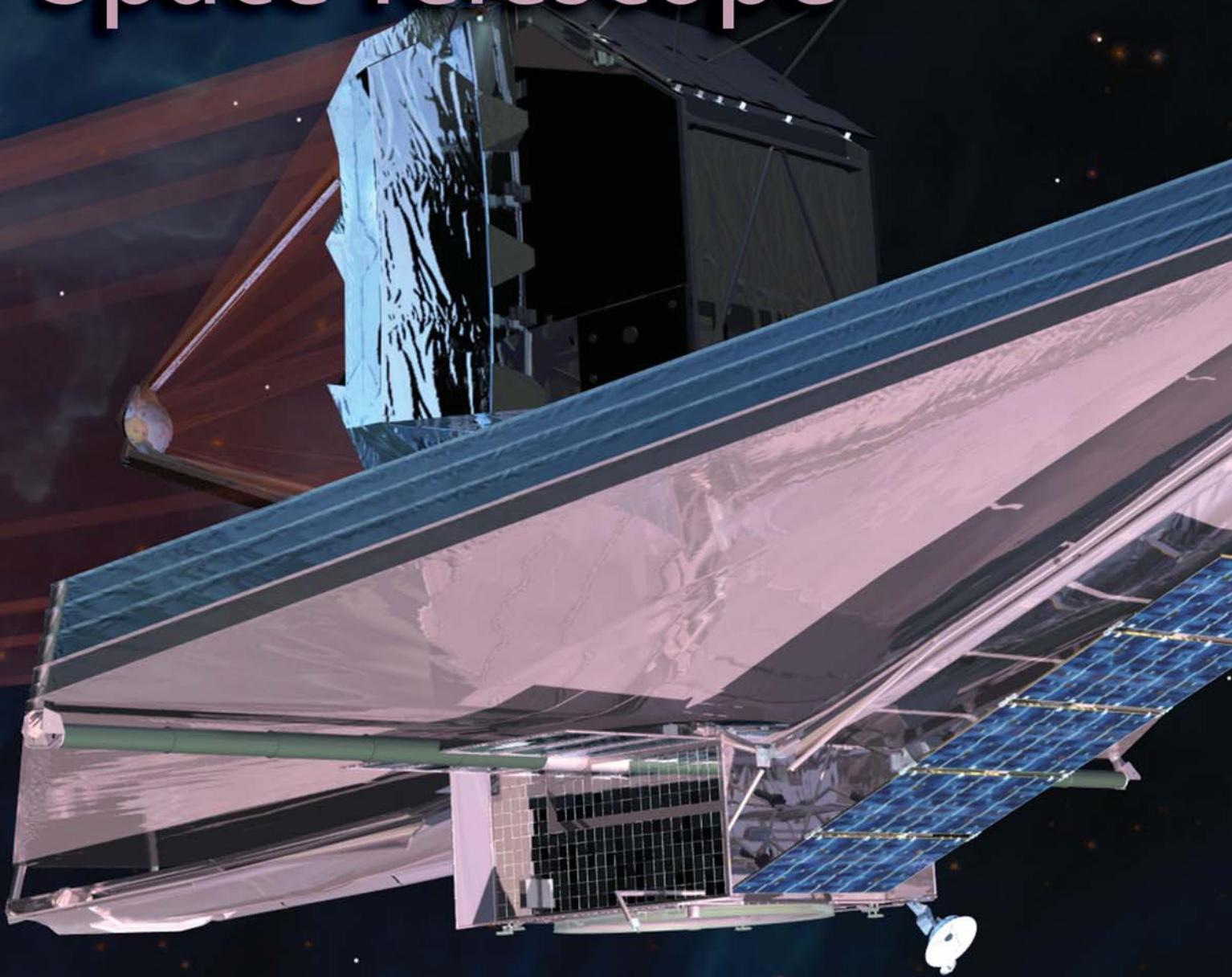


James Webb Space Telescope



A Bigger and Better Time Machine

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Inspired by the success of the Hubble Space Telescope, NASA, ESA and the Canadian Space Agency have collaborated since 1996 on the design and construction of a scientifically worthy successor. Due to be launched from Kourou in 2013 on an Ariane-5 rocket, the James Webb Space Telescope is expected to have as profound and far-reaching an impact on astrophysics as did its famous predecessor.

Introduction

Astronomers cannot conduct experiments on the Universe, instead they must patiently observe the night sky as they find it, teasing out its secrets only by collecting and analysing the light received from celestial bodies. Since the time of Galileo, the foremost tool of astronomy has been the telescope, feeding first the human eye, and later increasingly sensitive and sophisticated instruments designed to record and dissect the captured light.

With the coming of the Space Age, astronomers soon began sending their telescopes and instrumentation into orbit, to operate above the constraining window of Earth's atmosphere. One of the most successful astronomical



James E. Webb escorts President John F. Kennedy during a visit to a NASA centre in 1963

Who was James Webb?

James E. Webb (1906-92) was NASA's second administrator. Appointed by President John F. Kennedy in 1961, Webb organised the fledgling space agency and oversaw the development of the Apollo programme until his retirement a few months before Apollo 11 successfully landed on the Moon. Although an educator and lawyer by training, with a long career in public service and industry, Webb can rightfully be considered the father of modern space science. During his tenure as administrator, Webb insisted that NASA not only focused on manned spaceflight, but also embarked on a balanced programme of scientific research. As a result, by the time of his retirement, NASA had already launched some 75 scientific missions in astronomy, planetary exploration and space science.

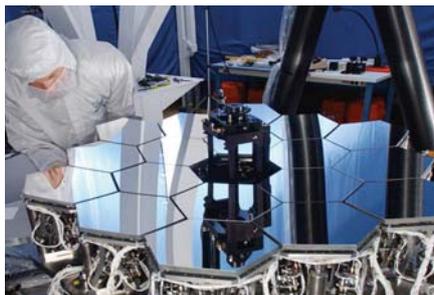


observatories launched into space to date has been the NASA/ESA Hubble Space Telescope (HST), which operates at visible wavelengths, with excursions to the ultraviolet and near-infrared.

Although HST's 2.4 m-diameter collecting mirror is dwarfed by many far larger modern telescopes on the ground, from its vantage point above the blurring turbulence of the upper atmosphere HST has provided the deepest and clearest views yet of nearly all types of astronomical object. Some of the more spectacular HST images have even achieved iconic status with the general public.

Launched in April 1990, HST has since been repaired, maintained and its instruments upgraded during four subsequent visits by the Space Shuttle. HST is presently scheduled to undergo its fifth and final servicing mission in August 2008.

Since 1996, NASA, ESA and the Canadian Space Agency (CSA) have cooperated on designing and constructing a worthy successor to the Hubble Space Telescope. Known initially as the Next Generation Space Telescope, the project was renamed in 2002 as the James Webb Space Telescope (JWST) after the former NASA administrator led the US agency during one of the most impressive projects in history – landing a man on the Moon.



Telescope elements: (top to bottom) scaled-down testbed; prototype mirror backplane segment; and mirror segment attachment and adjustment mechanism

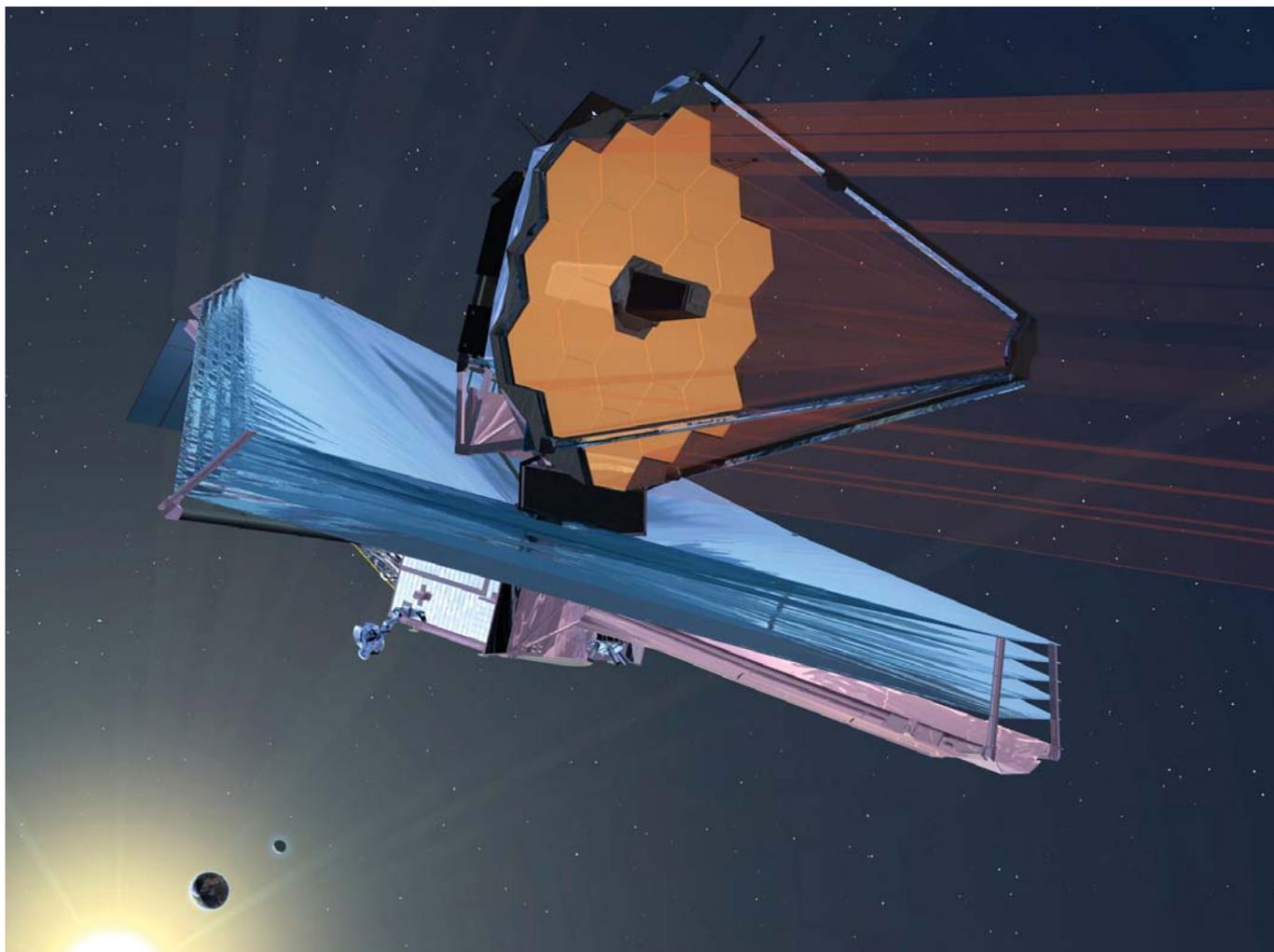
Although in several aspects JWST represents a radical departure from its predecessor, the astronomical capabilities of the JWST telescope and its instruments are very much driven by the scientific successes of HST, especially concerning exploration of the early Universe.

The Observatory

The JWST observatory consists of a 6.55 m-diameter telescope, optimised for diffraction-limited performance in the near-infrared (1–5 μm) and mid-infrared (5–28 μm) wavelength regions. The reason for the large telescope aperture and shift to the infrared is the desire to follow the contents of the faint extragalactic Universe back in time, to the epoch of 'First Light' and the ignition of the very first stars.

Nonetheless, like its predecessor, JWST will be a general-purpose observatory and carry a full suite of astronomical instruments capable of addressing a broad range of outstanding problems in current astrophysics. In contrast to HST, however, JWST will be placed into an orbit, known as an 'L2' halo orbit, some 1.5 million km from Earth and away from the Sun in deep space. This means that it is not designed to be serviceable after launch.

JWST will carry a total of four scientific instruments whose capabilities



Artist impression of the deployed JWST in orbit showing the 6.55 m segmented telescope mirror and matching sunshade (Northrop-Grumman)

together span the full contents of an astronomer's toolbox:

- NIRCam: a wide field (2.2 x 4.4 arcmin) near-infrared camera covering the wavelengths 0.6-5 μm
- NIRSpec: a wide field (3.5 x 3.5

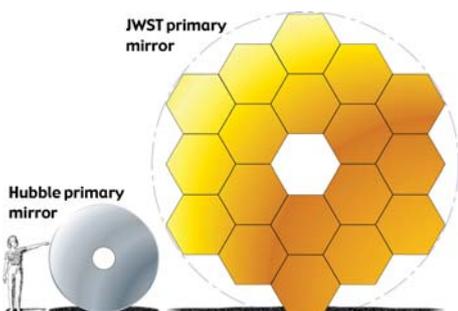
arcmin) multi-object near-infrared spectrometer covering the wavelengths 0.6-5 μm at spectral resolutions of R~100, R~1000 and R~2700

- MIRI: a combined mid-infrared camera (1.4 x 1.9 arcmin) and spectrograph (R~100 and R~2000) covering the wavelengths 5-27 μm
- FGS/TFI: a fine guidance camera that also carries a near-infrared tunable filter imaging capability (2.3 x 2.3 arcmin; R~100).

telluride (HgCdTe) detector arrays employed by the three near-infrared instruments. Cooling is achieved by keeping the telescope and its instrumentation in perpetual shadow behind a large deployable sunshade. Further cooling of the MIRI instrument to below -263°C is achieved with a dedicated mechanical cooler.

The telescope is made up of 18 hexagonal segments, and is specified to yield diffraction-limited performance at wavelengths above 2 μm in the near-infrared. In order to fit into the shroud of the ESA Ariane-5 launcher, the 6.55 m primary mirror needs to be folded and deployed with the secondary mirror once in orbit. The precise positioning of each telescope segment is individually

The telescope and its instruments are to be cooled in bulk down to -240°C , a temperature determined to avoid telescope self-emission in the near-infrared and the required operating temperature of the mercury-cadmium-



Comparison of Hubble and JWST mirrors (NASA)

Chasing the 'Redshift'

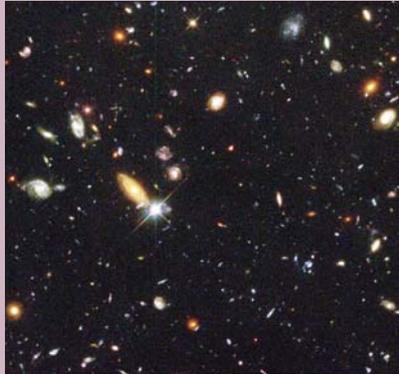
The story of modern astrophysics is one of ever-growing telescopes and ever-more sensitive instruments to look deeper into space. This obsession with the most distant objects has to do with the fact that the further away an object, the 'older' the light received, because of the finite speed of light. Astronomers can therefore 'look back in time' just by looking far enough away. They can observe directly the conditions in the Universe billions of years ago. With a big enough telescope, it is theoretically possible to map how stars and galaxies came into being and subsequently evolved nearly all the way back to the 'Big Bang', some 13.6 billion years ago.

An important consideration for exploration of the early Universe, however, is the accompanying 'redshift' effect. Because of the expansion of the Universe, the wavelength of light emitted by a remote galaxy becomes stretched during its long travel to Earth. The amount by which the received wavelength is stretched is determined by how much the Universe expanded in the time since the light was emitted.

The more distant the galaxy, the greater the redshift. The most remote galaxies known today have their light redshifted by a factor of nearly 8, meaning that we are viewing these objects when the Universe was only one eighth its present size. This is equivalent to looking back some 12.9 billion years into the past, or 95% of the way back to the Big Bang.

This 'redshifting' of light occurs at all wavelengths. To explore the 'normal' visible light emitted by the stars contained in more remote (i.e. younger) galaxies, astronomers have no choice but to chase this light deep into the infrared. This explains why JWST needs to both have a larger collecting mirror and be optimised for longer wavelengths compared to HST.

Redshift is also important because it allows astronomers to sort, by distance and age, the thousands of remote galaxies detected in very long camera exposures, such as those made in the Hubble Ultra Deep Field survey. Separating the light of a remote galaxy into its component colours, by passing it through a prism or reflecting it off a diffraction grating, allows the intensity of the light received to be measured at each wavelength. The detailed shape of the resulting 'spectrum' of the galaxy enables astronomers to infer not only the types, but also the ages and chemical composition of the stars that make up the galaxy. Equally important, the distance to the galaxy can be determined by measuring the redshift of the spectrum; that is, the amount by which the observed spectrum is shifted toward the red with respect to how it would look if the same galaxy were at rest. The task of measuring the redshifts of many faint galaxies simultaneously is one of the primary design drivers behind the ESA-supplied NIRSpec instrument on JWST.



The Hubble Ultra-Deep Field image is the farthest look into the Universe by astronomers to date. Some 10 000 faint galaxies are visible in this million-second exposure, the most remote of which emitted their light when the Universe was only 5% of its present age. Exploring these galaxies spectroscopically and probing even further back in time is a key scientific goal of the JWST mission (NASA/ESA/STScI)

controllable in six degrees of freedom, and the radius of curvature of each segment can also be adjusted if needed. Telescope fine alignment will be achieved on orbit with the help of various pupil-imaging diagnostic modes included in the NIRCам instrument.

Fine pointing of the telescope will be achieved by deflecting the beam by means of a fast steering mirror controlled by the Fine Guidance Sensor (provided by the Canadian Space Agency) located in the telescope focal plane.

JWST will be operated in a manner similar to the HST. The Space Telescope Science Institute (STScI), which operates HST, is under contract to NASA to serve as the operations centre for JWST and will take on responsibility for the scientific exploitation of the observatory and its instruments after successful commissioning.

At the time of writing, the JWST project is approaching completion of the final critical design phase and remains on schedule for a launch in 2013.

The NIRSpec Instrument

The ESA NIRSpec instrument on JWST is in many ways complementary to the NASA-funded JWST NIRCам near-infrared camera. While NIRCам takes direct pictures of a patch of sky through the JWST telescope, NIRSpec is designed to measure the spectra of pre-selected objects contained in it. This reflects the nature of celestial exploration: new interesting astronomical objects are often first discovered through imaging, but uncovering their astrophysical properties invariably requires detailed follow-up spectroscopy.

NIRSpec is a multi-object spectrograph, meaning that it is capable of measuring the spectra of up to 100 objects simultaneously. NIRSpec will be the first such astronomical spectrograph to fly in space. NIRSpec achieves this feat thanks to its novel micro-mechanical slit selection device. In the first stage of the NIRSpec optical chain, the field of view to be studied is imaged onto a Micro-Shutter Array (MSA) consisting of just under a quarter of a million individually addressable micro-shutters. The light from the objects under investigation is then isolated and allowed to enter the instrument by programming the MSA to only open those shutters coinciding with the pre-selected objects of interest. The remainder of the optical chain then serves to separate the light passing through the shutters into its component colours by means of a prism or a diffraction grating. The resulting



The qualification model of the NIRSpec front optical system undergoing testing (Sagem)

spectra are then finally refocused onto a large format (2k x 4k pixel) low-noise infrared detector array where they are registered and sent to the ground.

NIRSpec carries a total of six diffraction gratings and a prism as its dispersive elements. Depending on the source brightness and the astrophysical problem at hand, these allow the user to disperse the target light by different amounts, and separate adjacent wavelengths to a relative accuracy (or spectral resolution) of $\lambda/\Delta\lambda = R = 100, 1000$ or 2750 .

In addition to the MSA, a 3×3 arcsec Integral Field Unit and five fixed long slits are also available for detailed spectroscopic studies of isolated single objects and other specialised applications.

Another noteworthy feature of NIRSpec is the use of silicon carbide (SiC) ceramic as basic material for both the mirrors and the structural parts of the instrument. SiC is a unique material with a very high stiffness-to-mass ratio and a very high thermal stability expressed through its thermal conductivity to thermal expansion ratio. This

makes the material very suitable for low temperature optical applications. SiC was also used to build the ESA Herschel telescope and is the basic material for the complete telescope structure and mirrors of the ESA Gaia mission.

NIRSpec is being built by European industry to ESA's specifications and managed by the ESA JWST Project at

ESTEC. The prime contractor for NIRSpec is EADS Astrium in Ottobrunn, Germany. The NIRSpec detector and MSA subsystems are provided by NASA's Goddard Space Flight Center.

The MIRI Instrument

In contrast to the NIRCам, NIRSpec and the Canadian provided Tunable Filter instruments that operate exclusively in the near-infrared $1\text{--}5 \mu\text{m}$ wavelength range, the MIRI instrument on JWST is designed to sample the longer mid-infrared wavelengths at $5\text{--}28 \mu\text{m}$. The mid-infrared spectral region is important astrophysically for a number of reasons, not least of which is the ability of mid-infrared light to penetrate the dense interstellar dust clouds that enshroud star forming regions and make them impenetrable to study at shorter wavelengths.

As MIRI is the only instrument on JWST sampling mid-infrared wavelengths, its design is self-contained in that it carries both a camera mode for direct imaging and two spectrograph modes providing spectral resolutions of $R=100$ and $R=2000$ respectively. The MIRI mirrors and structure are made of aluminium throughout. The instrument mass is 100 kg.

One noteworthy feature of the MIRI camera is its novel coronagraphic mode.

Europe's Contributions to the JWST Mission

ESA's participation in the JWST mission was approved by the ESA Science Programme Committee in 2003. The four major European contributions to the mission are formalised in the Memorandum of Understanding on JWST signed by NASA and ESA in 2007:

- provision of the NIRSpec instrument;
- provision of the Optical Bench Assembly of the MIRI instrument through special funding from the ESA member states;
- provision of the Ariane-5 ECA launcher;
- manpower support to JWST operations.

In return for these contributions, ESA gains full partnership in JWST and secures full access to the JWST observatory for astronomers from Member States on identical terms to those of today on the Hubble Space Telescope. European scientists will be represented on all advisory bodies of the project and will be expected to win observing time on JWST through a joint peer review process, backed by an expectation of a minimum ESA share of 15% of the total observing time.

In this mode, placing the image of a star on a 'Quadrant Phase Mask' causes the light from the star to be dramatically attenuated, thereby allowing any planets orbiting the star to be searched for and imaged directly.

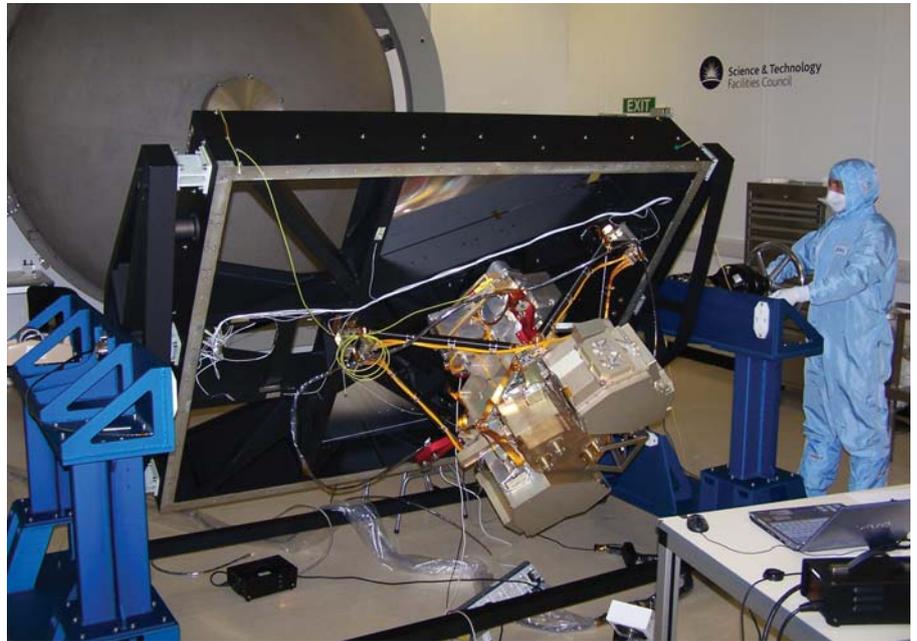
To limit the self-emission from the MIRI instrument and operate its three 1k x 1k SiAs detector arrays, parts of the MIRI instrument need to be cooled some 25° below that of the passively cooled near-infrared instruments to a temperature less than 10° above absolute zero. This is achieved by means of a dedicated mechanical cooler.

MIRI is being procured jointly by Europe and the USA. The MIRI Optical System is being built and funded by a consortium of ESA member states led by the United Kingdom and comprised of France, the Netherlands, Germany, Spain, Sweden, Switzerland, Denmark, Belgium and Ireland. Overall leadership of the European MIRI consortium rests with the European Principal Investigator, Dr Gillian Wright of the Astronomy Technology Centre in Edinburgh. The MIRI detector arrays and mechanical cryo-cooler are provided by NASA's Jet Propulsion Laboratory.

The Technical Challenges of JWST

The original name of JWST – the Next Generation Space Telescope – can be understood literally. JWST is the first space telescope whose primary mirror is larger than the diameter of the launcher fairing, and the first mission to use lightweight construction techniques and active adjustment of its mirrors in space.

The large size of the satellite and the need to fit inside an Ariane-5 launcher fairing requires a number of deployable features. The main telescope and its 18 hexagonal mirror segments have two deployable wings hinged and rotated against the back of the central telescope. The secondary mirror is suspended on a tripod in front of the main mirror that is folded and rotated against the back of the primary mirror during launch. During launch, the telescope rests on the spacecraft at four



Verification Model of MIRI undergoing testing (MIRI EC)

corner points to transfer the launch loads, which also makes the geometry more compact.

The sunshade that separates the warm spacecraft from the cold telescope is impressive, reaching the size of a tennis court when fully deployed. The sunshade is stowed in two segments along the front and back of the telescope during launch. The solar arrays and communication antenna dish are also collapsed against the spacecraft body for launch. After separation from the launcher, the observatory will literally unfold itself like a butterfly from its cocoon (see a JWST deployment animation available at <http://sci.esa.int/jump.cfm?oid=41816>).

The JWST system design is strongly driven by thermal considerations. Sunlight must be kept off the telescope and instruments at all cost, and this is achieved with a sunshade made of five separate foils acting as a multi-layer insulation. The spacecraft, with its attitude control electronics, power regulation, communications systems and on-board data handling and processing system, is situated on the 'hot' side of the sunshade and operate at near-room temperature as on most other spacecraft.

The telescope and the instruments on the 'cold' side of the sunshade need to be kept below -240°C. This is achieved by physically separating the warm spacecraft from the cold observatory by means of a deployable tower that is activated after launch, thus giving a low parasitic heat transfer from the warm to the cold region. All electronics and instrument parts located in the cold region must have extremely low power dissipation in order to maintain the low temperatures.

The full complement of four instruments with a total mass of 570 kg has an average power dissipation of less than 0.5 W, less than a small bicycle lamp. The telescope and its instruments are passively cooled to below -240°C by exposing them to the deep-space environment at a temperature of -270°C. It takes four months to cool down the observatory after deployment of the sunshade. This matches very well the time it takes to reach the final orbit at L2, where observations can begin.

The Management Challenges of JWST

In the ESA/NASA cooperation on JWST, mutual responsibilities and obligations are defined at global level in

the JWST Memorandum of Understanding. The Joint Project Implementation Plan (JPIP) defines the mutual responsibilities and obligation in further detail, and also describes the management interaction and coordination between the two projects. A key assumption made in the JPIP is the principle of equivalence between the engineering and product assurance standards to which the two agencies each work. This makes it possible for the ESA and NASA contractors to work to standards they are familiar with.

The JPIP is based on a partnership and not a contractual relationship. No money flows between the two agencies. As a partner, ESA supports all the programme-level activities such as reviews and approval of all higher-level project documents. However, NASA is responsible for the overall mission system, and ESA works to interface and functional requirements defined by NASA. ESA is responsible for the NIRSpec and the MIRI Optical Systems. NASA delivers subsystems to both instruments according to interface and functional requirements defined by ESA. This makes the overall technical and programmatic situation rather complex.

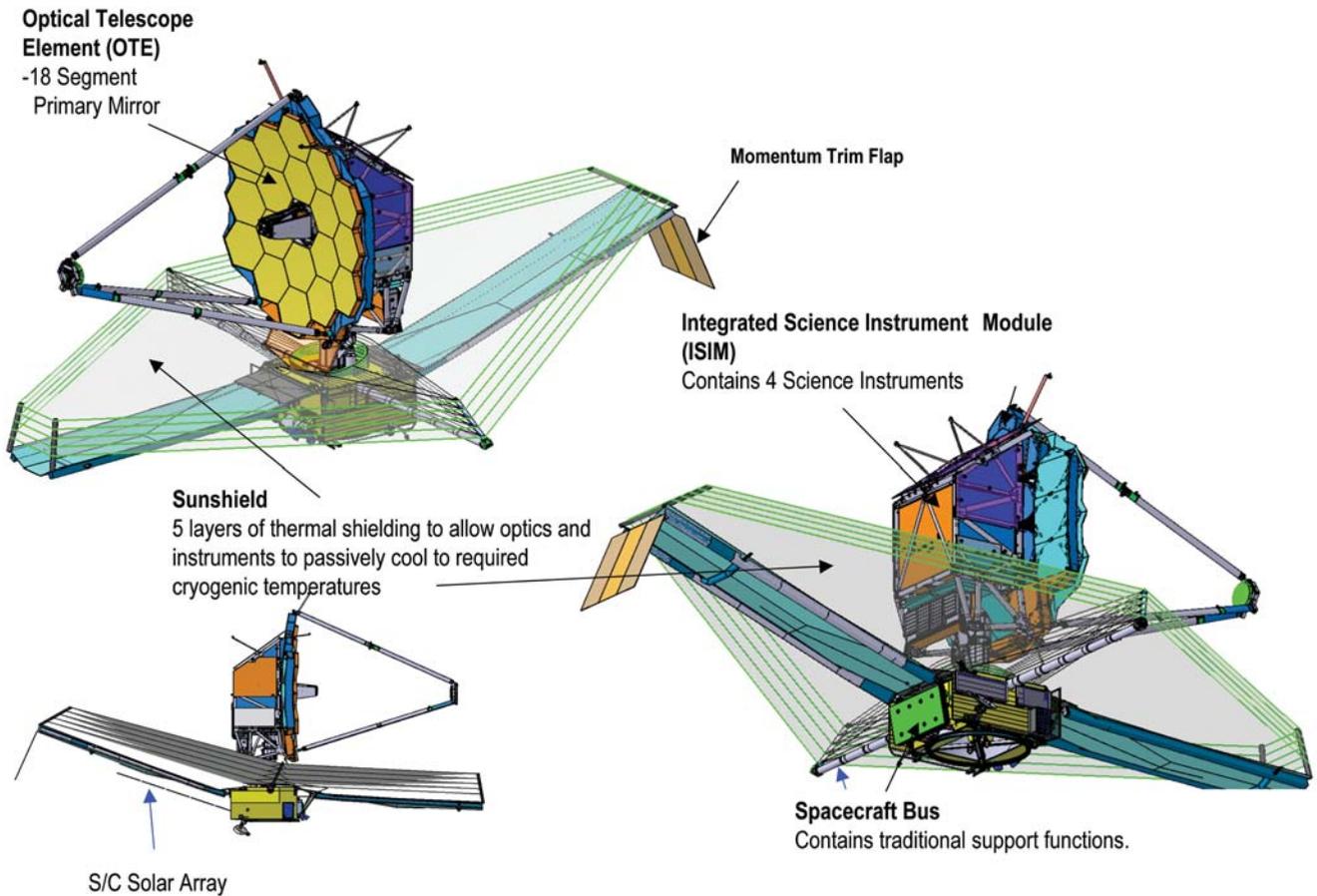
The guiding principle used in the definition of the ESA/NASA mutual responsibilities has been to identify 'Clean and Clear Interfaces'. This applies to both technical and management interfaces, and has probably been the most important aspect to ensure a smooth and efficient cooperation. An example is the delivery of detectors for NIRSpec and MIRI from NASA. Detectors, detector electronics, flight software, electrical and mechanical ground support equipment, calibration and qualification are the responsibility of NASA. This makes the detector systems fully independent subsystems and easy to manage from both a technical and programmatic point of view.

Working cultures are certainly different between ESA and NASA, and



JWST in launch configuration inside the Ariane-5 fairing





it is important that the two project teams on both sides of the Atlantic be conscious of this to avoid conflicts and irritation. The in-depth definition of deliverables: hardware, software, ground

support equipment and documentation captured in the JPIP has significantly mitigated conflict situations and smoothed the cooperation. It has been made clear from the beginning what was

expected from each party at the lowest possible level.

The ESA/NASA cooperation is further complicated due to the International Traffic in Arms Regulations (ITAR), which is a set of government regulations that control the US export and import of defence-related articles and services. Basically all space activities and products are considered defence-related. This makes it very difficult for a US company to share any detailed design information, analyses and test procedures with ESA. The exchange of information and service needs to be defined in a Technical Assistance Agreement (TAA), which is to be approved by the US Department of State (DoS). Typically, very strong provisos are applied by DoS, which precludes any exchange of detailed design information. This constraint makes it even more important to have 'Clean and Clear' interfaces, with a minimum of exchange of information required.

The JWST Technology Development Programme

JWST takes us outside the capabilities of today's technology and satellite design approach in several areas. Ten critical leading technologies were identified by NASA in the concept phase of the project. The leading technologies span a very wide range: mirror segment adjustability with nanometre accuracy, alignment of all 18 mirror segments, stability of the mirror segment support structure, large format and ultra-low noise near-infrared and mid-infrared detectors, mechanical coolers for MIRI and the Micro-Shutter Array for NIRSpec.

All technologies reached the required TRL-6 in spring 2007. TRL-6 requires a system or subsystem model or prototype demonstration in a relevant environment. This is an important achievement that allows the JWST project to progress to the implementation phase with the required technological developments in hand. A significant investment had been made early in the project development phase to achieve this.

To support the construction of NIRSpec, ESA also faced the need to develop new technologies in the field of high-performance mirrors and structures, which are compatible with use at -240°C . The development focused on qualifying silicon carbide (SiC) ceramic as the basic material for both the mirrors and the structural parts of NIRSpec.