# Status of the JWST Sunshield and Spacecraft

J. Arenberg[(1)], J. Flynn[(1)],A. Cohen[(1)], R. Lynch[(2)] and J. Cooper[(2)]

[(1)]Northrop Grumman Aerospace Systems, Redondo Beach CA
[(2)]NASA's Goddard Space Flight Center, Greenbelt MD

## Abstract

This paper reports on the development, manufacture and integration of the James Webb Space Telescope's sunshield and spacecraft. Both of these JWST elements have completed design and development testing. This paper will review basic architecture and roles of these systems. Also to be presented is the current state of manufacture, assembly integration and test. This paper will conclude with a look at the road ahead for each subsystem prior to integration with the integrated telescope and instrument elements at Northrop Grumman's Space Park facility in late 2017.

Keywords: James Webb Space Telescope, sunshield, spacecraft

## Introduction

This paper briefly reviews the major elements of NASA's James Webb Space Telescope that are located on the sunlit side of the observatory, namely the spacecraft and the sunshield. The cold side systems, the telescope and instruments have long been subjects for discussion at this conference for many years and this conference is no exception. [1]With launch rapidly approaching in 2018, this paper will very briefly illustrate how these warm side elements make the scientific mission possible. We will concentrate on how the sunshield's design and performance enable some selected areas of performance key to the scientific mission: thermal, pointing, sky coverage and stray light. The James Webb Space Telescope's primary science comes from infrared light, which is essentially heat energy. To detect the extremely faint heat signals of astronomical objects that are incredibly far away, the telescope itself has to be very cold and stable. This means we not only have to protect JWST from external sources of light and heat (like the sun and the earth), but we also have to make all the telescope elements themselves very cold so they don't emit their own heat energy that could swamp the sensitive instruments. The temperature also must be kept constant so that materials aren't shrinking and expanding, which would disturb the precise alignment of the optics.

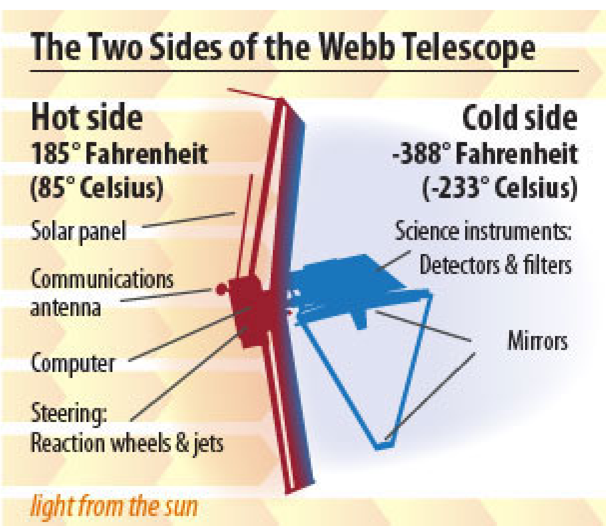

Figure 1: Webb Telescope "Hot side-Cold side" Architecture

Space Telescopes and Instrumentation 2016: Optical, Infrared, and Millimeter Wave, edited by Howard A. MacEwen, Giovanni G. Fazio, Makenzie Lystrup, Proc. of SPIE Vol. 9904, 990405 · © 2016 SPIE · CCC code: 0277-786X/16/$18 · doi: 10.1117/12.2234481

The location of these elements is shown in Figure 1 and shows the “hot-side/cold-side” architecture of Webb.

## Spacecraft

The spacecraft provides vibration isolation, telescope pointing and stabilization and all of the services needed to operate the Observatory. The spacecraft must be very mass efficient to place and maintain the mammoth Webb telescope in it L2 orbit. The spacecraft structure is so mass efficient it can support 64 copies of itself piled on top in 1 g. The spacecraft’s communication subsystem downlinks all mission data at 28 Mbps. That’s a pretty good wifi link from 1.5 million kilometers away. Additional services provided by the spacecraft include electrical power, propulsion for orbit insertion and orbit maintenance as well as momentum unloading, attitude control, thermal control, command and data handling (C&DH), deployment control, communication and structural.

The subsystems of the Spacecraft are:

- Electrical Power Subsystem (EPS)
- Attitude Control Subsystem (ACS)
- Thermal Subsystem (TCS)
- Communications Subsystem (Comm)
- Command & Data Handling Subsystem (C&DH)
- Deployment Control Subsystem (DCS)
- Propulsion Subsystem (PS)
- Structures Subsystem (SMS)
- Cable & Harness Subsystem (C&H)
- Flight Software Subsystem (FSW)

Due to limitations of space, this brief paper will discuss only the ACS, TCS and PS.

The overall function of ACS is to control Spacecraft pointing from separation from the launch vehicle upper stage through the end of the mission. The ACS points and stabilizes the telescope to better than 4 milli-arc-seconds, sufficient to keep a laser pointer shining from New York City to Los Angeles in the palm of a hand. The ACS also ensures the sun always remains on the hot side with no sun on Observatory cold side hardware. In addition, ACS ensure that the High Gain Antenna points at the Earth at all times. During science observations the ACS, within the constraints just mentioned, points the Observatory toward the science target to allow the Science Instruments to acquire and collect science data from the targets.

The ACS hardware used to perform these functions are illustrated in the block diagram in Figure 2.

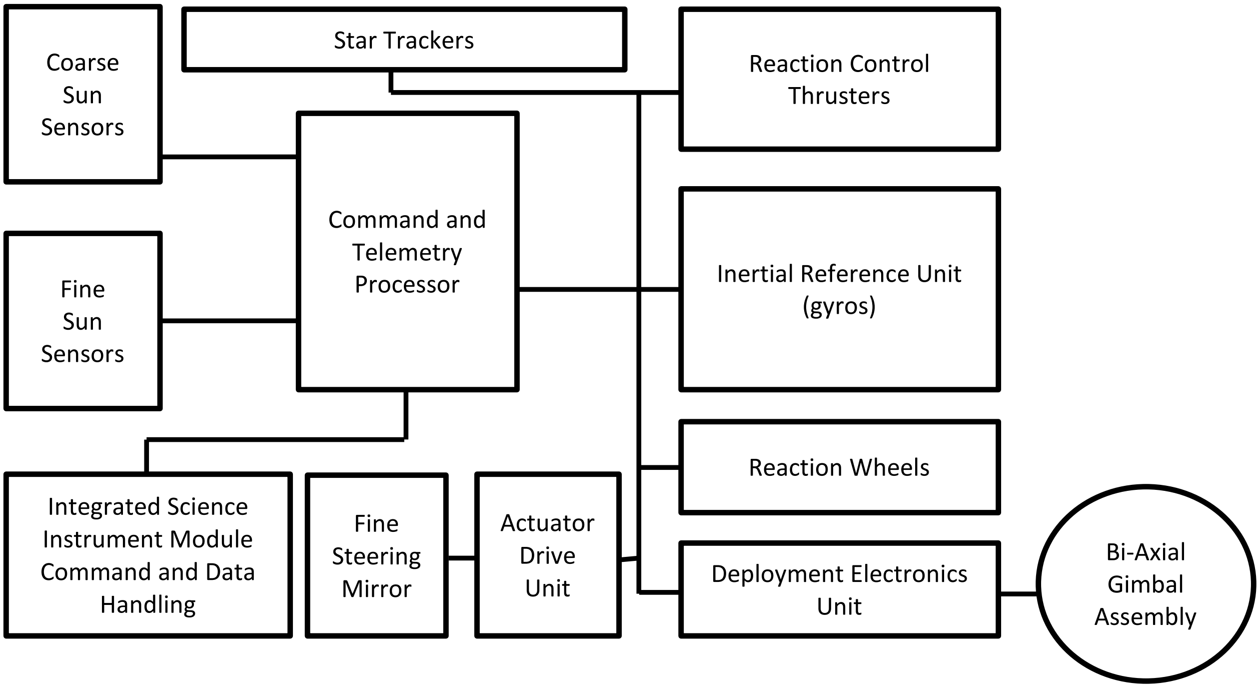


**Figure 2 JWST ACS Hardware Block Diagram**

The Coarse Sun Sensors (CSS) and Fine Sun Sensors (FSS) are used to determine where the sun is relative to the Observatory and help ensure no solar impingement on the telescope.

The Inertial Reference Unit (IRU) is a device used to sense the rate of rotation of the spacecraft with respect to the inertial frame. The IRU uses "Hemispherical Resonator Gyros" or HRGs, similar to those in use on the NASA Chandra X-Ray Observatory. Sometimes called "wine glass gyroscopes," HRGs measure the inertia of flexing vibration in a bowl-shaped stemmed crystal to sense angular motion. HRGs operate in a vacuum and have no rotating or rubbing parts, so they suffer virtually no wear. Webb's HRGs and the Fine Guidance Sensor (FGS) instrument work with the final optic in the telescope, called the fine steering mirror (FSM), to stabilize the beam of light coming from the telescope and going into the scientific instruments. The FSM can tip and tilt a minute amount very quickly to compensate for small motions or "jitter" in the light beam, thus avoiding the need to point the whole observatory extremely precisely. With this scheme, Webb can tolerate less accuracy from its gyros and still perform its science mission.

To turn and point at different objects in space, Webb uses six reaction wheels to rotate the observatory. The reaction wheels are basically flywheels, which store angular momentum. The effect of angular momentum is familiar in bicycle riding. It is much easier to stay up on the bike when it is moving than when it is standing still, and the bicycle will tend to go straight in 'no hands' mode thanks to the angular momentum of the spinning wheels. Slowing down or speeding up one or more of the Webb's reaction wheels alters the total angular momentum of the whole observatory and consequently the observatory turns to conserve angular momentum. Hubble uses reaction wheels also to turn to point at different objects.

The reaction wheels work in combination with three star trackers and six gyroscopes that provide feedback on where the observatory is pointing and how fast it is turning. This enables coarse pointing sufficient to keep the solar array pointed at the Sun and the high-gain antenna pointed at the Earth. To take images and spectra of astronomical targets (i.e., galaxy, star, planet, etc.) finer pointing is needed. Additional information for finer pointing from the Fine Guidance Sensor in Webb's integrated science instrument module (ISIM) is used to move the telescope's fine steering mirror (FSM) to steady the beam of light coming from the telescope and going into the science instruments. Webb's reaction wheels, star trackers, gyroscopes, Fine Guidance Sensor, and fine steering mirror work together in the observatory's attitude control system (ACS) to precisely point and stare at targets so that the science instruments can see them and see them clearly. The system works much the same way your body uses multiple methods of differing precision -your inner ears and eyes and nervous system and muscles - to catch a baseball in the outfield.

The ACS fine pointing also provides time-dependent control of the FGS guidestar position to allow observations of Solar System targets, which move with respect to the background stars at rates of up to 30 mas/sec. The control loops associated with science observations are shown in Figure 2. These include the Spacecraft pointing control loop, the Fine Guidance control loop, and the FSM offload loop.

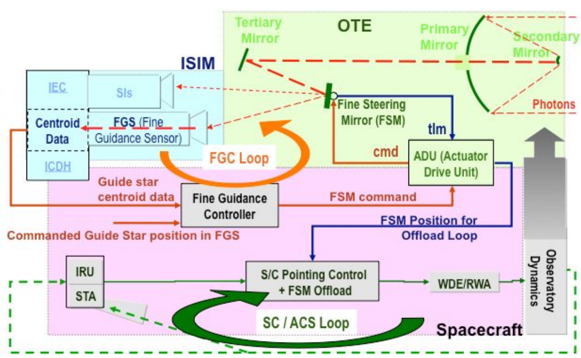


Figure 3 Point loop block diagram

The purpose of the spacecraft Thermal Control Subsystem (TCS) is to perform the following functions:

1. Maintain spacecraft components within required temperature limits
2. Maintain cryocooler, OTE, and ISIM components in Region 3 within required temperature limits
3. Maintain spacecraft to cryocooler, OTE and ISIM interfaces within defined temperature ranges
4. Provide FSW heater control to maintain thermal stability for critical interfaces and components.

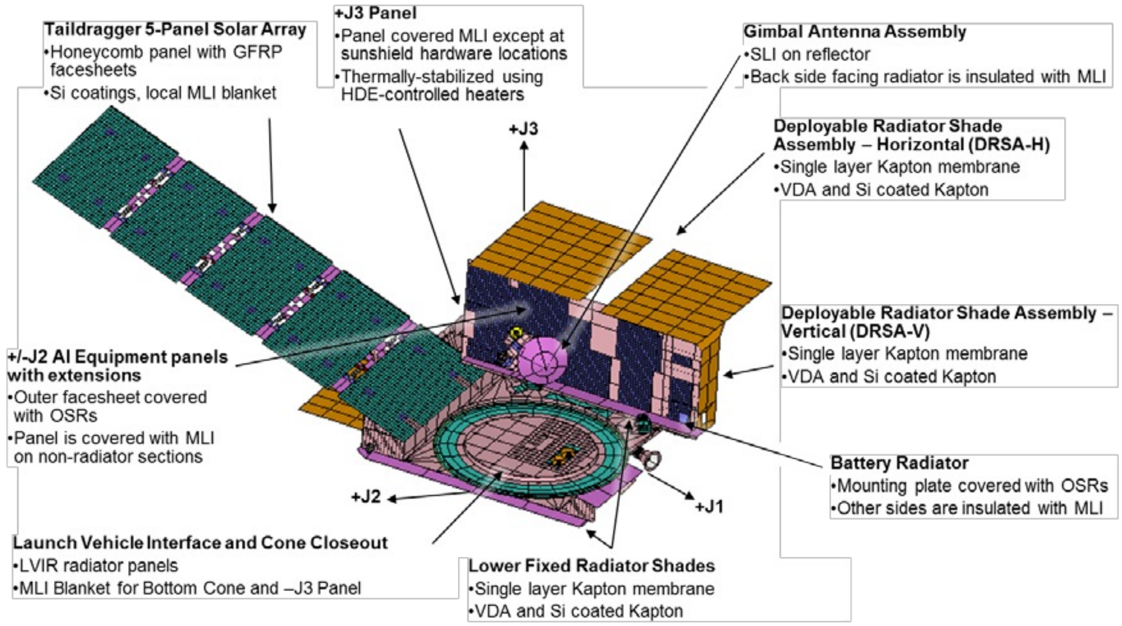


Figure 4: External architecture of the Spacecraft.

The TCS design challenges on Webb include the large back heating from the Sunshield, high dissipation from the cryocooler and temperature stability demanded by multiple precise components on the Observatory. The equipment radiator panels are mounted on the +/-J2 sides of the spacecraft to provide favorable radiator environments in the L2 orbit. Fused silica optical solar reflectors (OSR) are used on the +/-J2 panels as the radiator surface and multilayer insulation (MLI) blankets are used to cover non-radiating surfaces. Constant conductance heat pipes (CCHPs) are used in the +/-J2 equipment panels and cryocooler radiator panels for heat spreading. Radiator shades are used to enhance the heat rejection capability of the radiators by reducing the absorbed infrared energy emitted by the sunshield and reflecting sunlight away from the radiator panels. Thermostatically control heaters are used to maintain equipment above minimum required temperature while under cold conditions. Heater drive electronics (HDE) controlled heaters are used to maintain the +J3 panel, propulsion lines, battery, star tracker, and 1 Hz isolators within the required stability range.

The spacecraft component temperatures are maintained within the required limits by the use of radiators, heat pipes, MLI, and heaters. Thermostat and software controlled heaters are the two types used on this spacecraft. The software control heaters are used to maintain tight temperature control for critical spacecraft components and structures. The heaters are controlled by flight software with temperature feedback control. The flight software enables the ground to modify any TCS mission constants which include on/off heater set-points and failure thresholds.

The Propulsion Subsystem (PS) performs the following functions:

- Provides impulse to inject observatory into desired operational L2 orbit from launch vehicle provided transfer orbit, including attitude control impulse

- Provides impulse for on-station functions including stationkeeping, momentum unloading, thruster-based contingency modes and attitude control
- Provides propellant storage and distribution to thrusters
- Provides thermal hardware used to control the temperature of PS elements
- Provides PS State of Health (SOH) telemetry signals

The PS design challenges on Webb include the high design temperatures from the constant sun and Sunshield back heating and requirements to unload momentum with minimal perturbation to the L2 orbit. The PS is a dual-mode bipropellant subsystem using hydrazine ($N_2H_4$) and nitrogen tetroxide MON-3 ($N_2O_4$) for major delta V and station keeping impulse and hydrazine for attitude control and momentum unloading. The PS operates in a pressure blowdown mode during all mission phases with propellants and gaseous helium pressurant stored in two titanium tanks.

Four bipropellant Secondary Combustion Augmented Thrusters (SCATs), two primary and two redundant) and eight monopropellant hydrazine MRE-1 Dual Thruster Modules (DTMs) provide the required impulse.

Figure 4 shows the locations of the thrusters on the spacecraft. The spacecraft delta V is provided mainly by the bipropellant SCAT thrusters which deliver high specific impulse (Isp), approximately 295 sec (this high performance limits the propellant mass required to perform the mission). The delta V for mid-course corrections 1a and 1b (MCC-1a and -1b) is provided by the SCATs located approximately in the middle of the spacecraft structural cone near the –J3 plane. These thrusters are oriented through the stowed observatory/deployed solar array CG location. The delta V for mid-course correction 2 (MCC-2) and stationkeeping is provided by the SCATs located on the thruster boom. These thrusters are nominally oriented through the fully deployed observatory mid-mission CG location. There is one primary and one redundant SCAT at each location. The SCATs provide a thrust level between ~33N and 24 N during the first 51.4 m/sec of mission delta V delivery (highest potential MCC-1a value).

Eight MRE-1 DTMs are located on thruster brackets attached to the –J3 panel with two DTMs near each corner of the spacecraft. Outboard DTMs are used primarily for yaw momentum unloading while the inboard DTMs are used primarily for pitch and roll control. The MRE-1 DTMs provide attitude control during SCAT thruster firings as well as momentum unloading and impulse for thruster based contingency modes. During on-orbit operations, an MRE-1 can provide a minimum impulse bit (Ibit) of less than 0.16 N-s when fired with an electrical pulse width of 0.040 seconds at a 0.1 percent duty cycle.

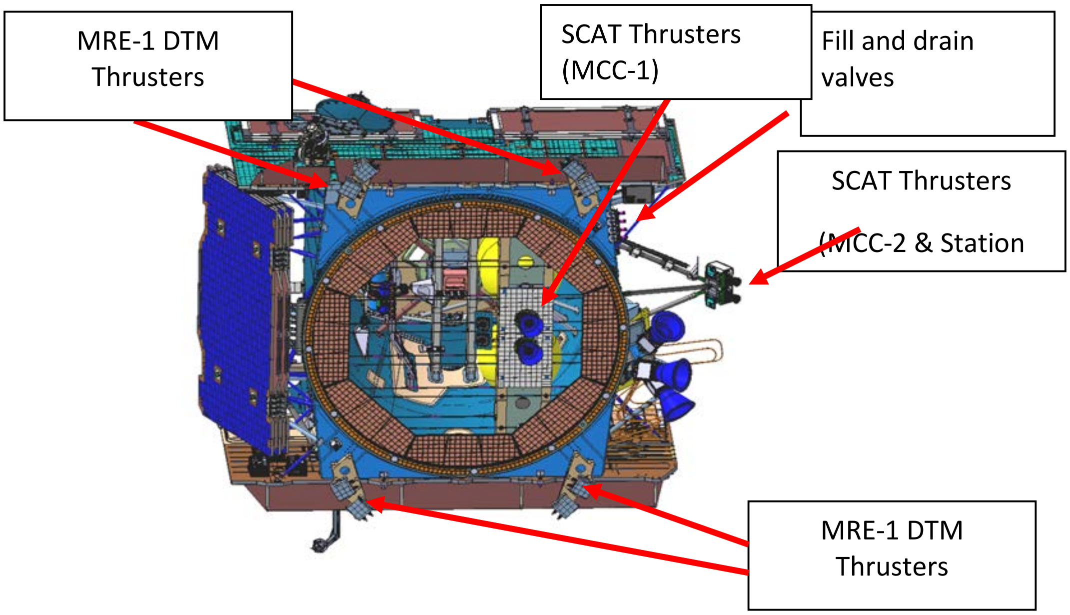


Figure 5 Thruster location on spacecraft

The PS is single fault tolerant, and includes a primary and redundant unit at each thruster location. The thrusters are provided propellant through primary and redundant latching isolation valves (two isolation valves control the flow of hydrazine and two control the flow of oxidizer).

Figure 6 (Left) Central cone (Lower right) Spacecraft structure in assembly (Upper right) Spacecraft structure in test

Figure 6 shows progress on the flight spacecraft structural hardware, which is now complete. The spacecraft is currently undergoing propulsion and electrical integration at Northrop's Space Park in Redondo Beach, CA.

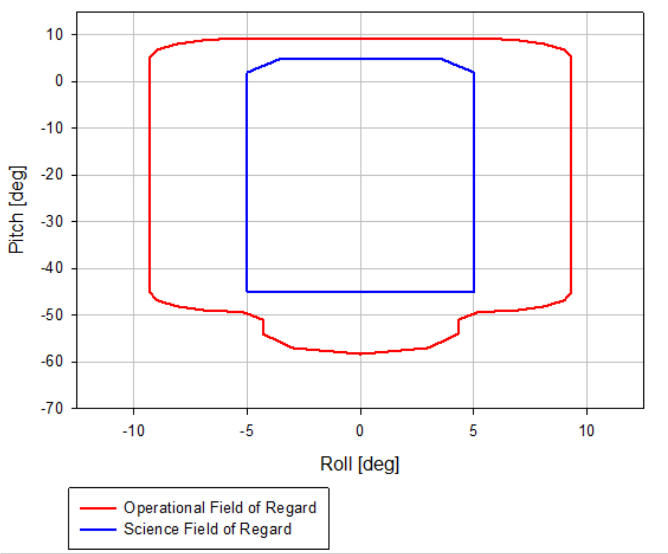


Figure 7 Scientific and Operational Fields of Regard

## Sunshield

The sunshield is the largest by area of the four major elements of the observatory and in many respects the most novel. It is a complicated thermo-opto-mechanical subsystem that enables the Webb mission. The sunshield enables passive cooling of the 6.5 meter telescope and instruments, enables the sky coverage requirements and protects from stray light sources, celestial and local.

The Sunshield subsystem shields the OTE and ISIM from ~300 kW of power received from the Sun and shields the observatory from the light of the Earth and Moon. This thermal barrier reduces the received radiation to less than 1.8 W, enabling passive radiative cooling to maintain the OTE and ISIM at their cryogenic operating temperatures over the field of regard. The scientific field of regard is shown in Figure 7.

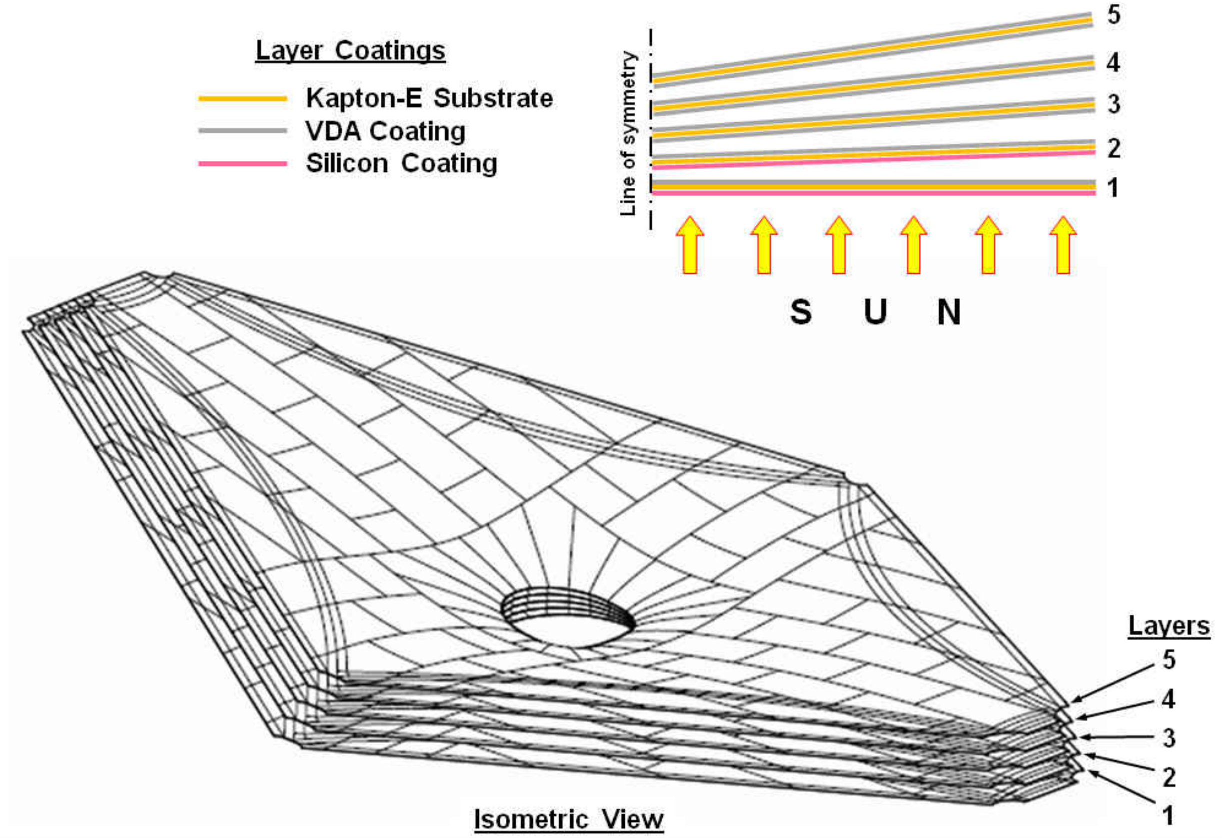


Figure 8 Sunshield Membrane System

The sunshield plays a key role in the minimization of stray light by ensuring that the telescope is shielded from the brightest objects in our sky, the Sun, Earth and Moon. Additional design requirements assure that the telescope and instruments only have a view to Sunshield layer 5 and very rare glimpses of small slivers of layer 4. Similarly, the layers are sized and their edge locations are controlled to ensure that over the entire field of regard the sun can only illuminate Layer 1 and occasionally the edges of Layer 2. The cold layers 4 & 5 can never get local hot-spots that would create a stray light issue or thermal instability issue.

The Sunshield size, shape and aft momentum trim flap minimize torque build-up due to solar pressure, thus reducing fuel consumption.

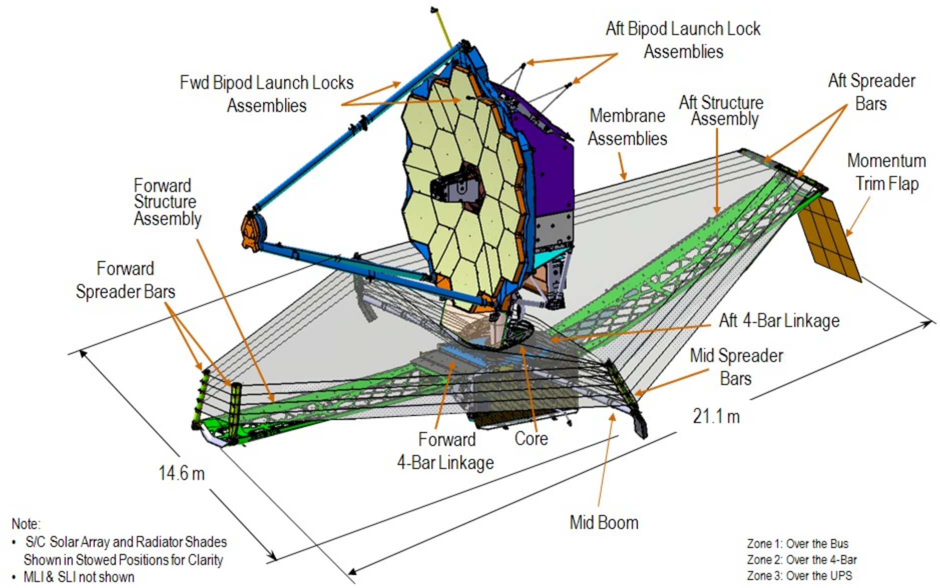


Figure 9 JWST with Sunshield in the deployed configuration

The Sunshield subsystem consists of five 14.4 m x 21.1 m Kapton Membranes, six Spreader Bars, two Unitized Pallet Structures (UPS), two telescoping booms (Mid-Boom Assemblies, or MBAs), Momentum Trim Flap, the Core Area, and four UPS Bipod Launch Lock attachment points, as shown Figure 9.

The largest parts of the Sunshield are the five Kapton membranes composed of Kapton E polymer film substrate. Layers 2 -5 are 25 $\mu$m (1/1000$^{th}$ of an inch) thick, and layer 1 is 50 $\mu$m thick. The Sun-facing surfaces of layers 1 and 2 have a ~600 Å Si coating to prevent over heating from direct solar impingement. All eight remaining surfaces have a ~1100Å VDA coating to provide high reflectance and low emittance surfaces that minimize energy transfer through the sunshield to minimize heat penetration through the sunshield. The membranes are separated from each other by a few centimeters at the Core, but are arranged with a dihedral angle relative to their neighboring layers such that the gaps increase to approximately 30 cm at the outer edges. This helps to direct heat energy from the top of the Spacecraft bus radially outward between the layers.

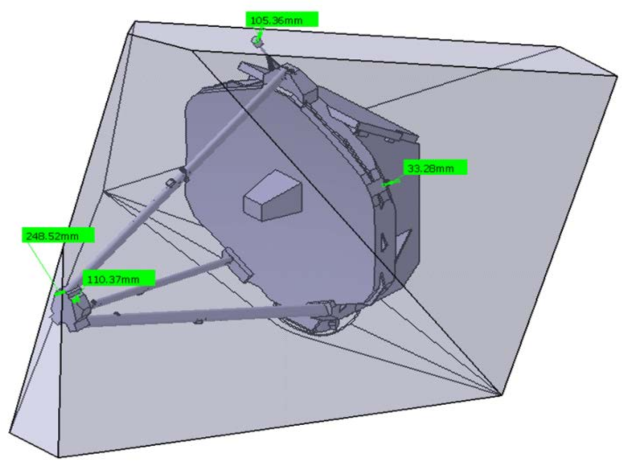


Figure 10 Shadow Envelope

Figure 8 shows the overall shape of the membranes and the layering scheme. The stowed Membrane is folded to be accommodated on the UPS.

The size and shape of the Sunshield membranes were determined using a ray-tracing modeling technique to determine the optimal shape for shielding the OTE and ISIM from solar and terrestrial radiation while simultaneously minimize solar radiation pressure torque.

The sunshield must protect the OTE and ISIM from solar illumination over the entire field of regard including the contingencies. The minimum coverage is found when the smallest possible sunshield at the extremes of its allowed tolerances is used to calculate the shadow facets and determine the minimum clearance between the OTE and ISIM and the shadow. This calculation was done using several methods, computer aided design and pure analytic geometry to assure the requirement is met under all circumstances.

The Webb telescope has the requirement to be able to see the entire sky in one year, continuous viewing zones of 5° around the ecliptic poles and access to at least 35% of the sky at any one instant.

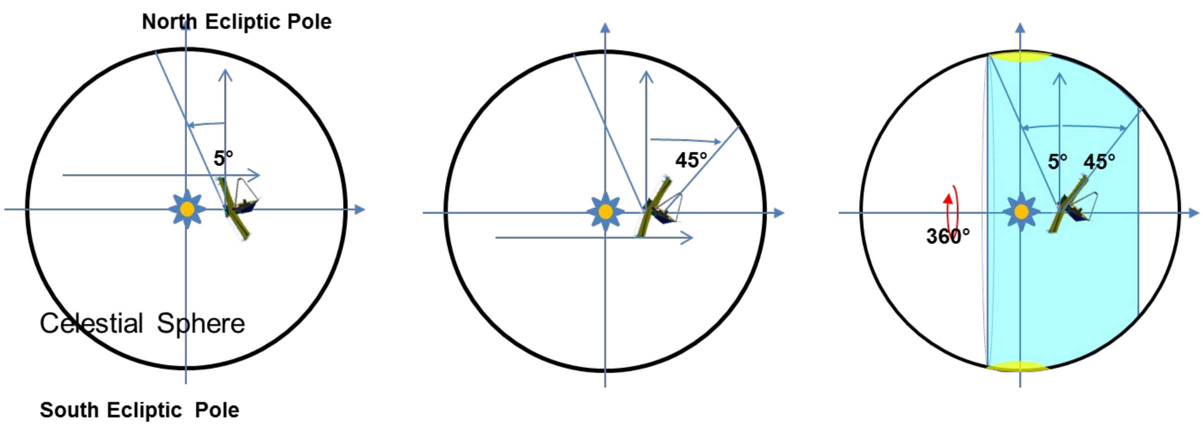


Figure 11 Sky view for sunshield

In the left most panel of Figure 9, the sunshield is tipped 5° towards the sun and the limiting ray as is shown, missed the OTE, showing that the sunshield is sufficiently sized. In order to meet the requirement is seeing at least 35% of the sky at any one time the sunshield must be large enough to allow the observatory to tip in the opposite sense, shown in the second panel. For this tip back, the sunshield is sized that when the observatory is pointed 45° from the sunline there is shadow coverage. The entire observatory can spin around the sunline and sweep out a sector on the celestial sphere as depicted in the right most panel. This gives JWST a capability to see a bit over 39% of the sky at any one time, in excess of the requirement. As the observatory orbits the sun the shaded sector rotates, and over the course of a year sweeps out the entire sky, satisfying the all-sky in a year requirement. Since the zone around the ecliptic poles can be see all the time, it is a continuous viewing zone and depicted in the third panel.

Figure 12 1/3 Scale Sunshield

The flight sunshield is too large to be placed in any existing vacuum chamber to be directly verified by test and so must be verified by analysis. Figure 11 shows the so called 1/3 scale sunshield that was the largest test article that would fit in a chamber at Northrop Grumman. This test article was manufactured using flight processes and flight like materials, with the membrane component gores and seams scaled to 1/3 size. This test, performed in 2010, was correlated to analytical models and demonstrated that the design meets requirements and that there is a test validated thermal model to be used for flight verification.

In July 2014 the first of two deployment tests of the full scale engineering development model was performed and filmed. (See also the upper left panel of Figure 14) This test was the culmination of many years of subscale and subassembly testing. A video of this key milestone is freely available.[2]

The sunshield is rapidly progressing to completion. Figure 12 shows a small part of the overall progress as of the time of the writing of this paper. In the upper left, the hardware in the photograph is the engineering development unit, this shot was taken after its first (of two) full scale ground deployments, which occurred in 2015.

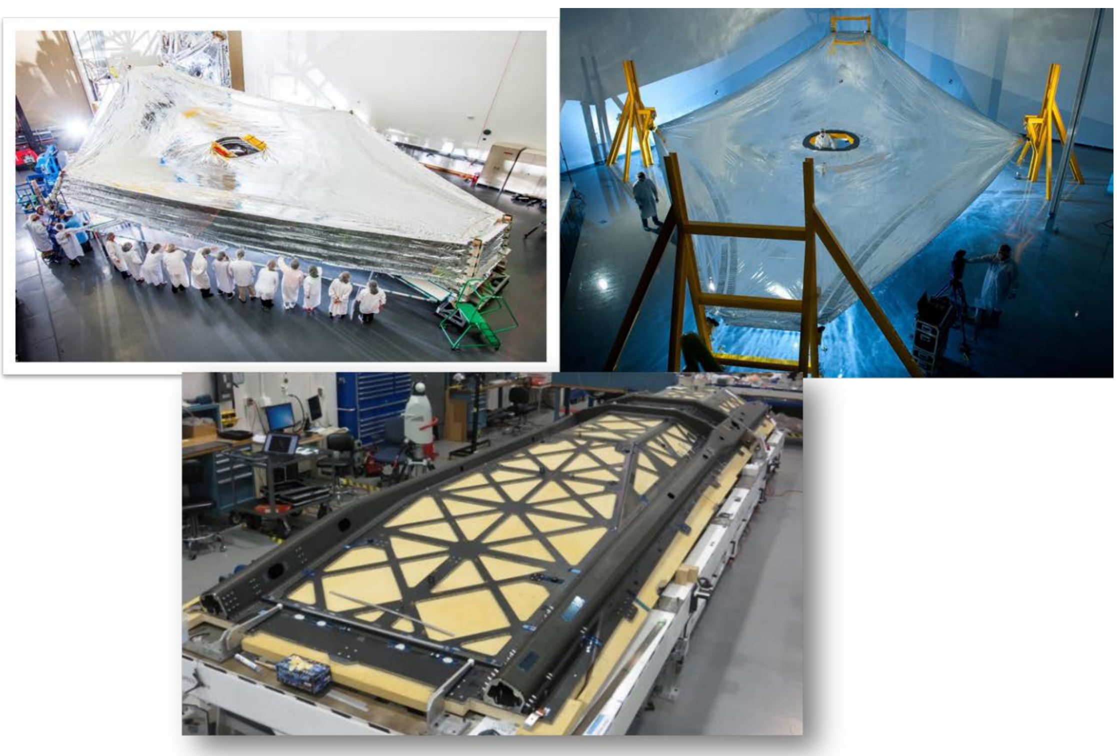

Figure 13 (

The upper right is a picture of a flight membrane, the deliveries began in 2015 and will end later this year. The sunshield UPS structures, shown early in manufacture, are largely complete and being assembled and tested. The core area is complete and shown following a deployment test, Figure 14.

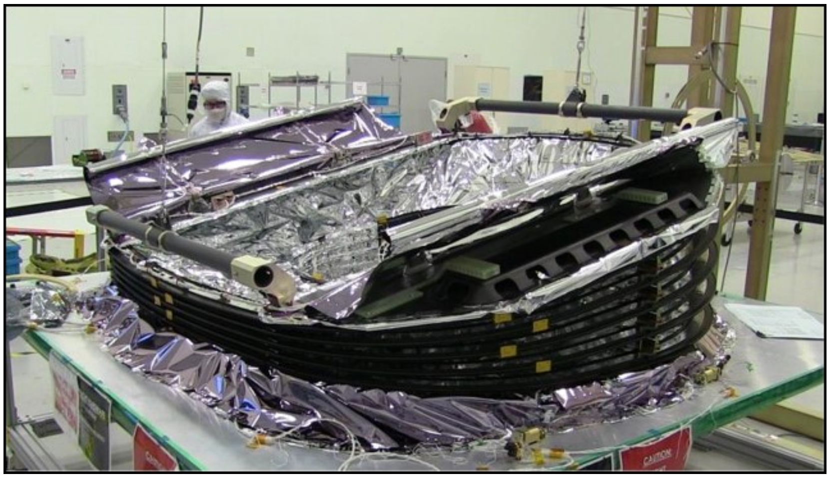

Figure 14: Deployed Core

The mid-boom parts are all manufactured and the first complete assembly is shown in the stowed configuration, Figure 15

Figure 15: Stowed Mid-Boom

## Remaining Steps

The spacecraft and sunshield are well into their integration and test phases. As of the time of this writing the spacecraft has completed mechanical assembly and proof testing and been fit checked with the telescope structure. Panel and electrical integration and test are underway. The sunshield is completing the building of the flight membrane which will complete in 2016. Later this year the sunshield structure will be integrated onto the spacecraft and the flight membranes integrated. When completed in 2017, the integrated sunshield and spacecraft will be mated to an telescope simulator and undergo environmental testing. Following the completion of OTIS testing, the cold side systems will be mated to the hot side, completing the integration of the Webb telescope flight segment. A final environmental test and deployment verification will take place prior to shipment to the launch site in 2018.

## References and endnotes

[1] A review of the program for this conference returned 57 papers with the key word, "JWST", subtracting this paper leaves 56 other contributions all concentrated on some aspect of the cold side of the observatory.

[2] "James Webb Space Telescope (JWST) Sunshield Deployment Test" https://www.youtube.com/watch?v=sM_N1lzM3gU last accessed 4 June 2016