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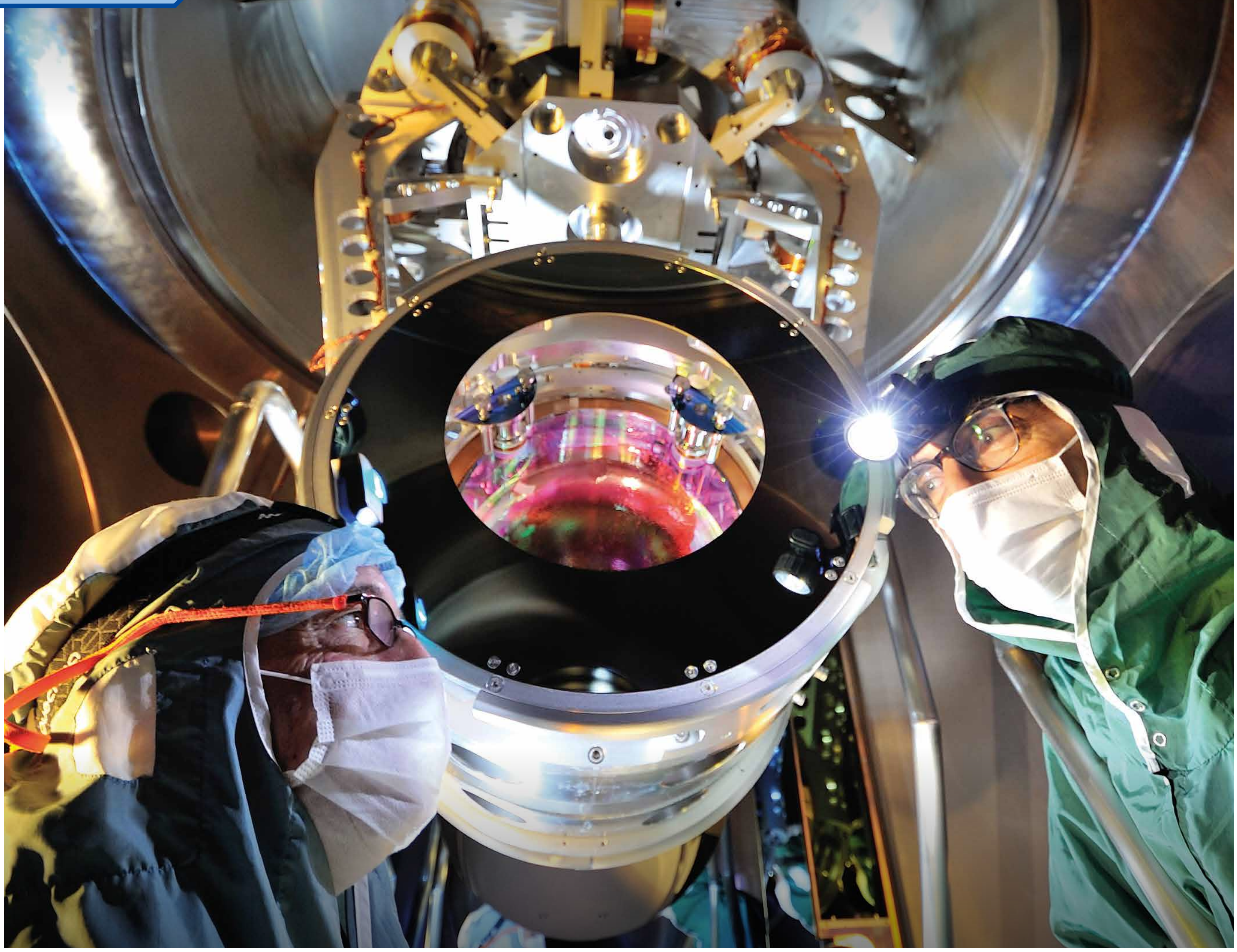

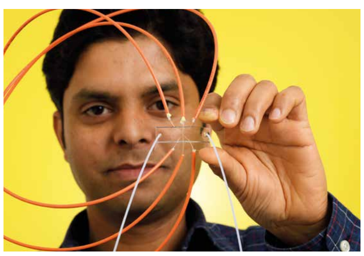

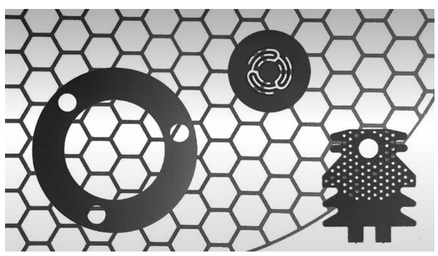

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- PRECISION FAIR 2018 PREVIEW
- MICRO-OPTOFLUIDICS
- SWISS WATCH FEATURING DUTCH PRECISION

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DSPE
Annemarie Schrauwen
High Tech Campus 1, 5656 AE Eindhoven
PO Box 80036, 5600 JW Eindhoven
info@dspe.nl, www.dspe.nl

Editor
Hans van Eerden, hans.vaneerden@dspe.nl

Advertising canvasser
Gerrit Kulsdom, Sales & Services
+31 (0)229 – 211 211, gerrit@salesandservices.nl

Design and realisation
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+31 (0)40 – 251 99 29, info@snep.nl

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The main cover photo (representing an input mirror of Advanced Virgo, suspended from a super-attenuator) is courtesy of Maurizio Perciballi. Read the article on page 5 ff.

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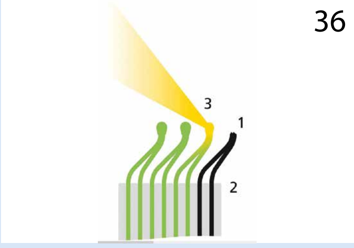

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FEATURES

BIG SCIENCE, **BIG OPPORTUNITIES**

A lot has changed since Galileo Galilei pointed his simple telescope at the sky and discovered Jupiter's four largest moons around 1609. It's possible to regard this event as the start of what we now call modern science. In some respects, you could also think of it as the start of 'Big Science'. New discoveries are made and new insights gained on the basis of observations. Instruments are required for the purposes of these observations, as are specialists capable of designing and building them. Galileo was dependent on a lens-maker in the Low Countries for his telescope.

That principle hasn't changed, as we still need new instruments to be able to make new discoveries, as well as physicists and engineers to design and build them. Nevertheless, the instruments are getting ever bigger, more expensive and technologically complex. This is certainly the case in astronomy, or in particle physics. A telescope like the one used by Galileo no longer suffices if we're looking to discover planets around stars other than our own sun.

The first European organisations for the joint development, construction and operation of large-scale research facilities were set up in the 1950s and 1960s: CERN, for nuclear research; ESO, for large astronomical observatories on earth; and the European Space Agency ESA. The Netherlands was in the vanguard of all these initiatives and is still continuously contributing to further developments. Large particle accelerators, vast telescopes containing mirrors several dozen meters in diameter, and large scientific satellites are too expensive to be funded by a single nation. European cooperation – and in many cases global cooperation – is the order of the day.

Thus ensuring that Big Science continues to produce spectacular scientific results and data that can be worked on for years to come, ultimately leading to Nobel Prizes. The Netherlands funds the facilities in conjunction with other European nations, and a proportion of this contribution is recouped in the form of assignments awarded to high-tech industry. Hence Big Science is a firm route to innovation, even if the path to practical applications for society is sometimes long and those applications are usually not predictable.

What is clear, however, is that groundbreaking science is increasingly reliant on industry. In order to bridge the gap between science and high-tech industry, industrial liaison officers (ILOs) are active within scientific institutes. They draw companies' attention to the opportunities that exist in terms of capitalising on possible assignments (tenders) from Big Science organisations, and give some of the guidance when it comes to securing those assignments. Thus contributing to improving the 'geographic return' on our national contributions.

It's far from easy, though; the scientific community is a demanding customer, and when developing entirely new, complex technology companies are running more risks than usual, sometimes spanning many years too. And so the onus is on the government to create facilities to mitigate the risks, thereby giving considerable impetus to innovation driven by curiosity. The Dutch ILO-net – which is the network of ILOs and part of the Netherlands Organisation for Scientific Research (NWO) – is doing its utmost to reinforce the connection between the business community and Big Science, along with a large number of other parties active in this area. This issue of Mikroniek gives several examples of the challenges being worked on at present ...

Gerard Cornet
Policy officer SRON, coordinator ILO-net
g.cornet@sron.nl, www.bigscience.nl

Note
The Netherlands contributes around 150 million euros each year for the construction of large-scale infrastructure through its membership of CERN, ESO, ESA and several other Big Science organisations. The aim is to 'earn back' at least 70% of that amount in the form of assignments put to Dutch industry.

HOW TO MEASURE SUB-Å DISPLACEMENTS ON THE EARTH-JUPITER DISTANCE

Recent joint observations of gravitational waves from binary black hole and neutron star mergers have demonstrated the potential of a global network of interferometers. The unprecedented accuracy in the source localisation, achieved with a network of only three detectors, has made multi-messenger astrophysics a reality. This article gives an overview of the measurement principle and instrumentation of the detectors, with a focus on the thermal compensation system needed to achieve the highest possible sensitivity in the coming years.

ALESSANDRO BERTOLINI AND ERIC HENNES

The discovery of gravitational waves (GWs) originating from merging black holes in 2015 and 2016 [1] [2] with the two LIGO detectors in the USA was awarded the 2017 Nobel Prize in Physics. During the first joint observations with the Virgo detector near Pisa in Italy (Figure 1) in 2017, another GW signal from a binary black hole merger was observed by all three interferometers [3], the first significant GW signal ever recorded by Virgo.

Three days later, the merger of two neutron stars was detected for the first time [4]. About seventy electromagnetic telescopes, both space-borne and Earth-based, also observed the event; each in its own wavelength range varying from X-rays to radio waves. This allowed for the second identification ever of a kilonova, a brief burst of electromagnetic radiation that is characteristic for the synthesis of heavy-element nuclei. Presently, both LIGO and Virgo are being further upgraded towards the next joint observation period starting in early 2019. Their final versions, coined Advanced Virgo [5] and Advanced LIGO, will be simply called Virgo and LIGO, respectively, hereafter.

Detector operation principle

Gravitational waves arise during events in the cosmos in which large masses undergo extreme accelerations. They cause ripples in space-time that propagate outward at the speed of light, and were conceived by Einstein in 1916 as a direct result of his general theory of relativity [6]. GWs are transverse waves that stretch the space along one axis while squeezing it along the perpendicular axis (and vice versa). They can be observed by measuring the distance between test masses in free-fall, which is just what a Michelson interferometer is suitable for (Figure 2a). Here, the mirrors and beam splitter serve as test masses.

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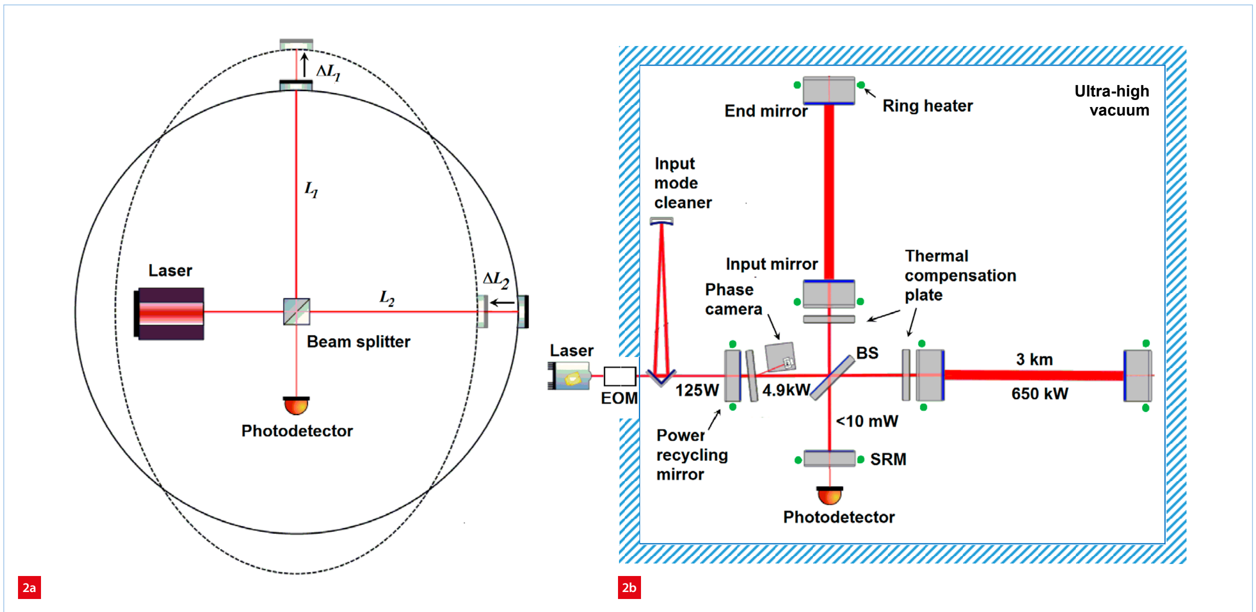
Aerial photo of Virgo, the gravitational-wave detector with its 3-km-long arms.

AUTHORS' NOTE

Alessandro Bertolini and Eric Hennes are both working at Nikhef (Dutch National Institute for Subatomic Physics) on the instrumentation of gravitational-wave detectors.

a.bertolini@nikhef.nl
e.hennes@nikhef.nl
www.nikhef.nl



Gravitational wave-detection principle.
(a) Effect of a GW that passes perpendicular to a Michelson interferometer. It deforms the space in such a way that one arm becomes shorter and the other longer, as a result of which the intensity of the light on the photodetector is modulated.
(b) A somewhat detailed optical layout of Virgo. The laser beam first passes the electro-optic modulator (EOM), followed by a 144-m triangular resonator, the so-called input mode cleaner. It filters out jitter noise and all laser modes other than the Gaussian TEM_{00} mode. Each interferometer arm consists of a 3-km-long optical resonator formed by an input mirror (which is also output) and an end mirror. This effectively increases the arm length by a factor of 280 (see text for explanantion). Thanks to the Power Recycling and Signal Recycling mirrors (PRM and SRM), the signal-to-noise ratio of the photodetector signal is further enhanced. Almost all components are placed in ultra-high vacuum and equipped with vibration isolation. On several locations a small quantity of light is tapped to measure the position and orientation of the mirrors to an accuracy of 1 nm and one nrad, respectively.

A GW impinging on the surface of the interferometer makes one arm longer by ΔL_1, for example, while the other arm becomes shorter (ΔL_2) and vice versa. The degree of space strain at any time is defined as $h(t) = (\Delta L_1 - \Delta L_2)/L$, where $L = L_1 = L_2$ is the length of the interferometer arms. As a consequence, the two reflected light beams recombining at the beam splitter show a mutual phase shift $\varphi = 4\pi Lh/\lambda$, where λ is the laser wavelength; λ = 1,064 nm for both LIGO and Virgo. φ is measured as a change in intensity of the light on the photodetector according to:

$$P_{out} = \frac{P_L}{2}\left[1 + \cos\left(\varphi_0 + \frac{4\pi L}{\lambda}h\right)\right] \qquad (1)$$

Here, P_L is the laser power. In practice, the detectors are operated close to the dark-fringe condition ($\varphi_0 \approx (2n + 1)\pi$, with n an integer), in order to suppress as much as possible the effect of laser power fluctuations that could mimic a signal.

Increasing the signal strength

The amplitude of GWs is inversely proportional to the distance to the source. The expected GW strain h from distant sources is therefore very small, in the order of 10^{-22} m/m, which is less than 1 Å on the Earth-Jupiter distance. To enhance the detector response, the interferometer arms are replaced by Fabry-Pérot optical resonators, called arm cavities, in which the photons travel back and forth many times before recombining at the beam splitter (Figure 2b). In this way, we benefit from the long timescale of the signal phase, milliseconds, compared to the round-trip time of the light in the arms (~20 µs).

At Virgo, the input mirrors (Figure 3) have a transmission coefficient of T_s = 1.4%, enhancing the arm length effectively by a factor of $4/T_s$ = 280 to L_{eff} = 840 km. For a GW of frequency f_{GW} the phase shift per unit of GW strain h is given by:

$$\frac{d\varphi}{dh} = \frac{4\pi L}{\lambda}\frac{L_{eff}/L}{\sqrt{1+(f_{GW}/f_c)^2}}\ ,\ f_c = c/2\pi L_{eff} \qquad (2)$$

Equation 2 is valid for $\lambda_{GW} >> 2L$, or in this case, f_{GW} << 50 kHz and shows that the amplification factor L_{eff}/L (280 for low frequencies) gradually decreases above the cut-off frequency, f_c = 57 Hz, down to 1.6 at around 10 kHz.
A second way to enhance the signal strength is to increase the light power on the beam splitter. This is realised with the same laser source, as follows. In the dark-fringe state all the light energy is reflected back towards the laser. If we place an extra mirror, the Power Recycling Mirror (PRM), between the laser and the beam splitter (Figure 2b), most of this light is reinjected into the interferometer.

The position of the PRM is chosen such that the reinjected light interferes constructively with the ‘fresh’ light from the

FROM FIRST LIGHT TO THE ASSEMBLY OF GALAXIES

The James Webb Space Telescope (JWST), the largest space observatory ever constructed, is awaiting the journey to its final destination, to unravel some of the biggest mysteries of astronomy. With 6.5 meter the primary mirror of JWST exceeds the collective imaging area of the famous Hubble Space Telescope by almost a factor of 7, thus increasing resolution significantly. JWST is extra special because of its dedicated infrared observing capabilities. This article focuses on the Dutch JWST content in the Mid Infrared Instrument.

GABBY AITINK-KROES

The evolution of space observatories is slow but impressive. The famous Hubble Space Telescope (HST) was launched in 1990 and just recently put on hold because of gyroscope failure. Its successor, the James Webb Space Telescope (JWST), is to be launched in 2021. Over this period of thirty years, the diameter of the primary mirror has changed from 2.5 to 6.5 meter, yielding a nearly sevenfold increase of the collective imaging area (Figure 1).

JWST is a joint international mission (NASA/ESA/CSA) involving scientists and engineers from all over Northern America and Europe. On board, the Integrated Science Instrument Module (ISIM) is the heart of the observatory, housing the four science instrument of JWST (Figure 2). Each instrument has its dedicated function targeting a specific wavelength range. This combination offers images and spectra at several resolutions for various fields of view at a wavelength range from 0.6 to above 25 micron. The instruments are mounted into a dedicated support which is then mounted to the JWST support structure, behind the primary mirror.

The following instruments are on board:

- The combined Fine Guidance Sensor/Near-InfraRed Imager and Slitless Spectrograph – FGS/NIRISS
- The Near-Infrared Camera – NIRCam
- The Near-Infrared Spectrograph - NIRSpec
- The Mid-Infrared Instrument – MIRI

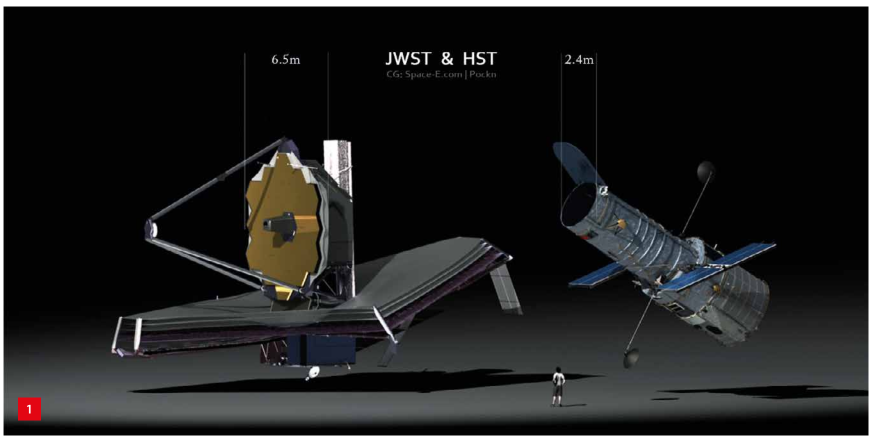
Mid Infrared Instrument

From the Dutch perspective, the prime instrument on board is the Mid Infrared Instrument (MIRI), which as the name suggests is specifically targeting the mid-infrared wavelength range. MIRI is being built by: ESA, the MIRI consortium (a collaboration of nationally funded European institutes), the Jet Propulsion Laboratory (JPL) and NASA's Goddard Space Flight Center (GSFC). It provides imaging and spectroscopy over the 5-28 micron wavelength range by dedicated modules.
In the Netherlands, NOVA-ASTRON, together with TNO and SRON developed, designed and realised part of the spectrometer. MIRI comprises two main modules: MIRIM and MRS (Figure 4).

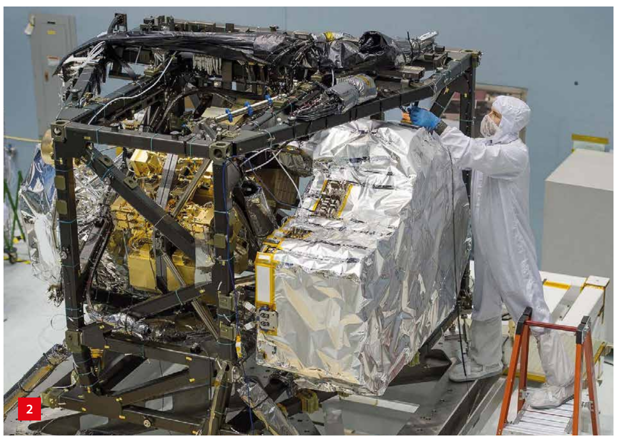
AUTHOR'S NOTE

Gabby Aitink-Kroes worked for over twenty years as a mechanical systems lead engineer at NOVA-ASTRON; the NOVA Optical InfraRed Instrumentation group of ASTRON, the Netherlands Institute for Radio Astronomy, based in Dwingeloo, the Netherlands. Recently, she joined the Netherlands Institute for Space Research, SRON.

g.aitink-kroes@sron.nl
www.astron.nl/nova



The Hubble Space Telescope (HST) versus the James Webb Space Telescope (JWST). (Image: NASA)



JWST's Integrated Instrument Science Module with its instruments: MIRI (left, wrapped in aluminium-coated multi-layer insulation), in the centre NIRCam at the front and GFS in the back, and NIRSpec (right). (Image: NASA)

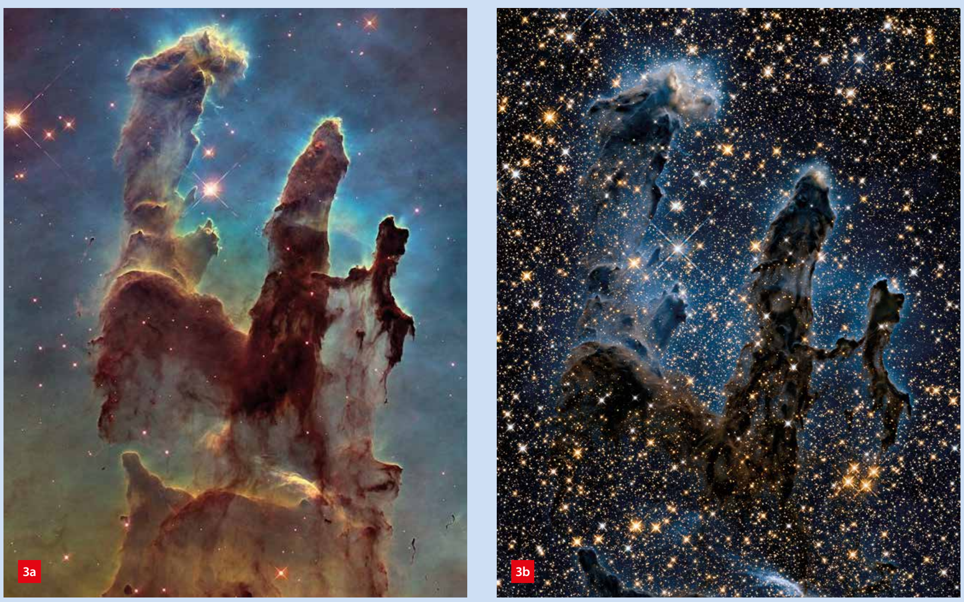
Astronomy – Science with JWST

Astronomy – the knowledge of the universe – is one of the oldest natural sciences, dating back to antiquity. Modern astronomy started with Galilei, who was the first to use technology for sky observations. He pointed a self-built version of the 'kijker' at the sky. The Dutch spectacle maker Lippershey tried to obtain the first patent for this two-lens telescope a little earlier in 1609. This was soon followed by the rapidly increasing size and quality of the telescopes thus improving on resolution, contrast and reduced observing times. An impressive suite of revolutionary scientific instruments allows observations to cover a wide wavelength range from the ultra-short gamma rays to very long radio waves. In a relatively short time this has offered new insights and discoveries that revealed the diversity and extent of the universe.

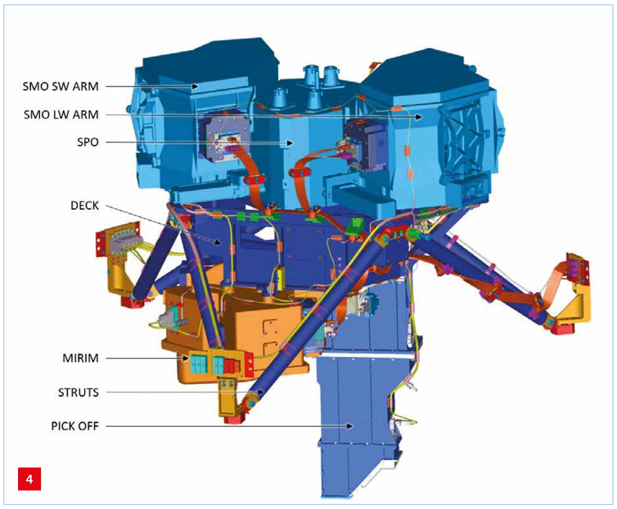
The James Webb Space Telescope (JWST) is being built to specifically target the infrared wavelength and aims at unravelling some of the biggest mysteries of astronomy through four main science targets:

- First light & reionisation:
  Understanding the emergence of the first sources after the 'dark ages of the universe' is critical as they act as seeds for the later formation of larger objects, such as galaxies.
- Assembly of galaxies:
  Observing galaxy formation and evolution and comparing the faintest, earliest galaxies to today's enormous array of different galaxies in size and shape. Trying to understand how galaxies assemble over billions of years.
- Star birth & protoplanetary systems:
  Understanding how stars and planets are created by observations of planets and left-over debris around (young) stars. Trying to understand how they evolve and release the heavy elements they produce back into space for recycling into new generations of stars and planets.
- (Exo) planets & origins of life:
  Observing the atmospheres of extrasolar planets, and perhaps even finding the building blocks of life elsewhere in the universe. In addition to other planetary systems, also studying objects within our own solar system.

Galaxy, star and planet formation particularly take place inside dense gas and dust regions. The longer wavelength of infrared light makes it possible to see what happens inside (and behind) these regions as it penetrates through the clouds, contrary to visible wavelengths (Figure 3).
Far away galaxies emit radiation at shorter wavelengths, but will be observed in the infrared region. This is because of the Doppler Effect; as the cosmos expands the signal is elongated in wavelength, causing the so-called 'red shift'.



The 'pillars of creation' in the Eagle nebula.
(a) In visible wavelengths. (Image: NASA/ESA/Hubble Heritage Team (STScI/AURA)/J. Hester, P. Scowen (Arizona State University).
(b) In infrared wavelengths. (Image: NASA/ESA/Hubble Heritage Team (STScI/AURA)).



The Mid InfraRed Instrument (MIRI) with the spectrometer (top), the deck that connects the modules to the CRFP struts (middle), and the imager and pick-off mirror assembly (bottom). (Image: MIRI consortium)

MIRI Image Module (MIRIM)
The camera module provides wide-field broadband images that will continue the astrophotography that has made Hubble famous. The spectrograph module will enable medium-resolution spectroscopy to provide new physical details of the distant objects it will observe. The specially developed arsenic-doped silicon detectors provide yet unknown levels of sensitivity and are used in both the imaging as well as the spectroscopic module.

Medium Resolution Spectrograph (MRS)
The MRS is an Integral Field Unit (IFU) grating spectrograph. The IFU allows extended objects to be studied in more detail. The image is cut into several slices, these slices are laid out side by side in one long line that is offered to the spectrograph as a single (pseudo) slit. Each slice (also called slitlet) is then optically dispersed by a grating and imaged side by side onto the detector. This results in separate spectra for each discreet part (strip) of the extended objects.

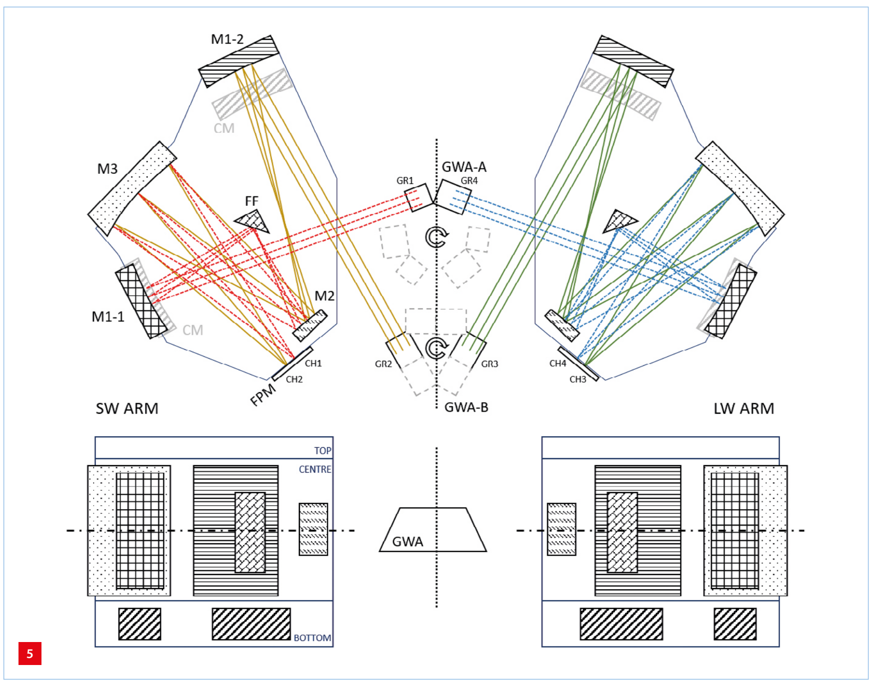
In order to cover the full wavelength range with a minimum of observations the MRS consists of four channels used simultaneously, each covering in total one fourth of the full wavelength range. Per channel, one single exposure samples one third (called a sub-spectrum) of the specific range. So a full 5-28 μm spectrum requires three exposures, providing in total 12 sub-spectra (3 exposures x 4 channels). For each sub-spectrum a dedicated grating is provided

Structurally, the MRS is divided into two subsystems: the Spectrometer Pre-Optics (SPO) and the Spectrometer Main Optics (SMO). The previously discussed IFU is part of the pre-optics. The pre-optics also splits the light in four specific wavelength ranges, using dichroics on a rotating selection mechanism. This mechanism also selects the corresponding gratings to disperse the light. The main optics consists of the collimators and camera systems for the four channels.

Spectrometer Main Optics (SMO)
In the Netherlands, NOVA-ASTRON together with TNO and SRON developed, designed and realised the SMO. The early interaction between the optical and mechanical design together with high-level design choices resulted in a very compact and seemingly simple layout.

The SMO has two arms (Figure 5): SMO-SW for the short-wave channels 1 and 2, and SMO-LW for the long-wave channels 3 and 4. The very low optical *f*-ratio (close to 1) and the shared optics allow a minimum number of components and a very compact design. The two arms are each other's mirror image with respect to the mirror plane (dotted line) through the mechanism (GWA) axes.

This mirror symmetry and the symmetry through the centre plane (centre line) of the camera optics allow the camera mirrors and central support to be identical. The FF top, bottom and baffles are mirror images. Because the arms are very similar one arm was fully designed and tested while the other arm followed with little effort after proof of design, providing advantages in design effort and hence cost and schedule.



The SMO layout showing the SW arm (left) and LW arm (right) , from the top and the front. Two channels reside in each box. Each channel has its own collimator mirror (CM) in the bottom and a separate first mirror (M1-1 and M1-2) of the three-mirror anastigmat camera system in the central support. The 'FF' folds one channel onto the shared last two mirrors (M2 and M3) of the camera system and the detector (FPM). So, a channel enters the SMO at bottom level and is reflected by its CM onto the GWA at central level. The dispersed beam is then imaged onto the FPM by the camera system. The two 3-position grating wheels GWA-A and GWA-B contain the 2x3 gratings, one for each sub-spectrum, in the SPO on top of the selection mechanism. (Image: NOVA-ASTRON, UK-ATC)