Thoughts on the seismic isolation for ET

Paolo Ruggi - EGO
Giovanni Losurdo – Pisa
THIS TALK

• Discuss the ET baseline for seismic isolation (8 years after the conceptual design)

• Outline possible R&D paths

• Is there room for coordinated R&D?
• OCTOPUS (developed by P Ruggi): dynamical models, in frequency domain and linear approximation, of rigid bodies and elastic links, arbitrarily interconnected
  - Used successfully to reproduce the behavior of the Superattenuator (SA), including its active controls

RIGID BODY
m: mass
I: inertia

ELASTIC LINK (beam)
e: Young modulus
r: density
l: length
s: surface of the section
J: inertia of the section
D: displacement from/to CM
T: tension

For each element, a 12X12 impedance matrix is defined:

\[
\begin{bmatrix}
X_O \\
F_O
\end{bmatrix} = \mathbf{Z}
\begin{bmatrix}
X_i \\
F_i
\end{bmatrix} \Rightarrow \mathbf{B}(m,I,\omega) ; \mathbf{L}(e,r,l,s,J,D,T,\omega)
\]

For a given layout and a given pair IN/OUT, an algebraic functional of impedances defines a 6x6 TF (modulus/phase)

\[
X_i \rightarrow X_o = \Omega(\mathbf{B}_1,\mathbf{B}_2,\mathbf{L}_1,\mathbf{L}_2) |_{\omega}
\]

\[
F_i \rightarrow X_o = \Gamma(\mathbf{B}_1,\mathbf{B}_2,\mathbf{L}_1,\mathbf{L}_2) |_{\omega}
\]
TRANSFER FUNCTIONS: CONTROLS OFF

TRANSFER FUNCTIONS: CONTROLS ON
TEST MASS MOTION (ADV)

Seismic noise at VIRGO site

Seismic noise at Test Mass

REDUCE MIRROR RMS MOTION

REDUCE $f_{\text{low}}$

GWADW, Elba, May 22nd, 2019

P Ruggi - G Losurdo
REDUCING $f_{\text{min}}$

MAKE THE ISOLATOR LONGER

$ f_0 \propto \sqrt{\frac{g}{L}}$

OR

• CASCADE INVERTED PENDULUMS?
• ?
ET CONCEPT – VIBRATION ISOLATION

REFERENCE SOLUTION

• Technology: superattenuator (SA)
• Height: 17 m (9 in Virgo)
• Seismic wall: ~2 Hz (~3 in Virgo)

\[
2 \sim \sqrt{\frac{9}{17}} \cdot 3
\]

S Braccini et al., 2010

ET book, fig. 122
IS IT OK?

THE TECHNOLOGY IS RIGHT

• **SA** works beautifully since ~20 years

• The stability of Advanced Virgo is impressive

BUT...

• Making it longer is not sufficient to reach the 1 Hz goal \(f_{\text{min}} \propto \sqrt{L}\), 81m needed

• Cavern cost/engineering issues

• We have the chance to improve the performance further
"SA works beautifully"
### COST - SUMMARY TABLE

<table>
<thead>
<tr>
<th></th>
<th>ET book p.313</th>
<th>Triangle “realistic”</th>
<th>L</th>
</tr>
</thead>
<tbody>
<tr>
<td>TUNNELS</td>
<td>280</td>
<td>727</td>
<td>367</td>
</tr>
<tr>
<td>CAVERNS</td>
<td>110</td>
<td>97</td>
<td>60</td>
</tr>
<tr>
<td>ACCESSES</td>
<td>61</td>
<td>164</td>
<td>117</td>
</tr>
<tr>
<td>TOTAL</td>
<td>451</td>
<td>988</td>
<td>544</td>
</tr>
</tbody>
</table>

Cost in Meuros, no contingency

Caverns cost ~10%
Caverns’ height is not a crucial money saver

Main Cavern:
H=36m; \( V_{\text{int}} = 90000 \text{ m}^3 \)
SA MODELS

HORIZONTAL ATTENUATION

Frequency [Hz]

10^{-10}

10^{-9}

10^{-8}

10^{-7}

10^{-6}

10^{-5}

10^{-4}

10^{-3}

10^{-2}

10^{-1}

10^{0}

ADV 5e
ET Sa 17 m
ET Sa 12 m

9 m

12 m

17 m

LONGER SA
INPUT SEISMIC NOISE

GOING UNDERGROUND NATURALLY REDUCES MIRROR RMS MOTION

VIRGO

SOS ENATTOS
GOING UNDERGROUND NATURALLY REDUCES MIRROR RMS MOTION.

GOING FURTHER: ACTIVE SUPPRESSION (aLIGO) OR ULF STAGES

Seismic noise at Test Mass

10^{-8} m/sqrt(\text{Hz})

10^{-10}

10^{-12}

10^{-14}

10^{-16}

Frequency [Hz]

10^0

VIRGO

SA 17m – SOS ENATTOS

SA 12m – SOS ENATTOS

ET reqs
**BENCHMARK OPTIONS**

- **Baseline:** 17m SA, same Virgo design/control strategy
- **Shorter:** 12 m SA, same Virgo design/control strategy
- **R&D:** 12 m SA on a inertial platform
  - Platform "mildy" controlled (gain comparable to aLIGO SEI)
  - Conservative sensor noise: \(\sim 10^{-12} \text{ m/}\sqrt{\text{Hz}}\)
  - One dof simulated, no actuation noise considered
Sensor Noise

Seismic Noise

Residual Noise (mild loop)

Seismic noise at Base Platform

- Seismic Noise - Virgo
- Seismic Noise - SOS ENATTOS
- Platform Residual Noise
- Sensor Noise
RESIDUAL MIRROR MOTION

Seismic noise at Test Mass

VIRGO

SA 17m – SOS ENATTOS
SA 12m + IN. PLAT. – SOS ENATTOS
MESSAGE 1:

IN PRINCIPLE COUPLING A 12 m SUPERATTENUATOR TO A "MILD" INERTIAL PLATFORM MAY LEAD TO BETTER PERFORMANCE THAN A 17m SA

CAVEAT: experiments are more difficult than simulations
SUPERATTENUATOR

- **THE SA IS NOT JUST A PASSIVE ISOLATOR**
- The IP pre-isolator is a soft platform used for inertial damping and tide control
- The entire **SA** sits on a tilt controllable base
Test of inertial control of a suspended table: surprising result!

This could be explained by considering the tilt in the Accelerometer response. This finding triggered the design of tilt control in the SA.

(Gennai, Giazotto, Losurdo, Paoletti, Passuello, 1992)
INVERTED PENDULUM: passive pre-isolator 
And soft platform for active controls 

SA sits on a rigid ring, resting on 3 elastic feet, actuated by a PZT
• The combination of the tilt control on the base and the HOR/VER controls on the IP can realize a full 6 dof inertial platform
  - IP so far is used just for damping the resonances
  - With some modifications (e.g. remove blade resonances) the control bandwidth could be extended to make it a high gain inertial platform

• However, moving the HOR control (at least the sensors) on the base would allow to exploit better the IP passive isolation and have better final performance

• Eventually, the final performance will be determined by the sensor/actuator noise
  - This is the crucial line of research
INTERESTING CONCEPT, LONG-TERM R&D: EXTREME PASSIVE ISOLATION + ADVANCED ACTIVE CONTROLS

REDUCE MIRROR RMS MOTION

REDUCE $f_{\text{low}}$

2-IP SA

Virgo SA

GWADW, Elba, May 22nd, 2019
THE 2IP DESIGN HAS THE POTENTIAL TO ACHIEVE THE ET ~1 Hz GOAL.
MESSAGE 2:

NOT ONLY THE **ET** BASELINE: THERE ARE (AT LEAST) TWO ALTERNATIVES BASED ON **SA** TECHNOLOGY:

- A SHORTER **SA** COUPLED TO AN INERTIAL PLATFORM (MID-TERM R&D)
- A NEW **SA** BASED ON A DOUBLE INVERTED PENDULUM (LONGER TERM R&D)
MESSAGE 3:

THE R&D ON THIS TOPIC COULD BE AN IDEAL FIELD FOR A COORDINATED/COLLABORATIVE EFFORT: SENSOR DEVELOPMENTS, CONTROL STRATEGY, MECHANICAL DESIGN
CONCLUDING REMARKS

• A reliable simulation tool (OCTOPUS) to help in mechanical design/control strategy is available

• SA technology works fine but can be further improved and even meet ET requirements by enhancing the active controls
  - We have proposed some investigation lines for the ET vibration isolation system

• Next steps:
  - Move from sketchy ideas to more refined designs
  - Design suitable control strategies
  - Make comprehensive 6 dof models
  - Study the noise budget
  - Propose a prototype