# DESIGN AND QUALIFICATION OF THE CRYOGENIC COVER MECHANISM FOR THE MID-INFRARED INSTRUMENT ON THE JAMES WEBB SPACE TELESCOPE

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## ABSTRACT

In 2013 NASA and ESA will launch the successor of the legendary Hubble Space Telescope – the James Webb Space Telescope (JWST). One of the four scientific instruments – the Mid-InfraRed Instrument (MIRI), will be equipped with a Contamination Control Cover (CCC). This cover will have three main functions: 1) to protect the instrument against external particular and molecular contamination through the optical aperture 2) to allow for a dark current calibration of the Medium Resolution Spectrometer 3) to protect the detector during coronographic observation.

The CCC mechanism is designed for a total of 2570 open/close cycles in flight and is fully operational between room temperature and a cryogenic temperature of 6.5K. As the CCC represents a single point failure for the whole instrument, reliability has been assigned top priority. We present the detailed design of the CCC mechanism and the results of the qualification campaign according to ECSS.

## 1. JWST MISSION AND MIRI INSTRUMENT

The James Webb Space Telescope (JWST, see *Figure 1*) is a near- to mid-infrared astronomic space facility with the scientific goals of detecting first light objects in the universe, studying the formation of galaxies, stars and planets and delivering important pieces in the search for origins of life [1]. The satellite will be launched in 2013 and has an orbit in the L2 which is $1.5 \cdot 10^6$ km distant from the earth.

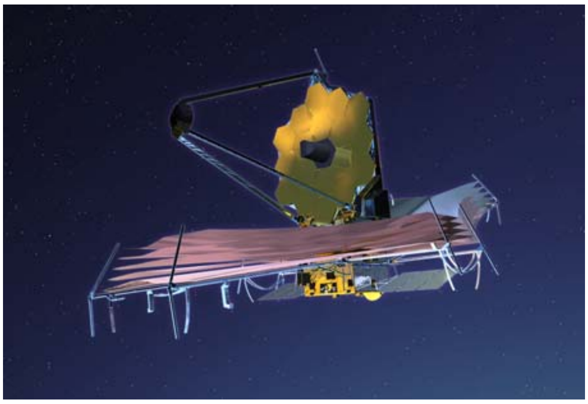

*Figure 1: Artist's view of the James Webb Space Telescope.*

The space telescope consists of a 6.6 m primary mirror which is segmented into 18 hexagonal segments to make it deployable (technical description can be found in e.g. [2]). The whole telescope will be shielded by an approx. 10 m x 23 m wide solar shield to allow an operating temperature below 50 K. Four instruments are sharing the light beam, one for guiding the telescope and three scientific instruments, two working in the near-infrared (NirSpec and NirCam) and one working in the mid-infrared regime (MIRI, see *Figure 2*). All these instruments are located behind the primary mirror and are mounted on a structure called "Integrated Science Instrument Module" (ISIM) which will be cooled passively to 40 K. The lifetime of JWST is planned to extend 10 years while MIRI is designed to operate longer than 5 years.

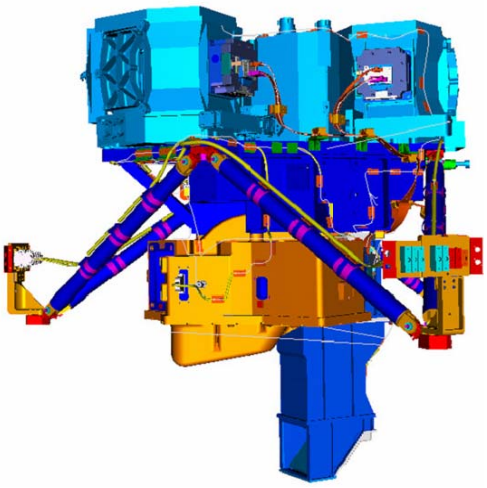

*Figure 2: CAD model of the Mid-InfraRed Instrument.*

MIRI (see e.g. [3]) is the combination of an imager with coronographic and low-resolution spectroscopic capabilities and a medium-resolution integral-field spectrometer, both working in a wavelength range between 5-28 µm. To reduce thermal background and to operate the SiAs-Detectors, MIRI is actively cooled to 7 K with a Pulse Tube pre-cooler and a Joule Thomson loop heat exchanger. MIRI is mainly constructed of the light-weighted Aluminium 6061 and is mounted to the telescope's instrument module via a hexapod structure made of carbon fibre reinforced plastic (CFRP).

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## 2. REQUIREMENTS

### 2.1. Functional Requirements

Since MIRI is the coldest part on JWST, it will act as a cryogenic pump for the whole telescope. Molecules like e.g. $H_2O$, $NH_3$, CO, $SO_2$, etc. are present in the expected residual gas and will result in an absorption line in the 5-28 µm spectra, if they are frozen on the mirrors of MIRI. However, exactly these molecule-lines are scientific objects of investigation since they provide indicators for traces of life on extra solar planets. Therefore, MIRI has to be protected against external particular and molecular contamination with an instrument cover - the “Contamination Control Cover” (CCC). The CCC will be also used during warm (300 K) and cold (7 K) ground tests to avoid any pre-launch contamination.

In addition, MIRI requires a shutter to allow for dark current calibration of the MIRI Medium Resolution Spectrometer. Instead of having an additional shutter mechanism, the CCC will be used for this purpose (max. 70 cycles in flight). Moreover, the MIRI Imager has a coronagraph with four different masks and corresponding filters, mounted on a filter wheel mechanism. During the change of the filters the detector has to be protected against illumination by closing the CCC (max. 2500 cycles in flight).

### 2.2. Design and Environmental Requirements

As the CCC represents a single point failure for the MIRI instrument, it had to be designed one failure tolerant. In the same sense the reliability of the mechanism was required to be better than 0.9999. Further major design and environmental requirements are the minimum operational temperature, the low mass, the low power consumption, and the high vibration loads. A summary of the key design and environmental requirements for the CCC is given in *Table 1*.

*Table 1: Summary of design and environmental requirements.*

| Requirement | Value |
|---|---|
| Reliability | >0.9999 |
| Mass | <600g |
| First eigenfrequency | >200Hz |
| Quasi-static design loads | 85g |
| Sine vibration loads | 40g |
| Random vibration loads | $15.65g_{rms}$ |
| Operational Temperature | 6.5-300K |
| Non-operational Temperature | 4-353K |
| Rate of temperature change | <14K/hr |
| Power consumption at 6.5K | <80mW |

## 3. DESIGN

The CCC design consists mainly of a light-weighted 14x11cm aluminum cover plate (Al 6061) that closes on a sealing base plate, which is mounted onto an actuator bracket. The actuator bracket together with the sealing base plate serves as the structural backbone of the whole mechanism and as the interface to the MIRI instrument. To change the CCC from the closed to the open configuration (and vice versa) the cover plate is rotated around a main pivot, which is equipped with pairs of redundant plain bush bearings (cover bearings and frame bearings). All plain bush bearings are coated by a hard anodizing coating (Hard Ematal). The main pivot pin has the same coating with an additional PTFE finish. If one of the plain bearings is jammed, the rotation can still be guaranteed by the other one. In addition, the cover plate and the sealing frame are separated by Vespel SP3 washers which prevent a mutual blocking.

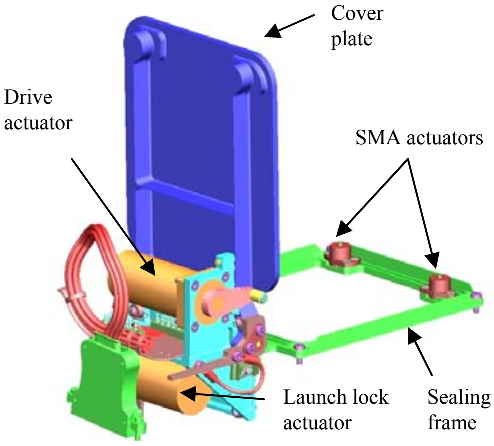

*Figure 3: Schematic drawing of the CCC.*

The opening of the cover is done by one of two independent 2-phase stepper motors (equipped with a 100:1 gear head) from CDA Intercorp, which transmits its force via a small crank lever to another lever on the cover plate. A summary of the characteristics of the actuators is given in *Table 2*. The stepper motor bearings and the gear head are lubricated with sputtered $MoS_2$. The closing of the cover is done by redundant torsion springs made of stainless steel. In addition, the stepper motor has to drive back the crank lever to allow for the cover closing. The duration for the opening or closing is approximately one minute. The lower actuator (see *Figure 3*) allows a twisting of the cover in an open position against an end stop. This provides a certain preload of the cover plate, in order to withstand the launch loads. The upper actuator may not engage or disengage the launch lock position and will therefore be used as the drive actuator in flight. Nevertheless, the launch lock actuator provides full redundancy.

*Table 2: Summary of CCC actuator characteristics.*

| Characteristic | Value |
|---|---|
| Number of phases | 2 |
| Number of poles | 6 |
| Motor step angle | 30° |
| Step rate | $15s^{-1}$ |
| Nominal current | 40mA |
| Maximum current | 75mA |
| Nominal voltage at 300K | 28V |
| Nominal voltage at 6K | 0.22V |
| Maximum power consumption at 300K | 4.3W |
| Maximum power consumption at 6K | 33mW |

The sealing of the cover to the base plate is done by a labyrinth. The labyrinth seal provides a non-contacting seal against particular and molecular contamination as well as against external stray light. In addition, the non non-contacting labyrinth seal avoids any possibility of freezing during the cool down. The gap of the labyrinth is temperature-dependently adjusted by redundant shape memory alloy (SMA) actuators, which consist of Nitinol and stainless springs. The inner side of the cover plate is roughened to a certain specification to meet stray light requirements for the dark current calibration in the closed position. The total weight of the CCC mechanism without harness amounts to 594g.

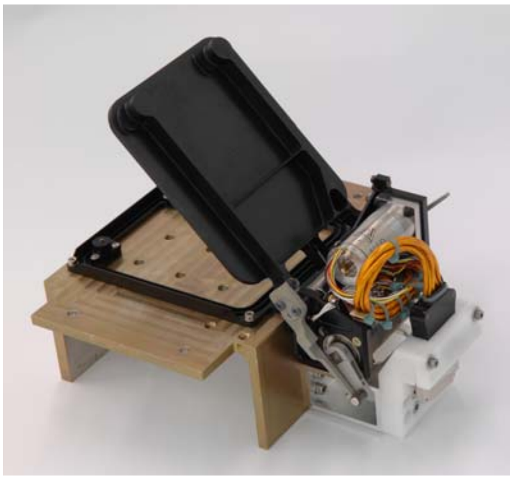

*Figure 4: Picture of the CCC Qualification Model in an intermediate position.*

The CCC is equipped with position sensors of the type Infineon Double Differential Magneto Resistor Sensor FP 420L90B to indicate the position of the cover. There are three distinct states, “open”, “closed”, and “launch lock” as well as one intermediate state. The signal of the position sensor is activated by two corresponding SmCo magnets Vacomax 225 by Vakuumschmelze and one stainless steel magnetic pin, which are mounted on the movable parts of the CCC. The four resistors of one position sensor are wired as a half Wheatstone Bridge and show an increase of the resistance with an increasing magnetic field.

The CCC is also equipped with one temperature sensor of the type Cernox™ 1070 thin film resistor by Lakeshore Inc. The sensor is used with the detailed specification CX-1070-HT-CU-4L: HT version for bake out, CU package with Copper bobbin for better thermal contact. The Cernox temperature sensors offer high accuracy (<10mK at 6.5K, <200mK at 300K) and high stability over the required temperature range.

Since inability to open the CCC is a single point failure for the whole MIRI instrument, the CCC has been designed one failure tolerant. All actuating parts (stepper motor, closing spring, crank lever, cover lever, SMA actuator) as well as the plain bearings are fully redundant. Should the nominal actuation system or one of its components fail, the fully independent redundant actuation system will guarantee the opening of the cover.

## 4. QUALIFICATION TESTING

Because of the particularly low temperature requirements ($T_{min}$ = 6.5K) the overall qualification approach has been done in two steps.

In a first step parts, components, materials, and processes (PCMP) have been qualified at their specific level. The approach was to select only PCMPs which are generally space-qualified and have substantial space-heritage. In case this was not possible, PCMPs with the best promising background were selected and qualified within this program. In addition, all selected PCMPs were delta-qualified for their applicability for cryogenic temperatures. This included several cryogenic tests with liquid Nitrogen and Helium and corresponding functional and performance tests as well as analyses like metallurgic microscopy, secondary electron microscopy, radiography, adhesion tests, etc. The qualification on parts and components level was focused on the following items:

- Stepper motors
- SMA actuators
- Main hinge
- Position Sensor/Magnets
- Temperature Sensors

The qualification on materials and processes level addressed the following critical issues:

- Hard Ematal coating
- Hard Ematal with PTFE coating

- Black Anodisation
- Vespel SP3
- Stycast 2850FT

All selected parts, components, materials and processes passed successfully the qualification on their specific level.

In a second step a qualification model (QM) of the whole CCC mechanism has been built. The QM has been subjected to a dedicated qualification test campaign according to ECSS-E-30 Part 3A (space mechanisms), but tailored for the particular mission requirements. This test campaign included functional and performance tests, vibration and shock tests, thermal vacuum tests, EMC tests as well as life tests. The detailed qualification test sequence is shown in *Figure 5* and has been accomplished with the CCC QM from end of 2006 until June 2007.

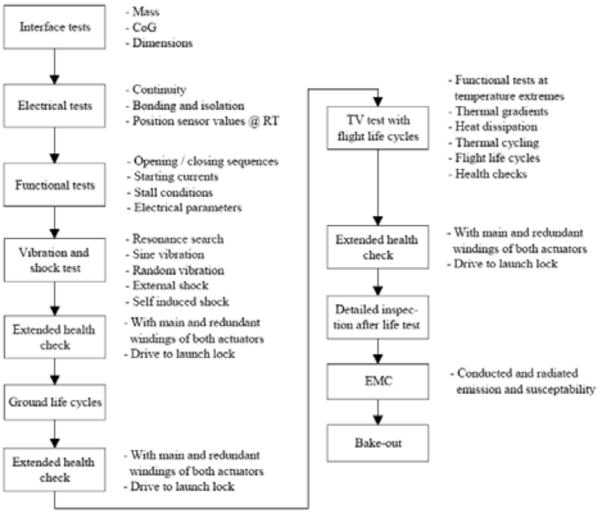

*Figure 5: Overview of the qualification tests at mechanism level.*

In addition to the qualification test campaign with the CCC QM a pre-qualification with an engineering model, which is called verification model (VM), has been performed. This verification model has been flight-representative for all critical parts/components. The purpose of the pre-qualification was to mitigate the risks for this crucial mechanism for the MIRI instrument. It turned out that this pre-qualification testing was a real asset in the overall development program.

### 4.1. Functional & Performance Tests

The functional and performance tests with CCC QM included the following main tests:

- Actuator characterization (torque vs current profile) at ambient temperature
- Overall performance at ambient and cryogenic temperatures
- Life test at ambient and cryogenic temperatures

Before integration into the mechanism all actuators have been characterized for their torque versus current profile. The measurements showed consistency for both actuators in either operation direction. Base on the actuator characterization a nominal current of 40mA was chosen (see *Table 2*). When operated with the nominal current the CCC fulfills all ECSS motorization margins in all relevant cases.

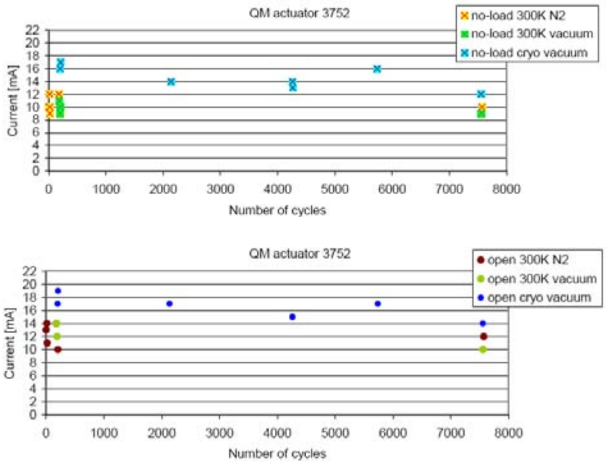

*Figure 6: Measured actuator starting current for different conditions (warm vs. cold, no load vs. cover load, nitrogen atmosphere vs. vacuum).*

The overall performance of the CCC mechanism has been measured in various configurations. This has been done by measuring the necessary starting current to drive the mechanism in different environmental and load conditions (see *Figure 6*). It can be seen that most of the parasitic loads originate from the losses in the motor-gear head assembly. The increase of the parasitic loads by the cover-main hinge assembly is only about 10%. The performance of the mechanism at room temperature in dry nitrogen atmosphere and vacuum is comparable. When cooling the mechanism down to 7K the necessary starting current increases by about 40% compared to the according current at ambient temperature.

The life test with the CCC QM has been performed during the cryogenic thermal vacuum cycling (see section 4.3). According to the nominal open/close cycles in orbit (2570) the CCC has been qualified for a life of 7200 open/close cycles. In addition, the CCC VM has been life tested for a double life to demonstrate that the CCC QM can be refurbished to a flight spare model after having already experienced one life cycle. The life tests have been successfully passed. All tribological surfaces were still in perfect shape and the actuators were still showing a positive run-in behavior (decrease of starting current).

Additional functional and performance tests have been performed to demonstrate that the CCC can withstand stall conditions in nominal operation for a period of five times the opening/closing time. Moreover, the heat dissipation has been measured in cold conditions to verify that the stringent dissipation requirements are met.

### 4.2. Vibration & Shock Tests

The CCC qualification model has been successfully tested for the vibration and shock loads given in *Table 1*. These tests have been performed at the Deutsche Zentrum für Luft- und Raumfahrt in Berlin, Germany (DLR). A picture of the CCC QM on the vibration table at DLR is shown *Figure 7*.

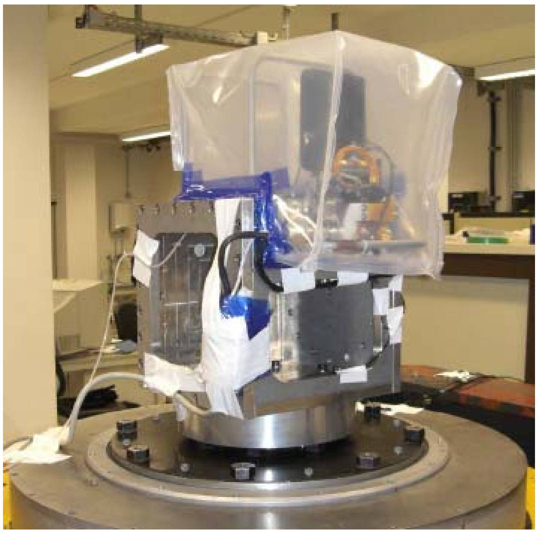

*Figure 7: Picture of the CCC Qualification Model on the Vibration Table at DLR.*

### 4.3. Thermal Vacuum Tests

The CCC qualification model has been successfully subjected to 18 cryogenic thermal cycles in vacuum between 7K and 300K. The detailed cycling sequence is shown in *Figure 8*. These TV tests have been performed in a dedicated cryogenic test chamber (CTC) at the Paul Scherrer Institut in Villigen, Switzerland (PSI). A picture of the CCC QM and VM in the CTC is shown in *Figure 9*. The evolution of the pressure and the temperature during the TV tests is shown *Figure 10*.

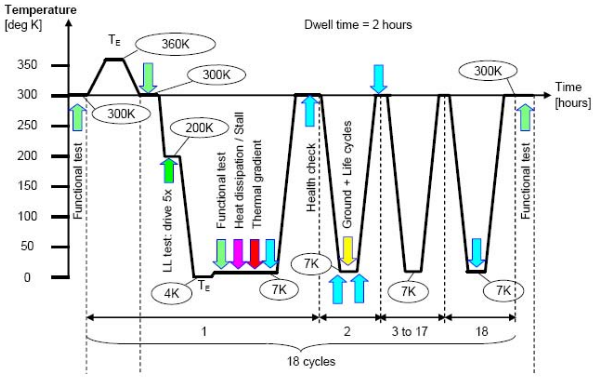

*Figure 8: Thermal cycle sequence with the CCC Qualification Model.*

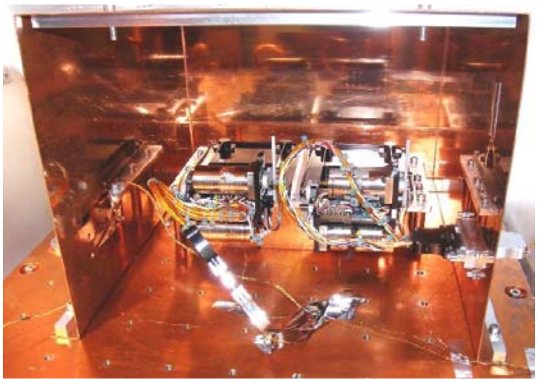

*Figure 9: Picture of the CCC Qualification Model and Verification Model in the Cryogenic Thermal Vacuum Chamber at PSI.*

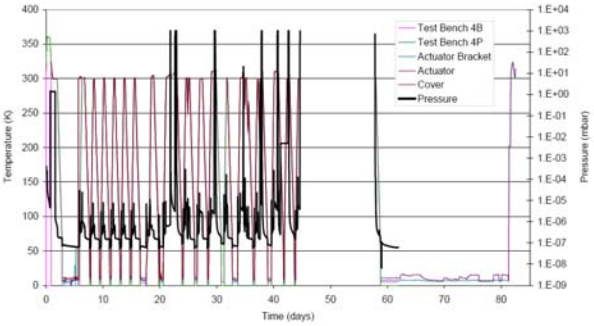

*Figure 10: Evolution of pressure and temperature during the QM thermal vacuum tests.*

## 5. CONCLUSION

We presented the detailed design and the full qualification of the CCC mechanism for the MIRI instrument on the JWST telescope. The flight model of the CCC is currently built and will be delivered to ESA by the end of 2007. Our main lessons learned are:

- It is really mandatory to build early "flight"-representative engineering models in order to mitigate the risks during the development process of space mechanisms.
- It is generally important to have reliable and fully functional ground support electronics during the various testing phases.
- Never try to skip procurement requirements for EEE components ;-)

## 6. ACKNOWLEDGEMENTS

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