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80 YEARS: WHERE WE ARE by Paul H. Geithner

A generation in the making, the James Webb Space Telescope is the synthesis of scientific vision, technological advancement, and engineering achievement.

BUILDING THE JAMES WEBB SPACE TELESCOPE

Telescopes are powerful tools of exploration, enabling humans to probe far beyond where we can go ourselves or with robots. And arguably no instrument better embodies the advances spurred by our cosmic curiosity thus far than the James Webb Space Telescope. Scheduled to be ready for launch by October 31st when this article went to press, Webb is the long-awaited scientific successor to the Hubble Space Telescope and promises to be the world's premier space science observatory.

Even before the Hubble Space Telescope launched in 1990, scientists were considering what machine ought to follow it. Hubble "sees" primarily ultraviolet and visible light, with some capability to observe at the shortest near-infrared wavelengths. Scientists understood even then that, as mighty as Hubble would be, its 2.4-meter primary mirror and suite of instruments likely lacked the capability to explore the era when the first luminous objects formed. That era, called the *cosmic dark ages*, occurred in between the condensation of the primordial plasma into neutral hydrogen and helium (roughly 400,000 years after the Big Bang) and the ionization of those atoms by the first objects to emit visible and ultraviolet light (a few hundred million years later). This is the time when "the lights turned on" in the universe. But what exactly happened then? What were the first stars like, and how did they form in an environment so different from the one we think contemporary star formation requires? How did galaxies, which are the universe's large collections of ordinary matter and unseeable dark matter, assemble and evolve? How and when did the supermassive black holes that we observe at the hearts of most galaxies form? What came first: stars, black holes, galaxies . . . or something else?

Hubble can't answer these questions. Instead, to observe the end of the cosmic dark ages, we need a telescope exquisitely sensitive to infrared light. This is because the universe has been expanding since the Big Bang 13.8 billion years ago, which means that everything is moving away from everything else. The farther away something is, the faster it is receding. Light travels at a finite speed, so this expansion stretches light's wavelengths as the photons travel toward us, such that the farther away an object is, the redder it appears. The very first luminous objects to form after the Big Bang, whatever they were, are so distant that the ultraviolet and visible light they emitted more than 13 billion years ago reaches us today *redshifted* into the infrared spectrum.

CHRIS GUNN / NASA

OPTICS READY
The completed telescope looms above technicians at Northrop Grumman in this 2019 photo while awaiting integration with its spacecraft and sunshield.

WEBB'S MISSION GOALS

Search for the universe's first galaxies

Study galaxies' evolution over cosmic time

Observe the formation of stars and planetary systems

Measure properties of the solar system and other planetary systems and investigate the potential for life

So the goal was not only to gather enough light to reach back to the cosmic dark ages, but also to achieve a resolution at longer infrared wavelengths comparable to what Hubble provides at visible ones. To do this, Webb needed a primary mirror of at least 6 to 7 meters (about 20 feet) in diameter, and preferably a symmetrical one to reduce unnecessary image distortion. Such a mirror would also enable it to peer deeply at much closer targets, such as newborn stars and exoplanets sheathed in dusty gas clouds. The targeted wavelength and sensitivity ranges meant the telescope had to be space-based, above the interference from water vapor in Earth's atmosphere. And the telescope needed to be cold — below 60 kelvin (–213°C, or –352°F) — so that its own thermal emission didn't blind it to the infrared light coming from celestial sources.

This is how mission planners settled on creating a large, infrared telescope stationed in space and far from Earth's room-temperature glow — some 1.5 million kilometers (1 million miles) from Earth's nightside, at a gravitational balancing point in the Sun-Earth system called L_2 (see page 25). Building the envisioned telescope has been a feat of invention, ingenuity, and perseverance that makes it a milestone in the creation of space observatories.

Engineering Challenges

Several inventions and technological advances were necessary to make Webb feasible. Size, combined with the need to operate at cryogenic temperatures, conspired to present the greatest challenges. Webb's aperture exceeds the 5-meter diameter of standard, commercially available launcher fairings — in other words, there was no nose cone wide enough to carry the telescope to space if we built it with a symmetrical, one-piece mirror. Moreover, using the technology behind Hubble's lightweight, monolithic glass mirror would have required an impractically massive support structure.

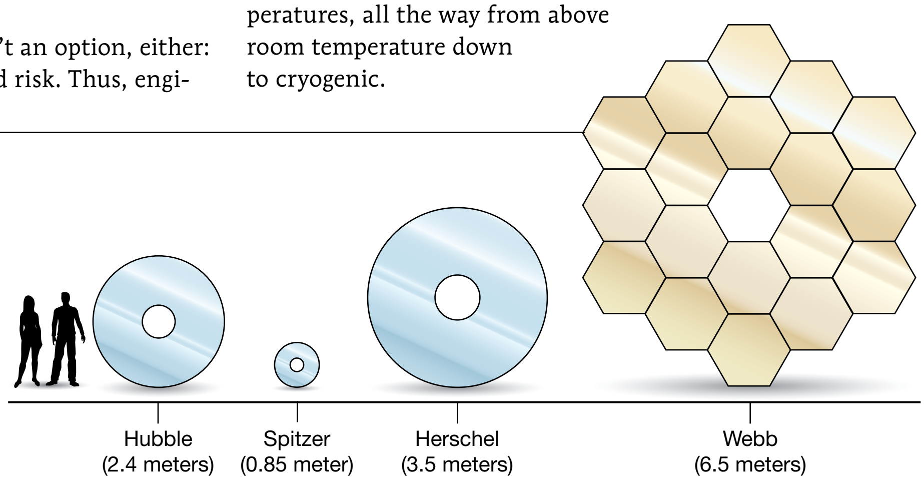
Assembling the telescope in space wasn't an option, either: It would have added too much expense and risk. Thus, engineers developed *foldable* optics and structures so that the telescope could fold up to fit into a rocket fairing and withstand the rigors of launch, then deploy in space into a different, operational configuration.

Instead of one big primary mirror, we built a segmented one of 18 hexagonal mirrors, each 1.3 meters across and about 40 kg (88 lbs). Together, they make a 6.5-meter-wide honeycomb.

Nor is unfolding the only transformation the telescope will undergo once in space. The challenge of operating at cryogenic temperatures is a daunting one that affects every aspect of design and testing. Materials change dimensions with temperature, typically expanding when warm and shrinking when cold. What's more, different materials behave in different ways, and we had to use more than one kind of material to build Webb, so we had to account for each part changing in its own way. This meant developing new processes to shape and polish optical surfaces "perfectly wrong" at room temperature, such that they become "precisely correct" at cryogenic operating temperature. The surfaces also had to attain that shape predictably, over and over again through repeated testing, and finally once launched and cooled down.

Beryllium became the mirror material of choice. Beryllium is light and stiff, and it virtually stops changing dimensions at temperatures below 100K. Ordinary beryllium is unpredictable, however, so technologists developed a new beryllium microsphere powder that the team then fused using intense pressure and heat into mirror blanks. Once the blanks were machined, ground, and polished, technicians coated each mirror in gold, which is excellent at reflecting infrared wavelengths.

The segmented mirror, along with the other optics and scientific instruments, are mounted on structures made of a special formulation of carbon graphite-epoxy that is very stiff, strong, and relatively stable over a wide range of temperatures, all the way from above room temperature down to cryogenic.



▶ **BIGGER IS BETTER** The larger a telescope's mirror, the more resolving power and sensitivity it can have: At a given wavelength, a telescope with an aperture twice as wide will resolve detail twice as fine and collect four times as much light. All four of these telescopes had (or have) infrared capabilities: Hubble can detect near-infrared wavelengths as well as visible and ultraviolet, while NASA's Spitzer covered only infrared. Europe's Herschel observed far-infrared wavelengths, much longer than those Webb will detect.

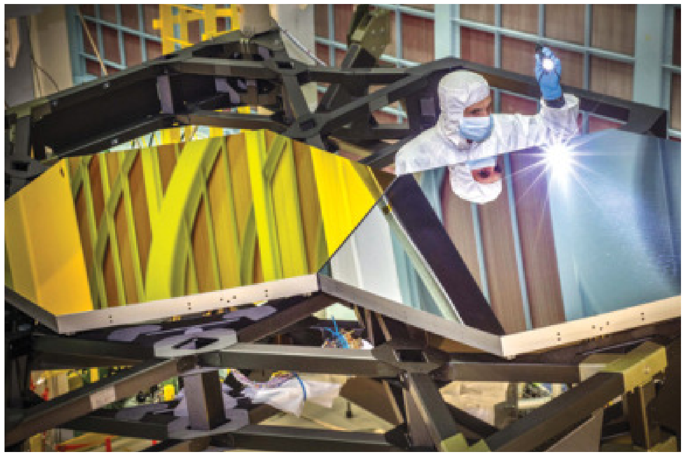
LEAH TISCIONE / S&T

The Origami Observatory

The sting of Hubble's spherical aberration was fresh in people's minds during Webb's early conceptual development, and naturally when thinking about a new space telescope one thinks of optics and how to make and test them. But there's more to Webb than its optics. Webb is a giant — and frigid — origami observatory, and the difficulties presented by a folding space observatory that will deploy in space by remote command and operate at cryogenic temperatures add to the challenge.

Virtually every modern spacecraft unfurls, deploys, or releases in some fashion, such as extending a solar array for power generation. By necessity, Webb takes on-orbit releases and deployments to the extreme:

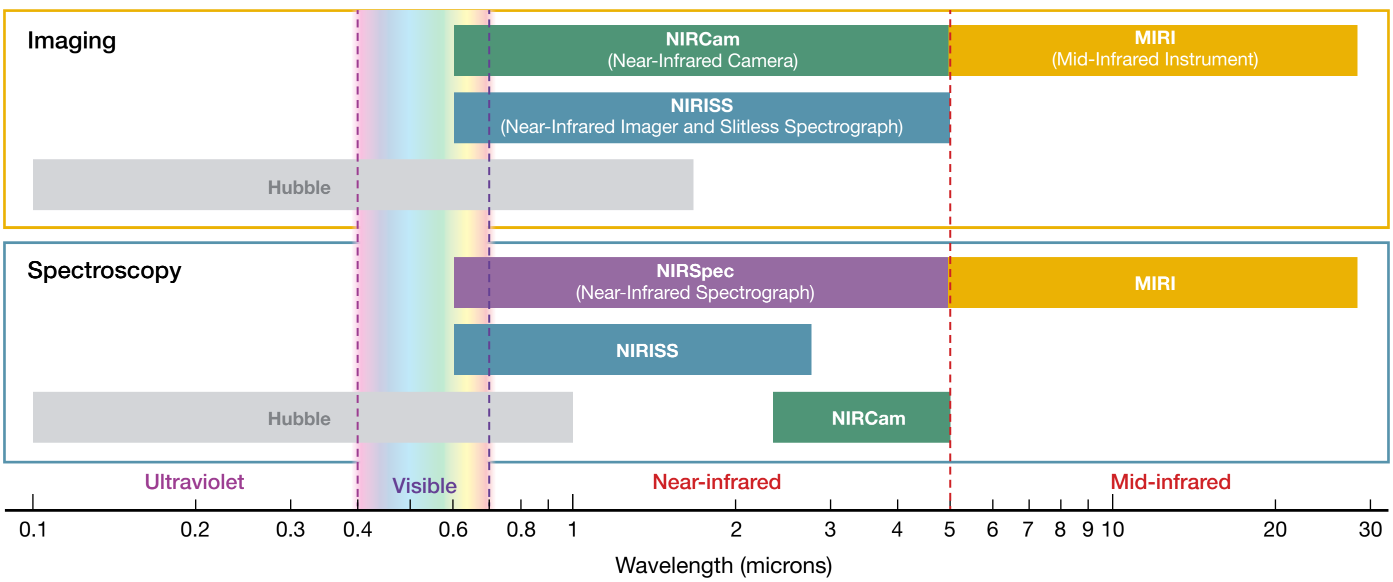
- The telescope primary mirror backplane structure has to fold up for launch and then deploy precisely.
- Primary mirror segments have to be movable in any direction so that they can correctly align to a few millionths of a millimeter and act as one.
- The secondary mirror must deploy on a hinged tripod (seen folded on page 21) and also move in any direction.
- The telescope structure is attached to the spacecraft bus when stowed for launch, but a telescoping tower must extend to separate the structure and bus, so that the telescope is isolated from any mechanical vibrations or heat from the spacecraft and sunshield.
- The star tracker, used to monitor the telescope's position in space, is attached to this extendable tower and must release from launch locks on the bus once in space.
- Various radiators must also release from launch locks and deploy to provide thermal and mechanical isolation.



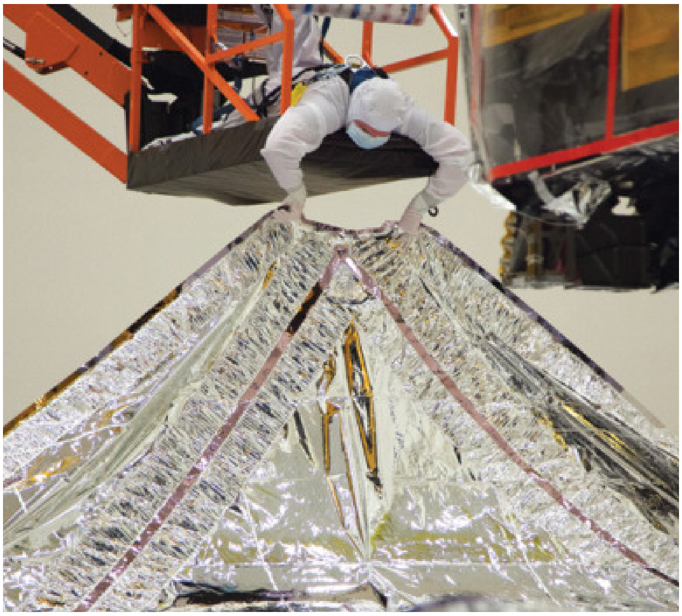
▲ **GO FOR GOLD** An optical engineer examines two test mirror segments, one coated in gold. The frame is a composite material designed to handle Webb's space environment.

The sunshield posed the grandest stowage and deployment engineering challenge of them all. The sunshield's job is to be an umbrella, shielding the telescope from the heat of the Sun as well as stray light from Earth and the Moon. This protection allows the telescope and instruments to radiate their own heat away and stay cool in the 7K deep space at L_2. The shield needs to let through a mere millionth of the total heat hitting it, attenuating more than 200 kilowatts of solar insolation down to a fraction of a watt. It also needs to span a much larger area than the telescope itself — roughly that of a tennis court — so that it provides adequate shadow for the telescope to access as much of the sky as possible. Lastly, it must weigh extremely little, stow compactly for launch, and

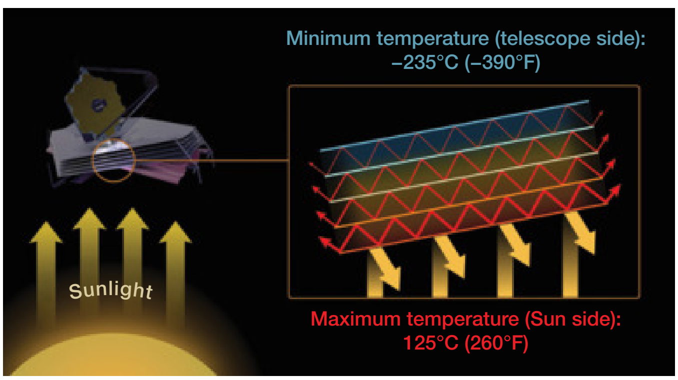
▼ **INFRARED EYE** Unlike Hubble's instruments, which focus primarily on ultraviolet and visible wavelengths, Webb's observe the near-infrared and mid-infrared parts of the spectrum. Each instrument is a specific combination of observing modes, wavelength range, field of view, and resolution, combining multiple instruments within themselves. NIRCam, NIRISS, and MIRI can do both imaging and spectroscopy, but the NIRCam and NIRISS spectrographs cover a smaller wavelength range than their cameras.



MIRRORS: CHRIS GUNN / NASA; INFRARED: LEAH TISCIONE / *S&T*, SOURCE: STSCI



▲ **SUNSHIELD** *Top:* This photo from 2014 shows the first time engineers stacked and unfurled a full-size test sunshield. *Above:* A technician carefully folds the real sunshield in 2020, in preparation for stowing the telescope into its launch configuration.



▲ **PARASOL** The five-layer design of Webb's sunshield protects its mirror and instruments from unwanted infrared radiation from the Sun, Earth, and Moon. Because none of the layers touch, heat doesn't conduct from one layer to another and instead flows to the layers' edges and into space.

deploy reliably, both on the ground multiple times for testing and in space for the one time it really counts.

These requirements are met by a design consisting of five kite-shaped, gossamer membranes stacked in layers. Each membrane is about 165 square meters (1,780 ft^2) in area and coated with vapor-deposited aluminum. When deployed, the space between each membrane gets progressively wider from the center to the edges. This allows heat that isn't reflected away and manages to pass to the next layer to then bounce its way out to the edges and overboard to space. Even the membrane edges are aligned to millimeter tolerances, to ensure no infrared photons from edges heated by the Sun will have a line of sight to telescope optics and become a source of stray light.

As the largest element of Webb, the sunshield will unfold in grand fashion. A graphite-epoxy frame will cradle the *Z*-folded membranes for launch and then extend to deploy the membranes in space. An elaborate system of motors, stem drives, pulleys, and cables will deploy the sunshield skeleton and pull the membranes taut. Because membranes and cables are non-rigid floppy things, hundreds of simple, ingenious straps and elastic clips must restrain them as they're deployed in the weightlessness of space to preclude snagging and entanglement.

In all, deployment of flight hardware involves 178 non-explosive release devices, more than 40 major deployments of 30 different types, 155 motors, more than 600 pulley assemblies, and nearly 100 cables totaling about one quarter mile in length.

Beyond the State of the Art

Then there are the advances spurred by Webb's instruments. To accomplish the science goals, infrared detectors had to become better than what existed when we began planning. Engineers had to adapt electronics so that the combination of any "noise" from the detectors with heat from the mirror itself would be less than the signal from the zodiacal light, the background glow from diffuse dust in the inner solar system. This is where the 60K requirement comes from.

But to observe mid-infrared wavelengths takes even more extreme measures. The mid-infrared instrument's detectors have to be colder than 7K to operate, which they won't achieve by simply sitting out in space at L_2. Instead, Webb needs its own cryocooler, which required more development.

From the invention of a new slit mask for the main spectrometer to advances in cryogenic testing, many technologies had to lurch forward to make Webb possible. Of course, we had to leap over various engineering hurdles throughout the long development, but tackling challenges is part of what makes this work rewarding.

Then there are the international hurdles. Science is a worldwide community, and contributors the world over wanted in on the mission from the beginning. The

DEPLOYED SUNSHIELD: CHRIS GUNN / NASA; **SUNSHIELD** FOLDING: NORTHROP GRUMMAN; SUNSHIELD DIAGRAM: STSCI

European and Canadian space agencies are both providing instruments and operations support, and the European Space Agency (ESA) is also handling the launch. But there are laws regulating the sharing of information, even with friendly allies. Finding ways to collaborate with our partners and their contractors added a degree of difficulty to this process, but the return in scientific capability has been worth it.

Proving It Works

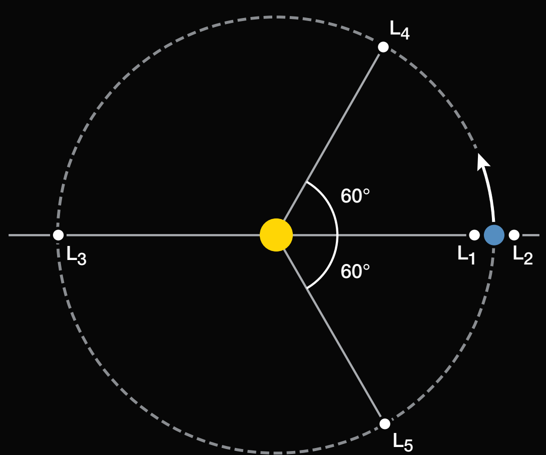
A major difference from some other spacecraft is that the entire Webb observatory cannot be tested faithfully as one fully assembled unit before launch: It's simply too big and complex. That may be nerve-wracking to readers who remember the blurred images Hubble returned when it first looked at the cosmos. To be clear, we've tested Webb's optical system in one piece end-to-end. What's impractical is creating on the ground the environment that Webb will unfurl in. We can't easily emulate weightlessness and perform deployments while in a vacuum chamber, nor is it feasible to replicate Webb's thermal condition — with intense sunlight heating one side and extreme cold chilling the other — and simultaneously run end-to-end optical tests on the complete, deployed observatory in the vacuum.

This led engineers to test the observatory in halves — the telescope and instruments as one unit, and the combined spacecraft bus and sunshield as the other. Each was shaken and blasted with sound and subsequently tested for performance in temperature-controlled vacuum chambers. Then once put together, the observatory was shaken some more to verify workmanship of the final assembly.

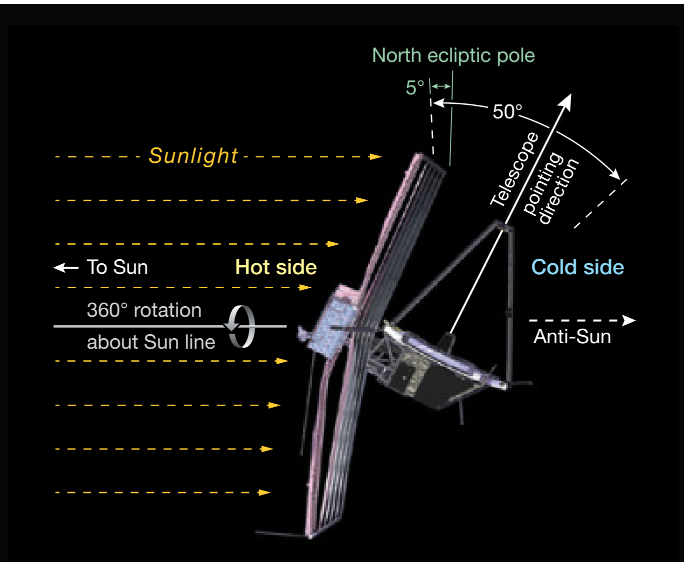
▲ **MEGASIZE INSTRUMENTS** Engineers prepare the Near-Infrared Spectrograph for acoustic tests.

We learned a crucial lesson from the Hubble spherical aberration experience: Don't rely on the same tools used to make the optics when you test them. This meant we had to build different devices to verify, crosscheck, and optically test the entire telescope and instrument assembly end-to-end. The testing required a vacuum chamber capable of cooling the entire telescope and instrument assembly to about 40K, suppressing background mechanical vibrations, and housing sophisticated testing equipment.

A relic of the Apollo era, the enormous Chamber A at NASA's Johnson Space Center, was refurbished and upgraded



▲ **LAGRANGIAN POINTS** In a system of two massive bodies orbiting each other (such as the Sun and Earth), five gravitational "balance points" exist where a third, much smaller object can orbit in a constant pattern. A craft at L_2 can always keep the Sun, Earth, and Moon behind itself, making it a frequent choice for space missions. Previous denizens of L_2 include Europe's Planck and Herschel missions; the sky-scanning Gaia spacecraft is currently there.



▲ **THE VIEW** Webb's mirror is perpendicular to its sunshield, and the spacecraft can tilt to point the telescope within a 50° arc while still keeping the mirror and instruments safely in shadow. It can also rotate full circle. Over time, Webb will see the entire sky as it orbits the Sun.

▲ **CHAMBER A** Webb emerges from months of cryogenic vacuum testing in 2017.

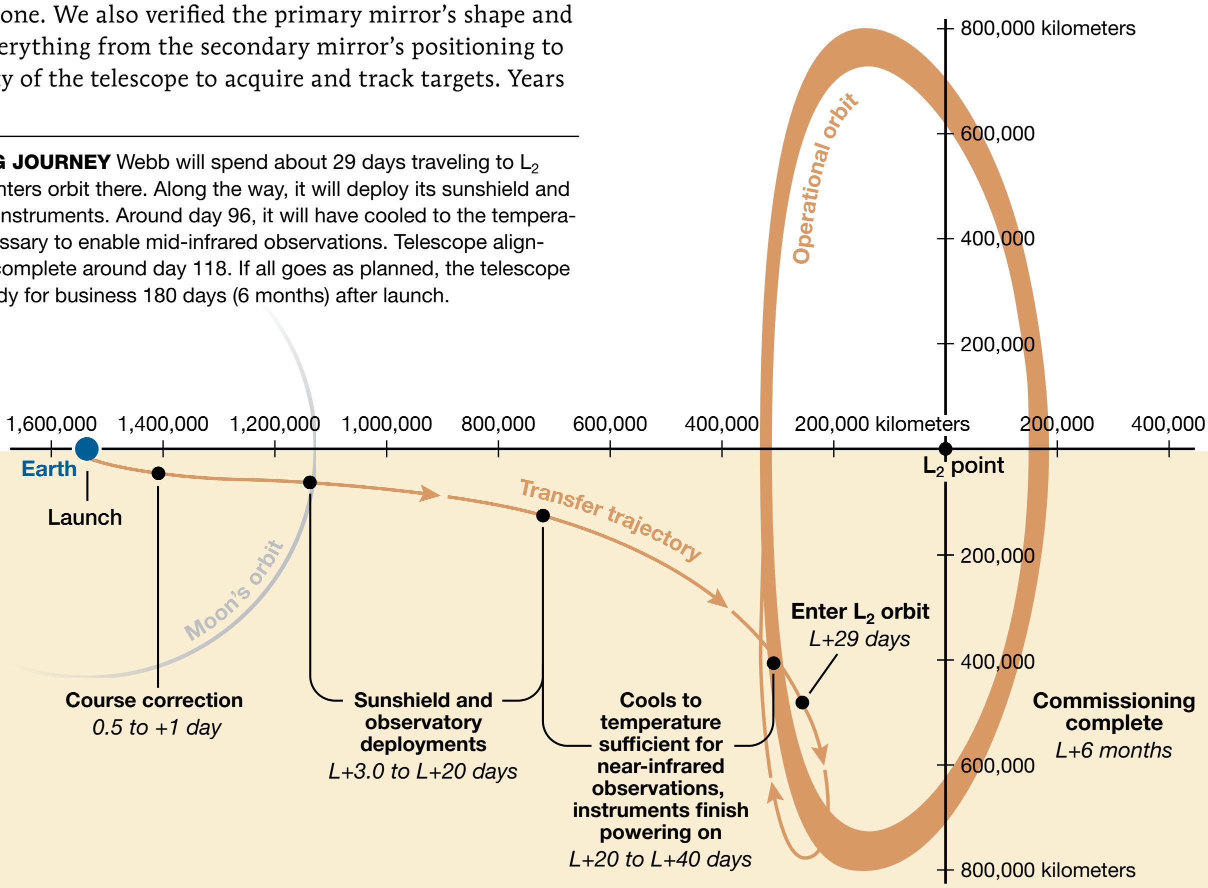
into the world's finest large cryo-vacuum optical test facility for the work. This chamber is about nine stories tall, taller than the Lincoln Memorial Building — so large that the air inside it weighs 12 tons (before all but 2 grams gets pumped out for testing). Engineers placed the deployed flight hardware on a truss structure platform and rolled it into the bottom of the chamber on rails, then connected it to long steel rods suspended from the ceiling. Using a combination of mirrors, cameras, and other carefully tested instruments positioned inside the chamber, we successfully aligned all 18 segments to act as one. We also verified the primary mirror's shape and tested everything from the secondary mirror's positioning to the ability of the telescope to acquire and track targets. Years of careful planning meant that even when Hurricane Harvey hit right in the middle of this 100-day-long cryo-vacuum test in 2017, we completed it without interruption.

Meanwhile, to prove that the observatory could properly manage heat not only from the Sun but also from its own electronics, we had to combine results from multiple tests. To check the sunshield design, we tested a ⅓-scale model of the deployed sunshield in a temperature-controlled vacuum chamber. To verify that the telescope and instruments would stay cool despite the heat the electronics give off, we built and tested a full-scale version of Webb's core section — the thermal Grand Central Station of the observatory — to confirm that heat moves around the way it needs to. Such tests required milliwatt-level precision. We then combined these results with those from the thermal-vacuum test of the bus-plus-sunshield assembly and the cryo-vacuum test of the assembled telescope and instrument package.

On top of all that, we've done exhaustive, iterative checks of the unfolding processes. All flight-deployable items have been unfolded multiple times; the flight sunshield, for example, has been stowed four times and deployed three times before flight. So much of the observatory can fold out that every stow operation was like reassembly, with a regimen of extra checks and precautions.

And after more than a decade of testing flight hardware, we'll soon be ready for the next step: launch.

▼ **A LONG JOURNEY** Webb will spend about 29 days traveling to L_2 before it enters orbit there. Along the way, it will deploy its sunshield and power up instruments. Around day 96, it will have cooled to the temperatures necessary to enable mid-infrared observations. Telescope alignment will complete around day 118. If all goes as planned, the telescope will be ready for business 180 days (6 months) after launch.



CHAMBER A TESTING: CHRIS GUNN / NASA; TRAJECTORY AND COMMISSIONING TIMELINE: GREGG DINDERMAN / *S&T*, SOURCE: NASA

Opening Webb's Eye on the Cosmos

Once it lifts off from French Guiana, Webb will undergo an action-packed six-month commissioning period. Moments after completing a 26-minute ride aboard ESA's Ariane 5 rocket, the spacecraft will separate and deploy its solar array automatically per a stored command. After that, we'll initiate all subsequent deployments over the next few weeks from the ground. This is in stark contrast to the "7 minutes of terror" for projects landing on distant Mars, for example. For them, every step of entry, descent, and landing is pre-programmed and autonomous because of Mars's distance — it's all over before engineers on Earth receive a signal that it has even begun. Webb, however, will be mere light-seconds away, so we will be able to control deployments carefully.

Webb will take one month to fly to L_2, slowly unfolding as it goes. Sunshield deployment starts at day 2.7 and will finish a few days later. Once the shield starts to deploy, the telescope and instruments will enter shade and cool rapidly. Over the ensuing weeks, the mission team will closely monitor the observatory's cooldown, managing it with heaters to prevent escaping moisture from freezing onto sensitive surfaces. In the meantime, the secondary mirror tripod will unfold, the primary mirror will unfold, instruments will slowly power up, and midcourse maneuvers will insert Webb into a prescribed orbit around L_2 on day 29.

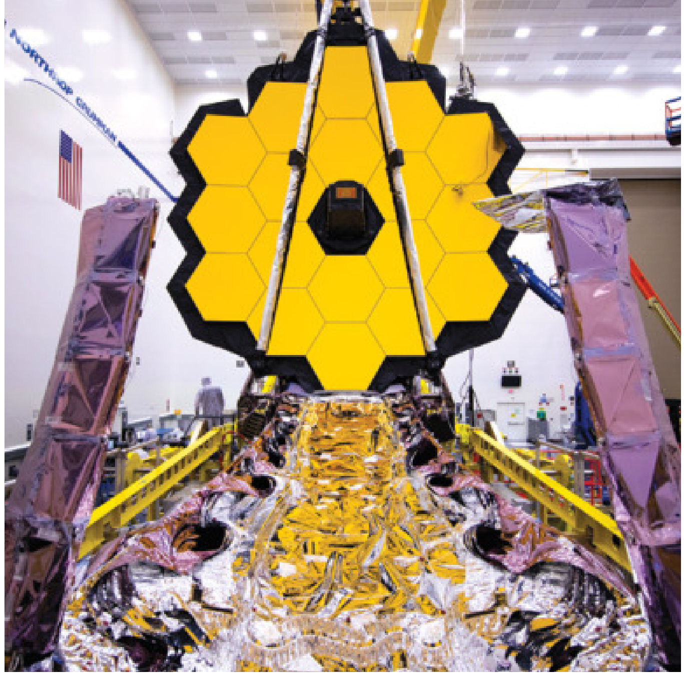
Once the observatory has cooled to the necessary low, stable temperature, it'll take several months to align the optics and calibrate the scientific instruments. Assuming commissioning goes as planned, scientific operations will commence about six months after launch. Webb's mission lifetime is designed to be at least five years, but the observatory could last more than a decade depending on how much fuel we use to achieve and maintain orbit around L_2 and how quickly the telescope's components degrade in space.

Flagship missions like Webb are generational. They take a long time because they are difficult, and they are expensive because they take a long time. Webb has built on both the legacy and the lessons of missions before it, such as the Hubble and Spitzer space telescopes. It will in turn provide the foundation upon which future large astronomical space observatories may one day be developed.

Webb is a marvelous machine. It is a remarkable engineering achievement full of scientific potential and promise. It has been built to explore the frontiers of cosmology and astronomy, from observing the end of the cosmic dark ages to "sniffing" the atmospheres of exoplanets around nearby stars to perhaps detecting the chemistry that makes life as we know it possible.

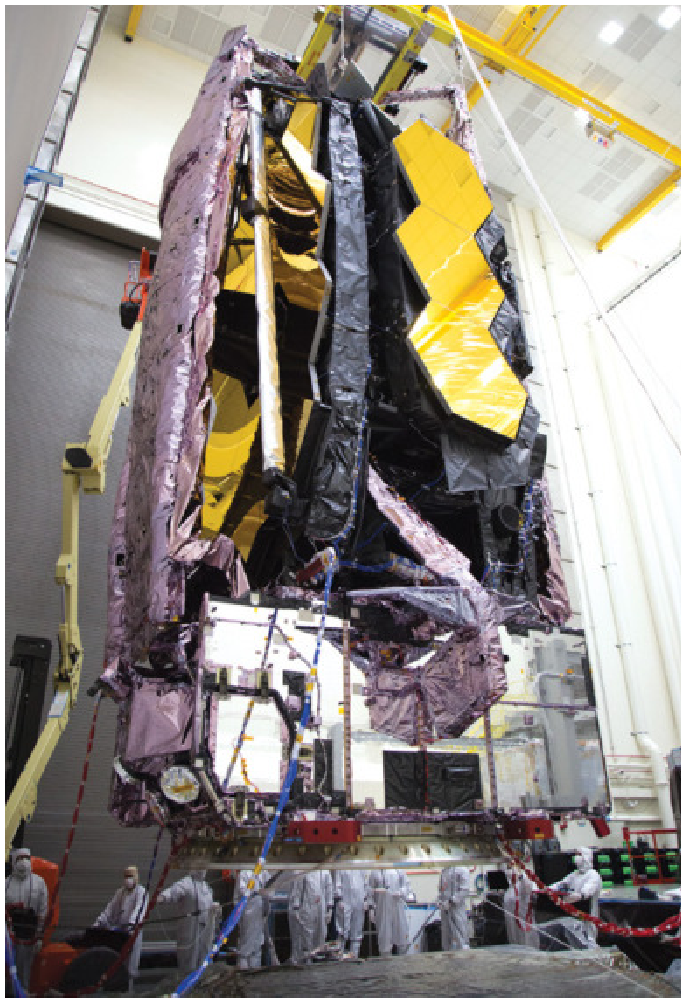
But its greatest discoveries will likely be answers to questions that we have yet to ask or imagine.

■ Deputy Project Manager **PAUL H. GEITHNER** has held several jobs on Webb since 1997 after coming to NASA in 1991 to help fix and upgrade Hubble. On the side, Paul rebuilds cars and houses and is borderline obsessed with golf.



▲ **SEMI-DEPLOYED** The sunshield lies furled below the unfolded primary mirror. For launch, the shield will fold up and sandwich the mirror.

▼ **FOLDED FOR LAUNCH TEST** The telescope successfully endured deafening noise and jarring vibrations tuned to simulate conditions aboard the Ariane 5 rocket during launch. These 2020 tests were the last environmental tests before launch.



NORTHROP GRUMMAN (2)