ESA EXECUTIVE SUMMARY		
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ABSTRACT:

The project entitled "System analysis of deployable components for micro landers in low gravity environment" is conducted within the framework of the ESA contract no. 4000117150/16/NL/HK/hh. Its goal is to perform an analysis and trade-off between the various design options for antennas and solar array deployment mechanisms (including a comparison between the fixed and deployable configurations) of the MASCOT-2 lander in the micro-gravity environment of Didymoon. Moreover, a preliminary design of the concept selected based on the Trade-off Report will be performed, and the preparation of the MASCOT-2 deployable components development plan also constitutes a significant part of the project.

Work under the project was divided as follows: Space Research Centre of the Polish Academy of Sciences (CBK PAN) was responsible for the preparation of development concepts for the solar array deployment mechanism, whereas Astronika Sp. z o. o. handled the MASCOT-2 antennas, including both the lander's main (LFR) and secondary antennas. In addition, DLR, Technische Universität Dresden and IPAG provided specific requirements concerning the deployment mechanisms, including indispensable interfaces for both deployable components, i.e. solar array and antennas.

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MASCOT-2

Executive Summary

Date	**Place**
20.02.2017	Warszawa

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1 Abbreviations used in this report

AIM	Asteroid Impact Mission
AIV	Assembly, Integration and Verification
Astronika	Astronika Sp. z o. o.
CBK PAN	Space Research Centre Polish Academy of Sciences
CDR	Conceptual Design Review
EQM	Engineering Qualification Model
FM	Flight Model
FS	Flight Spare Model
HDRM	Hold Down and Release Mechanism
IPAG	Institute de Planétologie et d'Astrophysique de Grenoble
ITAR	International Traffics in Arms Regulation
L&RM	Lock & Release Mechanism
LFR	Low Frequency Radar
LLI	Long Lead Item
MA	MASCOT-2 Main Antennas
MAB	Micro- Antenna Boom
MASCOT	Mobile Asteroid Surface Scout
OM	Oscillatory motor
SA	MASCOT-2 Secondary Antennas
SADM	Solar Array Deployment Mechanism
SOW	Statement of Work, Appendix 1 to ESA Contract No. 4000117150/16/NL/HK/hh
STM	Structural Thermal Model
TUD	Technische Universität Dresden
TRL	Technology Readiness Level
TV AC	Thermal Vacuum

2 About the project

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Work under the project was divided as follows: Space Research Centre of the Polish Academy of Sciences (CBK PAN) was responsible for the preparation of development concepts for the solar array deployment mechanism, whereas Astronika Sp. z o. o. handled the MASCOT-2 antennas, including both the lander's main (LFR) and secondary antennas. In addition, DLR, Technische Universität Dresden and IPAG provided specific requirements concerning the deployment mechanisms, including indispensable interfaces for both deployable components, i.e. solar array and antennas.

The main purpose of the document is to describe the various deployable components concepts developed during this project: the solar array deployment mechanism, the MASCOT-2's main antennas, the MASCOT-2's secondary antennas. Each of the abovementioned chapters discusses two solutions for each of the deployment components constituting the subject of the Contract. For the solar array deployment mechanism, the baseline solution adopted for the purpose of this development plan is an Oscillatory Motor, whereas the second (backup) solution is a Stepper Motor. Regarding MASCOT-2 Main Antennas, the baseline solution lies in the application of the Oscillatory Motor (the so-called "Solution with Oscillatory Motor"). The backup solution proposed for MASCOT-2 Main Antennas is referred to as the "Solution without Drive Unit". As far as MASCOT-2 Secondary Antennas are concerned, the baseline solution is called a "deployable solution", whereas the backup solution involves a spring fixation ("non-deployable solution").

3 Solar panels

A trade-off which analysed four different solutions was performed and consequently, a solution utilizing a drive with torsional springs and an active damper which uses an oscillatory motor invented in Astronika was chosen for development. This solution comprises both the features of a passive damper and an active actuator. The proposed lock is a non-shock device and is based on the melting of the Dyneema string method, which has extensive heritage. The selected design provides a highly-recommended feature – redundancy in the key components, which undoubtedly has a positive impact on the reliability of the complex subsystem. The redundant elements are the driving torsional springs and heaters in the lock. Additionally, the active damper can also operate in a redundant mode in case of electronics failure. The entire deployment mechanism's mass is estimated to be 260 grams. Operation can be arranged for any predicted deployment angular velocity taken from the range of 2deg/s up to 10deg/s.

3.1 Hinges and spring drive

The solar panel (4) is attached to the main MASCOT structure by three hinges (1) which allow the panel to rotate by 180°. Tension springs (2) with an Active damper (3) were selected as hinge drive (Figure 3.1).

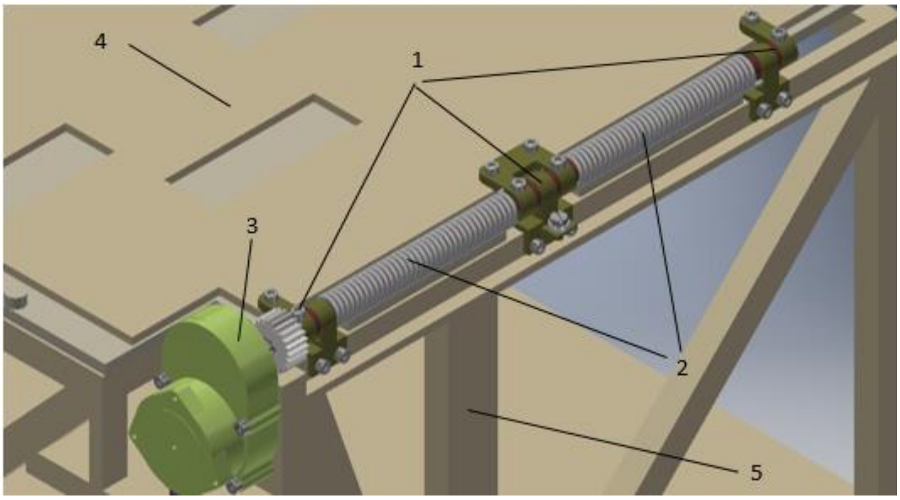

Figure 3-1 Overview of the hinge design

The application of sliding bearings in the hinges allow for a low mass and a small mechanical envelope of the hinge. The shaft conjugates the separated hinges and transfers the torque from the drive springs to the panel attachment points.

The drive springs in the hinge must rotate the panel and retain it in the deployed configuration. The type of springs was determined by the mass and mechanical envelope constrains. The main reason for the selection of tension springs was the axial shape which enabled the design of a complex and small deployment mechanism. The tension springs are attached to the passive and active parts of the hinge. Two springs provide the required torque and increase the reliability of the drive.

To provide an accurate and repeatable deployed position, the central hinge is equipped with an adjusted bumper. The bumper allows to regulate the opening angle and adjust it in the required position by changing the washer's thickness. The latch is not expected to be necessary.

The hinge mechanism requires a redesign of the MASCOT structure. The hinge's mechanical envelope is almost fully covered by the general MASCOT envelope (Figure 3-2). The proposed configuration is preliminary; if required, the mounting points can be easily rearranged.

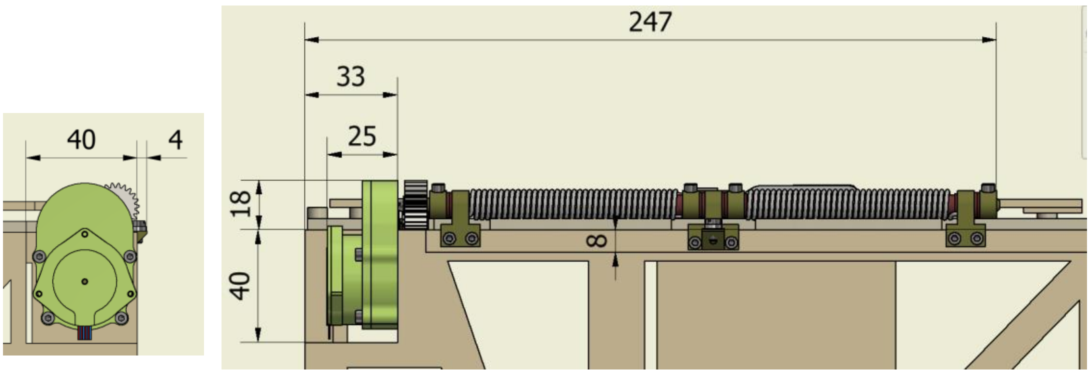

Figure 3-2 Mechanical envelope

When it comes to MASCOT2 design, placement of the damper needs to be coordinated with MASCOT2 structure requirements. In MASCOT, the structure had a launch preload pull of 2.5 kN at the bottom center point that transferred to 4 standoffs on the bottom corners and needed also the upper framework parts for stiffness. Final placement can be in or out of the 'box', left or right.

Although dust has so far not become a critical influence on mechanisms on the Moon or Mars, the low gravity environment may lead to previously unobserved dust behaviour on asteroids. For example, ballistic capture of dust grains entering a mechanism cavity may over time lead to increasing dust accumulation and clogging of the moving parts inside. (E.g. the Hayabusa probes use ballistic capture for their sample pick-up mechanism.) Also, a moving lander could shove surface dust into any opening that plows into a dusty surface during touchdown and bouncing. The dust may then stick inside in the same way as a straw pushed into a bag of flour retains some of it inside when it is pulled out again. We therefore envisage the use of the anyway present thermal insulation foils (MLI, SLI) to cover the mechanisms against intruding dust by creating a ballistic dust barrier or labyrinth seal around the moving parts. This type of protection is not as tight as a purpose-built seal but it costs no mass by dual-use of anyway required thermal protection and structural elements and it can be friction-free. Also, the number of motion events for MASCOT2 which move dust to the spacecraft or the moving parts is very limited when compared to e.g. a geological tool on the Moon or Mars. A few tens of impacts, bounces and self-rightings are expected, and they are distributed over all the edges, corners and faces of MASCOT2 due to the stochastic bounicing motion. Therefore, dust is not an overriding concern although it certainly needs to be taken into account. The oscillatory motor (probably the most sensitive item) will be extra protected by sealing the output shaft.

The deployment energy constrain necessitates the use of a damper. The Active damper is connected to the rotating shaft through a spur gear. The spur gear enables shifting of the damper and its placement in the MASCOT structure without a significant increase of the envelope.

The proposed hinge is a complex assembly which requires interfaces with the main MASCOT structure and the solar panel. In the proposed design, the Active Damper is placed on the left side of the hinge but it can be located on the right side without impact on its function.

3.2 Lock

In the case of the AIM-MASCOT 2 project, the proposed configuration consists of outer support posts on which the cover rests. The cover is restrained from opening by a locking element that mechanically holds the pin attached to the cover. The HDRM made by Astronika was chosen. The proposed lock uses melting strings as a main principle of operation. Proposed 200N HDRM with the complementing latching mechanism can safely secure the AIM cover. As the AIM cover mass target would be around 0,3kg therefore the maximum force put on both the lock and the cover hinge would be less than 120 N. The force than has to be divided between the hinge and the lock resulting in the maximum force exerted on the lock being less than 60 N. The lock's holding capability of 200N gives a solid margin of safety. Mounted configuration on the AIM MASCOT model is presented in the Figure 3.

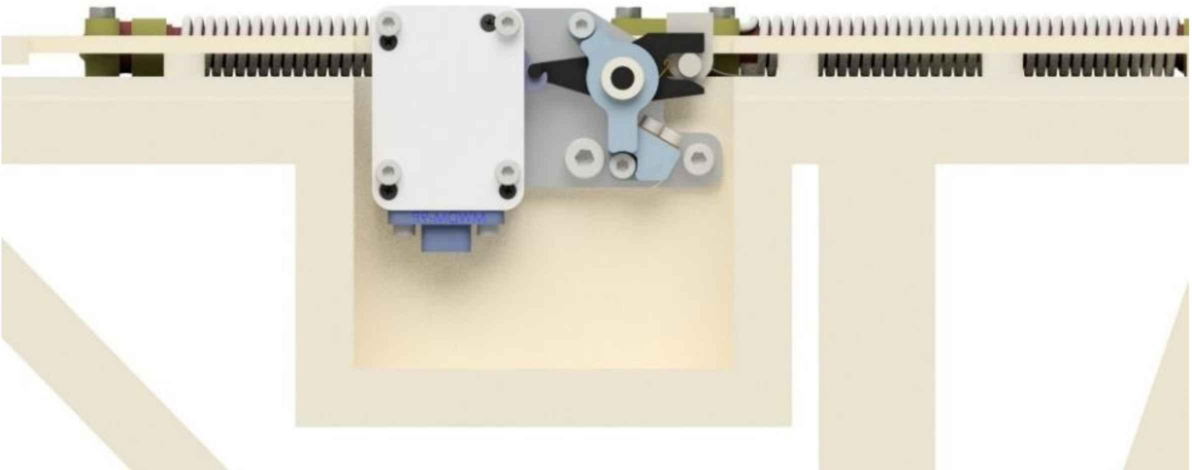

Figure 3-3 HDRM with latching mechanism as mounted on the AIM MASCOT model

Proposed HDRA with the latching mechanism provides the enhanced security due to the usage of the double locking mechanism. The principle of its operation is as follows: The HDRM receives the electrical signal to release. When lock is released the rotary arm turns counter-clockwise allowing the cover holder to go upwards. The lock itself initially prevents the arm from rotating. The mechanism is presented in Figure 3-4 in locked and release phases.

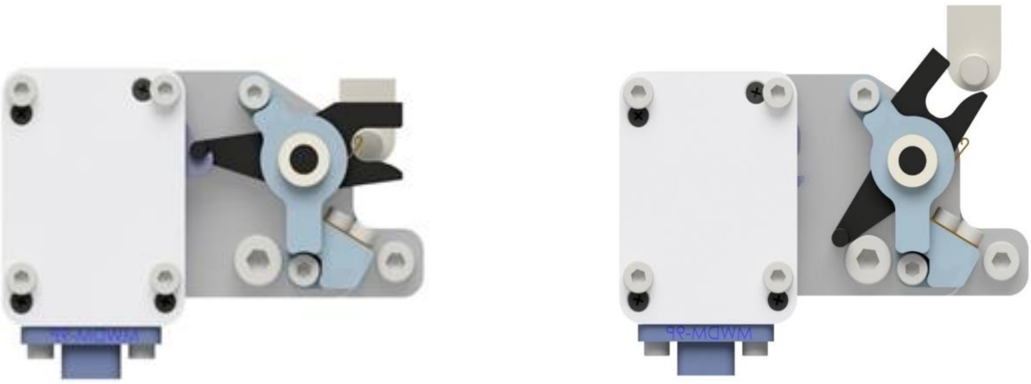

Figure 3–4 HDRM with arm locking mechanism – locked (left) and released (right)

3.3 Active damper (gear + oscillatory motor)

The preliminary design of the active damper which is placed in the housing is shown in **Błąd! Nie można odnaleźć źródła odwołania.**Figure 3-5. The housing is split into two parts: a bottom nd upper one; the gear occupies the bottom housing while the oscillatory motor (OM) occupies the upper one.

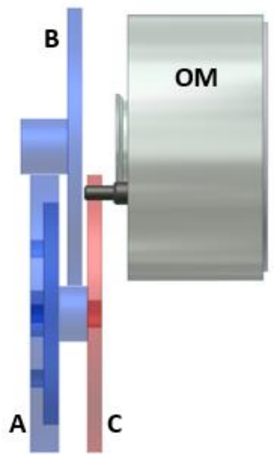

Figure 3-5 Oscillatory motor drive (OM): gear and the motor; **A** – outer spur wheel with interfaces to the hinge axis, **B** – mid toothed spur wheel with pinion, **C** – pinion with escapement, special toothed wheel, **OM** – oscillatory motor with four coils and pins engaged with the escapement wheel.

The oscillatory motor (OM) consists of two main subassemblies: a stator and a rotor (presented in Figure 3-6). The stator includes four small reluctant electromagnets (no permanent magnets) which, in the non-operating mode, do not produce magnetic flux. An electrical connection to the OM is provided by eight wires (two for each coil). The rotor is joint with the stator by a special ball bearing.

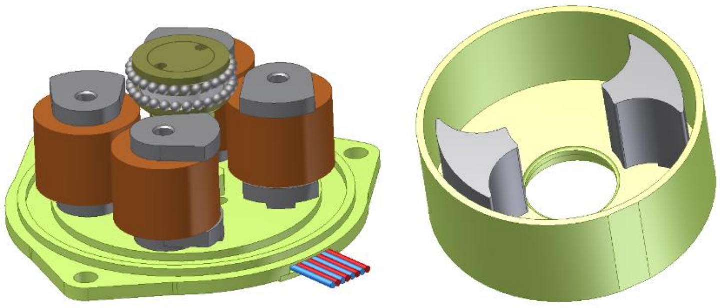

Figure 3-6 Left: Four electromagnets are fixed to the stator, in the upper central part is two row special angular bearing. Right: Rotor cup with two electromagnet's armatures – view from inside.

Drawing with basic dimensions of the active damper is shown in Figure 3-7.

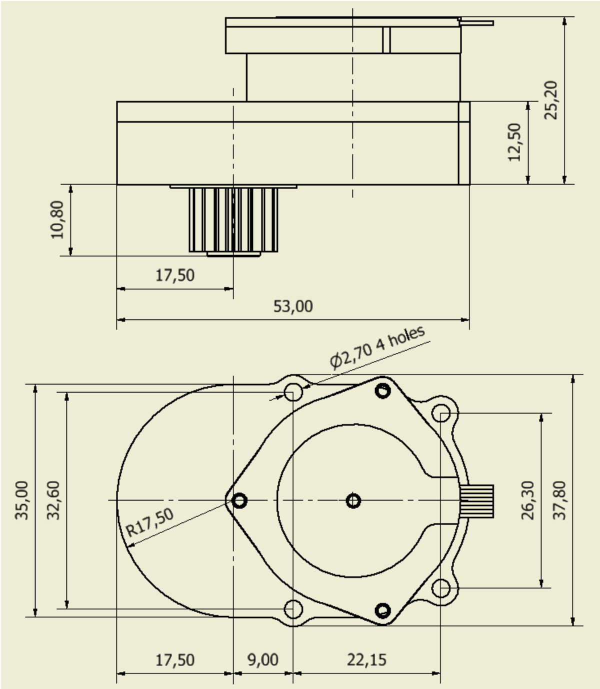

Figure 3-7 Dimensions in millimeters of the active damper

3.4 Analysis and simulations of dynamics

The purpose of the simulation is to determine the actual minimal damping constant that should be provided by the Oscillatory Motor for its further design. Simulations were executed for different hinge damping constants shown in Figure 3-8.

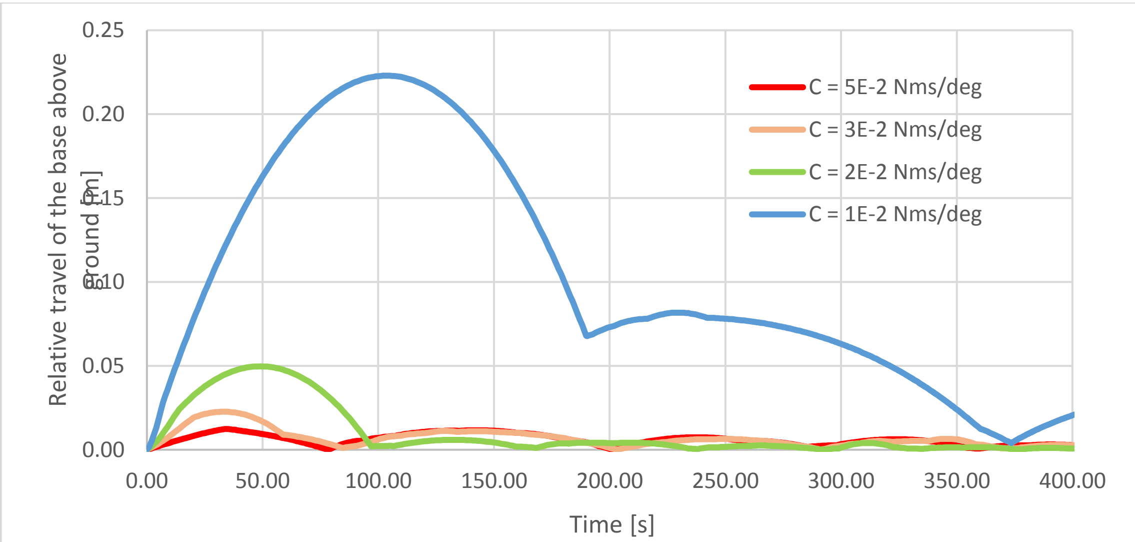

Figure 3-8, Relative travel of the base above ground [m] for various hinge damping constants

A scenario with MASCOT-2 deploying the Solar Panel form an upside-down orientation was also checked for the purpose of this analysis, to verify what damping constant should be implemented for such a case. It was shown that the above selected C = 2e-2 Nms/deg is not necessarily enough – MASCOT-2 would be able to fly away at significant distances. The safe deployment, allowing a relatively static behaviour of the system, should have to be at 3 orders of magnitude higher, c.a. C = 2e1 [Nms/deg]. The deployment time in that case would be above 3 [h]. The deployment sequence is shown in Figure 3-9.

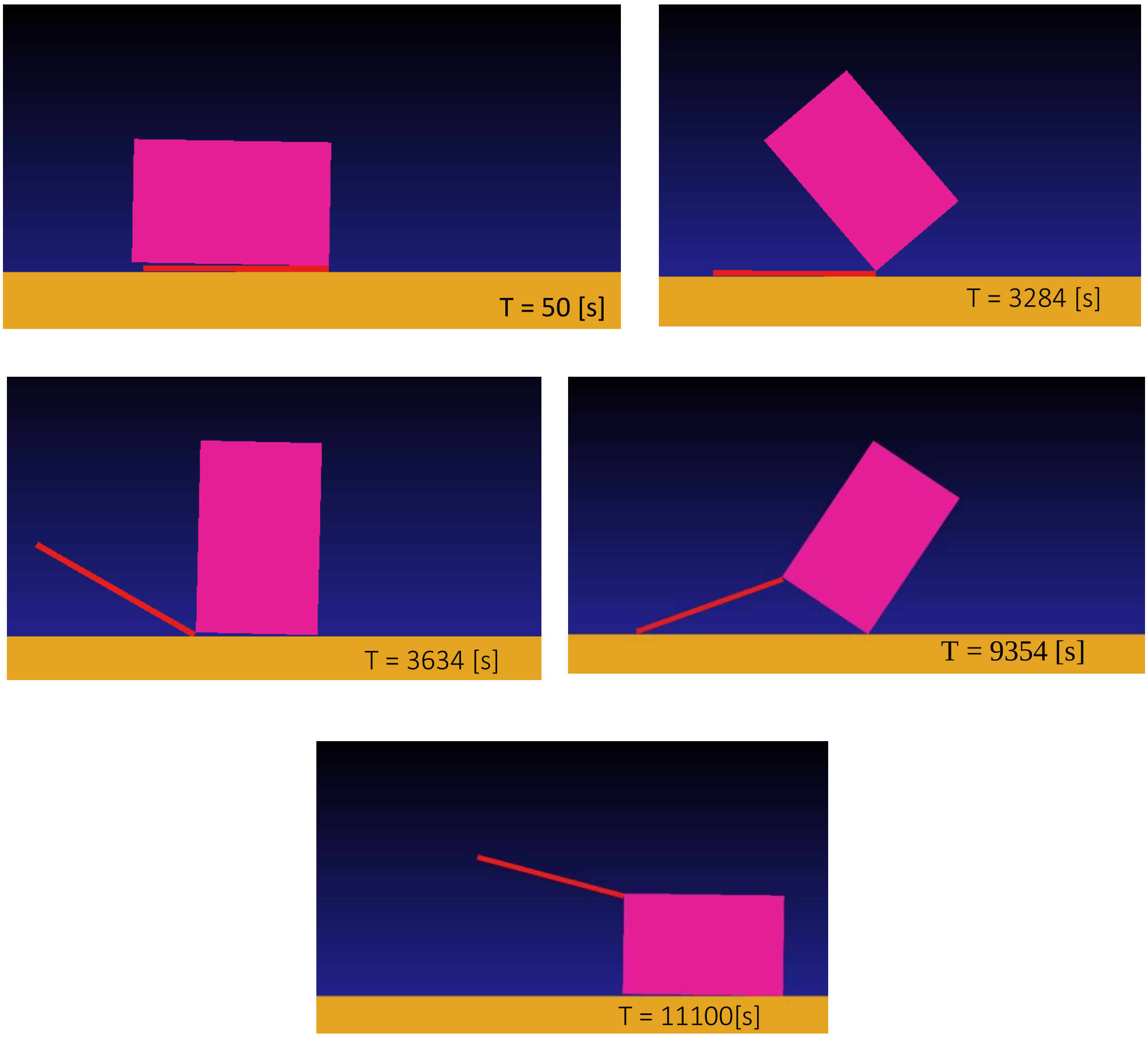

Figure 3-9, Deployment sequence from upside down configuration and hinge damping constant C = 2e1 [Nms/deg]

Conclusions from analysis:

- When only the nominal deployment is considered (MASCOT-2 sits with its base on the surface), the expected critical damping of the Oscillatory Motor (with a gear) should be greater than C = 2e-2 [Nms/deg]. With this damping constant MASCOT-2 should not elevate more than 5cm above the surface (assuming flat surface).
- The actual deployment will take 13.5 seconds or longer.
- In case of failure scenarios (i.e. upside down configuration), the actual damping should be 3 orders of magnitude greater than the selected one. Therefore, an actual confirmation of the proposed orientation of the MASCOT should be considered.
- The maximum expected kinetic energy of the Solar Panel is 0,8 mJ (assuming a velocity of c.a. 10deg/s). The actual shock determination depends on the Solar Panel's flexibility, and the potential decision if flexibility should be added to the panel limit stopper.

4 Deployment mechanism of MASCOT Lander Main Antennas

Among the main research payload instruments of the Asteroid Impact Mission (AIM) there is the bistatic Low-Frequency Radar (LFR) which consists of two subsystems: one on the main S/C and one on the MASCOT-2 Lander. Its primary goal is to obtain data on the asteroid internal structure.

The MASCOT-2 Lander LFR subsystem includes two Main Antennas (MA) located at the front of the Lander and two Secondary Antennas (SA) at the back (see Figure 4-1).

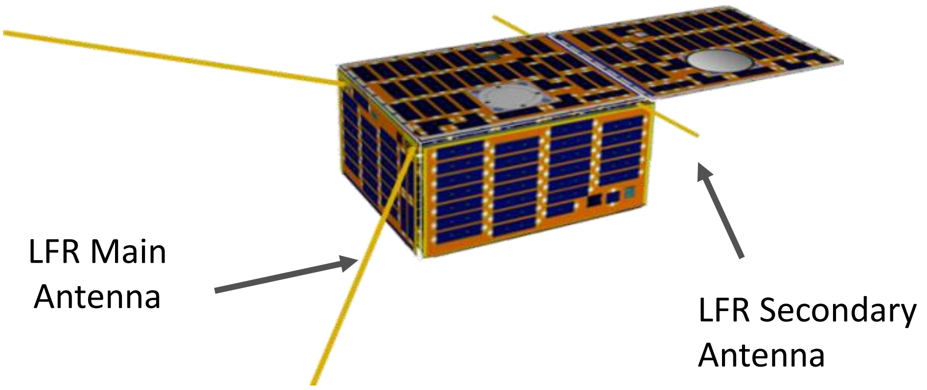

Figure 4-1 MASCOT-2 Lander LFR subsystem [**Błąd! Nie można odnaleźć źródła odwołania.**]

The Main Antennas need to be deployed after MASCOT-2 landing and relocation operations on Didymoon and they will be responsible for radar tomography.

According to the requirements the MA needs to be very compact to fit into a small space under solar panel cover and very lightweight not to exceed the given mass limit. To be compliant with those restrictions Astronika decided to propose the lightest possible design based on the **tubular boom** technology. The MA will make use of ø6mm beryllium bronze tubular boom made by Gutronic. There is no other type of tubular booms suitable enough for the MA System. Figure 4-2 shows the tubular boom rolled up on the storage reel and ended in the tip.

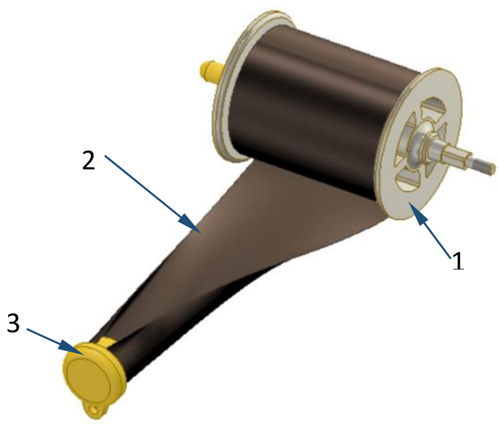

Figure 4-2 Main Antenna tubular boom:

1 – Storage reel; 2 – Tubular boom; 3 – Tip.

The tubular boom is guided in a proven and effective manner for years applied by team in mechanisms of that kind. Proposed guidance system (Figure 4-3) consists of the set of surrounding rollers and the specially designed guide for tubular boom leading end. Adjustable tilt angle for antenna is possible.

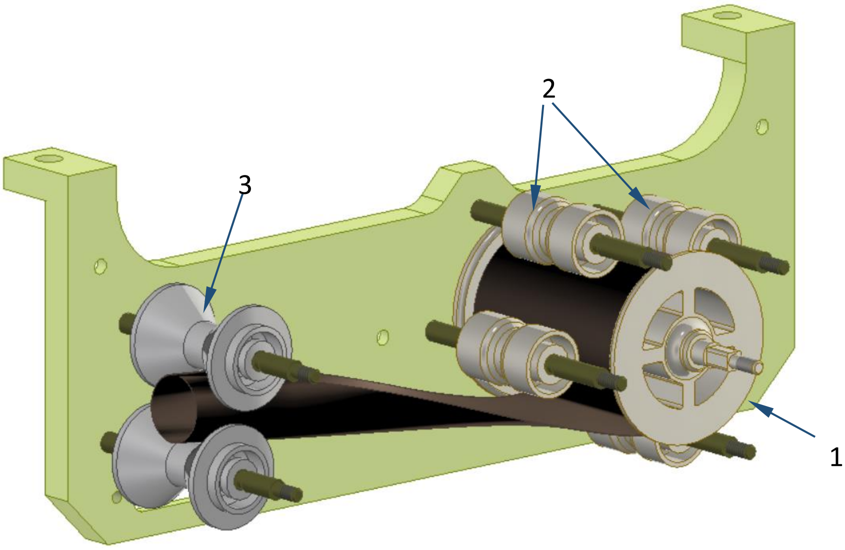

Figure 4-3 Main Antenna tubular boom guidance system:

1 – Storage reel

2 – Surrounding rollers

3 – Guide rollers for tubular boom leading end.

The tubular boom technology perfectly fits into specificity of deployable single-shot antennas, both monopoles and dipoles. The functional principle is based on a tubular boom mechanism. The tubular boom strip is stored on a reel in stowed configuration. When deployed it forms cylindrical tube of given length. The unquestionable advantage of this technology is the most advantageous antenna weigh to length ratio, convenient storage in small volume as well as design simplicity. In general the deployment is based on energy accumulated in winded tape and its self-release during transformation of the input flat profile to the original round one. Figure 4-4 shows the MA preliminary design proposed by Astronika.

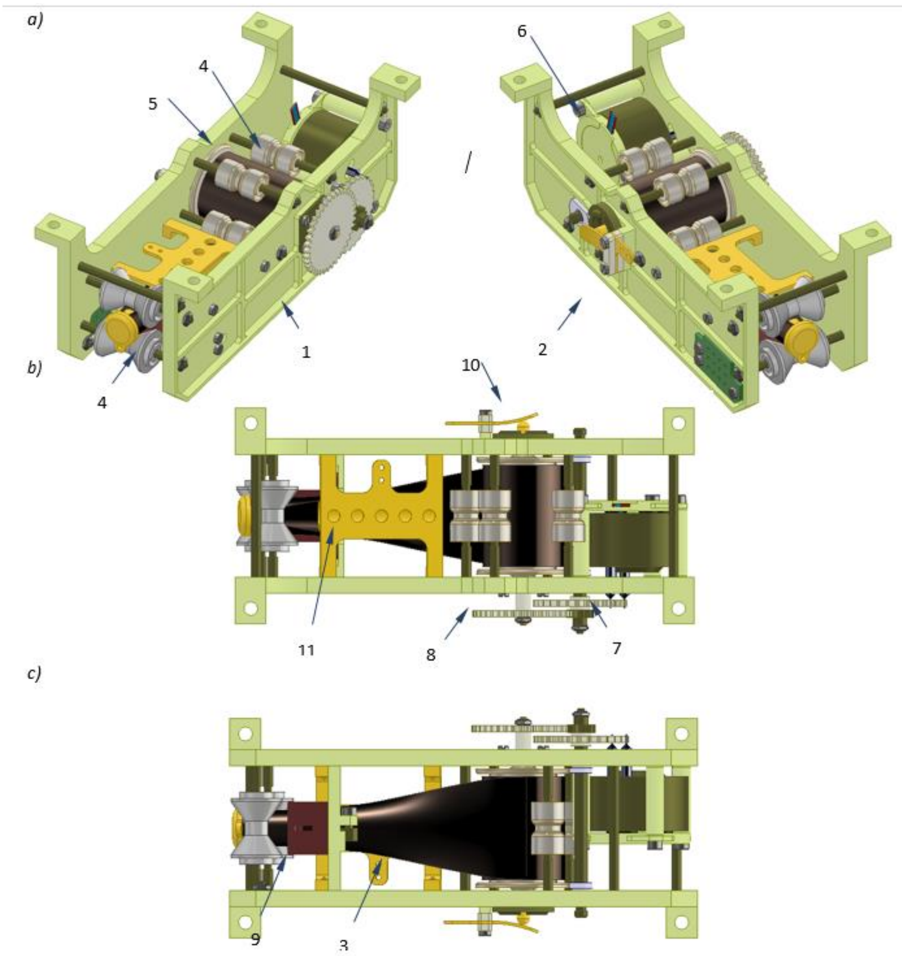

Figure 4-4 Main Antenna preliminary design: a) side isometric views, b) top view, c) bottom view: 1 – Right side wall, 2 – Left side wall, 3 – Tubular boom, 4 - Tubular boom guidance system, 5 – Storage reel, 6 – Oscillatory motor, 7 – Escapement mechanism, 8 – Gear (1:4 ratio), 9 - L&RM, 10 – Side spring for prime electrical connection, 11 – Connective rod for redundant electrical connection.

The baseline solution of the MA consists of:

- Structure: in the form of two side-walls made of aluminum.
- Tubular boom: ø6mm beryllium bronze boom made by Gutronic.
- Tubular boom guidance system: all rollers in the form of angular contact bearings.
- Drive and damping unit: solution with oscillatory motor (OM) working with escapement-based mechanism, with additional mechanical gear; the MA not equipped with drive unit control module.
- L&RM: thermal cutting of Dyneema string, redundant heaters; no L&RM control module.
- Electrical connection: redundant connection consisting of two solutions - with a side spring and with intermediary kapton tape.

The MA structure ensures the most compact, solid and functional possible arrangement of all antenna sub-assemblies and components being able to survive vibrations generated during the launch.

The drive and damping unit is the main issue and most crucial part of the MA mechanics. The basic component of proposed unit is the OM working with the escapement wheel. The additional gear was added to reduce the speed of deployment.

There are two operational modes of the MA deployment:

- Mode without OM operation. In this mode, the only driving force is the force coming from tubular boom itself. The tubular boom rolled up on the storage reel is coupled with the reduction gear which in turn is coupled with the escapement wheel. The wheel works with two pins of the OM. Once released, tubular boom starts free unwinding causing rotation of the gear and thus the rotation of the escapement wheel. The pins, sliding on the escapement wheel teeth, are forced to perform swinging motion. The deployment speed is regulated via fixed frequency of the OM playing a role of a damper.
- Mode with OM operation. Drive unit serves as a motion-inducer making the system much more reliable. In case of any boom jam the OM can be activated and forces the pins swinging motion. As a result, the escape wheel begins to rotate and thereby the aided unreeling action takes place. Moreover, the OM working at high frequencies can act as a generator of vibration also valuable in providing better unwinding (confirmed by tests). What is also important, this mode provides the system with any deployment speed dependent only on OM frequency range.

Proposed L&RM design is the lowest-risk undertaking and best recognized issue. L&RM based on Dyneema fibre thermal cutting manner activation is a well-proven and effective manner for years applied by project team (repeatedly TRL 9). One end of the string is attached to a tubular boom tip (via knot) and then wrapped around a heater, while the second end is locked in heater housing structure. The string cutting is achieved by resistance heating. Astronika plans to apply two heaters: prime and redundant. Each heater will have its own separate electrical circuit activated via its telecommand and will be powered sequentially, one by one, to release antenna.

The electrical connection provides a reliable connection between the antenna boom and pre-amplifier. There are two connections to increase the reliability of antenna (Figure 4-5). Side spring provides continuous connection during antenna deployment. Connective rod provides connection at the end of deployment.

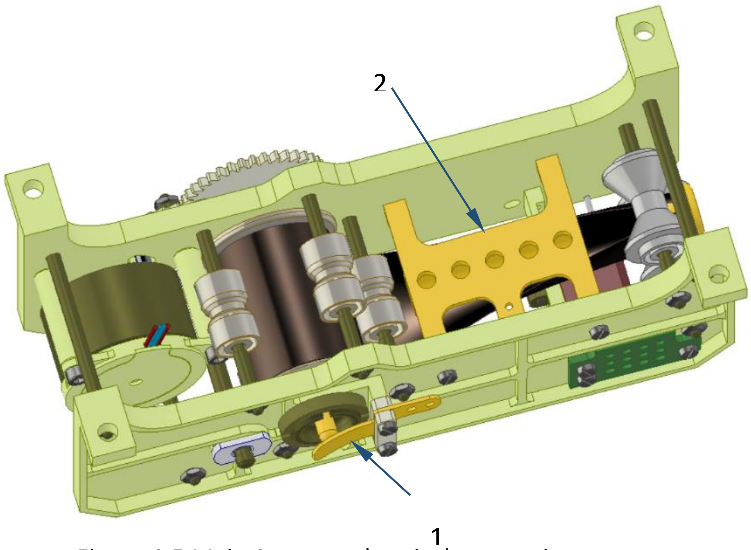

Figure 4-5 Main Antenna electrical connection:

1 – Side spring (for prime electrical connection); 2 – Connective rod (for redundant electrical connection).

Both Main Antennas need to be deployed after MASCOT-2 landing and relocation operations on Didymoon. It is unacceptable for the MA System to change the final orientation of the Lander as a result of the deployment action. The only exception is the lateral displacement of even couple of meters which is acceptable. This constraint imposes limitations on the MA deployment speed and pushing force. The Astronika team was given a first estimation of acceptable deployment speed about 2÷3cm.

The main characteristic parameters of the Main Antenna are listed below:

- Antenna type: fixed reel, monopole
- Tubular boom used: Ø 6 mm beryllium bronze
- Length: 1.25m
- Overall dimensions (stowed): 36.4 x 44.3 x 90 mm
- Mass: 90 g (108 g with 20% contingency)
- Additional electromagnetic drive (OM)
- Power consumption:
  1) 3÷4 W per 15 s (for Lock & Release Mechanism)
  2) 1.25 W per 60 s (for OM, when used) (TBC)
- Smooth and regular deployment
  1) Average speed of 2.5cm/s without OM operation
  2) Average speed of TBD cm/s with OM operation
- Non-explosive Lock & Release Mechanism based on a thermal cutting system (Dyneema holding string)
- Single shot device – once deployed, the antenna cannot be retracted.

5 Deployment mechanism of MASCOT Lander Secondary Antennas

5.1 Deployable Secondary Antenna

Two Secondary Antennas (SA) are included in the MASCOT-2 Lander LFR subsystem and located at the back of the Lander, as already shown in Figure 4-1. SA System will be responsible for MASCOT-2 Lander localization and operational support as well as for supplying the information about Didymoon mass and gravity field. Both Secondary Antennas need to be deployed just after MASCOT-2 separation from AIM S/C and need to be operative during cruise, landing on the Didymoon surface and relocation operations. The SAs folded for launch were the baseline, however non-deployable, permanently fixed rods are now under consideration. Since the decision has not been made yet, Astronika were asked to present the preliminary design of both options. Regardless of the chosen type of SA the antenna shall survive hitting the asteroid surface at a speed of approx. 7cm/s.

The antennas are designed as a pair of two Rods (left and right), fixed to the Hinges and held by the common L&RM in the middle. The L&RM holds the Rod in the stable position before and during the start of the S/C. The Rod is attached to the S/C through the Hinge and the Interface on one side and through L&RM on the other side (Figure 5-1**Błąd! Nie można odnaleźć źródła odwołania.**).

Figure 5-1 Preliminary design of the Deployable Secondary Antenna.

Hinge and the Rod are made from one piece of material being a specially shaped Berylco 25 tape – special beryllium bronze alloy with the space heritage (TRL 9).

Lock and Release Mechanism is the assembly based on the use of the Dyneema string and resistors generating the heat. The resistors are powered up to melt the string, which holds the L&RM arm in the closed position (Figure 5-2). After melting the string the two torsion springs force the arm on the Shaft to rotate to the open position.

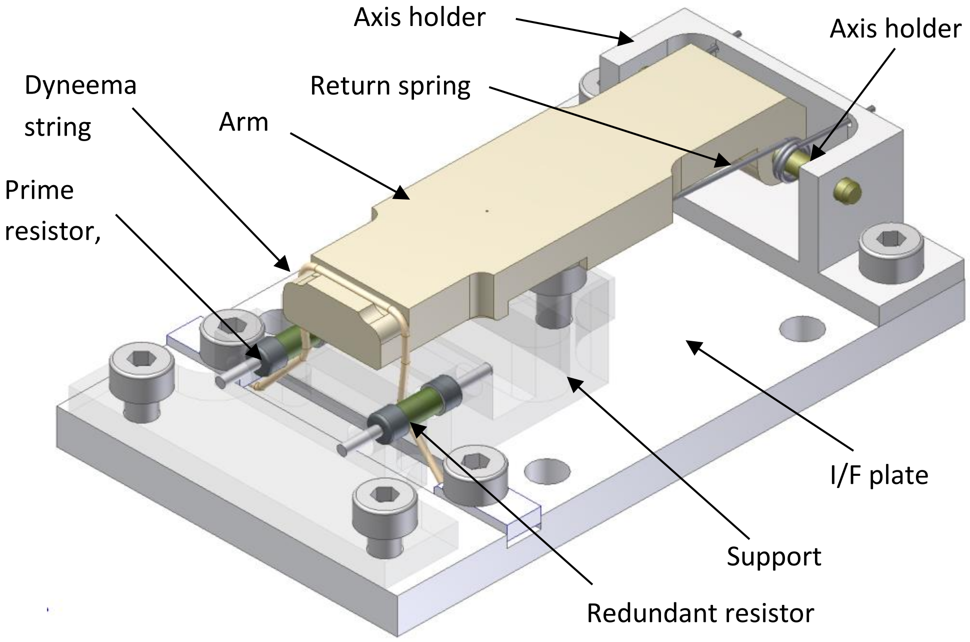

Figure 5-2 L&RM in closed position.

5.2 Non-deployable Secondary Antenna

The non-deployable SA consists of the Interface, which serves as a mean to mount the Rod Fixation together with the Rod to MASCOT-2 lander. The SA is in the permanently fixed configuration, without any deployment. It means that during the mission lifetime, since launch, the SA is in its final position.

The preliminary design of Non-deployable Secondary Antenna consisted of interface plate, rod fixation and antennas rod is shown in Figure 5-3.

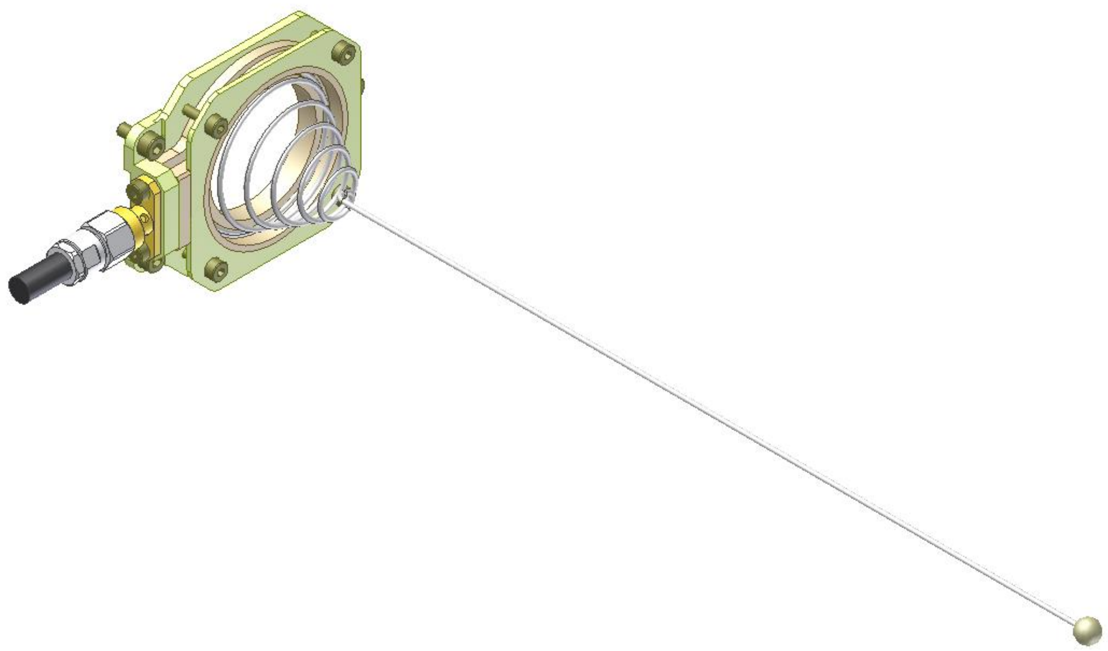

Figure 5-3 The Non-deployable Secondary Antenna preliminary design (Astronika)

The Rod Fixation and the Rod are made as a one-piece component made from spring steel wire to obtain the flexibility and durability at the same time. The part of wire playing the role of Rod Fixation has a form of conical spring which absorbs vibrations and provides the system with flexibility, which protects the Rod from severe bending or braking. The remaining part of wire is just a stiff straight Rod which is ended in the spherical tip. The Interface is an intermediate part enabling the mounting of the conical spring to the Lander.