LIGO and Virgo Detector Characterization and Data Quality: Contributions to the O3 Run and Preparation for O4

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On behalf of the Virgo & LIGO DetChar groups

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Outline

- Ground-based gravitational wave (GW) detectors
- "DetChar" in a nutshell
- Detecting gravitational waves during the O3 run
- Transient and spectral noises
- Sensitivity improvements
- Validating GW candidates
- <figure>
- Preparing the O4 run and beyond



LIGO Hanford ("H1")



Virgo ("V1")



Ground-based GW detectors

- The Advanced Virgo detector • Suspended, power-recycled Michelson interferometer during the O3 run (2019-2020) with 3-km long Fabry-Perot cavities in the arms B8 SWEB • Working point WE Not to scale: Michelson on the dark fringe the arm cavities are km-long All Fabry-Perot cavities resonant Input Mode \rightarrow Feedback control systems acting on Cleaner the mirror positions and on the laser WI • GW passing through SIB1 CP SPRB CP NI NE SNEB Differential effect on Faraday BS Isolator В7 Т the arm optical paths Laser PRM POP 🔁 В5 \rightarrow Change of interference condition 🕀 B2 at the detector output SIB2 \rightarrow Variation of the detected power SDB1 • Sensitivity limited by noises 🔁 В1 SDB2 Fundamental Continuous struggle:
 - Technical
 - Environmental

Continuous struggle: design, improvement, noise hunting, mitigation

LIGO detectors are conceptually the same

3

"DetChar" activities in a nutshell

- DetChar
 - Abbreviation for "detector characterization and data quality"
 - \rightarrow Includes / connects to many other topics as described in the following
- Typical 'instrument cycle' for ground-based GW detectors
 - Upgrades \rightarrow Commissioning \rightarrow Data taking \rightarrow Upgrades \rightarrow (...)
 - Relevant DetChar activities during all steps
 - Track noise sources \rightarrow Sensitivity
 - \rightarrow Average detection range for a given source
 - <u>Typical figure-of-merit:</u> BNS (Binary Neutron Star) range
 - ◆ Help improving stability → Duty cycle
- Data quality
 - Global dataset
 - Individual GW candidates
- Focusing on two main levels
 - Single instrument
 - Global network as a whole



The stage: detecting gravitational waves

- From: A guide to LIGO-Virgo detector noise and extraction of transient gravitational-wave signals
 - B. P. Abbott et al., 2020 Class. Quantum Grav. 37 055002
- Detector Characterization SEARCHES & Data Quality Template Make Triggers Matching (with False Alarm Rates. Signal to Noise Ratio) • Event validation Whitening Identified Signals • Auxiliary & environmental sensors PARAMETER ESTIMATION Whitening Interferometers Detector h(t) Event Chararacterization Calibration Validation Data Quality Bavesian Analysis Auxiliary Environmental Sensors CATALOG Instrument Performance 5

The stage: detecting gravitational waves

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The O3 run

- LIGO-Virgo Observing run 3: O3
 - \rightarrow All 3 detectors from the beginning and for the whole run
 - O3a: 6 months $-2019/04/01 \rightarrow 2019/10/01$
 - I-month commissioning break: 2019/10
 - O3b: 5 months $-2019/11/01 \rightarrow 2020/03/27$
 - Shortened by covid-19 pandemic



Gravitational Wave Open Science Center: <u>https://www.gw-openscience.org</u>
 → Open data (for individual events and entire runs), software tools and tutorials

The O3 gravitational-wave signals

https://www.ligo.org/science/Publication-O3bTGR/images/cumulative_events_200322.png

- O3: 79 new signals
 - All 3 types of compact binary mergers now observed
 - No new multi-messenger observation
 - Rates and populations studies
 - Tests of General Relativity
 - Targeted searches triggered by external inputs
 - GRBs, FRBs, supernovae, etc.
 - Searches for continuous signals

OBSERVING 01 2015-2016 03a+b 2019-2020



UNITS ARE SOLAR MASSES $1 \text{ SOLAR MASS} = 1.989 \times 10^{30} \text{kg}$

https://www.virgo-gw.eu/#news_gwtc3

Note that the mass estimates shown here do not include uncertainties. which is why the final mass is sometimes larger than the sum of the primary and secondary masses. In actuality, the final mass is smaller than the primary plus the secondary mass.

The events listed here pass one of two thresholds for detection. They either have a probability of being astrophysical of at least 50%, or they pass a false alarm rate threshold of less than 1 per 3 years.





DATE(TIME)

Transient noise

- Glitch: transient excess of noise with a distinctive time-frequency signature
 - Duration
 - Bandwidth
 - Signal-to-noise ratio (SNR)
- Multiple origins
 - Hardware equipment
 - Software (controls, etc.)
 - Unknown, with witness channels
 - Unknown and no witness channel
- Manifold damages
 - Decrease GW search sensitivity
 - Hide actual GW signal
 - Worsen stability











UTC Time

Spectral noise

- Excess power on long timescale in a given frequency range
 - Narrow lines or wider bumps
 - Many different types: fundamental, harmonic, comb, sideband, modulation, etc.
- Potentially cover real GW signal in the same frequency range
- Hardware or software artefact may mimic, to some extent, a real GW signal

 \rightarrow Some only appear when analyzing the whole dataset



Typical "lin.-log." Virgo O3 amplitude spectrum density

500



• Noises may appear/disappear/change over time

• Coherent magnetic noise between sites: Schumann resonances

Fighting noises

- Ideal scenario
- Pick-up a frequency range of interest
 - Find the origin of the dominant noise contribution

y [Hz]

- Fix the cause, or mitigate its effect
- The dominant noise goes down: another one starts dominating the sensibility
- Iterate...

- → In practice, we rely a lot on auxiliary channels and environmental sensors
 ■ Most of the acquired data
- To help identifying the source of a given noise, we look for
 - Correlations in the time domain
 - Coherences in the frequency domain
 - \rightarrow Neither of these implying causation a priori







 PZT Accelerometer
 FB Accelerometer
 Velocimeter
 Thermometer
 Comb. (temp.+press.+hum.) Microphone
 Microphone
 Magnetometer
 Voltage probe
 Current probe
 Radio frequency antenna



Fighting noises: two examples

- Successive reductions of noise around 50 Hz (mains frequency in Italy) in Virgo
 a) Reducing bumps around 50 and 55 Hz
 b) Reducing the 50 Hz peak
 c)-d) Cleaning structures
 below and above 50 Hz
 → At each step: before
 after
- Noise created by a compressor in LIGO
 - Top: signal in a magnetometer
 - Middle: compressor on/off sequence
 - Bottom: glitches in the GW signal



Performance improvement

• Virgo sensitivity O2-O3 progress [2017-2020]



• O2-O3 network BNS ranges [2016-2020]



Event validation

- Calibration Online GraceDB Validation checks GW Raw IFOs -→ Triggers -Analyses strain – data Reconstruction candidates h(t) pipelines Information Vetting studies • Vet GW candidates enrichment Data quality DetChar Online Near real-time Offline timescales Consistency checks Corresponding Seconds Minutes Hours Days latencies Weeks Months
- Global transient noise investigations
 - All DetChar tools working together to provide the most complete set of information



Vetting alerts in low latency

- Goals: confirm/retract public alerts in O(few minutes)
 - Dedicated database with a public-facing interface: GraceDB <u>https://gracedb.ligo.org/superevents/public/O3</u>
 - Public information: GPS time, type of event, skymap
 - Use of the Gamma-ray Coordination Network (GCN)
- Rapid Response Team meeting at short notice immediately after each significant alert
 - On-duty experts from all relevant areas
 - Including DetChar
 - \rightarrow Deciding the fate of the alert
 - ◆ O3: 80 alerts, of which 24 retracted







Gravitational-wave candidate validation

• Identifying real signals and separating them from possible glitches



 \rightarrow Situation can be as complicated as the spectrogram above (from O3a)

Gravitational-wave candidate validation

• Identifying real signals and separating them from possible glitches



- Scattered light noise
 - Parasitic beam created by imperfections (optics defect, misalignment, etc.), scattering off some moving surface and recombining to one of the main interferometer beams
 - Glitches, control inaccuracies
 - \rightarrow One of the main noise sources for all detectors in the network
 - → Mitigations: isolate more / suspend further hardware components, dump parasitic beams onto absorbing surfaces

Gravitational-wave candidate validation

• Identifying real signals and separating them from possible glitches



- Assess whether data quality issues could bias the estimation of the source parameters
 - If yes the glitch(es) can be excised from the data first done for GW170817



Normalized amplitude

From O3 to O4

https://dcc.ligo.org/LIGO-G2200736/public

- Major upgrades on all detectors
 - \rightarrow Should lead to significant sensitivity improvements
 - LIGO
 - Doubling arm power (~400 kW)
 - Reduce further quantum noises
 - Reduce technical noises below ~100 Hz



- Virgo
- Project Advanced Virgo+, Phase I [Phase II after O4 run]



- KAGRA (Kamioka, Japan) joining the network
- Planned schedule impacted by worldwide covid-19 pandemic
 - O4 is currently expected to start at the end of 2022, for about a year

DetChar: O4 preparation

- Characterization of the upgraded ("new") detectors
 - So-called "noise hunting" phase
 - Noise budget
 - Example from O3 for Virgo



- Prepare for a larger rate of GW signals with personpower not scaling up the same way
 - Continue automation of current DetChar methods and tools
 - Reduce their latency and increase the rate at which these analyses will run
 - Extend the scope of DetChar monitoring
 - Study the impact of data quality issues on the increasing number of detections
 - Prepare for potential detections of new GW sources

Outlook: O4 and beyond

- O4 run to start by the end of the year
 - Schedule still subject to changes
 - → Up-to-date information: <u>https://www.ligo.org/scientists/GWEMalerts.php</u>
- LIGO-Virgo-KAGRA network
 - 4 detectors operating jointly in the near future **Today**



https://www.ligo.org/s cientists/ObsScen_tim elineMarch2022.png

- Then another upgrade period followed by the O5 run
 - Temptative schedule
 - Post-O5 plans are being developed

Recent DetChar references

- Virgo References
 - Virgo Detector Characterization and Data Quality during the O3 run
 - arXiv:2205.01555 [gr-qc]
 - Submitted to Class. Quantum Grav.
 - The Virgo O3 run and the impact of the environment
 - <u>arXiv:2203.04014 [gr-qc]</u>
 - Submitted to Class. Quantum Grav.
- LIGO References
 - LIGO Detector Characterization in the Second and Third Observing Runs
 - D. Davis et al., 2021 Class. Quantum Grav. 38 135014
 - <u>arXiv:2101.11673 [astro-ph.IM]</u>
 - Detector Characterization and Mitigation of Noise in Ground-Based Gravitational-Wave Interferometers
 - <u>D. Davis and M. Walker Galaxies 2022</u>, **10**(1), 12
 - Environmental noise in advanced LIGO detectors
 - P. Nguyen et al., 2021 Class. Quantum Grav. 38 145001
 - arXiv:2101.09935 [astro-ph.IM]
 - Sensitivity and Performance of the Advanced LIGO Detectors in the Third Observing Run
 - <u>A. Buikema et al., 2020 Phys. Rev. D 102, 062003</u>
 - arXiv:2008.01301 [astro-ph.IM]

Posters on the Virgo and ET suspensions



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extension of the observing horizon to more than 150 Mpc.

and heavier (104 kg) to deal with the larger beam size.

The seismic isolation system of AdVirgo+ Phase II A. Basti, V. Boschi, P. Chessa,

V. Dattilo, R. Passaquieti, P. Ruggi 1 Istituto Nazionale di Fisica Nucleare (INFN) 2 Università di Pisa

3 European Gravitational Observatory

By the end of 2024, the Advanced Virgo+ gravitational wave interferometer (AdVirgo+) will

undergo a major upgrade, called Phase II and aimed at a reduction of thermal noise and an

The laser beam size will be enlarged on end test masses and better coatings will be implemented

upgraded version of the SuperAttenuator (SA), a passive attenuation system capable of reducing

the seismic noise by more than 10 orders of magnitude in all six degrees of freedom above a few Hi

on mirrors to lower mechanical losses. In particular, end mirrors will be larger (55 cm in diameter)





The new end mirrors will require a re-scaling of the payload and, consequently, a re-design of all the elastic elements of the end SAs (blade springs, suspension wires, magnetic AntiSprings and Inverted Pendulum flex joints), in order to sustain the new loads without significant changes of the resonant frequencies. Several studies are being performed in order to design and validate the required mechanical updates.

Such studies are also providing useful insights on the design of seismic isolation systems for the The seismic isolation of AdVirgo+ mirrors and suspended benches will be provided by an third generation detectors.





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ET mass black holes.

A seismic isolation system for the test masses

of the Einstein Telescope

BHETSA

A. Allocca¹, V. Boschi², E. Calloni¹, M. Carpinelli³, P. Chessa⁴, D. D'Urso³, R. De Rosa¹, L. Di Fiore², F. Fabrizi⁵, I. Ferrante⁴, F. Fidecaro⁴, A. Gennai², M. Montani⁵, M. Razzano⁴, D. Rozza³, P. Ruggi⁶, L. Trozzo², A. Viceré⁵



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Abstract

The Einstein Telescope (ET) gravitational wave interferometer will be the biggest research infrastructure built in Europe in the next decade and its design and construction will bring

The Ensemin telescope (E) gravitational wave interferometry will be the objects research ministructure out in Europe in the next occesse on its beings and construction will only imprecedented technological challenges. The set of the ensemble is the invest possible level for an Earth bound detector, broadening their detection band down to 2 Hind Sentencing and the ensemble, with respect to Vigo and LLCO, we access to the early Universe by detecting high red-shift black hole mergers, to the extreme space-line curvature of high mass black holes. It makes possible to detect neutron star inspirate well before they merger, allowing a nutlimesenger observation of extreme states of matter they mass black holes. It makes possible to detect neutron star inspirate well before they merger, allowing a nutlimesenger observation of extreme states of matter the sensibility minimes in the low frequency region will gut however challenging constrains on the suppression of estime noise. On the basis of the experience accumulated in construction and mining the Might indefendence for the last too decades we are developing a supervised space to the same developing a supervised space of the last too decades we are developing a supervised space of the same developing a sup mine in Sardinia, candidate as the site to host ET, due to its unique seismic characteristics

Introduction

New Mechanical Design

mass black holes. Even in a site with very low seismicity, the required seismic attenuation from the ground to the mirrors of the interferometers is of more than eight orders of magnitude. In Vigo the has been achieved at a frequency of 4 Hz with the Vigo Superatenuate [1]. However extending the present scheme at lower frequency leads to an increase of dimensions that implit the incompatible, technically and francusity, with locating the meter underground, as required to minimize local gravity fluctuation

The gravitational-wave interferometers of next generation, Einstein Telescope [ET []], see figure 1) and Cosmic Explore [2] aim at gaining a factor of 10 in noise level, respect to Virgo and UGO but allow extending at low frequency their detection band as shown in Figure 2. This improved sensibility gives access to the early Universe by detecting high not-shift black hole merges, to the activene space-line curvature of high detecting high not-shift black hole merges, to the active space-line curvature of high sensibility.



Black Holes for ET SArdinia (BHETSA) [*] is a 3-year project funded by the rin a Black Moles for ET SArcinia (oncreak) [] is a Syster project involved by the PRIN2020 MUR call. Its goal is the design of a suspension system that isolates esismically the test masses of ET at frequencies above 2 Hz with a height of about 10 m, similar to the one of the Virgo Superatinumust (SA), shown in figure 1. To test the new design a prototype will constructed, tested and validated. m new design a prototype will constructed, tested and valuated. The current ET baseline solution has a height of 17 m, requiring suitable underground halls, where the test masses must be located to minimize local gravity fluctuations; lovering the experimental hall height would lead to a reduction of the volume of excavated rock and consequently a simplification of ovil engineering works, with an estimated cost reduction of the order of 10 million euro. -

estimated cost relation of the order of 10 million sum. The mechanical activities proceed environment suggrade of the standard filters (see Equire 2) and of the inverted pendulum pro-science) (PL A two-needs IP despin sporced (figure 3), baing out one attraution filter from the chain and reducing its length. This improved pre-isolation stage relaxes requirements on the passive filtering chain and might allow poing well beyond the stated ET requirements, in the perspective of a planned lifetime of 50 years with further improvements in the ET detector. Figure 4

New Control System

 Accelerometers: VIRGO accelerometers [:] (figure 6 and 7) have shown high reliability and very good noise performances but need to be redesigned comparing the seismic noise level at VIRGO [] with the one in ET candidate sites such as So Entantics (see Signer 9). The lower expected displacement of the suspended mass allows using an optical readout, while a lower maximum force needs to be applied. reducing the actuation noise

reducing the addition holes. The set of the months and control estimic isolation system displacement has constraints similar to hole of invarial sectors. Several displacement sensors will require the need of extended dynamic range. The arms of ET are 10 km long and the tidal strain of the Earth cruit is 3 km higher as in Virgo. This strain needs components of n humbrids of microrus is buge the instifution locked around the clock. On the other hand, the noise introduced must be below the sessimic noise activity possibly measured. If the top of the first Ply dynamic fram close locked around the clock. ore than 10° sqrt(Hz) ore than 10° sqrt(Hz) sntrol: We propose to develop a prototype of control system based on machine lear

Centror we propose to develop a prophytic do control system based on matche sensitivity and that can hange be trained on a simulated version of the system, and alter refined on the real suspemsor pattern. A first result who a set of definitions that describe the data format used to store the data corring from the hardware, and development of Richards capabilis of realizing and writing data to this format. The second result will be an integrated system mode of GPU-based hardware and software package capabile o training deep learning daptime for controlling the suspensions, using reminecent learning approximation.

Tests at SAR-GRAV facility

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The prototype will be installed in the SAR-GRAV central hall. The first tests Letter the processes while ensurement of the service service neural number that the tests will concern the measurement of the resonance frequencies and their functions. The service servic











15th Pisa Meeting on Advanced Detectors







Figure 3



Latest O4 update

<u>https://www.ligo.org/scientists/GWEMalerts.php</u>
 → Redirecting to <u>https://observing.docs.ligo.org/plan</u>

LIGO, VIRGO AND KAGRA OBSERVING RUN PLANS

(15 May 2022 update; next update by 15 July 2022)

LIGO, Virgo, and KAGRA are closely coordinating to start the O4 Observing run together. We plan to start the O4 Observing run in mid-December 2022, with an Engineering Run to start in mid-November; low-latency alerts for candidate events identified during engineering time may be released, both to exercise the system and to exploit their scientific value.

At present, the run is planned to start with only LIGO Hanford, Virgo, and KAGRA. While the commissioning of the detectors is progressing, the plan towards readiness is being reviewed. The completion of LIGO Livingston's upgrades is taking longer than planned. We project that Livingston could join the run in February 2023, but we are looking into options to reduce the delay.

The projected sensitivity of the detectors remains unchanged: LIGO projects a sensitivity goal of 160-190 Mpc for binary neutron stars. Virgo projects a target sensitivity of 80-115 Mpc. KAGRA should be running with greater than 1 Mpc sensitivity at the beginning of O4, and will work to improve the sensitivity toward the end of O4.