Innovative Escapement-Based Mechanism for Micro-Antenna Boom Deployment

Marta Tokarz*, Jerzy Grygorczuk*, Stanisław Jarzynka* and Henryk Gut**

Abstract

This paper presents the prototype of a tubular boom antenna developed for the Polish BRITE-PL satellite by the Space Research Center of the Polish Academy of Sciences (CBK PAN). What is unique about our work is that we developed an original type of the tubular boom antenna deployment mechanism that can be used widely as a basic solution for compact electrical antennas, booms deploying sensitive instruments, ultra-light planetary manipulators etc. The invented electromagnetic driving unit provides a dual complementary action – it adds extra energy to the driving spring, making the system more reliable, and at the same time it moderates the deployment speed acting as a kind of damper. That distinguishing feature predetermines the mechanism to be applied wherever the dynamic nature of a spring drive introducing dangerous vibrations and inducing severe local stress in the structure needs to be mitigated. Moreover, the paper reveals a product unique in Europe – a miniature beryllium bronze tubular boom free of geometry and strain defects, which is essential for stiffness and fatigue resistance. Both the deployment mechanism and the technology of tubular boom manufacturing are protected by patent rights.

Introduction

In December 2009, The Minister of Science and Higher Education signed a decision to grant funding for the project: 'BRITE: First Polish Scientific Satellite'. Two satellites: BRITE-PL Lem and BRITE-PL Heweliusz are the Polish contribution to the BRITE mission, developed by a consortium of Canadian, Austrian and Polish institutes. In total, six satellites will perform astronomical observations of the brightest stars, two from each partnering country [1].

The BRITE-PL satellites are almost identical (both measure 20 x 20 x 20 cm and weigh about 7 kg), although BRITE-PL Heweliusz contains some additional experiments designed by CBK PAN. Among them there is an experiment called Micro-Antenna Boom (MAB) – a miniature tubular antenna driven by a modified escapement mechanism. This paper describes the MAB background, technical features of the new deployment mechanism used in MAB, conducted test campaign and lessons learned from the project. It also concisely presents the technology developed for manufacturing a miniature Ø6 mm beryllium bronze tubular boom, not available in Europe before.

CBK PAN Heritage

CBK PAN has successfully developed devices based on a tubular boom technology since 1993, gaining therefore an outstanding experience in development of space mechanisms with the use of tubular booms as a lightweight construction material, ideal for antennas and special manipulators where the relation between mass and operational range is crucial. Some of its achievements are shown in Figure 1 and thoroughly described in [2, 3].

* The Space Research Center of the Polish Academy of Sciences, Warsaw, Poland
** GUTRONIC Henryk Gut, Warsaw, Poland

Proceedings of the 42nd Aerospace Mechanisms Symposium, NASA Goddard Space Flight Center, May 14-16, 2014

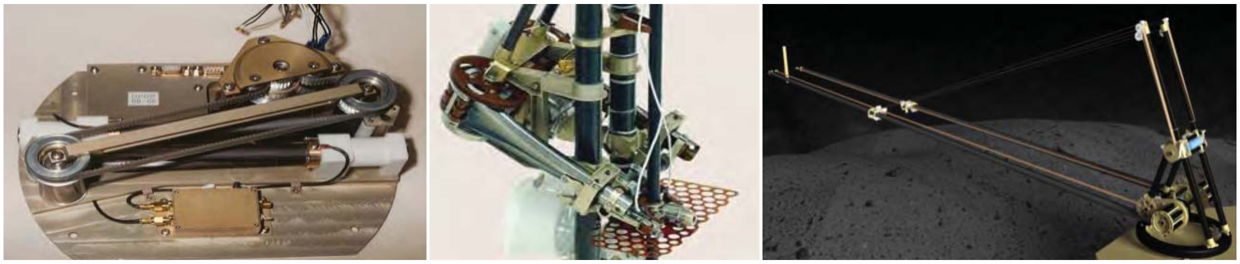

Figure 1. (Left) 2 x 2 m, 40-MHz Rabber antenna, three times successfully launched by Indian rocket, (Middle) MUPUS Deployment Device for Rosetta mission, (Right) laboratory model of Ultra-Light Planetary Manipulator (ULPM) – 3-dof, 3-m operational range, mass of 2.5 kg.

All the above-presented devices used Ø15-mm or Ø25-mm tubular booms of stainless steel strips produced in Ukraine. Recently, the CBK PAN activities were concentrated on application of a miniature Ø6-mm tubular boom made of beryllium bronze, more compact and lighter than the stainless steel ones (it weighs 8 g per 1 m, while the previous booms weigh 50 g and 100 g per 1 m respectively). The original manufacturing method developed by the Polish enterprise GUTRONIC, a longtime CBK PAN partner, will be described later in the paper.

The demand for such an ultra-light and scaled-down solution arose from the Russian RELEC mission. Within the framework of that mission, CBK PAN developed the Radio Frequency Analyser (RFA) – an instrument devoted to measure three electrical components of radio frequency emissions in the frequency range from 50.0 kHz up to 18.0 MHz. One of the main units of RFA was a three dimensional electric antenna set shown in Figure 2.

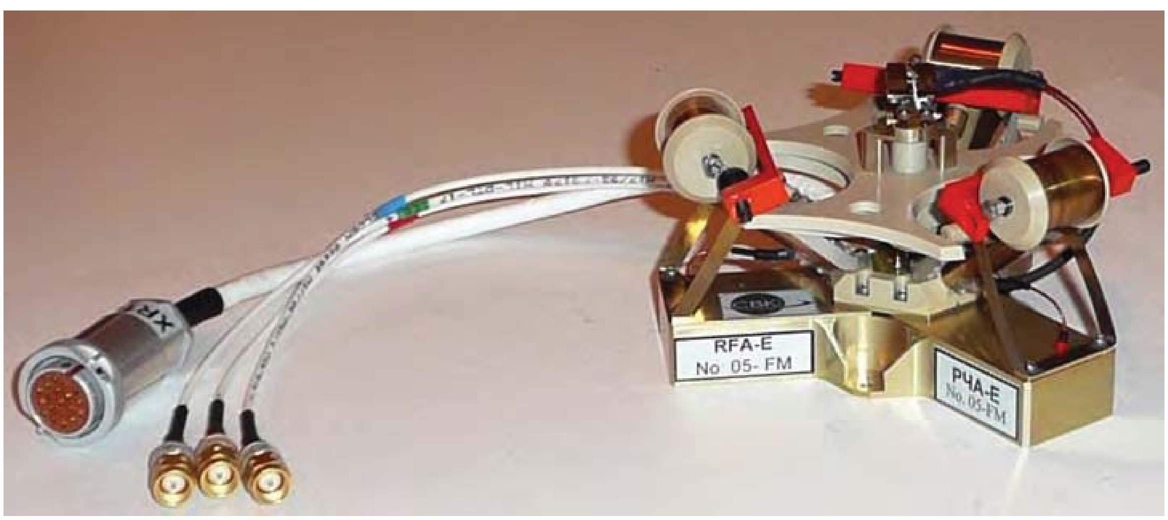

Figure 2. RFA – set of three orthogonal 1 m long antennas for RELEC mission.

As mentioned above, the RFA antenna set is based on miniature Ø6-mm tubular booms stored on a reel. In principle, the tubular boom is to extend itself by spring energy, which is released during transformation of the input flat profile to the original round one. The storage reel is on the front and performs rotational and translational motion. The reel is attached to the tubular boom to never become space debris after deployment. This solution, despite intrinsic advantages like design simplicity and lack of a motor drive, cannot be recommended as the perfect one, for three reasons:

- The deployment process is characterized by high and uncontrolled speed. This can be against certain mission constraints, especially in small satellites threatened with stability loss in case of rapid and dynamic actions.
- As a baseline, a reel is separated from the boom at the end of deployment and becomes space debris. A design allowing keeping the reel at the antenna end, like in RFA, is applied, however, from the electrical point of view, it is an unfavourable solution.
- The tubular boom acts as a driving spring. In case of spring relaxation (e.g. as a result of a long flight to a destination) or an unexpected boom jam, there is no deployment salvage.

MAB Background

Bearing in mind the aforesaid disadvantages of free deployment with the leading reel, CBK PAN undertook a task to create an alternative solution with significant improvements. Roughly at the same time CBK PAN was allowed to place additional payload instruments on board BRITE-PL Heweliusz satellite. In this way, MAB was proposed as a prototype of the tubular boom antenna driven by the modified escapement mechanism. MAB is a technology demonstrator aimed only at showing correctness of the novel deployment mechanism idea without testing the antenna performance itself (i.e., reception characteristics, antenna response and sensitivity). The fully functional prototype developed for the BRITE-type spacecraft is presented in Figure 3.

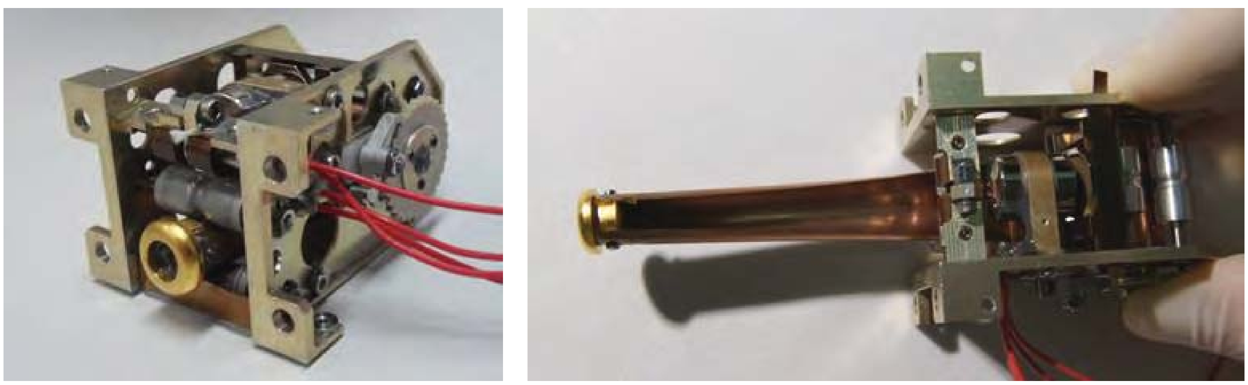

Figure 3. MAB – technology demonstrator for BRITE-PL Heweliusz satellite: (left) stowed, (right) partially deployed configuration.

In general, the tubular boom strip made of beryllium bronze (like the one used in MAB) can be stored on a reel and when deployed, it can form a 1.5-m long cylindrical tube. However, for safety reasons, in case of antenna deployment failure, the tube on BRITE mission is only 120-mm long and deployed inside a cylindrical casing (Figure 4). A closing contact placed at the free end of the safety casing verifies and confirms the antenna deployment.

The device passed qualification tests, described in detail hereinafter, achieving therefore TRL 6, and is ready for launch. BRITE-PL Heweliusz was to be launched in December 2013 on board the Chinese CZ-4B rocket. Unfortunately, due to the failure of the preceding flight of the same rocket type, the launch was postponed. The Chinese investigation is still ongoing and, according to recent update, the satellite will be probably launched in February 2014. Following the performance in a space environment, MAB is expected to gain TRL 7.

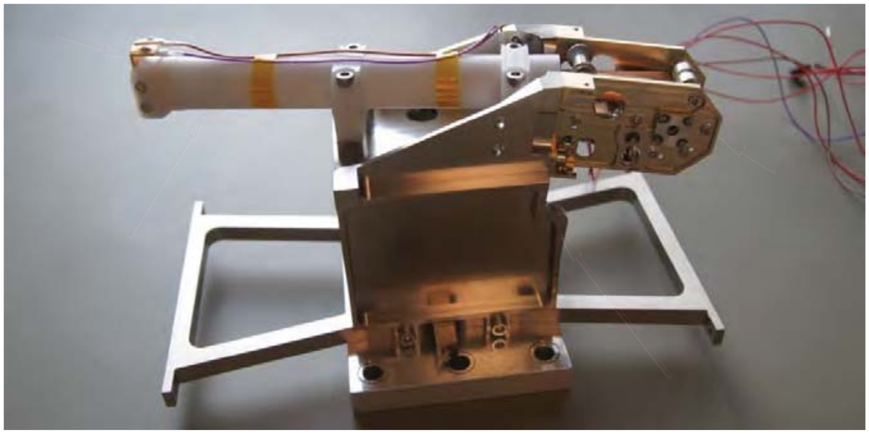

Figure 4. Flight model: 1 – MAB, 2 – safety casing, 3 – closing contact, 4 – bracket.

Technical Features of the New Deployment Mechanism

The idea of the new deployment mechanism applied in MAB originates from an escapement – a device commonly used in mechanical watches and clocks.

Traditional clock escapement

A perfect example to show the principle of operation of a traditional escapement mechanism is a gravity clock (Figure 5). The escapement is driven by force from a suspended weight (1) while a pendulum (2) acts as a timekeeping element. An escape wheel (3) works with a detent (4). The detent releases a tooth of the wheel, which therefore changes from a locked state to a drive one until the opposite detent arm strikes another tooth on the gear, which locks the gear again. Such a mechanism, with meticulously selected pendulum properties, allows clocks to precisely indicate the passage of time. A characteristic clock ticking is nothing but the sound of the gear stopping when the escapement locks.

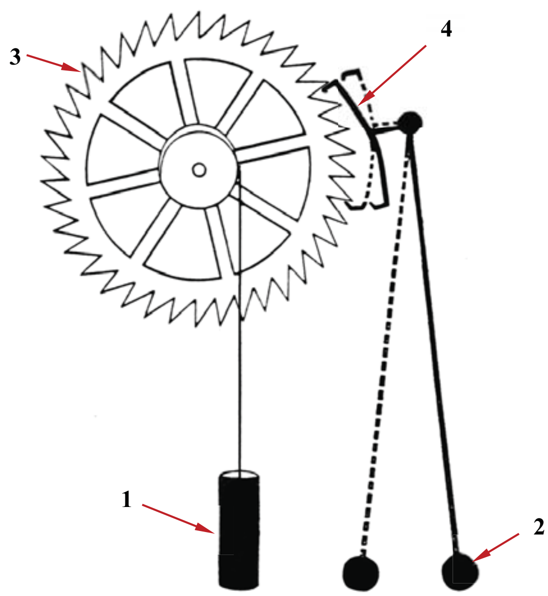

Figure 5. Gravity clock escapement mechanism: 1 – weight, 2 – pendulum, 3 – escape wheel, 4 – detent.

Initially, the traditional Graham escapement (an escapement type used in almost all modern pendulum clocks) was developed in MAB that constituted the antenna solution with the reel joined to the spacecraft and the escape wheel fixed to the reel shaft. The tubular boom, stored on the reel, performed a function of a weight and thus a driving force. A pendulum was replaced with an electromagnet. In that way MAB was provided with a very precise speed regulation dependent only on the electromagnet timing rate. One of the main RFA disadvantages – high and uncontrolled deployment speed – was eliminated. However, the solution was still not free of consequences of the driving spring relaxation or accidental boom jam.

Innovative escapement-based mechanism

The modified escapement mechanism proposed by CBK PAN turned out to be an innovative solution free and clear of any RFA defects. The geometry of the detent and escape wheel underwent a significant change aimed at the breaking properties decrease corresponding with efficiency improvement and higher deployment reliability. The main modification was that the escapement lost its self-locking attribute.

The schematic of MAB deployment mechanism is shown in Figure 6. The tubular boom (1) is rolled up on the reel coupled with the escape wheel (2). The wheel works with the detent (3) fixed to the armature (4) which is driven by the electromagnet (5) and return spring (6). Once released, tubular boom starts free unwinding. The detent, sliding on the escape wheel teeth, is forced to perform swinging motion. The deployment speed is regulated via eigenfrequency of the detent mechanism. No electromagnet action is required.

In case of a much lower than desired deployment speed or unexpected boom jam, the escapement-based mechanism serves as a motion-inducing unit. With the use of electromagnet and return spring the detent swinging movement is forced, the escape wheel begins to rotate and thereby aiding the unreeling action. Moreover, the electromagnet working at high frequencies can act as a generator of vibration, also valuable in providing better unwinding (confirmed by tests).

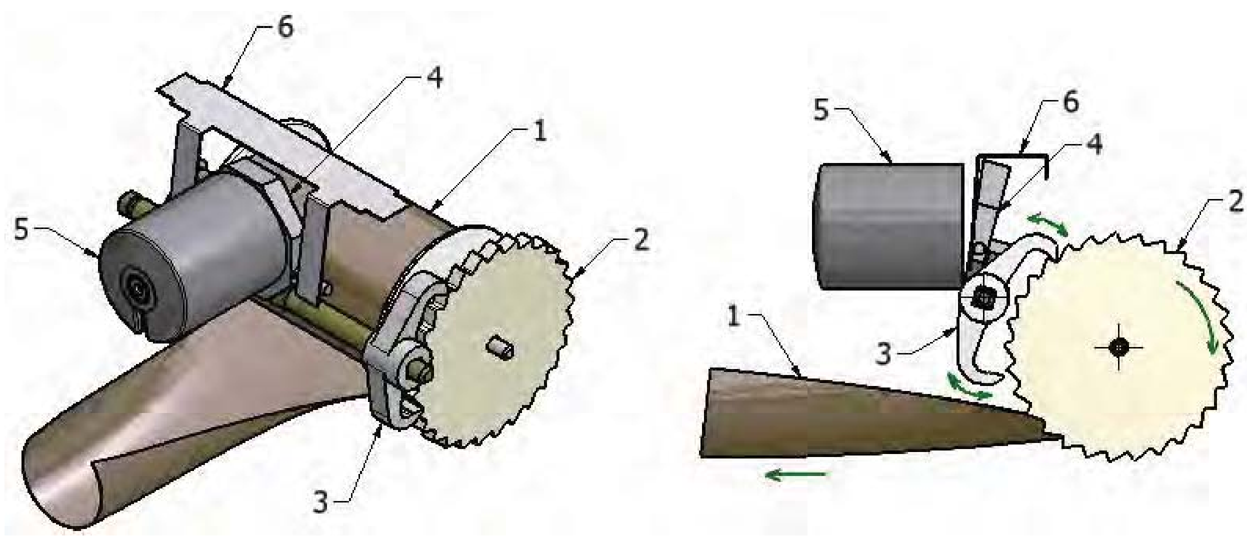

Figure 6. Modified escapement mechanism for MAB deployment: (left) isometric view, (right) side view; 1 – tubular boom stored on the reel, 2 – escape wheel, 3 – detent, 4 – armature, 5 – electromagnet, 6 – return spring

The only inconvenience of the proposed mechanism is the limited speed control. The deployment rate, although satisfactorily mitigated and slowed down, depends closely on the detent mechanism inertia. The inertia properties of the detent subassembly strictly determine the deployment speed. The pictures in Figure 7 present two versions of MAB: initial (with the traditional Graham escapement) and the final one (with the modified escapement). CBK PAN has made an effort to obtain a patent for the invention described in this paper since the special escapement mechanism has a potential to be reused in other devices in the future. The property rights registration process commenced in October 2013 (Polish Patent Office no. P.405646).

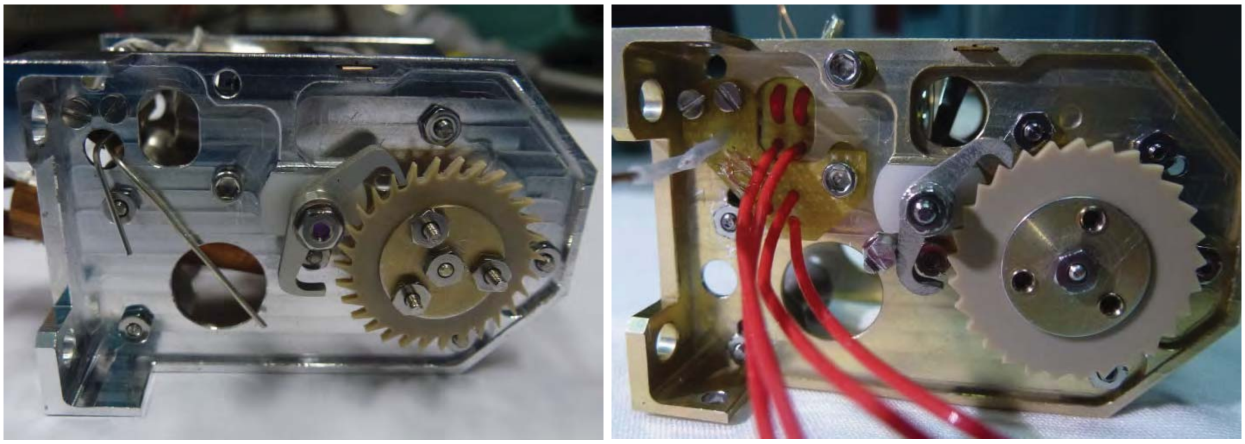

Figure 7. Comparison of MAB versions: (left) with Graham escapement, (right) with modified one.

<u>MAB basic characteristics</u>
MAB is a prototype of the antenna equipped with: the innovative escapement drive acting simultaneously as a speed damper and a new type of a miniature tubular boom – these are paramount distinguishing MAB features. A non-explosive lock & release mechanism is also noteworthy (Figure 8). It is based on the Dyneema string melting system (with the use of a resistor as a heater), which was space proven in several CBK PAN previous instruments [4]. This kind of actuator is very reliable, especially at low temperature applications. The Dyneema string continuous tension is realized by an extra kick-off spring that also supports the release action.

The MAB operation is fully controlled by an external control board. Once initiated, the deployment system receives a deployment command – the resistor is heated up for 10 s, which makes the Dyneema filaments melt. The released tubular boom starts free unwinding at moderated speed until leaning against the closing contact. Then a signal is sent that stops the operation.

In case of the boom jam (and hence the lack of the stop signal after 10 s), the electromagnet serving as an extra motion-inducing unit is powered and thereby the unreeling action takes place. The procedure is stopped either via the stop signal sent from the closing contact or after 120 s. In the latter case (or in any when the unplugging signal is not sent), the deployment would be considered as unsuccessful.

The main MAB characteristic features:

- miniature size and low weight: 30 x 40 x 50 mm, 35 g,
- smooth and regular deployment without rapid and dynamic actions (no risk of satellite stability loss), deployment speed – 10 cm/s,
- usage of no electrical motors resulting in a simpler construction and higher reliability – the electromagnet individually optimized to the specific requirements must be a more reliable and higher-class solution than a common motor, especially the one with a reduction gearbox, where the number of moving parts and frictional joints is significant,
- advantageous length to weight ratio (120-mm-long boom weighs less than 1 g),
- relatively low power consumption: 4 W for 10 s (for lock & release mechanism), 1.25 W for 30 s (for electromagnet, if needed to be used),
- once deployed, the antenna cannot be retracted.

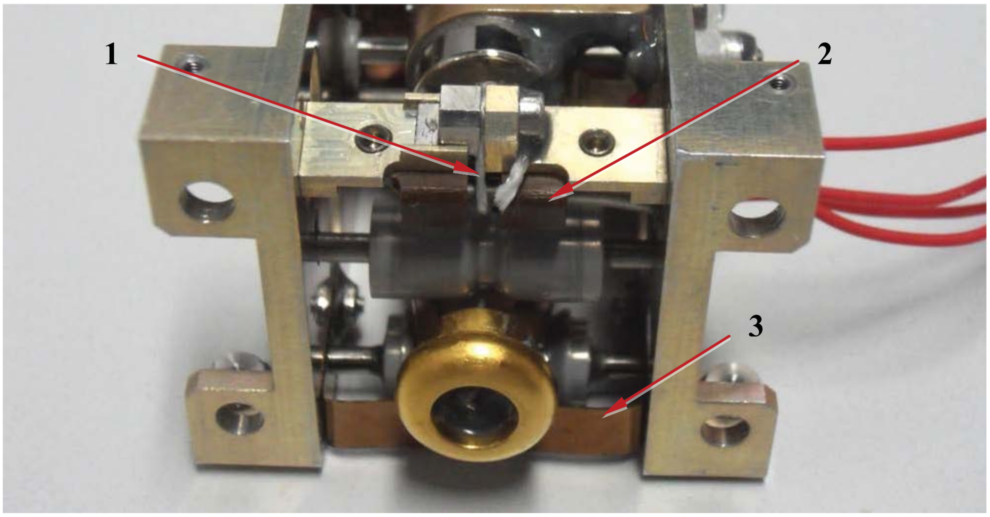

Figure 8. Lock & release mechanism used in MAB: 1 – Dyneema string, 2 – heater, 3 – kick-off spring

Technical Features of the New Manufacturing Technology

Another challenging and innovative issue is the manufacture of the new kind of miniature tubular booms (6 mm in diameter). The manufacturing process requires several factors to be taken into account: low thickness of the boom, its fragility, tendency to torsional/bending deformations, and geometry degradation arising from multitude of manufacturing effects such us heterogeneous material properties, uneven heat treatment, and aging of material. A careful control of dimensional tolerances during production of the boom may be crucial for a successful mission [5]. Therefore, the chosen production method must ensure as precise manufacturing of tubes – free of any material defects – as possible.

Analyses showed that none of the reviewed existing methods of open profile metal tubes manufacturing fits completely to such a specific task as production of thin-walled tubular booms. The innovative method for producing beryllium bronze tubular boom – 0.05-mm thick, 1.5-m long and 6 mm in diameter – has been developed by the Polish enterprise GUTRONIC during the ESA PECS 4000105010/11/NL/KML project. That innovative method, undeniably unique in Europe, has been a subject of a patent since April 2013 (Polish Patent Office no. P.403660). The employed method of tubular booms manufacturing is presented in Figures 9 and 10 in a simplified form. The scheme is shown in Figure 9.

The tape (1) is placed on a susceptible tie (2) travelling in a prismatic base (3). The tie is clamped to the prism by a forming rod (4) being a part of the pressure providing unit. A beryllium tape being formed travels on a tie and is inserted under a forming rod and thereby into the working area (5). The rod rolls on the tape making it bend. The working area is determined by radiuses of the rod cross-section, perpendicular to the prism surface.

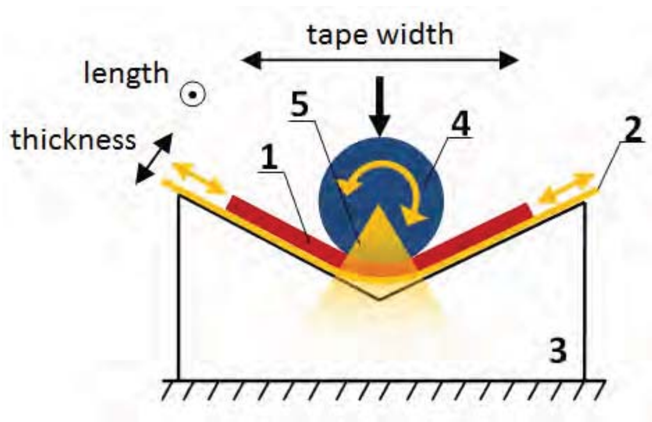

Figure 9. Local bending – process scheme: 1 – tape, 2 – susceptible tie, 3 – prismatic base, 4 – forming rod, 5 – working area

Figure 10. Hardening heater – pictoral view: 1 – aluminium tube, 2 – tubular boom, 3 – heating element, 4 – mandrel rod

An advantage of the proposed solution is a fully controlled, precise shape of the manufactured tubular boom, homogeneity of the material deformation, no folding either bending of beryllium tape during production process, economical construction and easy control. A disadvantage is dependence of the manufactured tubular boom length on the device size (the longer the tape, the longer the device) and low production rate. At the moment the maximum length of the manufactured tape is 1.5 m.

A separate issue worth paying attention to is the hardening of the final product – a process necessary for obtaining the required stiffness and elastic properties of the final tubular boom. The proposed method (Figure 10) is the one of hardening with a thick-wall aluminium tube (1), inside of which there is a segment of the tubular boom (2). The aluminium tube is reeled with a heating element (3) that heats it evenly. The tubular boom is loaded over a mandrel rod (4) and heated to the hardening temperature of 315°C (according to the heat treatment procedure provided by the BERYLCO 25 distributor).

Numerous optimization tests were conducted using 25-cm prototypes of the bender and hardening heater that allowed some parameters to be determined, i.e. the tape pulling strength, the tape travel time, the tape leading system, the pressure force, the forming rod diameter, the mandrel rod diameter, etc. Based on the results of a foregoing analysis, the target device, including two modules – the bender and hardening heater – was developed and the first series of 1.5-m long tubular booms was successfully manufactured (Figure 11).

In space applications the tubular boom is to be stored on a reel. When deployed it is to form a cylindrical tube. In order to confirm such a possible use of the manufactured tubular booms and to characterize them as well, the final product underwent a series of relevant validation tests carried out by GUTRONIC in close cooperation with CBK PAN. The tests-proved the mechanical and resilient properties of the product met all requirements.

Figure 11. First series of five hardened 1.5 m long tubular booms

MAB functional tests

MAB underwent a series of acceptance and qualification tests, all conducted at CBK PAN. Table 1 shows the sequence of tests performed on the MAB flight model and their results.

Table 1. MAB Test Campaign

No.	Test	Result	Remarks
1.	Functional test at room temperature (~20°C)	passed	
2.	T-shock test (25 cycles of rapidly changing temperature in the range of +60°C ÷ -25°C)	passed	
3.	Functional test at room temperature (~20°C)	passed	
4.	Vibration test	passed	
5.	Functional test in Thermal-Vacuum Chamber (-6°C)	failed	
6.	Functional test in Climate Chamber (-20°C)	–	Investigation of failure cause
7.	Functional test at room temperature (~20°C)	passed	
8.	Vibration test	passed	
9.	Functional test in Climate Chamber (-10°C)	Passed	
10.	Functional test in Thermal-Vacuum Chamber (-6°C)	Passed	Approved for flight

As indicated in Table 1, the first functional test in the Thermal-Vacuum Chamber at -6°C ended up in a failure. A number of failure scenarios were considered in order to explain this result, however two causes were most likely:

- thermal shrinkage causing mechanical jam of the rotating components,
- failure of the Dyneema string melting – the force with which the string leaned against the resistor could be too low, causing poor adhesion and resulting in ineffective temperature dissipation.

As a part of a thorough investigation test 6 was carried out. It showed that thermal shrinkage was the cause of the detent deadlock and consequently the mechanism malfunction. At a low temperature (below 0°C) the detent axle could not rotate despite the proper electromagnet drive action. Remedial measures were taken: MAB was disassembled and the hole in the bearing bush was enlarged. The normal running fit became the easy running one. During MAB disassembly, an extra tension spring was added to increase the lock & release mechanism reliability (showed in Figure 8). The main spring task was to generate an additional tension force for the Dyneema fiber to better wrap it over the heater.

Since the problem was successfully detected and eliminated, the set of tests was repeated. The device passed all subsequent tests, achieving TRL 6. Figure 12 shows MAB during functional and vibration tests.

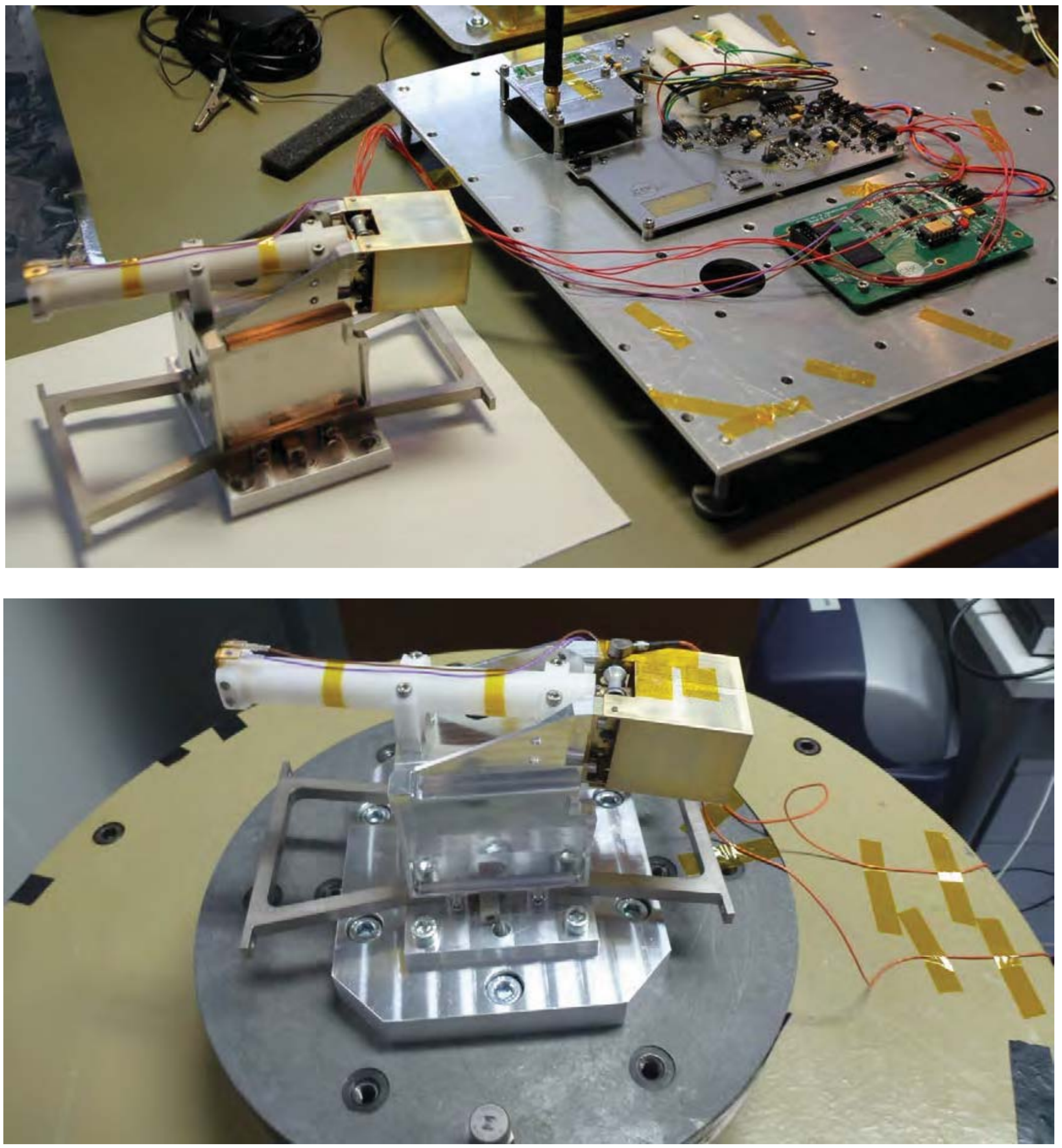

Figure 12. MAB during: (top) functional test at room temperature, (bottom) vibration test.

Conclusions & Lessons Learned

The prototype of the miniature antenna called MAB, driven by the modified escapement mechanism, has been successfully developed together with the innovative technology of tubular boom manufacturing. The mechanism has been qualified through the dedicated test campaign, thereby proving correctness of the novel deployment mechanism idea – the idea assuming a dual complementary action of the driving system which simultaneously performs a role of a drive unit and a kind of moderator.

As with any mechanisms development, some important lessons were learned:

- Dealing with the new type of tubular boom showed how delicate and troublesome the tape is. It was very easy to damage it at every stage of assembly and testing. Once the project team had to cope with a tape crack (Figure 13) as a result of numerous winding and unwinding actions. It was initialized by rugged edges caused by careless hole drilling. Working on MAB, the team got to know the mechanical properties of the tubular boom.

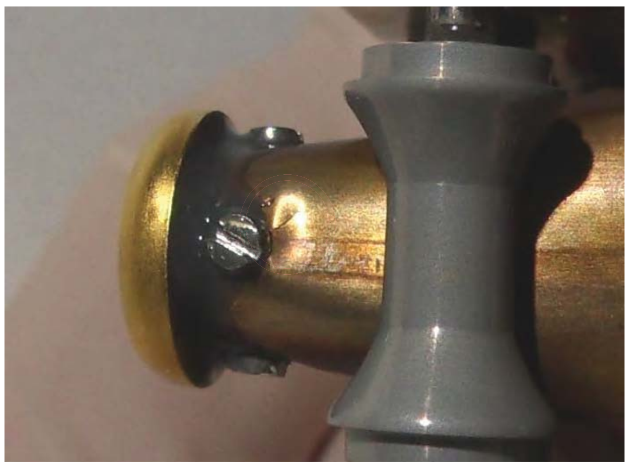

Figure 13. Tubular boom fatigue (marked in red)

- Thermal difficulties – in the case of such a miniature mechanism thermal phenomena is of a key importance. During the first series of tests MAB failed the functional test at low temperature due to the detent deadlock. It turned out that the normal running fit was too restrictive.
- Assembly and manufacturing difficulties – the mechanism assembly and miniature components manufacturing turned out to be very challenging. A pinpoint accuracy was required.

Furthermore, GUTRONIC company, for many years closely cooperating with CBK PAN, gained a complete and unique knowledge of manufacturing tubular booms of BERYLCO 25. It got to know advantages and disadvantages of the developed method as well as the comprehensive characteristics of the final product. Now GUTRONIC specializes in manufacturing tubular booms for space applications and is able to improve its method, at the same time enriching the range of products with various tubular booms lengths, diameters and materials.

<u>Possible application</u>

The foreseen applications of the MAB-type deployment mechanism equipped with the miniature tubular boom or another spring drive are as follows:

- compact electrical antennas,
- ultra-light planetary manipulators (the torsional stiffness of structure can be strengthened by combining booms into a pair),
- dual action units used wherever the dynamic nature of spring drive introduces dangerous vibrations and induces severe local stress in the structure that need to be mitigated and

smoothed (i.e. in hinges with a latching system commonly used to deploy booms with small sensors or measuring instruments, in solar panels systems, etc.),

- active dampers/actuators.

As it was shown in this paper, MAB is a properly functioning and reliable instrument. Its miniature character predetermines the device to be applied particularly on board nano- and micro-satellites.

Future development

The already studied solution seems to be a perfect starting point for future space projects. The subject aroused ESA's interest. Under Polish Industry Incentive Scheme, the agreement between ESA and ASTRONIKA (spin-off company founded by a CBK PAN group of engineers), GUTRONIC and CBK PAN was signed. Within the framework of the contract, a new generation of the electrical antenna will arise. The device will be significantly improved in comparison to MAB – it will be a fully functional, 2.5-m long antenna designed on the basis of the new type Ø10-mm tubular booms. The existing one (Ø6 mm) does not cover applications on small and medium satellites, representing a large number of present-day projects. Therefore, taking into account a more common use of tubular booms, production of Ø10-mm profiles of thicker beryllium bronze strips seems to be favorable.

References

1. Matthews S. E.: "The Seven Most Incredible Telescopes In Existence. The Biggest, Smallest and Most Robotic Stargazing Tools." *Popular Science*, 12 (2013).
2. Grygorczuk, J., Banaszkiewicz, M., Seweryn, K., Spohn, T.: "MUPUS Insertion Device for the Rosetta Mission". *Journal of Telecommunications and Information Technology*, 1 (2007), 50-53.
3. Grygorczuk, J. et al.: "Prototype of Ultra-Light Planetary Manipulator – Design, Test and Simulations". *Proceedings of the 12th Symposium on Advanced Space Technologies in Robotics and Automation (ASTRA 2013),* Noordwijk, the Netherlands.
4. Grygorczuk, J. et al.: "Advanced Mechanisms and Tribological Tests of the Hammering Sampling Device CHOMIK". *Proceedings of the 14th European Space Mechanisms and Tribology Symposium (ESMATS 2011),* Constance, Germany.
5. Collective work: "Tubular spacecraft booms (extendible, reel stored)". *NASA space vehicle design criteria (guidance and control)*, February 1971