Realization and preliminary tests on an innovative deployable structure for a high resolution telescope for microsatellite.

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ABSTRACT

High resolution images of the Earth surface in the visible wavelength are useful in a variety of human activities, from agriculture, to urban area monitoring, but the utilization is often limited by the high cost of the images and the relatively small number of satellites equipped with high resolution telescopes. In order to encourage the utilization of high resolution images, Italian Space Agency (ASI) funded a project aimed to investigate the possibility of utilization of microsatellites for this task. The objective of the project MITAR (MIcro Telescope, high Resolution) is to realize a prototypal telescope, capable of a 1m resolution from 400Km altitude, compatible with a microsatellite platform.
The necessity of a compact, lightweight and highly performing payload has been achieved designing a Cassegrain configuration with composite material mirrors and an innovative deployable structure.
The feasibility analysis and preliminary design have been presented at the SPIE Remote Sensing Europe 2003 congress in the paper titled "High resolution deployable telescope for satellite application".
Present paper focuses on the activities developed by Second University of Naples. In the university it has been designed a structure capable of a smooth deploy, without active control systems. The structure is deployed by lenticular tape springs (LTS), damped with viscoelastic polymer.
In the paper it is quickly described the optical system, then the peculiarity of the lenticular tape springs are shortly described. The characterization of the visco-elastically damped LTS (VEDLTS), and the description of the efforts aimed to have numerical and analytical instruments for the prediction of this innovative elements are exposed with more details.
We report then some relevant detail of the deployable structure and the realization related aspects.
The paper is concluded with the results of the very preliminary tests, aimed to verify the ability of the structure of performing a correct deploy and the accuracy of the deployed configuration.
The tests have evidenced that the structure does not easily deploy spontaneously, then it has been necessary to use some conventional springs in order to trigger a correct deploy, obtaining a structure with the needed characteristics.

Keywords: Deployable telescope, microsatellite, damped lenticular tape springs

1. INTRODUCTION

Aerospace and Mechanical Department of the Second University of Naples, is involved in MITAR project. The objective of the activities, partially founded by Italian Space Agency (ASI), is the realization of the prototype of a high resolution telescope for microsatellite.
The feasibility analysis and preliminary design have been presented at the SPIE Remote Sensing Europe 2003 congress in the paper titled "High resolution deployable telescope for satellite application"[1]. In that paper authors describe the system configuration: a 400mm diameter Cassegrain reflector, 561mm long, utilizing a linear CCD sensor. For weight reduction the mirrors will be realized in composite materials and the structure will be stowed during the launch phases and deployed once in orbit.
The optical design has been conducted keeping in consideration the peculiarity of the mission. The objective of a deployable telescope requires a short telescope, even if with a large focal length. It has to mount lightweight mirrors and

mostly important it is required a small diameter of the secondary mirror in order to guarantee a high luminosity and a relatively good tolerance to small displacement of the secondary mirror in the direction of the optical axis.
The results of the optic design, conducted by the Consortium for Research on Advanced Remote Sensing Systems are resumed in the following table:

Telescope focal length	Distance primary-secondary	Primary mirror diameter	Primary mirror focal length	Primary mirror conic coefficient	Secondary mirror diameter	Secondary mirror focal length	Secondary mirror conic coefficient
2500mm	520mm	400mm	690mm	-1	100mm	230mm	-2.8657

Table 1 Telescope characteristics

The spherical and the coma aberration have been minimized by using the parabolic and the hyperbolic for the primary and the secondary mirror respectively, while the field curvature has been corrected by putting a doublets of plano-convex lenses outside the telescope having a diameter of 2.5 cm each.

2. VISCO-ELASTICALLY DAMPED LENTICULAR TAPE SPRINGS

2.1 Lenticular tape springs

Lenticular tape springs (LTS) are thin-walled beams with a curved cross section that can be elastically deformed to yield a flexible region of high curvature known as a fold [2-3].

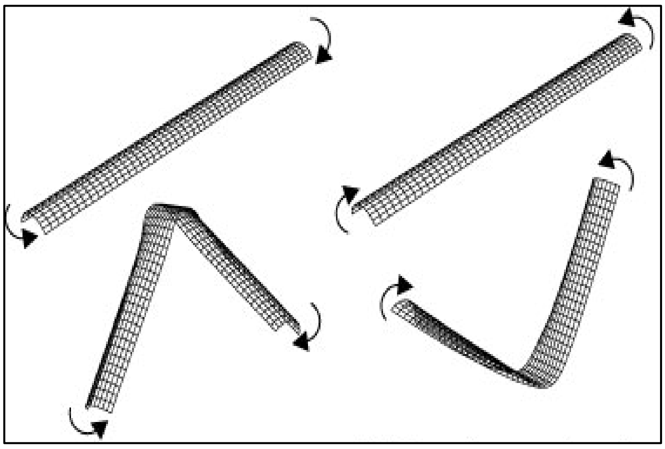

Figure 1. Bending of a lenticular tape spring

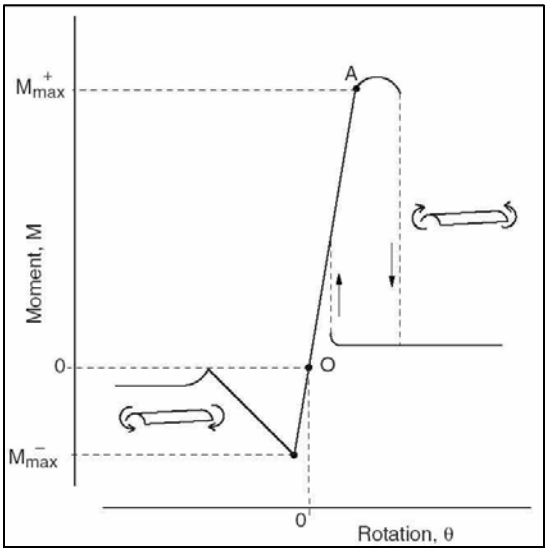

Figure 2. Diagram of the moment with respect the deflection angle

When one of these springs is loaded with a small bending moment, it bears the load as a usual beam, showing a uniform curvature along the whole beam. If the bending moment exceeds a critical value (see Figure 1), the LTS shows a no more linear behaviour. The deflection is localized in a small region, the fold, while the other parts of the spring are almost rectilinear.
In the folded area the transverse curvature is no more present and the tape is curved in the longitudinal direction only. It can be proved that the longitudinal curvature of the fold is equal to the cross curvature of the lenticular spring in the unfolded area and that this curvature is not influenced by the angle between the two rectilinear parts on the LTS. The inertia moment of the section drops dramatically, passing from the moment of a curved section to the moment of a rectangular and very thin section.
Plotting the moment with respect the deflection we have the diagram showed in Figure 2. The stiffness of the beam in the linear region ($\theta \ll 1$) is given by the well known beam formula. It depends by the characteristics of the material (Young modulus) and by the geometry of the section. In this linear area, it is more important the curvature radius of the section, than the thickness of the tape. The spring is stiffer when the curvature is greater.

When the springs change configuration and the fold appears, the moment drops to a much lower value. This value is now constant and does not change with θ because the curvature in the fold is constant.
This constant moment is equal to the moment required to bend a flat tape (without transversal curvature) up to a curvature equal to the curvature of the cross section of the unloaded LTS.
It is interesting to notice that, because the longitudinal curvature in the folded part is constant, increasing θ we see a greater part of the LST interested by the fold, and then a shorter part of LTS with original transverse curvature.
Negative bending (left in F1gure 1) and positive bending (right in Figure 1) have a different transition moment, but the behaviour is equal before and after transition.
Negative bending causes a smoother transition, while the positive one is faster and, because of this, generates noises when transition occurs.
As seen a folded tape spring tends to return to its straight equilibrium configuration, with a little force, but can keep its equilibrium position with a great rigidity and stability, because the higher moment of inertia on the curved cross section.
LTS acts like a couple of beams hinged together (Figure 5 in the following pages), but without allowances caused by coupled parts, and with the interesting characteristic that the hinge get locked when it is plain.

2.3 Viscoelastic damping

The Lenticular tape springs, have been widely studied. Because their peculiarity they can be useful in the realization of deployable structures for space applications. A structure composed by LTS does need a retain system in order to be kept folded, but does not need power for the deploy. More over, the deployed structure locks itself in a stable position spontaneously, without external mechanisms.
One of the most interesting characteristics of the tape springs is the spontaneous deploy and the spontaneous locking, but these aspects can also be a source of troubles. A spontaneous deploy is not easy to control, and the locking of the springs in the equilibrium configuration could cause heavy vibration and shocks, mostly if the locking comes from a positive folding.
Since we are realizing the structure of a high resolution telescope, we cannot allow excessive and unpredictable solicitation, because they can cause a misalignment of the mirrors. We have been forced to design a system capable of slowing down the deploy; a system simple enough to be compatible with a microsatellite, low cost, and, most important, a system that will never be able to stop the deploy.
These objectives have been achieved with a distributed damping system, embedded in the LTS. Each spring in the structure is composed by two LTS glued with a viscoelastic polymer, obtaining a VEDLTS.
When the VEDLTS is folded the two tapes experience a relative sliding, because, in folded part, the inner and the outer tape lies on two concentric circular arches with same angle but different radii, then different length. This causes a shear deformation of the viscoelastic polymer.
When the VEDLTS returns to its equilibrium position the shear deformation is recovered, and because of the peculiarity of the viscoelastic polymer, the run toward the equilibrium position is slowed down.
In conclusion we can sentence that the VEDLTS embeds:

1. a deployable mechanism actuated with a constant force
2. a locking systems that forces the mechanism in the deployed position
3. a speed limiter that prevent excessive deploy speed.

The first 2 characteristics cam from the LTS by themselves, the third characteristic has been introduced with the viscoelastic polymer.

2.4 Realization of the VEDLTS

First step for the realization of VEDLTS is the choice of the material of the LTS. We need a spring steel, but with a smooth and high energy surface, in order to have an easy adhesion with the viscoelastic polymer.
Because the initial phase of the project, we are interested in a workable material, without long, complex and expensive treatments. We have so chosen AISI 301 stainless steel.
Second step regards the choice of the geometry. Since geometric limitation imposed by the large primary mirror and by the small amount of space on a microsatellite, and after structural analyses, we have chosen 10mm wide tapes.
In order to have a good performance of the LTS, it is required a radius of curvature smaller than the width of the tape. Keeping in consideration this important aspect, we have chosen a 7mm radius in order to have the momentum of inertia needed for a sufficiently stiff deployed structure.

Thickness of the tape has been chosen looking at the elasticity limits of the material. An excessively thick tape will risk to deform permanently during the fold, preventing a correct deploy. An excessively thin tape will not guarantee a sufficient deploy force and a sufficient stability of the deployed structure.
These considerations, and the availability of tapes off the shelf, drove us toward a 0.05mm thick tape.
We can resume the LTS characteristics in the following table.

LTS Specifications	
Material	AISI 301 Stainless steel
Tape width	10mm
Tape thickness	0.005
Curvature radius	7mm

Table 2. LTS Specifications

The LTS chosen are suitable for the application, but because their characteristics they are not very easy to realize.
Because the small thickness and the high elasticity of the material, the LTS cannot be obtained from the plain tape by pressing it between two moulded parts. In order to have a permanent curvature radius equal to 7mm, we have to impose a deformation with a 1.5mm radius. This means that we have to wind the tape around a 3mm diameter bar.
This was done designing and realizing the small calender pictured in Figure 3.

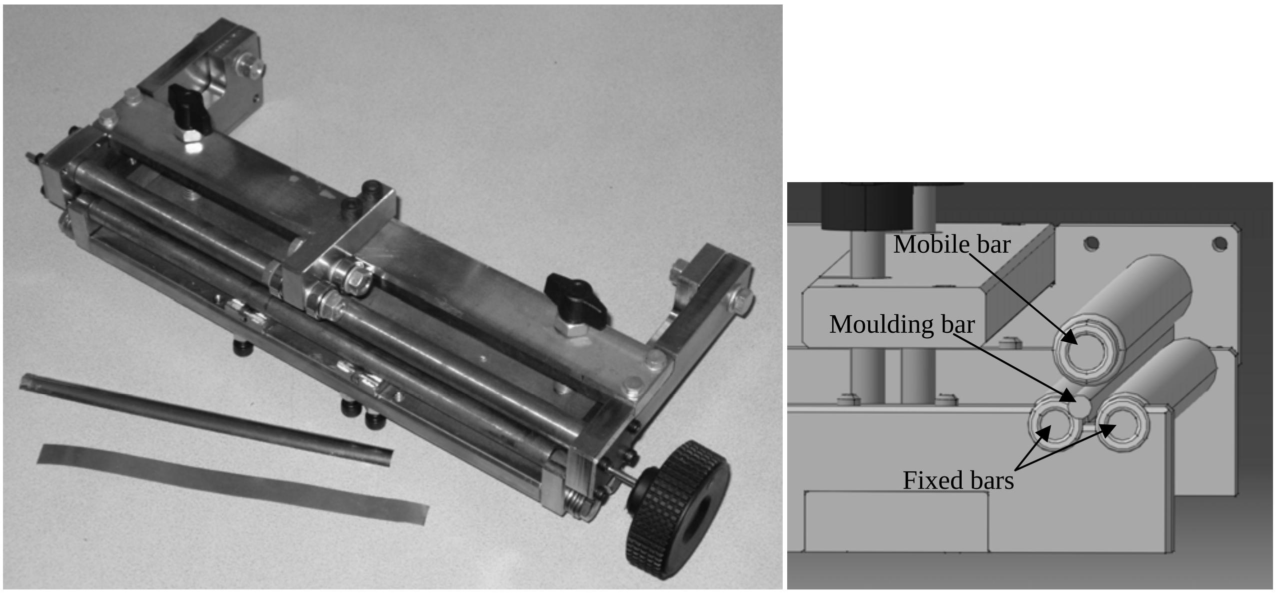

Fig 3. The calender. In the picture are also present a LTS and a tape not yet curved. In the drawing on the right it is shown the configuration of the 4 bars

The calender is operated manually. It consists of two fixed bars (10mm in diameter) on which is placed the moulding bar (3mm in diameter) and by a mobile bar (16mm in diameter), over the moulding one.
The flat tape is placed on the two fixed bars and the moulding bar is pressed on it. The mobile bar is needed in order to stiffen the moulding bar and prevent bending of the moulding bar itself.
The bars have been stiffened by other constrains, realized with sets of ball bearings.
When the tape is between the two fixed and the moulding bars, this last is pressed down by a screw mechanism, causing the bending of the tape along the direction of its width. Then, moving manually and carefully the black handle forward and backward, the tape is forced to pass between the bars for all its width, assuming then an uniform and permanent curvature.
After the curvature we notice a light deflection of the spring in the longitudinal direction. This is due to the Poisson ration of the material. The calender imposes a compression of the material close to the concave surface of the LTS. This compression in the transversal direction causes an extension in the longitudinal direction on the concave surface. Analogously, the convex surface experiences a longitudinal contraction. These two effects added cause the longitudinal deflection shown in the left picture of Figure 4.

This deflection can be foreseen, but we have seen that it can be easily corrected, as shown in the right picture of the figure.

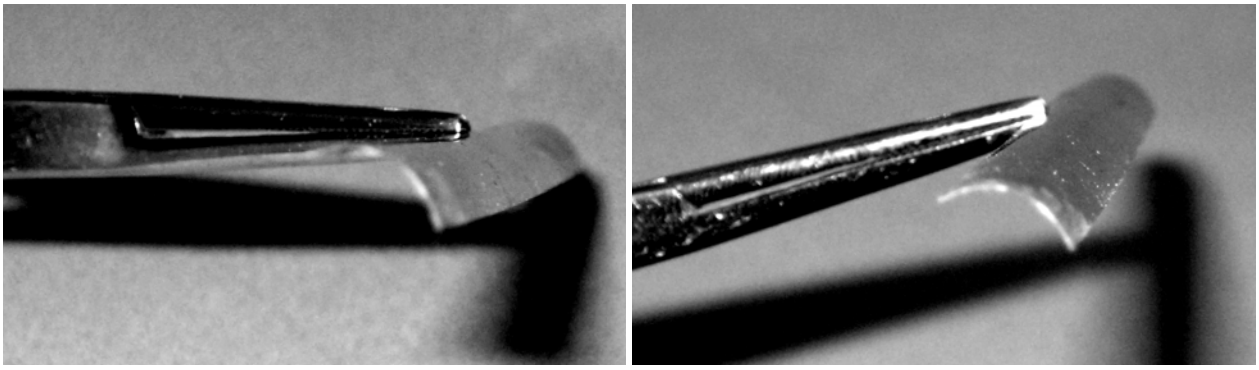

Figure 4. The same LTS just after the moulding in the calender and after the longitudinal deflection recovery.

Once obtained a rectilinear LTS it is needed to assemble them with the viscoelastic polymer. 3M, produce a wide variety of viscoelastic tapes for noise and vibration suppression [4-5]. More over, many acrylic high bonding tapes produced by other factories have very accentuate viscous characteristics [6]. Generally all the bi-adhesive transfer tapes realized with acrylic resin, present a polymerization characterized by particularly short molecules. This makes the resin highly tacky and viscous. Both characteristics are excellent for our application.
More complex is the out-gassing problem. Once the VEDLTS is exposed to vacuum any volatile particle of the polymer will tend to separate and could be able to separate the two tapes or to transform the polymer in foam, with very different and unwanted characteristics. For the spatialization of the prototype, this aspect needs to be analyzed with care, avoiding intrusion of air during the assembling operation of the VEDLTS and using polymers characterized by a very low out-gassing. 3M produce a set of tapes with these characteristics, even if not yet commercialized in Italy.

2.5 Characterization of the VEDLTS

As seen VEDLTS behaviours are the combination of the LTS and viscoelastic polymer behaviours. The moment applied by the fold to the rectilinear parts of the LTS is given by equation of elastic bending of a beam, applied to the fold:

$$M = \frac{EI}{R}$$

Where *M* is the moment applied to a beam, *R* is the curvature radius imposed to the beam, *E* is the Young modulus and *I* is the inertia moment of the section.
In the fold of a LTS, *R* is equal to the transverse curvature of the LTS, and *I* is the inertia moment of the flat tape:

$$I = \frac{w \cdot t^3}{12}$$

Where *t* is the thickness of the tape (0.05mm in our case) and *w* is its width.
Because the stiffness of the folded part of the LTS is much smaller then the stiffness of the unfolded parts, we can suppose these rigid and we can use the scheme composed by two rigid beams connected with a hinge and with a constant moment applied. We have to add in this scheme that the hinge disappear when the two beams get adjacent.
If we can suppose that the fold keeps its position, we have a system with only one degree of freedom.

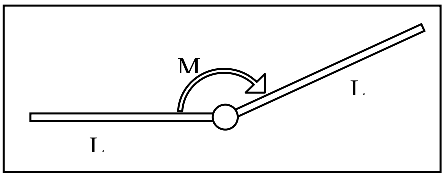

Figure 5. Hinged beams, schematisation of folded LTS

The viscoelastic polymer introduces a damping in this system.
From experimental observation we have seen that the fold of the VEDLTS can be described by the following linear system:

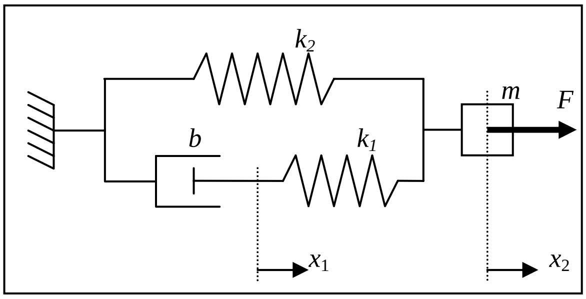

Figure 6. The linear model of a VEDLTS folded

In the model the deflection θ has been replaced by linear displacements *x*, in order to have a more homogenous representation.
The damper *b* represents the viscous part of the polymer; the springs k_1 and k_2 are the elastic part of the viscoelastic polymer. The force *F* is introduced as an external input, but it represents the constant moment generated by the fold in the LTS.
The system has now two degree of freedom, and is described by the following differential equations:

$$\begin{cases} \dot{X} = AX + BU \\ Y = CX + BU \end{cases} \Rightarrow \begin{cases} \begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \ddot{x}_1 \end{bmatrix} = \begin{bmatrix} -\frac{k_1}{b} & \frac{k_1}{b} & 0 \\ 0 & 0 & 1 \\ -\frac{k_1}{m} & -\frac{k_1 - k_2}{m} & 0 \end{bmatrix} \cdot \begin{bmatrix} x_1 \\ x_2 \\ \dot{x}_1 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \cdot F \\ \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix} \cdot \begin{bmatrix} x_1 \\ x_2 \\ \dot{x}_1 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \end{bmatrix} \cdot F \end{cases}$$

In order to make this model an useful tool for the analysis and prediction of the deploy of a VEDLTS, it is necessary to know the values of *k* and *b*, while *m* can be easily evaluated by the moment of inertia of the pivoting part of the spring, and *F* can be obtained easily from the momentum calculated before.
The values of *k* and *b* are hard to be found. Polymer producer give a few data only on the tapes realized for damping, and when information are available, they are expressed in terms of loss factors, at high frequencies, useful for vibration damping, but almost useless for the damping of a deploy.
Vibration are characterized by high frequencies and small displacements, a deploy is characterized by very low frequencies and large displacements.
Since the polymer experience a shear deformation when the VEDLTS is folded, we have realized a test facility in which we can impose a shear deformation to a specimen of polymer, and measure the force and its evolution in time.
The facility is composed by a dynamometer, a digital ruler and a couple of aluminium plates, designed appositely to apply only shear tension without normal components.

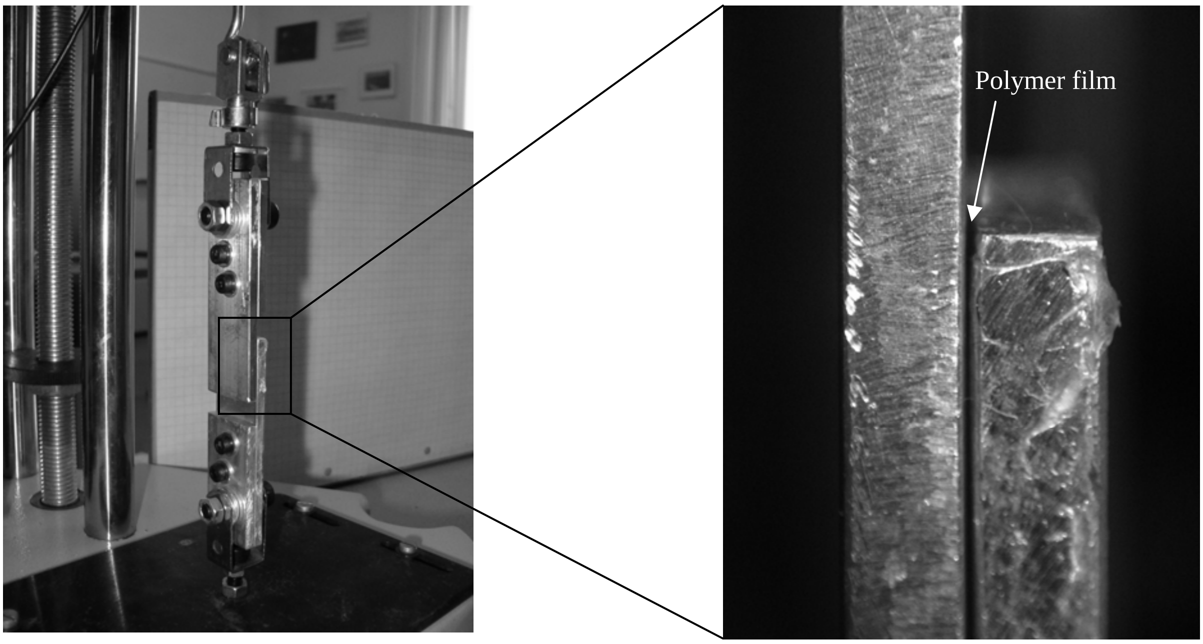

Figure 7. The Viscoelastic polymer tests equipment

The procedure adopted to evaluate a preliminary value of *k* has been not very simple.
When the polymer is deformed, we measure a force, but this force is due to both elastic and viscous behaviour of the specimen. The elastic part is not time dependent, while the viscous part tends to zero with time. We have left specimens deformed for more than 24 hours, and we have been able to see a relaxation of the stress even after a so long time.
More over, it is very hard to repeat an experiment from the same starting conditions, when the starting conditions are quickly time dependent.
So, in order to set up a procedure that could be repeated with different specimens, we have fixed this following scheme:

1. Deform the specimen in order to reach a fixed value of force. (accuracy is not very important)
2. Allow the specimen to relax the stress imposed for a time that is long if compared with the relaxation curve
3. Impose an additional deformation (accuracy is not very important)
4. Measure the force after a time equal to the interval of point 2
5. With these two values of force and the displacement step, we can calculate a value of *k*

The plot in Figure 8 reports force and displacement measured during one of the many tests performed.
The axis on the left report the force measured by the dynamometer. The right axis report the displacement imposed.
The piecewise constant curve describe the displacement imposed. The curve with the two spikes is the force measured.
We have spikes in force in correspondence of the steps in the displacement imposed.
In the plot reported, we have stopped the deformation of the specimen when the force measured was 23N, then we have awaited 885seconds and we have imposed 0.51mm additional deformation and we have measured a force of 28.67N.
After other 855s the force dropped to 17.32N. Then we have been able to calculate a value of k equal to 20.9Nmm^{-1}.
Similar experiments have been conducted with different polymers, different thickness and with different times.
The estimation of *k* has been not trouble free. The experiments can give a good idea of the different characteristics of different polymers, but the complexity of the dynamics inside the material make hard to find a unique value of k for each polymer. In any way, repeating the experiment, correcting errors, and averaging the results we have obtained the interesting results, reported in the next pages.

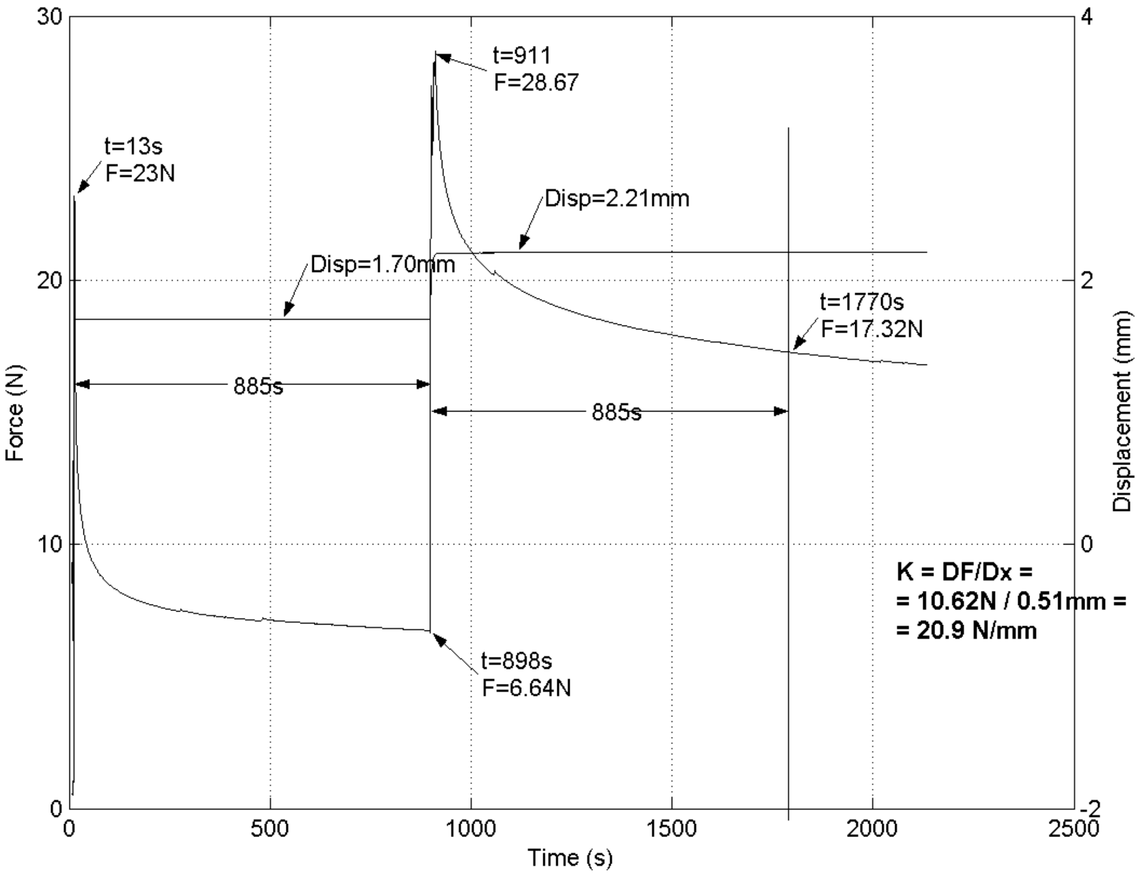

Figure 8 Results of a test on a specimen of Viscoelastic polymer

Once obtained a static characterization of the parts of a VEDLTS, we are ready to study the whole VEDLTS, during the unfolding phase.
A VEDLTS has been constrained at an extremity, it has been folded up to 180 degrees, and the unfolding has been filmed. In order to characterise the dynamic of the process, we have measured the displacements step by step.

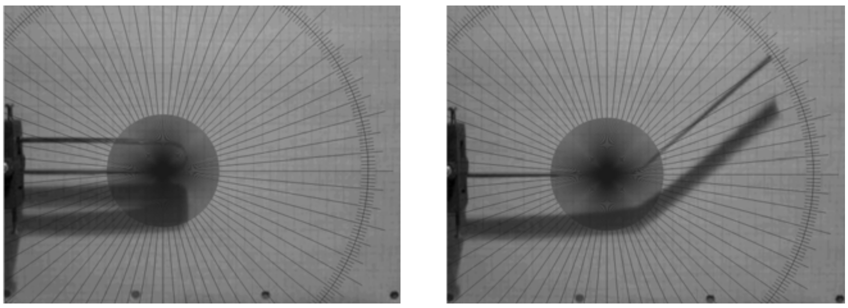
Figure 9. Two frames of a movie of a VEDLTS while unfolding

The following graphic shows, on the same plot, three curves obtained by 3 filmed unfolding and the results of a simulation of the linear model.

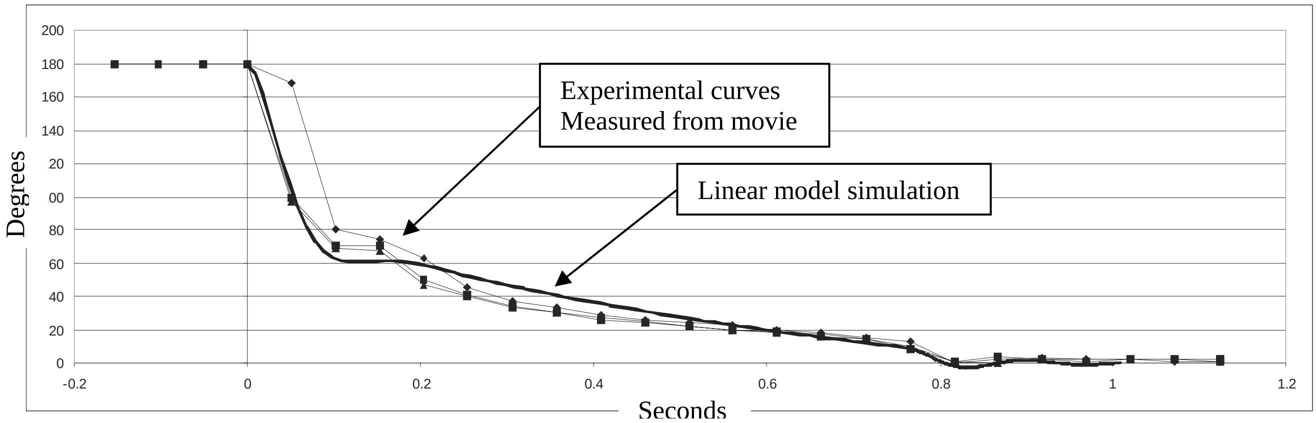

Figure 10.Linear simulation of unfolding, compared with experimental curves

The almost perfect matching shows that an accurate choice of the values of *k* and *b* allow a very accurate simulation. The model is almost perfect; the most critic part is the determination of the numeric values of the parameters. It requires time and is not yet very accurate.

3. DESIGN AND REALIZATION OF THE DEPLOYABLE STRUCTURE

3.1 The octagons

Once the VEDLTS have been designed, realized and once the linear model created has proved its ability in foreseeing the behaviours of these innovative structural elements, we can pass to the detailed definition of the whole structure.
It will be realized by 5 octagonal rigid elements aligned and connected by 8 VEDLTS.
The three intermediate octagons are identical. The octagons number one and number five are more complex, and more rigid.
Octagon one has a raised edge, to be bolted to the base of the telescope. The octagon number five, is much more complex than the others, because it embeds, in one piece of aluminium, the elements for the installation of the secondary mirror.

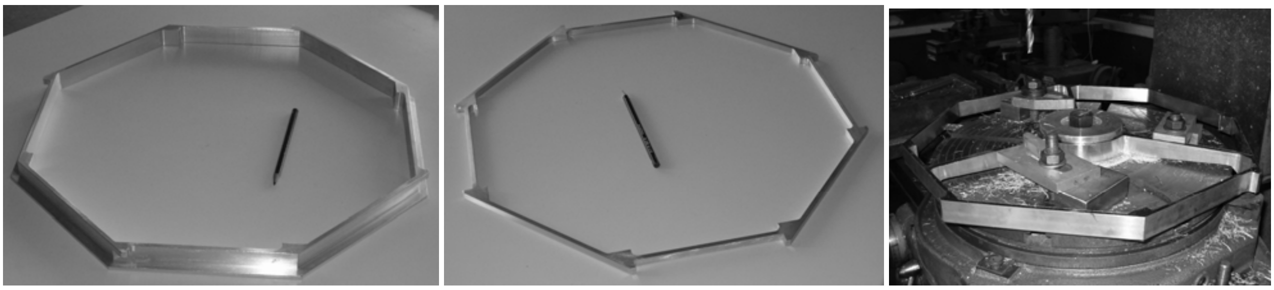
Figure 11. From left to right Base Octagon, one of the three Mid Octagon and Tip Octagon still under tools

3.2 The connections between VEDLTS and the octagons

One of the most challenging aspects of the realization is the connection between the VEDLTS and the octagons. It is fundamental to preserve the curvature of the springs in the attach points, and, since we are realizing a prototype, we need an assembling system that allows mounting, tuning and eventually disassembling.
We designed a clamp composed by two small pieces of aluminium that will lock the spring in it with a M3 screw.
In order to have an accurate assembling, the VEDLTS are holed at the extremities using a tool that permit to have an accurate distance between the two holes of each spring.
The clamps are then attached to the octagons with two rivets as shown in figure 12.

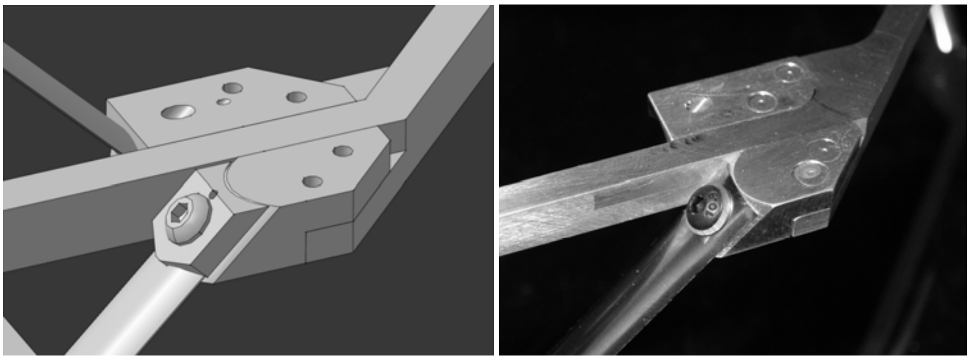

Figure 12. Design and realization of the connections

The attach system has been designed with a screw and a pin, in order to constrain all the degree of freedom of the spring. In order to simplify the realization of the prototype, the pin has been removed, using only the screw and a washer and locking the system for friction.

4. PRELIMINAR TESTS

4.1 Two octagon tests

Primary objective of the preliminary tests is to evaluate the ability of the structure to deploy correctly, reaching its final stable configuration. Secondary objective of the tests is to evaluate the precision of the deploy.

For the very early tests we have assembled only two intermediate octagons with 8 VEDLTS. The structure, placed on a table, has been assembled and measured, then it was stowed, deployed and measured again.

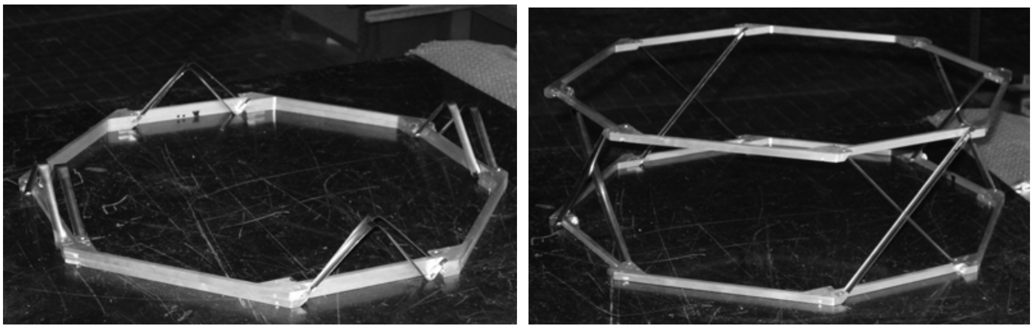

Figure 13 Two octagons stowed and deployed

As seen in the picture the octagons can be stowed as foreseen, reducing dramatically the space occupied. In the picture, the VEDLTS folded are higher than the structure, but this will be less evident when all the five octagons of the complete structure will be assembled and, moreover, the VEDLTS can be easily forced to occupy less space.

Once proved the ability of the structure to be stowed correctly we have measured its height after many stowing-deploy operations. The deployed structure accuracy and rigidity has been preliminary evaluated.

The deployed structure is very stiff in each direction and the height is variable in a range so small (much less than 0.1mm) that it is hard to measure during these preliminary tests.

We noticed also, in rare cases, a non perfect deploy of one or two VEDLTS, but we have seen that these are caused by a pivoting of the spring around the locking screw. Realizing the attach like foreseen in the definitive design, with a screw and a pin, this inconvenient will be removed.

More relevant and threatening has been the non spontaneous tendency of the structure to deploy. When it is in stowed configuration, it tens to stay stowed!

We have seen that the deploy force, during the initial phase, has a small component in the axial direction. In this phase the octagons are almost free to move in the plane perpendicular to the deploy axis. These displacements in the early

phase can cause the contact between the VEDLTS and the sides of the octagons. Friction between the sharp edges of springs and the aluminium of the octagons is high enough to prevent deploy.
Although the force needed to win this friction is small and it has been furnished by conventional torsional springs installed on the 4 edges of the octagons without VEDLTS.

4.2 Three octagons and torsional springs

After the first set of tests and observation, we have performed tests with three octagons aided in the deploy by eight torsional springs. Once assembled, the structure has been suspended and some deploy have been executed.
Next picture shows the structure composed by three octagons assembled, deployed and with the torsional springs installed. Successive pictures are three frames of a deploy movie.

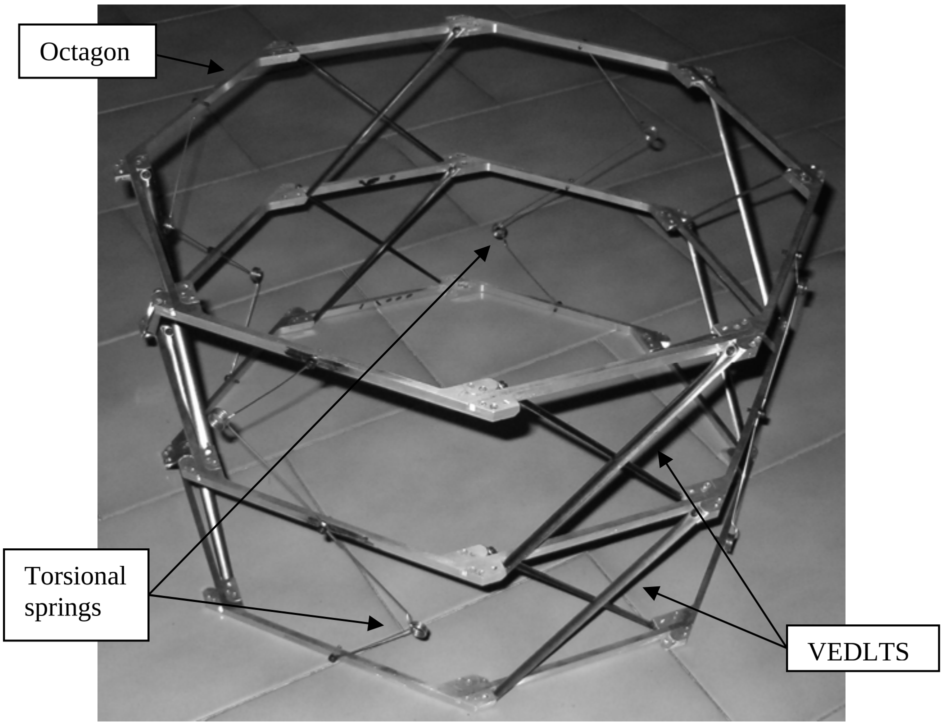

Figure 14 Three octagons deployed with torsional springs

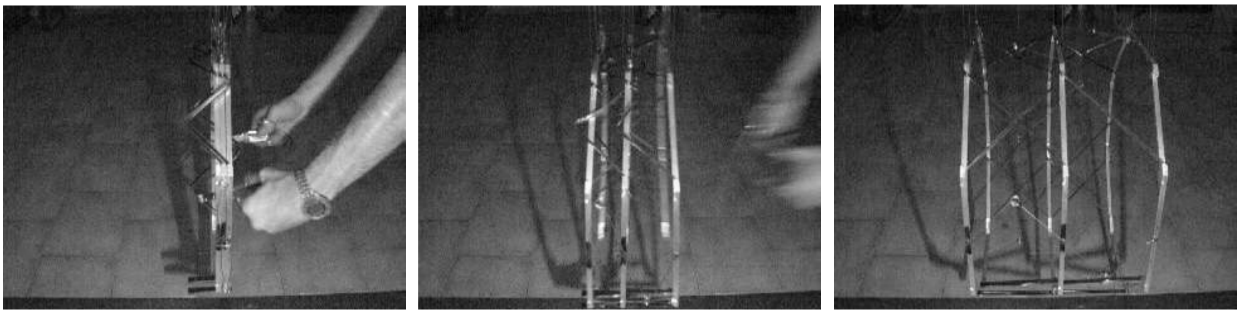

Fig 15 Three frames of a movie of a deploy

The structure has been kept stowed by nylon wires that have been cut with scissors, as shown in pictures, when needed. This time the structure deployed spontaneously, reaching its final stable and stiff equilibrium configuration. More over the deploy was relatively fast (about one second) but it ended without shocks. The springs have reached their final configuration smoothly and not all together, causing many very small and damped shocks instead one single dangerous shock.

5. CONCLUSIONS

In this paper we have shown the objectives achieved during the design and the realization of the first prototype of the deployable structure of MITAR. We have ideated a very simple deployable structure based on lenticular tape springs. The problem of the abrupt deploy of the springs has been solved introducing a viscoelastic polymer between two lenticular tape springs, realizing a very innovative mechanical element, capable of a spontaneous and smooth deploy. These new elements are the key element in the structure, and then they have been deeply studied. Numerous experimental observations have been used to set up a linear model of the system, capable of accurate predictions.

The structure has been assembled and many deploy tests have been performed. The structure has shown its ability to be stowed in a small space and the performances of the deployed structure have been very satisfactory.

Very important, and unexpected, has been the inability of the structure to begin spontaneously its deploy, because friction between tape springs and octagons. The force needed to win this friction is small and it is needed only at the beginning of the deploy. The installation of conventional torsional springs has solved this problem and the structure, completed with torsional springs, is really capable of spontaneous deploy.

More work is although needed before the realization of a deployable structure "ready to fly". It has been found that the characterization of the viscoelastic polymer at very low frequencies is not easy. More over we have seen that the polymer continues to creep when the springs are kept stowed for a long time. This makes the deploy dynamics dependent by the time that the structure has been hold stowed. This behavior has to bee better understood and most import it has to be quantified through more and longer stowage and deploy experiments.

Last critical point that requires accurate investigation is the behavior of viscoelastic polymer in vacuum environment. It is fundamental to individuate the polymer that is more tolerant to low pressure and that will not transform in foam and that will not tend to separate the two lenticular tapes springs.

6. REFERENCE

1. G. Pica, L. Ciofaniello, S. Mattei, M.R. Santovito, R. Gardi. *High Resolution Deployable Telescope for Satellite Application.* Proceedings of SPIE Remote Sensing Europe, 8-12 September 2003, Barcelona (Spain).
2. K A Seffen. *On the Behaviour of Folded Tape-Springs.* (2001) Journal of Applied Mechanics, Trans. ASME, 68, pp. 369-375
3. K A Seffen, Z You & S Pellegrino. *Folding and Deployment of Curved Springs.* (2000) International Journal of Mechanical Sciences, 42, pp. 2055-2073
4. Data sheets for 3M™ Ultra-Pure Viscoelastic Damping Polymer 242F02, 242F02, 242F02
5. Data sheets for 3M™ Viscoelastic Damping Polymer 110P02, 110P05, 112P02, 112P05
6. H-Hold data sheets for Acrylic Transfer Tapes