Design, Development and Verification of the METimage Scanner and Derotator Mechanisms

Sebastian Rieger* and Armin Jago*

Abstract

This paper presents the major design choices and lessons learned from the development and verification of the METimage Scanner and Derotator mechanisms. The modification of a standard drive unit design to project-specific requirements is described. This includes a presentation of design modifications that were implemented to meet long-term storage requirements. Tests with notable lessons learned are explained and the derived lessons learned are discussed. Details on the design and development of the optical components, the METimage Solar Calibration Device mechanism, and the control electronics are not presented in the paper.

Introduction

METimage is a cross-purpose, medium resolution, multi-spectral optical imaging radiometer for meteorological applications onboard the MetOp-SG satellites. It is capable of measuring thermal radiance emitted by the Earth and solar backscattered radiation in 20 spectral bands from 443 to 13,345 nm [1]. The instrument is developed by Airbus Defence and Space on behalf of the German Space Administration.

The METimage instrument is based on three key optical assemblies which include mechanisms. These are the Scanner Assembly, the Derotator Assembly, and the Solar Calibration Device (see Figure 1). All three mechanisms are developed by Airbus and the mechanisms team is embedded in the instrument team. The optical elements and the mechanism control electronics are developed by external partners. This paper focusses on the Scanner mechanism and the Derotator mechanism.

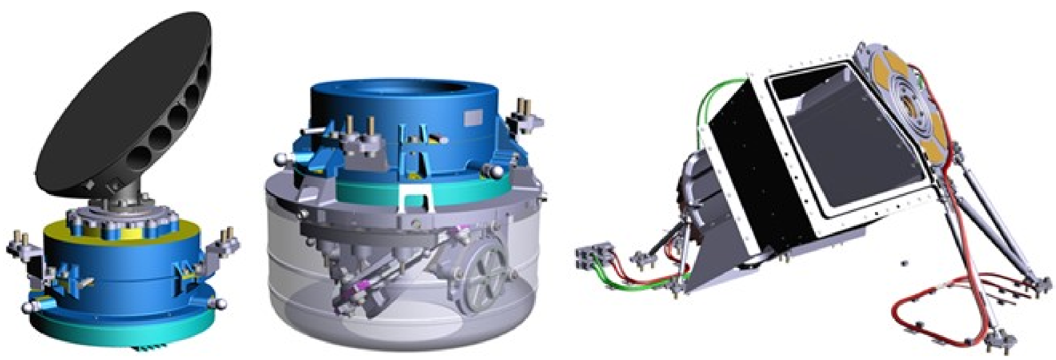

Figure 1. Scanner, Derotator, Solar Calibration Device (left to right, not to scale)

As shown in Figure 2, the Scanner mechanism is located at the Nadir-side entrance of the optical head of the instrument. The Scanner mirror is tilted by 45 degrees and reflects the optical beam into the telescope at an angle of 90 degrees. The Derotator is located inside the instrument, between the telescope and the detectors. It rotates at exactly half the speed of the Scanner in order to achieve a regular imaging geometry in the focal plane. During sun calibration phases, the Solar Calibration Device mechanism rotates one of its diffusors such that it is exposed to sunlight; the sunlight is reflected into the field of view of the scanner.

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* Airbus Defence and Space GmbH, Friedrichshafen, Germany
sebastian.rieger@airbus.com / armin.jago@airbus.com

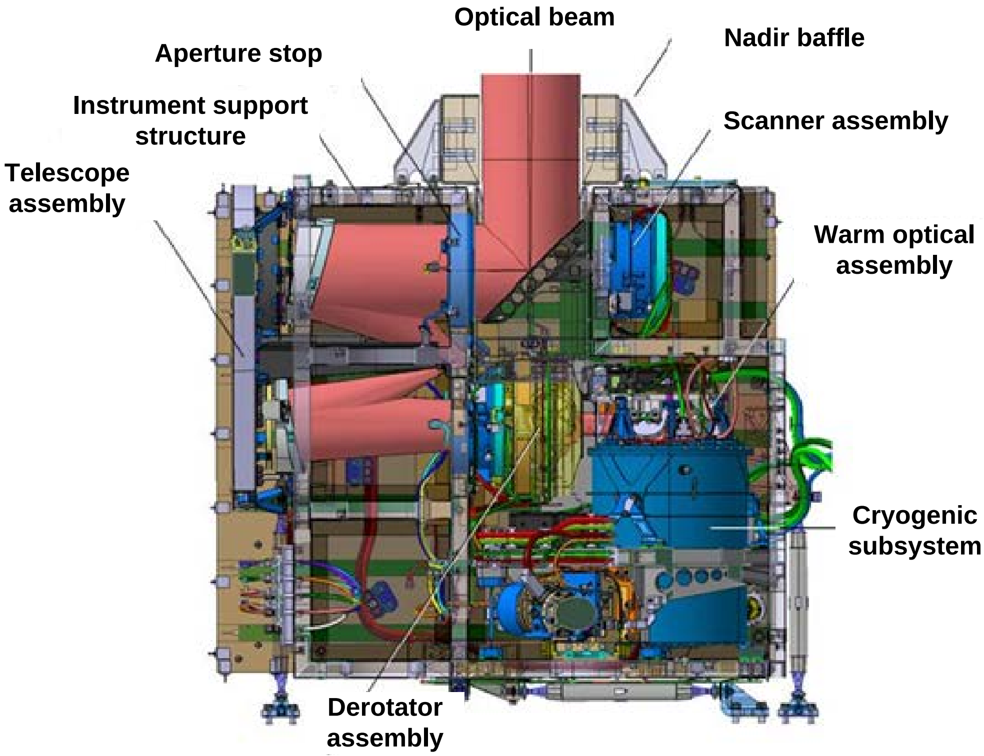

Figure 2. METimage Scanner and Derotator embedded in the optical head of the instrument

Design Overview

The Scanner mechanism and the Derotator mechanism consist of a drive unit (blue/cyan in Figure 1) and the scanner mirror and derotator mirror assembly, respectively. The Scanner drive unit design comprises two sets of angular contact ball bearings (hyperstatic layout), whereas the Derotator drive unit comes with a single bearing pair (isostatic layout). The motor and encoder concept is identical to the standard drive unit of Airbus Defence and Space for both mechanisms (Figure 3). This design has been flown on several missions, such as MHS (NOAA, MetOp) and the FY3 satellites; it also forms the design baseline for the MWI, ICI and MWS scanning mechanisms for MetOp-SG. The standard design was adapted to meet the needs of the respective project.

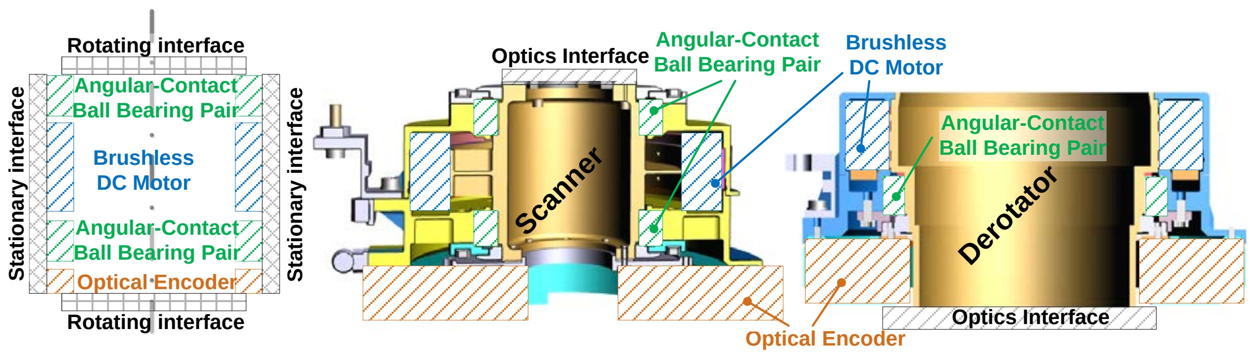

Figure 3. Standard drive unit concept (left) and cross-sectional views of Scanner (center) and Derotator (right) drive units

Adaptation of Standard Design to METimage Requirements

In order to reduce programmatic and technical risk, existing (flight-proven) concepts, designs and components were selected wherever feasible. This came with the following benefits:

- Use of high TRLs was made and, hence, qualification effort was reduced
- Common procurement with other projects could be performed
- A well-advanced design was available early in the project
- Testing of flight-representative mechanisms/components was possible at an early stage
- Flight-grade components of early models could be re-used for flight models

The METimage Scanner and Derotator designs are based on the existing standard drive unit concept but were modified in order to meet the specific METimage needs.

Performance requirements

The performance drift error (PDE) of the Scanner and, to a lesser extent, of the Derotator is one of the key performance parameters of the METimage instrument. The PDE has a direct impact on the image quality as it affects the co-registration of the instrument. The Scanner PDE during earth view shall not exceed 25 µrad over a period of 10 ms; the Derotator PDE shall not exceed 100 µrad. The PDE is the maximum pointing error in a window of 10 ms, relative to the pointing error at the beginning of this window.

Significant effort was spent on both mechanisms and control electronics in order to obtain designs compliant to this requirement. The major mechanism contributors to the PDE are

- Bearing friction variations
- Motor disturbance torques
- Encoder measurement accuracy

Bearing friction and friction variation were minimized by reducing the diameter and the preload of the bearings. Consequently, different bearing dimensions were selected for Scanner and Derotator, respectively; the large diameter of the Derotator shaft and the corresponding Derotator bearing size would have resulted in too high friction for the Scanner mechanism.

The disturbance torques of the motor occur mainly at the following frequencies (per motor revolution):

- Rotor pole number: caused by magnets passing an imperfection on the stator
- Stator slot number: caused by imperfections on the rotor passing the stator slots
- Product of rotor pole number and stator slot number, divided by their greatest common divisor: motor cogging, caused by the fact that the magnetic field is dependent on the distance between magnets and stator slots

The brushless DC motor design of the standard drive unit comes with a keyway at the stator outer diameter (Figure 4). This keyway was introduced as a positioning feature for projects where drive electronics without modifiable commutation angle offset are used. For these cases, the motor needs to be integrated into the mechanism in a pre-defined orientation. This positioning feature is neither needed for the METimage mechanisms, nor can the corresponding motor disturbances be accepted. Therefore, the keyway was removed for the METimage motor design.

Figure 4. Motor stator positioning keyway that was removed in the METimage design

Manufacturing tolerances and imperfections on magnets or stator sheets might cause unacceptable disturbances. In order to mitigate this risk while maintaining cost-efficient motor design and manufacturing without unnecessarily tight tolerances, feed-forward harmonics suppression was implemented into the controller of the mechanism drive electronics. The feed forward allows compensation of known, repeatable disturbances by means of pre-programmed, position-dependent motor current variation.

Motor cogging was reduced by skewing of the stator sheet metal stack (refer to Figure 5). Skewing also reduces the torque constant of the motor slightly. This was acceptable for both the Scanner and the Derotator.

Motor disturbances could have been minimized by using an iron-less motor. However, the torque constant of an iron-less motor was expected to be approximately 40-50% lower than the one of the baseline (iron) motor. This would not have been acceptable from a power and torque budget point of view.

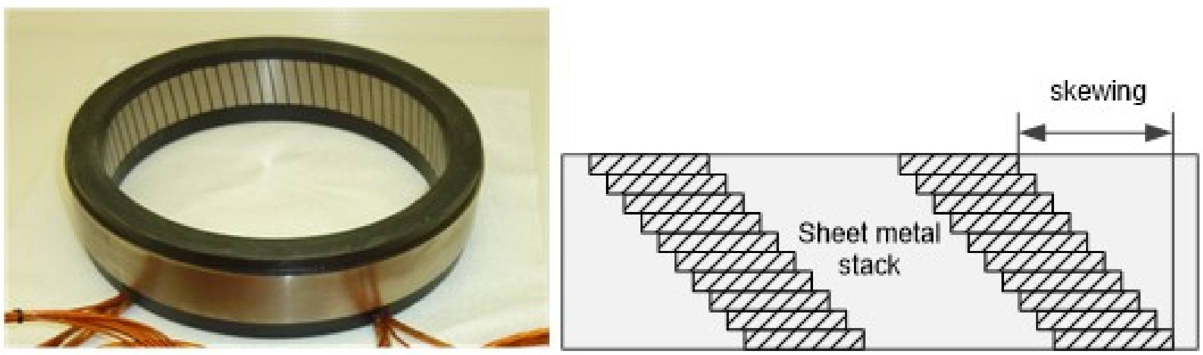

Figure 5. Motor stator skewing

The Performance Drift Error is calculated from Absolute Performance Errors (APE). The APE is the difference between actual position and target (commanded) position for any given point in time. During flight, the actual position is determined with the absolute optical encoder that is part of the mechanism. Therefore, measurement uncertainties of the encoder have a direct impact on the APE and PDE:

- Low-frequency encoder errors (below the controller bandwidth) are followed by the mechanism. This results in a deviation to the target scan profile. The actual (physical) performance of the mechanism is affected, but this cannot be determined from the position data.
- High-frequency encoder errors (above the controller bandwidth) are not followed by the mechanism but corrupt the recorded position data. The actual (physical) performance of the mechanism and, hence, the co-registration of the instrument is not affected.

In order to minimize the impact of measurement uncertainties on the mechanism performance, stringent requirements were imposed on the encoder. The performance of all encoders was checked with an external reference encoder during mechanism assembly.

The second major performance requirement is off-axis motion of the scan mirror ("wobble"). The time-independent (also referred to as asynchronous or random) wobble of the Scanner mechanism shall be <10 µrad peak-peak; the one of the Derotator shall not exceed 20 µrad. In contrast to the synchronous (repeatable) wobble, the asynchronous wobble cannot be corrected during ground processing.

The time-independent wobble is caused by any non-deterministic behavior of the bearings. Non-deterministic behavior of the bearings can be attributed to the balls, which rotate and spin in a unpredictable manner. The variation of the ball diameter, as defined in ISO 3290, was identified as the major contributor to the time-independent wobble. Surface roughness is approximately one order of magnitude lower, and the deviation of the spherical form of the ball has a minor influence as the ball is the softest element in the bearing. Therefore, balls of grade 3 were selected for the bearings. The distance between the rings of the bearing pairs was maximized as much as possible.

Power consumption requirements
The scan profile of the Scanner and Derotator was optimized for integration time per pixel during earth view. The scan period of 1.728 seconds is defined by the satellite orbit and the spatial resolution of 500 m at Nadir. Consequently, a dynamic scan profile with a low velocity during earth view and sun calibration and a high-acceleration/deceleration phase outside this range was defined (refer to Figure 6). The need to maximize earth view duration was traded against power and exported torques requirements.

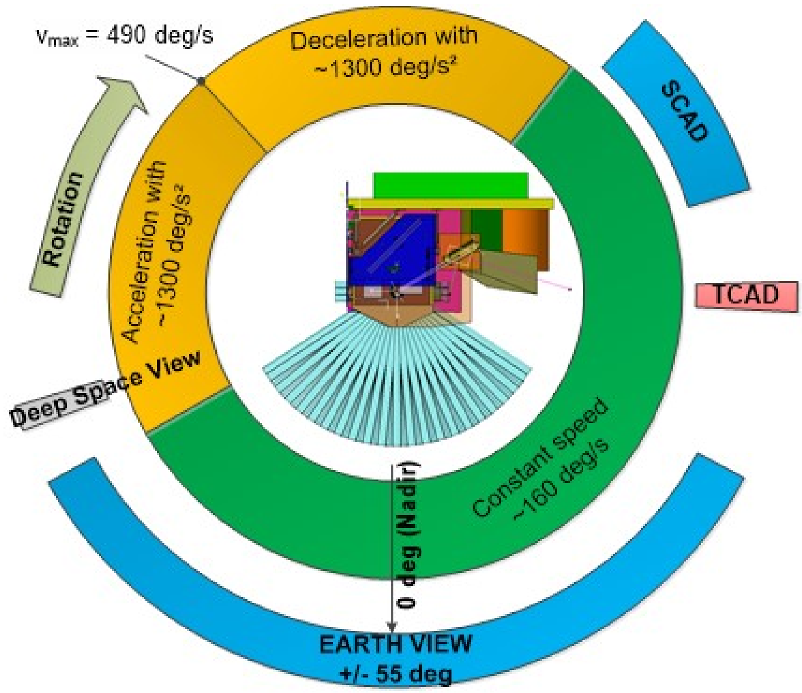

Figure 6. Scan profile of Scanner and Derotator

The combined peak power consumption of the Scanner and Derotator mechanisms had to be less than 40 W. The average power consumption over one revolution had to be less than 8.0 W and 6.0 W, respectively, for the Scanner and Derotator mechanism. A multitude of parameters affect the power consumption of a mechanism. The major ones are:

- Bearing friction
- Motor losses (mainly iron and copper losses)
- Inertial moments during acceleration phases
- Encoder power consumption

In order to re-use existing designs as much as possible, the encoder was not modified. Motor power could have been reduced by approximately 30% by using NdFeB magnets; however, motor magnets made from SmCo were preferred for programmatic reasons (refer to section *Long-term storage*). Bearing friction was minimized by sizing the bearings to the actual needed dimension, and by reducing the preload to the minimum possible value that was required to ensure that the mechanisms withstand the launch environment (Scanner: 88-mm pitch diameter, Derotator: 124 mm). In addition, the Derotator bearing concept was modified for power as well as lifetime reasons: instead of two bearings in hyperstatic layout, one bearing in an isostatic layout was chosen. This was found feasible in a trade of power against performance requirements.

Inertial moments that need to be overcome by the motor occur during acceleration and deceleration phases. They are dependent on the rotating inertia and the acceleration. The resulting inertial moment is overcome by motor phase current increase and, hence, causes higher power consumption. Together with the instrument team, a scan profile was found that satisfied the instrument needs and for which the Scanner and the Derotator were compliant to the power requirements with SmCo magnets. This permitted avoiding NdFeB magnets.

Cleanliness and contamination control

METimage is an optical instrument. The mechanisms carry optical components and, thus, had to meet stringent cleanliness and contamination requirements. In general, the CVCM (Collected Volatile Condensable Materials) and RML (Recovered Mass Loss) limits of Table 1 applied to the mechanisms.

Table 1. Particulate and molecular contamination requirements

Mass of material concerned	CVCM [%]	RML [%]
> 100 g	< 0.01	< 0.1
10 – 100 g	<0.05	<1
< 10 g	<0.1	<1

The CVCM and RML limits were considered for selection of surface treatments (paints) and lubricants. It was decided not to use polyurethane-based paints as these paints show high outgassing levels over long time. Black Keronite and Acktar FractalBlack™ were implemented for all thermo-optical coatings. A surface modification process developed at Airbus which creates black surfaces with high solar absorptivity (titanium: 0.98, aluminum: 0.84) and infrared emissivity (titanium: 0.94, aluminum: 0.95) while at the same time providing an excellent bonding pre-treatment (e.g. for bonding heaters, thermistors) [4] was not selected by the time the decision for the coatings was made. This was due to the – by that time – unclear handling constraints of the surfaces treated with the laser. However, laser processes developed by Airbus were applied for increasing friction coefficients (refer to section *Temperature ranges*) and for performing REACh-compliant bonding pre-treatment for motor bonding [11].

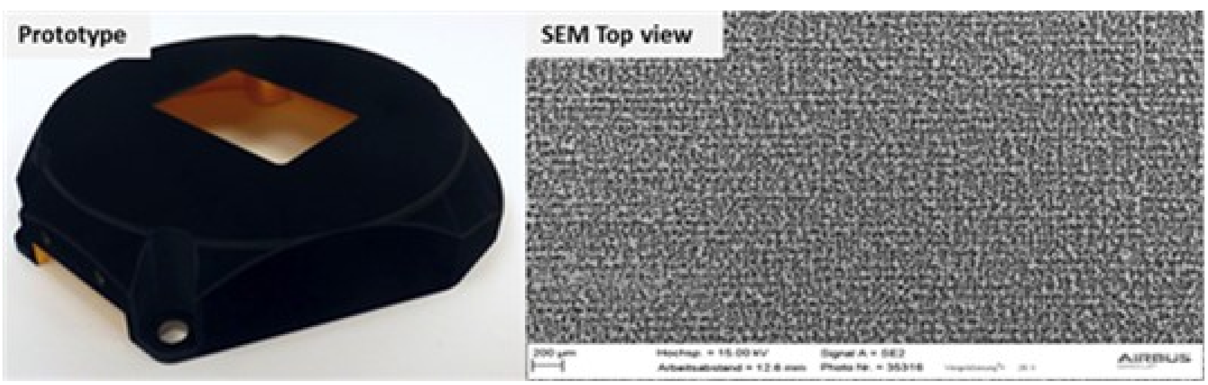

Figure 7. Blackening by surface modification with laser (left: laser-treated titanium prototype, right: microscopic view of laser-treated surface) [4]

The heritage bearing lubricant for most scanning mechanisms at Airbus Friedrichshafen is grease Maplub SH051-a, in combination with phenolic resin cages that are impregnated with Nye 2001a. These MAC-based lubricants were chosen due to their excellent lifetime (in terms of revolutions) which exceeds the lifetime of PFPE-based lubricants by far [2]. However, according to current literature, PFPE-based greases and oils like Braycote 601EF and Fomblin Z25 have a better outgassing behavior; for instance, the vapor pressure of Fomblin Z25 is reported to be one order of magnitude better than the one of Nye 2001a [3].

Table 2. Lubricant outgassing data

Lubricant	Vapor pressure at 20°C [mbar]	Vapor pressure at 100°C [mbar]	TML [%]	CVCM [%]	Reference
Requirement	N/A	N/A	1 (RML)	0.1	Table 1
Fomblin Z25	1.60E-13	2.80E-09	0.04	0.01	[3]
	9.35E-10 (25°C)	3.53E-09	0.17	N/A	[10]
Nye 2001a	5.33E-12	1.33E-08	0.40	N/A	[3]
	N/A	1.80E-09	0.08	0.12(*)	Test [6]

(*) Correcting the CVCMs for bulk evaporation losses was not possible due to QCM saturation. Therefore, non-compliance (0.12% vs. specified <0.10%) was accepted.

In order to assess the suitability of the heritage MAC-based lubricants for METimage, an outgassing test of the batch of Nye 2001a foreseen for the METimage Scanner and Derotator was performed. This test yielded that the actual outgassing behavior of Nye 2001a was far better than expected and, except for the CVCM, was in the same order of magnitude as the one of Fomblin Z25 [6]. It is not clear whether this observation is valid only for the tested batch, or whether literature data on Nye 2001a are in general too conservative.

Temperature ranges

The specified non-operating temperature range of the Scanner and Derotator mechanism is -35°C to +55°C (design temperatures). In order to ensure zero slippage, the following modifications of the standard drive unit design were implemented:

- Iso-static mounts added at the interface between mechanism and instrument panel (Figure 8)
- Laser treatment of slippage-critical surfaces performed (Figure 9)

Iso-static mounts are widely used design features for optical instruments. They compensate thermal expansion mismatches in radial direction. This prevents slippage of interface bolts due to thermal loads.

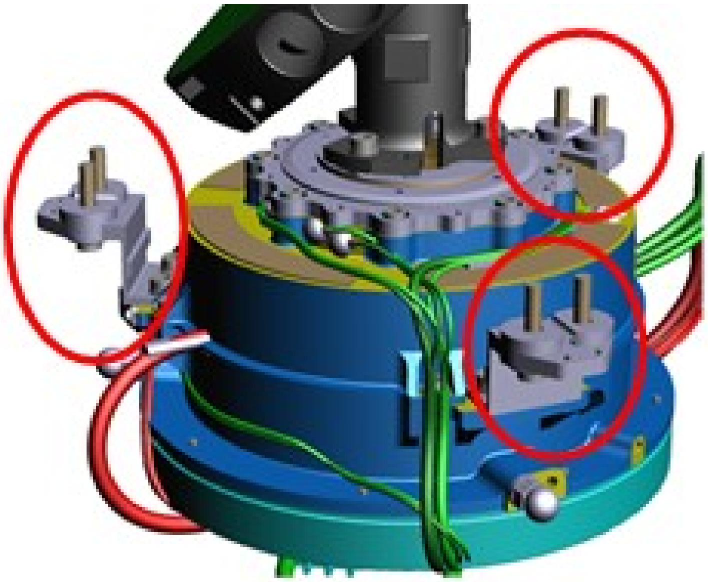

Figure 8. Iso-static mounts of Scanner

As mentioned in section *Cleanliness and Contamination Control*, a surface functionalization process that increases friction between adjacent parts has been developed and qualified at Airbus. This process is based on a laser treatment of the surfaces between two friction partners. Application of this process increases the friction coefficient significantly, which helps to prevent bolt slippage. For instance, the friction coefficient for laser-treated surfaces of titanium on titanium (Ti6Al4V) is >0.5, the one for titanium on aluminum 7075 is >0.8.

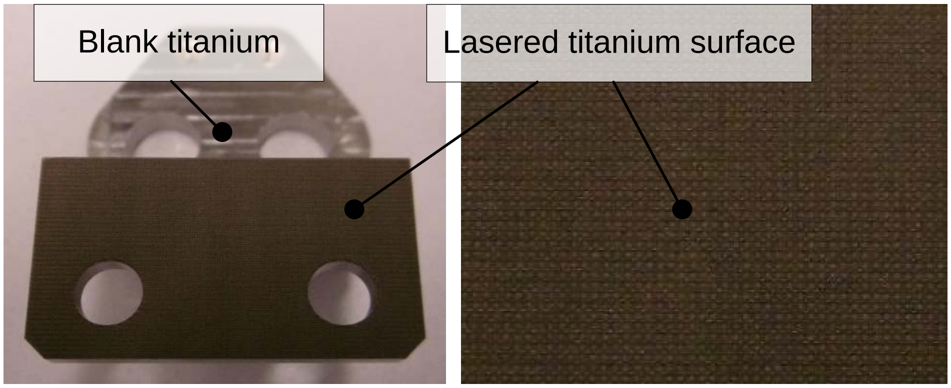

Figure 9. Laser-modified surfaces for increased friction coefficient

Lifetime

The lifetime requirement of the Scanner mechanism is 201 million revolutions; the requirement for the Derotator mechanism is 101 million revolutions. Both values include on-ground operation and margins as per ECSS-E-ST-33-01C. The design operating range of both mechanisms was specified as 10°C to 34°C. Due to local dissipation, bearing temperatures were calculated to reach more than 50°C during operation. Lifetime analysis per ISO 281 of the standard drive unit concept (hyperstatic bearing layout) with the bearing size required for the Derotator (pitch diameter 124 mm) yielded that this design was not feasible for the given temperature environment and lifetime requirement. Due to its design principle, the Derotator has to accommodate the conic optical path (105 mm to 89 mm in diameter) and the bearing size could not be reduced. Therefore, the Derotator bearing layout was changed to an isostatic one (one bearing pair in back-to-back configuration), the contact angle was increased to >30 deg, and the preload was decreased by approximately 25%. This yielded a drastic improvement in calculated life: 60 billion revolutions for the iso-static design vs. 62 million revolutions for the original hyperstatic design. The Derotator performance requirements, which are less stringent than the Scanner ones, were still met.

Long-term storage

The specification required that the mechanisms be designed, manufactured and qualified to sustain at least 15 years of storage on satellite level plus 5 additional years on-ground lifetime. This requirement imposed careful selection of materials and processes with respect to corrosion, stress corrosion cracking, long-term stability, creep, etc. The following major design choices were made:

- Nickel plating of motor rotor yoke and stator sheet metal stack
- Selection of SmCo magnets (instead of NdFeB)

Nickel plating of steels is a widely used low-risk process. However, the plating of the stator sheet metal stacks was a major concern. Protrusions of the bonding varnish between the metal sheets cannot be avoided during stator baking. The protrusions can be removed on the outer diameter of the stator by turning. On the inner diameter and in the stator slots, the bonding varnish cannot be removed. As nickel does not adhere to bonding varnish, a continuous nickel layer cannot be achieved on the inner diameter of the stator and in the stator slots (refer to Figure 10, left). This was confirmed in a damp-heat test (7 days, 50°C, 95% relative humidity): the stator sample showed significant levels of corrosion at these locations, whereas the outer diameter and the entire rotor yoke did not show corrosion at all. Corrosion at the inner diameter of the motor stator, which is only 1 mm away from the rotor magnets, could not be accepted. In order to increase the corrosion resistance of the stator while maintaining the robust nickel layer, it was decided to add a secondary moisture barrier on top of the nickel layer. Parylene, a polymer primarily used as moisture barrier on printed circuit boards, was selected. Parylene is less robust with respect to handling than nickel, but adheres well to many substrates, including the bonding varnish of the stators. Hence, the chosen approach came with the following advantages:

- At least one continuous moisture barrier available at all locations on the stator, even at spots where the nickel did not adhere well

- All handling surfaces (outer diameter) have two continuous layers, i.e. any potential damage to the outer Parylene layer (e.g. during AIT) could be accepted

The entire stator was coated with Parylene after nickel plating and before wiring and potting.

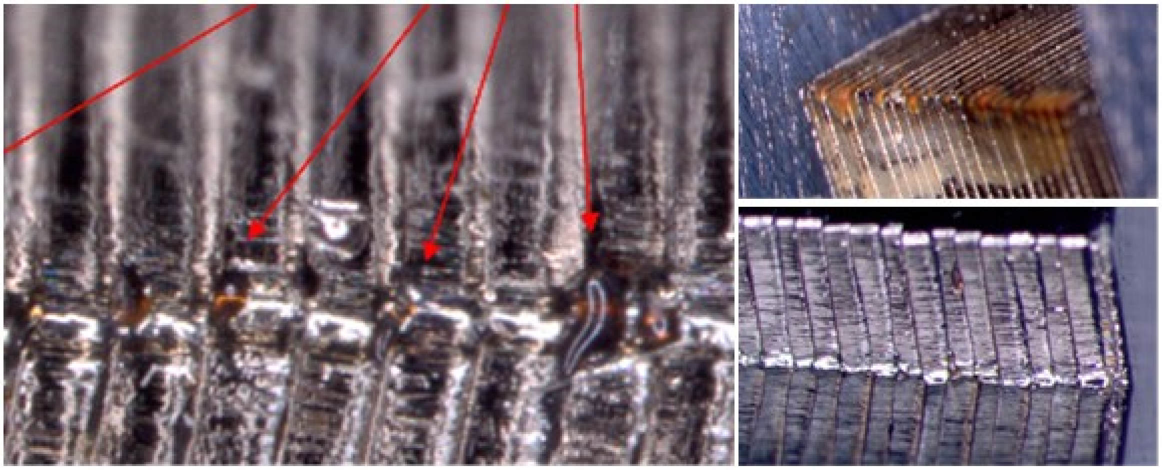

Figure 10. Bonding varnish protrusions visible after Nickel plating (left), corrosion on nickel-plated stator sample after humidity test (top right) and sample with Parylene layer after humidity test (bottom right)

Two types of magnet materials were considered during the design of the motor: NdFeB and SmCo. By the time the MetOp-SG projects were started, an alert had been raised on a previous NdFeB type used on MetOp (first generation). The nickel-plating of the motors had delaminated and the magnets had corroded. SmCo is resistive to corrosion but is known to be brittle and its remanence is approximately 30% lower than the one of NdFeB, which causes higher power consumption of the mechanism.

More corrosion-resistant NdFeB types had become available since the development of the MetOp satellites. However, our magnet supplier recommended not using nickel plating due to several issues observed with such platings on magnets in the past. Hence, the new type of NdFeB and a coating or plating would have had to be qualified for space and long-term storage.

From an accommodation point of view, motor designs with SmCo magnets as well as with NdFeB magnets were feasible. The higher power consumption of a SmCo magnet motor was traded against technical and programmatic risk associated with a qualification program for the MWI, ICI, MWS and METimage projects, with two agencies, four instrument primes, and the satellite prime involved. After a scan profile had been agreed that permitted the use of SmCo magnets from a technical point of view, the decision was made to use SmCo magnets. It should be noted that this resulted in some handling issues during AIT; even our most experienced AIT personnel struggled with the brittleness of the magnets and – despite being extremely careful – damaged a couple of magnets.

Figure 11. SmCo magnets damaged during AIT

Breadboard Testing

The breadboard model of the BepiColombo Antenna De-Spin Mechanism was used to demonstrate the feasibility of the chosen control loop design and to obtain an understanding of the required motor and encoder performance at an early stage of the project. As its design comprised a single bearing pair in back-to-back layout, it was also used to assess the suitability of a back-to-back bearing layout for the Derotator. The Antenna De-Spin Mechanism breadboard was hardware-in-the-loop during controller testing with an xPC and Simulink models of the controller. The outcome of the tests was:

- Chosen cascaded control loop (motor current, velocity, position) suitable
- Motor stator to be skewed in order to reduce cogging torque disturbances
- Encoder spikes at high speeds during acceleration phase to be filtered
- High-frequency error of encoder has significant impact on measured PDE of mechanism

Consequently, a skewed motor design was selected (also refer to section *Performance Requirements*), a median filter was implemented into the controller design, and the high-frequency error specification of the encoder was narrowed.

Lubricant Testing and Re-lifing

An outgassing test of Nye 2001a oil was performed in order to assess the suitability of this oil and the Maplub SH051-a grease for the project. As pointed out in section *Cleanliness and Contamination*, the oil outgassing behavior was significantly better than expected from literature.

The grease Maplub SH051-a has been discontinued. This type of grease was used for most heritage scanning mechanisms at Airbus Friedrichshafen. To date, no successor showing similar performance has been identified. Maplub SH type b lifetimes are expected to be approximately one order of magnitude lower than that of the type a greases [2]. In addition, torque peaks at low speeds and de-mixing at temperatures higher than 40°C were reported for the Maplub type b greases in an information note distributed by supplier MAP. The torque peaks were later confirmed by analysis and bench testing [7]. Based on these findings, the project decided to keep using the discontinued Maplub SH051-a grease. The batch of grease available for the MWI, ICI, MWS and METimage projects was manufactured in 1999 and its shelf life has formally expired. It was tested in a spiral orbit tribometer at the European Space Tribology Laboratory (ESTL) and compared against test data of a freshly manufactured sample of the same grease. The tribological performance (friction and lifetime) of the 20-year-old Maplub SH051-a grease is presented in Table 3; it was demonstrated to be no worse than that of a freshly manufactured grease batch. The variance of spiral orbit tribometer test data was higher for the re-lifed grease. Therefore, mixing of the re-lifed grease was recommended as a precaution, although improvements gained by physical re-mixing of the grease were anticipated to be marginal at best at bearing level. This is due to the fact that the amount of grease in a bearing is several orders of magnitude higher than the amount applied to the ball in a spiral orbit tribometer test. [5]

Table 3. Mean tribological data for re-lifed vs. fresh Maplub SH051-a grease [5]

Grease	Lifetime (orbits/μg)	Initial friction coefficient	Mid-life friction coefficient
Re-lifed grease	11,050	0.07	0.093
Fresh grease	9,569	0.07	0.100

Life Tests

Life testing of Scanner and Derotator was performed in order to demonstrate that the mechanisms met the specified lifetime requirements of 201 million revolutions for the Scanner and 101 million revolutions for the Derotator, respectively.

<u>Life test approach</u>

The bearings were considered the only life-limited (in terms of revolutions) items of the mechanisms. The following approach was chosen:

- Build up full mechanism model (with optics dummy and industrial encoder)
- Perform cumulated environmental testing
- Perform accelerated life test in thermal-vacuum conditions

Full models of Scanner and Derotator were built up. This was necessary as different bearing layouts and types had been selected for the two mechanisms (refer to sections *Design Overview* and *Lifetime*). Life-testing of standalone bearings was ruled out; such an approach would not have been flight-representative: pre-conditioning of the bearings by representative environmental testing would not have been possible and mounting conditions of the bearing in the mechanisms could not have been considered.

Environmental testing of the life test models was performed in order to stress the bearings in a similar manner as the flight bearings. The worst-case environmental loads of a flight mechanism would be three times proto-flight testing (mechanism level, instrument level, satellite level) plus launch loads and in-orbit loads. Therefore, the following environmental pre-conditioning was performed:

- Vibration testing along three axes with qualification loads and 4x proto-flight duration (= two times qualification duration)
- Shock testing along three axes (3 full-level shocks per axis)
- Thermal-vacuum testing (1 cycle non-operating temperatures, 7 cycles operating temperatures)

The predicted contact stresses during vibration were much higher than the ones during non-operational temperature cycling (2,000 MPa vs. 1,500 MPa for the Scanner bearings). Therefore, no additional benefit would have been obtained from doubling the thermal vac (TV) test duration (and cost).

The life test was performed under consideration of the following constraints:

- The life test has to be accelerated in order to finalize it in reasonable time. The duration of the life tests at nominal speed would have been 11 years.
- The baseline temperature of the life test should not be overly conservative; the average temperature over one orbit, including hot case margins, was considered a reasonable choice.
- Analytical predictions yielded that the bearings operate in the mixed lubrication regime; any acceleration of the life test (= speed increase) required an increased temperature during the test in order to keep the oil film thickness constant
- It was decided to limit the temperature to 60°C at the bearing; there is little experience with fluid-lubricated bearings permanently operated beyond this temperature for such a long duration.
- The Hertzian pressures in the life test environment had to be similar to the ones on orbit
- The number of load changes (rotational acceleration/deceleration, stops) in the accelerated test had to be the same as in a non-accelerated test
- The rotational acceleration should be the same for the non-accelerated test and the accelerated test in order to avoid overstressing the bearing cages

Accelerated testing

Accelerated testing of bearings lubricated with fluid lubricants (oils and/or greases) is not trivial. It is widely accepted that the lubrication regime should be maintained when accelerating a test in order to keep the test representative. For lubrication containing grease instead of pure oil, no tribological validation can be performed beyond any tribological criticism. In addition, there is no practical means to measure the oil film thickness in an assembled mechanism [8, 9]. The test data evaluation performed to select the METimage life test temperatures was based on the assumption that, when varying speed and temperature, same torque is an indication for same oil film thickness. Despite the mentioned uncertainties, keeping the oil film thickness constant was considered the most suitable and widely accepted approach when accelerating a test with fluid lubricants. In addition, this approach is considered conservative due to accelerated tribo-chemical degradation of lubricants at higher temperatures.

The maximum possible acceleration factor was initially determined from bearing film thickness calculations. The final value was confirmed by friction measurements of the bearings of the life test models. The friction measurement was performed with the bearings integrated into the mechanism; the motor was not mounted as its resistive torque would have corrupted the bearing friction measurements. The friction measurements were performed at different temperatures and operating speeds in a dry nitrogen atmosphere. The results of the Derotator bearings are shown in Figure 12. Subsequently, the friction torque ((3) in Figure 12) at the nominal average speed of the mechanism (1) and at the nominal average temperature (2) over one orbit was determined. Assuming that same friction torque meant same oil film thickness, the life test temperatures (4) for different speeds could directly be read from the plot. Respecting the 60°C limit this yielded an acceleration factor of 3 for both mechanisms.

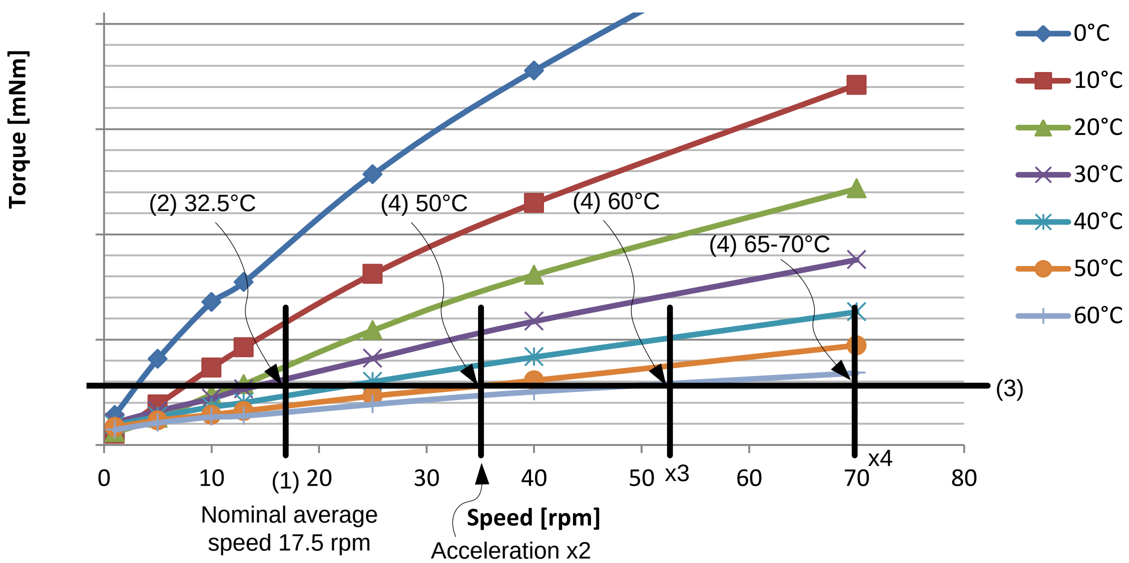

Figure 12. Bearing friction measurement results and life test acceleration factor for Derotator

The MWS and MWI/ICI projects ran their life tests with acceleration factors of 3.9 (MWS, discontinuous scan profile like METimage) and 5 (MWI/ICI, constant speed), respectively, and at temperatures between 40°C and 50°C. The life tests of the IASI-NG mechanisms developed by Airbus Toulouse for CNES were performed with an acceleration factor of approximately 11 at a temperature of 62.5°C. This was possible due to the lower operating temperature of IASI-NG.

Life test profile

The profile for the accelerated life test of the Scanner is shown in Figure 13. The major constraints were:

- The average velocity was increased as described in the previous paragraphs.

- The same number of load direction changes as for a life test at nominal velocity had to be performed. This implied that that a dynamic profile with one acceleration phase and one deceleration phase per revolution had to be performed.
- The acceleration/deceleration during the life test was kept the same as in the nominal scan profile in order not to over-stress the cages of the bearings
- The ratio between constant velocity phases and acceleration/deceleration phases was kept constant (approximately 69% constant speed, 15.5% acceleration, 15.5% deceleration)
- Controller capability and power availability had to be given for the accelerated test case (the peak power consumption of the profile was optimized by inverting the acceleration and deceleration phases)

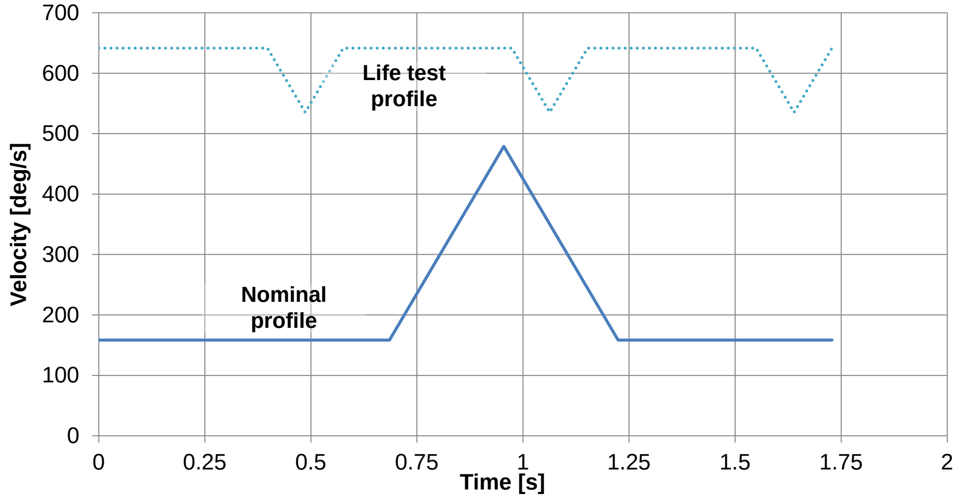

Figure 13. Scanner life test profile for acceleration factor 3

<u>Life test results</u>

Both the Scanner and the Derotator life tests are still running. The environmental campaigns (vibration, shock, thermal-vacuum cycling) have been finalized successfully.

The life tests are continuously monitored automatically by EGSE and the set current is recorded. Once per day, the accelerated profile is interrupted and current measurements are performed at pre-defined constant speeds. Motor current is used as an indicator of bearing friction. The motor current during the first 55 million revolutions of the Scanner life test is shown in Figure 14. The low-speed motor current slightly decreased during the initial phase of the test. This is attributed to a smoothening of the bearing internal surfaces. The motor set current readings became noisier during summer (approximately day 230 onwards). This behavior is attributed to the fact that – besides bearing heating – no active temperature control of the TV chamber is performed. Temperature variations of the facility, which are more pronounced during summer when the air conditioning is working with high effort to keep the room temperature within the specified limits, directly impact the temperature in the TV chamber.

The spikes at the beginning of the test and around day 90 are related to automatic switch-offs of the setup. The industrial encoder that is used for the life tests instead of the flight encoders provided erroneous position feedback to the control loop, which reacted by increasing the current beyond the limit defined for automatic switch-off. The initial root-cause analysis at the beginning of the test came to the conclusion that the analog-to-digital converter of the encoder, which had been placed inside the TV chamber, was not vacuum-compatible. After replacing the original analog-to-digital converter and mounting it outside the chamber, the test was re-started and the position spike issue seemed to be solved. When it returned around day 90, a more thorough assessment had to be performed. After initial assembly of the mechanism, the industrial encoder had been calibrated using its auto-calibration & reference search feature and its performance had been demonstrated in a test with an external reference encoder. The encoder stator had then been temporarily dismounted for the vibration test. After re-integration, encoder performance was again demonstrated using an external reference encoder. Subsequently, TV testing was started and the mechanism including encoder was operated successfully under thermal-vacuum conditions. No position spikes were observed in any of the tests. The root-cause analysis finally led to the conclusion that the industrial encoder should have been re-calibrated using its auto-calibration & reference search feature after the second integration to the mechanism. AIT personnel had integrated the encoder stator twice in almost identical positions and orientations, i.e. within some microns; this is why the encoder worked at all after the vibration test. However, the missing proper calibration led to a spontaneous loss of reference from time to time, which caused the position spikes and, consequently, triggered the overcurrent protection. During the encoder performance test after vibration and during the TV test, this issue had – for either good or bad luck – simply not occurred. Based on this assessment, the TV chamber was opened and the industrial encoder was re-calibrated. The encoder spikes did not re-appear.

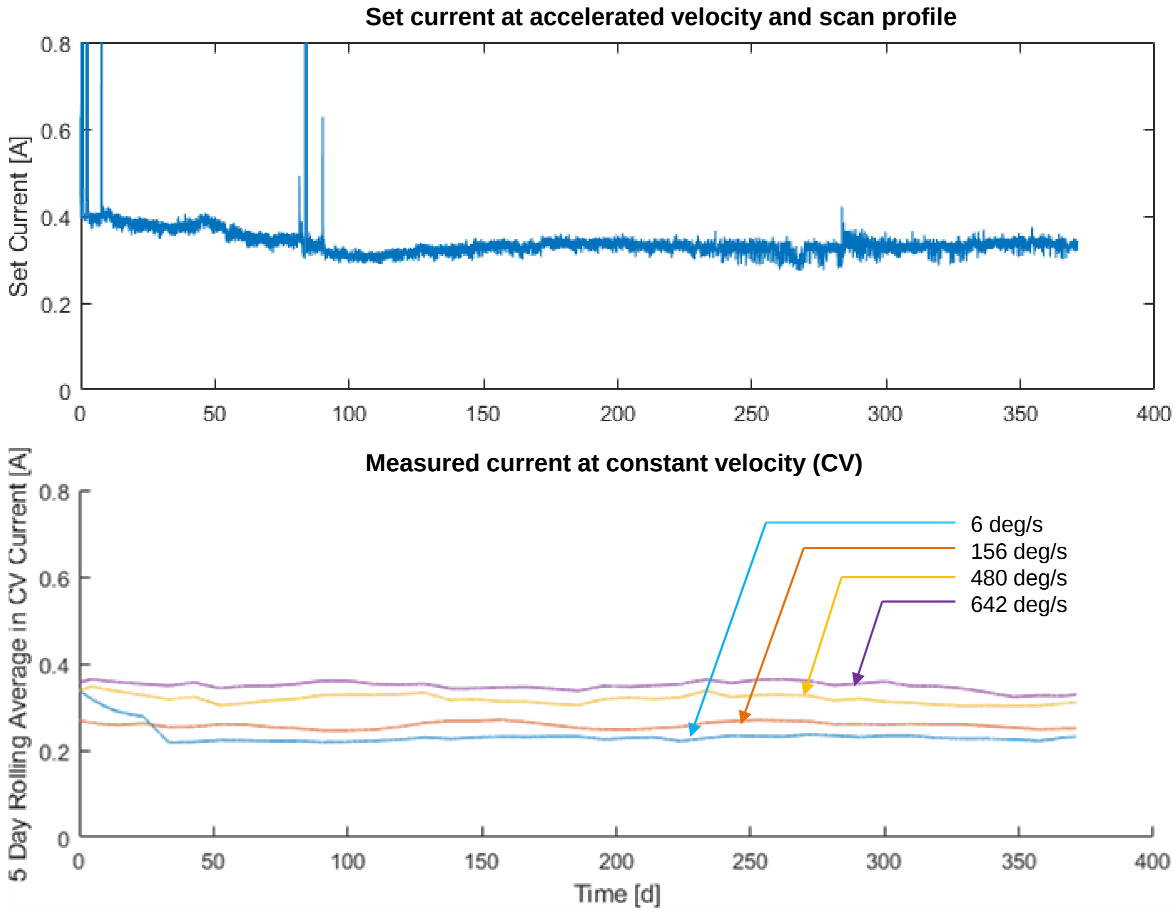

Figure 14. Scanner motor current during first 55 million revolutions

Summary and Conclusion

The METimage Scanner and Derotator mechanism designs were established by modifying a standard drive unit design to project-specific requirements. Breadboard- and component-level testing was performed in order to reduce the design risk at an early stage. Flight-representative life test models (except for the industrial encoder) were built up. Environmental testing of the life test models has been completed successfully. The accelerated life tests of both models under thermal-vacuum conditions have been started and are ongoing.

The following major lessons learned have been derived from the project so far:

- Despite efforts to minimize the development and qualification activities, significant modifications of the standard drive unit design were required in order to meet the specific requirements of the Scanner and the Derotator, respectively.
- The tribological performance (friction and lifetime) of 20-year-old Maplub SH051-a grease was demonstrated to be no worse than that of a freshly manufactured grease batch.
- The actual outgassing behavior of the used batch of Nye 2001a is far better than expected and, except for the CVCM, was in the same order of magnitude as the one of Fomblin Z25.
- Design for long-term storage comes with very specific challenges concerning material choice. For programmatic reasons, SmCo magnets were selected instead of the technically more feasible NdFeB ones. A secondary moisture barrier had to be added on top of the traditional Nickel plating on the motor stator in order to guarantee corrosion resistance at all locations.
- Representative accelerated life testing of fluid lubricated bearings is (still) a major challenge. The widely accepted approach of maintaining oil film thickness by increasing the test temperature is considered conservative but comes with uncertainties (oil film thickness calculation, lubrication regime assessment, validity for greased bearings). Dynamic scan profiles require particular attention in order to ensure that the cages are stressed in a representative manner during the life test.
- A surface functionalization process that increases friction between adjacent parts was implemented to prevent bolt slippage. The qualification of this process yielded excellent results: the friction coefficient for laser-treated surfaces of titanium on titanium (Ti6Al4V) is >0.5, the one for titanium on aluminum 7075 is >0.8.

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