Schenberg microwave cabling seismic isolation.

Bortoli, F.S.¹, Frajua, C.¹ and Aguiar, O.D.²
¹ Sao Paulo Federal Institute – Sao Paulo, SP, Brazil
² INPE – Divisão de Astrofísica, São Jose dos Campos, SP, Brazil

E-mail: Frajua@gmail.com

Abstract: SCHENBERG is a resonant-mass gravitational wave detector with a frequency about 3.2 kHz. Its spherical antenna, weighing 1.15 metric ton, is connected to the external world by a system which must attenuate seismic noise. When a gravitational wave passes the antenna vibrates, its motion is monitored by transducers. These parametric transducers use microwaves carried by coaxial cables that are also connected to the external world, they also carry seismic noise. In this analysis the system was modeled using finite element method. This work shows that the addition of masses along these cables can decrease this noise, so that this noise is below the thermal noise of the detector when operating at 50 mK.

1. Introduction
The detection of Gravitational Waves (OG) came after a long road of efforts [1,2,3,4,5,6,7,8,9]. The Brazilian efforts towards the detection of gravitational waves are centered on the Schenberg detector. In the Schenberg detector six sensors are connected to the surface of the sphere, arranged according to the distribution of Merkowitz and Johnson [10,11]. These transducers are located as if they were in the center of 6 pentagons connected in a surface corresponding to half dodecahedron. Each transducer mechanically amplifies the motion occurring on the region of the sphere in which it is connected. The already amplified movement excites the membrane of one resonant cavity. In this resonant cavity microwaves are pumped, which generate the electronic signal that will return taking all the information of the OG's. Intensity and direction of the OGs can be obtained from the analysis of the output signal of these 6 transducers.

To reach the resonant cavities, first the microwaves are conducted from the outside of the dewar (thermo flask where every antenna system is contained) by cabling to microstrip antennas. These antennas, located in front of the parametric transducers, conduct the microwaves into the resonant cavity and another set of antennas pick up the returned signal. The Brazilian efforts on the field can be seen in [12,14,15,16,17,18,19,20,21,22,23,24,25,26,27].

The cabling has two parts: the first comes from the exterior of the dewar and mechanically connects the last mass of the sphete suspension (lower mass, will be refered here as mass 5) and the second, which is also connected to this mass, continues until it connects to the microstrip antennas. Here the analysis will be done on the first section of the cabling and will propose a way to reduce the seismic noise introduced by the cabling, so that the noise on the transducers does not become greater than the thermal noise. This analysis, as well as the others, were done using simulation using the Finite Element Method (FEM) [28,29].

2. Necessary noise attenuation
Taking into account Schenber detector parameters the displacement noise square by thermal noise is estimated at $10^{-46}$ m$^2$/Hz (this dimension is chosen because it is easier to work in FEM). The detector site parameters for seismic noise was estimated at $10^{-30}$ m$^2$/Hz. Under a pessimistic approach this value was used to excite one end of the cabling, more specifically, the one connected to the environment outside the detector. Thus, from the point of the cabling in contact with the external environment of the region of the sphere where the transducers are connected, it is necessary to obtain an attenuation of the order of $10^{16}$ or 16 decades.
3. The proposed attenuation system
To obtain the required attenuation, the use of a mass-spring system using the cabling itself was studied. In each cable, a plurality of masses were applied in the form of small disks and spaced apart in such a way that each portion of the cable functions as a spring of this mass-spring system. If this system is properly calibrated, the movement due to the seismic noise that excites the cable will be partially reflected by each of these masses, so that the total attenuation produced by all the masses is sufficient so that there is no interference in the measurements made by the detector.

4. Selecting the best cabling configuration using FEM
Several simulations were performed using the finite element method, in which several configurations were tested. In a first step a simpler, symmetrical and constant radius cable was used. The more complex systems were tested, in each simulation the thicknesses of each disk (here used only as mass in a mass-spring system) and the spacing between them along the cabling were changed. Figures 1 and 2 show one of these simulated configurations and its graph of frequency response, where URES is the resultant displacement squared.

Figure 1: System composed of the copper cable connected to five disks with a diameter of 20mm and a thickness of 5mm and the rigid mass (rigid mass meaning the this mas has no vibration modes).

Figure 2: Frequency response curves for the system shown in Figure 1. The upper curve refers to the point at the excited end (left side point) and the other to the point at the end where the rigid mass is connected.
5 Some conclusions obtained up to this stage

The main characteristics observed when analyzing the response curves were the attenuation produced in each configuration used and the quality of this attenuation.

In the graphs obtained the attenuation produced in a given frequency is the measure of the distance between the curve referring to the place where the excitation occurred and the curve of the analyzed point. This measure is given in m²/Hz by the program.

The quality of the attenuation is observed from the oscillation of the curve in the frequencies of interest.

Taking into account these criteria, the analysis of the Frequency Response Curves obtained in this stage led to the following conclusions: the addition of equal disks increases the attenuation, but this is only representative up to the fifth mass added; the quality of the attenuated curve is improved by the addition of equal disks; increasing the size of all masses connected to the cable does not produce a significant increase in attenuation, although slightly improving the quality of the attenuated curve and the increase of the radius of curvature improves the attenuation, and the best value for the attenuation with this configuration (10⁻¹⁸) was obtained, although the attenuated curve did not present good quality.

The attenuation obtained with a cable with 80mm length and another with a length of 160mm, both having 5 disks (masses), with decreasing spaces, demonstrated this but there was no place to show it here. With the longer cable an attenuation of the order of 10⁻¹⁸ was achieved around the frequency of 2530 Hz, whereas with the shorter length this attenuation was of the order of 10⁻¹⁵. As there is space constraint inside the dewar, it is not possible to freely increase the cable length to improve the attenuation. The use of disks with different thicknesses did not alter the attenuation or the quality of the attenuated curve.

It is important to note that the peaks observed in the frequencies of interest could be shifted to other regions by appropriate calibration of the parameters involved, thus altering the "windows" around frequencies of interest. The results for the attenuation obtained with the models tested so far was 10⁻¹⁵ to 10⁻¹⁸.

5.1 Cable with uneven ends, remote mass and five disks

With the knowledge of the systems studied so far a realistic configuration was designed. That is, one that takes into account the space available inside the Dewar, as well as the position of the ends of the cabling (which depend on the position of their connections), now better defined by the overall design. In addition to defining the horizontal and vertical distances between the connectors at the ends of the cabling, the overall cable length has also been defined. In this way, a project that is adequate to the detector is made, from the study of a cabling that is appropriate to the constraints and real characteristics of the project.

Figure 3 shows the best configuration tested, as well as having a format suitable for the detector design. In this configuration the ends of the cable are in 190mm difference in height, have a vertical projection distance of 190mm and the total cable length is 460mm. The disks are positioned in such a way that they have increasing distances and their masses are decreasing.

Table 1 shows the diameters of the disks, their spacings (measured from the end of the cable that was excited), their thicknesses and their masses.

Figure 4 shows the frequency response graph of this configuration, where the attenuation of 10⁻¹⁶ is shown for the 3200Hz and vicinity frequency.

Figure 3: System composed of the remote mass, the copper cable with a diameter of 0.5 mm and a total length of 490 mm, a horizontal spacing of 190 mm and a 190 mm difference between the ends of the cable. The five disks with a diameter of 20mm and thicknesses of 10.0 - 9.0 - 7.5 - 6.0 – 5.0 mm were connected to the cable with increasing distances between the disks. The excitation considered acts on the left end of the cable.
Figure 4: Frequency response curve for the system shown in figure 3 obtained for two points of the cabling. One point is situated at the excited (left) end and the other at the end where the rigid mass is connected.

| Diameter (mm) | Gap (mm) | Thickness (mm) | Mass (g) |
|---------------|----------|----------------|---------|
| 1             | 20       | 38.3           | 10.0    | 28.2    |
| 2             | 20       | 92.0           | 9.0     | 25.4    |
| 3             | 20       | 161.0          | 7.5     | 21.1    |
| 4             | 20       | 245.3          | 6.0     | 16.9    |
| 5             | 20       | 345.0          | 5.0     | 14.1    |

6 Frequency response of the seismic noise originated in the cabling at the transducer locations on the sphere

After some conclusions a cable configuration with a more realistic conformation and dimensions compatible with the available space within the Dewar was used.

Having obtained a good cabling design, a simulation was performed to evaluate the remaining seismic noise and the attenuation, on the surface of the sphere, in the same places where the transducers will be connected.

Figure 5 shows in detail the cabling with the best configuration obtained, connected to suspension last mass 5 (located at the bottom of the suspension) and an overview of the suspension with cabling. To simplify the simulation, the model does not include connectors and other elements, but this should not compromise the results, as these elements are rigidly attached to the suspension.

The effect produced by the seismic noise on the locations where the transducers will be connected, obtained in the simulation, is shown in figure 6. In this figure the locations of the transducers are identified as upper and lower cavities. In the simulation the excitation was made only through the free end of the
cabling in the model. It is estimated that the addition of the other cables would not result in a significant increase in noise. In the response graph of this analysis it can be observed that: an attenuation of the order of 20 decades ($10^{20}$) between the excited end of the cable and the underside of the mass 5 and an additional 19 decades attenuation between the lower face of the mass 5 and the upper and lower cavities on the surface of the sphere.

Thus, the attenuation between the excited end of the cabling and the transducer locations was estimated at 39 decades at frequencies of the order of 3200 Hz.

Figure 5: Cabling model using the best mass-cable attenuator (mass 5 is located at the bottom of the suspension) and an overview of the suspension with cabling.

Figure 6: Frequency Response Curve for cabling model connected to suspension mass 5 (mass located at the bottom of the suspension). In this analysis, the effect of seismic noise from the end of the cabling on the locations where the transducers are connected, identified here as upper and lower cavities, were evaluated in this analysis. The excitation was made through the cabling end and can be seen in the upper curve.

7 Conclusions

The effect produced by the seismic noise that is transported by the cabling, on the places where the transducers will be connected, was obtained in the simulation. In the model the excitation was made only at the end of the cabling, to consider only the effect of the cables. It is estimated that the addition of the other cables will not result in a significant increase in noise. In the response graph of this analysis it can be observed that: an attenuation of the order of 20 decades ($10^{20}$) between the excited end of the cable and the the lower face of mass 5; and an additional 19 decades attenuation between the lower face of the mass 5 and the cavities upper and lower surfaces of the sphere.
Thus the attenuation between the excited end of the cabling and the transducer locations has been estimated at 39 decades at frequencies of the order of 3200Hz, attenuation is sufficient so that the sensitivity designed for the detector can be achieved.

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