International Conference on Space Optics—ICSO 2022

Dubrovnik, Croatia

3–7 October 2022

Edited by Kyriaki Minoglou, Nikos Karafolas, and Bruno Cugny,

ICSO 2022
International Conference on Space Optics
3 – 7 October 2022 | Dubrovnik | Croatia

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icso proceedings

International Conference on Space Optics — ICSO 2022, edited by Kyriaki Minoglou, Nikos Karafolas, Bruno Cugny, Proc. of SPIE Vol. 12777, 127775D · © 2023 ESA and CNES · 0277-786X · doi: 10.1117/12.2691005

The Rotating Mirror Assembly (RMA) onboard the Comet Interceptor Mission: Design, breadboard activities and development plan

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ABSTRACT

The Comet Interceptor mission was selected by ESA in June 2019 as ESA's new fast-class mission in its Cosmic Vision Programme. Comprising three spacecraft, it will be the first to visit a Long Period Comet (LPC) or even an interstellar object that is only just starting its journey into the inner Solar System. The RMA, under CSL responsibility, is a mechanism rotating a mirror which ensures that the comet is kept within the FoV of the CoCa instrument during the closest part of the approach. The RMA is composed of the Scanning Mirror Assembly (SMA), including a protection baffle, and the associated electronics (SME). The technical role of CSL is to design, develop, build and verify the SMA to be finally delivered to ESA as part of the RMA. This paper introduces the current activities on the RMA development with a deeper insight on the design steps and the preliminary results of the performed breadboard tests (mechanism actuation and coating impact tests).

Keywords: RMA, mechanism, comet, CoCa instrument, F1 ESA mission

1. INTRODUCTION

1.1 Mission objectives

The Comet Interceptor mission was selected by ESA in June 2019 as ESA's new fast-class mission in its Cosmic Vision Programme in cooperation with the Japanese Space Agency JAXA. Comprising three spacecraft, it will be the first to visit a Long Period Comet (LPC) or even an interstellar object that is only just starting its journey into the inner Solar System[1].

All comets that have been encountered by spacecraft so far are short-period comets: objects that have approached the Sun many times, and have thus undergone changes on their surfaces, hiding their original appearance and make-up. A true, pristine comet has yet to be encountered and explored. Such objects are difficult to target because they can only be discovered when approaching the Sun for the first time, leaving little time to plan and launch a mission to them.

The only way to encounter dynamically new comets or interstellar objects is to discover them inbound with enough warning to direct a spacecraft to them. The time between their discovery, perihelion, and departure from the inner Solar System has until recently been very short, historically months to a year: far too little time to prepare and launch a spacecraft. This timescale is, however, lengthening rapidly, with recent advances allowing observational surveys to cover the sky more deeply, coherently, and rapidly, such as the current Pan-STARRS and ATLAS surveys, and the Large Synoptic Survey Telescope under construction in Chile, LSST[2][3][4],.

Long Period Comets are now discovered much further away, considerably more than a year pre-perihelion; e.g. C/2017 K2 (Pan-STARRS) was discovered beyond Saturn's orbit in 2017, and will pass perihelion in 2022. From 2023, LSST will conduct the most sensitive search for new comets ever, providing a true revolution in understanding their populations, and making this mission possible.

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Comet Interceptor will be a new type of mission, launched before its primary target has been found. The mission will indeed travel to an as-yet undiscovered comet, making a flyby of the chosen target when it is on the approach to Earth's orbit. Its three spacecraft will perform simultaneous observations from multiple points around the comet, creating a 3D profile of a 'dynamically new' object that contains unprocessed material surviving from the dawn of the Solar System.

The Comet Interceptor mission was selected to combine this breakthrough in comet discoveries with a compact, agile set of spacecraft that can reveal to us a huge amount about a long period comet, ideally one is truly pristine, entering the inner Solar System for the first time. Although far rarer than long-period comets, Comet Interceptor will also have the capability of encountering an interstellar object passing through our Solar System if such an object is found on a suitable trajectory.

Comet Interceptor is planned to be launched with the ESA ARIEL spacecraft in 2029, and delivered to the Sun-Earth Lagrange Point L2. It will be a multi-element spacecraft comprising a primary platform which also acts as the communications hub, and sub-spacecraft, allowing multi-point observations around the target. All spacecraft will be solar powered. The spacecraft will remain connected to each other at L2, where they will reside until directed to their target. The mission cruise phase will last months to years.

Before the encounter, the spacecraft will split into its separate elements, probably a few weeks pre-flyby. For very active comets, separation will be earlier, to maximize separation of the spacecraft elements, whilst for low activity targets, separation will occur only a few days before the encounter takes place.

The Comet Interceptor team comprises an international group of experts led by Geraint Jones (Mission Principal Investigator, UCL Mullard Space Science Laboratory, UK) and Colin Snodgrass (Mission Deputy Principal Investigator, University of Edinburgh, UK).

Comet Interceptor was adopted by ESA during the Agency’s Science Programme Committee meeting on 8 June 2022, meaning the study phase is complete and, following selection of the spacecraft prime contractor, work will soon begin to build the mission.

1.2 The CoCa instrument

The Comet Camera system on-board Spacecraft A, CoCa, is required to provide detailed imaging of the nucleus and the innermost coma of the target. The design uses previous heritage to establish a baseline performance that surpasses that of previous fly-by missions to comets. The instrument is based upon two elements. Firstly, it uses the telescope of the Colour and Stereo Surface Imaging System (CaSSIS)[5] that is successfully operating at Mars on the European Space Agency’s ExoMars Trace Gas Orbiter (TGO). Secondly, the CoCa design uses the detector system of the JANUS instrument from ESA’s JUICE mission. By integrating these two elements, CoCa can achieve an angular scale of 8 µrad px-1, which is nearly a factor of three superior to that of the Halley Multicolour Camera on-board Giotto. The detector system uses a rolling shutter technique to allow rapid image read-out with a minimum possible exposure time of 220 µs to avoid motion smear at closest approach for even the highest velocity fly-bys. A major difference here is that, unlike Giotto which was a spinning spacecraft, Comet Interceptor is a three-axis stabilised system implying that the exposure times can be selected. The detector allows saturation of the nucleus without blooming of charge. This, in turn, implies that the exposure times of selected images can be programmed to provide high signal to noise observations of the dust coma while saturating on the nucleus. This capability will increase the flexibility of the mission if targets are eventually found that have only weak dust emission.

The CoCa system will be provided by a highly experienced team from Switzerland, Germany, Hungary and Spain. Nicolas Thomas is the CoCa instrument Science Lead.

1.3 The Rotating Mirror Assembly (RMA)

Description & Definitions
The Rotating Mirror Assembly (RMA) is the complete assembly including the scanning mirror assembly and the control electronics. Each element is separated mechanically and thermally interfaced with the S/C.

The Scanning Mirror Assembly (SMA) is the mechanism to rotate the mirror. It is composed of:

- The Scan Mirror reflecting CoCa FoV
- The Baffle protecting the CoCa FoV from unwanted straylight
- The Drive Mechanism moving the Mirror and interfacing with the S/C

The Scanning Mirror Drive Electronics (SME) is the required control electronics to drive and monitor the scanning mechanism.

Function

Considerable effort has been invested in protecting CoCa from hyper-velocity dust impacts during the fly-by. It is to be recalled that HMC was damaged severely during the 1P/Halley encounter despite being mostly behind the Whipple shield of the spacecraft[6][7]. In the case of Comet Interceptor, a rotating mirror assembly (RMA) has been developed which will allow CoCa to be mounted behind the protection shield while still providing a continuous view of the nucleus. The RMA has two elements - the SMA (Scan Mirror Assembly) and the SME (Scan Mirror Electronics). The SMA (see Figure 4) is a mechanism holding the folding mirror and that will rotate this mirror in order to orient the field of view of CoCa towards the comet during encounter. It is based on a brushless DC motor moving the mirror via a gear system and an optical position sensor in order to allow closed loop control. The mechanism will be driven by the SME that will take care of powering the motor to position the folding mirror based on encounter parameters provided by the spacecraft platform combined with the read-out of the position sensor. The SMA includes a protection system that will hide the mirror from incoming dust particles during the most critical part of the encounter, when the spacecraft is closest to the nucleus. The objective of the RMA is to rotate the CoCa Field of View (FoV) in order to follow the object during fly-by without requiring moving the spacecraft.

During initial approach, while the object is angularly close to the relative velocity vector, the scan mirror is orienting the FoV along this velocity vector. The optics will be designed in such a way to minimize its optical degradation during this period.
When the spacecraft will be flying-by the object (meaning the object will be angularly going away from the velocity vector up to 180 degrees), the scan mirror will rotate the CoCa field of view in order to follow the object. The Dust Protection System will protect the SMA optics from damages due to dust environment as far as possible.

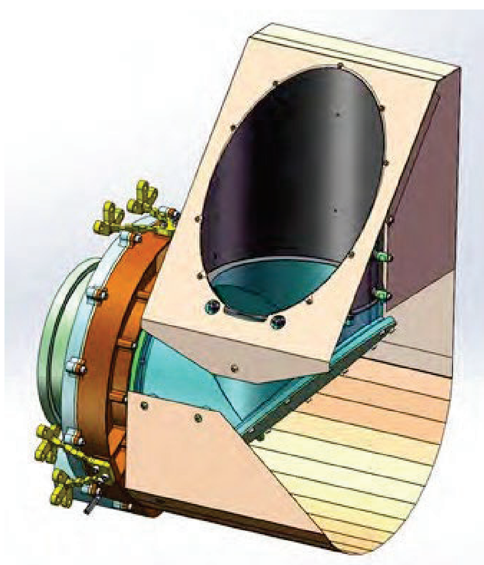

Figure 1. CAD/CAM drawing of the RMA showing the opening and the fold mirror mount (turquoise colour) and the mounting feet

RMA consortium

The RMA development project is led by the Centre Spatial de Liège (CSL), a R&D Center of the University of Liege (ULiege) and an ESA-certified Test Centre, located in Liege, Belgium. CSL has a long heritage and experience in designing, producing, verifying and delivering optical calibration subsystems and space mechanisms. The RMA development is based on experience gained on past and running programmes like COROT, CHEOPS, PACS, Sentinel-3, Sentinel-4,… The current CSL involvement in the RMA project is funded through an ESA EXPRO contract while future Phases CD will be implemented under the PRODEX Program of ESA, funded by BELSPO.

The SME responsibility is shared with the Swiss Company Thales Alenia Space Switzerland (TAS-CH). This activity is covered via Swiss national funding and ESA funding independent of CSL funding. Work with TAS-CH is in close collaboration with CSL team and is also supervised by University of Bern (UBE) as Swiss institute and ESA/Prodex who placed the industrial contract. UBE is the CSL partner as part of the consortium (UBE is PI of the CoCa instrument).

2. INSTRUMENT DESIGN

2.1 Overview and design drivers

Requirements

In terms of optical performances, the following topics are considered critical:

- The pointing stability of the RMA is critical in order to ensure that during rotation the image of the comet remains stable on the detector. In this respect, the way the mechanism is driven, the uniformity on the rotation (limited jitter) and the correct alignment of the mirrors w.r.t rotation axis are important factors to be taken into account.
- The optical degradation of the first surface exposed to dust environment during approach shall be limited to a maximum in order to perform the required scientific observations before fly-by.
- The reduction of straylight is an important requirement for the CoCa instrument in order to properly evaluate the characteristics of the Comet environment and surface without being disturbed by the straylight generated by the Sun during approach and the Comet itself during fly-by as well.

Among the technical constraints on the assembly design and development, the following ones are considered as the main drivers:

- The mass allocated to the RMA is limited and is a critical parameter for the complete S/C. This constrain will required a close follow-up during the entire design phase and the AIV in order to ensure all performances and functionalities of the assembly are kept within the required budget.
- At system level, the Rotating Mirror Assembly is definitely a single-point failure with respect to the CoCa instrument measurements. A failure of the mechanism to operate could result in the impossibility to observe the Comet during fly-by. A particular emphasis is therefore given to the mechanism reliability and robustness. Specific care is given to the selection, preparation and verification of possibly life-ageing parts (e.g. bearings).

For reasons of robustness and reliability, the design philosophy is mainly based on design heritage and lessons learnt from S3/OLCI Calibration Assembly and S4/UVN Calibration Assembly as well as from UVS scan mirror on the JUNO mission[9][10][11][12]. OLCI Calibration Assembly was also based on the heritage of the MERIS Calibration Assembly, successfully flown on Envisat mission.

Design philosophy and early tradeoff on Dust Protection System (DPS) need

The role of the DPS is to protect the SMA optics from degradation during approach to the Comet. Indeed, the S/C will enter a zone named dust zone while progressing towards the comet. This means that the S/C will intercept dusts and particles with a potentially high relative velocity (up to 70 km/s). The exact environment naturally remains unknown and the protection design shall be based on available experience. During this period, the CoCa instrument will look along the relative velocity vector to observe the comet, exposing the first optics to this dust/particle flux and potentially to an intense degradation.

In order to maintain the CoCa instrument input optics as clean as possible for the fly-by observation, a protection system was initially planned to be placed at the front of the RMA, looking to the forward direction of the system.

This system shall:

- Allow observation through it without deviation or too large attenuation of the light;
- Keep sufficient throughput up to the end of the approach despite the harsh environment;
- Prevent dust and particles to reach the SMA scan mirror.

In addition, the DPS will:

- Attenuate straylight from the Sun based on the worst Sun-S/C-Comet configuration;
- Minimize the obstruction when the SMA starts rotating and leaves the DPS.

Three solutions were envisaged:

- A periscope system where the first 45° mirror will be exposed to the incoming dust and the second will straighten out the beam towards the SMA;
- A window system;
- No DPS and partial protection at the level of the SMA.

The periscope option were preferred on previous mission, for example the Stardust mission from NASA[13][14]. The drawbacks of this solution are:

- Large size mirrors, off-centred with respect to the optical axis;
- increased mass (2 mirrors + structure)
- Potential large vignetting during the start of the rotation.

The first impression on the window solution is that there is an increased risk of break-out following an impact due to the brittle nature of transparent glasses. Moreover, break-out would eventually mean large loss of optical transmission but also protection.

Some way forward could be implemented to limit these risks:

- Implement less brittle material to avoid break-out;
- Largely tilt the window to limit the energy transferred to the window by bouncing the particles instead of stopping them;
- Implement a second window to further protect the SMA in case of break-out of the first surface.

However the major drawback of these two solutions occurs when the rotation starts. Indeed, the CoCa FoV will cover the edges of the mirror/window and disturb the observations. A solution to this issue would be to increase the distance between the SMA and the DPS so that the disturbed angle is reduced. For a realistic distance of 400 mm (for accommodation on S/C) and a pupil of about 150 mm, the angle would be between 25 and 30 degrees, which is reached about 25 s before closest approach. Assuming that the clear view through the DPS would be lost at rotation angle of about 1 deg (815 s before closest approach), 790 s of data would be deteriorated, i.e. most of the science data during approach.

In order to limit the duration of the degradation to about 15% of the observing time (which is the general approach of allowable science time loss), an angle of a few degrees would be required, which leads to distance of about one meter between SMA and DPS. This configuration is not affordable for S/C accommodation.

Another solution to reduce the effect of the DPS on the FoV when the movement starts would be to move the DPS out of the FoV. However, this solution would also come along with several drawbacks:

- An additional mechanism shall be implemented with impact on technical budgets;
- Need for resettable mechanism (for multiple tests/rehearsal/observations);
- Alignment difficulties.

Following the above discussion, it has been decided to consider the complete removal of the DPS and replacing it by a baffle/shield on the SMA. Indeed, the SMA would anyway need a baffling solution in front of it to protect, first partially, then completely the scan mirror from the incoming dust. In additional to this, it is known that the maximum density of dust will be received very close to the encounter point. In other words, the DPS would efficiently protect the SMA only when the environment is the less damaging.

The idea of the DPS-less solution was to design the scan mirror front baffle not only as an optical baffle but also as a dust shield. When the mirror and its shield start rotating, the baffle is hiding partially the mirror up to complete protection from dust impacting along the relative velocity vector. This solution would imply defining the evolution of the baffle length as a function of the desired angle at which we require full protection. The selected angle, combined to a dust model will then define the amount of particles we can allow reaching the mirror. The evolution of the baffle length as a function of the full protection angle is depicted in Figure 2.

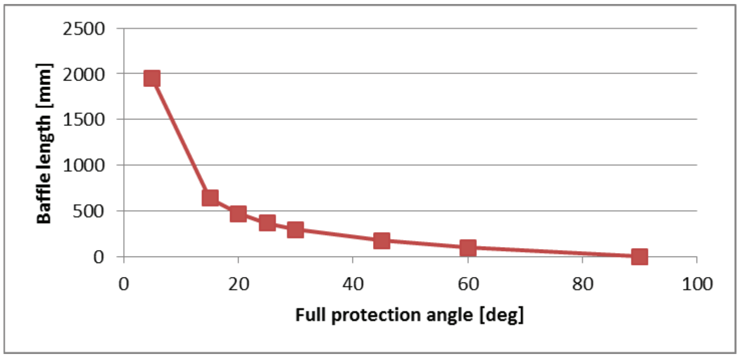

Figure 2. Relation between the baffle length and the full protection angle

In order to evaluate the amount of dust that would reach the mirror, the Engineering Dust Coma Model of the Comet Interceptor mission (issue 4.1) is used. From this model, only the particles with an impact probability higher than 1 % are taken into account (trials have been made with other threshold probability without a real impact on the baffle length conclusion). The value covering the 50th percentile is taken into account.

The number of particles impacting the mirror takes considers the projected surface of the mirror and the evolving partial protection. The top edge of the shield is assumed to be linear and scans a circular mirror projection. Figure 3shows the amount of protection for the different bins of the dust model relative to no protection (value at 90 deg). It can be seen that we have a mostly linear behaviour.

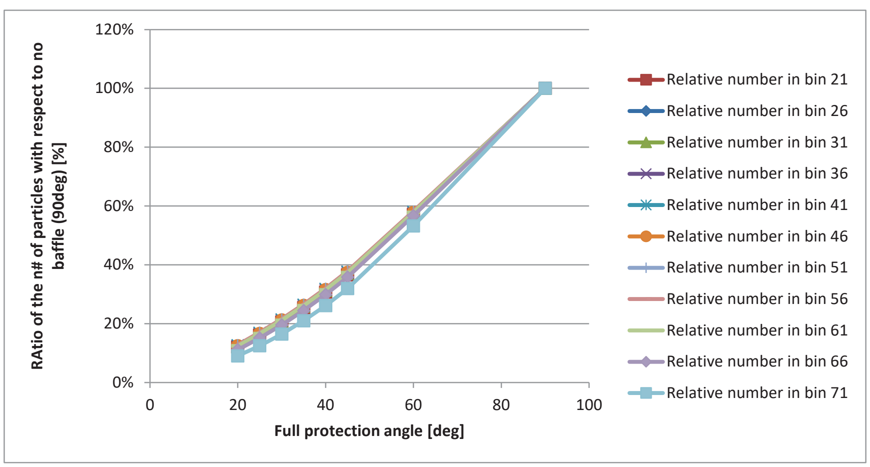

Figure 3. Ratio of protection of the mirror by the rotating baffle vs the full protection angle

An evaluation of the damage as a function of protection angle has been performed based on review of literature assessing the relation between particle size, particle impact speed and damage (crater) size[15][16][17][18].

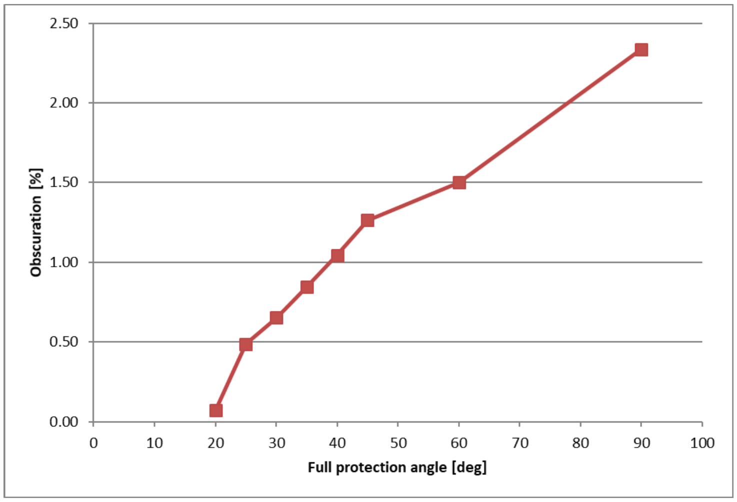

Figure 4. Obscuration factor as a function of full protection angle (in %)

Figure 4 testifies of an approximately liner behaviour of the obscuration with respect to the protection angle. Please also note that no protection on the mirror implies an obscuration of 2.3 %.

A last important factor to be taken into account is the added torque the baffle will impinge on the mechanism. Indeed the shield, when rotating and capturing dust, will accumulate some energy and convert it into a perturbation torque on the mechanism. This torque will be at its highest when the mirror rotated at 90 deg. Figure 5 shows the evolution of the torque with the full angle protection.

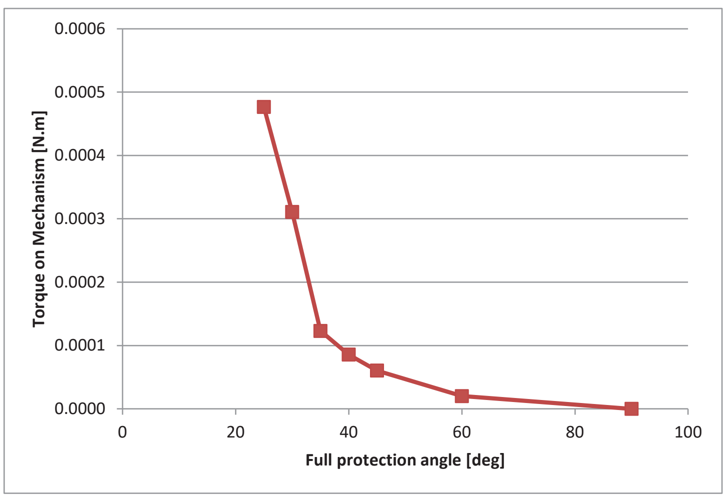

Figure 5. Torque on mechanism as a function of full protection angle

As expected, the longer the baffle, the larger the torque. A fast decrease is to be noted at about 25-30 deg. This torque seems to remain acceptable at first sight but shall still be taken into account in the mechanism dimensioning.

As a conclusion to this design trade-off, Table 1 introduces the different solutions that shall be compared.

Table 1. Trade-off description of the solutions

	Periscope	**Window**	**Additional mechanism to remove DPS**	**No external DPS (30 deg baffle)**
Scan mirror degradation	0 ppm	0 ppm	0 ppm	0.65 % (damage size estimated from literature, 50th percentile)
Mass	6 kg	2-3 kg	Additional 0.5 kg	0.5 kg
Impact on mechanism	No impact	No impact	Additional mechanism to design and drive. Needs to be resettable for multi usage.	External torque of 0.003 N.m (peak)
Impact on science	825 s lost up to 25 s before closest approach	825 s lost up to 25 s before closest approach	Limited to the “removal” time (few seconds probably)	No loss, slight degradation
Complexity	Alignment of the DPS (internal and external)	Edge free and wedge required	Additional mechanism	Enlarged moving baffle
Materials	Aluminium mirrors seems working based on heritage	Transparent, not fragile material to be found	Need to be independently protected from dust ?	Aluminium mirrors seems working based on heritage

Based on Table 1 the no-DPS option is the preferred solution. This latter will largely solve the mass problem and maximize the scientific observation time. The negative point is a perturbation torque on the mechanism (but it may not be completely absent from the other solutions if the optical baffle is long) but this can be taken into account in the mechanism design. The degradation of the mirror shall be further refined but a first realistic hypothesis is to assume it will remain below 1-2 % of obscuration.

2.2 Subsystems description

Scanning Mirror Assembly (SMA)

The SMA will be split into two parts:

- The Scan mirror and baffles that will interface on the mechanism.
- The mechanism and the structure ensuring its interface with the platform.

Such a distinction is made in a way to separate development and manufacturing of the “dirty” part that is the mechanism that will go through a preliminary bake-out after assembly and the “clean” part, the optics that will be separately pre-baked to ensure cleanliness.

Optics assembly

The Optics assembly is composed of the scan mirror and its mount on which will be integrated some baffling to protect the system from straylight and an additional plate that will be used as dust shield in conjunction with the optical baffle. Thicknesses, distances and materials are optimised to resist at best to the estimated dust impacts while limiting the mass. As defined in the Section 2.1, this baffle length is such that the mirror will be fully protected from particles when the SMA has rotated by 30deg. The SMA Optics Assembly is depicted in Figure 6.

The goal of the scan mirror is to flip the line of sight of CoCa towards the velocity vector during approach and to rotate the line of sight of CoCa during fly-by to ensure that the Comet image remains stable on the detector. This mirror will be exposed to the harsh dust environment and as such shall be optimized in order to minimize the damages during approach. The baffle will surround the scan mirror, ensure light tightness at interface on the mechanism, and reduce straylight when observing the comet.

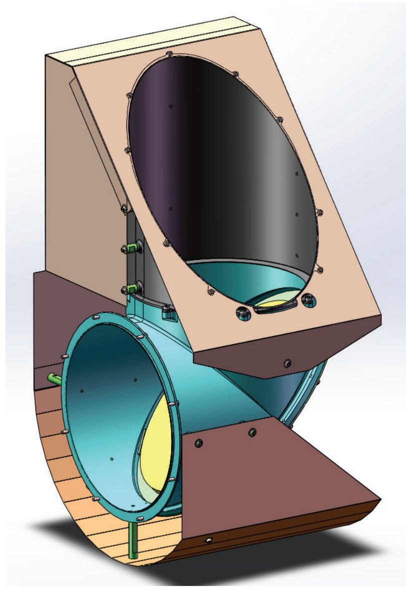

Figure 6. View of the SMA Optics Assembly including dust shield

Mechanism Assembly

The purpose of the SMA is to rotate the CoCa Line of sight during fly-by.

The states of the mechanism are the following:

- **Stable position** in which it holds the mirror such that the CoCa line of sight is deviated along the velocity vector during approach and most of the mission.
- **Movement** during which the line of sight of CoCa is deviated by the scan mirror to follow the Comet. The orientation of the mechanism is defined externally (by the S/C) based on trajectory extrapolation, NavCam observations …
- **Post fly-by stable position** in which it holds the mirror such that the CoCa line of sight is deviated at the opposite of the velocity vector to continue observing the Comet

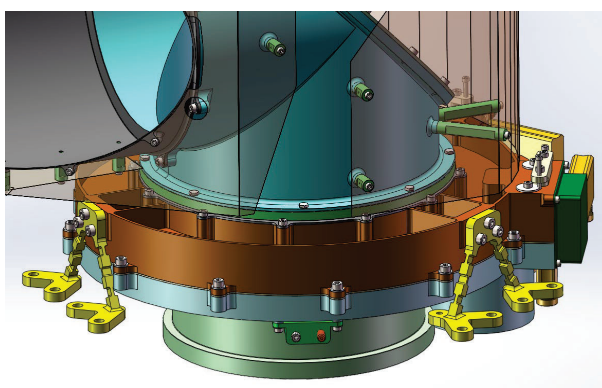

Figure 7. View of the SMA Mechanism Assembly

The concept of the driving assembly is driven by the fact that the optical beam is coming through the interface plate.

The driving assembly is based on an O-configuration bearing doublet (as for OLCI and UVN mechanisms) surrounding the optical beam. As for UVN mechanism, a custom solution will be developed for the bearings with the provider. The pair of bearing will share a single outer ring that will include a fixation flange to our structure. This way, the differential thermal expansion between the ball bearings (stainless steel) and the surrounding structure (aluminium alloy) will be controlled and taken away from the bearing tracks to avoid potential high friction. The inner rings remain separated in order to allow hard preload at the right value. The shaft (interfacing with inner rings) will be made of titanium allow to limit differential expansion.

A large spur gear of similar diameter is placed on the rotor and is activated by a smaller spur gear on the rotating shaft of a motor. The number of teeth of these spur gears shall be refined but current concept is 273/21, giving a ratio of 13:1.

A trade-off for the motorisation type has led to the selection of BLDC motor in order to fulfil the stability/jitter requirements. In order to avoid being lost in case of any glitch in the system during fly-by and to avoid performing a homing to redefine the actual mechanism position, an absolute position sensor shall be selected. In order to be absolute, the position sensor cannot be placed on a secondary pinion on the main gear (because of the multiple rotation that would occur on the position sensor). In order to limit risks of damages on the motor and on position sensor read-out head, they have been placed behind the structure with respect to the encounter relative velocity vector. The motor is also very low on the structure meaning that it will be partially hidden in the thickness of the mounting panel.

Scanning Mirror Electronics (SME)

The SME architecture includes the following functional blocks:

- Power conversion from primary power to secondary power needed for SME and SMA
- SMA motor driver
- SMA angular position sensor acquisition
- Closed-loop motor current and position control
- Telecommand (TC) and telemetry (TM) handling
- Monitoring of SME internal parameters
- Enclosure

The main functional chains of the SME are

- Primary power reception and conversion to secondary power and distribution for SME internal controller, motor driver and encoder acquisition circuitry and consequently for SMA
- Reception of discrete TC and related ON/OFF switching of power conversion function
- Acquisition of SMA angular position information and rotor position and provision via TM interface to higher level system
- Closed loop control of SMA angular position
- Acquisition of SMA thermal sensor and provision via TM interface to higher level system
- Reception of TC and related conversion to motor rotation commands
- Reception of TC and configuration of SME, as required
- Calculation of SMA angular position reference trajectory based on parameters provided through TC
- On-board time management
- Acquisition of SME internal HK monitoring information and provision via TM interface to higher level system
- Acquisition of SME internal protection monitoring information, activation and provision of protection status via TM interface to higher level system

The SME functions are distributed over the following main components:

- Main Board
- Driver Board
- DCDC Converter
- FPGA Firmware
- Mechanical Housing

The SMA contains redundant position sensors (encoders), redundant temperature sensors but a non-redundant motor. In order to save mass the SME is not fully redundant on unit level, but provides limited functional redundancy:

Fully-redundant components:

- Interfaces between SME and the S/C are fully redundant (power, TCTM)

Functionally redundant components:

- The motor driver is redundant with isolation switches between the driver stages and the SMA motor I/F to select the active driver. The motor driver is operated in cold redundancy to improve reliability.
- The SMA position sensor (encoder) acquisition interface is redundant. The encoder interface is operating in cold redundancy to improve reliability, but could be operated in hot-redundancy when needed (e.g. during critical mission phases)

Non-redundant components:

- DCDC converter
- FPGA and its supporting circuits and local supplies
- Housekeeping circuits

Performance simulations

To evaluate the performances of the mechanism, a MatLab Simulink model was established. It simulates the dynamic mechanic behavior of the system. This model takes into account for the PID control of the motor, the bearings, the gears and the friction in each element.

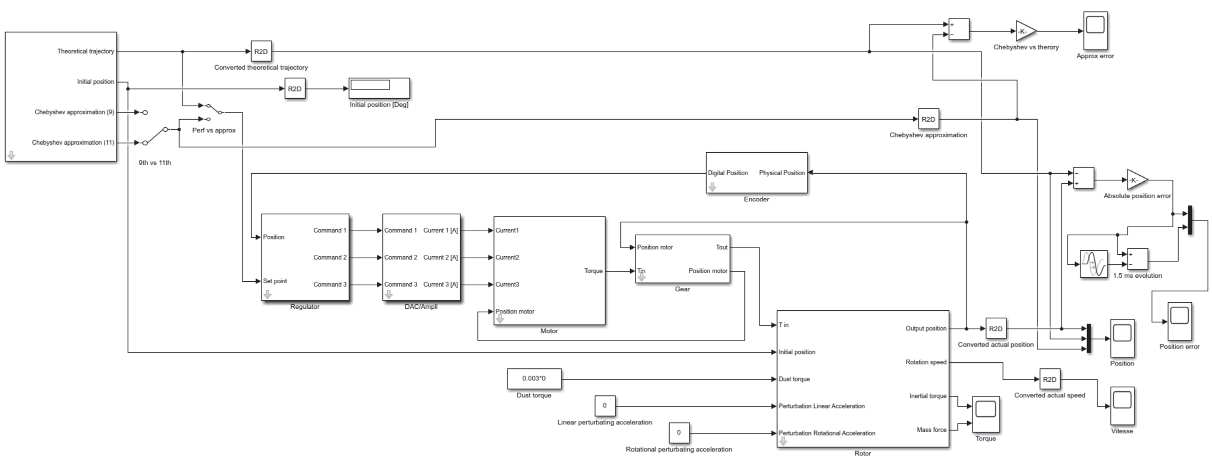

Figure 8 : Mechanism Simulink Model

This model is used to evaluate the performances of the mechanism and once it is correlated with a physical model, it allows also extracting some useful parameters that cannot be obtained by direct measurements.

Rotating mechanism accuracy

The mechanism accuracy is driven by three different error budget: the Absolute Pointing Error (APE), the Relative Pointing Error (RPE) and the Absolute position Knowledge Error (AKE).

The APE refers to the error in position with respect to the target to be tracked. A large error means that the target might be out of the Field of View of the instrument. The evaluated APE is lower than 0.05° in plane and 0.07° out of plane.

The RPE refers to the error in position due to instabilities during the tracking. A large error means that the images taken by the CoCa will be degraded. The current RPE is lower than 1.24''.

The AKE refers to the error in position on the knowledge. Following the encounter, the images taken will be aggregated with the tracking data. A large error means that the images will not be referenced correctly wrt. the spacecraft. The current AKE is lower than 0.03°.

Structural analysis

The structural analysis is composed of the usual analysis for space systems: Modal analysis, Quasi-static load, Sine load, Random load, Shock load, Thermo-elastic deformation. The computations are done in the SAMCEF software which is the usual Finite Element Analysis software used by CSL on all projects.

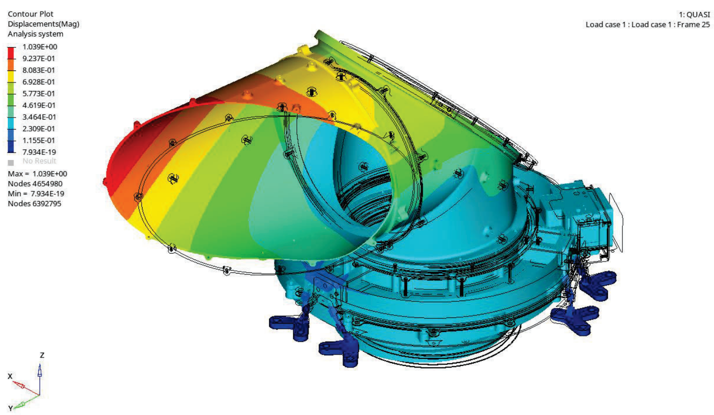

Figure 9 : Quasi-static load

The current design has passed the Preliminary Design Review (to be closed within the following month). Some design modifications will have to be included for the next phase.

Thermal analysis

A thermal model was created in NASTRAN to evaluate the temperature that will be reached on the instrument. The mechanism is exposed on one side to the direct space environment and to the other side it is interface with the spacecraft and the CoCa.

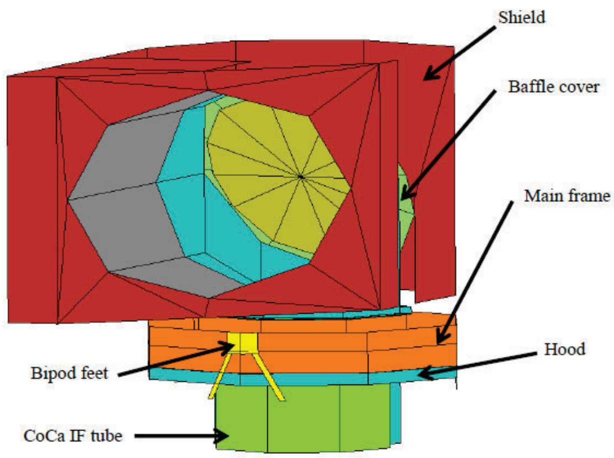

Figure 10 : NASTRAN thermal model

The environment is then very cold for the system and temperatures as low as -90°C are currently anticipated on the structure. The need and feasibility of survival heaters is under evaluation to maintain an acceptable temperature around the driving assembly.

Optical analysis

The optical analyses for the RMA consist in a straylight analysis. A model was made in ASAP and used in two cases : during the approach and during the fly-by.

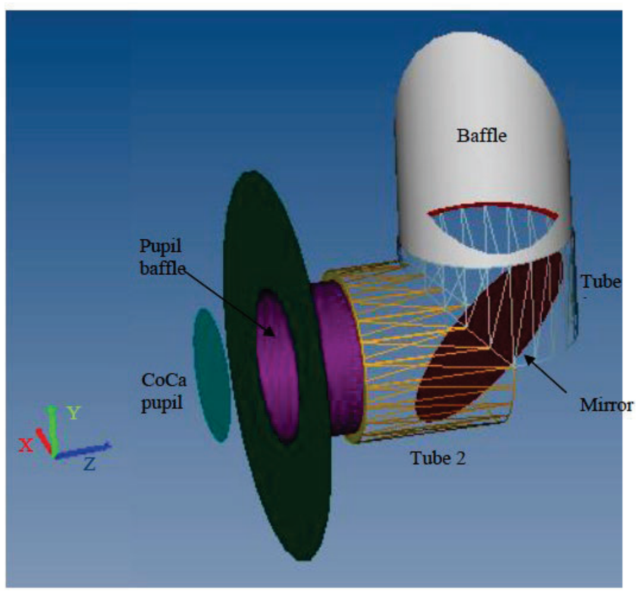

Figure 11 : Straylight model

To limit the straylight in the system, the baffle was truncated. This allows reducing significantly the reflections at the entrance of the tube.

The different sources taken into account are the reflections of the Sun and scattering of the surfaces.

During the approach, the worst case will be having the Sun at 45° from Line of Sight (LoS).

During the fly-by, the mirror will be rotating so that the Sun will have less impact. Nevertheless, the Sun can go up to 135° from LoS which means that when the RMA will reach 180° at the end of the fly-by, the aperture may be exposed.

3. BREADBOARD ACTIVITIES

The breadboarding activities consist in dust impact tests on mirror samples, the development of a SME breadboard, a SMA breadboard and performance tests on both. The different activities are detailed hereunder.

3.1 Breadboarding activities general objectives

SMA and SME BB

The SMA BB is used to validate the design and driving concepts of the mechanism. It will follow a development sequence including the following steps :

- Select the components to drive the mechanism (motor, position sensors, launch-lock need …);
- Design the SMA based on these elements;
- Specify the SME based on these elements;
- Design, manufacturing and assemble a SMA breadboard with these elements (in commercial grade);
- Design, manufacturing and assemble a SME breadboard to drive the SMA BB;
- Use this set up to assess the performances of the proposed concept;
- Tune the driving parameters to evaluate robustness.

Mirror coating samples

The Mirror coating samples goal is to select and validate the best concept for resistance against dust environment that will be encountered in the vicinity of the comet.

- Extract from the dust model the actual amount of particles that will be received;
- Select mirror materials and optical coatings based on best practice and heritage;
- Manufacture samples of these mirrors;
- Expose the samples to representative dust environment as far as possible;
- Evaluate degradation of the coating, extrapolate to expected degradation in flight and select best coating candidate.

3.2 Dust impact tests

The rotating mirror will be exposed to (relatively) incoming flux of dust when entering the Comet dust coma. Models, as previously introduced, have been built to predict the amount of particles of various sizes that the S/C should encounter. During the fly-by, the scan mirror will be rotated and a baffle will progressively hide the mirror from incoming particles flux. After rotation of about 30°, the mirror is fully hidden for the rest of the fly-by.

Baseline coatings are based on state-of-the-art coatings already qualified for space and documented in papers about similar missions (Giotto, Stardust) and on experience of qualification of mirror coatings for space at CSL[19][20]. Coatings shall be reflective in the visible and near infrared wavelength range from 400 nm to 975 nm. The reflectivity shall be higher than 85% and a degradation of the order of 1-2 % of the transmission after exposure to dust environment is considered acceptable.

The three coatings described in Table 3 were selected for the breadboarding tests.

The aluminium coating (type 1 in Table 2) was chosen on basis of the heritage of the Giotto mission. The MgF_2 protection layer thickness was adjusted to have a sufficient protection to space environment while being thin enough to limit the reflectivity reduction. Unprotected aluminium has a minimum reflectivity slightly lower than 85% around 825 nm at 45° (~86% at 8°). With the selected thin MgF_2 thickness, a reflectivity curve (at 8°) similar to the one presented in the article about the reflectivity of the Giotto mirror1[21][22]. With this protected aluminium coating, it is however difficult to obtain a reflectivity higher than 85% around 825 nm and an incidence of 45° which is the requirement for the mission.

The silver coatings (type 2 & 3 in Table 2) were chosen to have a better reflectivity on all the wavelength range of interest (90-98%, minimum at 400 nm) and two different protection layer were tested.

Table 2. Coating types

Coating type	**Reflective layer**	**Protection layer**	**Reflectivity @ 45° (400-975 nm)**	**Comment**
1	Al	MgF_2	84-92%	Coating similar to Giotto mission
2	Ag	MgF_2	90-98%	High reflectivity
3	Ag	SiO_2		

Using ESA EDCM model and taking into account the movement of the scan mirror, the amount of particles expected on the mirror is shown in Table.

Table 3. Dust particles expected on mirror

Bin	**Size (µm)**	**Number on mirror (#)**	**Number per unit area (#/cm²)**
21	1 → 3.16	31512	164
26	3.16 → 10	1418	7
31	10 → 31.6	67	0.28
36	31.6 → 100	3	0.016
41	100 → 316	0.2	0.0001
46	316 → 1000	0.01	0.00006

Computations are based on 50th percentile of the model. The dust impact velocity defined by the relative velocity between S/C and Comet is expected between 10 km/s and 70 km/s. Dust density is expected between 0.3 g/cc and 1 g/cc.

Two different facilities were used to perform the dust impacts:

- Van Den Graaf Accelerator (VDG) at the IMPACT facility of the University of Colorado (USA)
- Light Gas Gun (LGG) at the University of Cranfield (UK)

At the University of Colorado, two different tests were conducted:

- The first test showed from 600 to 800 impacts with velocities from 6 to 10 km/s and particle size of 1.2µm.
- The second test showed around 100 impacts for each sample with a velocity range from 10 to 15 km/s and particle size of 0.4µm.

For these tests, no impact can be seen with naked eyes. Using a microscope, small craters with limited radius can be seen. The roughness and the reflectivity of the samples are unchanged compared to measurements performed prior the impact tests.

At the University of Cranfield, six shots with the LGG were performed. For each coating type, a shot with 30 µm particles and another with 100 µm particles was done at a velocity of 5.1 km/s.

For the shots with 30 µm particles, a lot of degradation was seen on the sample. It seems that the particles aggregated together and made large craters in the sample. For the shots with 100µm, the degradation can also be clearly seen but the craters are smaller and more spread.

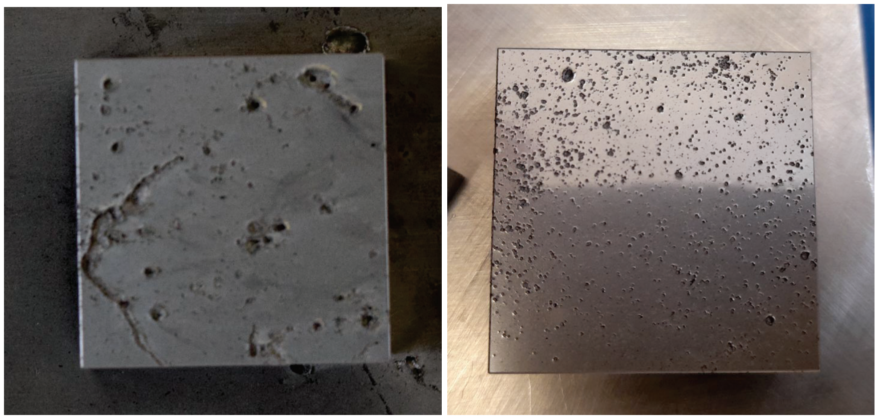

Figure 12. Samples impacted at LGG (left 30µm, right 100µm particles)

The samples are currently being returned to CSL for further analysis (crater dimension, reflectivity and roughness measurement).

3.3 Mechanism tests

Dynamic measurement

One of the most important performance parameter is the target tracking accuracy. This parameter can be evaluated by comparing the commanded trajectory to the achieved trajectory.

As the EGSE is able to record the encoder data at a frequency of 1 kHz, the dynamic behavior of the CM will be characterized based on the encoder measurements during the motion.

These measurements allows characterizing:

- Movement trajectory vs. commanded movement
- Oscillation / Micro-vibration behavior during a movement
- Stabilization time after commanded position is reached
- Jitter & Drift after stabilization

The simulation model will be adjusted to fit with test observations and will be used to provide data that cannot be directly obtained by test, like the micro-vibration torque.

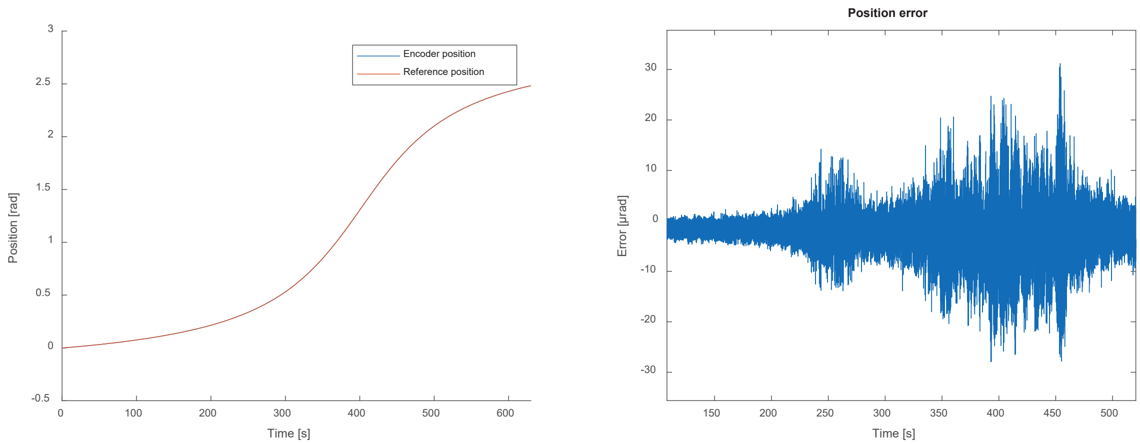

Figure 13. Commanded position vs achieved position

An example of trajectory tracking result is shown in Figure 12 along with the measured position error. The maximum error is currently around 30 µrad which is higher than the requirement of 3 µrad. Further analyses and optimizations are required to reduce this error.

Static measurement

Static angular measurements are made to verify the accuracy and repeatability of the mechanism. For the breadboard, only theodolite measurements will be used. The measurement accuracy for this kind measurement is around 4” which is much larger than the resolution of the encoder (0.3”). This measurement will only allow identifying large deviation from the commanded position.

The measurement is made using an optical cube mounted on the rotor of the mechanism. When a transfer is done between cube faces, a total error of 12” applies.

For small motions of +-0.5 and +-1° around fixed points, the accuracy of the motion was within the error of the theodolite measurement except for some points that were on the edges of the mirror and difficult to measure accurately.

Motorization margins

To evaluate the motorization margins, the maximum input current is limited in the EGSE. A trajectory is then injected in the mechanism and the tracking performance is evaluated.

The minimum input current which allows a good tracking of the trajectory is then compared to the nominal current to extract the motorization margins.

In ambient conditions, the minimum current to reach a good tracking of the trajectory is 50% (margin of 1). In **Figure 14**, a comparison between 40% and 50% limit current is shown. For the first, the trajectory is not followed completely. For the second, the trajectory is well followed.

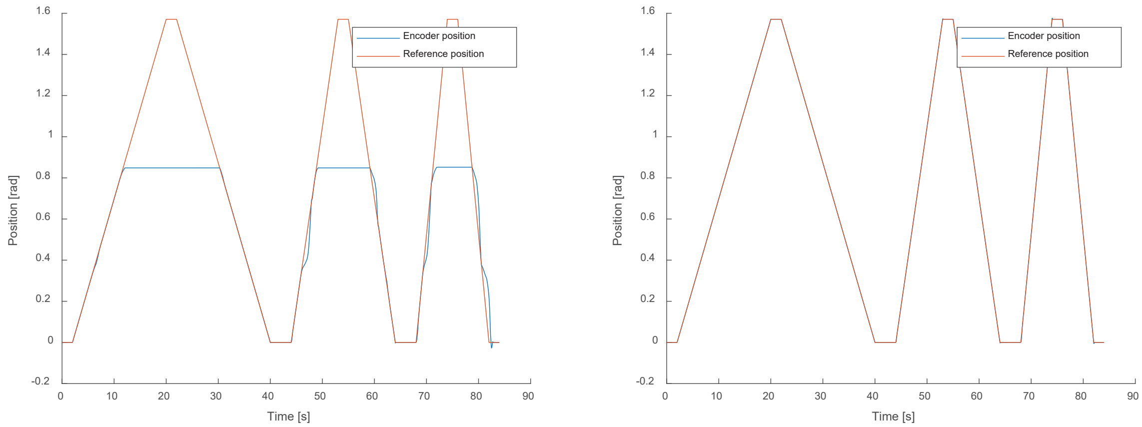

Figure 14. 40% current limit (left) vs 50% current limit (right)

It is expected to have larger margin for the following models because the motor used for this breadboard is not the nominal one. Because of procurement delays, a commercial motor with less torque was used.

Vibration test

The breadboard was not designed to withstand the vibration loads. Hence only a low level sine test was performed for each axes. The comparison with a Finite Element Model (FEM) is not possible because the model is not in the same configuration as the tested model.

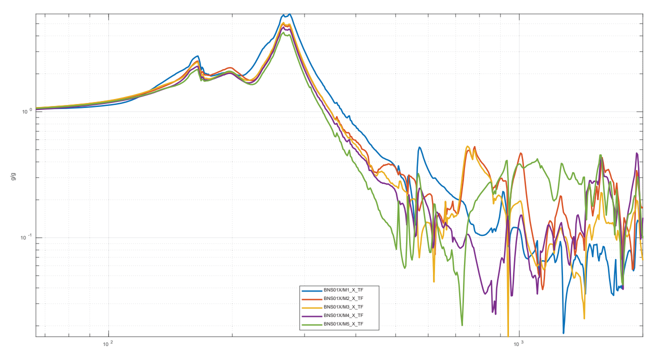

Figure 15. Frequency signature of the mechanism

The vibration test showed a first eigenfrequency around 266 Hz for the main peak. The expected first eigenfrequency for the complete mechanism is 125Hz.

Thermal vacuum test

The thermal vacuum test is used to verify the functionality of the mechanism in the cold environment. Different temperature steps were made at 20, 0°C, -20°C, -50°C. As the breadboard was using a different motor than the nominal one, it was expected to have difficulties moving the mechanism at the lower temperature.

For each step, a measurement of the trajectory tracking performance is done at different speeds and different current. The minimum current allowing for a motion gives an indication on the motorization margin.

The following results were obtained:

Table 4. Minimum current during TVAC

Temperature	**Minimum current**	**Comment**
20°C	70%	
0°C	90%	
-20°C	90%	The mechanism showed misbehavior at all currents for the highest speeds
-50°C	-	No motion was possible

The test was stopped after the -50°C step as it was not possible to activate the mechanism anymore. On the previous step at -20°C, the mechanism already showed some misbehavior at all current levels. The tracking of trajectory was not possible with the highest values.

It is also noted that the performances of the mechanism were already degraded at 20°C when under vacuum and that the current could only be reduced to 90% when subjected to an environment of 0°C. The decrease in performance is quite sharp and is a good lesson learned from this breadboard.

Once back at ambient, the performances were measured again and the nominal levels were achieved.

Lessons learned

From the dust impact test, the biggest difficulty was to find a facility capable of performing the required tests. On top of this difficulty, once the tests are performed, some additional limitations are found and compromises had to be made in terms of particles velocities, sizes and counts.

From the static and dynamic measurements, the lessons learned were mainly on the usage of the SME to control the SMA. Being the first time both were connected together, some parameter tuning had to be made. Additionally, the SME is controlled using scripts that needed to be developed for the specific use at CSL.

During the Thermal Vacuum test, the mechanism showed some, larger than expected, performance degradation. Improvements of the mechanical design in terms of thermo-elastic behavior are already under evaluation to improve the performance at lower temperatures.

4. DEVELOPMENT PLAN

Video and audio files can be included for publication. Table 3 lists the specifications for the mulitimedia files. Use a screenshot or another .jpg illustration for placement in the text. Use the file name to begin the caption. The text of the caption must end with the text "http://dx.doi.org/doi.number.goes.here" which tells the SPIE editor where to insert the hyperlink in the digital version of the manuscript.

4.1 General aspects

Preliminary development activities are made in Phase B, which includes the SMA, SME and mirror coating breadboarding phases.

Major developments are performed in phase C/D, including:

- Mirror coating qualification testing at sample level
- SMA and SME STM manufacturing, assembly, acceptance testing and delivery
- SME EM manufacturing, assembly, acceptance testing and delivery
- SMA and SME EQM manufacturing, assembly, qualification and performance testing
- SMA and SME PFM manufacturing, assembly, acceptance testing and delivery

Remaining developments are concerning recurrent productions:

- FSK parts procurements, verification and delivery

4.2 Model philosophy

The proposed model philosophy for the RMA is given in Table 4.

Table 4. RMA model philosophy

Model	Objectives	Representativeness	Applicability
SME BB	• Validation of concept • Drives the SMA BB	• Representative interface with SMA (motor, position sensor) • S/C interface representative	• Drives the SMA BB
SMA BB	• Validate selection of components and concept • Validate performances	• Functionally representative • Representative interface with SME	• Early validation of mechanism performances (pointing)
SMA optics BB	• Trade-off between optics material and coatings to optimise resistance to dust environment • Delta-qualification	• Small samples of same material and coating	• Resistance to dust impact evaluation • Final selection of optical solution
SMA Optics qualification samples	• Exposure to environment • Verification of BOL-EOL degradation	• Fully identical to flight in terms of materials and processes • Smaller size	• Coating level qualification • Degradation testing
SMA STM	• Delivery of a flight representative SMA in terms of mechanical interface	• Representative of flight H/W in terms of mechanical interface, mass properties and power dissipation	• To be integrated on the COMET-I S/C A STM
SME STM	• Delivery of a flight representative SME in terms of mechanical interface	• Representative of flight H/W in terms of mechanical interface, mass properties and power dissipation	• To be integrated on the COMET-I S/C A STM
SME EM	• Delivery of a flight representative SME in terms of electrical interfaces	• Representative of flight H/W in terms of electrical interface	• To be integrated on the COMET-I S/C A EFM
SMA EQM	• Qualification of structural and thermal design on the SMA • Measuring of mechanism performance, optimisation of driving parameters and characterisation and matching of simulation models • EMC test (with SME EQM) • Life test of mechanism	• Fully identical to flight mechanism and structure • No coatings on structural parts • Mirror is dummy from same material, shape and dimensions as FM mirror	• Used for unit level life testing, qualification and EMC testing

Model	Objectives	Representativeness	Applicability
SME EQM	• Qualification of structural and thermal design on the SME • Measuring of electrical performance • EMC test (with SMA)	• Fully identical to flight mechanism and structure • No coatings on structural parts • Reduced grade components	• Used for unit level qualification and EMC testing
PFM SMA	• Acceptance testing for flight use	• Fully flight standard	• To be integrated on the COMET-I S/C A PFM
PFM SME	• Acceptance testing for flight use	• Fully flight standard	• To be integrated on the COMET-I S/C A PFM

4.3 Verification approach

Verification will be performed at a maximum of levels. Major components will be submitted to an independent verification by the supplier versus their own specifications. Major components are :

- Motor
- Position Sensors
- Bearings assembly

All other parts will be verified by any of the methods mentioned here under before its integration on the assembly (metrology for mechanical parts, roughness and wavefront measurement on optics, …).

An assembly level verification program is then run on the full assembly. This is performed at qualification level for the EQM to validate the design and at acceptance level for the flight models to validate the construction.

5. SUMMARY

This paper presents the current status of the RMA, a rotating mirror mechanism that will fly on the ESA's mission Comet Interceptor. The RMA is a mechanism rotating a mirror which ensures that the Comet is kept within the FoV of the CoCa instrument during the closest part of the approach. This instrument takes advantage of the CSL's experiencesgained on past and running programmes, both scientific and earth observation, like COROT, CHEOPS, PACS, Sentinel-3, Sentinel-4,… The Phase AB was successfully ended with the mission adoption, testifying of the satisfying results of the breadboard activities run through the entire program. At RMA level, the engineering analyses were validated by several tests including coating resistance to the harsh comet environment and an environmental campaign. The RMA is built by a European consortium including Belgium and Switzerland.

6. ACKOWLEDGEMENTS

The Comet Interceptor RMA project will be developed under the auspices of the ESA's Prodex Programme thanks to the sponsorships of Belgium through the Belgian Science Policy (BELSPO) and Switzerland.

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