems and cameras. The avionics control the thermal system, actuators, and mechanisms; provide the power interface to the Spacecraft; distribute power to the internal components; and receive commands from and send telemetry to the Spacecraft C&DH. Like the WFI, Coronagraph science data is routed directly to the SDR for ultimate downlink.

## 4. SURVEY MISSION CHALLENGE

One of the most notable features of the Roman mission is that it is a true survey mission. To achieve the Wide Field Science surveys described in the Mission overview, the Observatory must be capable of implementing a large number of small slews followed by relatively short observations that need very stable pointing. In order to show the feasibility of meeting the top-level science requirements within the baseline five-year mission lifetime and to assess many aspects of the mission, including data storage requirements, slew requirements, data downlink time, etc., a notional timeline, referred to as the design reference mission (DRM) was established to capture key parameters of the various surveys and to map them into the minimum required life[7]. As can be seen in Table 3, based on the DRM, there are expected to be over 630,000 WFI exposures during the baseline Science mission with a comparable number expected should the mission be extended an additional five years. This large number of slews coupled with the need for highly stable observations has presented design challenges for the Roman Observatory team. The Observatory architecture and mission operations concepts must be implemented with high degrees of observing efficiency and stability.

**Table 3. Projected Roman Observations based on DRM**

| Observing Program | DRM Time Allocation (days) | WFI Exposures (qty) |
|---|---|---|
| High Latitude Wide Area Survey – Imaging | 290.5 | 135,304 |
| High Latitude Wide Area Survey – Spectroscopy | 230.5 | 44,352 |
| High Latitude Time Domain Survey | 180.7 | 47,304 |
| Galactic Bulge Time Domain Survey | 372.0 | 273,420 |
| General Investigator Program | 411.0 | 132,928 |
| Exoplanet Coronagraphy Technology Demo | 90.0 | |
| TOTAL | 1574.7 | 633,308 |

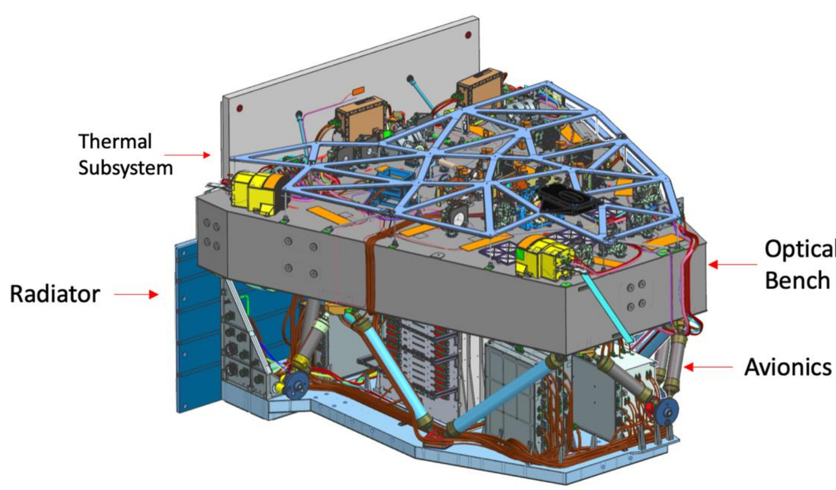


**Figure 11. Coronagraph Instrument**

*Event-Driven Operations*

One way in which Roman achieves high efficiency is through the implementation of event driven operations within the Spacecraft flight software. Rather than queuing activities such as slews and instrument observations based on relative time, the event driven operations software queues the next step in an observation sequence based on conditional flags exchanged between the instruments and the Spacecraft. The architecture not only optimizes observations in a time-wise sense but also allows for parallel execution of flight procedures, for instance slewing the Observatory while configuring the WFI instrument with the optical element that will be used for the next observation. Given the large number of observations planned for Roman, allowing activities to progress immediately upon completion of the previous activity and performing activities in parallel where possible is predicted to save months-worth of observation time.

*Balancing Stability with Speed*

As was noted previously, the Roman Observatory is quite large. The projected wet mass at launch is around 10,500 kg with moments of inertia around (24,000; 42,000; 42,000) kg-m2 for (Ixx, Iyy, Izz), respectively. Ideally, a survey mission wants to be able to slew very quickly from target to target to optimize the amount of observing time. However, Roman's large size and need for very stable, quiet (i.e. low jitter) pointing makes such agility challenging. Control Moment Gyros (CMGs) are usually the optimal actuator to provide large amounts of torque to enable fast slewing. Unfortunately, a trade study determined that CMGs were not an option for Roman. The coarse torque command resolution found in commercially available CMGs would not allow for fine enough control to meet the Roman pointing stability requirements, 8 milli-arcseconds/axis (1-sigma) for most observations. In addition, CMGs would induce too much disturbance through the Observatory, which would cause line-of-sight jitter at the WFI focal plane to exceed requirements, 12 milli-arcseconds/axis (1-sigma) for most observations.

Another option to optimize agility would be to pair CMGs with reaction wheels, with CMGs providing slewing torque and reactions wheels being used for high precision pointing and momentum storage. However, Roman had neither the space nor the power to support both CMGs and reaction wheels. With CMGs eliminated as an option, the Roman team had to rely on reaction wheels alone for slewing, stable pointing, and momentum storage. In order to improve slewing agility with the lower torque reaction wheels, Roman opted for six reaction wheels mounted in a pyramid configuration that optimizes the amount of torque in the Observatory pitch and yaw axes, where the majority of slews take place. In addition, the selected reaction wheels will be augmented to provide higher torque (approximately 0.6 Nm vs. the standard 0.2 Nm) at the cost of lower momentum storage capability.

To further improve agility, the Roman Attitude Control System (ACS) control modes are designed to optimize both slew and settling times. Slews are accomplished by designing optimal target-to-target slew profiles that maximize available torque authority. Throughout the slews, control torque is further optimized to minimize deviations from the ideal slew profile such that settling time at the final target is minimized. The ACS control algorithms provide flags to the event driven operations software when the Observatory is "sufficiently settled" to begin Science observations.

While reaction wheels are quieter than CMGs by default, Roman's pointing stability and line of site jitter requirements are such that additional mitigations are necessary to ensure the disturbances from the rotating reaction wheels do not induce excess jitter at the instrument focal planes. The LLVIS provides some isolation of the IPA from the Spacecraft-induced disturbances; however, that isolation alone is not enough to meet science requirements. The reaction wheels will be finely balanced and are each individually mounted on a vibration isolation system. In addition, the reaction wheel speeds will be controlled through the system null space in order to push the wheels through any speed ranges that are determined to detrimentally excite structural modes. In addition to the LLVIS and reaction wheel vibration isolation system, Roman jitter mitigation efforts also include a passive jitter damper on the HGAS boom and passive tuned mass dampers on the SASS.

## 5. DATA VOLUME CHALLENGE

The iconic feature of the Roman mission is the six-by-three detector mosaic implemented in the WFI and shown previously in Figure 10. A single image readout produces 4.98 Gbits of data and continuous readout of raw images translates to a data rate of ~2.6 Gbps, including interleaved guide window readouts and overheads. Continuous readout is, in fact, an important implementation feature as it is a key method used to reduce noise, since the H4RGs are read out non-destructively, and maintain thermal stability of the detectors over the course of observations. In combination with downlink from L2, data volume is a cross-cutting challenge that requires careful architecting so that no single subsystem finds itself in an overly constrained design space. This challenge has implications that stretch across multiple aspects of the Mission, from the design of the mission L2 orbit to maximize use of White Sands ground station to the need for a large-capacity, high-speed science data recorder and a high-speed Ka transmitter to the size of the High Gain Antenna to the design of the science data management flight software to allow for selection and prioritization of which data is downlinked to the scheduling of science observations and ground station time to get all of the data to the ground each day.

**Table 4. Science Data Volume by Survey Type. WFI data is sampled (i.e. "Resultant Frames per Exposure") and compressed (i.e. "Effective Reduction Factor") to fit within 11 Tbits/day average downlink requirement**

| | Design Reference Mission Parameters | | | | Required On-Board Storage | | |
|---|---|---|---|---|---|---|---|
| Program | Average Exposures (qty) | Exposure Duration (sec) | Resultant Frames per Exposure (qty) | Resultant Frames (qty) | Raw Daily Volume (Tbits) | Effective Reduction Factor[1] | Volume to SDR (Tbits) |
| High Latitude Wide Area Survey - Imaging | 472 | 146 | 8 | 3785 | 18.9 | 2.7 | 7.0 |
| High Latitude Wide Area Survey - Spectroscopy | 236 | 322 | 10 | 2363 | 11.8 | 2.5 | 4.7 |
| High Latitude Time Domain Survey | 261 | 900 – 3600[2] | 10 | 1881 | 9.4 | 2.6 | 3.6 |
| Galactic Bulge Time Domain Survey | 739 | 55 | 6 | 4410 | 22.0 | 2.1 | 10.4 |
| General Investigator | 323 | | | | 15.5 | 2.1 | 7.4 |
| Exoplanet Coronagraphy | 7 | | | | 0.8 | - | 0.9 |

***Notes:***
***1. The effective reduction factor takes into account overheads due to data packaging protocol, additional housekeeping telemetry required for science data processing, and compression of the full WFI data to fit within the 11 Tbit/day average.***
***2. Worst case***

Balancing implementation risk starts with establishing a daily downlink volume. Early science studies, along with compression studies, found that sufficient science return isachieved with a minimum daily downlink of 11 Tbits. This daily downlink includes both WFI and Coronagraph data but is driven by the WFI data. While the Mission is designed to achieve an average daily science data downlink of 11 Tbits per day, the DRM accommodates varying amounts of data for the different science campaigns as shown in Table 4. In addition to the average data volume requirement, the Mission is designed to collect uncompressed, raw WFI data for short durations of time for calibration and engineering purposes. With these fundamental requirements established, the Observatory design is driven in key areas: data compression and sampling, data storage, and data transmission.

*Data Compression and Sampling*

Data sampling and compression is the first "knob" that can be turned in data volume management as it reduces the amount of data to be managed in the first place while maintaining the information content that is necessary to meet science objectives. The WFI implements both multi-accumulation and compression methods to reduce data volume. Multi-accumulation allows for sampling of detector frames, either individually or in linear combinations, at ground-specified intervals during an exposure. This function grants great flexibility to the design of science campaigns such that the exact read out scheme of the detectors can be specified while limiting the downlinked data to meet the daily science downlink volume requirement. Rice compression within the WFI is used to losslessly compress the data to further reduce the data volume.

*Data Storage*

The Roman SDR stores science data for both WFI and the Coronagraph Instrument, in addition to guide window and ancillary engineering data needed for science data processing. Data storage requirements are driven completely by WFI, with the Coronagraph instrument requiring only a very small fraction of memory. The current architecture evolved over time as requirements changed during the early phases of the mission. One trade studied the functional split of WFI electronics along the science data path (from detectors to data storage) to create the interface between the WFI cold sensing module and Spacecraft-mounted electronics. After balancing thermal, mechanical, electrical, and jitter transmissibility constraints, it was determined that the data sampling, compression, and multiplexing functions should be co-located with the detectors and the SERDES interface would be used to transport the digitized data to storage. To maintain signal integrity, the SERDES harness is limited to a six-meter length, which poses implementation challenges given the size of the Observatory. This early trade ultimately led to an architecture in which science data storage is handled in a dedicated Spacecraft avionics box with a processor separate from the main flight computer and direct interfaces with both the Instruments and the Ka transmitter.

The SDR is a new GSFC development, implemented with 9 Tbytes of flash memory, not only designed to handle the nominal data volume but also to accommodate a 24-hour period of missed downlink passes and brief bursts of uncompressed, raw WFI images. File management is a challenging area for the SDR flight software. High level functions include science data recording, file queueing for downlink, science data playback, and science data accounting. The queueing function allows files to be prioritized for downlink to support science targets of opportunity. Data accounting is an important function when it comes to file retransmission to the ground and memory release for overwriting.

*Data Transmission*

Science data transmission is achieved on Roman via a Ka-band downlink. The Observatory transmission path includes redundant Ka-band transmitters, connected directly to the SDRs via a SERDES link, and an RF network connected to the gimbaled High Gain Antenna (HGA). The Ka transmitter is a GSFC in-house development and extends the capability of a design used on a previous mission. It supports a downlink information rate requirement of up to 500Mbps while in the baseline orbit. This rate is based on a 20 deg elevation at 95% availability at White Sands on an 18-m antenna with 0 dB margin.

The HGA is a 1.7m dish with a +/-0.2 deg pointing requirement from L2. This pointing requirement from L2 is challenging and has necessitated careful consideration of the HGA pointing budget, including thermal distortion effects of the SC bus, the HGA boom, and the dish itself. Calibration of the HGA pointing using received power at the ground station is planned during commissioning to remove gross misalignments and bulk cool-down thermal distortion effects. Transient thermal distortion errors are being analyzed as part of the Roman integrated modeling effort and the need for thermal distortion testing is under consideration. The decision to live with one HGA was difficult technically, but physical constraints did not allow for another choice without upending mature designs in other areas.

Challenges with data transmission extend to operational and orbit design spaces. Operationally, the HGA is pointed ahead at the edge of ground station visibility, to avoid stepping during science observations, potentially inducing jitter effects in the science data. It is also stepped during slews to maintain pointing with the White Sands, the primary ground station for the Roman mission. As for orbit design, the data volume requirement translates to a daily minimum of seven hours of contact time with White Sands. This flight dynamics requirement, in turn, imposes constraints on the size and tilt of the orbit, which drives orbit maneuver knowledge and accuracy requirements. With the orbit designed for this contact time and international contributions of ground station time from ESA and JAXA, the daily downlink volume is met with margin.

## 6. Packaging and Opto-Mechanical Interface Challenges

One challenge for NASA's space telescope missions is the packaging of payloads and Spacecraft subsystems in order to fit within launch vehicle volumetric constraints while balancing thermal, mechanical, optical, environmental and electrical requirements of the mission. Defining envelopes around each element enables parallel development and iteration of each element's design, while maintaining static, dynamic and integration critical clearances between the envelopes. In addition to packaging, another critical interface to manage is stray light, which feeds into the optical performance of the telescope.

Defining and managing interfaces are key to ensuring all subsystems work together and perform as expected. On Roman, interfaces are controlled through Interface Control Documents (ICDs) and are generally organized as Element-to-Element ICDs (i.e., IC-to-WFI, SC-to-CGI, OTA-IC, etc.), in addition to a level-of-assembly ICD in the IPA-to-SC, to capture the higher-level configurations and complex interfaces that span across multiple elements. Figure 12 shows a simplified interface matrix and ICD structure for each Roman element and integration assembly. As the LV has not been selected, it is important to define interfaces in such a way that conservatism is maintained for the Observatory design with respect to the launch environment, LV fairing envelope, and launch through separation attitude constraints. Lacking an LV vendor, interface requirements have been established in an Interface Requirements Document (IRD) with LSP.

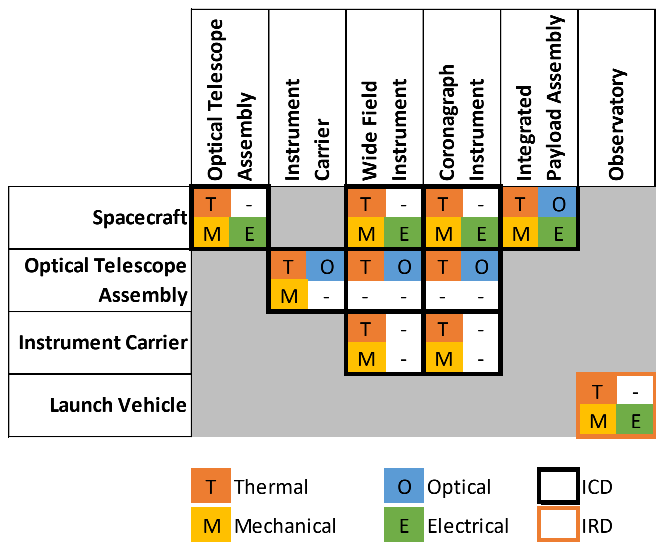


**Figure 12. Interface Control Document Structure and Content**

*Element Envelopes*

Packaging is especially challenging for Roman since the design needs to be managed around existing telescope hardware, as well as meet strict optical and thermal constraints. Figure 7 shows the areas where new IOA hardware was designed to interface with the instruments, and Figure 6 shows how the IOA fits on the truss structure of the IC.

During the packaging design process in the formulation phase, many interferences between the IPA Elements (shown in Figure 6) needed to be resolved in parallel to maintain development schedules and finalize the overall Roman optical design. This entailed multiple design iterations, between GSFC and Roman external partners, of the AOM, TCA, and IC, working a Tetris-like engineering problem to optimize the opto-mechanical packaging, while taking thermal and mechanical constraints into account. After negotiating volume and completing the Roman optical design, not-to-exceed, dynamic envelope requirements were created for the IPA Elements to maintain and manage critical clearances for the Observatory.

Envelope negotiation then expanded beyond IPA Elements to include the Spacecraft Element and its subsystems, shown in Figure 4. A large early effort of the Roman team was also focused on resolving interferences in two key areas of the Observatory: 1) between the OBA and the IOA and 2) between the OBA and the LLVIS. The OBA surrounds the FOA to provide thermal and straylight protection and is newly designed hardware. In contrast, the majority of the FOA, where the interference existed, was already built hardware. Resolving these interferences was a balance of minimizing changes to pre-existing FOA hardware while maintaining flexibility in the OBA design to meet thermal stability requirements. Through envelope negotiations and design assessments between organizations, these interferences were resolved. The OBA and LLVIS both mount to the Spacecraft top deck (see Figure 13), where volumetric constraints and additional interferences were found. By design, the OBA is mechanically decoupled from the telescope by mounting directly to the Spacecraft top deck. In this case, the team had to work with two evolving designs, with that of the LLVIS being much less mature than the OBA, in addition to the volumetric constraints. OBA and LLVIS envelopes were negotiated and iterated using computer-aided design to maintain desired clearances and close the design while minimizing cost and schedule impacts.

Lastly, packaging includes determining the routing of the harnessing between the IPA Elements and the Spacecraft. The harness between each IPA Element and the Spacecraft needs to be routed along the Spacecraft deck to connect with each appropriate avionics box within the Spacecraft Bus. Since space is limited on the Spacecraft top deck, the harness routing from each IPA Element and associated clearances needs to be negotiated among various stakeholders, while accounting for—sometimes competing—thermal, structural, electrical, accessibility and harness transmissibility constraints. The transmissibility constraint is especially important as it prevents the harness from acting as a mechanical "short" across the LLVIS, transmitting Spacecraft jitter disturbances to the IPA. The WFI to Spacecraft routing was one of the first IPA-Spacecraft harness routing design efforts, involving focused design support from GSFC and Roman external partners, and has set the example for current and future efforts to finalize the harness routing design for the remaining areas of the Observatory.

When working through the packaging, routing and Element envelope development and management process, one lesson learned of the Roman mission is that communication among internal and with external groups is key. This communication involves not only assessing and iterating on the design but balancing technical constraints and compromising across the Elements to minimize cost and schedule impacts for the good of the overall mission.

*Stray Light*

Stray light, or unintended light into the optical system, is a large concern that must be mitigated for space telescopes. One way to mitigate stray light is by implementing baffling around the optics in the design. Through multiple design iterations and coordination between optical, mechanical and thermal teams across the Observatory, Roman included new baffling around the primary mirror, secondary mirror, baffling mounted within the OBA, as well as scrapers on the secondary mirror support tubes and an entrance aperture plate in both the AOM and TCA. This work was critical and complex, as stray light assessments are end-to-end, span across the Observatory Elements, external-internal ownership, and require the most up-to-date models of the design for accurate analysis, which feeds into meeting optical performance and science data

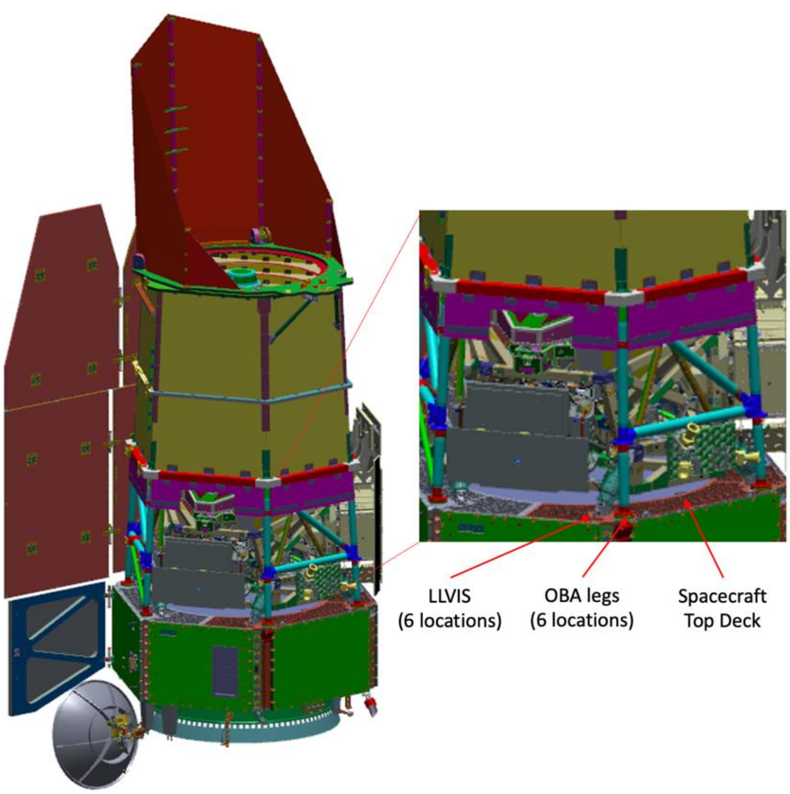


**Figure 13. OBA and LLVIS Mounted the Spacecraft**

requirements for the Mission. For example, the Coronagraph diffraction mask designs are sensitive to details of the pupil obscuration defined by the secondary mirror and its support tube scrapers and had to be defined early in the preliminary design phase to support the timeline for Coronagraph mask design, fabrication and testing schedule.

Another critical and complex effort was determining the closeout designs around the Instrument-telescope aperture interface for both WFI and the Coronagraph. The WFI-AOM interface was an extremely difficult design to finalize, as volume in this area is extremely limited, and design decisions needed to balance both clearance constraints (net volume-to-volume clearances of only a few millimeters) and cost/schedule impacts with meeting stray light, contamination control and thermal requirements for both the WFI and AOM interface. Through multiple, focused assessments, across GSFC and Roman external partners, the WFI entrance aperture and AOM exit aperture design was negotiated and completed. Likewise, the Coronagraph-TCA interface required negotiation and iteration, balancing clearance and integration constraints with meeting stray light, contamination control and thermal requirements for both the Coronagraph and TCA interface. In a similar fashion, the Coronagraph -TCA stray light guard design was negotiated and completed and included in the overall Observatory design. These key design efforts required, not only the most current models from each side of the interface, but good cross-organization communication to help facilitate compromise and convergence on designs that meet all appropriate mission requirements.

*Launch Vehicle Interface*

The Roman Observatory is very large, as previously discussed, sitting at approximately 8.5 m in height and 4.5 m in width in a stowed configuration. Given Roman's size, the LV selection is limited to those capable of launching such a large and massive payload on a trajectory to L2. Although the LV has not been named yet for Roman, interface requirements have been established with NASA's Launch Service Program (LSP). Even though the specifics of the LV are not known yet, assumptions were made in terms of conservative LV constraints and environments to which Roman can design. One challenge that the Roman team worked through during the early stages of the design was defining and negotiating the fairing envelope and maintaining proper clearances within that envelope. Roman must fit within this envelope to ensure feasibility with all appropriate LV options. This requires clear communication between the Roman team and LSP, as well as good clearance management between the Observatory and the fairing envelope as a part of the critical clearance management discussed previously. Other LV interfaces that impact the Roman mission, critical to its success, are structural load and dynamic environments, contamination and thermal environments, as well as electromagnetic compatibility, ground handling and launch through separation attitude constraints. Once the LV is selected, LV interface requirements will be refined and launch environments will be understood, allowing further assessment of the Roman Observatory and LV compatibility.

## 7. SUMMARY

The Roman Observatory is an exciting astrophysics mission that will expand humankind's understanding of the universe. Development of this complex space telescope is challenging and requires many systems engineering tools to be successful. First and foremost is the establishment of a DRM against which requirements compliance can be assessed at all stages of development. Architecture decisions are the next critical step and ideally include building on successful implementations from past missions as well as balancing new challenges across subsystems. Early trades are also key, allowing implications and risks to be identified and evaluated. Finally, open communication within the team and with external partners helps to establish a healthy forum for critical interface negotiations. Many of these tools will carry forward to the next phase of the Roman Mission.

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