MSc in Computational Mechanics

Industrial Training

Internship report

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1 Preface and acknowledgment

For 6 months (starting in February 2019) the internship was carried out in the premises of the Nano-Satellite and Payload Laboratory (UPC NanoSat Lab). This interdepartmental laboratory belongs to the Barcelona School of Telecommunications Engineering and it is located at Campus Nord of Universitat Politecnica de Catalunya.

The laboratory focuses on the design and development of nano-satellite missions with significant efforts directed towards the design of innovative small spacecraft concepts, subsystems and payloads for space applications.

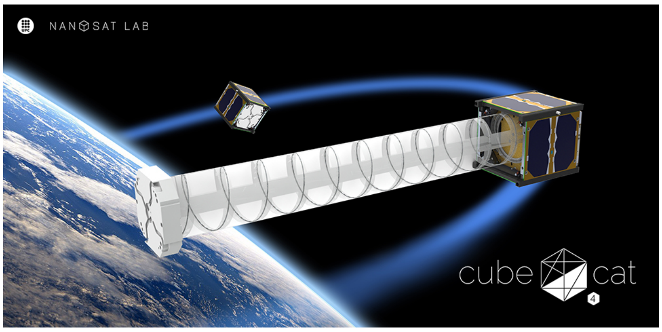


Fig. 1.1 – Render of one-unit 3Cat-4 - fourth member of the CubeSat series of UPCs NanoSat Lab.

After several successfully-completed and currently in-development CubeSat missions (see example in Figure 1.1), the staff at UPC NanoSat Lab decided to embark on a new challenge. The next CubeSat mission from the Universitat Politecnica de Catalunya seeks to develop a six-unit CubeSat spacecraft with a rotating dual-band deployable offset antenna at L- and Ka-bands with a diameter of 0.75 m - 1.5 m.

Considering the inherent multidisciplinary nature of the project, a group of students with different backgrounds was assembled. The group was comprised of two students from the Department of Telecommunications Engineering in charge of the electromagnetic analysis of the antenna and mission calculations; and the author of this report whose responsibility was the preliminary mechanical design of the deployable antenna. The group worked under the supervision of the director of the NanoSat Lab Prof. Adriano Camps Carmona.

To consider the multiple factors involved and to coordinate at the fullest, the group held weekly meetings with the supervisor in addition with several meetings between the students. Moreover, the author of this report consulted several times Prof. Francisco Zarate regarding mechanical aspects of the prototypes and different simulation difficulties faced throughout the internship.

The author of this report would like to express his profound appreciation to Prof. Adriano Camps for the valuable instructions, significant feedback and the contact with experts in the aerospace field. Furthermore, the author also acknowledges the important help Prof. Zarate provided during the consultation sessions.

2 Introduction

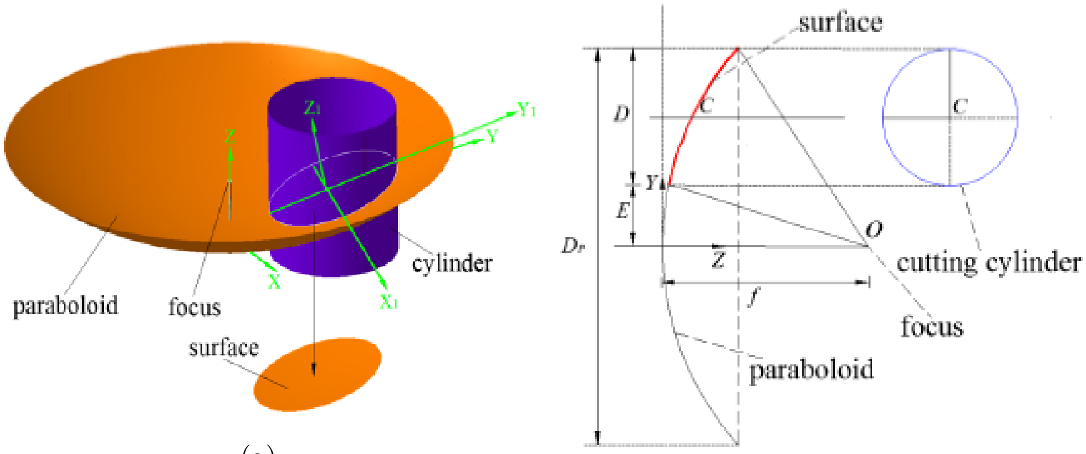
CubeSats have proven their outstanding value and benefits for scientific and commercial missions. Projections predict that in the following years most satellites will be in the range of less than 50 kg (nano and microsatellites), and the CubeSat market is expected to grow to USD 375 million by 2023 [4].

Because of the reduced size of CubeSat satellites, deployable antennas have to be developed for communications and Earth observation. Inflatables antennas were introduced in the 1950s, nevertheless they were only successfully adapted for CubeSat at S-band around 5 years ago by a group of MIT scholars [2]. Similarly, reflector deployable antennas were then developed for S-band [1] and Ka-band [3] with a diameter of 0.5 m within the framework of projects Aeneas and RainCube, respectively.

Within the framework of the internship, the author was given the task to carry out preliminary mechanical analysis required for the development of a rotating dual-band deployable offset antenna at L- and Ka-bands with a diameter of 0.75 m - 1.5 m. The work aimed to provide parametric and trade-off analysis taking into account multiple design variables, such as: reflector diameter, offset angle, focus distance, surface peak error, root-mean-square surface error and the overall complexity of the prototype. Moreover, mechanical design choices regarding the supporting ring structure (number and position of the vertices), mesh design and deployable mast design were discussed.

3 Technical background

The geometry of an offset reflector can be defined using the intersection of a parent paraboloid and a cylindrical structure as shown in Figure (3.1).



(a)

(b)

Fig. 3.1 – Definition of an offset reflector: (a) three-dimensional and (b) two-dimensional views [7].

Thus, given user-defined parameters such as diameter D, offset distance E and focus distance f, the reflector surface can be mathematically defined as follows:

$$\begin{cases} z = \frac{x^2+y^2}{4f} \\ x^2 + \left[y - (E + \frac{D}{2})\right]^2 \leq \frac{D^2}{4} \end{cases} \tag{3.1}$$

This configuration in which the projection of the intersection curve defining the surface is an ellipse and whose points are co-planar is called *standard*. An alternative was proposed by [5] where the projection of the curve is an circle instead of an ellipse. This configuration is called *circular*.

These configurations are only suitable for continuous surfaces and, in general, for engineering applications the surfaces are approximated with a mesh using polygonal facets. The error between the facets and best-fit parabolic surface is one of the most crucial aspects in the design of a reflector since this error deteriorates the overall gain of the antenna (refer to Figure (3.2)).

Subsequently and having constructed the approximating mesh surface, the root-mean-square normal error δ_{rms} can be found in the local coordinate system as:

$$\delta_{rms} = \sqrt{\sum_{i=1}^{n_f} A_i (z_i - z_{bfi})^2 \Big/ \sum_{i=1}^{n_f} A_i} \tag{3.2}$$

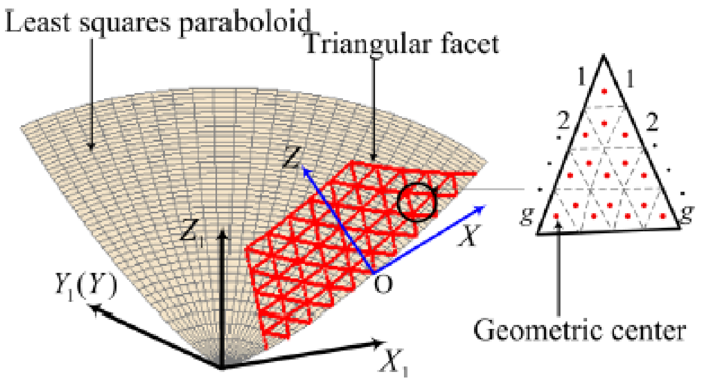


Fig. 3.2 – Best-fit paraboloid and a mesh with triangular facets [6].

where n_f is the number of facets on the mesh, z_i is the z-coordinate of a point located on the planar interpolation of the facet, z_{bfi} is the corresponding z-coordinate of the point located at the best-fit paraboloid and A_i is the projected area of the triangle on the XY local system.

Multiple aspects of the supporting structure of the reflector will affect the pattern of this error and a parametric analysis is usually of need.

4 Computational implementation and examples

A mathematical code to perform parametric analysis of the reflector prototypes was created and implemented in MATLAB. The latest version of the program has the following capabilities:

1. Geometric representation of the offset reflector.
2. Computation of the surface error for unstructured and structured meshes.
3. Parametric sweep of variables to determine optimal combination of parameters to reduce surface error.
4. Creation of STL files of the mesh that is used in electromagnetic simulations.
5. Preliminary mechanical design of the supporting articulated mast. The program creates an input file that can be imported in ANSYS Mechanical APDL to run mechanical analysis (natural frequency, static and thermo-elastic).
6. Form-finding algorithm for the ring's deployable mesh (still in development).

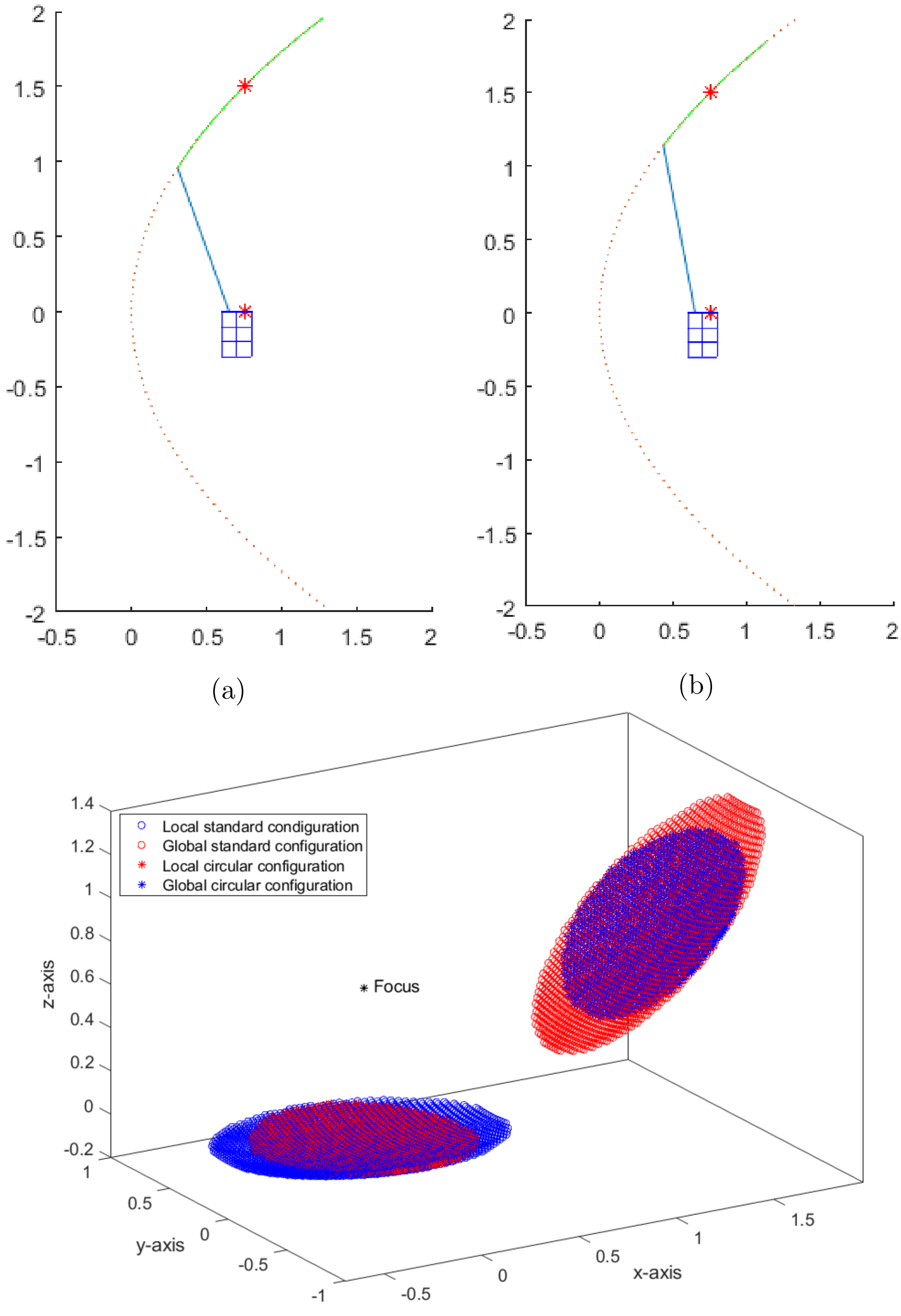
Figure (4.1) provides an illustration of the main differences between the standard and circular configuration of the reflector. The example provided corresponds to a reflector with a diameter of $D = 1$ [m] and a focus distance $f = 0.75$ [m].

Given the parameters defined by the user, a ring truss is created with a diameter of $D_r = 1.1D$. The design variable is the number of sides of the polygon of the ring.

Later on, an approximating mesh is constructed using the ring truss as the base. For the standard configuration, two mesh types are available within the software: unstructured mesh with fixed base connections (this mesh is created finding the intersection points of cables coming from each vertex of the ring structure) and structured hexagonal mesh with soft connections (see Figures (4.2) and (4.3)).

Given the multiple parameters involved in the design of the ring structure and the mesh, parametric sweeps can be performed and optimal combination of parameters can produce improved prototypes. Figure (4.4) shows the behavior of the root-mean-square error for different f/D ratio and varying the number of sides for an unstructured mesh and the number of soft divisions for a structured hexagonal mesh.

Figure (4.5) provides an example of the computation of the natural frequency for a prototype of the deployable mast. The program allows the user to select the main geometric values for the cross section as well as the material properties and type of analysis. The structure is comprised of beam units and cable diagonals to improve stiffness and load-capacity.

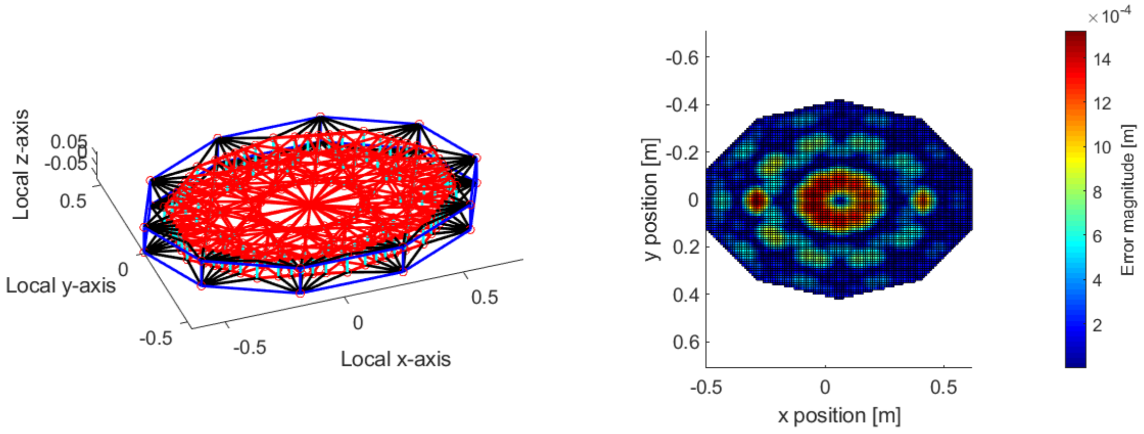


(a)

(b)

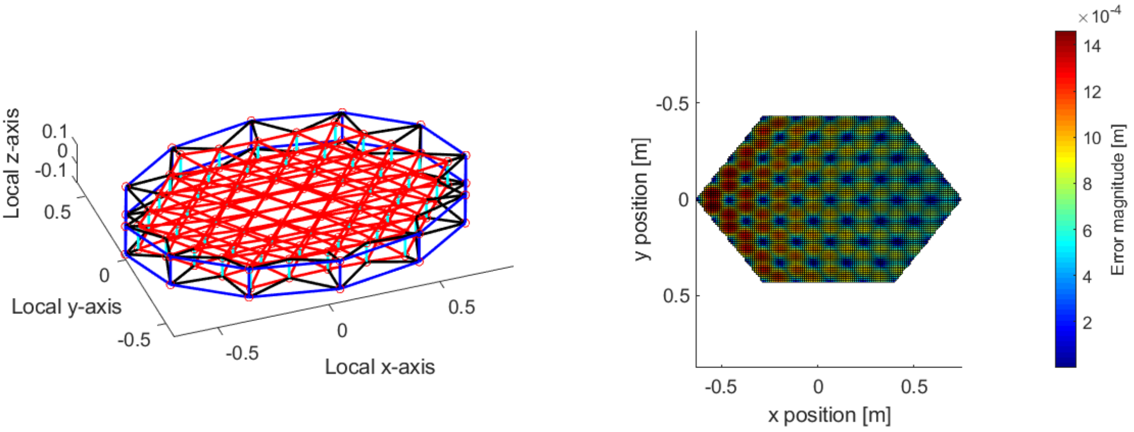
(c)

Fig. 4.1 – Comparison of standard (a) and circular configuration (b) with representation of the location of the CubeSat. Comparison of the reflectors in space (c).



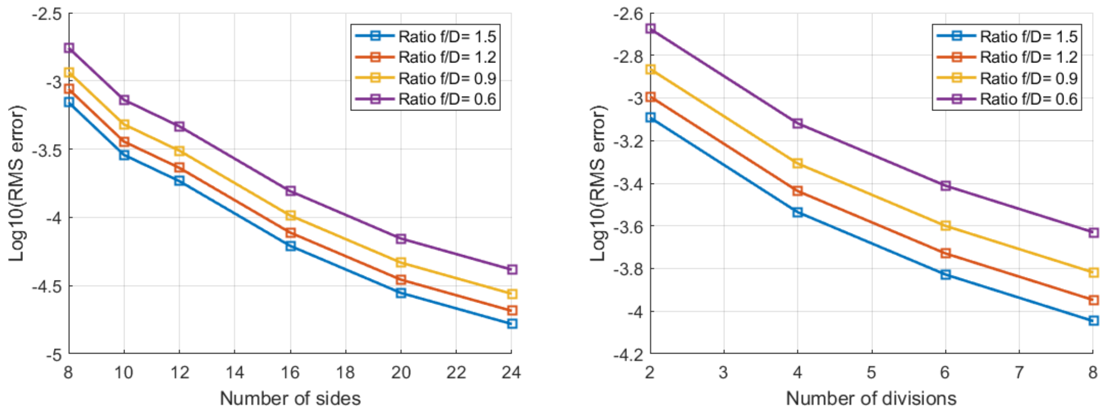
(a) (b)

Fig. 4.2 – Ring structure (a) and corresponding surface error (b) for an unstructured mesh of a reflector with $D = 1$ [m].



(a) (b)

Fig. 4.3 – Ring structure (a) and corresponding surface error (b) for a structured mesh of a reflector with $D = 1$ [m].



(a) (b)

Fig. 4.4 – Parametric analysis for unstructured (a) and structured (b) meshes for a reflector with $D = 1$ [m].

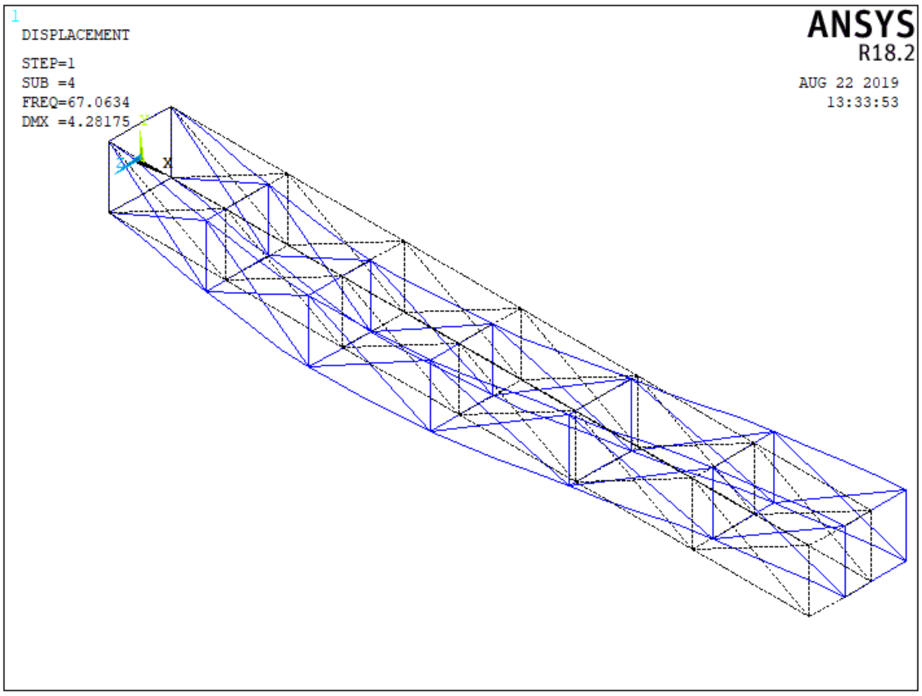


Fig. 4.5 – Third natural frequency of a supporting mast prototype made of CFRP.

5 Final remarks

It is worth pointing out that many more improvements and functions for the software are still in development and the author of this report will be partially involved in the process. New functions will include the creation of an input file for the geometry of the ring structure that could be used to analyze the effect of the rotational loads and temperature changes on the surface error of the reflector.

Moreover, the simulation procedures should include improvements regarding the effect of the springs, hinges and similar devices on the overall mechanical behavior of both the mast and the ring. Furthermore, efforts are currently directed towards the addition of pre-stress effects of the reinforcing cables to find optimal values that improve the load capacity of the structures and assure their successful deployment.

Additionally, preliminary basic simulations of the deployment for the mast structure using the software MSC Adams were performed but not included in this report.

Several of the results in this report are planned to be included in a paper to be presented on the Advanced Remote Sensing Instruments (ARSI) + Ka-band Earth Observations Radar Missions (KEO) Workshop 2019 organized by the European Space Agency (ESA) and to be held in November in Noordwijk, The Netherlands.

Bibliography

[1] Michael R. Aherne et al. “11-XII-7 Aeneas– Colony I Meets Three-Axis Pointing”. In: 2011.

[2] Alessandra Babuscia et al. “Inflatable antenna for cubesats: Motivation for development and antenna design”. In: *Acta Astronautica* 91 (2013), pp. 322–332. ISSN: 0094-5765. DOI: `https://doi.org/10.1016/j.actaastro.2013.06.005`. URL: `http://www.sciencedirect.com/science/article/pii/S0094576513001951`.

[3] N. Chahat et al. “CubeSat Deployable Ka-Band Mesh Reflector Antenna Development for Earth Science Missions”. In: *IEEE Transactions on Antennas and Propagation* 64.6 (June 2016), pp. 2083–2093. ISSN: 0018-926X. DOI: `10.1109/TAP.2016.2546306`.

[4] Bill Doncaster and Caleb Williams. *2017 Nano/Microsatellite Market Forecast.* SpaceWorks Enterprises, Inc. (SEI).

[5] C.Y. Lai. “Analysis and design of a deployable membrane reflector.” PhD thesis. Cambridge University, June 2001.

[6] Pei Li et al. “Dynamics of a Deployable Mesh Reflector of Satellite Antenna: Form-Finding and Modal Analysis”. In: *Journal of Computational and Nonlinear Dynamics* 11 (Apr. 2016). DOI: `10.1115/1.4033440`.

[7] Changguo Wang, Zhenmeng Xia, and H.F. Tan. “Initial Shape Design and Stability Analysis of Rib for Inflatable Deployable Reflector”. In: *AIAA Journal* 53 (Feb. 2015), pp. 486–492. DOI: `10.2514/1.J053469`.