MINIATURE MOTORIZED ANTENNA FOR LOW-FREQUENCY RADAR OF THE HERA-JUVENTAS MISSION

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ABSTRACT

There is still a lot to explore in asteroid science and it is time to utilize a low-frequency radar onboard Juventas CubeSat of the Hera mission. Four antennas, one of the world's smallest of that type, are located in the corners of the 6U cubesat to constitute the mechanical part of the radar - S/C primary payload.

In the paper we outline full lifecycle of the antenna device briefly starting with basic design, through manufacturing, integration, tests & improvements of subsequent development models up to the recent acceptance campaign of the flight units.

In the course of unit qualification some failed test activities were experienced, although being very problematic at the moment of occurrence, these led to significant improvements of the flight model and a flawless acceptance campaign. Several failure sources will be described and finalized with lessons learnt.

1 MISSION DESCRIPTION

After its journey in deep space Juventas CubeSat will be ejected from the HERA mothercraft near a binary asteroid system. Then radar antennas will be precisely deployed and will conduct research. Near the end of the mission the Juventas CubeSat is scheduled to land on the Didymoon asteroid thus, in order to facilitate proper landing as well as related scientific research, antennas will be retracted.

Figure 1. Antenna size

Astronika was responsible for the development & delivery of four motorized, deployable & retractable antennas, each not much larger than a box of matchsticks when stowed (See Fig 1). Deployed part of each antenna is 6 mm in diameter and 1.25 m long.

Right now antennas are already accepted & delivered, waiting for final integration and launch.

2 OVERALL DESIGN DESCRIPTION

Antennas design was based on well-known tubular boom technology, one of the key technologies used by Astronika. Challenges were mostly related to volume & mass restrictions since there was a need to equip a very small unit with a motor, gearbox & limit switches system while maintaining positive motorization margin in worst case conditions in deep space.

2.1 Simplifications

Several simplifications were implemented in order to have the unit possibly simple, keep the cost reasonable and cope with the requirements. Most important include: use of DC motor, custom gearbox, simplified worm gear – standard spur gear, limit switches instead of encoder, journal bearings instead of ball bearings, no lubrication (except for motor).

2.2 Designed device

Finally, it was possible to fit the designed unit into the volume of 50×44×32 mm^3 with the expected mass of abt 55 g. Fig. 2 depicts main components of the antenna.

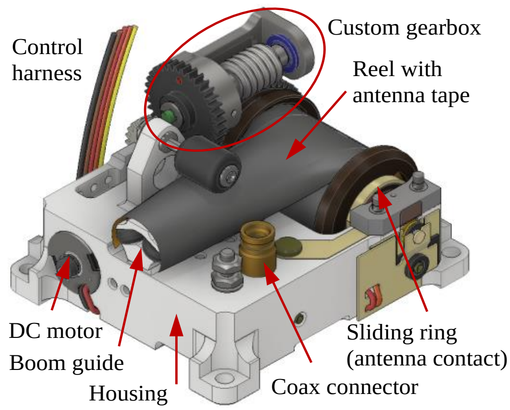

Figure 2. Antenna final CAD model

Main structure is made out of PEEK plastic while secondary structures utilize titanium.
During deployment or retraction of the unit DC Motor

power is transferred by 3-stage, custom gearbox (2-stage spur + 1-stage worm) onto the antenna tape Reel. While Reel is rotated, tape unwinds and sliding on its guide forms a tubular boom. Deployment process continues until proper length is indicated by limit switches located inside the Reel.

It is widely acknowledged that worm gearbox with the low efficiency is self-locking in static load conditions, but since boom tape is constantly creating some motorization torque, there was a need to prevent self-deployment of the unit when frictionless conditions occur during vibrations. As a solution custom one-way clutch was used between gearbox stages 2 & 3. It is located behind largest visible gear ant its external size is just ø12 mm × 4 mm.

2.3 First model

Since the design was new, it underwent full scope of models, starting with Breadboard (BB) with the main task of proving mechanical concept and functionality. Due to the cost optimization model was only equipped with parts required for above mentioned functionality, thus signal path was not installed. This model was extensively tested functionally and vibrated to levels much higher than required in order to prepare it for any possible requirements changes.

Motorization margin was calculated positive according to ECSS. Values based on measurements were used in calculations where possible. However, some resistive force values and coefficients used were only measured under ambient conditions since there was no cheap enough and fast enough way to obtain these values for worst case conditions at that time.

In order to judge the total resistive torque of the unit and compare it for different unit configurations and conditions, motor power supply current was used. For the initial models current measured under ambient conditions during deployment and retraction was up to 60 mA and up to 220 mA respectively. Compared to max. continuous current of 330 mA and stall current of 460 mA (both as specified in the datasheet) the resultant margin was considered sufficient and reasonable as a compromise between the motorisation margin assured and compactness to be achieved.

2.4 Additional model

After tests of the BB model were done, conclusions were implemented into the design and soon manufacturing of the next model could start. Initially it should be Engineering Qualification Model (EQM) but there was an unknown with the motor. Its final selection was not possible at that moment, only after proving the design concept on the BB and receiving the deep space version of the motor from the supplier, the delivery time of which was almost 2x longer than project schedule allowed. On the other hand, closing the milestone in time was a priority for the project. Since using different motors for EQM and FM was not an option, in order to cope with the situation a two-fold approach was implemented – additional Engineering model (EM) was introduced into the project, before the EQM, while the actual EQM was manufactured later, when its motor was finally available. For this new EM, lower grade motor (with shorter lead time) was additionally ordered. It was not as strong as deep space version but capable of taking all testing activities, including TVAC.

There was the other advantage of the approach taken – having the additional, non-deliverable model made it possible to enhance the development of further models and perform their de-risking.

2.5 Electrically Representative Models

Since only one limited BB and one EQM were initially planned before final FMs, there was a need to have some simpler models to test radio-related properties of the complete radar setup. With this reasoning 4 pcs of Electrically Representative Model (ERM) were designed and manufactured. This were basically EMs, manufactured with cheaper materials and stripped from motors, gearboxes and few other components not needed while radar functionality was tested on the S/C mock-up.

2.6 Qualification Model

Having the EM available beforehand and used extensively for further development and de-risking of the design, the EQM manufacturing and integration was much easier and faster, although it was not possible to avoid all the mistakes. Most of them were manufacturing related issues, where one or more of the below scenarios were present:

- parts with unchanged drawings were manufactured using a different method due to the change of CNC machine and new machining technology applied,
- new batch of material delivered for manufacturing had significantly different properties than previously,
- problem was related to the dimensions/features not measured during inspection; not all the dimensions were checked during inspection since some of them could not be measured at all, required sophisticated tools which were not present or were omitted as cost reduction.

In result of the above-mentioned problems, several changes were implemented for the future FM manufacturing:

- obligatory consultations and acceptance of the planned changes of manufacturing technology with the designers,
- changes in production techniques on subsequent models are limited to the essential needs,
- parts for subsequent models are manufactured from

the same source material batch whenever possible, even though delivered by the same proven supplier,

- all fittings revised and possibly loosen in order to increase parts compatibility when some conditions are changing (technology, material, etc.)

3 QUALIFICATION TESTING

3.1 First test campaign

EQM model of the antenna should undergo full qualification test campaign including: functional testing under ambient conditions, vibration test, shock test, TVAC test, bakeout and lifetime test. At that time Astronika's in-house testing abilities were limited thus some of the tests were planned in external facilities. Functional testing was performed without any significant problems and so was vibration and shock testing. During subsequent low level sine sweeps (LLSS) there were some amplitude & frequency shifts observed, exceeding success criteria, however it was later agreed fully acceptable. TVAC testing was planned with several cycles in non-operational and operational temperatures finalized with deployment & retraction of the antenna in both cold and hot cases.

Cold case deployment was the moment when good streak was over – after expected duration of deployment, the achieved antenna length was not full and did not increase despite the passage of activation time. In order to properly identify the problem, there was a decision during short NRB to have few more attempts of further deployment & retraction. Although some movement was observed the antenna was eventually considered as stuck. What was even more surprising, the unit control box in the end indicated that antenna is both deployed and retracted at the same time – very unlikely state even with severe mechanical malfunction. At this point antenna test was finished, antenna was removed from the chamber and delivered to Astronika's facility in the deployed state.

3.2 Inspection & repairs

During visual inspection and strip-down inspection of the unit it became clear that instead of single point of failure there are several smaller problems. The following major findings were noticed:

- manual rotation of the gearbox requires much higher torque – gear sleeve slid out of the gear, occupied all the clearance and caused increased friction; initially proper position was ensured by press fit but apparently faulty one due to high thermal expansion coefficient of the used POM plastic (see Fig. 3, left),
- faulty manufacturing of the limit switches inside antenna tape reel possibly causing "stuck" state in cold case due to thermal shrinkage and relative movement of the elements,
- metal particles found close to the limit switches, possibly causing shortcuts; particles origin was identified as faulty integration or adjustment of the antenna where metal piece was scrapped from the adjacent part (see Fig 3, right).

Apart from the above-mentioned mechanical issues, electrical tests and inspection of the control box and test harness didn't show any faulty behaviour or damage.

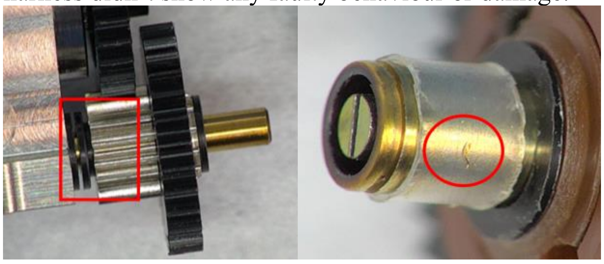

Figure 3. Inspection findings (left: washer + sleeve slid out of the gear; right: metal particle close to electrical contacts)

In order to resolve observed problems following actions were implemented:

- press fit of the gear sleeve was substituted with shape locking,
- change in the integration and adjustment procedures to prevent metal scrapping,
- additional insulation installed in order to prevent short-circuits even in the improbable case when metal pieces are present again,
- faulty parts were remanufactured using modified technology and thoroughly checked.

Unit was reintegrated with newly manufactured, corrected parts. Some components (i.e. boom) were additionally changed to ensure their lifetime is not affected by previous activities. In the end unit was ready for the test campaign repetition.

3.3 Second test campaign

Since NRB process after failed TVC test took whole 2 months with many discussions and additional checks, there was a strong belief in the successful TVAC test this time.

Functional, vibration and shock tests as before didn't show any major problems, but TVAC test resembled the previous one unfortunately – it was only partially successful. While deployment was properly done under any conditions, retraction was only successful in hot case. Similarly as during the first campaign some additional deployment/retraction tests were done while still in chamber to possibly identify failure root cause. In the end for cold case boom was stuck at abt. 1/3 of its length.

This time test setup was equipped with the multimeter thus it was possible to measure motor current for comparison. Max observed values for cold case reached 200 mA during deployment and 370 mA for retraction.

Apart from the technical aspects, two failed TVAC test campaigns had another significant drawback for the company – financial overhead. Since TVAC test is alone pretty expensive adding other tests to be repeated (functional, vibration, shock) along with HR costs, travels, etc. made these faulty tests pretty challenging for the project budget.
Nevertheless, despite tense project schedule there was an agreement to perform problem investigation in a slow and very detailed manner in order to exclude the risk of third failed TVAC testing.
In the meantime, Astronika developed its own test facility allowing for on-demand design verifications, material properties testing under various environmental conditions and final qualification or acceptance tests. In the end only vibration test and LLSSs for shock test were outsourced; all other tests were done internally.

Following conclusions were made:
- DC motor current is significantly higher in every case with respect to ambient operation,
- final max observed value of the current during deployment in cold (370 mA) should be considered as stall current and thus previously assumed high margin on the motor current doesn't exist in reality!
- lowered value for the stall current possibly comes from: too high resistance of the harness (few meters long), lowered supply voltage value (as per requirements), motor heating due to the operation with high resistive torque.

Several hypotheses were proposed for the failure cause:
- thermal shrinkage of the elements (rather doubtful as already corrected previously),
- DC motor damage,
- gearbox problem (i.e. decreased clearance increasing friction),
- increased antenna tape stiffness (doubtful).

Since during inspection nothing important was found (no mechanical damage of any kind, no obvious reason for problems), EQM functional test was carried out in ambient with following conclusions:
- DC motor current was fully OK!
- DC motor failure becomes doubtful.

In order to further identify the issue a short vacuum test (<1h; 10^{-6} hPa) accompanied by short functional test (200 mm) was carried out on the EQM with following conclusions:
- significant increase of the motor current appears right after vacuum is present,
- current increase disappears right after unit is taken out from vacuum, thus problem is most probably vacuum related.

At this point it was clear that problem most probably lies in the frictional properties of some materials. Following frictional pairs were identified in the unit to be analysed for potential problems:
- TiN coated titanium vs Vespel SP1 (limit switches),
- POM-H vs AISI 304 steel (worm gear vs worm),
- POM-H vs nickel coated bronze (gears),
- CuBe2 bronze vs Vespel SP1 (clutch),
- CuBe2 bronze vs PEEK (boom vs guide),
- DLC coated CuBe2 bronze + vs Vespel SP-1 (boom vs reel).

In the following weeks unit was thoroughly tested to identify problematic areas. Tests were done in various configurations (some parts removed, some parts changed, new parts added, etc.) and under various conditions (ambient, vacuum, different temperatures). Astronika facility was just recently equipped with the new TVAC chamber thus most important tests were done in vacuum since only in vacuum main problem was observed.
In order to avoid any additional wear of the EQM unit, the tests were done with the use of EM model. Only final confirmations were done on EQM. In total over 200 functional tests were performed with many of them in vacuum.

In the end it was not possible to identify a single, faulty element. Instead, several points were selected for slight improvement.

4 MODIFICATIONS

There were several small improvements as well as a few significant ones described below. Finally configuration of the device was optimized resulting in reduced observed resistive torque.

4.1 Change of boom coating

Antennas tape is coated with DLC in order to modify optical properties and prevent cold-welding. It was noticed that boom created much higher resistive torque than expected but the issue was not observed during the first test campaign. The reason was in the changed antenna tape before second campaign.
Measurements of the boom tape coating properties indicated that process of the external contractor wasn't fully stable, resulting in periodic variations of the coating thickness between batches (890 nm vs 760 nm; see Fig 4) as well in comparison with earlier qualified antennas for JUICE RWI (550 nm).

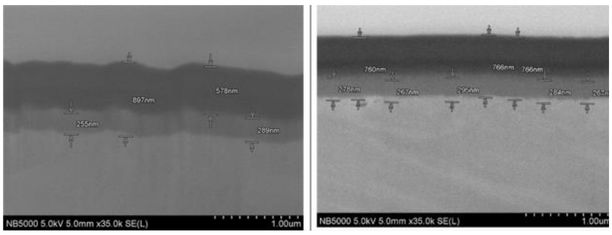

Figure 4. DLC thickness problem

Such changes of the coating thickness influence shape of the tubular boom and in turn resistive torque created by the antenna for the motor.
It wasn't initially clear what could be the reason for coating thickness variation, but after few weeks of work in close cooperation with the supplier it was possible to standardize the process and achieve booms with the desired coating.
Proper boom usage allowed for 20% reduction of the resistive torque.

4.2 Guiding rod

Guiding rod's function is to stabilize the antenna while it is being deployed. In bigger devices, complicated multi roll systems may be used, but for the Juventas antenna very small and simple, cylindrical part was used (see Fig. 5, left-most part). During TVAC failure investigation it appeared that guiding rod is creating a friction force with the value high enough to be worthy optimizing. Whole evolution process took several weeks in parallel to other optimizations. In the end 1-part guiding rod turned into quite sophisticated 11-part mechanism offering good guiding with the low friction. Step-by-step evolution process is depicted in Fig. 5.

Figure 5. Guiding rod evolution

4.3 Clutch

Antenna's clutch function is to prevent unwanted self-deployment during vibrations, when the motor is not powered while allowing possibly frictionless rotation during deployment or retraction. Its design was initially based on the well-known concept of one-way, frictional clutch.

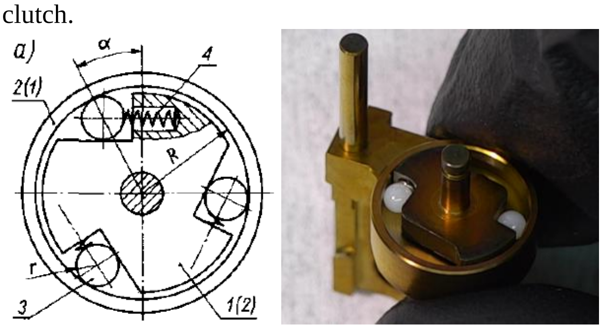

Figure 6. Clutch concept and first model

Available diameter was <12 mm thus all the elements including balls & springs were very tiny. Material choice ensured proper friction coefficients under different conditions.
Clutch concept and first model are presented in Fig. 6. There were several trials to make the clutch working fully and properly but all failed in the end. Main reasons were related to available manufacturing tolerance (including high temperature TiN coating) not high enough in such a tiny and precise mechanism. It was considered possible to make the design working but few more manufacturing rounds and modifications would be required. Effect was not worth the effort. There was a decision to go for a completely new clutch design. It still required many rounds of improvements but manufacturing was significantly easier, coatings on titanium not needed and final effect definitely valuable. Apart from non-functional housing new design utilized only brass flat springs sliding on Vespel SP-1 cams.

Clutch change was already done on BB model but during failed TVAC investigation its properties were reanalysed. Based on tests results mechanics of the clutch was determined as one of the most significant TVAC failure causes. When certain conditions were met (high resistive torque during retraction in vacuum) clutch fell into the unforeseen mode highly restricting the motion. Redesign process was not easy but in the end clutch was free from above mentioned defect.

4.4 Gears

During failed test investigation, particular effort was put on gears. Due to the unit restrictions (mainly size) there were several simplifications applied to the gearbox that could cause lowered performance:

- very loose fitting on the gear shafts (to prevent shrinkage problems),
- very high clearance between gears (to account for other manufacturing tolerances),
- specific choice of materials for gears (spur: Delrin & nickel coated bronze; worm: Delrin + AISI 304 steel),
- no lubrication.

After several rounds of tests it was determined that there is a factor far more important than the suspected material choice of the spur gears – vibration. Under specific conditions one gears-set (gear 2+3; see Fig. 7) could vibrate due to the large clearances. On the other hand, clearance couldn't be removed due to temperature related shrinkage of the elements.
In the end the solution was to apply a small but well controlled additional friction for this gears-set. On both sided of the gears-set small Delrin washers were used (two on each side) supplemented with a soft spring washer on one side. In result gears clearance was maintained but restricted with the use of soft spring reducing vibrations.

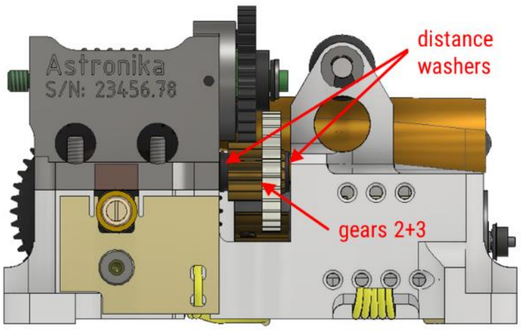

Figure 7. Gear motion improvement

Worm gearing was another point of concern due to materials choice. At first there was a decision to change the steel worm to titanium with nitriding coating as this material was known for its good tribological properties against Delrin under different conditions. It was manufactured, integrated into the EM and tested in ambient, vacuum and cold case environment. In result some reduction in resistive torque was observed but with a side effect of visible wear of the Delrin counterpart.
Second choice was based on leaving the initial material (AISI 304) but applying nitriding. The results were very good this time – lowered friction and no visible wear.

4.5 NEW CHALLENGE

After all tests carried out in course of failed TVAC investigation were finished, modified parts were remanufactured and EQM unit was reintegrated. In order to prove proper performance of the unit final functional testing in ambient were performed and similar test in TVAC planned. During simple test in ambient, without any external factors new problem appeared – motor malfunction resulting in increased power consumption and distorted characteristics.
After several meetings, consultations with motor manufacturer and strip-down inspection of the motor, the malfunction was identified as commutator failure – section shortage due to the commutator wear debris accumulation. It was caused by significant over testing and over stressing of the DC motor during previous (failed) test campaigns, mainly TVAC tests. Very limited lifetime of the DC motor in vacuum is vell known, thus the problem was not that surprising after all. Fortunately, issue appeared before the final qualification of the unit.

It was agreed EQM unit will be reintegrated one more time with the new motor. Other parts or the assembly were considered in good condition to undergo qualification testing.

5 FINAL QUALIFICATION

Third test campaign was carried out 9 months after the first one. The unit was the same in terms of naming (still EQM) and physical properties (size & mass) but was a different device in terms of performance due to all the modifications implemented in course of NC investigation.
This time all test activities were flawless, without any new problems. Unit underwent all planned tests: functional, vibration, shock, bakeout, TVAC & lifetime. No new major problems were observed.

Implementation of all the modifications agreed in course of failed TVAC investigation was very time consuming but resulted in significantly better unit performance. Since during previous campaigns unit was stuck in TVAC, the real resistive torque under worst case conditions was unknown. Finally, during qualification, current measured during deployment and retraction reached only 120 mA & 245 mA respectively. It could be compared to 60 mA & 220 mA in ambient, at the beginning of the project or 200 mA reached during cold case deployment of the second test campaign as well as datasheet specified max. continuous current of 330 mA and stall current of 460 mA.

6 FM MANUFACTURING, INTEGRATION, ACCEPTANCE & DELIVERY

All the modifications applied for EQM were transferred to the FM design and manufacturing documentation. Same for conclusions regarding updates in integration and test procedures.
Since scope of the manufacturing activities was very significant, manufacturing activities started already before qualification ended, taking the risk of remanufacturing in case particular part design is changed after all. End-to-end manufacturing duration was 7 months taking into account some repetitions for parts that didn’t pass quality criteria, while integration and adjustment of the FM units was finalized 2.5 months after manufacturing accomplishment.
Acceptance testing campaign was mostly carried out in Astronika’s test facility, allowing for significant schedule and cost optimization. Thanks to time spent on the EQM testing and improvements, present campaign went very smoothly and without any major problems allowing for achieving prompt acceptance status.
FM antenna units were finally delivered in May 2023 and are currently awaiting testing activities onboard Juventas spacecraft.

7 ADDITIONAL LESSONS LEARNED

There are several more conclusions and lessons learned from the development of the Antennas for Hera-Juventas mission. Some of them are listed below.

7.1 Additional models

In many cases all manufactured models are delivered, thus are available for the design team for a limited time. For new projects there are usually many unknows as well as surprises to be experienced. In course of this project having the additional EM available all the time allowed for many additional testing activities and improvements to be implemented. Its presence was extremely beneficial, and certainly exceeded drawbacks related to additional cost of its manufacturing.

7.2 Exceeding the requirements

It is beneficial to initially design the unit and test against vibration for conditions harder than required. At the early stage of the project launch provider is usually not yet chosen thus vibration levels can be changed in the requirements. It already happened within this project. Having the unit tested for higher levels provided additional margin and allowed to avoid retesting after requirements change.

7.3 Manufacturing & inspections

Scope of the inspections of the manufactured parts may vary. Sometimes only critical dimensions are verified while in some cases certain features are not measured due to the lack of highly specialized instruments or dedicated verification tools, especially for first models.
Other issues come from manufacturing technology – certain design features should be discussed and agreed with the workshop beforehand in order to avoid possible problems during integration. Once technology agreements are done, should not be changed without notification.
Both areas (manufacturing and inspections) are significant contributors to the overall price of the device but tempting cost reductions quite often lead to future problems.

7.4 Test logging

Tests carried out on subsequent models (especially initial ones) are sometimes done "on spot". It is beneficial to record and save measurement data (i.e. power consumption) acquired during those tests (even if not required) to draw proper conclusions when problems are experienced during further development.
It is even more important for official tests (even if not required). Lack of power measurement data acquired during first qualification attempt in TVAC made it impossible to draw correct conclusions at the earliest possible stage.

7.5 Test facilities

It is extremely useful to have in-house (or near & reasonably priced) testing facilities available. In case of problems experienced during Antenna qualification, own, easily available facility allowed for relatively fast (and cheap) investigation of the failure cause. It is hard to imagine how would it look like when only foreign facilities were utilized. Having the own facility from the beginning of the project would most-likely help in avoiding some of the later problems.

8 SUMMARY

In most cases it is expected that EQM model that was designed based on the previous models (BB, EM) and their testing outcome is identical to following FM model(s). In our case initial EQM that underwent first qualification campaign was a completely different device that the one to pass final qualification and resemble FMs. However, the differences didn't manifest themselves in overall size or mass changes but in tiny, mostly internal features and manufacturing details.
Failed test activities experienced during unit qualification were very problematic and stressful at the moment of occurrence, but in turn led to significant improvements of the flight model and a flawless acceptance campaign.

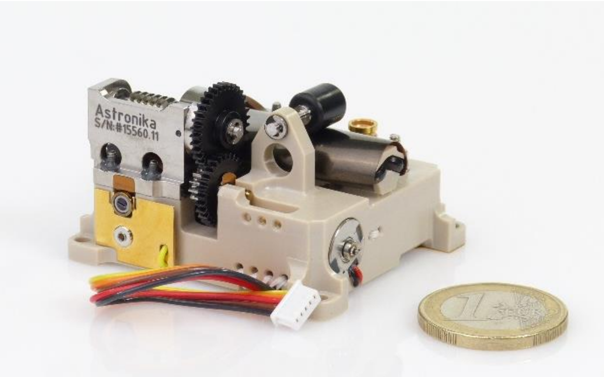

Figure 8. Flight unit

The Antenna FM is presented in Fig. 8 while Fig. 9 shows FM units integrated onto the brackets allowing for pointing after placement inside Juventas spacecraft. Brackets and PCBs presented in the last photo were out the scope of Astronika responsibilities and delivered by Technische Universität Dresden and GomSpace.

Figure 9. Brackets with FMs and interface PCBs