# Mechanical Diagnosis of Coronelli's Globes with a View to their Straightening-up

***Philippe Galimard*[1] Alain Cointe[1] *Emmanuel Maurin*[2]**
Unité des Sciences du Bois et des Biopolymères UMR 5903 -69, route d'Arcachon -33612 CESTAS[1]
Laboratoire de Recherche des Monuments Historiques -29, rue de Paris -77420 Champs sur Marne[2]

## I. Introduction

Known as Coronelli's globes (figures 1) these two spheres with a wooden structure, a 3.80m diameter and a weight of 23 kN were built and painted in 1683 to represent the Earth and the sky. They were presented to the public until the end of the 19th century in their initial position (their North-South axis with a 23° vertical angle) and they have since then been transported and stocked in a horizontal North-South axis position. The North-South axis is materialised in its ends by a full metal disc with a length of 28 cm and a 60 mm diameter that serves as a support in both positions and enables the rotation of the globes. Their structure is made of 3 metre long and 10 centimetre wide at the equator spindle-shaped wooden arches, each hemisphere being made up of 120 such arches. The internal structure is accessible through a trapdoor and ventilated by two 15 cm-diameter opposed openings. The wood is covered with a plaster shell onto which strong linen has been glued. A layer of coating and a number of finer plaster-coated linen layers are then superimposed and one last layer of linen made up of a number of pieces was prepared to act as support for the paintwork. These globes now belong to the collections of the Bibliothèque Nationale de France who would now like to make these works of art accessible to the public once again.

An initial diagnosis of the material will show that the structure only presents a structural pathology which concerns the angle of a few degrees from the horizontal of the polar supports of the globes.

*Are the angles of the polar supports likely to compromise the straightening-up of the globes?* Corollary : *What is the mode of transmission of the weight of the globes on their supports when straightened-up ?*

Two simultaneous studies have been carried out : 1 – The modelling of the transmission effort between the globe and its metal support from X-rays.

2-The measurement of angular variations during the rotation of the globes in order to detect possible wood/metal play in connection to wood damage.


**Figure 1 :** a) The terrestrial globe b) The celestial globe

## II. Initial Diagnosis

An initial diagnosis concerned the quality of the wood of the load-bearing structure. The results are as follows :

The wood is covered with a coat of red lead protection paint that was probably applied in the late 19th or early 20th century. The structure has ventilation openings that enabled an adequate ventilation on the internal wooden structure prior to the application of the red lead paint. The few exposed areas of wood do not show any degradation. There has therefore not been any development of decay of the wood since the restoration work carried out in 1980.

The load-bearing axes of the globes have a horizontal angle of 1° to 3°. Each globe is made up of two structurally independent hemispheres mechanically linked by :

- o The equatorial line.
- o The bolting together of two wooden beams in prolongation of the metal load-bearing axes to a metal joint cover.

The rigidity of each hemisphere is provided by the shell made of longitudinal boards that end on an internal polar disc (figure 2). The shape of these boards lattes is maintained by hoops connected to the central half beams with small radiating pieces of wood.

The small radiating pieces of wood (figure 2) are orthogonal at the end connected to the axial beams and do not therefore allow the transmission of the normal component to the axis. Identification of the wood : casing : Quercus (oak), Inner frame : Larix (oak) , Poles : Pomoïdees Pirus type (larch)

**Figures 2 :** inner and outer view of the polar disc

## III. Transmission of the weight of the globes to the supports

Depending on the disposition of the globes, the weight is transmitted to the supports : through shear /bending when the polar axis is horizontal (since 1901), through a normal compression effort when the polar axis is vertical and by a coupling of both forces when the polar axis is at an angle. This is the case for the position of the final presentation : the transmission of the weight for a 23° angle is partly through shear /bending (15%) and partly through a normal compression effort (85%).

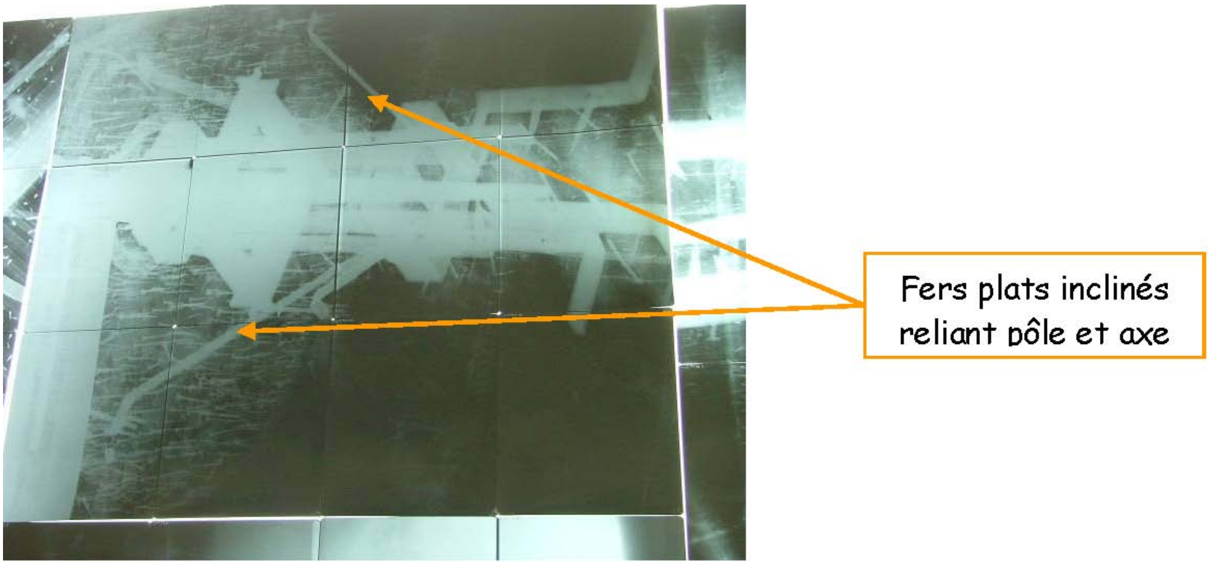



**Figure 3 :** X-ray of the link area

1 The polar axis consists of two nails driven into the half beams along a longitudinal axis. The half beams are flanged with metal collars in two sections accessible through the interior of the globes and a third one between the external pole and the internal polar plateau.
2 The fastening of the flat iron bars to the plateau is lightweight and cannot transmit the tensile weight of the globe to the axis and hence to the supports.
3 The bent iron bars are nailed to the central beam : their function is unknown but does not affect the structure in operation (assembly-related function ?).
4 Flat iron bars that are along the wooden beams and bolted to the latter clearly show up. These flat iron bars go through the internal wooden polar plateau.
5 There does not seem to be any other metal element, besides nails, than the previously mentioned elements, despite the apparent opacity on certain photos.

The following figure is based on measurements made on the accessible parts and the information and estimates of distances from the X-rays for the items that are not visually accessible.

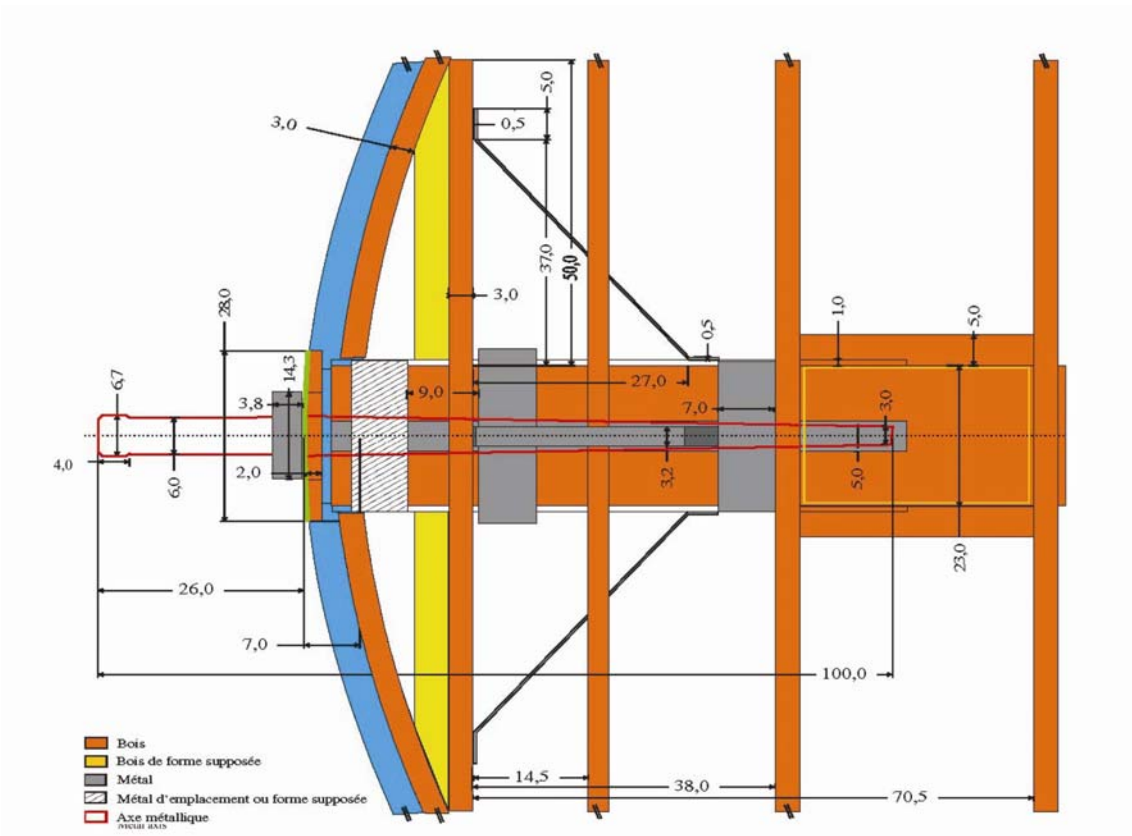



**Figure 4 :** Details of a pole

The principle of weight transmission through bending does not raise any questions. The weight of each hemisphere is transmitted through the poles : the small radiating pieces of wood have no other function but that of maintaining the spherical shape. The nail is submitted to the bending/shear between the pole and the support. It is possible to determine its bending strain.

## Calculation of the deformation of the axes due to the weight of the globes

Steel deformation due to strain generated by the weight of a globe can be determined considering that each steel bar (20 cm long and with a 6 cm diameter) bears half of the weight of the globe, i.e. 1.125 tons as a punctual load at the point of the clamped joint. Steel resistance is set at 200 MPa, which corresponds to a maximum bend momentum of 2520 N.mm ; the quality of steel at the time is most uncertain and must be determined with greater precision. Modern construction steel has a greatly superior minimal resistance.

- The maximum deflection induced by the weight can reach a 0,002 rad (0,11°) angle which only represents 10 % of the measured deflections. The globe's own weight does not therefore provoke these distortions.
- The resulting momentum at the clamped joint due to the weight of the globe is 2500 N.mm.

## Conclusion

The deflection of the supports observed when the globes were stored cannot be attributed only to the sole bending of the metal axes due to the weight of the globes. It is however possible that they be due to the conjunction of weak resistance steel and a hazardous manipulation. The probability remains weak when considering the recurrence of the phenomenon on the four supports. The progressive indentation of the wood by the bars due to inappropriate storage over a long period of time remains the most probable cause.

The small transversal pieces of wood cannot transmit the strain, because, as their diameter is small and they are orthogonal when they reach the axes, the weight is transmitted by the wooden lattice of the envelope at the polar plates. The information collected from other globes with a similar build, but of a lesser size confirm this mode of operation, although polar plates and axes make up a single block.

The leaning flat iron bars (figure 3) cannot transmit the strain to the main axis as their dimension is not sufficient : buckling under compression and insufficient traction link.

The plate rests on the invisible flange (figure 3) of the axis situated between the plate and the pole. The analysis of the X-rays shows flat iron bars connected to this flange which then come out of the polar plates along all four sides of the wooden axial beam. It is also possible to observe that these flat iron bars are solidly fastened (nailed?) to the beam. The path of the strain is therefore as follows :
The lattice rests on the periphery of the wooden polar plate, the latter rests on a flange
the metal flange is made up of flat iron bars running along the central wooden beam and going through the plate
the flat iron bars are fastened to the beam with high diameter nails ( ?).

## IV. Numerical modelling of the behaviour of the plates

We wanted to corroborate this hypothesis by simulating the condition of strain and deformation of the plate due to the weight of the envelope resting on the flange. A numerical modelling was conducted using the ABAQUS finite element software.

The calculation hypotheses are conservative. The plate is made up of crossed boards. It is considered as a Young Modulus of 6000 MPa. It is 60 mm thick and its external diameter bearing the total weight of the globe is 1 metre. It is pierced to allow for the path of the beam and rests on a fixed support around the central square hole.

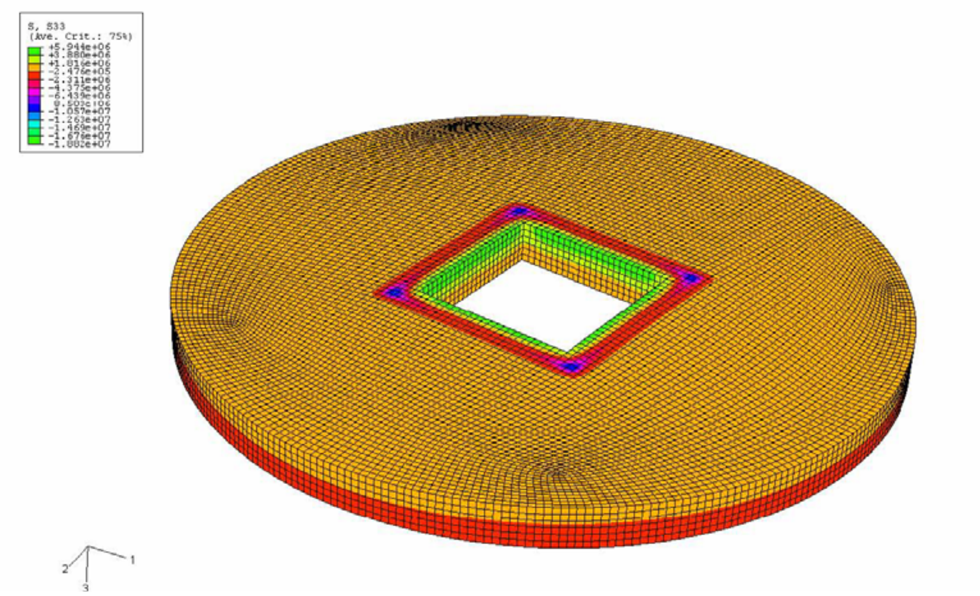


**Figure 4 :** Modelling of the load strain status of the plate

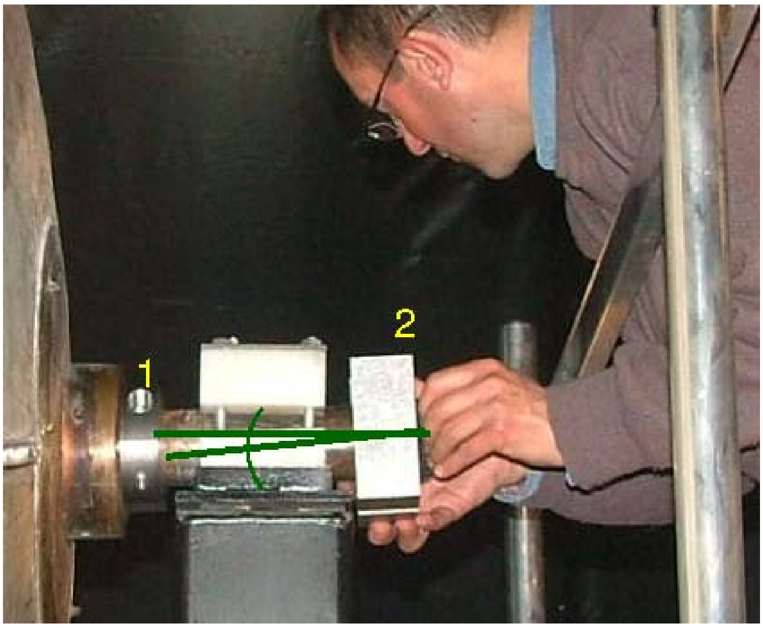
The plate bends by less than 1 mm. The average strain status, apart from the singular load bearing area is about 1 MPa. This value remains very low in regards to the characteristics of an even partially altered wood.

## IV. Measurements of the angular variations of the metal axis supports

The objective is to determine if, despite a vertical angular variation due to storage, the metal axis remains interdependent with the globe, notwithstanding its bending, during the rotation of the globe. We therefore wanted to determine the vertical angle variation for each support during rotation of the globe.

On one side of the globe, two 46123 Sensorex® inclinometers coupled to a National Instrument® NI 6023 acquisition card were installed:

- One to just measure the rotation angle of the globe,
- The other to measure the vertical deflection around the y axis




**Experimental results.** The results are presented below on a radar chart. This shows the deflections of the North pole (right deflection) and of the South pole (left deflection) in relationship to the globe rotation angle. The pole deflection can thus be determined on the radial axis of the chart and the globe revolution angle is indicated on the outer circle.

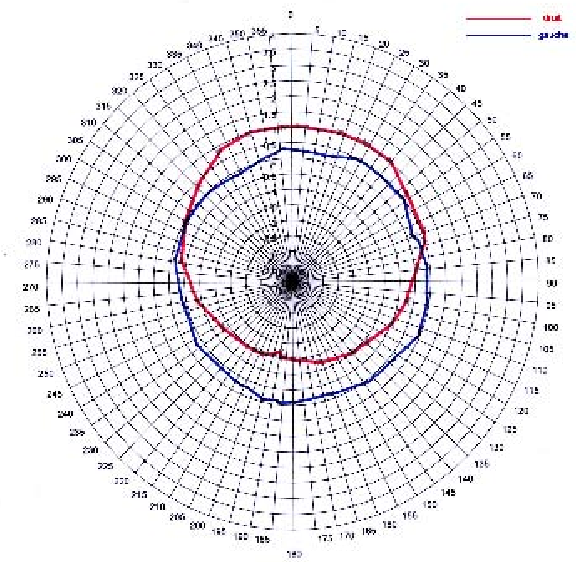


**Figure 5 :** Angular deflection of the axes of the celestial globe

To interpret these results, four specific points must guide our study : the deflection value at 180° is inverse (with the same absolute value, but of opposite sign) to that of 0°, the values at 90° and 270° should be 0. Indeed, the tilted axis at the outset (by a few degrees) turning on itself, describes a theoretical elliptical orbit (flattened revolution cone, see figure 10) going through these four points, if it is supposed that there is no play in the link between the wooden beam and the metal axis.

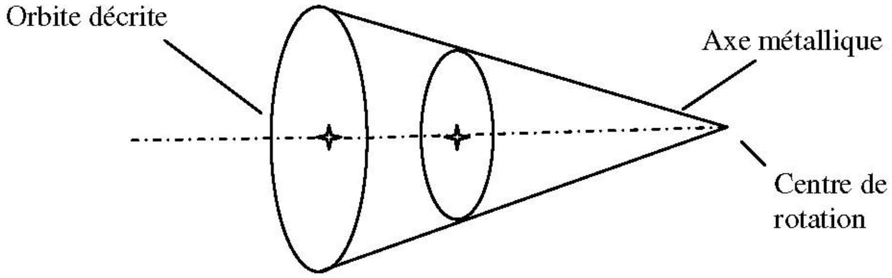



**Figure 6 :** Figure of the rotation principle with a constant angle of the

The table below provides the values of the angular deflections (in degrees) obtained for the successive rotation values of the celestial globe at 0, 90, 180 et 270°. The experimental values are compared to the theoretical values for the elliptical orbit of the axis turning around its rotation centre (supposing there is no play).

| | 0 | 90 | 180 | 270 |
|---|---|---|---|---|
| Theoretical left axis | 1 | 0 | -1 | 0 |
| Experimental left axis | 1 | 0 | -1.5 | -0.7 |
| Theoretical right axis | 0.25 | 0 | -0.25 | 0 |
| Experimental right axis | 0.25 | 0.25 | -0.1 | -0.3 |

**Table 1 :** Comparison of the theoretical and experimental angular deflections of the celestial globe

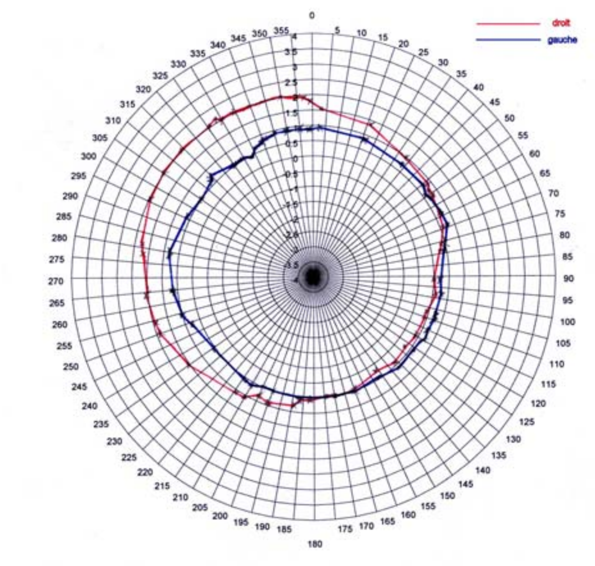



**Figure 7 :** Angular deflection of the axes of the terrestrial globe

The table below provides the values of the angular deflections (in degrees) obtained for the successive rotation values of the terrestrial celestial globe at 0, 90, 180 et 270°.

| | 0 | 90 | 180 | 270 |
|---|---|---|---|---|
| Theoretical left axis | 1.75 | 0 | -1.75 | 0 |
| Experimental left axis | 1.75 | 0 | 0.1 | 1.5 |
| Theoretical right axis | 0.9 | 0 | -0.9 | 0 |
| Experimental right axis | 0.9 | 0.2 | 0 | 0.7 |

**Table 2 :** Comparison of the theoretical and experimental angular deflections of the terrestrial globe

The obtained variations are very weak (below one degree) for the rotation values indicated above. Between these values, there is no major deflection which would indicate the existence of a major play in the link. This representation enables us to conclude that there is no pathological play even if the North pole of the terrestrial globe shows a play amplitude of almost 2° (comparison between the experimental and theoretical deflection of the right axis at a rotation of 180°). Additionally, there is no dramatic slope rupture between these values on any chart.

## Conclusion

The measurements allow to consider the straightening-up of the globes as well as a measured exploitation of their rotation equanimity. In fact, they did not reveal any major structural defect. The progressive indentation of the wood by the rods due to inappropriate long term storage remains the most probable cause for the weak estimated play at the link between the wooden beam and the metal axes.

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