Development of a Filter Wheel for VenSpec-H

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ABSTRACT

EnVision, ESA's upcoming Venus orbiter, seeks to comprehensively understand the planet's evolution, building on the success of Venus Express. It will map Venus's interior, surface, and atmosphere with unprecedented detail, enhancing insights into its geological evolution [1]. VenSpec-H – one of the instruments within the VenSpec Suite – is focusing on the atmosphere both below and above the clouds as it will analyze volcanic plumes, as well as complementing surface and subsurface observations [2]. The results are foreseen to support the research teams of BIRA-IASB under Instrument Lead (IL) Dr. Séverine Robert and ETH Zürich under Profs. Paul Tackley and Taras Gerya – Co-ILs of the VenSpec-H Instrument – in understanding commonalities and differences between the planetary evolutions of Venus and Earth [3][4]. VenSpec-H is an optical spectrometer using an echelle grating to diffract uniform light for detailed compositional analysis. A cooled spectrometer section is preceded by a band selection section based on a combination of a filter wheel and a fixed horizontal double stripe filter.

This paper focusses on the development approach of the Filter Wheel Mechanism (FWM) lead by the Swiss Team of VenSpec-H (HSLU, ETH, FHNW, KOEGL Space) and its drive electronics lead by BIRA. It also gives insights in the tests that were performed with a detailed breadboard built within phase B1 of the project.

Keywords: spectrometer, space mechanism, filter wheel

1. INTRODUCTION

EnVision Mission Background

EnVision is the fifth medium-class mission of the European Space Agency (ESA), planned for launch in the early 2030s to study Venus's internal dynamics, surface features, and atmospheric dynamics. It will also explore the interactions between Venus's interior, surface, and atmosphere. The mission's key instruments include two radars: VenSAR, a **Ven**us **s**ynthetic **a**perture **r**adar from NASA for high-resolution surface imaging and a ground-penetrating radar for subsurface mapping. Additionally, EnVision features a VenSpec (**Ven**us **Spec**trometer) spectrometer suite to analyze the chemical composition of Venus's atmosphere and surface, seeking signs of volcanic activity. A radio science experiment will investigate Venus's internal structure and gravitational field.

The spectrometer suite consists of three channels: a Multi-Spectral Imager (VenSpec-M), an Ultraviolet Spectrometer (VenSpec-U), and a High-Resolution Near-Infrared Spectrometer (VenSpec-H), all controlled by a Central Control Unit (CCU). Each channel has independent optics for different imaging concepts and wavelength ranges.

The High-Resolution Near-Infrared Venus Spectrometer VenSpec-H

The VenSpec-H spectrometer plays a crucial role in characterizing volcanic plumes and other phenomena that influence gas exchange between Venus's surface and atmosphere. By focusing on volcanic and cloud-forming gases, VenSpec-H aims to detect composition anomalies potentially linked to volcanic activity, complementing the surface and subsurface observations from VenSAR and VenSpec-M. On the night side of Venus, VenSpec-H will survey the near-surface atmosphere (0-20 km) and the atmosphere below the cloud layer (20-45 km), while on the day side, it will focus on the

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atmosphere above the cloud deck (65-80 km). To achieve its scientific goals, VenSpec-H uses four narrow spectral bands tailored for atmospheric probing. Three of the bands are especially useful for penetrating the cloud layer during nighttime observations, known as the spectral night windows of Venus. Further details on the scientific objectives of VenSpec-H and the entire VenSpec suite are available in [5] and [6].

The instrument's functional diagram and a 3D CAD image are shown in Figure 1 and Figure 2. After passing through an entrance baffle, the incoming light is filtered by optical filters on a filter wheel, then passes through a filter slit assembly and an echelle grating spectrometer diffracts the light to be finally processed in a cryo-cooled infrared detector. Until just before the science phase the instrument is closed off by a Turn Window Unit (called shutter in the functional diagram). Most of the electronic modules are detached from the optical bench into a separate electronic box.

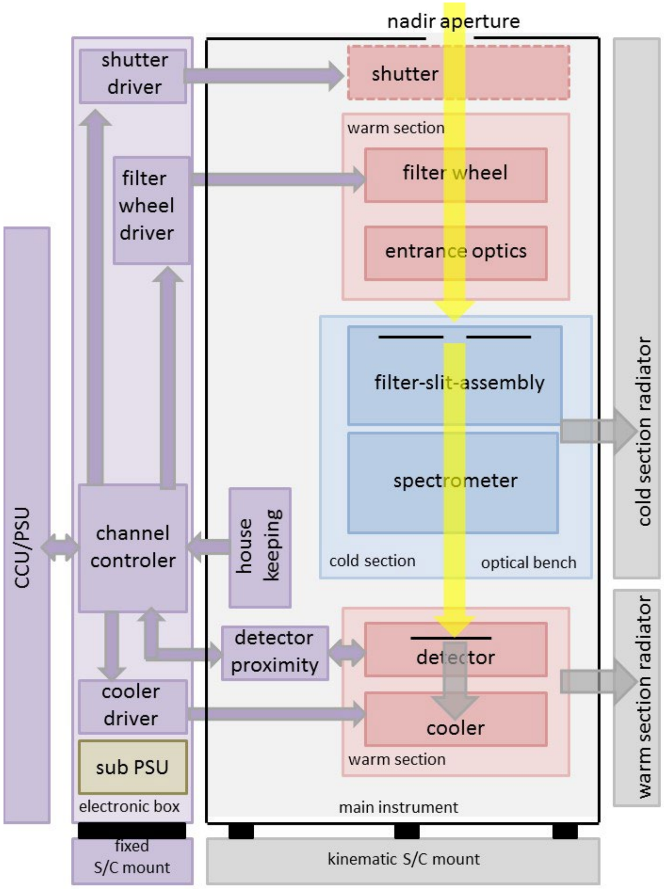


Figure 1. VenSpec-H instrument functional diagram.

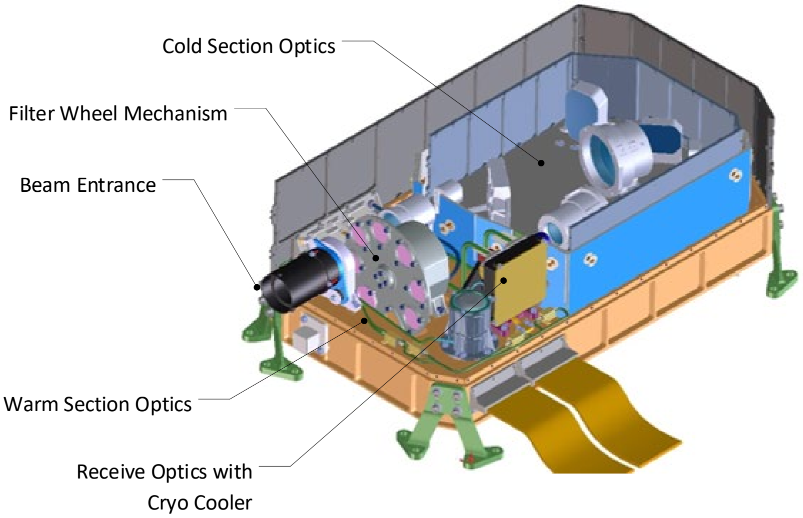


Figure 2. VenSpec-H instrument 3D CAD image.

The Filter Wheel Mechanism of VenSpec-H

A 3D CAD image of the VenSpec-H filter wheel mechanism is given in Figure 3. It provides space for four band selection filters, two polarizers, and two positions are used for calibration (one fully closed, one fully open). In addition to allowing the change of the different filters by rotation of the central axis, the mechanism must survive the severe launch load conditions and protect the filters from shocks and thermal deformations.

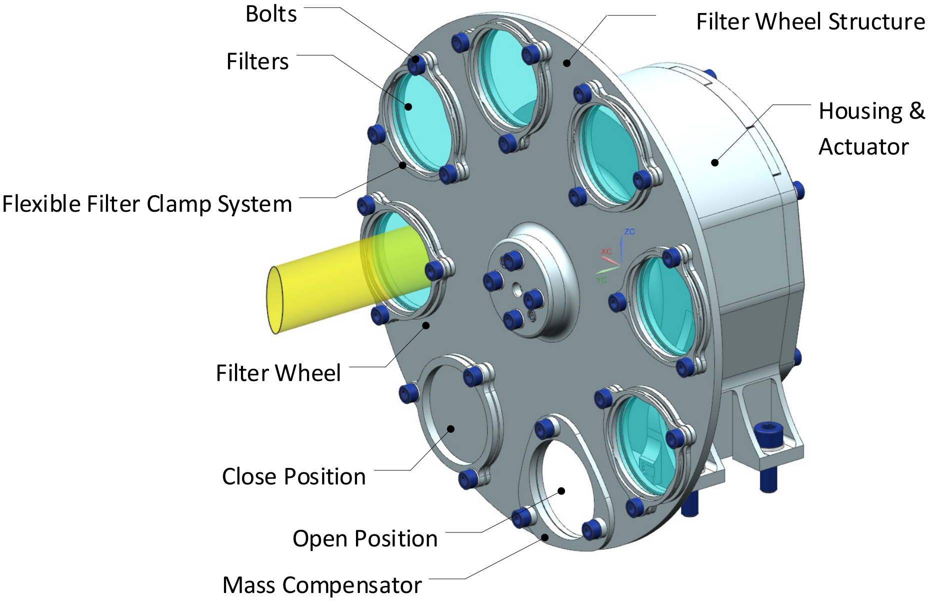


Figure 3. VenSpec-H FWM 3D CAD image.

The goal of this paper is to explain the design of the filter wheel mechanism, describe its operational environment and the associated design challenges. It also shows the different steps in the development of an elegant breadboard that has been built and tested in order to reach a technical readiness level (TRL) of 6 for this mechanism early in the project.

2. OPTICAL NEEDS FOR THE FILTERS

The passbands of the four standard filters in the filter wheel match the four scientifically required wavelength bands of VenSpec-H (Table 1). The FWHM of bands #1, #3 and #4 are not larger than the free spectral range of the spectrometer grating. This means that they will be imaged on the detector without overlapping wavelengths. The FWHM of band #2 is wider than one grating order. To avoid overlapping wavelengths an additional dual band horizontal filter, splitting band #2 in two smaller bands #2a and #2b, is placed outside the filter wheel further down the optical path. The transmission curves of the four filters in the filter wheel are given in Figure 4.
Two wire grid polarizer filters are added in the filter wheel corresponding to the day side spectral bands #2 and #4. These polarizers will be used to performed polarization measurements at one hand, and to correct measurements in the standard filter channels for polarization perturbation by the instrument itself.
All filters will have relatively steep edges to avoid as much as possible the disturbance of the signal by out-of-band straylight.

Table 1. Minimum required spectral range of the 4 standard filters.

	goal spectral band	
dayside	**band#2a**	2.34 – 2.42 µm
	band#2b	2.45 – 2.48 µm
	band#4	1.37 – 1.39 µm
nightside	**band#1**	1.16 – 1.18 µm
	band#2a	2.34 – 2.42 µm
	band#2b	2.45 – 2.48 µm
	band#3	1.72 – 1.75 µm

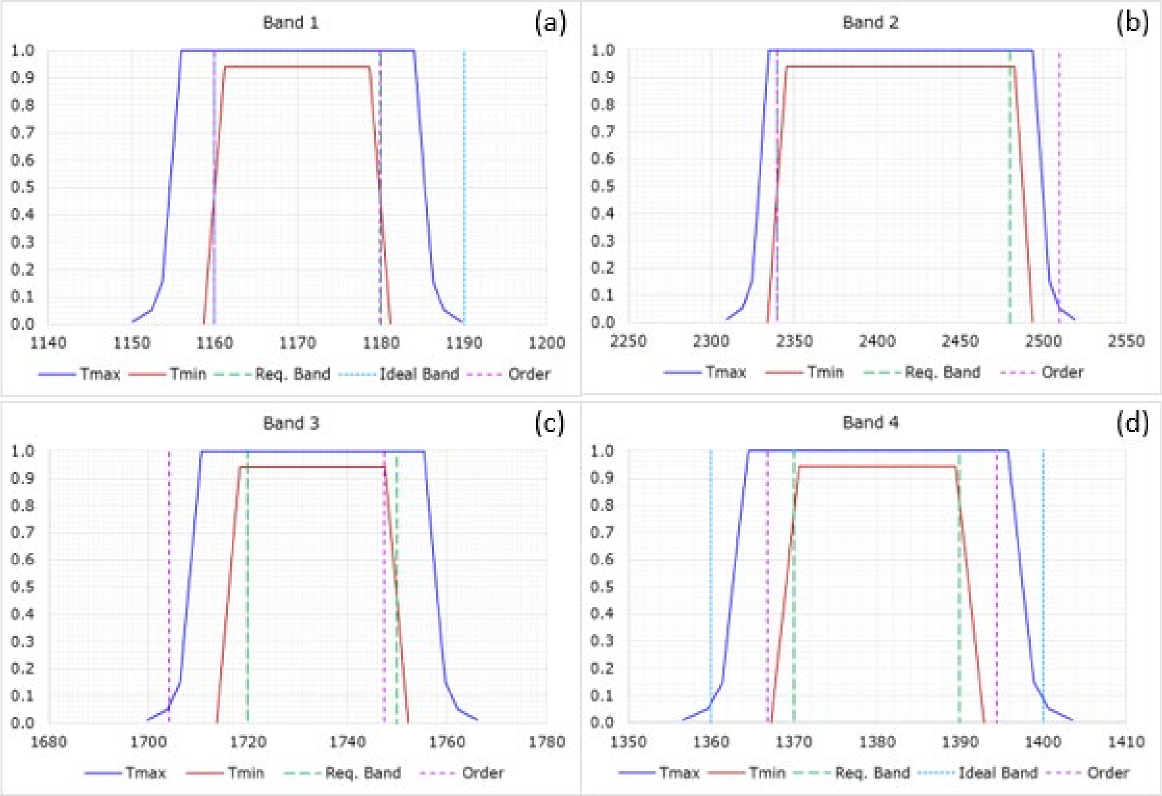
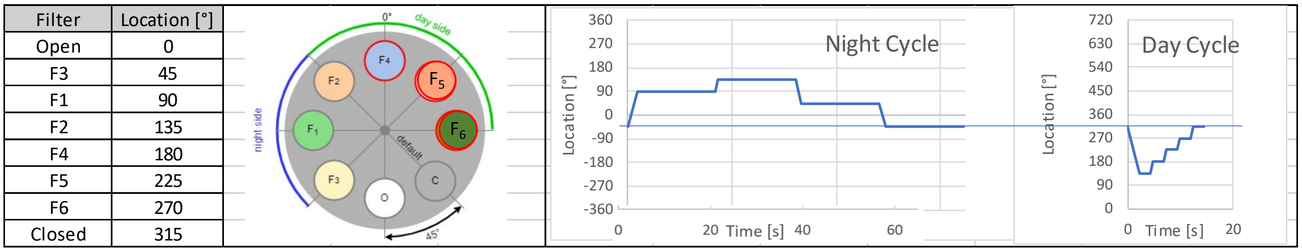


Figure 4. Transmission curves of the 4 standard filters.

3. DEVELOPMENT CHALLENGES

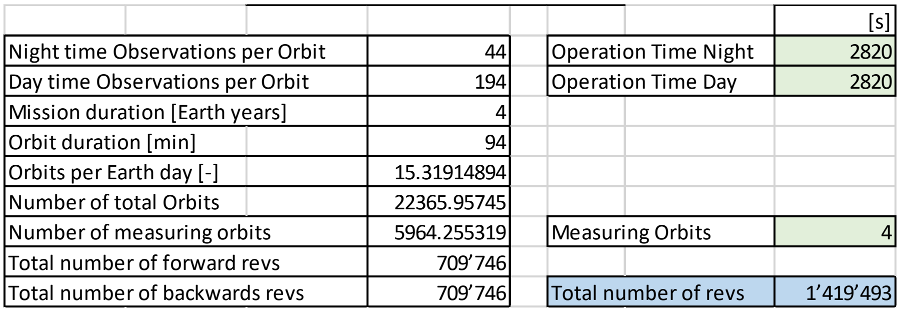
During a phase A study, it became clear that using an acousto-optical tunable filter (AOTF) as spectral band selector, like was done in earlier planetary spectrometers (SOIR on Venus-Express, NOMAD on ExoMars TGO) was not an option in the given spectral domain of VenSpec-H and with the given resources. The fact that for VenSpec-H only a limited number of four spectral bands was required, lead to the decision to use a Filter Wheel Mechanism running an observation sequence with filters for the spectral bands. A typical observation sequence, both at Venus day side and at night side, is shown in Figure 5.



Filter	Location [°]
Open	0
F3	45
F1	90
F2	135
F4	180
F5	225
F6	270
Closed	315

Figure 5. FWM observation sequence.

With a typical orbit duration of 94 minutes, it is expected that 44 observation sequences can be performed during the night side and 194 during the day side. With a mission duration of four earth years and considering that VenSpec-H will be active on 4 out of every 15 orbits, the FWM is expected to deliver a total of 1.42 million revolutions, as shown in Figure 6. When applying the ECSS safety factors, in total about 2 million revolutions need to be tested, corresponding to a life test of 3.4 months of run-time.



			[s]
Night time Observations per Orbit	44	Operation Time Night	2820
Day time Observations per Orbit	194	Operation Time Day	2820
Mission duration [Earth years]	4		
Orbit duration [min]	94		
Orbits per Earth day [-]	15.31914894		
Number of total Orbits	22365.95745		
Number of measuring orbits	5964.255319	Measuring Orbits	4
Total number of forward revs	709’746		
Total number of backwards revs	709’746	Total number of revs	1’419’493

Figure 6. FWM number of required revolutions.

The FWM operates very close to sensitive optics and hence molecular contamination must be strongly minimized. For this reason, solid lubrication is required, which is known to have less lifetime than liquid lubrication. Furthermore, the FWM is situated close to the cold spectrometer section that operates at -45°C and thus heat dissipation by the mechanism must be minimized.

Besides that, the launch vehicle, the spacecraft, and the location of VenSpec-H on the spacecraft were not known in the beginning of the project. Therefore, in coordination with ESA, approximations given in [7] and the experience of the authors were used to derive the mechanical launch load conditions – arriving at peak loads of over 220g during random vibrations.

As for any optical element in VenSpec-H, also the filters in the FWM must safely survive the launch loads as well as thermo-elastic effects during all mission phases – including the cruise phase to and the aerobraking phase around Venus. During operations, the filters need to be positioned with a repeatability of less than 0.1 mm in each direction.

On the programmatic side the challenge was to build a highly representative breadboard and perform all tests necessary to reach TRL 6 in a time frame of 1.5 years.

4. FILTER WHEEL DESIGN

To meet the technical requirements and to face adequately the different challenges, it was decided to reduce the design complexity to the absolute minimum. The concept of the VenSpec-H FWM relies on the following technical paradigms:

- to reduce tribological issues as much as possible, a direct wheel drive is foreseen, where the filter wheel as well as the motor are sitting on the same axis and are supported by a single bearing pair (i.e., no gearbox is present);
- as the bearings shall be solid lubricated and the number of revolutions is high, the wear shall be minimized by low wear distance and as low preload as possible;
- to have minimal heat dissipation, a stepper motor is selected;
- the stepper motor has to have a high position repeatability when in idle mode, i.e. in zero-current position;
- a position sensing concept shall be put in place that is as simple as possible;
- if possible avoid the implementation of launch locks, i.e., all launch loads need to be carried by the bearings.

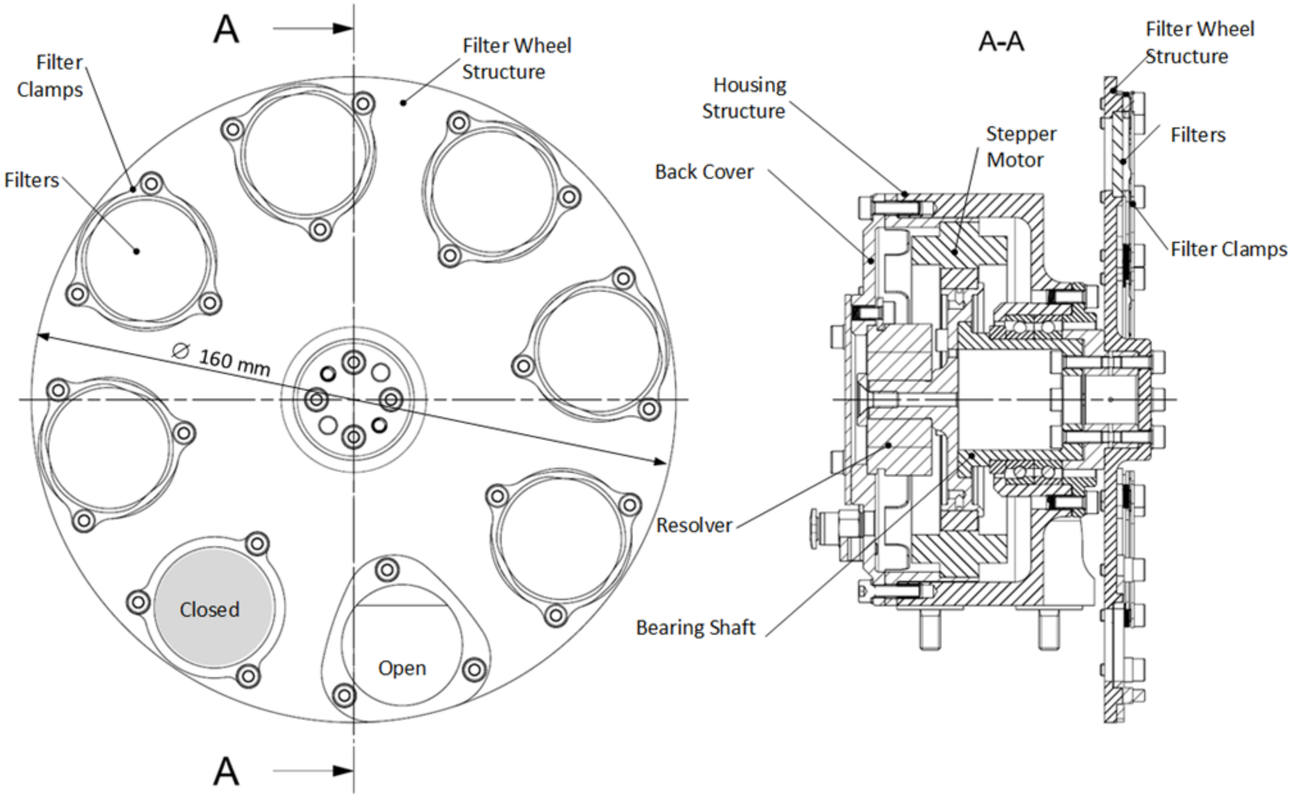


Figure 7. FWM breadboard design.

The final FWM breadboard design is shown in Figure 7. The filters are clamped into recesses in the filter wheel structure using flexible clamping rings of a titanium alloy. The clamping ring preload is evenly distributed by an aluminum alloy crown ring to the fused silica filter substrate. This allows reducing the pre-load to the minimum and for thermo-elastic "breathing" of the glass in its aluminum support.

The mechanism design itself is built around the bearing shaft, that is supported by a hard preloaded bearing pair in back-to-back configuration from ADR. 440C bearing races and balls are lubricated with sputtered MoS_2. The cage is made of PGM-HT with PTFE and MoS_2. The filter wheel structure is directly attached to the front shaft part. The design is optimized such that the filter wheel can be equipped with filters parallel to the mechanical assembly of the mechanism.

The mechanism is driven by a 1° per step stepper motor from SAFRAN/SAGEM, which has sufficiently repeatable zero-current positions. To minimize micro-vibration and to further optimize the stop position repeatability, the mechanism is driven in micro-stepping mode. By careful balancing the rotating axis around the central axis and the center point of the

duplex bearing pair, a launch lock can be avoided. The balancing of the open position on the filter wheel itself is managed by a special balancing clamp, that has the same mass and inertia properties as a glass/clamp-system.
The breadboard has been assembled with a resolver for position information. During the project it was concluded that for the flight models position measurement by Hall effect sensors will be implemented.
Rather than ordering the absolute best components for motor and bearings, which appeared costly and had long lead times, it was decided to use stock components readily available from the suppliers and design the other parts around them. This significantly reduced the development time of the breadboard FWM.

5. FILTER WHEEL ELECTRONICS

In the VenSpec-H instrument, the filter wheel stepper motor will be driven from a central Field Programmable Gate Array (FPGA) (NanoExplore NG-MEDIUM NX1H35AS) in micro-stepping mode. The stepper motor has two sets of independent windings, one nominal and one redundant. The FPGA can generate for each phase of each motor winding set a pulse-width modulated drive signal. This signal is transmitted over an LVDS interface to a motor driver section from where power is applied accordingly to the motor. This power stage consists of a full bridge driver (HS-4080AEH) in combination with 4 switching N-channel power MOSFETs (Infineon IRHNJ67130). Either the nominal or the redundant driver can be activated by non-latching double pole relays, electrically coupling the active motor windings with the driver.

There is no continuous hardware position measurement (i.e., no resolver) in the flight model of the FWM. The filter wheel position is instead kept in software by a processor (MicroChip SAMRH71). However, two Hall effect sensors, one nominal, one redundant, are used to zero-reference the position of the filter wheel. The signals of the Hall sensors, together with some temperature measurements at the FWM, are transmitted via a Serial Peripheral Interface (SPI) bus back to the processor.

6. BREADBOAD TESTING

Representativity and Test Plan

The main purpose of the FWM breadboard is to verify the lifetime of the bearings. To be able to conclusively perform such a test, the breadboard design needs to be representative, as shown in the previous section – except for some non critical details, such as e.g. the absence of optically representative coatings and the usage of a resolver instead of reference Hall effect sensors. Therefore, the design is highly representative for the later flight models.

As the breadboard contains flightworthy components, it has been assembled under clean room conditions and subject to a bake-out. The breadboard FWM is shown in Figure 8.

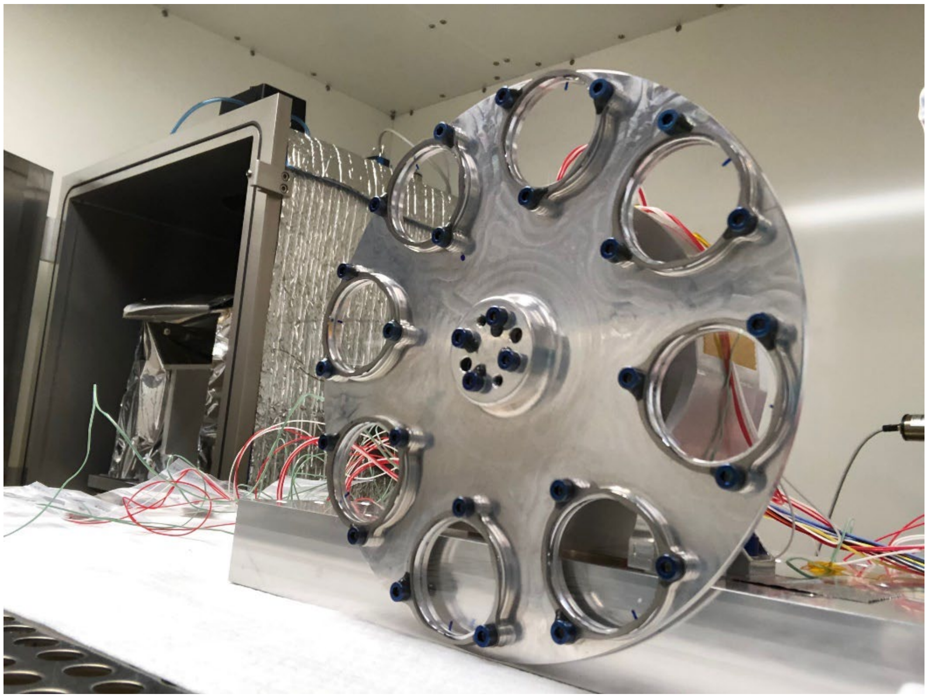


Figure 8. FWM breadboard in front of the TV chamber at FHNW.

A second important aspect is the representativity of the testing itself. To demonstrate the life of the mechanism it is necessary to simulate all environmental conditions which are seen by the flight model and in the same order. This way, potential deterioration due to the different launch and cruise phases is considered. In the case of the FWM, this means the simulation of the launch vibrations and a cycling sequence between maximum and minimum non-operational and operational temperature conditions. Generally, shocks are not detrimental to the mechanical parts of mechanisms. But since this breadboard also serves at qualifying the mounting concept of the filters, a shock test has been performed as well. At the end of the qualification test campaign, the breadboard has been dis-assembled and visually inspected. The complete test flow is shown in Figure 9.

In an early phase of the project, interface tests have been performed between the FWM and the instrument driving electronics. During the abovementioned qualification testing, an EGSE has been used instead to drive the FWM.

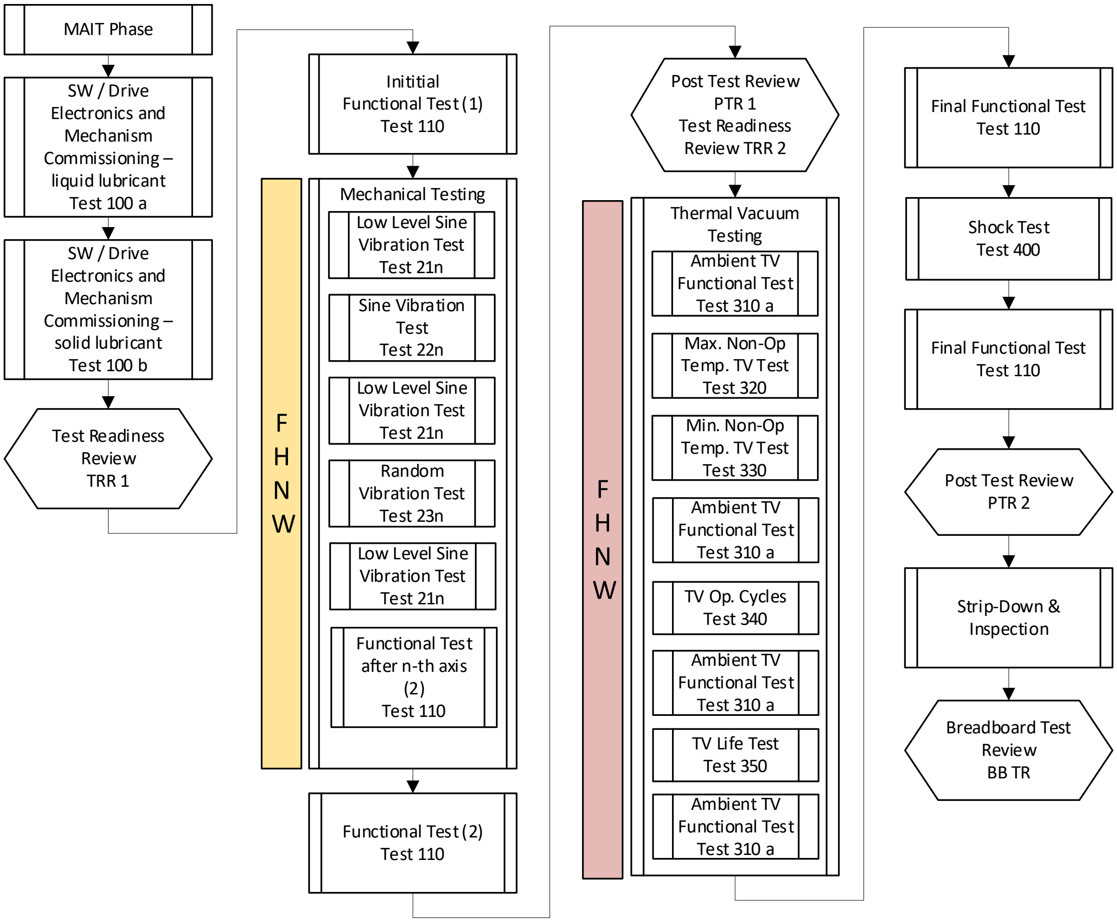


Figure 9. FWM breadboard test program.

Test Results Summary

Abovementioned test program has been successfully finished.

A pre-programmed *functional test* sequence is used to determine the state of the mechanism at intermediate inspection points, as shown in Figure 10. This test sequence starts with two full revolutions forward and backward at nominal current (0.18A) to prove correct command execution in nominal operation. Then two day and two night cycles are simulated to check proper stopping during the sequence. After this, the mechanism is tested with 1/3 of the nominal current (0.06A) to prove the torque margin. A repositioning test sequence shows the repeatability of the stopping points. The most crucial step is the start-up-current test at the end of the sequence. Starting from each filter position (including closed and open position) the start-up current is stepped down from one position change to the other starting at 0.06A and in steps of 0.01A until the mechanism loses steps. This test is aimed at revealing an increase of bearing friction, especially during the life test. It shall be noted that due to the use of MoS_2 as lubricant, all functional verification tests are run under dry nitrogen, if not under vacuum.

A vibration test with very conservative (high) input levels was run. In the filter wheel shaft up to 76.9 g_{RMS} random loads – corresponding to approximately 231 g peak – have been measured as shown in Figure 11. No significant changes of the mechanism behavior have been seen during the functional tests in between and after mechanical testing.

Two *non-operational thermal load cycles* between -50°C and +70°C have been applied to the FWM in the thermal vacuum chamber, followed by six *operational thermal load cycles* between -30°C and +20°C. During the dwell times functional tests have been run (cut out in Figure 12). Since at this point absolutely all moisture in the MoS_2 lubricant was dissipated and the bearings were run-in completely, the start-up current under vacuum conditions improved slightly with respect to the earlier tests performed under dry nitrogen conditions.

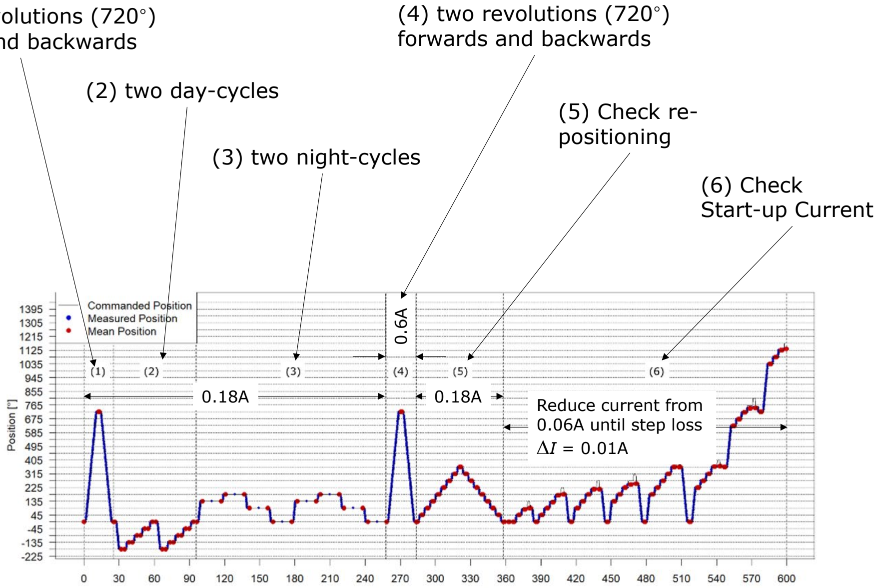
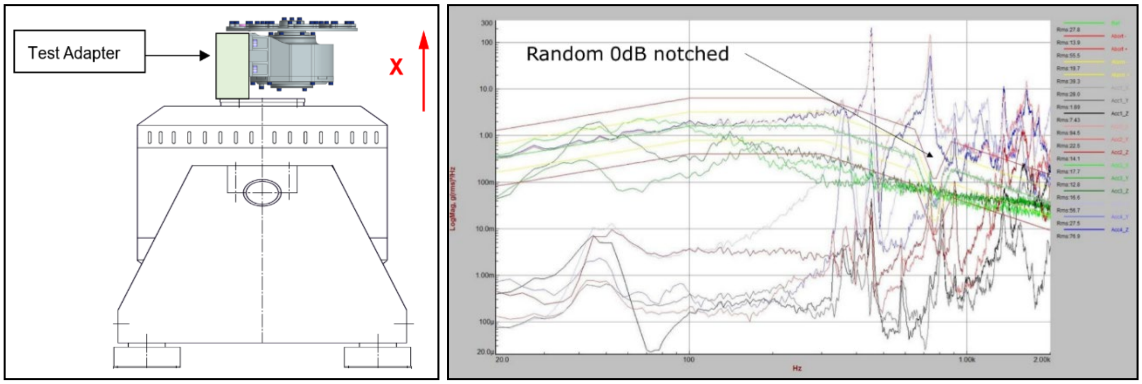


Figure 10. FWM breadboard functional test sequence.



At 0dB: max. acceleration on the filter wheel axis:

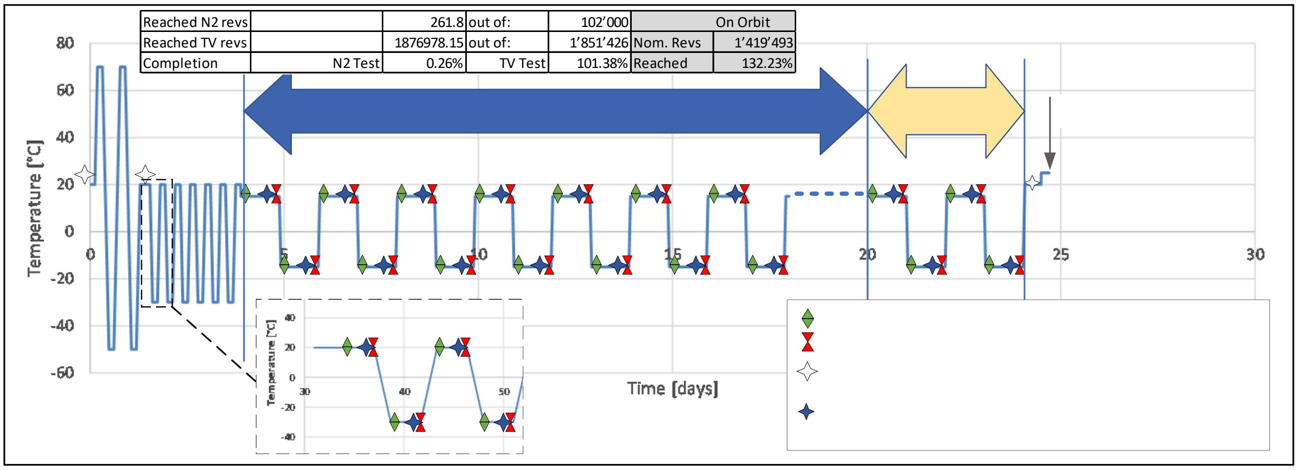
X: 76.9 g_rms
Y: 27.5 g_rms
Z: 56.7 g_rms

Resonance frequencies well above the required 140Hz

Frequency shifts very small

Figure 11. FWM breadboard vibration test main results.

In the slipstream of the thermal cycling test, a *life test* has been performed. The first part of this test was dedicated to simulating the in-flight sequence with thermal load cycles between -15°C and +15°C and with dwell times of 12h, during which half of the time the mechanism was running forward and half of the time backwards (Figure 12 and Figure 13). After reaching the orbital life plus additional test margins, a second part of the test was dedicated to simulating pre-launch ground conditions, with the test chamber flooded with dry N2. During the total duration of thermal cycling and life testing, no problems have occurred with the FWM. As shown in Figure 14 the minimum start-up currents varied slightly within the setup-accuracy but stayed systematically under 0.06A (the 1/3 nominal value, i.e., including torque margin).



Reached N2 revs		261.8	out of:	102'000	On Orbit	
Reached TV revs		1876978.15	out of:	1'851'426	Nom. Revs	1'419'493
Completion	N2 Test	0.26%	TV Test	101.38%	Reached	132.23%

Figure 12. FWM breadboard thermal vacuum and life test sequence

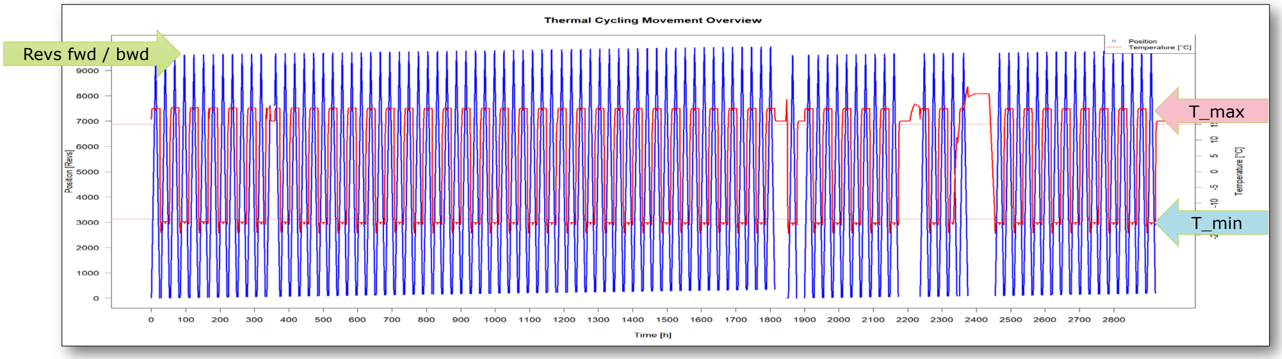


Figure 13. FWM breadboard life test recording of revolutions and temperatures.

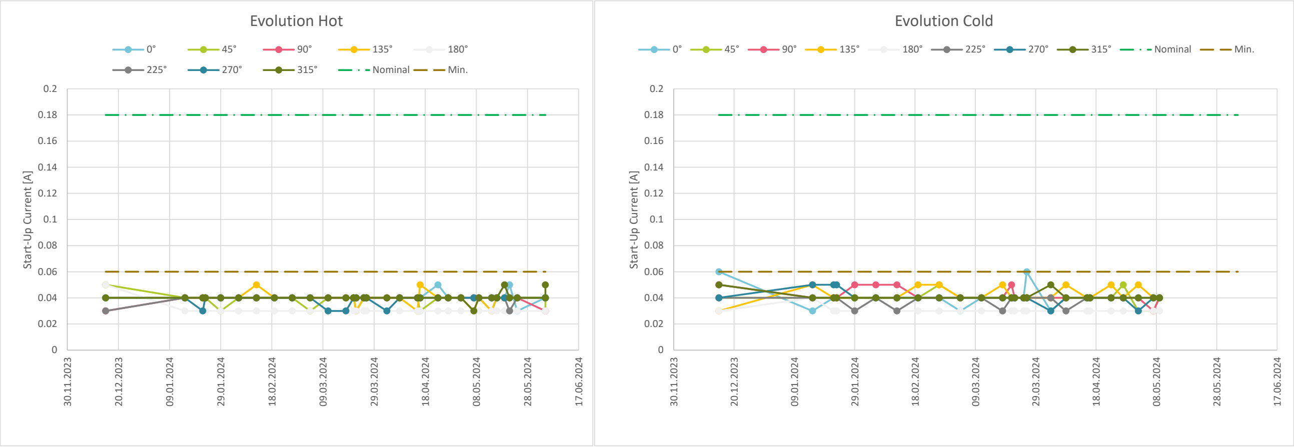


Figure 14. FWM breadboard evolution of start-up currents.

Finally, the mechanism was subject to *shock loads* of maximum 320 g in each axis direction without any significant changes in the mechanism behavior during intermediate functional tests.

At the end of the full test sequence (vibration + TVAC cycling + life + shock) and after final functional testing, no visible outside damage has seemed to have occurred on the FWM. For further internal inspection, the FWM has been disassembled and the parts were visually inspected. Also here, no damage has been observed on the mechanical parts, bearings, motors and resolver.

7. CONCLUSIONS AND OUTLOOK

The design and development of a filter wheel mechanism was presented. To verify the design, an elegant breadboard has been built and has undergone an extensive test campaign. The results show that the mechanism design as well as the design of the holders for the filters are fit to be rebuilt accordingly for the qualification and flight models. We note that in the next phase, the design will have to be slightly tweaked to include, amongst others, the Hall sensors and alignment provisions. Driver electronics for this FWM is under development. A first interface test was performed. A complete prototype electronics driver will be available soon to work together with the FWM breadboard, as part of the VenSpec-H instrument.

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