


Article

Tie-system calibration for the experimental setup of large deployable reflectors

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Abstract: The tradeoff between the design phase and the experimental setup is crucial to satisfy the accuracy requirement of Large Deployable Reflectors. Manufacturing errors and tolerances change the RMS of the reflecting surface and require careful calibration of the tie rod system to be able to fit into the initial design specifications. To give a possible solution to this problem, here two calibration methods, respectively for rigid and flexible ring truss support, are described. Starting from the acquired experimental data on the net nodal coordinates, the initial problem of satisfying the static equilibrium at the measured configuration is described. Then, two constrained optimization problems, for rigid and flexible ring truss support, are defined to meet RMS accuracy of the reflecting surface modifying the tie lengths. Finally, a case study to demonstrate the validity of the proposed methods is presented.

Keywords: large deployable reflector; tie adjustment; experimental setup

1. Introduction

In recent decades, satellite communications have been increasingly spread thanks to the possibility of having high transmitting capacities at a relatively low cost compared to the establishment of a terrestrial broadcasting network. The deployable reflectors represent the most widely used type of structure because of their features such as large scale, high packaging efficiency, high accuracy and lightweight. Typically, its architecture consists of a deployable ring truss support, two cable nets, facing each other and linked by a series of tension ties, and an RF mesh attached to the backside of the front net. The most representative kind of this type of reflector is the AstroMesh [1], and its components are shown in Fig. 1. The electromagnetic performance of these antennas is closely related to the shape of the reflector surface. In turn, this depends on the position of nodes located on the front net. Therefore, it is clear how the measurement process of 3D node coordinates is to be made with extreme accuracy so as to avoid invalidating the real root mean square (RMS) value.

In recent years several measurement systems have been developed depending on the application area. Generally, they can be summarised in three categories:

- Photogrammetry
- Laser tracker
- Laser radar

The photogrammetry is a measurement technique that uses two-dimensional images of an object to obtain its dimensions. As depicted in Fig. 2 the photogrammetry is based exclusively on angle measurements: three-dimensional coordinates are calculated via optical triangulation (or *intersection*) of two or more images taken from different positions. The object to be measured is identified by targets mounted on it, usually made of reflective material so as to produce high contrast between the target and the background [2]. Typically, a calibrated scale bar is integrated into the object in order to reproduce it in true scale. At the end of measurements, a dedicated software calculates the 3D coordinates into the chosen Cartesian coordinate system (x, y, z).

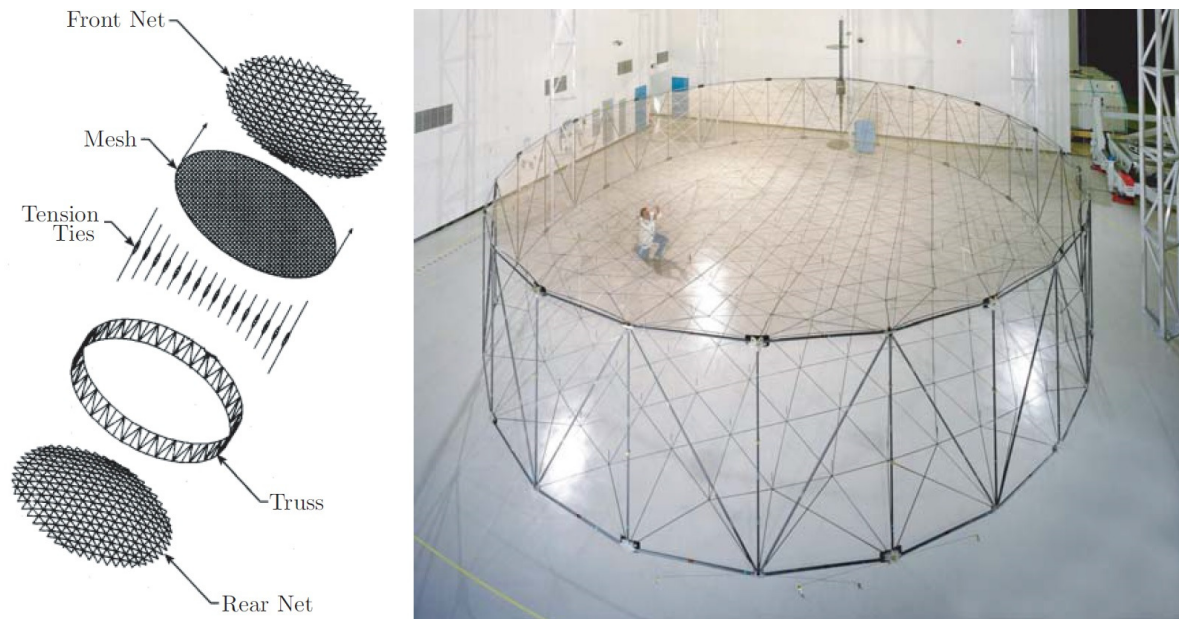


Figure 1. AstroMesh

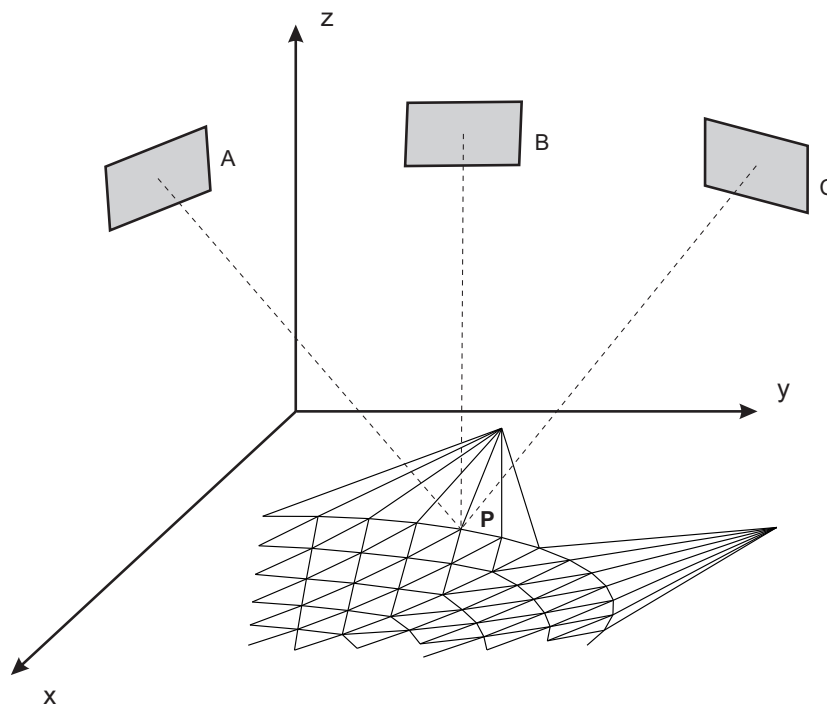


Figure 2. Photogrammetry

37 Laser tracker and laser radar, instead, are measurement systems based on the estimation of two
 38 angles and one length, as shown in Fig. 3. Two high-resolution encoders measure the azimuth (θ) and
 39 elevation (φ) angles, whereas the radial coordinate (r) relative to the center of the target is measured
 40 by means of optical interference [3]. Several types of target can be mounted, but the most widely used
 41 is the spherically mounted retroreflector (SMR). Differently from laser tracker, laser radar does not
 42 require a retroreflector. As a matter of fact, it is capable of measuring the surface of the object with just
 43 1% of the reflected signal [4].

44 Each of these measurement systems, however, has advantages and disadvantages, which need
 45 to be assessed on the basis of various factors. Van Gestel *et al.* [4] identify the influencing factors to
 46 be taken into account before making the measurement, i.e.: task requirements, part restrictions and

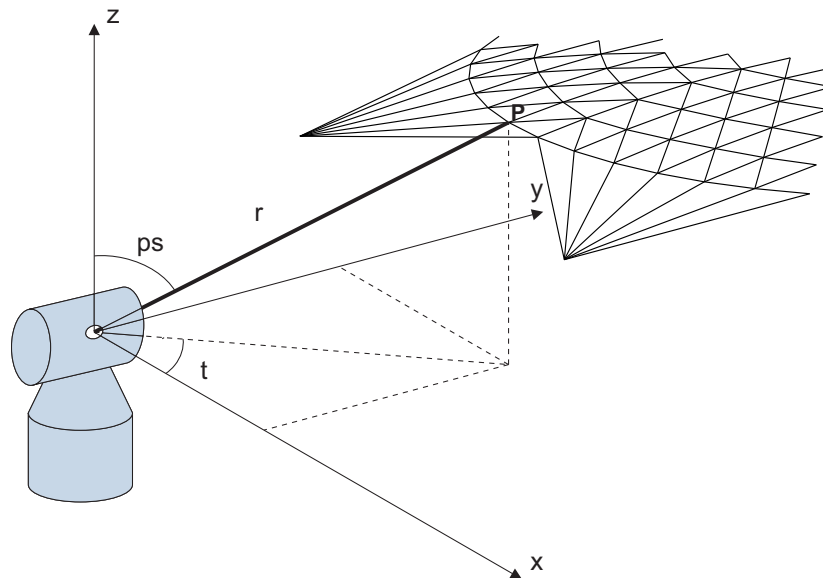


Figure 3. Laser tracker

47 environmental restrictions. Regarding task requirements, the main element to be considered when
 48 measuring the position of nodes is the accuracy, since the permissible RMS error on the reflecting
 49 surface is less than 1 (mm). Whilst the laser tracker has errors on the order of $1 \mu\text{m}$, it is too costly due to
 50 the high price of each SMR and given the number of nodes (at least a hundred). The photogrammetry
 51 turns out to be the best choice [5,6], considering the affordable cost and accuracy of the measure.
 52 Furthermore, the possibility of obtaining multiple images from different angles makes it possible to
 53 overcome the lower accuracy of the angular encoders of laser trackers.

54 The acquisition of node coordinates is essential for the next calibration step in order to meet the
 55 RMS design requirements of the reflecting surface. Generally, the main strategies followed by LDR
 56 developers and designers is to use the tie system, connecting front and rear nets, to locally move
 57 single nodes. This operation is long and delicate but allows to adjust different error sources such as
 58 manufacturing errors [7–9], material definition errors, clearance [10,11], friction [12,13], hysteresis [14],
 59 mechanical vibrations [15,16], not perfect behaviour of elastic properties of components. This paper
 60 describes a method for the tie system calibration of LDRs with rigid or flexible ring truss. To our
 61 knowledge this topic has not been deeply investigated in the literature and the adjustment phase is
 62 entrusted with proprietary solutions of LDR companies. The outline of this paper is as follows. In
 63 Section 2 the problem of correcting the parameters to satisfy the static equilibrium in the deployed
 64 configuration is first addressed. Then, the method to find the necessary corrections to the tie-system
 65 is discussed for the two cases of LDR with rigid and flexible ring truss. In Section 3 the method
 66 is applied to a LDR with asymmetric ring truss developed by Thales Alenia Space. A simulated
 67 error distribution is superimposed to the design configuration to represent a real experimental test.
 68 Tie-system corrections, expressed in terms of length elongation or shortening, necessary to meet RMS
 69 design requirement are obtained for both rigid and flexible ring truss cases. Finally, conclusions close
 70 the paper.

71 2. Experimental setting for calibration

72 Once the antenna has been manufactured, it is necessary to carry out some experimental tests
 73 in order to check for the RMS of the reflector in the deployed configuration. To do this, the first
 74 operation consists of measuring the position of all nodes of the nets with respect to a reference system
 75 through one of the methods described in the Introduction. Due to different sources of errors such as
 76 manufacturing errors, assembly errors, the deployed configuration will be different from the design
 77 configuration and the RMS will be usually greater than the design requirement. Even the measurement

operation of the nodes coordinates will be affected by errors. Laser trackers and photogrammetry have errors on the order of $1 \mu\text{m}$; while laser radar reaches $0.1 \mu\text{m}$. Anyway, errors related to measurement systems maintain significantly below the proceeding mechanical errors. In the following, two methods for the experimental setting of the rigid and flexible ring truss support are described.

Several experimental methodologies [17–20] based on multibody approach have been developed [21–29]. Recently, methods based on the Fuzzy logic [30–34], neural networks [35] and genetic algorithm have been applied for the tensioning of space trusses [36,37]. The proposed methods act on the tensioning system of the ties to fix the errors coming from the construction of the antenna.

2.1. Rigid ring truss support: construction length determination

Tie cables regulation is usually independent from the actuators used for the LDA deployment [38–40] and from the control system [41–44]. Here, the method to regulate tie cables tension of an antenna with rigid ring truss support is first described. Once the deployment has been carried out and all node coordinates of the net have been measured the reflective surface deviated from the design configuration due to mechanical errors. As a consequence of this deviation, the system of equilibrium equation is not satisfied for the current configuration. Then, denoting with E_{ij} , A_{ij} , L_{ij} , L_{ij}^0 the Young modulus, the cross-section area, the measured length, the construction length of cable/tie ij , respectively and with k_{ij} the spring constant of tie ij , the system of nonlinear equations for each free node i , with j adjacent nodes, is not satisfied:

$$\begin{cases} \sum_j [E_{ij} A_{ij} \frac{L_{ij} - L_{ij}^0}{L_{ij}^0} + k_{ij} (L_{ij} - L_{ij}^0)] \frac{x_i - x_j}{L_{ij}} \neq 0 \\ \sum_j [E_{ij} A_{ij} \frac{L_{ij} - L_{ij}^0}{L_{ij}^0} + k_{ij} (L_{ij} - L_{ij}^0)] \frac{y_i - y_j}{L_{ij}} \neq 0 \\ \sum_j [E_{ij} A_{ij} \frac{L_{ij} - L_{ij}^0}{L_{ij}^0} + k_{ij} (L_{ij} - L_{ij}^0)] \frac{z_i - z_j}{L_{ij}} \neq 0 \end{cases} \quad (1)$$

where x_l , y_l and z_l are the measured Cartesian coordinates of the l -th node. It is noteworthy to remark that the only measured parameters are the node coordinates; while the *measured* length is derived using the Euclidian norm. The remaining parameters of the previous system are design parameters instead, each affected by different types of error. Here, we choose to gather all these errors inside the construction length L_{ij}^0 defined as the distance between the centers of the eyelets i and j belonging to the same cable, as shown in Fig. 4. This choice is motivated by the fact that the construction length of the cables is affected by two main sources of errors such as the *manufacturing errors*, generated during the cutting operation of CNC machines [45], and the *assembly errors*, coming from a bad placement of the eyelets necessary to connect two or more cables. In order to restore the equilibrium condition in system (1) only the design parameters can be adjusted while the measured parameters describe the real configuration of equilibrium: the measured configuration is already of equilibrium, thus system (1) is to be satisfied in this configuration without changing node coordinates.



Figure 4. Layout of a cable: the construction length L_0 is affected by *manufacturing errors*, generated during the cutting operation and *assembly errors* coming from a bad placement of the eyelets necessary to connect two or more cables

Then, as each cable works in traction force only, the constraint $L_{ij} \geq L_{ij}^0$ must be imposed. To solve the system of nonlinear equation, Matlab[®] provides the command `fsolve`, but it does not allow to include any constraint. To overcome this problem it can be used the nonlinear programming solver

fmincon by giving a constant objective function and setting the eq.(1) as the nonlinear equality constraint, in addition to the linear inequality constraint $L_{ij} \geq L_{ij}^0$. The resulting constrained optimization problem is described below:

$$\begin{cases} \text{find} & L_{ij}^0, \forall \text{cables and ties} \\ \text{min} & \text{constant objective function} \\ \text{s.t.} & L_{ij} \geq L_{ij}^0 \end{cases} \quad (2)$$

Hence, a first check is required. Because the springs used in tension ties require a prestress value, here denoted with F^0 , representing the minimum value necessary for their activation, the condition $F_{ij} \geq F_{ij}^0$ for each tension tie cable must be verified, where

$$F_{ij} = k_{ij}(L_{ij} - L_{ij}^0) \quad (3)$$

99 is the spring force of tie ij . If the condition is satisfied the next step can be conducted, otherwise the
100 spring belonging to the tie which has failed the test must be replaced and the algorithm starts again
101 calculating the array \mathbf{L}^0 of all construction lengths.

102 2.2. Rear nodes determination

103 In the event that only the coordinates of the nodes of the front net are known by measurement,
104 before implementing the algorithm described above, the rear nodes coordinates have to be estimated.
105 Their coordinates are initialized with the design data and the system (1) for each free node of the front
106 and rear net is implemented. It can be noted the dualism between the two methods: in the former, the
107 unknowns are the construction lengths, in the latter the rear node coordinates. Then, the construction
108 lengths are obtained as a consequence using the Euclidian norm. We checked that both methods lead
109 to the same results, unless negligible errors, if the experimental configuration is not too distant from
110 the design one.

111 2.3. Rigid ring truss support: tie calibration

112 Once the configuration satisfying the static equilibrium has been found, the algorithm continues
113 with the estimation of the values of stretching or shortening for each tension tie cable that ensure that
114 the surface accuracy of the reflector can be met. The Figure 5 shows the screw adjustment system of a
115 tie. One fixed part is connected to a node of the front net while one mobile part, adjustable through a
116 screw, is connected to a node of the rear net. Now, the system of nonlinear equation of each free node i
117 can be written as follows:

$$\begin{cases} \sum_j [E_{ij} A_{ij} \frac{L_{ij} - L_{ij}^0}{L_{ij}^0} + k_{ij}(L_{ij} - L_{ij}^0 + \delta L_{ij})] \frac{x_i - x_j}{L_{ij}} = 0 \\ \sum_j [E_{ij} A_{ij} \frac{L_{ij} - L_{ij}^0}{L_{ij}^0} + k_{ij}(L_{ij} - L_{ij}^0 + \delta L_{ij})] \frac{y_i - y_j}{L_{ij}} = 0 \\ \sum_j [E_{ij} A_{ij} \frac{L_{ij} - L_{ij}^0}{L_{ij}^0} + k_{ij}(L_{ij} - L_{ij}^0 + \delta L_{ij})] \frac{z_i - z_j}{L_{ij}} = 0 \end{cases} \quad (4)$$

This system is similar to (1), used to determine the vector \mathbf{L}^0 , with the difference that, this time, the variables to be found are the stretching/shortening values δL_{ij} and the coordinates of the free nodes of the front and rear net. The values δL_{ij} can be positive or negative: here we assume positive values for tie shortening and negative for tie stretching. Also this system is subject to some constraints. One condition for all net cables is that $L \geq L^0$. For the tension tie cables, for which the values δL_{ij} are to be considered, the constraint condition is that the final force F_{ij} must be of traction:

$$F_{ij} = k_{ij}(L_{ij} - L_{ij}^0) + k_{ij}\delta L_{ij} \geq 0 \Rightarrow L_{ij} + \delta L_{ij} \geq L_{ij}^0 \quad (5)$$

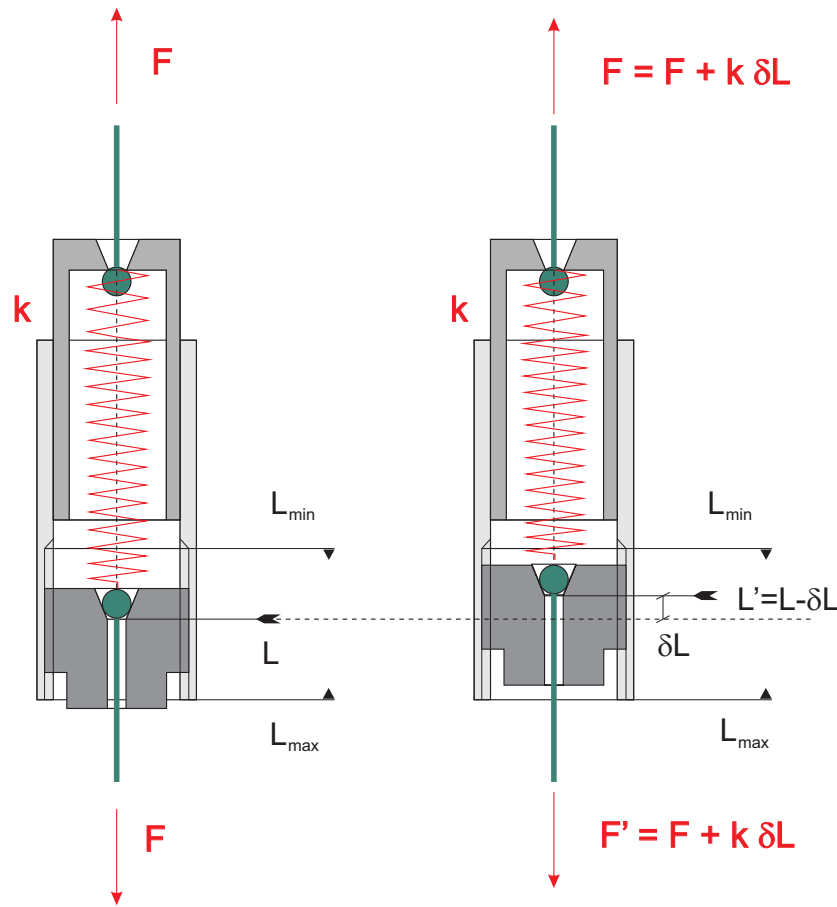


Figure 5. Screw adjustment tie system: (left) tie system before the adjustment; (right) tie system after the screw regulation.

118 Finally, the third constraint is related to the surface accuracy since the RMS error must be lower than
 119 the desired design value RMS_{target} . This is a typical constrained optimization problem largely used in
 120 design optimization of complex systems [46–49] and mechanisms [50–52]. The optimization problem
 121 can be summarised as follows:

$$\left\{ \begin{array}{ll} \text{find } \mathbf{x}_1, \mathbf{y}_1, \mathbf{z}_1 \text{ and } \delta \mathbf{L} & \\ \text{min} & \text{constant objective function} \\ \text{s. t. } L_{ij} \geq L_{ij}^0 & \text{net cables} \\ L_{ij} + \delta L_{ij} \geq L_{ij}^0 & \text{tension tie cables} \\ RMS \leq RMS_{target} & \text{reflecting surface requirement} \end{array} \right. \quad (6)$$

122 where \mathbf{x}_1 , \mathbf{y}_1 and \mathbf{z}_1 are the free node coordinates and $\delta \mathbf{L}$ is the array containing all corrections δL_{ij} .
 123 The RMS is calculated by measuring the minimum distance of the free nodes of the front net compared
 124 to the ideal surface of the paraboloid (citazione primo articolo). The initial condition for the free nodes
 125 is represented by their experimental measurement, while the guess value for $\delta \mathbf{L}$ is set equal to zero.

126 2.4. Flexible ring truss support

127 The truss support is generally manufactured in carbon fiber and is therefore reasonable to consider
 128 the truss deformation under the effect of the tension of the cable net.

129 The elastodynamic model of the flexible ring truss support can be found using analytic techniques
 130 combined with the Matrix Structural Analysis, [53–56], elliptic integrals [57,58], FEM models [59–61],
 131 and flexible multibody formulations [62].

132 This implies the displacement of the nodes connected to the truss support, also called vertices,
 133 when the net system is tensioned. By considering the stiffness of the structure, the nonlinear system (4)
 134 described in the previous section becomes as follows:

$$\left\{ \begin{array}{l} \left[\sum_{j=1}^{c-r} E_{ij} A_{ij} \frac{L_{ij} - L_{ij}^0}{L_{ij}^0} + \sum_{j=1}^r (E_{ij} A_{ij} \frac{L_{ij} - L_{ij}^0}{L_{ij}^0} - k_{xx_{ij}} (x_{v_j} - x_{v_j}^0)) \right. \\ \quad \left. + k_{ij} (L_{ij} - L_{ij}^0 + \delta L_{ij}) \right] \frac{x_i - x_j}{L_{ij}} = 0 \\ \left[\sum_{j=1}^{c-r} E_{ij} A_{ij} \frac{L_{ij} - L_{ij}^0}{L_{ij}^0} + \sum_{j=1}^r (E_{ij} A_{ij} \frac{L_{ij} - L_{ij}^0}{L_{ij}^0} - k_{yy_{ij}} (y_{v_j} - y_{v_j}^0)) \right. \\ \quad \left. + k_{ij} (L_{ij} - L_{ij}^0 + \delta L_{ij}) \right] \frac{y_i - y_j}{L_{ij}} = 0 \\ \left[\sum_{j=1}^{c-r} E_{ij} A_{ij} \frac{L_{ij} - L_{ij}^0}{L_{ij}^0} + \sum_{j=1}^r (E_{ij} A_{ij} \frac{L_{ij} - L_{ij}^0}{L_{ij}^0} - k_{zz_{ij}} (z_{v_j} - z_{v_j}^0)) \right. \\ \quad \left. + k_{ij} (L_{ij} - L_{ij}^0 + \delta L_{ij}) \right] \frac{z_i - z_j}{L_{ij}} = 0 \end{array} \right. \quad (7)$$

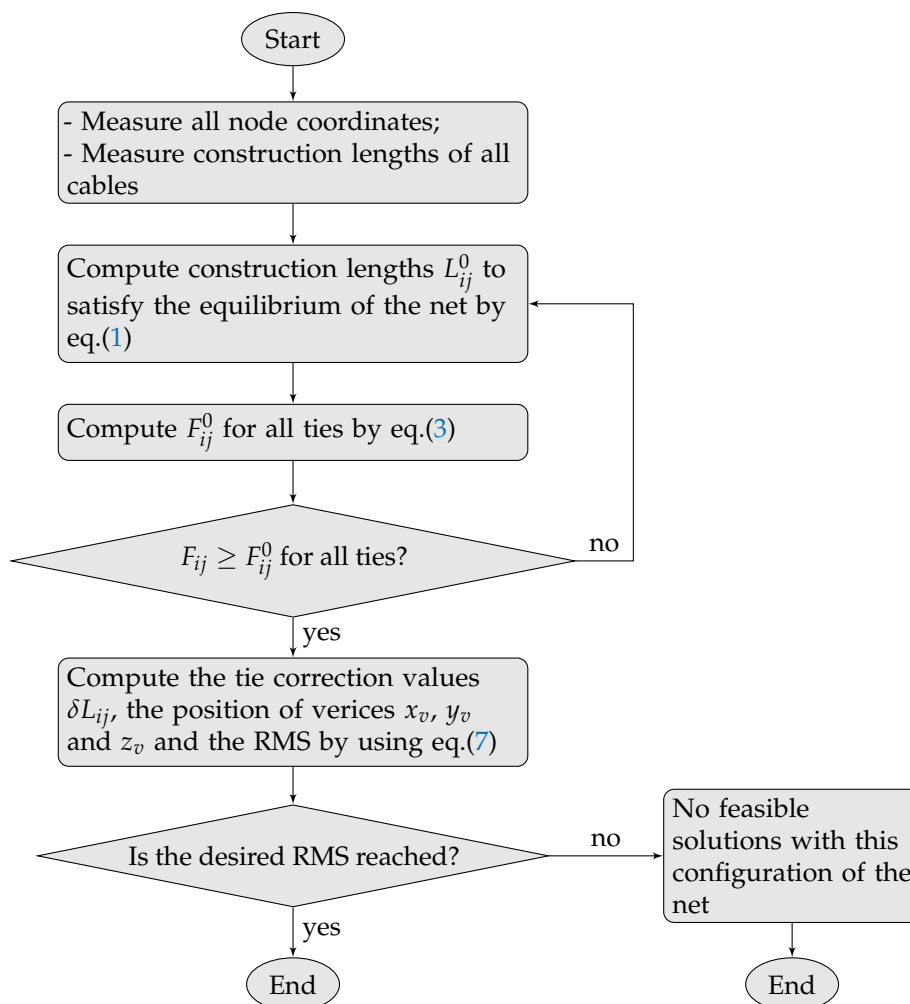


Figure 6. Algorithm of the method

135

136 where c is the total number of cables connected to the i -th node; r is the number of rods, x_v, y_v
 137 and z_v are the unknown coordinates of the j -th vertex and x_v^0, y_v^0 and z_v^0 the initial coordinates of the

138 vertex itself. The stiffness of the truss support can be represented as a three-dimensional bushing, with
 139 stiffnesses k_{xxij} , k_{yyij} and k_{zzij} , connecting the rods to the vertex, as shown in Fig. 7. The constrained
 140 optimization (6) still applies to this flexible ring truss case and the overall algorithm is summarised in
 141 the flowchart of Fig. 6.

142 3. Results

143 In order to verify the validity of the proposed method, the case study of an asymmetric large
 144 deployable reflector, designed by Thales Alenia Space [63], is described. Relevant parameters and
 145 geometrical data are listed as follows:

- 146 • Focal length: 6 (m)
- 147 • Number of free nodes: 296
- 148 • Number of vertices: 14
- 149 • Number of total cables: 1044
- 150 • Cable section: 4 (mm)^2
- 151 • Young modulus of cables: $8.3 \times 10^{10} \text{ (N/m)}^2$
- 152 • Initial RMS error: 0.5872 (mm)
- 153 • Design value of the RMS faceting error: 0.21 (mm)

154 The value of spring constant in tie cables ranges from $2 \times 10^3 \text{ N/m}$ to $68 \times 10^3 \text{ N/m}$ with radial
 155 step of $11 \times 10^3 \text{ N/m}$ starting from the centre (central node) to the outer ring cables. The initial RMS
 156 error on the front net was simulated by introducing an additional value to each node proportionally to

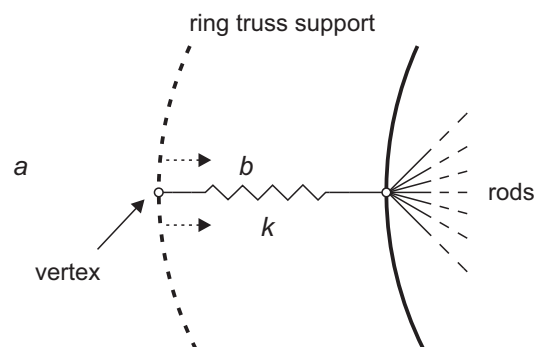


Figure 7. Displacement of the vertex due to the deformation of the flexible ring truss support

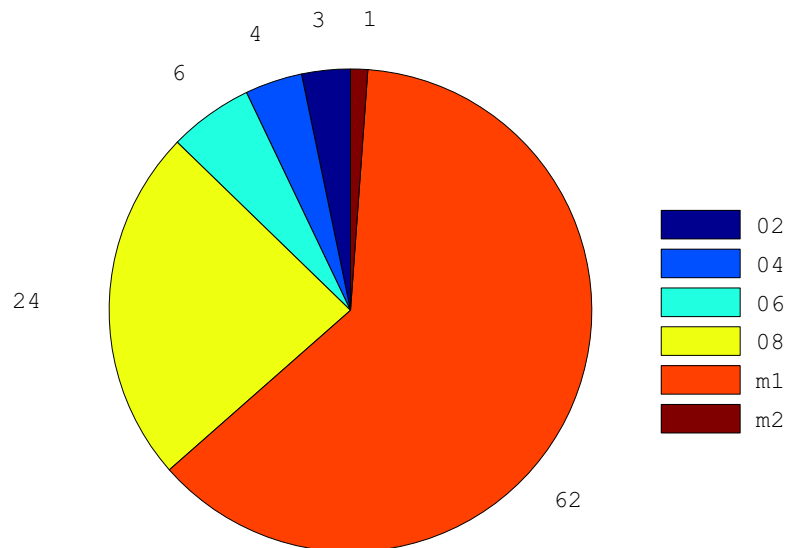


Figure 8. Pie chart of the error (absolute value), grouped by measuring ranges (mm), between the measured construction lengths and those obtained by solving equilibrium in system (1).

157 the length of the tie connected to it. By imposing the equilibrium in the system (1) we can determine the
 158 construction lengths described in Section 2. Nevertheless, from Fig. 8 it can be noted that the maximum
 159 error e_{L0} obtained is about 1 (mm), representing only 1% of total cables; the largest percentage (86%)
 showing an error between 0.6 (mm) and 1 (mm).

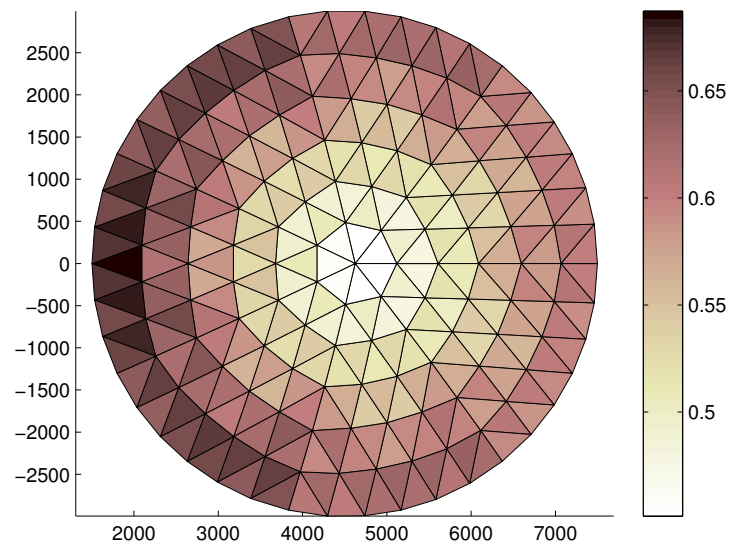


Figure 9. Faceted RMS (mm) of the front tension truss in the initial configuration.

160 In Fig. 9 the local faceting error for the chosen initial configuration is shown. The local faceting
 161 error is calculated considering the centroid of the triangular facets in which the surface can be
 162 decomposed [64–67]. As it can be observed, the faceting error follows the shape of the asymmetric
 163 reflector because the chosen error is proportional to the tie lengths. As a matter of fact, the central zone
 164 is the one with the shortest cables and therefore with the lowest faceting error. On the contrary, the tie
 165 lengths, and consequently the errors, grow moving from the centre to the outer perimeter of the net.

166 The optimization method described in the previous sections is first applied to the rigid ring truss
 167 support. The Figure 10 shows the error of each free node of the front net with respect to the ideal
 168 surface coupled with the stretching/shortening value necessary to reach the desired surface accuracy.
 169 The reason why correction values are all positive is that the initial error is simulated by positioning all
 170 nodes of the front net above the ideal surface, so there is the need to shorten the tie lengths to satisfy
 171 the RMS design value. The bars are grouped by spring constant value.

172 The corresponding faceting error is shown in Fig. 11. As it can be observed the RMS of the faceting
 173 error is lowered till the required value of 0.2036 (mm) furnished as specification.

174 Then, the same analysis has been performed for the flexible ring truss support. It can be noted that
 175 in the Fig. 12, the correction values are lower than the corresponding values with rigid truss support:
 176 this is because the additional tensioning of ties further deforms the shape of the truss support resulting
 177 in a closure of the support itself [68]. As a result, this causes a slight lowering of the front net thus
 178 reducing the shortening action of tie lengths. Finally, the Fig. 13 shows the faceting error distribution
 179 on the front net. Even in this case the final RMS faceting error reached 0.2045 (mm) representing
 180 the design value of the RMS. Comparing the two Figs. 11 and 13 it can be observed that the faceting
 181 error distribution is more uniform for the flexible ring truss support. This result can be explained
 182 considering that the deformation of the truss support relaxes the front and rear tension truss systems
 183 making the tension distribution more uniform.

184 Moreover, other simulations with different initial RMS errors revealed that, with the given design
 185 data, the maximum initial RMS error which can be fixed is about 1 (mm). Beyond this limit value, a
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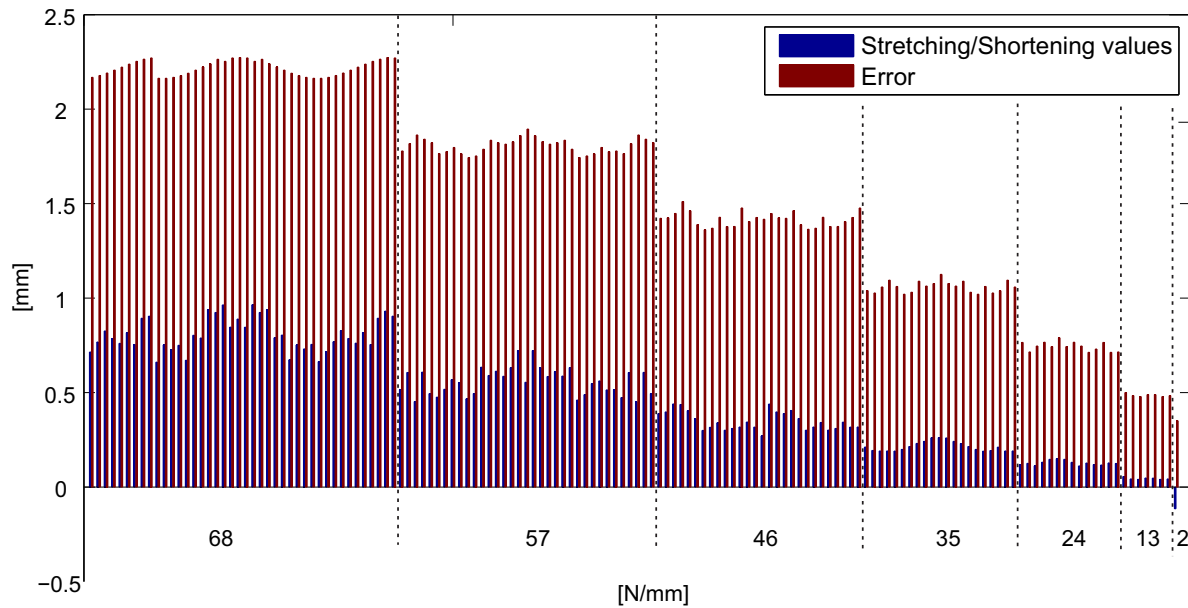


Figure 10. Error and correction values (rigid case)

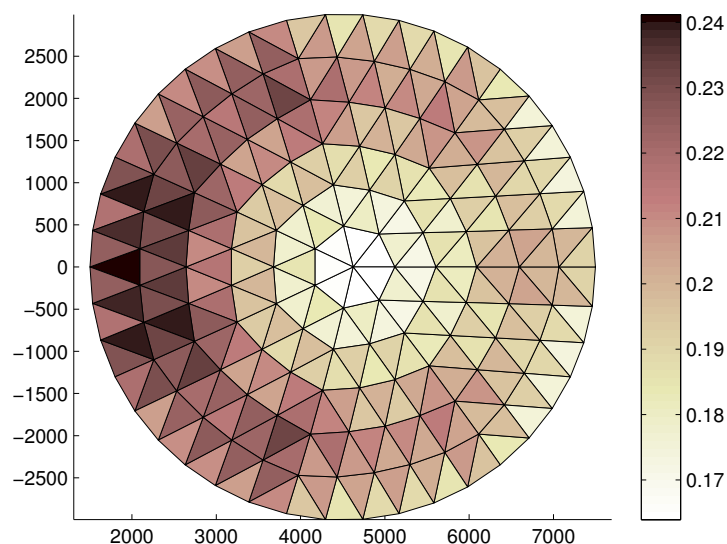


Figure 11. Faceting error (mm) distribution on the front tension truss obtained for the rigid ring truss support

187 revision of design data is needed. This demonstrates the validity of the method only for small RMS
188 errors.

189 4. Conclusions

190 In this paper a method for the tie-system calibration of Large Deployable Reflectors (LDRs) is
191 provided. The LDRs are very sensitive to errors and usually require a careful experimental setup to
192 meet the design requirement of surface accuracy. Due to manufacturing errors, clearance, friction, not
193 perfect behaviour of materials the real configuration moves away from the design configuration and a
194 fine calibration is needed to improve the quality of the reflecting surface expressed in terms of closeness
195 to the ideal paraboloidal geometry. The proposed method follows two steps: the determination of the
196 parameters satisfying the static equilibrium in the real deployed configuration; the fine calibration

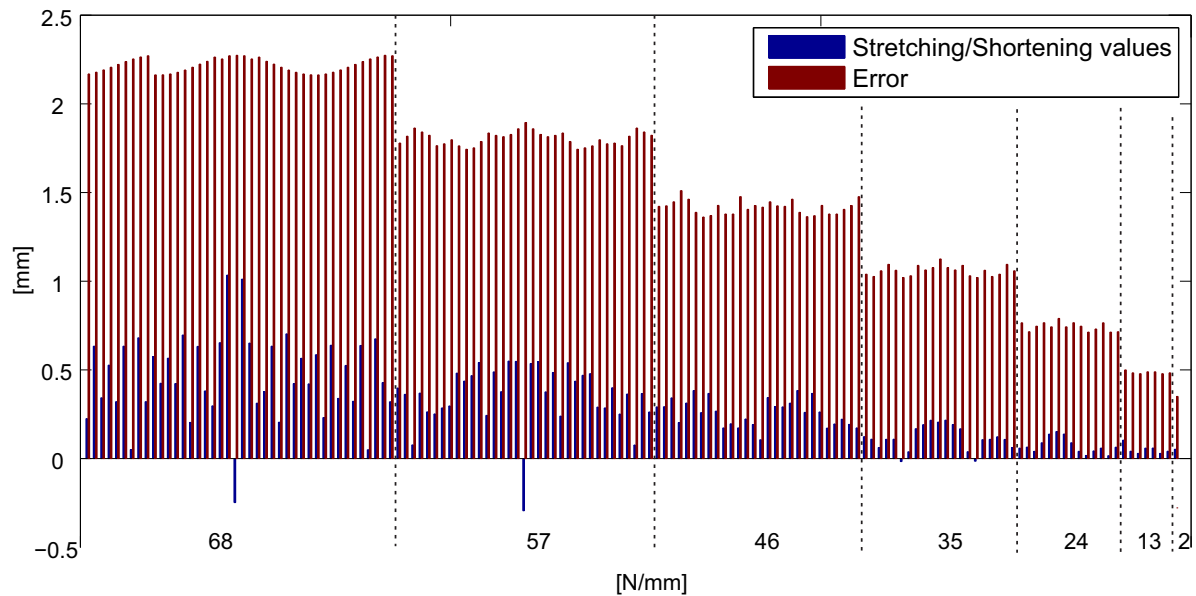


Figure 12. Error and correction values (flexible case)

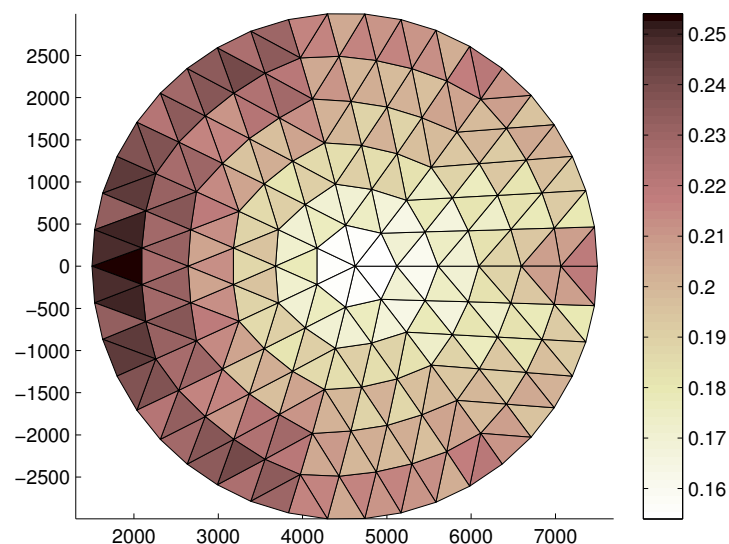


Figure 13. Faceting error (mm) distribution on the front tension truss obtained for the flexible ring truss support

197 to meet RMS design requirements. For the first step a constrained optimization problem has been
 198 proposed to find the cable construction lengths once all node coordinates have been measured. The
 199 second step has been developed acting on the system of screw adjustable ties. A further constrained
 200 optimization problem has been formulated to find the length corrections of each tie. Using the same
 201 approach the cases of LDR with rigid and flexible tension truss have been studied. Finally, the method
 202 has been applied to a LDR with asymmetrical ring truss designed by Thales Alenia Space. Considering
 203 an initial RMS of 0.58 (mm) the results, not yet validated by experimental test, seemed comforting in
 204 reaching the design RMS. The method convergency depends on the starting and desired RMS. Here,
 205 the convergency has been insured up to the reasonable high initial RMS value of 1 (mm): beyond this
 206 value the tie system is not able to reach the equilibrium and satisfy the constraints and a different
 207 solution should be adopted.

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215 Abbreviations

216 The following abbreviations are used in this manuscript:

217	MDPI	Multidisciplinary Digital Publishing Institute
	DOAJ	Directory of open access journals
218	TLA	Three letter acronym
	LD	linear dichroism

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