The JWST near-infrared spectrograph NIRSpec: status

Pierre Ferruit[a], Giorgio Bagnasco[a], Reiner Barho[b], Stephan Birkmann[a], Torsten Böker[a], Guido de Marchi[a], Bernhard Dorner[c,d,e], Ralf Ehrenwinkler[b], Massimo Falcolini[a], Giovanna Giardino[a], Xavier Gnata[b], Karl Honnen[b], Peter Jakobsen[f], Peter Jensen[a], Manfred Kolm[b], Hans-Ulrich Maier[b], Ralf Maurer[b], Markus Melf[b], Peter Mosner[b], Peter Rumler[a], Jean-Christophe Salvignol[a], Marco Sirianni[a], Paolo Strada[a], Maurice te Plate[a], Thomas Wettemann[b]

[a]European Space Agency / ESTEC, Keplerlaan 1, PO Box 299, 2200 AG, Noordwijk, The Netherlands;

[b]Astrium GmbH - Ottobrunn, 82024 Taufkirchen Germany;

[c]Université de Lyon, Lyon, F-69003, France;

[d]Université Lyon 1, Observatoire de Lyon, 9 Avenue Charles André, Saint-Genis Laval, F-69230, France;

[e]CNRS, UMR 5574, Centre de Recherche Astrophysique de Lyon, France;

[f]DARK Cosmology Centre, University of Copenhagen, Juliane Maries Vej 30, 2100 Copenhagen, Denmark.

ABSTRACT

The Near-Infrared Spectrograph NIRSpec is one of the four instruments of the James Webb Space Telescope (JWST). NIRSpec will cover the 0.6-5.0 micron range and will be capable of obtaining spectra of more than 100 objects simultaneously in its multi-object spectroscopy (MOS) mode. It also features a set of slits and an aperture for high contrast spectroscopy of individual sources, as well as an integral-field unit (IFU) for 3D spectroscopy. We will first show how these capabilities are linked to the four main JWST scientific themes. We will then give an overview of the NIRpec modes and spectral configurations with an emphasis on the layout of the field of view and of the spectra. Last, we will provide an update on the status of the instrument.

Keywords: JWST, NIRSpec, spectroscopy, infrared

1. INTRODUCTION

The James Webb Space Telescope (JWST)[1,2], often presented as the successor of the Hubble Space Telescope (HST), will be one of the "great observatories" of the next decade. It is a collaborative project between the National Aeronautics and Space Administration (NASA), the European Space Agency (ESA) and the Canadian Space Agency (CSA). JWST is due to be launched in 2018 from the French Guiana space center and will be placed in its orbit around the anti-Sun Earth-Sun Lagrangian point (L2) by an Ariane 5 launcher provided by ESA.

Its payload contains four scientific instruments: a near-infrared camera (NIRCam)[3], a combined mid-infrared camera/spectrograph (MIRI)[4], a near-infrared imager and slit-less spectrograph (NIRISS)[5] and a near-infrared spectrograph (NIRSpec)[6]. A Fine Guidance Sensor (FGS)[5] completes this instrument suite.

Among these 4 instruments, the NIRSpec spectrograph will cover the full 0.6-5.0 micron range and will be capable of obtaining spectra of more than 100 objects simultaneously in its multi-object spectroscopy (MOS) mode. It also features a set of slits and apertures for high contrast spectroscopy of individual sources, as well as an integral-field unit (IFU) for 3D spectroscopy. NIRSpec is manufactured in Europe for ESA by an industrial consortium led by Astrium GmbH.

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In this article, we first provide an overview of the capabilities of the NIRSpec instrument. We then present in more details how these capabilities have been implemented. Last, we give an update on the status of the instrument development.

2. THE SPECTROSCOPIC CAPABILITIES OF THE NIRSPEC INSTRUMENT

2.1 From the JWST key science objectives to the need for infrared spectroscopic capabilities

The key JWST mission science objectives have been divided in four broad themes[1]: the end of the dark ages, first light and re-ionization; the assembly of galaxies; the birth of stars and planetary system; and planetary systems and the origin of life. In the following we give a very brief description of the contents of each theme and identify the associated needs for near-infrared (up to 5 microns) spectroscopic capabilities.

The end of the dark ages – first light and re-ionization: the so-called "dark ages" of the Universe end with the appearance of the first light sources that marks the beginning of the phase of re-ionization of the Universe that is now believed to take place between redshifts 15-14 and 6 (see e.g. [8] and references therein). JWST will study the nature and properties of the first stars, galaxies and active nuclei as well as their contribution to the re-ionization. This requires the ability to perform deep near-infrared spectroscopy at spectral resolutions around 100 and 1000 of the bright end of the first light objects that will be discovered through ultra-deep field imaging surveys.

The assembly of galaxies: despite the progress made in the last decade (see e.g. [9]), many questions regarding the assembly of galaxies are still unanswered and will remain unanswered when JWST will start observing. In this context, JWST will investigate the growth and evolution of galaxies and their relationship with their environment and nuclear activity by looking at large samples of galaxies throughout a wide redshift range (typically from 1 to 7). This requirement to observe a large number of galaxies translates into a need for a near-infrared multi-object spectroscopic capability at spectral resolutions around 1000. At the same time, it will be necessary to conducted detailed studies of a smaller number of objects (see e.g. [10]) and this requires the ability to perform spatially-resolved near-infrared spectroscopy at spectral resolutions around 1000 and 3000.

The birth of stars and planetary systems: in order to have a more complete view of the formation and evolution of the stars and their planetary systems it is critical to gain a better understanding of the first phases of their life. Thanks to its wide wavelength coverage (from 1 to 27 microns) and unprecedented sensitivity and spatial resolution, JWST will make major contributions to the study the collapse of proto-stellar clouds and formation of proto-planetary disks. It will also allow studying the interplay between the newly born stars and their environment, as well as the shape of the low-mass end of the initial mass function (IMF). Some of these topics (e.g. the study of proto-star evolution) will mainly be addressed using mid-infrared imaging and spectroscopy but, even in these cases, near-infrared spectroscopy will add very valuable complementary information. In addition to the need for multi-object and spatially resolved spectroscopic capabilities shared with the extra-galactic topics, this science theme also requires high-contrast slit spectroscopy. Spectral resolution ranging from 100 to several thousands will be needed.

Planetary systems and the origin of life: this fourth science theme is connected to the previous one through the study of (proto-) planetary disks. It calls for observations of various components of our solar system (from planets and satellites to comets and Kuiper-belt objects) as well as of extra-solar planetary systems. For this, high-contrast and spatially resolved near-infrared spectroscopy at medium to high spectral resolution is needed. Note that spectroscopic observations of transiting extra-solar planets are also very demanding in terms of relative spectro-photometric stability.

2.2 Overview of the NIRSpec modes and spectral configurations

The NIRSpec instrument is required to provide the following capabilities:

- Deep multi-object spectroscopy at low (~100) and medium (~1000) spectral resolution over a wide (several square arc-minutes) field of view.
- Spatially-resolved, single object spectroscopy at "high" (~3000) spectral resolution and over a small (a few square arc-seconds) field of view.
- High-contrast slit / aperture spectroscopy at medium (~1000) and "high" (~3000) spectral resolution.

This is implemented through the three main spectroscopic modes of NIRSpec: MOS (multi-object spectroscopy), IFU (integral field spectroscopy) and SLIT (high-contrast slit / aperture spectroscopy). A short description of each of these modes can be found in **Table 1**. Note that NIRSpec also has an imaging mode, which is used for target acquisition.

Table 1: Summary of the main characteristics of the four modes of NIRSpec.

Mode	Description	Main characteristics
MOS	Multi-object spectroscopy	• Total field of view of 9 square-arcminutes covered using 4 arrays of programmable field masks (micro-shutter arrays) for object selection. • Mode available in the low (30-300) and medium (500-1300) spectral resolution configurations. Full spectral coverage at high (1400-3600) spectral resolution is only possible over a small fraction of the field of view. • MOS mode cannot be used simultaneously with the IFU mode.
IFU	Integral Field Unit (IFU) spectroscopy	• 3" by 3" field of view with a 0.1" sampling. • Mode available in the low (30-300), medium (500-1300) and high (1400-3600) spectral resolution configurations. • IFU mode cannot be used simultaneously with the MOS mode.
SLIT	High-contrast slit spectroscopy	• Five slits: three 0.2"-wide slits, one 0.4"-wide slit and one square aperture (1.6" size) for spectroscopic observation of transiting extra-solar planets. • Mode available in the low (30-300), medium (500-1300) and high (1400-3600) spectral resolution configurations. • SLIT mode can be used simultaneously with the MOS or IFU modes.
IMA	Imaging mode	• Used for target acquisition only. Available over the complete field of view.

These modes are associated with a set of spectral configurations covering the 0.6-5.0-micron range (see **Figure 1**). The prism-based "low" spectral resolution configuration provides a full coverage of the 0.6-5.0 micron range with spectral resolutions ranging from 30 to 300 in a single shot. A set of six gratings is used to cover the 0.7-5.0 micron range in four bands (0.7-1.2 micron, 1.0-1.8 micron, 1.7-3.0 microns and 2.9-5.0 micron) at "medium" (500-1300) and "high" (1400-3600) spectral resolution.

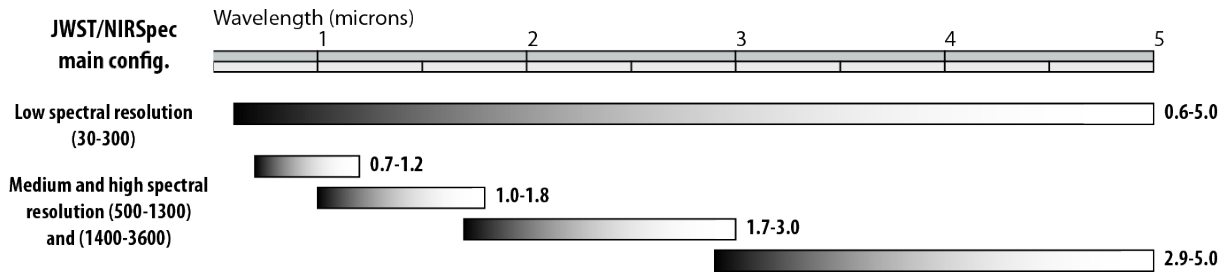

Figure 1: Overview of the spectral coverage provided by the various spectral configurations of NIRSpec.

3. OVERVIEW OF THE NIRSPEC INSTRUMENT

3.1 The hardware

The NIRSpec instrument has a size of approximately 1.9m by 1.3m by 0.7m for a mass just under 220 kg. It is manufactured for ESA by an industrial consortium led by Astrium GmbH and it includes two NASA-provided sub-systems (the micro-shutter assembly[11] and the focal plane assembly). Its elements are installed on an optical bench made of silicon carbide (SiC). Conceptually, the instrument can be divided in three stages (see **Figure 2**): first a pre-imaging stage that re-images the JWST field of view onto a mode selection stage and then the spectrographic stage.

The pre-imaging stage consists of the following elements: a periscope-like set of two SiC mirrors used to pick-off the JWST light beam and to redirect it in the plane of the optical bench; a SiC three mirror anastigmatic (TMA) fore-optics; an 8-position filter wheel[12]; and a refocus mechanism.

The mode selection stage is located in an intermediate image plane and contains: the NASA-provided micro-shutter assembly[11] (programmable masks and slit / aperture masks); and the integral field unit[13,14].

It is followed by the spectrographic stage that consists of: a SiC fold mirror; a SiC TMA collimator; an 8-position grating wheel[12]; a SiC TMA camera; and the NASA-provided focal plane assembly.

The instrument also includes an internal calibration source and a set of three electronic boxes for the instrument, the micro-shutter arrays and the detectors. For a more complete description of the NIRSpec hardware, we refer the reader to [6].

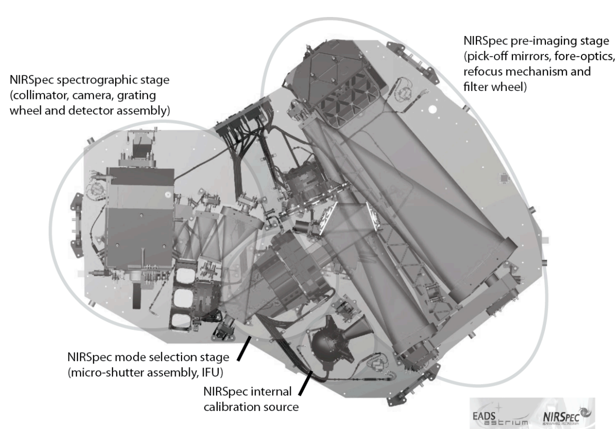

Figure 2: Drawing of the NIRSpec instrument without its cover showing its main elements as well as the light path. Credit for the drawing: Astrium GmbH.

3.2 The mode-selection stage and the layout of the NIRSpec field of view

The selection of the observation mode of NIRSpec is performed in an intermediate image plane within NIRSpec (mode selection stage). This selection is made primarily using the micro-shutter assembly that defines the layout of the NIRSpec field of view (see **Figure 3**).

MOS mode field of view layout: the location and size (9 square arc-minutes) of the MOS field of view are defined by the intersection of the projected position of the 4 programmable micro-shutter quadrants (arrays) and of the NIRSpec field stop (see upper-right panel of **Figure 3**). Each micro-shutter quadrant contains 365 by 171 individual micro-shutters with an open aperture size of 76 by 175 microns (corresponding to 0.2" by 0.46" on the sky) for a pitch of 105 by 204 microns. This gives a total of almost 250 000 individually addressable apertures with an operability larger than 85%. A picture of the "door" of a micro-shutter is shown in the lower-right panel of **Figure 3**. The actual micro-shutter array design includes a light-shield that prevents light from making its way between the "door" and the supporting structure. This allows to routinely achieve contrast levels of the order of 10^4 between the open and closed states.

The micro-shutter assembly contains a magnet mounted on an arm that can move along the x-axis direction. This magnet is used to open all the micro-shutters that are then, on an individual basis, either maintained open electrostatically or released so they can close. When using the MOS mode, the magnet arm blocks the entrance of the IFU aperture.

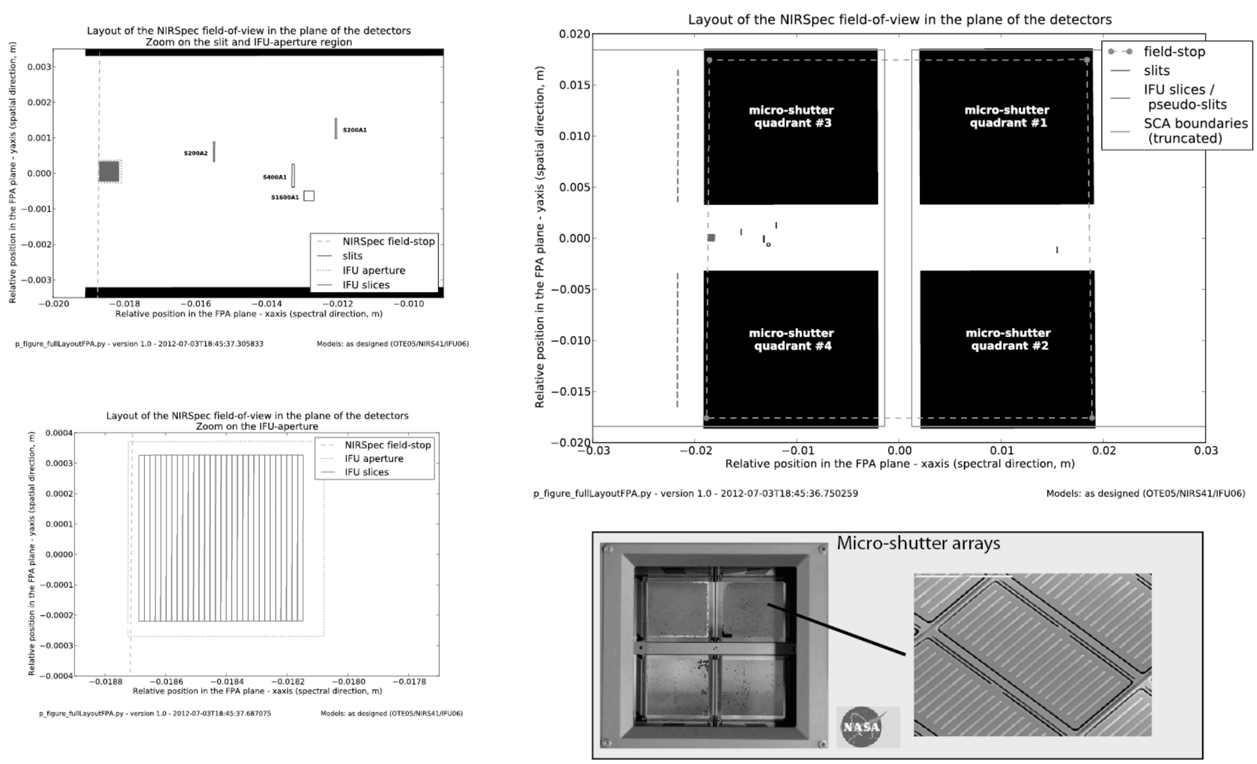

Figure 3: Layout of the NIRSpec field of view as projected in the plane of the detectors. Upper-right panel: sketch of the layout of the field of view with the location of: the four micro-shutter quadrants (arrays), the 5 slits, and the IFU aperture and pseudo-slits. Upper-left panel: zoom on the region of the IFU aperture that also contains 4 slits. Lower-left panel: zoom on the IFU aperture showing the position of the 30 IFU slices. Lower-right panel: photography of the 4 micro-shutter quadrants (arrays) with a strongly magnified picture of a single micro-shutter "door" (early design without light shield).

High contrast slit spectroscopy: the 5 slits for high-contrast spectroscopy are located between the lower and upper rows of micro-shutter quadrants (see upper-right panel of **Figure 3**) and have their dedicated detector real estate (see next section) independent from the MOS and IFU mode. The upper-left panel of **Figure 3** shows a zoom of the IFU aperture region where 4 out of 5 of the slits are located. The square S1600A1 slit will be used for spectroscopic observations of transiting extra-solar planets. Its relatively large size (1.6”) allows minimizing the impact of variations in the source position within the aperture on the source spectro-photometry.

IFU spectroscopy: the micro-shutter assembly also includes a square aperture feeding the pick-off mirror of the NIRSpec integral field unit (see upper-left panel of **Figure 3**). This aperture is slightly oversized compared to the actual 3” by 3” field of view of the IFU, as can be seen in the lower-left panel of **Figure 3** where the location of the projected images of the 30 IFU slices are displayed. Each slice is 0.1-arcsec wide and 3-arcsec long and is re-imaged as a “pseudo-slit” at the entrance of the NIRSpec spectrograph. The location of the “pseudo-slits” can be seen at the left of quadrants #3 and #4 in the upper-right panel of **Figure 3**. They have been gathered in two groups of 15 carefully avoiding the central area dedicated to the high-contrast slits / apertures.

3.3 The layout of the spectra in the plane of the detectors

The layout of the NIRSpec field of view described in the previous section has been generated keeping in mind where the spectra will fall on the two 2048 by 2048 H2RG[15] arrays of the NIRSpec detector system[16]. In Spring 2011, the NIRSpec flight model #1 (FM1) was tested and exposures in IFU and SLIT modes were obtained. In **Figure 4** we display an example of data from this test campaign. A flat-field illumination by a continuum source was used on input and NIRSpec was configured to obtain medium spectral resolution spectra over the 1.0-1.8 micron wavelength range.

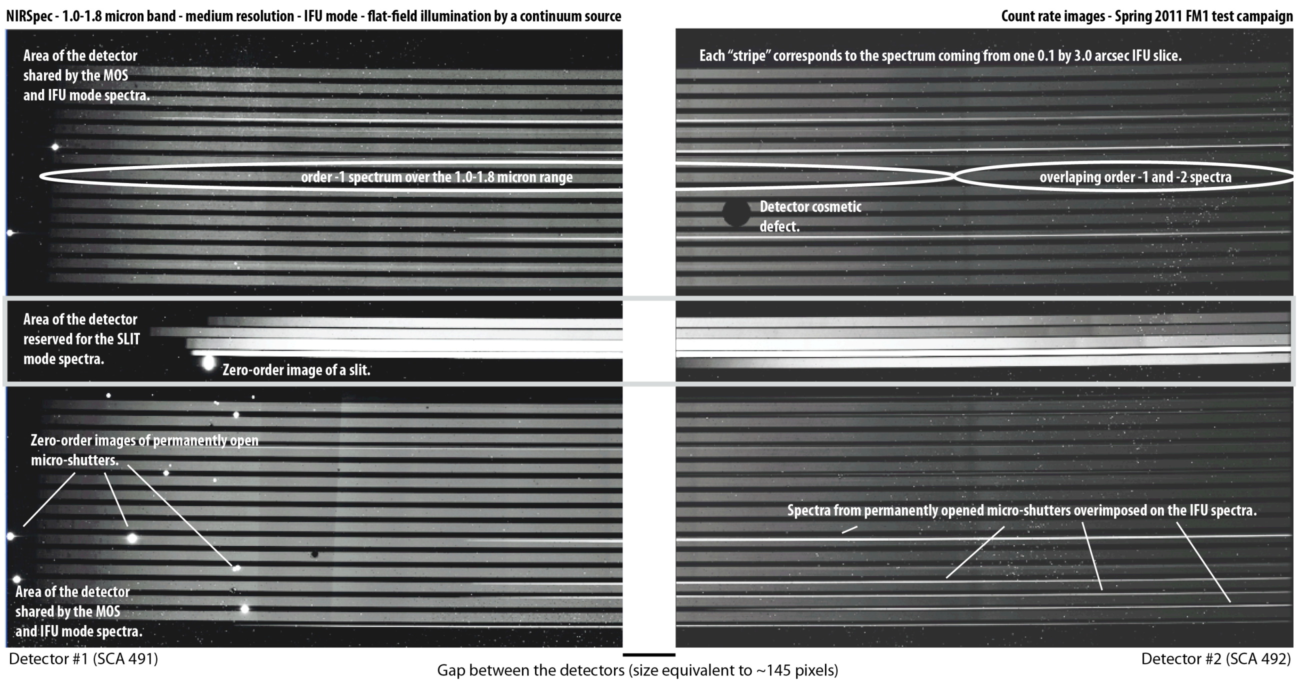

Figure 4: Example of NIRSpec data in IFU and SLIT modes.

The two detector images are presented side by side, reflecting their actual layout (including the gap between the detectors). The detector “real estate” is divided in three zones in the vertical direction. The central one is reserved for the spectra of the 5 slits while the MOS and IFU mode spectra share the two other regions. In our example, the IFU mode was used and two sets of 15 “stripes” can be seen, each one associated with the spectrum of one IFU slice (each with a vertical length corresponding to 3” on the sky). Superimposed to the IFU spectra, much narrower stripes can be observed that correspond to the spectra of faulty permanently opened micro-shutters (each with a vertical length corresponding to 0.46” on the sky).

Although the length of the spectra changes a lot between the different spectral resolutions, the overall layout of the spectra on the detectors will remain the same and this medium resolution example is a fairly good example of what

NIRSpec data look like. Note however that zero-order images are only present on the detectors at medium spectral resolution.

4. DEVELOPMENT STATUS AND NEXT STEPS

The integration of NIRSpec flight model was completed in early 2011 and was followed by a cryogenic test campaign. SLIT and IFU mode exposures were obtained that allowed an early demonstration of the good optical performances of the instrument. Results from this campaign are presented in [17], [18], [19], [20], [21] and [22]. Pictures of NIRSpec at the end of its integration and during various phases of environmental testing are displayed in **Figure 5**.

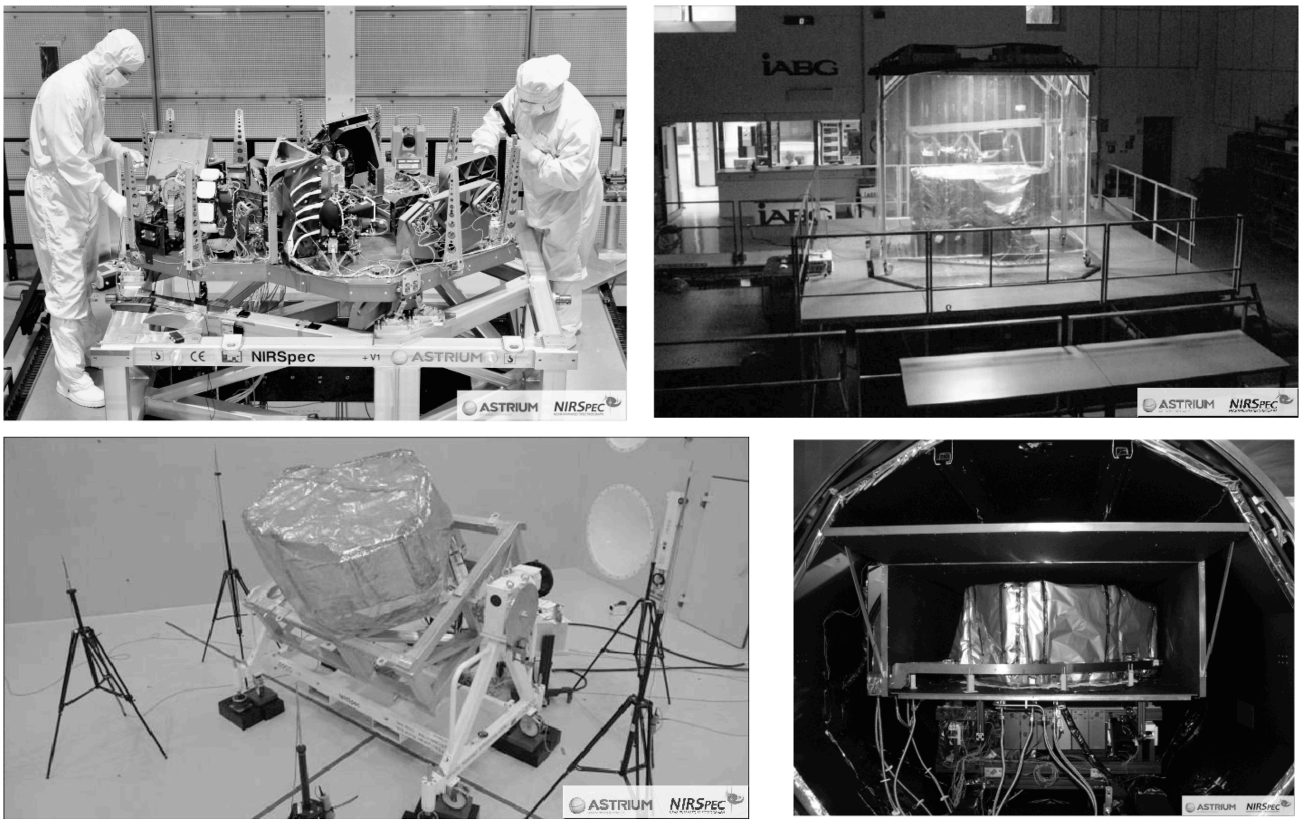

Figure 5: NIRSpec without its cover in the clean room at Astrium GmbH premises (upper left panel). NIRSpec with its cover in place during various phases of its environmental testing at IABG premises in 2011 (other panels).

After this successful test campaign it was however necessary to refurbish the instrument due to quality problems with the optical bench and contamination issues. For this purpose the flight sub-assemblies were removed from the bench and cleaned. They are now being re-integrated on the flight-spare bench.

This integration phase will be completed in September 2012 and will be followed by an extensive set of environmental testing (cryogenic exposure and vibration and acoustic testing). This testing will, in particular, include a month-long characterization and calibration phase. NIRSpec will then be delivered to NASA in the first half of 2013 for integration in the JWST integrated science instrument module (ISIM)[7].

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