Advanced Virgo detector: the path from O2 to O3

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on the behalf of the Virgo collaboration

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Several features being part of the AdV design were not implemented yet (SRM, high power laser) and will be installed at a later stage.

Virgo collaboration rushed to join observational run O2, August 2017, adopting a preliminary configuration.
Advanced Virgo performance during O2

After the failure of monolithic suspensions, the four test masses were suspended through steel wires.

Early scenario: 20-60Mpc BNS range

Sensitivity with steel wires still compatible with the goal for the early phase

**BNS range**: Standard figure of merit for the sensitivity of the interferometer. Volume- and orientation-averaged distance at which a compact binary coalescence consisting of two 1.4 $M_\odot$ neutron stars gives a matched filter SNR of 8 in a single detector.
AdV measured sensitivity compared to early stage boundaries

BNS range up to 28 Mpc during O2

See G. Losurdo’s presentation for more details
How do we increase the sensitivity?

O2 sensitivity as compared to the mid stage scenario (60-85Mpc)

From 2013 Observing scenario, arXive:1304:0670. We projected at least 60Mpc for 2018
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AdV design

Limiting noises at different frequency ranges:

- **Low-freq**: newtonian noise, seismic noise, suspension thermal noise, residual technical noises

- **Mid-freq**: Coating and mirrors thermal noise

- **High-freq**: quantum shot-noise
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Getting ready for O3

• Major upgrades
  • Reducing suspension thermal noise: monolithic suspensions installation
  • Reducing quantum noise: input power increase and squeezing installation

• Noise hunting activities and stray light mitigation
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Monolithic suspensions

SiO$_2$ fibers 400µm in diameter used to suspend SiO$_2$ mirrors 42kg in weight

Already installed during Virgo+. However, many cases of breaking fibers during the installation of Advanced Virgo occurred, and we decided to install steel wires in order to join O2, while investigating the problem.

After the O2 run, a deep investigation was carried out, and finally found out the problem.

- Careful cleaning of the vacuum system
- Improved dust diagnostics
- Installation of separated venting pipe and of a new dry pump
AdV sensitivity with monolithic suspensions

Improvement in the low-mid frequency region because of lower suspension thermal noise: about 10 Mpc gained.
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Quantum noise

Statistical fluctuations in the number of detected photons (shot noise) and radiation pressure fluctuations on test masses.

\[ h_{RP} = \frac{16\sqrt{2\mathcal{F}}}{LM(2\pi f)^2} \sqrt{\frac{hF_{PP}P}{4\pi^2c\lambda}} \left( \frac{1}{1 + \left( \frac{f}{f_{FP}} \right)^2} \right) \]

\[ h_{Sh} = \frac{1}{8L\mathcal{F}} \times \sqrt{2\frac{\lambda c}{\eta F_{PP}P}} \times \sqrt{1 + \left( \frac{f}{f_{FP}} \right)^2} \]

Not limiting, overcome by suspension thermal noise!

Limiting!
Input power increase

A quantum noise reduction can either be obtained by increasing the input power...
Input power increase

The increase of input power induces an improvement of the high frequency sensitivity, as the shot noise is proportional to $1/\sqrt{P_{in}}$.

Thermal Compensation System properly tuned to mitigate the increasing YAG thermal effects

[Graph showing strain vs. frequency with two lines, one for AdV - 13W $P_{in}$ and another for AdV - 19 W $P_{in}$, with a yellow arrow indicating a factor ~0.8 lower noise at high frequency.]
The Frequency Independent Squeezing

...or injecting squeezed vacuum
The squeezing principle

Vacuum fluctuations entering from the dark port cause quantum noise in interferometers. Squeezing was proposed as a solution over 30 years ago. [Caves, Phys. Rev. D (1981)]

For a coherent state, the uncertainty principle holds

\[ \Delta X_1 \Delta X_2 \geq 1 \]

There is a minimum uncertainty product, but the area can be re-distributed

Squeezing the field entering the dark port reduces the noise on the gravitational waves readout.
The squeezer installation

Thanks to a collaboration agreement with the Max Plank institute AEI, they installed the last generation of their frequency independent squeezer in Virgo.
Squeezing effect on the interferometer

Injecting frequency independent squeezing we could improve the sensitivity from 52Mpc to 55Mpc!
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Noise hunting and stray light mitigation

Noise injections are performed in order to spot possible coupling between the noise source and the detector and, therefore, mitigate it.

**Radio waves**
(6MHz, 8MHz, 56MHz)
Photodiodes RF modulated used for angular and longitudinal controls

**Electro Magnetic fields**
Act on mirror MAGNETS, possible electrostatic charges on the mirror

**Slow ground motion**
Excite mechanical modes of mirrors and optical benches suspensions

**Seism & Sounds**
- Excite vibrations of vacuum pipes and tanks, optics on in-air benches
- Imprint phase noise on spurious scattered light beams
**Analysis**

- **“Brute force” coherence tool (BruCo)**
  - *computes and ranks Coherence* between Hrec and all AUXILIARY channels (G. Vajente, [https://dcc.ligo.org/LIGO-G1500230](https://dcc.ligo.org/LIGO-G1500230))

  "brute force" approach = search for noise correlation in ALL (not obvious) channels (i.e. O(10000 channels)!

- **Non-stationary Noise Analysis (NonNA)**
  - Brute force correlation for noises which are non-stationary...
    - V1:LSC_DARM__FFT
    - ...in amplitude
    - ...or in frequency
How many Mpc do the structures “eat”? 

Sidebands around 50Hz count for 2/4 Mpc

The “bump” around 72Hz (now removed) counted for 0.9 Mpc
The “flat” noise

Main culprit preventing us from reaching 60 Mpc

The noise budget accounts for all the known technical noises, but cannot account for the noise “in the bucket”, in the region between 40Hz and 400Hz. This is what we call the “flat” noise

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"Flat" noise

It fits better the sensitivity curve between 60Hz and 300 Hz if it has a small slope ($\sim f^{0.25}$).

Still not completely clear what is the mechanism giving rise to this noise, but it was reduced after a stray light mitigation intervention.
“Flat” noise mitigation

Huge improvement in the mid frequency range after the flat noise was reduced
...in the end, could we get there?

Ready to join O3!

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Thank you