External Environmental Noise Influences on Virgo during O3

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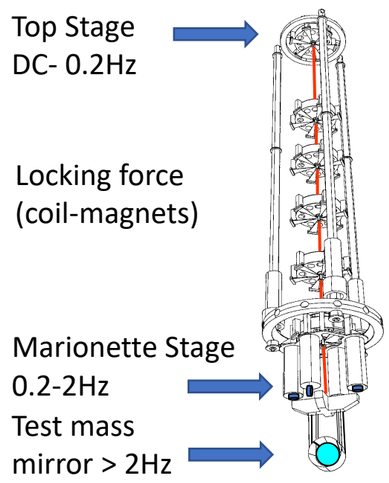
Introduction

Despite the **seismic isolation system** of test masses, the detector's performance has been significantly degraded during adverse environmental conditions (*e.g.* bad weather, sea activity, earthquakes):

- Worse low frequency sensitivity;
- Difficulty to keep the "locked" condition.

Goals of our study team:

- Understand Virgo behavior in different seismic environmental conditions:
  Topics: Wind, Sea, Earthquakes; Figures of merit: BNS range, Duty cycle, Lock losses
- Propose strategies to improve detector robustness for the future O4 run (2022)



The O3 run

April 1, 2019 to March 27, 2020: joint observation of the Advanced Virgo and Advanced LIGO GW detectors.

56 non-retracted alerts (39 confident detections in O3a published in GWTC-2 arXiv:2010.14527).

Summary of **Advanced Virgo** performance:

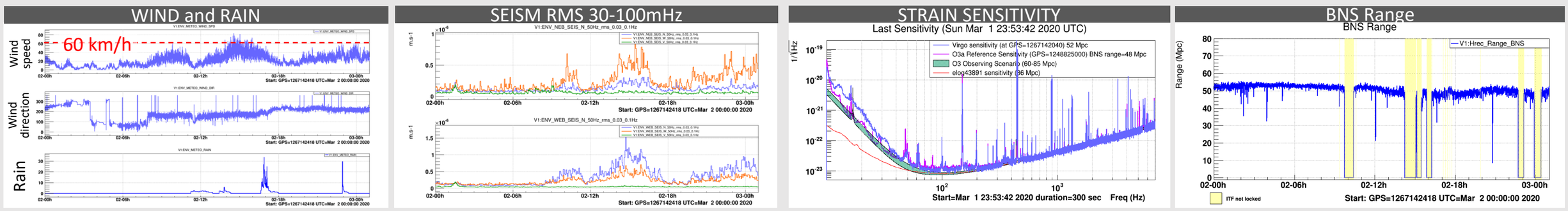
Record BNS range: 60.4 Mpc

Duty cycle (fraction of time observing): > 75%

Max continuous operation time: 5.5 days

N. Lock losses: 601

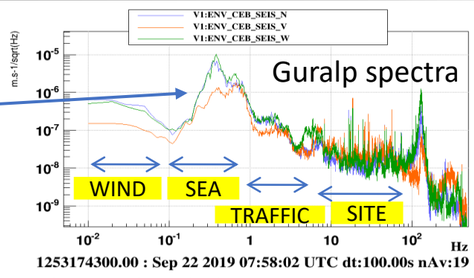
Example: one day of particularly unfavorable weather conditions

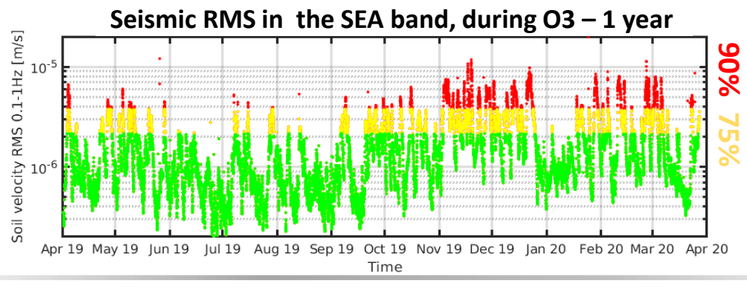


Soil seismicity

3rd micro-seismic peak; most intense in autumn/winter

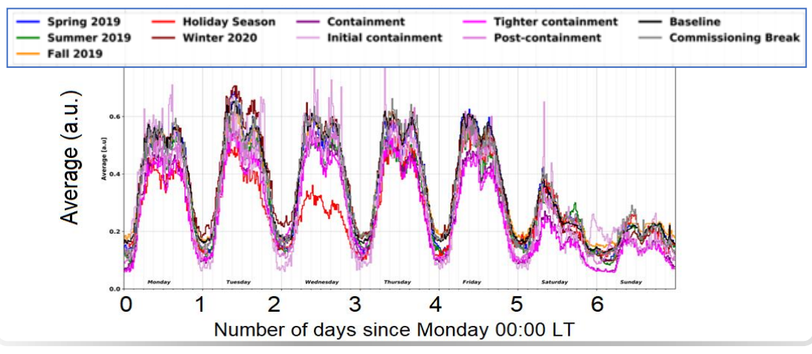
Guralp CMG-40T-60s triaxial velocimeter





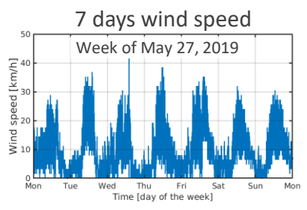
Anthropogenic seism

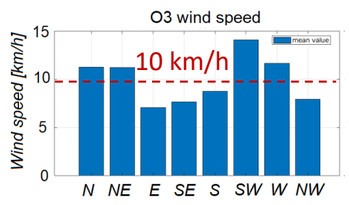
- **1-5 Hz band:** vehicle traffic on nearby elevated highways (bridges) – [S.Koley 10.1190/segam2017-17681951.1]
- Daily modulation, lower on week-ends and Holiday season.
- 20% reduction during the COVID pandemic lockdown

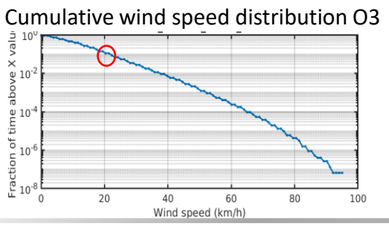


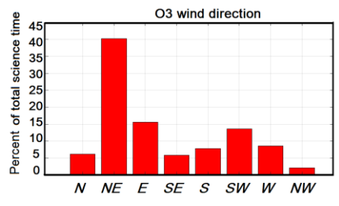
Wind during O3

Daily modulation, prevalent from NE direction, 10 km/h average



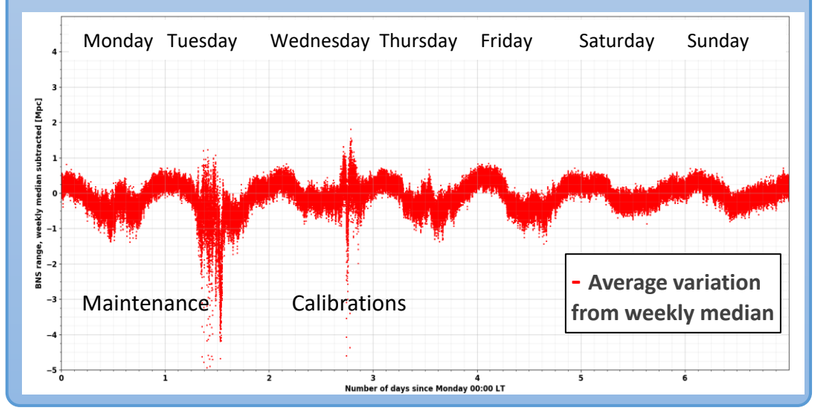






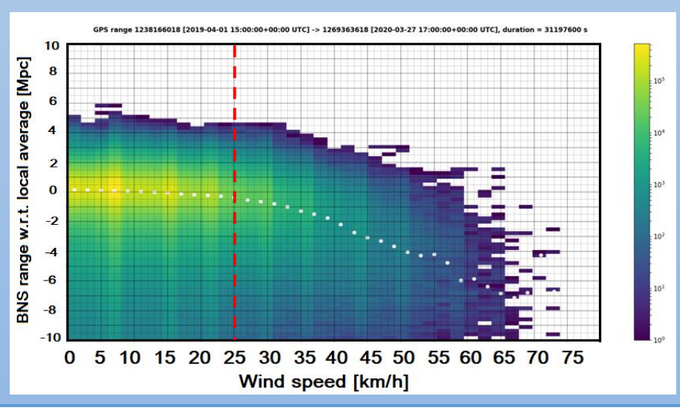
BNS range modulation

- Averaged over a week, variation w.r.t. local baseline;
- Day/night modulation similar to wind speed and anthropogenic.



Wind impact on BNS range

(Anti-)Correlation between local BNS range variation and wind speed, especially above **25 km/h**..



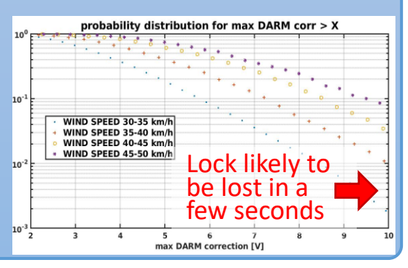
Wind impact on lock stability

Max DARM correction distribution in different wind speed ranges:

- When correction signal exceeds ±10 V actuators saturate, and lock is lost (14% of O3 lock losses)

Control strategy: widen actuation range to avoid saturation

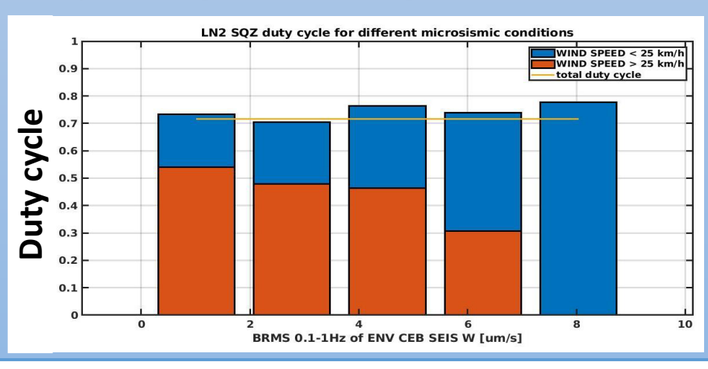
- **O3b**, Wind-robust version: move locking force from End to Input marionette suspension stage actuators that have wider actuation range, although a bit noisier;
- **O4 plan:** double the number of actuators using both input and end marionettes
  → double usable force before saturation, noise increases as sqrt(2), but not an issue.



Disentangling effects of Wind and Sea

Duty cycle as a function of RMS soil velocity in sea microseism band, for low-wind and high-wind data

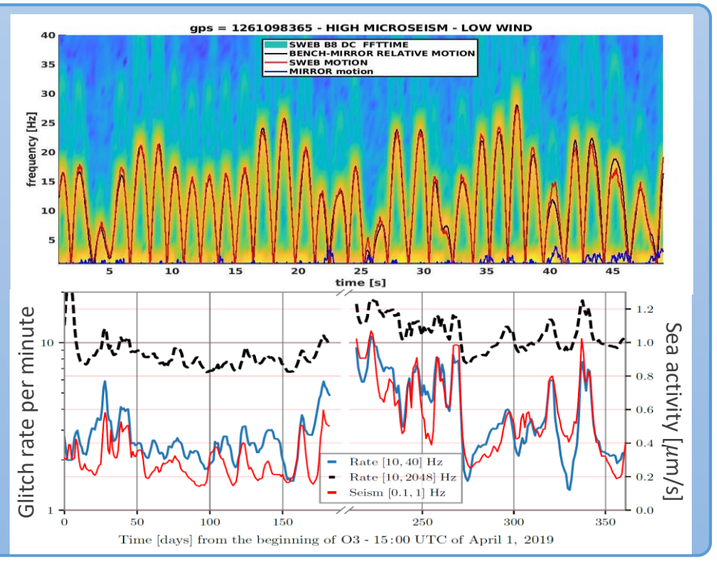
- If wind is low, duty cycle does not depend on microseism intensity ⇨ Locking is 100% robust against microseism.



Scattered light during high microseism

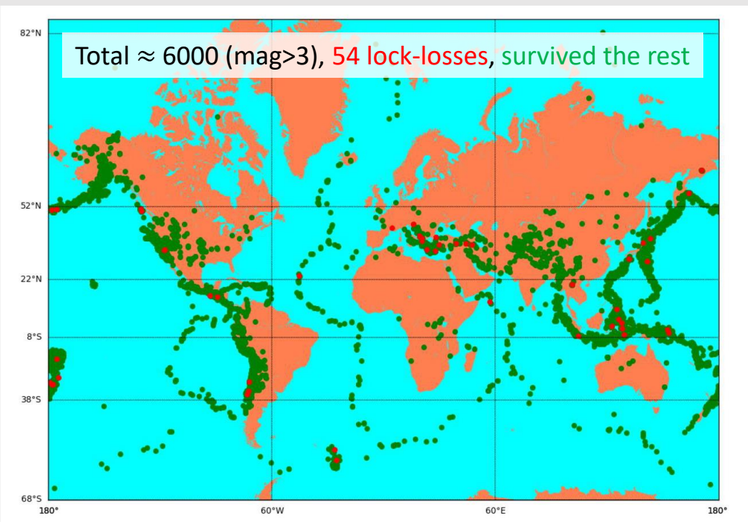
Main cause of O3 sensitivity worsening during bad weather

- Amplified by high relative velocity of the scattering source w.r.t. the interferometer beam;
- Mitigated in O3 for Virgo output and end benches, by acting on the suspension top stage to follow the test mass suspension ("tracking control");
- SWEB (Suspended West End Bench) inertial damping was the main culprit. SNEB mirror velocity at least 10 times smaller;
- Adaptive algorithms can be used to identify culprits of scattered light noise – A.Longo doi:10.1088/1361-6382/ab9719 and G.Valdes doi:10.1088/1361-6382/aa8e6b
- Noise can be modeled and subtracted online using auxiliary witness channels – M.Was, et al. https://arxiv.org/abs/2011.03539



Earthquakes during O3

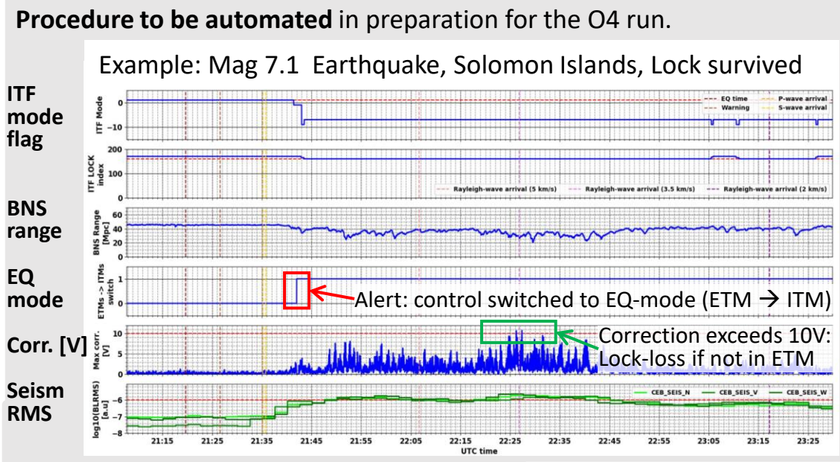
EQ seismic wave shake mirror suspensions (≈70mHz) causing lock-loss and long recovery time.



Earthquake Early Warning System (EEWS) during O3

If EQ warning is 'significant' enough (based on a rough magnitude-distance cut) the operator manually switches to a more robust interferometer control.

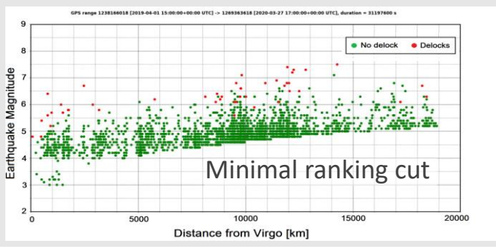
Procedure to be automated in preparation for the O4 run.



During O3: early warnings provided by ***Seismon*** – https://arxiv.org/abs/1611.09812

How to improve EEWS?

- Current **ranking**: $10^{\text{magnitude}/2}/\text{distance}(\geq 0.01\text{ cut})$;
  →Improved adding other parameters (depth, location, freq.);
- *Seismon* alert is based on US-based USGS network; not effective for Mediterranean areas.
  → Integrate **early warning stream from Italy-centered network** (INGV - Early Est, doi:10.5194/nhess-15-2019-2015)
- Implement a dedicated network of seismometers ≈100 km from Virgo (**ASPIS project**)
- Identify sensible degrees of freedom of the interferometer.



Distance vs. magnitude of O3 EQ and their effect on Virgo

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