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Data analysis report for the STAC and the EGO council. Activities in the period May-October 2012.

The Virgo collaboration, 29 October, 2012

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Abstract: The Data analysis report presented here gives highlights and updates on the activities carried on in the last semester, that is after the last report presented in May 2012 by the former "Data analysis coordinator" (DAC), for the collaboration. We have tried to answer to all the specific questions posed by the STAC and to fulfill their recommendations. We presents also the work the different DA groups are presently doing to get ready for the Advanced Detector Era and the methods which the LIGO and Virgo DAC are using to help the groups in monitoring their progresses. Even if the "DA, Computing and Software Plan" in view of Advanced Detector Era is still to be completed, we are now actively working on it, we have given short answers to the recommendations done by both the STAC and ECC committees, for all cases where we already had the opportunity to fix guiding lines for our plans.

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1 Introduction

We give here an update of the Virgo Data Analysis (DA) results and activities in the last semester. Last report is VIR-0179A-12 [1], and was presented in May 2012.

A good reference for a deeper understanding of the work done and planned by the collaboration is given by the "LVC White paper" updated every year by the joint LIGO/Virgo (LV) collaboration, which states the general roadmap of the activities (science goals, status and plans, priorities), thus giving more details in particular on the Science Case beyond each search [2]

Let's list here some choices done writing this report:

- Repeat the DA group's division, tasks, composition and FTEs, even if unchanged from the last report.
- Highlight in the Executive Summary the main scientific results and papers of the last semester, if any, for each DA group. Do not repeat Highlights for these groups in the "Groups activity" Sections.
- Highlight new achievements, even if not yet completed, in all those cases where we see at least one good motivation to discuss them now in this context.
- Add a few comments on "Software and Computing Plans" in the "Answers to STAC recommendation" section, as we feel it is indeed useful in view of the Plans we are defining for ADE and of a more extensive answer we are preparing to the ECC report.

Let's add that after having completed many of the flagship (that is, "most important") analysis with the LIGO and Virgo data taken in the years 2009-2011, we need now to concentrate on Advanced Detector Era (ADE) plans, which means we need to define a "Data analysis" (DA) plan supported by a Software and Computing Plan. This work begun with the former DA chair, who made an intensive study of the present situation, highlighting either strong and weak points of the Virgo DA organization.

1.1 DA working groups

The DA working groups have been organized to reflect the main lines of the research, even if -as will be clarified later- there are overlapping science cases which do need a strong coordination among the groups. In the following we will refer to group's "co-chair" in all cases when the work is done within a larger joint group with LIGO, co-chairing with one or two LIGO colleagues and we will refer to group's "chair" when this is not the case, although for all topics there is a similar LIGO group. In almost all groups, when this is needed, we have "review (co-)chairs", in charge of super-visioning the review processes underway and to indicate reviewers for each new task where a review is needed. We do have "reviews" for pipelines, results, papers. Follows the list of DA groups and DA and review (co-)chairs:

- Burst group: transient signal search.

  Co-chair: Giovanni Prodi (beginning term Feb. 2010)

  Review co-chair: Tomasz Bulik
- CBC group: compact binary coalescence signal search.

  Co-chair: Chris Van Den Broek (beginning term Feb. 2012. Former: Frederique Marion)

  Review co-chair: Gianluca Guidi
- CW group: continuous waves signal search.

  Co-chair: Andrzej Krolak (beginning term Feb. 2012. Former: Pia Astone)

  Review co-chair: Damir Buskulic
- SGWB group: stochastic background signal search

  Co-chair: Tania Regimbau (beginning term Feb. 2012. Former: Giancarlo Cella)

  Review co-chair: Fabio Garufi

In addition to these working groups, we have DA "support" groups in charge of calibrating the GW strain amplitude, understanding the quality of the data and the environment of the detector and managing software and computing resources. These groups are the natural link between DA and Detector Commissioning groups. A tight interaction between DA groups and DA support groups is of paramount importance, as been already pointed out in past reports.

- Calibration and h-reconstruction group: calibration of Virgo optical response and h(t) generation

  Chairs: Loic Rolland

  Review chair: Fabien Cavalier

- Virgo computing group

  Chair: Marie-Anne Bizouard (beginning term: Oct. 2012. New group.)

- Virgo Data Quality group: generation of data quality information used by searches.

  Chair: Didier Verkindt (beginning term: Jan 2009)

- Detector noise study group: study of noise coupling inside the detector

  Chair: Elena Cuoco (beginning term: Jan 2008)

The "Computing group" has just been created to help the DAC. The most urgent task now is the preparation of the ADV Computing Plan. This group has persons in contact with the Computing Centers, CCIN2P3 and CNAF, and with the EGO Computing group.

This report is divided in Sections and Appendices, with a structure quite similar to the last May 2012 report. The last Appendix, following the idea of the former DAC, is a Glossary, of terms and abbreviations used here, with summary explanations. Section1 is this introduction. Section 2 summarizes the main accomplishments in physics groups since the last report. Section 3 provides answers to the last STAC report (May 2012) comments.

Section 4 gives a full description of the work we are doing with "Engineering Runs" in view of ADE.

Section 5 provides details of the main Virgo groups' achievements.

Appendices contain support material.

2 Executive Summary

In the last semester, as in the Jan-May period, all the groups have mainly been busy with the analysis of the data taken in the period 2009-2011. While for the CBC, Burst, Stochastic and for the known sources search CW (sub-)groups the flagship analysis have been completed and in most cases published or going to be published soon, in the CW All-Sky sub-group, for reasons mainly related to the huge computational request of All-Sky blind searches, and the consequent complexity of the hierarchical analysis, we are now in the most intensive results production work. This has a relevant impact on the use of computing resources in our computing centers (CC), as we are now using EGI and we are saturating the Virgo actual resources. Having been in the past months in the situation to lend resources to other experiments we would now borrow resources .... This work is completely carried out using Virgo data and resources. A priority now, in parallel to these activities, is the definition of DA science goals, well tracked with milestones, and -as said in the introduction- the consequent preparation of a Software and Computing Plan in view of the ADE. Important issues are discussed in Sect.3, answering to valuable comments by the STAC (and partially to the ECC, for which a complete answer is being prepared and will be presented when appropriate). "Engineering runs" have been scheduled to test at different levels hardware, software and infrastructure, as our systems evolve towards ADE. Details are given in Sect.4. In addition to this, ADE preparation implies to be ready to the transition between the "Upper limit" regime to, hopefully, the first g.w. discoveries. To accomplish with this transition it is important to establish partnerships with astronomers and large instruments collaborations. As written in the previous report to the STAC, LVC has agreed on a policy on "Trigger release" , that defines when g.w. triggers will be publicly released and how we would like to carry out multi-messenger analysis in the pre-discovery phase ("closed era"), that is through signed MoUs with partners to establish the needed strong working relations. the text of the LVC policy on trigger release is given in Appendix A, even if it was already attached to the May 2012 report. Some work is now ongoing to decide which information (which is a scientific problem) and how (which is a more technical problem) to exchange the information during the "closed era". Another important document, to establish a good link with the astronomers, and on which we are working now is an "ADE observing and scenario" document, whose completion is taking much more than expected, proportionally to the growth in relevance of the information it contains. The main goal of the document is to assist the astronomy community in planning for multi-messenger astronomy with advanced gravitational-wave detectors. The document does not cover the whole scenarios of g.w. and astronomical observations, as it is intended to be only a first step in this direction. It concentrates only on transient signals. The main point raised is this: our network is expected to begin operations in 2015, but before two or more detectors have an average range of at least 100 Mpc [1] it is unlikely that the forecasted few months of observations will yield detections, unless the most optimistic astrophysical rates hold. In this context Electromagnetic follow-up of g.w. candidates may help confirm g.w. candidates that would not be confidently identified from our observations alone. The document reports the expected detector 's sensitivities and their progression with time, having expressed many caveats on the expected progresses of the commissioning work, and, on the basis of possible astrophysical scenarios for the source rate density, gives our expectations on the rate of triggers, Sky localization (when applicable) and expected number of detectable g.w. transient signals.

2.1 Highlights from all the DA groups

- **Virgo Data Quality (VDQ) group**

  The VDQ group and the noise group have published in Classical and Quantum Gravity [7] an important paper which summarizes the investigations and results obtained over the scientific runs VSR1, VSR2 and VSR3, describing the various types of noise that we were able to understand, the vetoes that have been designed and generated, their performances and their impact on the gravitational wave transient search results. The VDQ group also participated actively in the ER2 run by providing Data Quality flags and running online the Omicron search algorithm which is foreseen to be used in Advanced Virgo. Finally, the VDQ group started to define its strategy for Advanced Virgo, mainly through a document describing our main priorities, the various existing projects and the way we would like to organize our work before and during the commissioning of Advanced Virgo.

- **Noise group**

  The group has actively participated to the work in[7]. The group contributed to the ERs activity, in particular the "Noise Event Miner" (NoEMi) ran in-time (once per day) during ER2 on both Virgo (less interesting for the noise as we have used VSR3 recolored data) and LIGO (test on the central part of the Interferometer). The Wavelet Detection Filter (WDF) ran online during ER2 on Virgo data, testing the interface to on line data distribution and triggers database structure. Important studies linked to non linear analysis and spectral lines investigations are a priority for the group (three presentations at the GWPAW 2012 (June 2012) in Hannover).

- **CBC group**

  The CBC group has recently (Sept, 2012) submitted to PRD the High mass (25-100 M_0) search (Binary Black Holes (BBH) Inspiral, merger and Ringdown) paper. The work was carried out in collaboration with the Burst group. No signals were found and an new upper limit (UL) on the coalescence rate of BBH was put. This limit is very close to the to level needed to put non trivial constraints on astrophysical scenarios of BBH formation and evolution, as will be clarified in the report. The group actively participated to the Observing Scenario Document, which is being completed, as explained before in this Section of the report. Thanks to the experience gained up to now and to prepare for the ADE searches, a first step has been a group re-organization into sub-groups divided to reflect the main Science Goals, that is the Sources we are searching for. In addition to these, technical sub-groups are in charge of issues such Data

[1]The standard figure of merit for the sensitivity of an interferometer is the binary neutron star (BNS) range: the volume-and orientation-averaged distance at which a compact binary coalescence consisting of two 1.4 M_0 neutron stars gives a matched filter signal to noise ratio (SNR) of 8 in a single detector.

Quality, Waveform generation, parameters estimations ... Recent progresses we wish to highlight here are: The GWtools package, an analysis toolkit enabling the use of Graphical Processing Units, is reaching a mature stage. Tests were done on a variety of cards, and speed-ups in CBC matched filtering by a factor of ≈ 100 were seen; The MBTA pipeline for fast sky localization was tuned to further improve latency, reducing it from 4 minutes in the first engineering run to 40 seconds in ER2; PhenSpin, so far the only available Inspiral-merger-Ringdown waveform with fully dynamical spins, was incorporated into the Bayesian parameter estimation code; An analysis pipeline was created, called TIGER, to test general relativity using binary neutron star Inspiral. This led to the establishment of a new sub-group within the CBC to coordinate LSC/Virgo/IndIGO efforts in this direction.

- **Burst group**

  The LSC-Virgo burst group met its top priority science goals on past data, by publishing the observational papers on the all-sky search and on the GCN GRB triggered searches over S6-VSR2/3. Both these goals had Virgo burst groups co-leading the efforts, in close coordination with some LSC groups. Since June 2012, the preparation for the Advanced Detector Era started to be the main activity of the LSC-Virgo Burst group (in particular: development of cWB pipeline and development of STAMP pipeline for burst signals of longer duration). In addition, the contribution of burst group members to the preparation of the detector characterization for ADE has increased (in particular: developments of the Omicron pipeline to scan for glitch characterization over many Virgo channels and of the noise canceling by regression using auxiliary channels). All these activities get crucial contribution by Virgo groups. Remaining searches over past data are being completed: IPN GRBs triggered search, high energy neutrino triggered searches, optical telescope image analysis triggered by GW bursts, cosmic strings cusps all-sky search. All these analysis should complete in the next semester with publications ready for circulation in 2013 and see Virgo scientists in leading positions.

  At present, Burst group policy requires that all developing activities focus on their application to the ADE; in fact, future re-analysis of past observations are now primarily meant to provide test beds for the pipelines or methodologies for ADE. The internal organization of the LSC-Virgo burst group completed a migration from sub-groups sharing a common data analysis methodology to sub-groups oriented to astrophysical goals.

  The participation to Engineering Runs has been designed to test and validate progresses of analysis towards the initial ADE, starting in particular from the all-sky search and GRBs triggered searches. Since Engineering run 2, the fake data consisted in actual recolored noise and for ER3 burst group is preparing a specific challenge to stress test the low latency searches with a high rate of both simulated signals and glitches.

  Burst group is pursuing joint projects with other DA groups. The main joint projects are with the CBC group: two joint sub-groups have been formed targeting to the same astrophysical sources, Binary Black Holes mergers (low Virgo participation due to lack of manpower) and gravitational waves emitted by GRBs (co-led by Virgo scientist).

  The burst STAMP pipeline instead is a technical joint development with the stochastic group, led by Virgo scientists.

  Virgo burst group manpower decreased significantly to less than 7 FTEs. This is in part a physiological effect of a larger commitment of burst scientists on detchar activities in preparation for the Advanced Virgo commissioning, but it reflects also a pathological side due to the systematic net migration of young members to LSC groups and other communities, forced in part by lack of Virgo grants/positions. If this scenario will not change, Virgo burst groups will loose scientific opportunities of ADE, in particular in low-latency burst searches, binary black hole merger searches and some multi-messenger searches.

- **CW group**

  The group studies long duration signals, and this is the main reason to the fact that, even if results have already been published on the 2009/2011 data, many flagship analysis are now ongoing. The group is clearly also actively preparing plans for the ADE but the major experience to be ready for ADE is not, as for the other groups, being gained with intensive participation to ERs, whose duration is too short for our searches, but with the candidates analysis in all the All-Sky or Directed searches already completed or ongoing, where the effect of noise artifacts plays a dramatic role. As has been described in previous reports the group' s organization scheme is based on a redundant pipelines, which is opposite to the other groups. There are many reasons for this (cross-checks, comparisons of results, different robustness of pipelines versus the noise disturbances, different parameters space coverage . . .). To be able to better address this point, either by supporting the redundancy in ADE or not, we have now begun strong benchmarks for all kind of CW searches, using the same data with a same set of software injected signals, thanks to a good work done by our LIGO colleagues. To begin LIGO S6 data will be used, but we need to do the comparison also using VSR2 or VSR4 data as we perfectly know that most of the Virgo pipelines have been designed to accomplish noise features of the Virgo detector. In any case, out priority now in Virgo is to finish the ongoing analysis on VSR2/VSR4 data. We will thus the benchmark one these analysis will be ended, which we promise to accomplish by March 2013. Now, recent activities: The main work carried on in the last months is the Targeted search for g.w. signals emitted from Vela and Crab (and a few others for which we can approach the spin-down limit, that is we can constraint the fraction of spin-down energy due to the emission of g.w.). This work has a particular importance within the Virgo collaboration as it is mainly tied to Virgo VSR2 and VSR4 data, due to the very good sensitivity of our detector in the frequency region below 60 Hz. The new limit improves the previous one obtained with VSR2 data on Vela by a factor 1.7-2 (that is we constraint the fraction of spin-down energy to 10%) and the one obtained with S5 data on Crab by a factor 1.15-1.3 using S6/VSR2/VSR4 (that is we constraint the fraction of spin-down energy to 1%)

The Einstein@Home work on S5 data, an All-Sky search for unknown isolated neutron stars in the frequency range [50-1200] Hz, has been finally concluded, the paper sent in Aug. to PRD and already approved. Quoting Referee A:

"This paper describes the Einstein@Home all-sky search for periodic gravitational waves in LIGO S5 data, which provides a significant improvement on upper limits on continuous gravitational waves. Most of this improvement is due to advances in data analysis techniques, which are discussed in detail. This work is an important step in improving the sensitivity of the LIGO detectors to continuous gravitational waves"

Quoting Referee B:

"The paper "Einstein@Home all-sky search for periodic gravitational waves in LIGO S5 data" reports the results from the analysis on the LIGO S5R3 and S5R5 data using the Hough transformation method. The authors searched for periodic gravitational waves in the LIGO S5 data in the frequency range spanning from 50 Hz to 1190 Hz, but found no gravitational wave signal in the data. They then set an upper limit on the amplitude all over the sky on each half Hz band, the collection which covers the entire frequency band analyzed. This paper gives very detailed description of their very careful analysis. I am convinced of their result and recommend for publication in the Physical Review D." The contribution of Virgo to this activity, a part discussions within the CW group face2faces and teleconferences, dates back to the beginning of this search: the idea of using an Hough transform for these searches was originally suggested in Rome by Prof. Lucia Zanello and the Virgo group has begun to work on it. The core of the Hough algorithm was jointly developed by Rome and Potsdam AEI groups. Andrzej Krolak has been the Virgo reviewer for this paper.

Let's also highlight here, even if results are still not ready, the progresses made since June on the All-Sky search for unknown neutron stars using VSR2 and VSR4 data. In fact this is the computationally most intensive search in our group and it is completely carried on our CCs, in particular under Grid. The analysis procedure has now been completed in the frequency range [10-128] Hz and also the review is well under-way. We are now analyzing candidates in these frequency band to put, in case of no detection, an Upper Limit in a frequency region partly never explored before (before 50Hz) and partly improving latest results (shown in Fig.12 and Fig.14) in the range 50-70/100Hz Noise Lines investigation ability is very important for this work, as always in All-Sky CW searches.

- **Stochastic group**

Group	Oct2012	May 2012	June 2011	Oct. 2010
Burst	7.0 FTE + 6 REV	9.7 FTE + 6 REV	9 FTE + 6 REV	11 FTE+4 REV
CBC	10.8 FTE + 6 REV	10.8 FTE + 5 REV	12.1 FTE + 12 REV	9.4 FTE + 7 REV
CW	9.3 FTE + 6 REV	9.5 FTE + 4 REV	9.3 FTE + 4 REV	9 FTE + 3 REV
SGWB	1.8 FTE + 3 REV	1.5 FTE + 3 REV	1.5 FTE + 3 REV	1 FTE + 3 REV
Calibration and h-reconstruction	1.5 FTE + 6 REV	1.5 FTE + 6 REV	1.5 FTE + 6 REV	1.5 FTE + 6 REV
Data quality and vetoes	2.2 FTE	2.5 FTE	2.3 FTE [no rev]	2.2 FTE [no rev]
Noise	4.4 FTE	2.5 FTE	1.9 FTE [no rev]	2 FTE [no rev]
Total (FTE)	28.6 FTE + 8.1 (sup.)	31.5 FTE + 6.5 (sup.)	31.9 + 5.7 (sup.)	30.4 + 5.7 (sup.)
Total REV	21 REV	18 REV	23 REV	23 REV

Table 1: Full Time Equivalent (FTE) and number of persons involved in a review (REV) for each Virgo groups.

The stochastic group completed the analysis of the S6-VSR2 hardware injection. Compared to the upper limit obtained for S5/VSR1 [24] we observe (preliminary results, not published yet) with S6/VSR2 data an improvement of about 10% at frequencies < 600 Hz and of about a factor of 2 between 600-1000 Hz, where the LIGO/Virgo pairs contribution is the most important. That is, in the frequency band of 600-1000 Hz, where the best sensitivity is given by the LIGO-Virgo pairs, we obtained a 95% Bayesian upper limit on the amplitude of the energy density parameter $\Omega_{\rm GW}(f)$ of about 2 times better than for S5/VSR1.

In preparations for the ADE, the stochastic group has started to look in detail at the Detectability of various models (see website: http://homepages.spa.umn.edu/ cwu/). It has been shown that the background created by the cosmological population of compact binary coalescences could be detected by advanced detectors for realistic rates and masses [21]. This lead the group to start a Mock data Challenge to develop and test adapted data analysis techniques, and prepare the interpretation of the results in term of astrophysics and cosmology [22, 23].

2.1.1 Man Power and FTEs

The global manpower situation is quite stable ($\sim$ 28.6 FTEs + 8.1 (support groups) FTEs) but still fragile.

2.2 Last semester papers and talks by Virgo DA members (only DA groups)

This is the list with a few comments, when needed. Details on the search and results are in the specific group sections. The listed presentations are those given in external Conferences or Plenary sessions of internal meetings.

- **CBC group**

  Papers:

  The paper "Search for Gravitational Waves from Binary Black Hole Inspiral, Merger and Ringdown in LIGO-Virgo Data from 2009-2010" is now (dated Sept. 28th) on the archive [3] It has been submitted to PRD and we are waiting for the referee reports.

  Presentations and Posters:

  Gijs Nelemans , "Galactic binaries with eLISA", invited review at the LISA symposium (Paris, May 2012).

  C. Van Den Broeck, "Testing the strong-field dynamics of general relativity with advanced gravitational wave detectors", Gravitational Waves Advanced Detector Workshop, 14 May 2012, Kona, Hawaii, USA (invited).

  T.G.F.Li, "TIGER: A data analysis pipeline for testing general relativity using compact binary coalescence", Gravitational-wave Physics & Astronomy Workshop 2012 (GWPAW), June 2012, Hannover, Germany (contributed).

W. Del Pozzo, “Testing General relativity using Bayesian model Selection, GW New Horizons Workshop” AEI Hannover, Hannover, Germany, 8th June 2012.

C. Van Den Broeck, “Probing the dynamics of spacetime with gravitational waves”, High Energy Physics Colloquium, Radboud University, Nijmegen, The Netherlands, 13 June 2012 (invited).

C. Van Den Broeck, “Astronomy, Cosmology, and Fundamental Physics with Einstein Telescope”, Gravitational Wave Physics and Astrophysics Workshop, Hannover, Germany, June 2012 (invited).

C. Van Den Broeck, “Testing the strong-field dynamics of general relativity with advanced gravitational wave detectors”, Exploring New Horizons Workshop, Hannover, Germany, June 2012 (invited).

C. Van Den Broeck, “Astrophysics, cosmology, and fundamental physics with gravitational waves”, VESF School on Advanced Gravitational Wave Detectors, Cascina, Italy, 18-22 June 2012 (invited).

W. Del Pozzo, “Inference of the cosmological parameters from gravitational waves: application to second generation interferometers without optical counterpart identification” Virgo Week, Cascina, Italy, 25th June.

Gijs Nelemans,“Using astrophysical knowledge in gravitational-wave data analysis of binary inspirals” Virgo Week, Cascina, Italy, 25th June.

M. Agathos, “TIGER: A Bayesian method for testing general relativity using gravitational waves from compact binary system”, 13th Marcel Grossman Meeting, 1-7 July 2012, Stockholm, Sweden (contributed).

J. Veitch, “What can we measure with CBC parameter estimation?”, Rattle and Shine, Santa Barbara, USA, 3 August 2012 (invited).

G.M. Guidi, for the LVC, “Gravitational Wave research and their connection with EM observations” Gaia Science Alerts Workshop 2012, September 6-7 Bologna.

Gijs Nelemans, “Gravitational waves from Black Holes”, Blanford symposium in Groningen (october 2012)

Gijs Nelemans, “The formation of double white dwarfs”, EuroWD12, Krakw, Poland, 16 aug. 2012

- **Burst group**

  Papers (some joint with the CBC group):

  “All-sky search for gravitational-wave bursts in the second joint LIGO-Virgo run” Phys. Rev. D 85 (2012) 122007

  “Swift Follow-Up Observations Of Candidate Gravitational-Wave Transient Events” LIGO, Virgo, SWIFT collaborations, arXiv:1205.1124 submitted to ApJ, waiting for editor decision wrt ApJ or ApJS.

  We have received relevant comments by the referee on Aug., 22th to the paper [30] “A First Search for Coincident Gravitational Waves and High Energy Neutrinos Using LIGO, Virgo and ANTARES Data from 2007”, submitted to APJ (arXiv:1205.3018). The paper has not been accepted in its present form as the referee is not convinced on the Astrophysical Significance of the result. We are now actively working to answer. We are not ready to give details now, but this will be solved and addressed by the time of the next STAC report. We have remarked this here as one of the promises in the last May report was the final publication of this work.

  Presentations and posters:

  E. Chassande-Mottin for the LVC, “Data analysis challenges in gravitational-wave astronomy”, ARENA, June 2012, Erlangen (Germany).

  M. Drago et al., “Impact of noise canceling by regression on searches for continuous gravitational waves”, GWPAW, June 2012, Hannover (Germany) (Joint with CW group)

  B. Bouhou et al, “Triggered searches for gravitational-wave transients associated with high-energy neutrinos using coherent WaveBurst” Poster at GWPAW, June 2012, Hannover (Germany).

  V. Re et al, “Joint search for GWs and Neutrinos from Core-Collapse Supernovae” Poster at Marcel Grossmann 13, July 2012, Stockholm (Sweden).

G.A.Prodi for the LVC, “Searching for Intermediate Mass Black Hole Mergers” Marcel Grossmann 13, July 2012, Stockholm (Sweden).

M.Drago et al., “Sky localization and amplitude reconstruction of transient gws in future gw detectors networks” Marcel Grossmann 13, July 2012, Stockholm (Sweden).

- **Joint Burst and CBC**

  Papers “Search for gravitational waves from intermediate mass binary black holes” Phys. Rev. D 85 (2012) 102004

  “Search for gravitational waves associated with gamma-ray bursts during LIGO science run 6 and Virgo science runs 2 and 3” arXiv:1205.2216. Submitted to ApJ, in press.

  Presentations and posters:

  GWPAW “Gravitational Wave Physics & Astronomy Workshop” (June 4-7 2012, Hannover) Poster by Marica Branchesi on behalf of LSC and the Virgo collaboration: “Searching for optical counterparts of gravitational wave transients in the wide-Leld telescope observations”

  GWPAW “Gravitational Wave Physics & Astronomy Workshop” (June 4-7 2012, Hannover) Poster by Marica Branchesi “New perspectives in multi-messenger studies of gravitational waves and high-energy photons: a proposal”

  VirgoWeeek Meeting (June 25th-27th, Cascina) Talk by Marica Branchesi “New perspectives in multi-messenger studies of gravitational waves and high-energy photons: a proposal”.

  Talk by Marica Branchesi on behalf of LSC and the Virgo collaborations: “Transient Gravitational-Wave Astronomy: Electromagnetic Follow-Up of Gravitational Wave Candidates”. European Week of Astronomy and Space Science-EWASS (July, 1st 6th 2012, Rome).

- **CW group**

  Papers

  LVC collaboration “Einstein@Home all-sky search for periodic gravitational waves in LIGO S5 data”, submitted to PRD. On Oct., 4th we have received the two PRD referee reports on the Full S5 E@H paper [4]. Both the reports are excellent. See details in the CW section.

  Presentations and Posters

  Alberto Colla, for the LVC collaboration “Noise line investigations in Virgo VSR2-VSR4 data” GWPAW “Gravitational Wave Physics & Astronomy Workshop” (June 4-7 2012, Hannover)

  M. Drago, for the LVC collaboration “Impact of noise canceling by regression on searches for continuous gravitational waves”, GWPAW2012,(June 4-7 2012, Hannover). Joint with the Burst group.

  A. Colla, P. Astone, S. D’Antonio, S. Frasca, C. Palomba, “Search for continuous gravitational waves from known neutron stars: status and future prospects”, GWPAW2012 (June 4-7 2012, Hannover)

  A. Colla, P. Astone, S. D’Antonio, S. Frasca, C. Palomba, “The Frequency Hough All-Sky procedure for the search of isolated neutron stars”, GWPAW2012 (June 4-7 2012, Hannover)

  C. Palomba for the LSC and Virgo Collaboration, “Search for continuous gravitational waves from known neutron stars: status and future prospects”, Invited talk. Marcel Grossman 13, Stockolm July 4-7 2012

- **Stochastic**

  Papers

  Mandic V., Thrane E., Giampanis S., Regimbau T., “Parameter estimation in searches for the stochastic GW-background” [22]

  Physical Review D, in press ; http://arxiv.org/abs/1209.3847.

  LV coll., “Upper limits on a stochastic gravitational-wave background using LIGO and Virgo interferometers at 600-1000 Hz” [26]

Physical Review D, vol. 85, Issue 12, id. 122007.

Kowalska I., Regimbau T., Bulik T., Dominik M., Belczynski K.,

"Effect of metallicity on the gravitational-wave signal from the cosmological population of compact binary coalescences" [24] (arXiv:1205.4621).

3 Answers to STAC recommendations (May 2012 report)

STAC recommendation for DA have been reported in Appendix B. The main concerns from the STAC were not related to the report itself, which they have found of increasing quality, (we 'll do the best to maintain the same quality level . . .). One observation was on the need to have, in addition to the activity report presentation by the DAC, more targeted presentations by the chairs, or experts, of the different search lines, as done for the experimental groups. We do think this is a very important request and we have chosen to begin this time with a presentation on the activity of the Burst group. A comment which is directly related to the duties of the DAC regards the **organization of resources and penalty system**. The STAC comments that the organization of groups and targets have to fit with the lack of manpower. The DAC do agree with this vision, being fully convinced that the huge effort we all [2] are investing in this research is such that we do need to do our best to reach our goal, even if this means to focus only on a sub-set of well defined science targets. The status-of-the-art is indeed that we are jointly working with other institutions which are presently not limited in both human nor support resources. We should thus be so clever to be competitive and actors in the game even with limited resources, having clear that the contribution of the Advanced Virgo detector to the network will be relevant, as it has been so far, and the contributions to science still depend mostly on the quality of ideas. This stated, the unbalanced resources budget has conditioned our working scenario and we would like to lighten, in view of the ADE, some constraints we are having now. We are referring in particular to the heavy use of LIGO-GRID (Condor) oriented libraries (the so-called LAL-LALAPPS), which has so far limited us in the use local (e.g. CNAF, CCIN2P3) resources.

Coming back to the organization of the work, this is a need we share with LIGO colleagues. Jointly, the two DACs have the, often difficult, task to coordinate the DA work, respecting the individual attitudes and skills. Besides the weekly meetings and the 2 or 3 yearly collaboration meetings, we are organizing restricted DAC/chairs (one group at a time) meetings, to define a clear schedule for each task, with well stated and verifiable milestones. For each item we will be asking the name of a senior scientist responsible for the delivery. Prior to these the chairs were asked to reorganize group's activities according to science deliverables. This has been mostly done. For example the CBC group formed 5 sub-groups on BNS, NSBH, Stellar Mass BBH, Intermediate Mass BH binaries (IMBH), GRB. We have prepared a template matrix which, for each item, will be filled with milestones and names. As an example, the matrix for the BNS sub-group is at **https://wiki.ligo.org/DAC/BNS** and reproduced in Appendix C. In parallel to this we have renowned to the group chairs, the request, at **https://wiki.ligo.org/foswiki/pub/Bursts/AdvAna/AdvAnaDACcharge.txt** and reported in Appendix D , to identify papers we will want to write in the ADE. Once this will be done[3] we will be able to start the tracking process. Note that actually it is not so clear which will be our Publication policy in ADE as this is something we have just begun to discuss and we do expect will become a hot discussion topic in the Collaborations in the next period.

The DAC/CBC chairs meeting has been scheduled (November 5/6 in Hannover). One of questions we will point out, is that we want to have for each pipeline in each search a detailed scheme of "Limitations on usage", which goes in the direction suggested by the STAC (and by the ECC too): **we have to decide how to use CCs in view of ADE, both for computing and Disk storage** We need to know now, developing new pipelines for ADE, if there are infrastructure and software requirements which will constraint the use of that particular pipeline. As a general policy, we do want to work with pipelines which are "platform independents", making use -when possible- of basic architectures which are going to reasonably be on the air not only at the beginning of ADE, but also in the following years. We do want to avoid to remain in the situation, created for

[2] not only the collaboration, but all funding and support institutions

[3] an iterative process for which we have identified the main steps and put a deadline for a March 2013 LVC meeting

historical reasons and for unbalanced resource buckets, we have experienced up to now. The "Status of the Art" for Computing and Resources in our collaboration has been detailed in the document written by the former DAC, see [6] Starting from this, we have begun the work of defining a DA plan, which will be supported and completed with a Software and Computing Plan. To date, we have valuable comments to answer received from the ECC, which we plan to have ready by next winter. Our proposal to ECC will be to have the document **DA, Software and Computing Plan** ready by March 2013.

It's relevant to comment here that we are now working to take into account comments and criticisms and answer to the few others we disagree with. The data storage strategy is requiring more explanation than initially given in the computing plan document, having in mind the problem of the cost, data integrity and needs from users. For instance, given the increase of the rawdata volume for Advanced Virgo, we are forced to rediscuss the strategy of accessing to the different data set (h(t), reduced data set and rawdata) in order to guaranty quality of service and reduce cost. We also need to upgrade our data transfer system and develop a usable book-keeping database. This upgrade that involves both CNAF and CCIN2P3 facilities requires a tight collaboration with both centers. A reliable data access system has been a source of worries in the past. We have especially identified the lack of data book-keeping facility that would provide users an easy way to access to the data. We are investigating the use of GRID for both data transfer and data access to all Computing Centers. At the moment this has not been accomplished due to the different access protocol systems in CCIN2P3, CNAF and in the LIGO Computing Centers. Data transfer is an important task that is under the responsibility of the EGO Computing group. The Virgo collaboration is going to discuss the needs for this tool with the EGO computing group, also defining the associated time scale. The main goals of this projects are:

- to provide a transparent interface to the user to access the data independently on where the data is, maintaining in any case the possibility to use the already existing tools. This can be done hiding the various storage systems non-homogeneities with a "software layer";
- to provide a robust framework for the data transfer, which assures no latency and data integrity.

The planned increment in the use of our Computing Centers increases the relevance of this project in the Collaboration.

Another comment by the STAC was on VESF fellowships, on which we fully agree: we do need now to increase manpower in DA activities.

The final STAC comment is on the use of the farm in Cascina: while we insist that this will be part of a detailed Computing Plan for ADE, we ' d like to add here that we agree to use the farm in Cascina, with high priority, for all the low-latency searches, like the CBC MBTA ("Multiple Band Template Analysis") which, as explained in section 5.4, has shown to play an important role to produce triggers for the EM-follow-up, and for all detector's characterization activities, both "on-line" and "in-time", as explained in sections 5.2, 5.3.

4 Preparation for the ADE: The Engineering Runs

Engineering Runs (ERs) are important to test the requirements for hardware, software, infrastructure. We report here some information from the previous STAC report, to facilitate the reading of the new part.

4.1 Summary from the previous report

The LSC and Virgo collaborations are using the time of the installation of the advanced detectors to get ready for low latency all-sky GW searches starting in 2015. This also includes the EM follow-up alerts system. To assess the progresses towards this goal, some engineering runs (ER) have been scheduled as shown in figure 1. The main goal of these different runs is to provide a framework to manage and test all the components of the low-latency searches. It is an end-to-end system with h(t) production and distribution, data quality information generation and distribution, trigger generation, network analysis, sky position reconstruction and information transfer to external facilities for follow-ups of the most significant triggers. The first run (ER1) took place in January 2012. The primarily goal was to test the low latency data transfer infrastructure for one month where simulated Gaussian colored noise have been generated in each LIGO and Virgo sites, transfered to the processing centers (Cascina and Caltech) and processed with three low-latency pipelines. Different problems have been observed during the run mainly with data broadcasting at Caltech but also for transferring data from USA to Europe. Virgo was in charge of the production of the h(t) stream of our instrument and the transfer to Caltech as well as the reception of LIGO h(t) stream at Cascina. To test the different low-latency pipelines (one for burst and two for CBC) signals were injected using an astrophysical rate based on our present knowledge [8]. Some of these injections were also done in a blind way and results were un-blinded two weeks after the end of the run. **MBTA**: the Virgo low latency CBC pipeline ran on the Cascina cluster to participate to the challenge. The overall duty cycle of the analysis was of 32% mainly due to the data transfer problems. This had an impact on the blind injection challenge. However when the injections was detected by **MBTA**, the chirp mass was estimated with a few percent accuracy.

4.2 Activities and results from May 2012

The second run (ER2) took place in July 2012. The first run (ER1) had shown some problems with the data transfer (mainly on broadcasting on the Caltech cluster), one of the objectives with ER2 was to have a huge improvement on that task. Finally we reach a data transfer duty cycle of 94 % between Caltech and Cascina (the missing part was due to a failure on one of the machine used in the transfer that was reboot 28 hours after the failure). The transfer between Cascina and Caltech was affected also by the same problem. The Virgo data used for ER2 were VSR3 recolored data to the Advanced Virgo design sensitivity curve in order to have realistic glitches in our dataset. This strategy has been also used for simulating the Hanford detector. However to start detector characterization work, some data taken from the Livingston laser subsystem (and recolored) were used to simulate Livingston observatory. We also sent with the h(t) channel another channel containing the Data Quality information associated. In parallel we also restarted the transfer of Data quality (DQ) information through XML files to be feed in the LIGO segment database. As it was done with ER1, a blind injection challenge took place using an astrophysical rate based on our present knowledge. MBTA, the Virgo low latency pipeline ran on the Cascina cluster to participate to the challenge using only triple coincidence time. The results of the run are given in the CBC section of this report 5.4. We also started to implement a new pipeline, **Omicron**, an upgrade of the Omega burst search pipeline, to run with low-latency on many channels for a robust detector characterization. More details in section 5.2. Some tests were also done to test the idea of an online triggers database and the possible problems to expect with such project. **MBTA** ran during ER2. The main result, as described in the CBC section of the report5.4 is the reduction of low-latency time. **NoEMi** ran during ER2 on both Virgo and LIGO data, as reported in the Noise group activity 5.3. Next run, **ER3**, will take place in January 2013. The goals will be to continue the work with the different pipelines already started in the previous runs. We also want to work on a better monitoring system for the data transfer, which needs some improvements. Finally we would like to test the synchronization between the Virgo and LIGO segment databases to avoid transferring the DQ XML files.

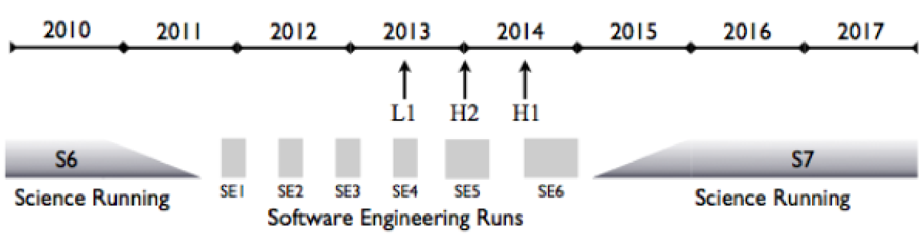

Figure 1: LSC-Virgo engineering runs time-line for the advanced detectors low latency searches preparation.

5 Activity of DA groups and DA support groups

5.1 DA support group: Calibration and h-reconstruction

The main results for this group have been the verification of the accuracy in the reconstruction of the data and the first direct calibration above 1 kHz.

5.1.1 Main achievements

No calibration has been needed since the Virgo+ shutdown. The two topics discussed in this section are the latest results of the VSR3/VSR4 verification of the h(t) channel using the NI photon calibrator, and the data generation for the LIGO-Virgo engineering runs.

The photon calibrator (gravitational-wave-like signal induced by the laser pressure of an auxiliary laser on the NI mirror) has been used during VSR3 and VSR4 to check the sign of the reconstructed h(t) and to cross-check the estimated uncertainties. Timothe Accadia is finishing writing his PhD about the use of the photon calibrator to check the reconstructed h(t) channel from 10 Hz to 6 kHz. He has shown that the data allow to properly take into account the presence of mirror deformations under the radiation pressure of the photon calibrator, using the internal modes of the mirror. The results are

(i) that the h(t) time series is properly reconstructed within better than 20 s in the whole frequency range,

(ii) that h(t) amplitude is also properly reconstructed within better than 10% below 400 Hz and

(iii) that a potential bias on the h(t) amplitude is lower than 20% up to 6 kHz.

This is the first direct verification of the h(t) above 1 kHz. This experience will be very useful to design the photon calibrator for AdV.

Manpower: 3 people at LAPP, representing 1 to 2 FTE depending on the calibration activity. Review: 6 people.

More information and notes can be found at:
https://workarea.ego-gw.it/ego2/virgo/data-analysis/calibration-reconstruction
Uncertainties on the reconstructed h(t) are summarized at:
https://wwwcascina.virgo.infn.it/DataAnalysis/Calibration/Reconstruction/index.html

5.1.2 Contribution to the Engineering runs

In the framework of the LIGO-Virgo engineering runs, some fake h(t) time series are permanently generated on Cascina online computing farm (olnodes machines) to be analyzed on-line in coincidence with fake LIGO data received at Cascina. The h(t) generated data are also permanently sent to LIGO clusters.

5.2 DA support group: Virgo Data Quality Group (VDQ)

The Virgo Data Quality group (VDQ) is a data analysis working group in charge of various aspects of the detector characterization. This includes glitch studies, online vetoes production, off-line vetoes production and the development of tools for monitoring, investigations and commissioning help.

Current FTEs are about 2.2, with contributions from Marie-Anne Bizouard, Florent Robinet, Nicolas Leroy, Frederique Marion, Gary Hemming, Bas Swinkels and Didier Verkindt. (and Francesco Berni, Fabio Gherardini and V. Dattilo for the Detector Monitoring System (DMS)).

In June 2012, an important paper for us has been published in Classical and Quantum Gravity [7] which summarizes the investigations and results we obtained over the scientific runs VSR1, VSR2 and VSR3. It describes the various types of noise that we were able to understand, the vetoes that have been designed and generated, their performances and their impact on the gravitational wave transient search results (all CBC and burst and stochastic LSC-Virgo papers are using these vetoes). A public outreach summary page has been also been written: http://www.ligo.org/science/Publication-VirgoDetchar/index.php

5.2.1 Advanced Virgo preparation

We are still working on a document describing the VDQ strategy for the coming years. This document lists the current tools available and their foreseen improvements. It describes also the current projects, the needs and requirements for various aspects of the glitch investigations, online vetoes production, monitoring tools for data quality assessment during scientific runs and tools for the commissioning team. This document is updated according to the feedback received from data analysis groups or commissioning people but also from discussions with our LIGO colleagues involved in detector characterization activities. It is accompanied by a web page listing the various projects linked to detector characterization activities:

https://wwwcascina.virgo.infn.it/DataAnalysis/DQ/dqtools.html

We are currently organizing our activity around four priority tasks:

- **Virgo Data Base (VDB) upgrade**: A large upgrade of the Virgo DataBase (VDB) which is the main repository of the Data Quality (DQ) flags produced online or off-line. This upgrade includes the cleanup and reorganization of the mySQL tables, the definition of users requirements and the corresponding upgrade of the access tools (web interface, Linux command line tool, python interface). Part of this upgrade work will dedicated to the synchronization with the LIGO database "segdb" and the direct access to Data Quality (DQ) flags by data analysis pipelines or by online monitoring tools. Cleanup and reorganization of the MySQL tables are mainly done now and various speed tests have been undertaken [9, 10], showing encouraging results. We are currently in the process of defining more carefully the users and software requirements. This is done in collaboration with our LIGO colleagues who investigate the possibility to use VDB to store also the LIGO data quality flags.

- **Omicron**: Many veto algorithms that study correlation between the Gravitational Wave (GW) strain amplitude channel and the auxiliary channels (collecting environmental and instrumental probes data) rely on the transient triggers generated by the algorithm KleineWelle (KW). The main advantage of KW is its ability to process all auxiliary channels (≈ 800) online, using only a few CPU cores. But the KW triggers are known to give an imprecise frequency and significance information. An ambitious program to upgrade the Omega burst search pipeline (especially to speed it up) has already started. This project is called Omicron. First tests have shown that about 80 computing cores will be needed to run online over about 800 channels. During the summer 2012, more than 580 channels over the full VSR2 run have been analyzed by Omicron, using the *CCin2p3* computing resources. The resulting triggers have been processed by an improved version of the veto algorithm called UPV. The performances of the resulting vetoes have shown to be better than those of the DQ flags used for the VSR2 run [11, 12]. Omicron is also a tool which raises interest from our LIGO colleagues.

- **Vetoes and DQ flags**: Traditionally, the group has tested and developed several algorithms and elaborated a strategy to produce online and off-line DQ flags (vetoes) that are fundamental for all GW transient searches. Strong constrains coming from the low-latency GW searches have been already fulfilled for the EM followup of GW candidates during VSR3, but the group is thinking to provide more data quality information for low latency searches within a latency of about 1 minute. New methods of glitch identification and methods to combine the triggers information will be tested for advanced detectors GW searches. On a shorter term, first tests of glitch classification have been done and a preliminary data quality performance number based on a set of a few usual criteria has been tested.

- **Monitoring tools**: We are in a time period of reorganization and we have started several improvements of the tools used to monitor the production, to check the safety, and to estimate the performance of the online DQ flags. We have decided to use the GWOLLUM project of Florent Robinet (whose Omicron is part of) [13] to provide the standard DQ flags performances monitoring tool. Work remains to be done to better define what will be the data quality work of a scientist on shift and what should be the tools to be used when deciding about GW candidates to be sent for follow-ups by satellites and telescopes. Definition or improvements work has also started in July on more general monitoring tools like the Detector Monitoring System (DMS), the dataDisplay and the MonitoringWeb

  (https://wwwcascina.virgo.infn.it/MonitoringWeb)

5.2.2 Virgo Data Quality in ER2 run

From July 11th to Aug 11th 2012, a Software Engineering Run called ER2 has been done in LIGO and Virgo. The main purpose was to exercise the coincidence run, low latency data exchange and low latency data processing. This was done by using VSR3 h(t) data, recolored in order to simulate Advanced Virgo noise level. We participated to this run in providing online the DQ segments produced during VSR3. This was done through the usual rsync process of xml files (required by LIGO to publish DQ segments in the LIGO database) and by storing also the DQ segments in the frames containing the h(t) data. We also provided in the h(t) frames a DQ vector whose bits contained all the data quality information. This DQ vector is going to be the main tool used by the Advanced Detectors online analysis. Also, during ER2, the Omicron triggers generator has been run successfully online on the Virgo and LIGO h(t) data, on the Virgo site. The Omicron triggers have then been used to check for the DQ flags produced. As soon as possible, Omicron will run also over auxiliary channels.

For the next run (ER3) in January 2013, we plan to use the upgraded VDB to store Virgo and LIGO DQ flags, to use Omicron online on LIGO auxiliary channels and to do first tests of the use of monitoring tools by a scientist on shift.

5.3 DA support group: Noise group

As reported in Section 5.2 one of the main achievements of the last months has been the work that led to the paper [7]. The group has actively participated to the ERs activity, in particular the "Noise Event Miner" (NoEMi) ran in-time (once per day) during ER2 on both Virgo (less interesting for the noise as we have used VSR3 recolored data) and LIGO (test on the central part of the Interferometer). The Wavelet Detection Filter (WDF) ran online during ER2 on Virgo data, testing the interface to on line data distribution and triggers database structure. The noise group presented three works at GWPAW 12 in Hannover. Two works are linked to non linear analysis "Impact of noise canceling by regression on searches for continuous gravitational waves"

"Non linear system identification in time domain: an application to Virgo Noise" and one on spectral lines identification: "Noise line investigations in Virgo VSR2-VSR4 data"

5.3.1 Activities and FTEs

The noise group is responsible of the characterization of the noise detector from point of view of noise contributions source identification, producing tools for commissioning and data analysis people devoted to noise understanding and helping in veto definition and environmental noise hunting. The group is involved in the following main activities:

- Noise characterization tools developing and on-line/in-time analysis for noise
- Environmental noise hunting and characterization
- Noise analysis linked to commissioning working group

All these activities are strictly linked to the work done by Virgo Data Quality group (VDQ). Total FTEs are 4.4.

Here the list of involved people:

Pia Astone 0.1, Giancarlo Cella 0.1, Alberto Colla 0.4, Elena Cuoco 0.7, Sabrina DAntonio 0.2, Marco Drago 0.3, Irene Fiori 0.4, Sergio Frasca 0.2, Gary Hemming 0.2, Cristiano Palomba 0.1, Francesco Piergiovanni 0.4, Giovanni Prodi 0.1, Virgina Re 0.3, Paolo Ruggi 0.1, Bas Swinkels 0.5, Gabriele Vajente 0.1, Gabriele Vedovato 0.2.

5.3.2 Noise characterization tools

Active projects: Noise Monitors API (NMAPI) and D-NMAPI, Noise Event Miner (NoEMi), Spectral Lines Identification and archiving in LinesDB, WDF (Wavelet Detection Filter) and triggers database.

We plan to integrate the existing noise monitor tools with new algorithms for detector characterization. In particular: Non-linear noise identification (as the one already tested on VSR4 data), non-stationary noise estimators and integrate them in NMAPI. Glitch characterization: produce a catalogue of transient noise event waveforms (using cWB or WDF pipeline) and archive them in a Database. Channels ranking for glitches. Tests and comparison on transient events found by Continuous Waves pipeline cleaning procedure and the ones found by WDF and other pipelines.

5.3.3 Environmental monitoring

Support to Infrastructure modification projects (INF: new clean rooms, new INJ lab isolation, new air conditioning systems)

Support to VAC noise mitigation projects (new vacuum racks, scroll pump room) characterization of new optical mounts for INJ (possible, if approved) realization of the external environmental station collaboration with IPGP seismologists in studies using Virgo data.

Integration of environmental sensors information in Hardware inventory database and preparation for Advanced Virgo (in collaboration and supporting Napoli group)

5.3.4 Detector characterization for commissioning

Contribution to noise hunting, noise suppression and veto strategy developing

5.3.5 Collaborations

We started collaborating with LIGO CW and Detchar people for NoEMI integration as noise characterization tool. We plan to start collaborating with Max Planck Institute for Gravitational Physics (Albert Einstein Institute) group.

5.3.6 Updated activities during the last months(May2012/October 2012)

- **NMAPI**

  NMAPI provides a framework into which different noise monitors can be plugged and then configured. The application enables authenticated users to not only access information, but also to produce results, e.g. HTML pages or text files, based upon bespoke search criteria specified by them via the user interface. NMAPI was setup before VSR4 and used during the run. No major developing in the last 6 months

- **NoEMi**

  NoEMi is running on-line on the Ligo Hanford "One Arm Test" (OAT) data, since April 2012. The framework has been adapted in order to run on the LIGO Condor clusters, allowing the analysis of more than 100 auxiliary channels in parallel. The NoEMi data are stored in a centralized database in Cascina, which is integrated in the Noise Monitors API (NMAPI) framework. Thanks to the NMAPI infrastructure it is possible to visualize summary pages and query data belonging to different detectors with a single and user-friendly interface. NoEMi also ran on the second Virgo and LIGO Engineering Run (ER2) during the Summer 2012. This work was presented at last LVC meeting.

- **LinesDB**

  LinesDB is the web interface to the lines database, the archive of noise lines identified in the Virgo data by the NoEMi framework. The database is updated in real time during the data taking by NoEMi, and is linked to the metadata table, which is filled with user-defined information (type of instrument used in measurement, general information relating to the line, etc.) once the source of the disturbance is understood. The identification of the noise lines found in VSR2-VSR4 data started just after the end of VSR4. Out of the O(1000) lines found in each run, 90% have already been identified and less than 100 lines still require investigation. The lists of identified lines are used for the veto of fake candidates in the stochastic and CW searches.

- **Wavelet Detection Filter (WDF)**

  Wavelet Detection Filter (WDF) is a pipeline for the detection of transient signals of generic waveforms. It was developed for detector characterization purposes. It is plugged in the NMAPI framework and so its results are available on the web as soon as produced. It ran online during ER2, testing the interface to on line data distribution and triggers database structure. Off-line analysis and tuning of WDF is in progress on ER2 and simulated data. The goal is to optimize the signal parameters estimation and make the filter much robust with respect the signal waveform. The connection of WDF and MySQL database and its integration in NMAPI framework was presented at last LVC meeting.

- **Non linear analysis**

  The Regression project is aimed to measure the linear couplings and some classes of non-linear ones among a primary "target" channel (e.g. h(t) or dark fringe) and a set of auxiliary channels (e.g. environmental or instrumental monitors). This information can then be used for commissioning and noise hunting activities, as well as for cleaning non Gaussian noises from h(t) by numerical subtraction of the measured correlation with the auxiliary channels. We are developing and tested two different procedures:

  A procedure based on non-linear system identification technique has been developed to reconstruct noise structure in target channel. A Volterra series expansion of auxiliary channels is employed, so the target channel has been decomposed in a regression of auxiliary channels combination. The identification accuracy is improved by filtering the error in a specifiedfrequency region. A ranking of the auxiliary channel contribution to the model can be obtained from the model structure selection procedure. Thanks to the orthogonalization procedure the evaluated contributions of each regressors is orthogonal with respect to the others. The ranking of most involved channels can give information and hints about noise sources and non-linearities production processes. Two different methods have been performed. The first one based on Orthogonal Least Square procedure (OLS - Billingset al. 1989) has been applied on modulation of calibration lines at 113Hzand 444Hz, on Vela pulsar region and on power lines of Virgo VSR4 data. Moreover the procedure has been applied on power lines of H1 LIGO S5 data using a list of 633 auxiliary channels parallelizing the code as much as possible to save computing time. A second method based on Sorted Fast Orthogonal Search (H.M. Abbas 2009,M.J. Korenberg 1989) has been used to solve memory usage problem. This method allows to keep in memory only regressors which give the highest contribution to the model allowing to handle high number of auxiliary channels without memory space trouble. In the future the idea is to use the system identification techniques also for glitches analysis identifying channels that are involved in glitch events (Poster presented at GWPAW 2012, LIGO-G1200496-v1)

  A procedure based on a coherent analysis of the target and auxiliary channels. It consists in a linear regression or Wiener-Kolmogorof filter which predicts the target channel part correlated to auxiliary channels. Considering as input the mixing of more auxiliary channels, it is possible also to characterize bilinear (or higher order) couplings to the target channel, for instance up-conversion of low frequency noise to side-bands of strong spectral lines. The algorithm is based on a chi-square minimization to find the optimal prediction, with the following steps:

  - perform analysis in the wavelet domain. This allows to split a complex computational problem in simpler ones, e.g. in many narrow frequency bands; - analyze coherently a set of many auxiliary channels including mixed channels per each narrow band. - select the most relevant auxiliary channels for the prediction by applying a regulator to their ranked list, to avoid increasing prediction noise due to not useful auxiliary channels.

  The prototype algorithm has been applied on Virgo data for a period of VSR4 data, focusing around some calibration lines and the mains. The algorithm has been tested by injecting software CW pulsar-like signals on Hanford data from S5 run. Applying CW pipelines (Hough transform and coherent pipeline) we tested the difference of performances on the two scratches of data, without applying and applying regression filter. The test has been made considering the power lines (50, 100, 150, 200, 250, 300 Hz) and relative side-bands. Preliminary results show that estimated parameters of the injected signals are compatible in the two cases, in particular the results show a gain in SNR of a factor of 1.2-1.5, at the prize of a loss on amplitude estimation of about 1%. Work presented at GWPAW 2012.

- **Environmental monitoring**

  For the advanced Virgo project we were involved in the following items. INF chapter of AdV TDR (definition of requirements and mitigation strategies) devices noise emission mitigation tests (new cooling fans, scroll pump room, racks seismic isolation, magnetic emissions of electronic components)

  For EGO site noise climate (preservation and monitoring): noise evaluation of one speedway project proposed for construction near Pontedera; project of one external environmental station isolated from the interferometer noise environment.

5.3.7 Activity in view of Advanced Detector Era

We report here the Advanced Virgo Noise strategy plans. The group described the strategy for noise study in the ADE in a dedicated document which is still in development (https://tds.ego-gw.it/ql/?c=9019). The idea was to collect information on all the projects linked to noise analysis and their computing requirements for ADE.

- **Centralized Data Base**

  We have in mind to have a centralized database to store and retrieve all Noise Monitor results having a transparent access via a web interface . The aim is to increase the inter-operability and communication between applications within this environment and NMAPI via the use of the Connections Database (CDB).

- **Framework: from NMAPI to D-NMAPI**

  Since we plan to integrate more analysis tools into NMAPI framework and having Advanced Virgo and LIGO in mind with a significant increases in channel examination, we foresee to upgrade NMAPI to a distributed version of the application (Distributed NMAPI) which will distribute the computational work on different computing nodes improving the performance of NMAPI. Fig.2 and Fig3 show a snapshot of NMAPI and its D-NMAPI Evolution.

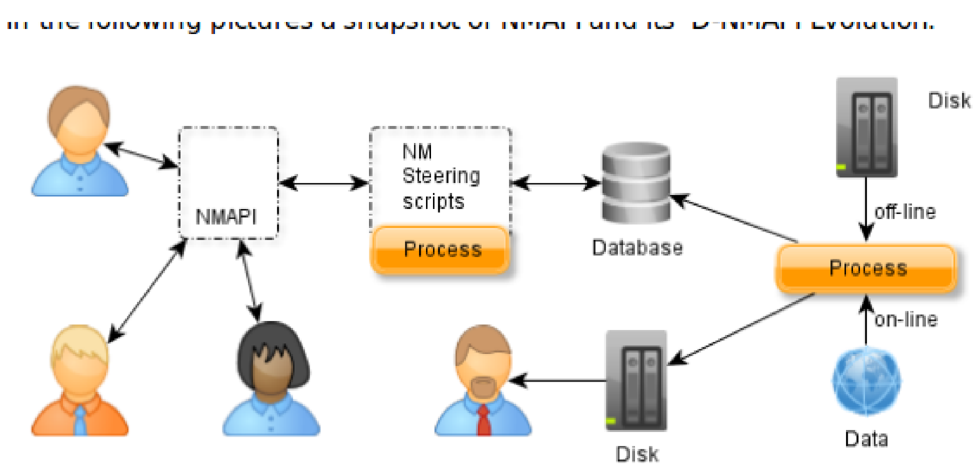

Figure 2: Work of the Noise group. Snapshot of NMAPI

5.4 Compact Binary Coalescence (CBC) group

Let's briefly recall the physic goals beyond this search. The inspiral and merger of a compact binary system generates gravitational waves which sweep upward in frequency and amplitude through the sensitive band of the Earth-based detectors. The detection of gravitational waves from these astrophysical sources will provide a great deal of information about strong field gravity, dense matter, and the populations of neutron stars and black holes in the Universe. The scientific program of the LSC/Virgo Compact Binary Coalescence (CBC) Group is designed to identify GW signals from compact binary sources in the detector data, estimate the waveform parameters and use these signals for the study of gravity and the astrophysics of the sources.

The first goal of the CBC group is to make the first detections of gravitational waves from compact binary systems with data from the LIGO and Virgo detectors, through computational methods that are as close as possible to optimal and to develop methods to gain confidence on the detections. Once signals have been identified, there is a need for the accurate recovery of parameters in order to perform detailed studies of both gravitational-wave astrophysics and fundamental physics. Let's thus report here research lines of the CBC group activities: Binary neutron stars; Neutron star-black hole binaries; Stellar mass binary black holes; Intermediate mass black hole binaries; Gravitational wave counterparts to GRBs (Gamma Ray Burst).

5.4.1 CBC group reorganization

In the past few months, the CBC group – both on the LSC and the Virgo side – has undergone a reorganization, with a view on science in the advanced detector era, as well as the technical requirements for making this a success. Two kinds of sub-groups were created: *source sub-groups* and *technical sub-groups*. Each member of the CBC group is meant to belong to at least one of each. The source sub-groups are:[4]

- Binary neutron stars (co-led by John Veitch, Nikhef).
- Neutron star-black hole binaries.
- Stellar mass binary black holes.
- Intermediate mass black hole binaries (joint with the Burst group).
- GRBs (co-led by Nicolas Leroy, Paris; joint with the Burst group).

[4]In principle, GRBs belong to BNS or NSBH, but the GRB sub-group was a well-established and productive group before the reorganization, so the decision was made to keep it separate.

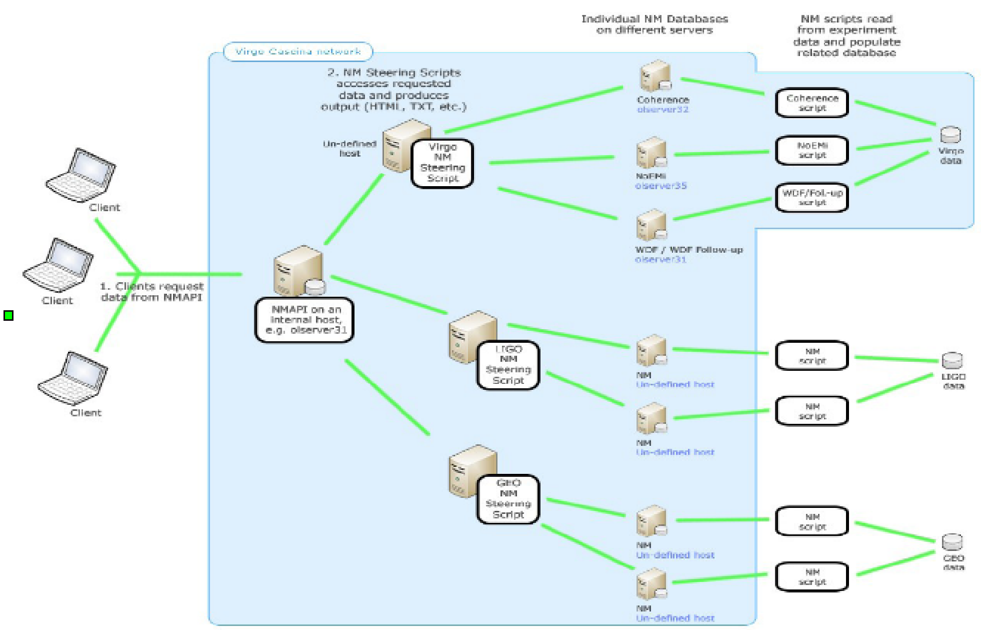

Figure 3: Work of the Noise group. Snapshot of D-NMAPI

The technical sub-groups are:

- Data quality (co-led by Frédérique Marion, Annecy).
- Engineering runs.
- Waveforms (co-led by Riccardo Sturani, Urbino).
- Streaming pipelines.
- MBTA pipelines (led by Frédérique Marion and Benoît Mours, Annecy).
- FFT-based pipelines.
- Rate and significance measurement.
- Parameter estimation.
- Electromagnetic follow-up.
- Strong field gravity (led by Walter Del Pozzo, Nikhef).

Source sub-groups are meant to focus attention of the CBC group as a whole on the different scientific questions to be addressed. The highest-priority question is how to optimize our chances of a first detection. Next, what will the frequency of first detections tell us about the intrinsic rates for the respective sources, and the different progenitor channels? Are short, hard GRBs really caused by BNS and/or NSBH mergers? Can we prove definitively that black holes exist? The direct detection of gravitational waves will give us our first empirical access to the strong-field dynamics of the gravitational field itself; how is this opportunity to be exploited in practice? On the basis of such goals, the source sub-groups formulate requirements to be addressed by the technical sub-groups.

The division into technical sub-groups reflects the expected challenges in the advanced detector era. In terms of pipelines, multiple methods are being pursued. FFT-based pipelines are the ones that were previously used for the analysis of S5/S6 and VSR1/2/3 data, but in the future they will need to handle much longer (BNS) waveforms due to the decrease in lower frequency cut-off, and also address the much denser packing of template waveforms in the low mass regime. An effort is in progress to make such pipelines run on GPUs as well as CPUs. The streaming pipelines are a separate GPU-based initiative where a new pipeline is being written from scratch. The new versions of FFT-based pipelines, the streaming pipelines, as well as the MBTA pipelines, are intended to be used both for off-line and for online analysis and fast pointing, which is important for electromagnetic follow-ups; these efforts also draw on the expertise of the parameter estimation group. The sub-group on strong field gravity is developing tests of general relativity, methods to measure the equation of state of neutron stars from the last stages of BNS inspiral, and techniques to use binary coalescence events as 'standard sirens' for cosmology; this too is done in partial collaboration with the parameter estimation sub-group. All these sub-groups benefit from the quick implementation into the LIGO Algorithms Library of new waveform approximants as they become available. Finally, the data quality and engineering run sub-groups are of obvious importance for all detection and parameter estimation efforts.

Sub-groups have one or two (co-)leads. Some have no Virgo co-lead because their activities are mostly concentrated within the LSC (*e.g.* streaming pipelines), while in other cases one or both (co-)leads are Virgo members because their subject is mainly a Virgo effort (such as MBTA).

The leads of both source and technical sub-groups jointly wrote the CBC section of this year's Data Analysis White Paper, outlining their expectations in the era of the very first detections as well as the science that can be done once $\mathcal{O}(10)$ detections are available. During the last LVC meeting, they presented roadmaps for their activities, with the approximate commissioning plans for both Advanced Virgo and Advanced LIGO as a guide, as outlined in the draft of the commissioning and observing document In due course, the source sub-groups will be asked to write 'science case' papers to be published in journals.

5.4.2 Development activities by Virgo members

To give an overview of Virgo members' research and development activities, it is convenient to list their contributions to the various technical sub-groups described above, as applicable.

Data quality. Within CBC, this will mostly be the responsibility of the Annecy group.

Waveforms. This sub-group has had important contributions from Urbino, RMKI, and Nikhef. Its main short-term goals have already largely been met: (a) to take stock of all the waveform approximants available in LALsuite, and (b) to make uniform the waveform generator codes themselves, as well as their input/output, for which a new package within LALsuite was created, called LALsimulation. It will now be a lot easier to keep track of the waveforms that are available, not only for the user but also for review purposes, and waveform approximants have become 'plug and play'. The idea is that in future, all pipelines that do not have their own waveform generators will make use of the LALsimulation facility. The waveforms sub-group stays in close touch with the so-called NRAR (Numerical Relativity – Analytical Relativity) collaboration, which generated a large number of numerical waveforms and is 'tuning' (semi-)analytic waveforms to have better agreement with numerical results. At Urbino, PhenSpin (Spinning phenomenological waveform tool) is being compared with the NR (Numerical Relativity) waveforms. The waveforms sub-group will implement new waveform approximants into LALsimulation as they become available, and have them reviewed.

As mentioned in the previous report, the RMKI group has developed CBwaves, a tool for computing gravitational waveforms from generic spinning binaries with eccentricity. CBwaves integrates the equations of motion and the spin precession equations, but unlike existing waveform generators, the radiation field is determined by a simultaneous evaluation of the analytic waveforms. Since May, all the higher order contributions available for generic orbits have been added. Efforts to incorporate CBwaves into LALsimulation are ongoing.

FFT-based pipelines. These are pipelines with the ability to run on either CPUs or GPUs. Here the main Virgo contribution is by RMKI. In particular, a package called GWTools is under development, which is an OpenCL/C++ based generic gravitational wave data analysis toolkit enabling the transparent use of GPUs and other emerging many-core architectures with a single code-base. Simple pilot applications are working both on CPUs and GPUs, such as template bank generation, effectualness studies, and a waveform chi-squared prototype. A website with documentation is soon to come online. Tests have been done on a variety of cards, and speed-ups in typical CBC matched filtering by a factor of ~ 100 were seen. Batch submission scripts for LSF, Torque and Condor were also made available. Plans for the near future include:

- The incorporation of the CBwaves waveform generator (see under 'waveforms') so that it can run either on CPUs or GPUs.
- Executing a single stage inspiral pipeline on a GPU cluster.
- Using the pipeline on the CNAF and CCIN2P3 clusters with native batch submission.
- Applying the tool to spinning searches and/or MBTA.

A longer-term project at Urbino is to develop a novel kind of template placement. The idea is to devise a dynamics in the space of configurations so that a swarm of interacting templates covers a given region in an optimal way, in particular so that possible small changes of the noise spectral density can be accounted for by a quick rearrangement of the templates induced by the same dynamics. In this sense, there would be a degree of stochasticity, partially driven by the detector noise variations, partially by some internal noise necessary to prevent the templates from getting stuck somewhere in the parameter space.

MBTA pipelines. This is an ongoing effort at Annecy. MBTA stands for 'multi-band template analysis'; among other things, it allows for fast localization of sources in the sky. Recently, activities have centered on running the low latency pipeline during the second engineering run (or ER2; see below) and a posteriori analysis of the results. The pipeline configuration was tuned to further improve the latency, which decreased from 4 minutes in the first engineering run to 40 seconds in ER2. In addition, a study was completed to investigate the timing accuracy expected in the advanced detector era with the MBTA pipeline and compare it to theoretical predictions.

Parameter estimation. Off-line Bayesian parameter estimation has become a major activity within Virgo, in particular at Nikhef. In parallel with the streamlining of waveform codes through LALsimulation, the three main Bayesian methods (Nested Sampling, MultiNest, and MCMC) have been incorporated into a unified framework called LALinference. The review of this new tool was recently concluded. LALinference has allowed for an easy comparison of the methods for a large variety of waveform approximants, finding remarkable agreement, as illustrated in Fig. 4. A paper on this, using both software injections and the 'Big Dog' hardware injection, is expected before the end of the year. Additionally, a limited author list paper on off-line sky localization is in the works. In the near future, various ways of speeding up the codes will be explored. There have also been preliminary discussions with Annecy and RMKI regarding future collaboration on low-latency sky localization involving MBTA and GPUs. At Urbino, PhenSpin was incorporated into the LALsimulation/LALinference framework; testing is in progress. Urbino is also working on the implementation of new methods for evidence calculation and parameter estimation, in particular a diffusive nested sampling algorithm. This code will also be able to use GPUs.

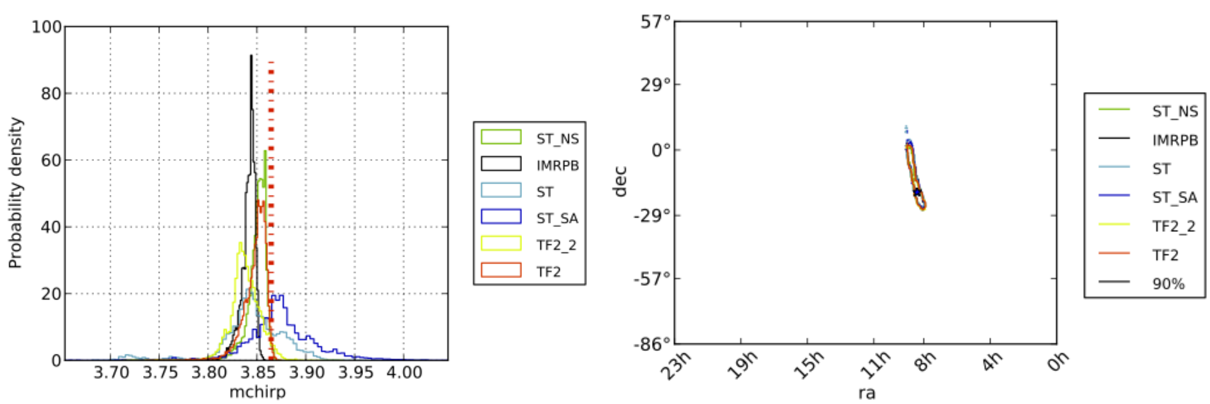

Figure 4: Estimation of the so-called 'chirp mass' (left) and sky localization (right) with the Bayesian parameter estimation codes, for a variety of waveform approximants. The source was a BBH hardware injection.

Electromagnetic follow-up. Here the groups involved are Nijmegen and Urbino. The latter has been involved in the analysis and interpretation of the optical data taken during S6-VSR2/3, in an electromagnetic follow-up effort of MBTA triggers. Nijmegen and Urbino are studying the GW/EM joint observation strategy for the advanced detector era. In particular, they are evaluating EM facilities that could be used for follow-ups.

Nijmegen recently submitted a grant proposal for an array of optical telescopes at La Silla, called BlackGEM, which would be fully dedicated to follow-ups of gravitational wave events. The initial proposal is for the first four of an envisaged 20 telescopes with 60 cm aperture, which could be pointed into the kind of elongated sky error boxes we expect for gravitational waves (see the right panel of Fig. 4). The first stage of evaluation will be in November.

Finally, within the Nijmegen group there is also an effort to determine how the exact localization in the sky by electromagnetic means would affect the estimation of all other parameters (masses, spins, orientation,..) of a CBC event.

Strong field gravity. This is mostly a Nikhef effort, with contributions from Urbino. Its main activities are:

- A Bayesian inference pipeline called TIGER has been constructed to use BNS signals to look for deviations from general relativity (GR) in the genuinely strong-field, dynamical regime. A variety of tests are in progress to address potential concerns: Are instrumental calibration errors important? What about differences between waveform approximants? Can we handle spins? Can we avoid confusion between a GR violation and matter effects in the final stages of BNS inspiral? So far simulations were done in stationary, Gaussian noise; what happens in real noise? See Fig. 5 for preliminary results on some of these issues. There are also plans to expand the method to BBH systems, but there one is limited by the (un)availability of sufficiently accurate waveform approximants. Another problem is the insufficient speed of the existing code when using time domain waveforms as templates. Urbino intends to use PhenSpin for BBH as a test case.

- Neutron star deformability near the end of inspiral affects the orbital motion and hence the gravitational waveform. Now assuming GR to be correct, can we infer the neutron star equation of state from this? Although this does not appear possible for individual BNS events, a method was developed which allows one to combine information from multiple sources, so that interesting statements can be made.

- Methods for using binary inspirals as 'standard sirens' to do cosmology are in an advanced stage. There are plans to incorporate these into the LALsuite in the form of a 'cosmology calculator'.

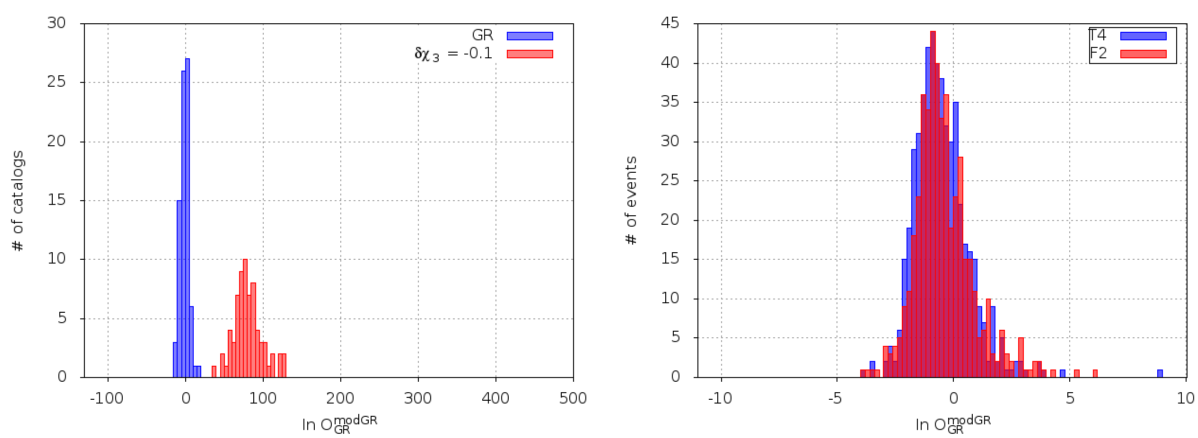

Figure 5: Left: Distribution of the TIGER detection statistic for a large number of simulated catalogs of 10 GR sources each (blue), and similar catalogs of GR-violating sources with an artificial 10% shift in the phase coefficient at 1.5PN (red). In both cases the sources have spins – in particular, there is the spin-orbit interaction at 1.5PN – but the two distributions are well separated. Right: For BNS sources, differences between injected waveform approximants (here TaylorT4 versus TaylorF2) have little influence on the distribution of the detection statistic.

5.4.3 Searches

The existing data from the initial/enhanced detector era have essentially been analyzed. In order to test new analysis methods, both for detection and parameter estimation, two kinds of 'mock data challenges' were been created.

- *NINJA2.* This is a collaboration between numerical relativists and data analysts. Numerical waveforms tend to contain just a few tens of cycles before merger, but can be 'hybridized' by stitching on a post-Newtonian waveform, arriving at a full inspiral-merger-ringdown waveform. The data analysts have created data sets based on S6-VSR2, but with detector outputs shifted in time with respect to each other. The hybridized numerical waveforms can be injected into this data set and searched for with a variety of algorithms. The NINJA2 blind injection challenge was created after the success of the initial NINJA (Numerical INJection Analysis), but now covering a wider range of parameter space, including non-precessing spinning binaries and non-spinning binaries with large mass ratio.

  At Nikhef, the most significant triggers produced by the standard 'ihope' pipeline in the blind injection set were analyzed using the Bayesian parameter estimation code, producing parameter estimates and Bayesian evidences for four different waveform models. These results will help in understanding which of the waveforms most accurately captures the full NR signal, including merger and ringdown, and what the systematic

  At Urbino, a stochastic template bank was developed for use with PhenSpin, with the intention of running on the NINJA2 data set. The implementation is now complete, and the analysis will soon begin.

- *Engineering runs.* Within Virgo, the engineering runs were mostly used by the Annecy group to further test and tune the MBTA pipeline, as explained above.

Finally, the codes for off-line Bayesian parameter estimation and strong field gravity efforts also have the built-in capability of generating short stretches of stationary, Gaussian data, colored with noise curves of one's choice, and containing single software injections.

5.5 Burst group

Highlights of burst group activity have been reported in the Executive Summaryn2. The science goals of the burst group are searches for general gw transients, i.e. in the widest transient signal parameter space. Top priorities are all-sky all-time searches, both off-line and low latency to trigger other astrophysical observations, and searches triggered by GRBs. These are complemented with other multimessenger searches and searches targeted to more specific classes of gravitational wave sources or signals, e.g. NSs excitations, SNs, BBH mergers, cosmic string cusps, non General Relativistic scalar component etc.. The last semester, since papers on the top priority searches have been published, current burst group activities are focusing mainly on the preparation for ADE, including pipeline developments, Engineering Run program and support to detector characterization activities. To better coordinate the activities, burst group internal organization migrated from the methodological/technical oriented one typical of the first generation detector era efforts to an organization oriented to scientific goals and astrophysical sources. This has been accomplished with the formation of the following subgroups:

All-sky (co-chair G.Prodi). In charge of all-sky all-time most general searches and methods, both low latency and off-line, including background rejection, signal reconstruction and parameter estimation

GRB (co-chair N.Leroy). Joint with CBC group. GW searches triggered by GRBs, off-line and low latency.

Binary Black Holes Joint with CBC group. Inspiral-Merger-Ring-down of binary black holes (approx 25-1000 solar masses), eccentric BHs binaries, intermediate mass ratio inspirals.

SuperNova Multimessenger searches for SuperNova core collapse, including neutrinos.

GW-EM Joint searches using electromagnetic observations different from GRBs and SNs.

Neutron Star Investigations of transient signals emitted from NSs

GW-High Energy Neutrinos (co-chair E. Chassande Mottin). Joint searches with high energy neutrino detectors.

Exotica Searches for non general relativity GWs and exotic sources (e.g. cosmic string cusps, bursts with memory,)

These team are charged to propose science and publication plans and submit them for discussion and approval by whole burst group. All activities in a given area should be coordinated and discussed through the relevant subgroup. As anticipated in the highlights, FTEs in the Virgo burst group decreased, in part because of the migration to LSC and other communities of young Virgo scientists due to the lack of grants and positions. Because of this, Virgo participation to some of the mentioned subgroups is currently poor (e.g. NS, SN, BBH). If this scenario will not change, Virgo burst groups will lose scientific opportunities of ADE, of which the most critical will be the low-latency all-sky burst searches and related multimessenger observations, binary black hole merger searches, NS astrophysics.

5.5.1 General burst searches on S6-VSR2/3 (all-sky and un-triggered)

In the last semester the paper describing the flagship all-sky all-time search has been published, requiring only a residual effort. The electromagnetic follow up analysis (i.e. the search for optical counterparts) is completed from the Virgo side, and the related paper by LSC-Virgo and astronomical partners is being drafted. Recent papers written in the Burst group are reported in [27]-[32]

Most general Burst search (0.2 FTE)

The Phys.Rev.D review of our observational paper on the off-line search on S6-VSR2/3 went smoothly and required little effort. Participation to Engineering Run2 was limited to LSC members responsible for the low latency search with "Coherent Wave Burst" (cWB). In the next semester, the Engineering Run 3 will accomplish the first stress test for the low-latency cWB pipeline, which will start including some upgrades developed by also Virgo members, but Virgo has not enough manpower to commit to low latency searches. For the future, burst group plans to repeat the all-sky search on past data before ADE, to improve the astrophysical interpretation in terms of a number of different GW source populations, once the improved versions of pipelines under R&D will be available (after mid 2013). This will be above all an important test in preparation for ADE and Virgo cWB group is planning to contribute.

Analysis of optical images as electromagnetic follow-up of candidates (0.8 FTE)

Within the wide range of LSC-Virgo activities on electromagnetic follow up of candidates aimed at the identification of electromagnetic counterparts of GW sources, Virgo members are leading the partnerships with TAROT, Zadko and Pi of the Sky optical telescopes, and have been crucial in supporting the partnership with the QUEST scope. Since the GW detector network has limited angular resolution, the sky regions to be analyzed are very large with respect to usual optical astronomical searches. This requires the development of pipelines of optical image analysis efficient for large field of view images and for the removal of contaminating optical transients, with specific features matching telescope characteristics. Analysis of TAROT and ZADKO is completed, analysis of QUEST and Pi of the Sky are close to completion. Analysis include efficiency studies of simulated KiloNova and GRBs sources, as well as the background estimate related to the analysis procedures. The analysis shows that GRB afterglows can be detected up to the LIGO Virgo horizon distance of 50Mpc, while the kilonova-type merger afterglows (from Metzger et al, arXiv:1001.5029) can be detected up to a distance of 15 Mpc (with a survey red limiting magnitude of 15.5), while keeping the false alarm probability under control (FAP¡10%).

Figure6 shows limiting magnitudes of the available optical images of different telescopes as a function of elapsed time from a sample LIGO-Virgo trigger.

A first draft of the observational is almost complete and the LIGO-Virgo+astronomers review process is starting. The lessons learned by this activity will be very useful for the planning of the future optical follow up observations during initial ADE, where LIGO-Virgo agreed on an organization based on partnerships with selected EM-groups.

5.5.2 Triggered searches by other astrophysical observations

Virgo main activities have been the Gamma Ray Burst (GRB) triggered search in coordination with the CBC group and the multi-messenger search triggered by high energy neutrinos (project GWHEN using neutrino triggers from Antares). In the last semester we published an observational results paper on the search for GRB triggers notified by the Gamma-ray burst Coordinated Network (GCN) with S6-VSR2/3 data and we are revising the first paper on a joint gravitational wave high energy neutrino search, which uses Antares and S5-VSR1 data. Most of the Virgo activities in the last semester have been dedicated to the extension of the GRB triggered search using InterPlanetary Network GRBs not notified by the GCN alerts and to the GWHEN-

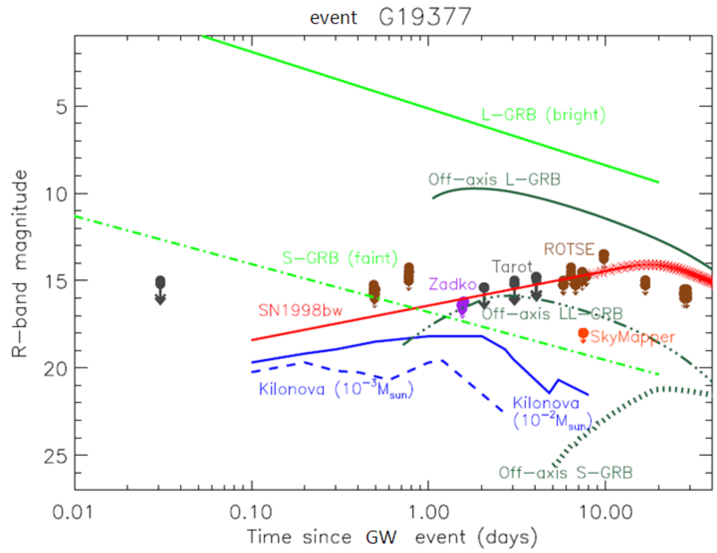

Figure 6: Data points are measured limiting magnitudes of the available optical images of different telescopes as a function of elapsed time from a sample LIGO-Virgo trigger. Curves are light curves for different source classes at a reference distance of 50Mpc: bright Long GRBs, off-axis Long GRBs, faint Short GRBs, off-axis Short GRBs, Supernova1998bw, Kilonova.

Antares triggered searches using S6-VSR2/3 data, both led by Virgo scientists [30]. Virgo members are leading the following searches:

GRB triggered searches (0.5 FTE)

The burst off-line analysis of IPN GRB triggers is ongoing using the same pipeline of previous GRB searches (X-pipeline). The MoU with IPN has become operative, according to which IPN provides to LSC-Virgo the necessary GRB characteristics, in particular the sky localization. This extension is relevant because it adds ≈260 GRB triggers during the past LIGO-Virgo observation time, allowing to reach 3 times the GRB number considered in the last publication. A CBC search is performed in parallel for the short GRB triggers. Fig7 shows the potential improvement of the published upper limit on the cumulative distribution of the redshift of burst gravitational waves related to GRBs assuming a GW emission of 10^{-2} solar masses.

In the next semester, we will start to exercise for 1 day latency GRB triggered searches during ER3. X-pipeline is considered ready for initial ADE; its computational performance could be possibly improved in the next years to allow searching over a wider frequency band.

High-energy-neutrino triggered searches (0.9 FTE)

The paper on the first GW-HEN search with ANTARES using S5-VSR1 data has been submitted to ApJ and referees comments are currently being addressed [30]. Virgo people are leading the second joint search with ANTARES, using all available LIGO-Virgo observations. The latter uses an improved methodology to determine the joint evidence for GW and HEN candidates, to cope with the much higher number of HEN candidates from Antares-12 line and using a tailored version of the cWB pipeline extends the frequency band of the GW search to cover possible SN core collapse sources. This analysis method is currently being optimized and the actual search and internal review process will begin shortly. A contribution from Virgo has also been dedicated to the preparation of the GWHEN search with IceCube on the S5-VSR1 data.

Low-energy-neutrino triggered searches (0.6 FTE)

This activity is a project involving people from LSC and Virgo aimed at designing a joint search between transient gravitational waves and low energy neutrinos (energy below 100MeV) from core collapse SuperNovae. The project proposal is currently awaiting for assessment by the low-energy-neutrino collaborations. Core collapse supernovae are potential sources of gravitational waves and emit neutrinos and EM signals. Neutrino

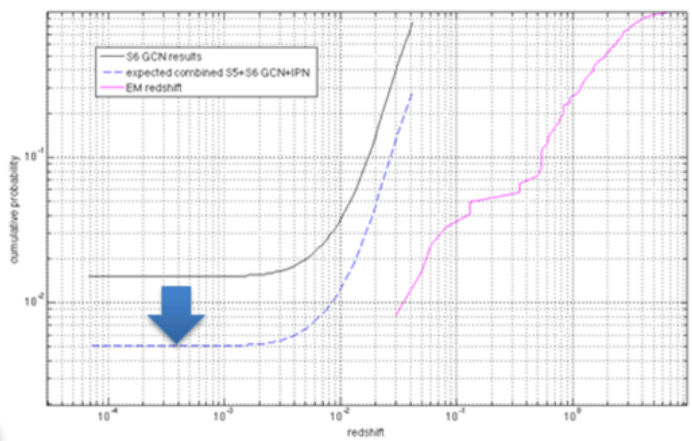

Figure 7: Potential improvement of the published upper limit on the cumulative distribution of the redshift of burst gravitational waves related to GRBs assuming a GW emission of 10^{-2} solar masses. Continuous line is the published upper limit for GCN GRBs, dashed line is the expected upper limit in case the null result is confirmed also for the additional IPN GRBs. The curve to the right is the measured red shift of observed GRBs so far. With Advanced Detectors we expect to grasp GWs from the population of GRBs.

triggers lead prompt information on the core collapse as they are emitted in the earliest stages of the collapse, several hours earlier than photons. Gravitational waves are expected to be emitted in a core collapse supernovae within a short time window (O(1s)) from neutrino emission, although uncertainties exist in the emission model due to to unknown source parameters. The benefits of a joint search include improved sensitivity and confidence of detection as well as clues into the physical model of the collapse.

5.5.3 All-sky searches for specific source classes

The LSC-Virgo burst group performs all-sky searches targeted to specific source classes in order to extend the detectable volume with respect to the general all-sky search. This is accomplished by adopting priors on the target signals, therefore making the all-sky search more selective and less general. The pipelines used are based on quite different approaches, e.g. matched filtering, correlation methods or specialization of a general burst search by including constrains on signal properties. Such searches are in general first performed on older data sets, S5-VSR1 data, and then extended to the entire data set. They include the Binary BH Inspiral-Merger-Ringdown search, the cosmic string cusps search, and the NS ring-down search. About the first, the project NINJA2 is steadily progressing and involves groups from the numerical relativity field and GW participation includes both CBC and Burst groups. In addition relevant progresses were achieved in the search for intermediate mass binary black holes mergers (BH of order 100-1000 solar masses). Due to lack of manpower, up to now there is no relevant participation to these IMR activities from Virgo burst members. On the contrary, Virgo is leading the cosmic string cusps search, on which we give a short update in the following. The activity on NS ring-down search has been frozen in the last year, even though it provided a longer range for such signal class with respect to the general all-sky search, both because this type of search is rather scientifically limited with current GW data sensitivity and because of lack in manpower. It is likely it could be resumed for ADE observations once better NS burst emission models are established.

Cosmic string cusps (0.3 FTE) The cosmic string cusps search is performed as a coincidence analysis on single detector searches over a bank of templates covering the band < 2 kHz based on predicted waveforms (Damour-Vilenkin). The pipeline has been fully developed and the analysis of past observations has been completed. The internal review process is at an advanced stage. In the next semester we expect to be able to release the results and the observational paper: a null result promises to beat for the first time the Big-Bang nucleosynthesis indirect bound in a significant part of the string parameter space. Moreover, it is expected that the LSC-Virgo direct observation and Planck indirect observation will give comparable results. Figure8 shows the potential upper limit on cosmic string parameters from a null result of the dedicated gw search (crosses) compared to previous upper limits from stochastic gravitational wave searches on LIGO (gray region), Big Bang Nucleosynthesis models (continuous line), Cosmic Microwave Background from Wmap (dashed line) and pulsar timing observations (dotted-dashed line). This LIGO Virgo limit would be comparable to what Planck satellite can indirectly set from CMB observations.

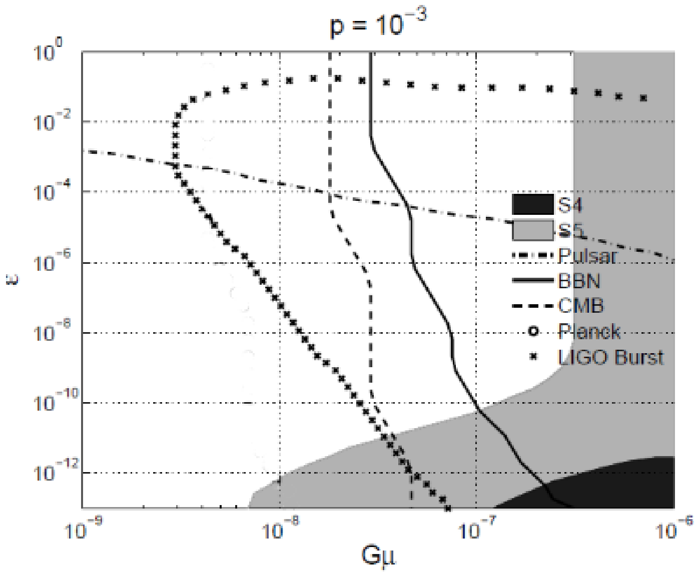

Figure 8: Projected upper limit on cosmic string parameters ($G\mu$ is string tension, ϵ is loop size parameter) from a null result of the dedicated gw search (crosses) compared to previous upper limits from stochastic gravitational wave searches on LIGO (gray region), Big Bang Nucleosynthesis models (continuous line), Cosmic Microwave Background from Wmap (dashed line) and pulsar timing observations (dotted-dashed line).

5.5.4 Development of pipelines and of burst searches

These R&D activities are not yet applied to the analysis of long term observations and aim at the improvement of already well established pipelines or to the development of new pipelines and searches to improve the future science throughput of the burst group. Most of these developments are performed as preparation to the future analysis of the initial ADE. In the last year the most relevant commitments by Virgo members have been the R&D on cWB pipeline, on STAMP pipeline for burst of longer duration, on Omega pipeline with chirplet basis functions and on a Bayesian pipeline to estimate gw waveforms. The cWB pipeline upgrades will be tested in all Engineering Runs, being the flagship analysis for all-sky all-time burst searches. LSC-Virgo burst group is evaluating how to increase scientific diversity to increase the robustness of general all-sky searches.

R&D on coherent WaveBurst (1.6 FTE + 1.6 FTE as noise regression)

cWB pipeline is a joint development project between LSC (Univ. Florida, LIGO Lab, MPG Hannover) and Virgo (Padova-Trento, Roma2). In the last semester the commitment to cWB R&D increased to a suitable level. In the last year and in the next, we aim to finalize an improved end to end burst search. Progresses include:

a)improved user friendliness and flexibility of cWB. A new structure of the pipeline has been implemented in the last semester, which provides user defined plug-in modules and more powerful tools for testing and optimization of searches.

b)Improved event trigger generator. We implemented a new time-frequency transformation (Wilson-Daubechies-Meyer) in place of the traditional wavelet transformation; this brings more uniform frequency bandpass filtering, a better null estimator (i.e. reconstruction of the incoherent noise in the network) and the disentangling of the h+ and hx gw polarization.

c) Improved reconstruction of signal characteristics. A new multi-resolution reconstruction of triggers is being developed by selecting the principal components of signal candidates from pixels of different time-frequency resolutions (previously the reconstruction of triggers was carried out at the fixed time-frequency resolution which was performing better overall). This feature will greatly extend the parameter space volume of burst searches, in particular for signals which show components on different time-frequency scales (e.g. inspiral-merger-ringdown phases).

d) Improved data pre-conditioning by noise regression (see Noise group section). Traditionally the data preconditioning was using only the h(t) data itself and used linear predictor filters to notch noise disturbances as frequency lines or non stationary spectral disturbances. cWB development has recently sprouted a methodological research on noise canceling in single detectors by regression analysis of the auxiliary environmental and instrumental channels, which is coordinated by the Noise group given its possible impact on noise coupling investigations. Since the regression makes a prediction for the excess non Gaussian noise in the GW channel related to auxiliary channel via linear or bi-linear couplings, we are investigating about its use to suppress those noise contribution in continuous wave searches, in collaboration with the CW group, and will start investigating in the next semester the application to burst searches. Figure9 shows the reconstructed energy of signal vs number of pixels considered for the new multi-resolution algorithm (Monster Cluster Analysis) compared to standard analysis at different fixed time-frequency resolution. The signal considered here for illustration is a NS-NS inspiral in the ADE network, a very difficult exercise for un-modeled burst signal searches.

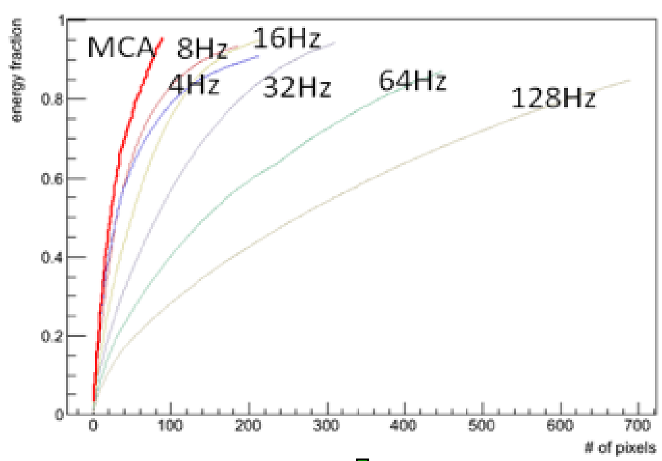

Figure 9: Reconstructed energy of signal vs number of pixels considered for the new multi-resolution algorithm (Monster Cluster Analysis) compared to standard analysis at different fixed time-frequency resolution. The signal considered here for illustration is a NS-NS inspiral in the ADE network, a very difficult exercise for un-modeled burst signal searches.

We are planning to test the new cWB pipeline in ER4, starting with some selected features in ER3. In 2013 we will re-analyze all the past LIGO-Virgo observations to demonstrate the improved performances of the new pipeline with respect to the previous one and to improve the astrophysical interpretation of burst search results.

R&D on STAMP for bursts of longer duration (1.3 FTE)

The goal is to extend the all-sky search to longer duration bursts (order of 10-1000s, as e.g. for some NS excitations) by developing the STAMP pipeline, originally implemented for triggered searches of long GW transients by the Stochastic group. This is a technical project in collaboration with the stochastic group, where the original STAMP pipeline was developed. The application to burst all-sky searches is much more computationally demanding, because it requires to scan over the sky and to analyze more than 2 detectors in simultaneous observation. In the next semester, we are planning to test the pipeline in triggered searches with good sky localization and to improve by one order of magnitude the initial computational performance.

R&D of the Omega pipeline using chirplets (0.2 FTE)

The traditional Omega pipeline uses sine-Gaussian waveform as templates; this work aims to use chirplet-like templates instead. This demonstrated at a better detection efficiency for burst signals with a rapidly varying frequency such as the last inspiral phase of NS and BH binaries. As shown by the blind injection, a general burst search can identify such transient signals without losing Signal-to-Noise Ratio with respect to CBC dedicated searches, but the resulting burst confidence can be improved a lot only if we restrict the search to a more limited class of signals (e.g. chirplet like signals). The Omega chirplet pipeline has been tested on binary BH signals, demonstrating an horizon increase of 50% with respect to the original Omega pipeline, at equal false alarm rate, for BH masses in the range 5-35 solar masses.

R&D on Bayesian pipeline for SN signals (0.1 FTE)

Bayesian parameter estimation is a very powerful tool to extract astrophysics out of gw candidates. Virgo members started to contribute to a pipeline to estimate the parameters of core collapse supernova events. It is based on a catalogue of accurate simulated waveforms spanning the parameter space. From them an orthogonal set of eigenvectors using principal component analysis is created. Bayesian inference techniques (Markov Chain Monte Carlo) are then used to reconstruct the associated GW signal that is assumed to be detected by an interferometric detector. Recent developments focus on transforming the pipeline into a multi-detector Bayesian search. The next semester the activity will focus on adaptation to run on real data.

5.6 Continuous wave signals (CW) group

Let's report here the research lines of the Virgo CW group activities:

- Targeted search for known pulsars for which the parameters (position, frequency and frequency derivatives) are known;
- All-sky searches for unknown isolated neutron stars (NS). In this kind of search the exploration of the large parameter space is computationally challenging;
- Directed searches, for sources of known position but unknown frequency and spin down;
- All-sky searches for unknown NS binary systems.

5.6.1 Updated activities for Targeted searches

- New, improved, results for the search of g.w. emission from Vela, CRAB and a few other pulsars for which we can approach the spin-down limit. Going below the spin-down limit means to put a constraint on the fraction of energy of spin-down energy due to the emission of g.w. As done for the results [14] obtained with VSR2 data, we have used three different pipelines developed in the Virgo Rome PSS[5] group, in the Virgo Warsaw group and in the LIGO Glasgow group. This work has a particular importance within the Virgo collaboration as it is mainly tied to Virgo VSR2 and VSR4 data, due to the very good sensitivity of our detector in the frequency region below 60 Hz. The new limit improves the previous one obtained with VSR2 data on Vela by a factor 1.7-2 (that is we constraint the fraction of spin-down energy to 10%) and the one obtained with S5 data on Crab by a factor 1.15-1.3 using S6/VSR2/VSR4 (that is we constraint the fraction of spin-down energy to 1%) The target paper for this work is APJ. Fig.10 gives the average noise spectra around the Vela expected g.w. frequency, after a cleaning procedure, for the VSR2 and VSR4 data. The average gain in sensitivity due to the better noise level in VSR4 compared to VSR2 is a factor approximately 2.6 and, given the shortest duration (a factor 2) of VSR4 compared to VSR2, the expected gain in sensitivity VSR4/VSR2 is:

$$S_{VSR2}/S_{VSR4} \times \sqrt{T_{VSR4}/T_{VSR2}} = 2.6 \times \sqrt{0.5} = 1.8$$

[5]PSS states for "Periodic Source Search" and this a Virgo group who has developed search pipelines for both Targeted and All-Sky searches for isolated neutron Stars. We are 4 active people in Rome and 1 in Rome 2

which is confirmed by the preliminary results we have presented during the LVC September meeting in Rome. Fig.11 gives the comparison of detector's noise around the expected g.w. frequency for the Crab

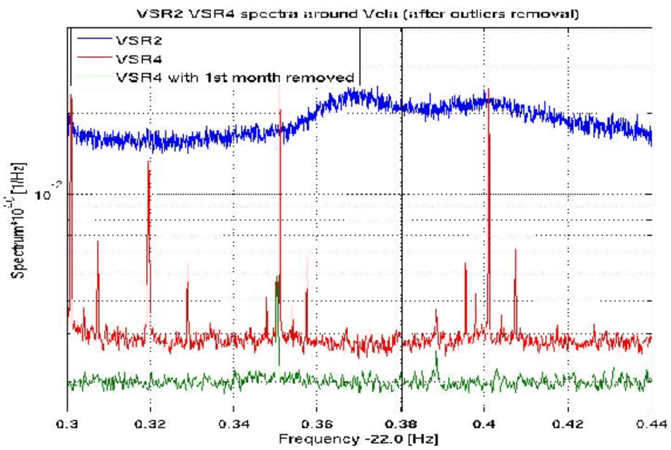

Figure 10: The figure gives the average noise spectra around the Vela expected g.w. frequency, after a cleaning procedure, for the VSR2 and VSR4 data. x-axis is frequency-22 Hz, thus the Vela g.w. signal is expected at 0.38 Hz

pulsar. In order to take into account the possibility that the GW signal frequency and spin-down are

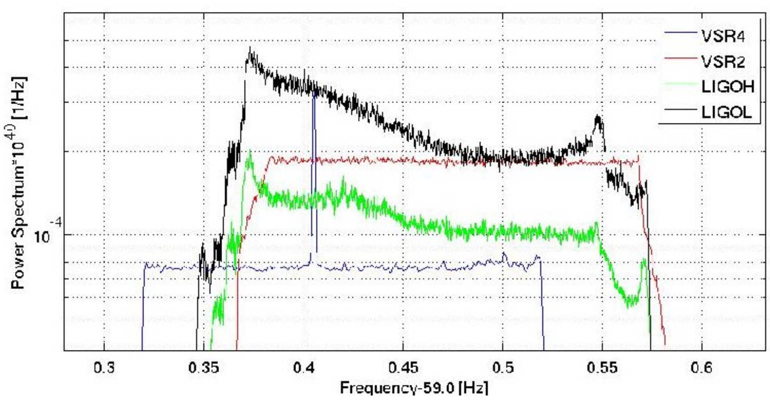

Figure 11: The figure presents the comparison of detector's noise around the expected g.w. frequency for the Crab pulsar. X-axis is the frequency- 59 Hz, thus the g.w. emission from the CRAB is expected at 0.55 Hz. Note a huge peak in VSR4 data very close to the expected CRAB frequency, probably due to sidebands of the 60 Hz line, which is a harmonic of the 10 Hz line.

slightly different from the EM observed one, the extension of the method to "narrow-band" searches is started.

- Work is in progress to search for g.w. emission at the spinning frequency. The Polgraw group is working to the extension of the targeted search from conventional search at twice the spin frequency to search at both once and twice pulsar spin frequency. In fact there is number of physical mechanisms that predict such a gravitational wave signal [15]. At the moment the group is preparing a method paper presenting data analysis tools to detect such a signal and estimate its parameters and extract astrophysically interesting information.

5.6.2 Updated activities for All-Sky searches of isolated neutron stars

- Polgraw group: results on VSR1 data. In the past six months the group has completed development of the code to search for coincidences among candidates obtained in the coherent analysis of 20419 two-day narrow band data sequences from VSR1 data. They have searched for coincidences with their code and at the moment they are analyzing them. They have also completed a full pipeline to determine the sensitivity of our search. The pipeline generates artificial gravitational wave signals from rotating neutron stars, adds them to the two-day narrow-band sequences, performs search around the true position of the injected signal, performs veto and searches for coincidences. The pipeline was tested for around 10% of the band analyzed and was found to produce satisfactory results. Consequently they are now ready to resume review of our code. They plan to complete the review withing next 3 month and have paper draft within 6 month.

- PSS (Rome and Rome 2) group The procedure has been described in past reports. Let's only underline now that, after having worked to the original idea of a transformation from the time/(observed frequency) plane to the Sky/(source frequency) plane (still used in the E@H pipeline) we had the, again original, idea of a simpler transformation (having heavy worked to solve practical issues and artifacts of the Sky Hough) to the Spin-down/(source frequency) plane. After preliminary studies and tests, we had decided to pursue this new approach. Now the codes have been completed and tested. The code review is well-under way. The search has begun to run during the summer. We are using distributed computing resources through the European Grid Infrastructure (EGI). In particular the Rome and CNAF clusters. This has heavily changed the scenario of our resources usage, very poor so far and very ambitious now. Our search, now high priority issue on VSR2 and VSR4 data, is covering the low frequency range, from 10 up to 128 Hz, and the higher frequency range, up to 1024 Hz. The duration of the basic FFTs for the search is different for different frequency band, being 1024 s for the highest and 8192 s for the lowest. We have the first candidates in the frequency region from 10 up to 128 Hz, obtained with FFTs of time duration of 8192 s. A robust understanding of noise lines is a tight need for these analysis which always tend to end up with a set of candidates due to the noise which for many different reasons were not been vetoed in early stages of the search and where not known to the "Noise hunting" team. This part of the work is going to be hard and we plan to finish and have a draft paper by March next year. Which is more than a 6/8 month delay compared to our original plans, declared for the White paper release in May 2011, but fits with the schedule given for the STAC May 2012 report.

- Einstein@Home search [4]: the paper has been approved by PRD.

  General comments, together with the role of Virgo, on this paper have been presented in Section2.

  The paper presents results of an All-sky searches for periodic gravitational waves in the frequency range [50,1190] Hz and with frequency derivative ranges of $-2 \times 10^{-9}, 1.1 \times 10^{-10}]Hz/s$ for the fifth LIGO science run (S5). The novelty of the search lies in the use of a non-coherent technique based on the Hough-transform to combine the information from coherent searches on timescales of about one day. Because these searches are very computationally intensive, they have been deployed on the Einstein@Home distributed computing project infrastructure. The search presented here is about a factor 3 more sensitive than the previous Einstein@Home search in early S5 LIGO data. The post-processing has left us with eight surviving candidates. A deeper follow-up studies rule each of them out. A new improved upper limits on the intrinsic gravitational wave amplitude h_0 has been put. Figure12 presents this UL. For example, in the 0.5 Hz-wide band at 152.5 Hz, we can exclude the presence of signals with h_0 greater than 7.610^{-25} with a 90% confidence level.

  Figure13 is the astrophysical reach, in terms of distance, in kpc, and maximum ellipticity Figure14 presents, for comparison, the results obtained with the "PowerFlux" pipeline and S6 data, presented in Sept. to the LVC collaboration [5] (and still not official).

Names of Polgraw and PSS group members actively contributing to CW Targeted and All-Sky searches for isolated neutron Stars, in the last 6 month: Michal Bejger, Kazik Borkowski, Orest Dorosh, Andrzej Krolak. FTEs= 1.3.

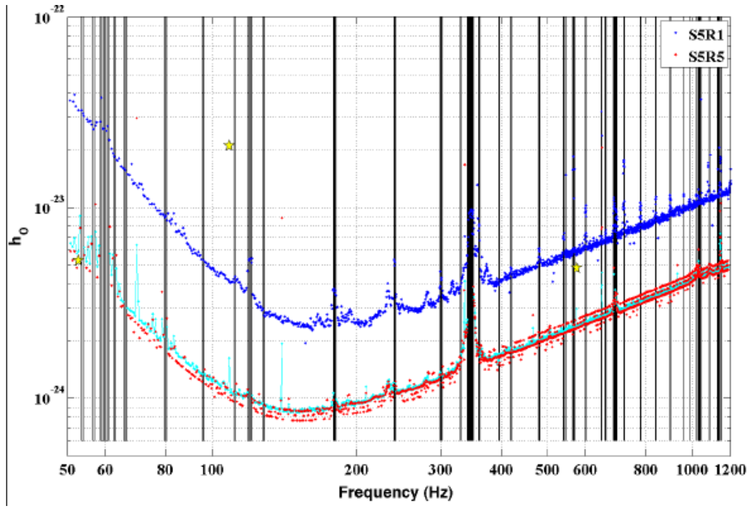

Figure 12: UL vs. frequency obtained for S5 data with the All-Sky search E@H pipeline [4]. Blue: previous search results. Red: new results. The three stars correspond to hardware-injected simulated pulsars which were recovered in the S5R5 search. The curves represent the source strain amplitude h_0 at which 90% of simulated signals would be detected. The vertical bars represent 156 half-Hz frequency bands contaminated by instrumental disturbances for which no upper limits are provided. The cyan curve is the expected limit for the detector noise

P. Astone, A. Colla, S. D' Antonio, S. Frasca, C. Palomba. FTEs= 4 (the remaining 1.0 are distributed in the Noise group, as the work on NoEMi is highly related to the CW work)

5.6.3 Directed searches

This is a task carried on in the Pisa group. The goal is to have a pipeline optimized for the so called "Directed searches", that is to search for isolated neutron stars for which the position is known but all other parameters are not. FTEs are stable. The group has developed an original technique to recover the signal as a monochromatic continuous signal, by simply resampling the data to cancel the Doppler shift [16]. This technique is working fine when the source position is known. After these preliminary steps we plan to start with a semi-targeted search, which is the best suited to the designed resampling algorithm. The first targeted search they will do will be the compact central object in the RX J0852.0-4622 SNR (Vela Junior). The following activities have been recently completed:

- A semi-analytical calculation of signal template has been introduced so as to reduce computation times.
- An analysis of simulated signals with varying amplitude, frequency and polarization has been performed.
- They introduced and studied an estimator, which we called Ro, orthogonal to the signal. This has been shown to be ineffective in the case of uncorrelated Gaussian noise. It could be more effective in instrumental line rejection.

The group is now working to convert the codes from Matlab into C. The next milestone is to do tests on the code using the Hardware injections.

The target for the first search is the compact object RX J0852.0 - 4622 SNR (Vela Jr.), whose nature remains somewhat controversial. It is most likely the compact remnant of the supernova explosion, a member of a class of radio and gamma quiet young neutron stars. It was located with good accuracy with X, gamma observations (with optical counterpart) [17, 18]. The angular uncertainty is dominated by systematic offsets of roughly two second of arc. Most reliable estimate for the distance is 750pc, while the age is most probably inside the 1777-4300 year interval [19]. No information is available about its periodicity, so it is an object well

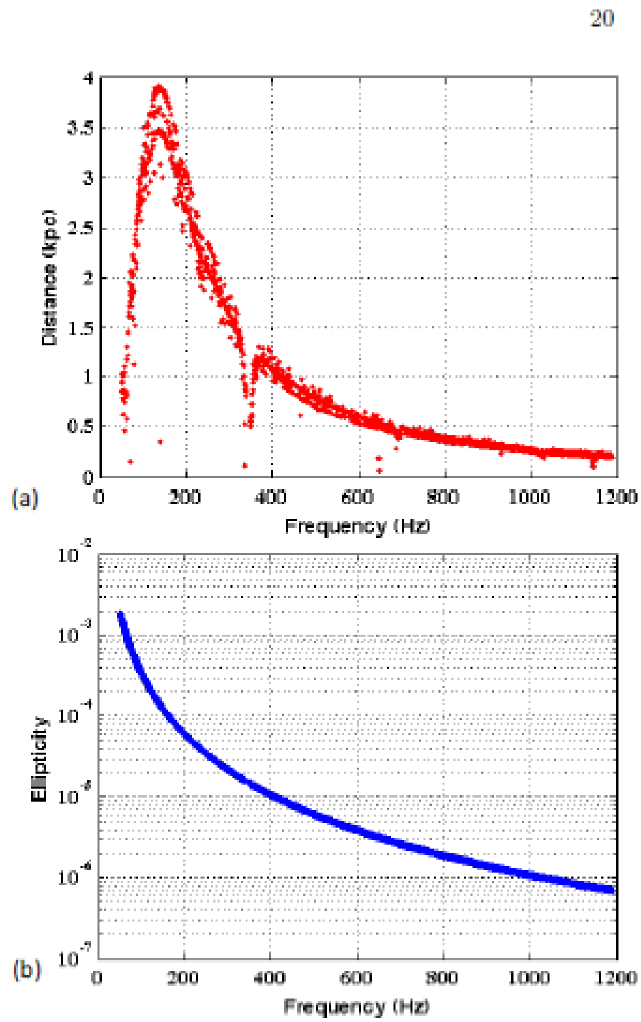

Figure 13: Astrophysical reach of the E@H search [4] Panel (a) and (b) represent the distance range (in kpc) and the maximum ellipticity, respectively, as a function of the frequency. Both the panels are valid for neutron stars spinning down solely due to gravitational radiation and assuming a spin-down value of -2 nHz/s.

suited for the semi-targeted search we want to implement. Owing to its young age there is hope for a non negligible GW emission. But it is fair to say that there is a large margin of uncertainty here. They plan to have preliminary results for the Vela Junior search by winter 2013.

FTEs for this task are only 2.0, thus the DAC feels the need to better understand the progresses of this work and if FTEs devoted to this task are adequate. The goal is ambitious and we do need to have clear milestones defined.

5.6.4 Searches for unknown neutron stars in binary systems

This is a task carried on in the Nickef group. FTEs are stable to 2. The group developed a strategy, called the polynomial search, where empirical templates for the signal are used. The phase of the signal in the template is expressed in terms of a (third order) polynomial of time. These templates are compared to the data for all times. Stretches of data that are coherent with the template can be found. The goal is to have a pipeline optimized to reduce the computation cost of an All-Sky search for neutron stars in Binary Systems. The task is

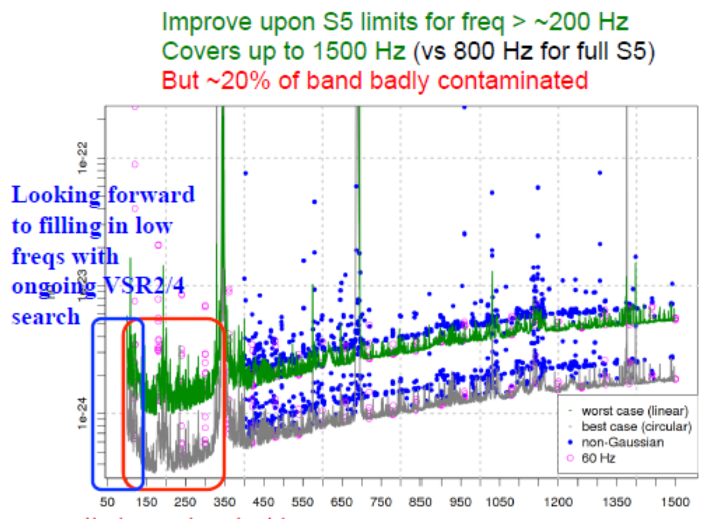

Figure 14: Preliminary. UL vs. frequency for S6 data obtained with the All-Sky search pipeline called "PowerFlux". We do expect to improve the limit in the region in the Blue rectangle, using VSR2 and VSR4 data

heavy, as confirmed by the fact that we still do not have results for these searches, even if on the LIGO side the "TwoSpect" All-Sky pipeline is almost ready to produce results (expected by next winter, thus the time of the next STAC report will be good to focus on these searches). No progresses to be highlighted in the last months, hence the DAC feels the need to better understand the progresses of this work. By the time of the next STAC report the DAC will have asked to have clear milestones for this work. Will report on this.

5.7 Stochastic gravitational wave background (SGWB) group

The strategy to search for a GW stochastic background, which can be confounded with the intrinsic noise background of the instrument, is to cross correlate measurements of multiple detectors. The activity of the group is then totally dedicated at the LSC/Virgo collaboration. Because of the present lack of manpower (two persons), the Virgo group participate very little to the analysis of real data. In revanche, our group contribute actively in the development of new methods and on the optimization of the search for Advanced detectors. One post-doc has just joined the Nice group. Thus FTEs are now 2.2 (1.5+ 0.3).

5.7.1 GW searches involving Virgo data

S6/VSR2/3 data analysis: The hardware injection done during the S6-VSR2 run was apparently successful, and we have now a better condense on calibration and synchronization issues. The standard isotropic analysis with time shifted data is now completed and ready for a review. Compared to S5/VSR1 [24] we observe an improvement of about 10% at low frequencies (frequency lower than 600 Hz) and of about a factor of 2 between 600-1000 Hz. An non-isotropic search is also on-going.

5.7.2 Developments

Non Gaussian background search (Nice):

Work is in progress in the LSC/Virgo group to develop a search for non Gaussian stochastic backgrounds that could arise either from astrophysical sources or cosmological sources like cosmic strings. Up to now, the main work has been done in Nice by Tania Regimbau and a student Lionel Martellini who derived a non parametric generalization of the standard cross correlation statistics, based on Gram Charlier and Edgeworth expansions. The first tests have shown that a gain of about 25% in sensitivity could be obtained, in addition to the ability to recover extra moments like skewness or kurtosis, that could provide extra information about the models. There has been little progress on this for the last few month, Lionel Martellini being involved in other activities at Princeton for the summer.

Detectability of models with Advanced detectors (Nice):

C.Wu, V. Mandic and Tania Regimbau have started to look in detail at the constraints that could be put on models of stochastic backgrounds with advanced detectors (see website: http://homepages.spa.umn.edu/ cwu/). After a first paper on compact binary sources [21] , they investigated the background from the population of magnetars and more recently from distorted black holes.

Parameter estimation:

Compact binary sources could give a detectable signal if the coalescence rate is the 'realistic' one predicted taken as reference by LSC/Virgo searches [23]. Given the rather high probability of detection, the stochastic group has decided to put efforts in developing methods that could optimize the search for this particular background and also provide astrophysical or cosmological constraints, for example on the star formation rate, the metallicity or the mass distributions of neutron stars and black holes. We developed a Bayesian method for estimating the parameters associated with different SGWB models using data from gravitational-wave detectors[22]. We applied this technique to estimate the sensitivity of the upcoming second-generation detectors such as Advanced LIGO/Virgo to these models and demonstrated how SGWB measurements can be combined and compared with observations of individual compact binary coalescence in order to build confidence in the origin of an observed SGWB signal.

Mock Data Challenges (Nice) :

The Nice group is developing a sophisticated generation package to simulate the signal (noise+GW) at the output of a network of GW detectors [23]. This package will be used to test and optimize detection strategies for Advanced detectors, and in particular searches for the SGWB from compact binary sources.

Non standard polarizations (Pisa):

In Pisa an exploratory study of the upper limits that could be obtained by a search of non standard gravitational waves (i.e. scalar degrees of freedom which are present in extended theories of gravitation) is in progress. We plan to publish a paper about this (which make no use of real data), and later analyze S6/VSR2/3 and possibly S5/VSR1 data. This will require minimal changes of the standard pipeline, at the level of post-processing.

Short author list papers are [20, 21, 22, 23]. Collaboration papers are [24, 25].

6 Appendices

6.1 Appendix A: LVC Trigger release policy

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"LSC AND VIRGO POLICY ON RELEASING GRAVITATIONAL WAVE TRIGGERS TO THE PUBLIC IN THE ADVANCED
DETECTORS ERA

The LSC and Virgo recognize the great potential benefits of multi-messenger observations,
including rapid electromagnetic follow-up observations of GW triggers. Both Collaborations
(the LSC and Virgo) will partner with astronomers to carry out an inclusive observing
campaign for potentially interesting GW triggers, with MoUs to ensure coordination and
confidentiality of the information. They are open to all requests from interested astronomers
or astronomy projects which want to become partners through signing an MoU. They encourage
colleagues to help set up and organize this effort in an efficient way to guarantee the best
science can be done with gravitational wave triggers.

After the published discovery of gravitational waves with data from LSC and/or Virgo detectors,
both the LSC and Virgo will begin releasing especially significant triggers promptly to the
entire scientific community to enable a wider range of follow-up observations. This will take
effect after the Collaborations have published papers (or a paper) about 4 GW events, at which
time a detection rate can be reasonably estimated. The releases will be done as promptly as
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possible, within an hour of the detected transient if feasible. Initially, the released triggers will be those which have an estimated false alarm rate smaller than 1 per 100 years. Partners who have signed an MoU with the LSC and Virgo will have access to GW triggers with a lower significance threshold and/or lower latency, according to the terms of the MoU, in order to carry out a more systematic joint observing campaign and combined interpretation of the results.

Throughout the Advanced Detectors era, the LSC and Virgo will release appropriate segments of data from operating detectors corresponding to detected gravitational waves presented in LSC/Virgo authored publications, at the time of the publication, including the first claimed detection of gravitational waves."

The text of this policy was approved by LSC Council on March 21st, 2012; it was approved by the EGO Council on May 4th, 2012. The LIGO Data Management Policy LIGO-M1000066 will take precedence in how LIGO data are released should this policy and the LIGO DMP be in potential conflict.

BNS	Core:up to signal veto	Coinc	Backg. est.	Coherent follow-up	Par. est.	UL	Limitations of usage
ihope	[responsible Sen. X] delivery time						Condor
PyCBC	[responsible Sen. Y] delivery time						
GWtools							
gstlal							
MBTA							

Table 2: CBC: Binary Neutron Stars searches

6.2 Appendix B: Requests by the LV Data analysis coordinators to the group's chairs

First Request by the DAC to the DA chairs: October 2012 We have begun the interaction with the group chairs to converge with a reasonable template. This is a matrix we would have filled with names and milestones. The matrix shown here is **only** an example. We will discuss with the chairs which are convenient inputs to easy the tracking process. Possible ideas to be discussed is to move from pipeline technical details to detailed science deliverables. In addition, we need to formulate goal and plans like this: **Goals and Plans**: (example given for BNS searches) 1-25 solar masses, in 2015 will be running both low latency and off-line on all available data, will be ready to claim a first detection if ρ_c ¿ XX with a paper written within YY months of data-taking. Will publish an upper limit not before we can exclude "realistic astro rate scenario" with ZZ % confidence.

Second Request by the DAC to the DA chairs. October 2012:

- Planning for ADE :

  identification of papers we will want to write for ADE. This charge dates back to April 2011. Reorganization of groups' activities according to science deliverables is the starting point. Done. Now we need goals (papers) and then we can start tracking progress.

- In the ADE : will we have different criteria for publishing papers than up to now ? Discussions are now ongoing.

- Plan for scientific deliverables (i.e. papers) :

  first discussed separately in every science subgroup and search group through internal discussions and then communicated to DAC chairs. This process is happening now and should be concluded by the end of the year, at least for burst and CBC (e.g. DAC chairs are meeting with CBC chairs on Nov 5th and 6th and will schedule EVO meetings with burst group chairs). This process is going to be iterative. We will need a DAC retreat in Jan/Feb 2013 during which we take a look at these plans together and see where we stand.

6.3 Appendix C: DA STAC Comments to the May 2012 report

The STAC had an extended presentation of DA work from the Virgo DA coordinator in person as this was skipped last time. The STAC feels that while the DA report has improved dramatically in the last couple of years, it must more clearly show the good performance. The STAC also sees the difficulties in having a single person present the complex different DA tasks. We suggest that in the future the DA coordinator give a general overview of the achievements of the Virgo DA teams in terms of major contributions, papers, presentations etc. The STAC would then ask for a presentation on a particular source search by the search group leaders. There would then be a subset of the entire DA effort at each meeting, rather than just the DA coordinator. This is the way things are usually done for instrumentalists, and would allow us to focus on any important issues regarding a particular search in a more coherent manner.

It was also felt that due to the complexity of the analysis, the presenters must find a way to explain what they are doing and planning of future analysis to non GW DA people. The presenters should also refrain from presenting preliminary results that may lead to confusion by non-experts in the field. As the STAC meets twice a year, it is better if a fully validated coherent result is presented.

The STAC was also informed that there was a problem with manpower regarding the DA effort. As the STAC sees no immediate improvement in the level of finance available in Europe, it was suggested that the project focusses as much as possible on the most relevant sources, and even relocate manpower in the first few years of operation from the less pressing areas of research. In any case a better reporting system on DA activities is needed.

It was also mentioned to the STAC that it is difficult to convince groups to work on certain problems or achieve certain milestones. The STAC suggests that External MOUs are evaluated and updated every year. Individual working groups should report at a roughly quarterly rate to DA leader, and the chairs of the individual search groups should make themselves available for face-to-face meetings with the Virgo DA coordinator on a regular basis, with the goal of clearly identifying analysis priorities and speeding up the publication process. As occurs at the LSC, the STAC would be in favor of a "penalty" system regarding the groups that do not meet the milestones outlined in their annual MOU. This system could reach from, in the first instance, a meeting with the DA coordinator and the Virgo spokesperson to discuss why deliverables had not been made, to the exclusion from the Advanced Virgo author list, should the under-performance continue. The STAC welcomes the fact that an External Computing Committee has been established. The ECC has no clear scope of its mandate. Clarification whether this is a one time, temporary or permanent committee is needed. The ECC also needs clearer information on computing finances in order to carry out its mandate. The STAC discussed the usage of the computing centers at Bologna and Lyon. Data sets are being stored in each location both on tape and on disk (for faster access). Whereas the on-tape storage in both locations seems advisable for redundancy reasons it should be evaluated whether disk storage can be restricted to one of the sites. This may reduce data storage costs. As the costs for CPU cycles is estimated at the beginning of each year and finally paid by incurred usage, increasing the CPU usage of the computer centers would result in increased costs and would currently bring no significant DA benefits. The project has to decide on what is the most practical and cost efficient system for Advanced Virgo. In terms of DA, the Data quality group has a high priority as this work can only be done within Virgo. The low latency data analysis becomes more important with multi messenger work expanding.

While the VESF fellowships were very useful in the past in bringing new groups to the project, as there is a shortage of manpower, the STAC recommends only funding real DA related work, in contrast to theoretical source modelling through EGO financing. The STAC also recommends that the DA coordinator be involved in the selection process for the fellowships. For more theoretical work, the project should try to attract external groups into Virgo collaboration, and until such time as the funding situation improves, refrain from using VESF grants. The STAC also feels that the duration of fellowships should be two years. Given the practicalities that go with taking a fellowship, the belief is that one year is not long enough for an extended efficient working phase that can make real contributions to the project. The STAC also agrees with the ECC that the computing infrastructure on site should only be dedicated to Control tasks, data storage and computation for detector characterization in the context of commissioning and low latency on-site searches.

6.4 Glossary

- **Chirp mass**: the chirp mass $\mathcal{M}_c$ of a binary system of mass m_1 and m_2 is given by

$$\mathcal{M}_c = \mu^{3/5} M^{2/5} \quad (1)$$

$$\mu = \frac{m_1 \times m_2}{m_1 + m_2} \quad (2)$$

$$M = m_1 + m_2 \quad (3)$$

- **Closed box/open box**: many pipelines searching for transient events have free parameters that require to be tuned. Furthermore, to claim for a GW discovery one requires to estimate the significance of the most significant GW events with respect to background events. As GW detectors' noise is far from being Gaussian and stationary, the background is estimated using data time shifted (assuming that coincidence between at least 2 detectors is performed). Pipeline parameters tuning is performed by maximizing the detection efficiency with a sample of targeted GW signals and minimizing the false alarm rate. Closed box results consist in showing background events distributions after tuning. This step allows to detect potential problems in a pipeline before looking at the set of triggers which can contained GW event candidates (foreground events or zero-lag events obtained with coincidence with non time-shifted data). Comparing foreground events distributions with background event distributions is what is called opening the box.

- **Compact Binary Coalescence (CBC)**: It is used to name the astrophysical object composed of two compact objects, neutron star (NS) and/or black hole (BH) in orbits each one around the other, loosing orbital energy by emission of gravitational radiation. The GW signal waveform emitted by such astrophysical source is a direct solution of the Einstein equations. It consists in a quasi monotonous signal with a frequency increase (chirp-like signal) following the orbital period decrease as the 2 objects get closer and closer until the final plunge. Ground based detectors are sensitive to stellar mass binary system just few minutes before their final plunge where the emitted GW signal frequency is within the frequency band of the detectors [20 Hz 2 kHz] after millions of cycles that usually circularize the orbits when the system is isolated.

- **Coherent WaveBurst (cWB)**: cWB is coherent network algorithm for detection and reconstruction of gravitational wave bursts. The algorithm works for two and more arbitrarily aligned detectors and can be used for both all-sky and triggered burst searches. A time-frequency transform is performed in a wavelet domain. This is then use for the construction of the likelihood time-frequency maps. Triggers are then selected by applying a threshold on pixels.

- **DQ flag**: or Data Quality flag, is a list of time segments for which some transient noise is suspected to pollute the GW signal. Those time segments may be used by data analysis to veto part of the data they analyze or part of the events they found.

- **E@H** Einstein@Home is a volunteer distributed computing project hosted by the University of Wisconsin-Milwaukee and the Max Planck Institute for Gravitational Physics (Albert Einstein Institute, Hannover, Germany). Running on the Berkeley Open Infrastructure for Network Computing (BOINC) software platform, Einstein@Home searches through data from the LIGO detectors for evidence of continuous gravitational-wave sources, which are expected for instance from rapidly spinning non-axisymmetric neutron stars. Einstein@Home also searches radio telescope data from the Arecibo Observatory for radio pulsars. On August 12, 2010, the first discovery by Einstein@Home of a previously undetected radio pulsar J2007+2722, found in data from the Arecibo Observatory, was published in Science. The project has discovered 46 pulsars as of August 2012. Einstein@Home's first analysis used data from the "third science run" (S3) of LIGO. Processing of the S3 data set was conducted between 22 February 2005 and 2 August 2005.

- **Effective One Body (EOB)**: it is a formalism which replaces the two-body interaction Hamiltonian with a Hamiltonian which depends only on the relative position and momentum of a binary system. In this formalism, PN expansion has remarkable simplification features with respect to the standard two-body formalism. Another nice feature of this formalism is that for Binary Black Hole system (BBH), with and without spins, it allows to describe the inspiral, merger and ring-down phases and this prediction is in remarkable agreement with Numerical Relativity BBH waveform results.

- **F- and G-statistic pipeline** This is a pipeline for searching CW signals that has been developed by the Virgo Polgraw group. It consists of a matched-filter in the time domain. When no assumption is done for the polarization angle and the inclination angle of the star rotation axis (4 degrees of freedom) matched filtering is realized by computing the well known F-statistic. If the computed value of the F-statistic is not significant they can derive an upper limit on the gravitational wave signal. In the 2 degrees of freedom case the authors of the method derive a new optimum statistic called the G-statistic The software has been reviewed and it is placed in Virgo CVS directory.

- **Gram Charlier and Edgeworth expansions**: The GramCharlier A series are series that approximate a probability distribution in terms of its cumulants. The series are the same but, the arrangement of terms (and thus the accuracy of truncating the series) differ.

- **GWTools** GWTools is completely C++ and OpenCL based, entirely new, modular, portable, platform, vendor, OS and batch system independent implementation of many mathematical, theoretical and data analysis algorithms widely used in the Ligo - Virgo community. The OpenCL implementation inherently allows the automated and invisible parallelization of the various routines on CPUs as well as on GPUs.The user and/or the application developer can use these modular building blocks to easily construct a readable, portable analysis pipeline of desired complexity.

- **Hough Transform** Used in CW All-Sky hierarchical searches. The biunivocal transformation from the time/observed frequency plane to the Source frequency plane/Sky (Sky Hough) or to the Source Frequency/Spin-down plane (Frequency Hough)

- **Ihope**: name of the generic CBC multi-stage pipeline developed the LSC CBC group. The first stage consist in filtering each data stream with a bank of templates. The second stage performs coincidence between triggers in the parameter space and applies signal based vetoes. The last stages concern the post-processing of triggers (candidates follow-up, efficiency estimation, upper limit calculation,). Ihope is used for almost all cbc searches: all-sky low and high mass CBC searches, GRB triggered CBC searches, binary black-hole ring-down search,

- **Inter-Planetary Network (IPN)**: it is a group of spacecraft equipped with gamma ray burst (GRB) detectors. By triangulation, using the timing of a burst at several spacecraft, location of the source can be estimated. The sky localization depends on timing precision of each detector and the distance between detectors. The accuracy can be as good as few arc-minutes, up to thousands square degrees.

- **LAL/LALapps**: LAL is the LSC Analysis Library that gathers many C functions. Lalapps is a repository of utilities written in different language that make use of LAL. For instance the ihope pipeline is making use of LAL and lalapps.

  https://www.lsc-group.phys.uwm.edu/daswg/projects/lalsuite.html

- **Multi Band Template Analysis (MBTA)**: this is a low-latency implementation if the standard matched filter developed by Virgo many years ago. Time domain templates with phase evolution accurate to 2PN order are currently used by MBTA. The original feature of MBTA is to divide the matched filter across two frequency bands. The phase of the signal is tracked over fewer cycles meaning sparser template banks are needed in each frequency band. A reduced sampling rate is used for the lower frequency band reducing the computational cost of the fast Fourier transforms involved in the filtering. The full band signal-to-noise ratio (SNR) is computed by coherently combining the matched filtering outputs from the two frequency bands. The boundary between the low and high frequency bands is chosen such that the SNR is roughly equally shared between the two bands.

- **Nested sampling / inspnest**: the nested sampling algorithm is a computational approach to compute marginalization integrals that appears when one computes a Bayesian probability. Marginalization is necessary when the probability depends on a set of parameters that are not known. The nested sampling algorithm was developed by John Skilling in 2004 specifically to approximate these marginalization integrals, and it has the added benefit of generating samples from posterior distribution. It is an alternative to methods from the Bayesian literature such as bridge sampling and defensive importance sampling. inspnest is the name of the Markov Chain Monte Carlo Bayesian pipeline to estimate the parameter of a CBC that makes use of the nested sampling algorithm to compute marginalization integrals.

- **NINJA2 project**: name of a scientific collaboration between LIGO, Virgo and the second Numerical INJection Analysis Collaboration. The goal of this collaboration is to study the sensitivity of gravitational wave search and parameter estimation algorithms using numerically generated binary black hole waveforms. It builds upon the success of the first NINJA project [1] but will cover a wider range of parameter space than NINJA1 (including non processing spinning binaries and non spinning binaries with large mass ratio). The numerical relativity waveforms, the late inspiral, merger and ring-down, are stitched to PN waveforms.

  [1] http://www.ninja-project.org

- **Omega pipeline**: Omega search algorithm is a multi-resolution time-frequency search for statistically significant excess signal energy. It uses sine-Gaussian as template. Sine-Gaussian are characterized by central time (t0), central frequency (f0) and Q (ratio of central frequency to bandwidth). The time-frequency decomposition is performed by filtering data against bi-square-enveloped sine waves, in what amounts to an over-sampled wavelet transform. The filtering procedure will generate a value for each tile of a time-frequency plane. This value is called the normalized energy Z. A tile is called a trigger if its Z energy exceeds a predefined threshold.

- **Omicron Pipeline**: An improvement of the Omega pipeline, which is planned to be used in ADV, to scan for glitch characterization over many Virgo channels

- **Pi of the sky**: Wide-field telescope (20 degrees $\times$ 20 degrees) to detect optical counterparts of GRBs at the very beginning and during the gamma emission or even before it. The observation strategy is based on the continuous monitoring of the large part of the sky with high temporal resolution and the fast image processing algorithms, allowing for optical transient recognition in real time. The full system will consist of 2 sites separated by a distance of the order 100 km in Chile, each site consisting of 12 custom-designed survey CCD cameras. Pairs of cameras from two sites work in coincidence and observe the same field of view to allow rejection of false signals coming from near-earth objects. For the S6/VSR3 EM follow-up campaign, a manual Pi of the Sky telescope located in Warsaw has been used.

- **PhenSpin**: it is a new family of waveforms describing the three phases of a spinning compact binary coalescence (inspiral, merger, ring-down). The waveforms are obtained by interpolating between the perturbative PN inspiral description and the ring-down, both admitting physically motivated analytic models, with a phenomenological phase over the merger portion of the signal, which accurately describes the phase evolution. These waveforms are constructed by bridging the gap between the analytically known inspiral phase, described by spin TaylorT4 approximants in the restricted waveform approximation, and the ring-down phase through a phenomenological intermediate phase, calibrated by comparison with specific, numerically generated waveforms, describing equal mass systems with dimension-less spin magnitudes equal to 0.6

- **Polynomial search**: this is a pipeline developed by the Nikhef group to search for CW emitted by non axial-symmetric neutron stars in binary system. It is a hierarchical search that employs a limited number of filters, while maximizing the coherence time of the signal in a frequency band. The parameter space of a pulsar binary search is huge (more than 12 parameters). The polynomial search reduces the parameter space to 4 parameters by the use of an empirical model of the signal phase evolution. The other advantage is that the coherent time is increased and the data segments length can be increased.

- **Post-Newtonian (PN) expansions**: they are use in General Relativity to find an approximate solution of the Einstein equations for the metric tensor. A PN expansion is a linear expansion in a parameter assumed small which is the ratio v/c of the velocity of the GW source to the speed of light. PN approximation assumes that the source is moving slowly and weakly self-gravitating (adiabatic approximation).
- **PowerFlux** A method to search for isolated neutron Stars. It estimates the power coming from a particular direction on the sky by computing a weighted sum. The weights are the noise in the frequency bins.
- **pyCBC project**: This is an effort aimed at developing interfaces and algorithms for many-core implementations of various CBC searches with python interface (for instance GPU applications). Parts of the CBC search pipeline that are concerned: template generation, PSD calculation, matched filtering, chi-square calculations, windowing, clustering, and coincidence algorithms. These are to be used in high performance searches with extended template banks.
- **QUEST**: it is a wide-field (4.1×4.6 degrees) optical telescope hosted at La Silla (ESO). From the ESO web page: "The ESO 1-metre Schmidt telescope at La Silla began its service life in 1971 using photographic plates to take wide-field images of the southern sky four degrees across which would cover the full Moon 64 times over. The original photographic camera was decommissioned in December 1998, but the telescope now has a new lease of life as a project telescope. In 2009, a group at Yales Center for Astronomy and Astrophysics installed a new large camera to conduct a southern hemisphere search for new Pluto-sized dwarf planets and supernovae: the LaSillaQUEST Variability survey. The camera is a mosaic of 112 CCDs, with a total of 160 million pixels, covering the full field of view of the telescope. The survey is expected to cover about one third of the full sky (about 15 000 square degrees repeated almost every four days). The system is fully operational and controlled remotely from Yale. This project follows the groups northern hemisphere search at Palomar that led to the discovery of the dwarf planet population, including Eris and Sedna."
- **ROTSE**: the Robotic Optical Transient Search Experiment (ROTSE) is dedicated to observation and detection of optical transients on time scales of seconds to days. It is composed of 4 wide field of view (1.85 degrees $\times$ 1.85 degrees) fully automatized telescopes with fast response located in the USA, Namibia, Turkey and Australia.
- **SkyMapper**: it is a fully automated 1.35 m wide field of view (5.6 square degrees) optical telescope in Australia. The camera has six filters which span from ultraviolet to near infrared wavelengths. The SkyMapper telescope was built to carry out the Southern Sky Survey, which will image the entire southern sky several times over in SkyMapper's six spectral filters over the course of five years. This survey will be analogous to the Sloan Digital Sky Survey of the Northern hemisphere sky.
- **TAROT**: it is a wide-field (1.85×1.85 degrees) optical telescope hosted at La Silla (ESO). From the ESO web page: "The 25 cm TAROT (Tlescope Action Rapide pour les Objets TransitoiresRapid Action Telescope for Transient Objects) is a very fast moving optical robotic telescope on La Silla. It is able to react very quickly to a signal from a satellite indicating that a gamma-ray burst is in progress and can provide fast and accurate positions of transient events within seconds. The data from the TAROT telescope will also be useful for studying the evolution of bursts, the physics of the fireball and of the surrounding material. A twin TAROT telescope is located at the Calern observatory, in France. Both are operated by a consortium led by Michel Bor (Observatoire de Haute Provence, France)."
- **TaylorF2**: PN approximation computes the evolution of the orbital phase of a compact binary coalescence as a perturbative expansion in v/c. PN expansions are valid until the orbital frequency change over each

orbital period remains small (adiabatic approximation). This corresponds more or less to the last stable orbit (LSO). Re-summation methods, such as the effective-one-body (EOB) are then needed if one wants to go beyond the LSO. Different PN approximations exist. TaylorF2 is one of them. It corresponds to a description of the waveform in the Fourier domain using the Stationary Phase Approximation (SPA)

$$\tilde{h}(f) = Af^{-7/6}e^{i\Psi(f)} \tag{4}$$

where $\Psi(f)$ is the orbital phase and A is an amplitude factor that depends on the chirp mass of the binary system.

- **TwoSpect** Algorithm to search for rapidly rotating neutron stars in binary systems.Since current search methods for unknown, isolated neutron stars are already computationally limited, expanding the parameter space searched to include binary systems is a formidable challenge. TwoSpect is a hierarchical binary search method, which exploits the periodic orbital modulations of the continuous waves by searching for patterns in doubly Fourier-transformed data.
- **X-pipeline**: it is a GW burst pipeline that combines data from arbitrary sets of detectors, taking into account the antenna response and noise level of each detector to improve the search sensitivity. The result is a list of transients, or events, that may be candidate gravitational wave signals. Each event is characterized by a measure of significance, based on energy
- **5-vectors targeted CW search pipeline**: the method is based on the use of the Fourier components of the signal at the 5 frequencies at which the signal power is split by the amplitude and phase modulation (due to the time-varying detector beam pattern functions). The related software is part of the Rome Periodic Source Search (PSS) software package and thus starts from the short cleaned FFT database (SFDB) built from h-reconstructed data at 4096 Hz. These are the main steps of the analysis

  1. Extract a small band (fraction of Hertz) around the frequency of interest;
  2. Compute the analytical signal;
  3. Correction of Doppler and spin-down by construction of a non-uniformly sampled time variable followed by a down-sampling to 1Hz;
  4. Construction of the data and signal 5-vectors;
  5. Computation of two matched filters for the + and x signal components using the corresponding 5-vectors;
  6. Use the output of the two matched filters to build the detection statistics;
  7. On the base of the detection statistics value claim detection or set upper limit.

  The pipeline has been fully reviewed. It has been used to analyze VSR2 data searching for the Vela pulsar. An upper limit below the spin-down limit has been placed.

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