

Noise monitor tools and their application to Virgo data

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Abstract.

The understanding of noise in interferometric gravitational wave detectors is fundamental in terms of both enabling prompt reactions in the mitigation of noise disturbances and in the establishment of appropriate data-cleaning strategies. Monitoring tools to perform online and offline noise analysis in areas such as transient signal detection, line identification algorithms and coherence are used to characterise the Virgo detector noise. In this paper, we describe the framework into which these tools are integrated - the Noise Monitor Application Programming Interface (NMAPI) - and provide examples of its application.

1. Introduction

The detection of gravitational wave (GW) signals is one of the big challenges of astrophysical research. The interferometric detectors [1] can detect gravitational waves by measuring the relative displacement of mirrors suspended at the end points of optical cavities. Virgo [2], the 3km-long French-Italian interferometer, located in Italy, is one of these detectors. The LIGO [3] laboratory, in the USA, operates two 4km-long detectors, while a 600m-long detector is operated by GEO [4] in Germany.

For all of them, the detector noise, which limits their sensitivity to gravitational wave signals, is a major challenge to face. As a result, understanding detector noise and the identification of physical noise sources and the ways in which they affect the Dark Fringe (DF) channel ¹, is a major goal. The DF is sensitive to gravitational waves and is calibrated [5] to produce an equivalent strain signal. It is important to be able to follow the noise behaviour, not only to enable prompt reactions in the mitigation of noise disturbances, but also to help in the development of appropriate data-cleaning strategies. Before the last Virgo Scientific run (VSR4, June 3th - September 5th 2011) a new framework for detector noise monitoring was implemented. The idea was to have tools (Noise Monitors, sometime referred to as NM) able to process data that were either acquired in real-time by the online data acquisition system [6] (these are referred to as online data) or data archived on disk (offline data). The results of this processing are then archived in MySQL databases or similar storage solutions.

From these sources, users would be able to produce plots based on available data, including those that had been recently acquired. The aim was to give, to both scientists and the commissioning crew, instruments that are able to easily provide a snap-shot of noise behaviour at any given moment. Tools to monitor transient noise signals [10] and spectral lines [13], as well as to check coherence with signals from auxiliary sensors monitoring external noise sources, were included in a common framework, the Noise Monitor Application Programming Interface (NMAPI) [8]. One of the main requirements for NMAPI was to make the integration of new noise monitors as straightforward as possible.

This paper is organised as follows: in section 2 the NMAPI framework is described; in section 3 the monitoring tools used during VSR4 are briefly detailed; section 4 looks at the noise spectral lines catalogue application (LinesDB); while in section 5 a typical NMAPI use case is explained. In section 7 a possible evolution strategy for the NMAPI project is discussed.

2. Noise Monitor Application Programming Interface (NMAPI)

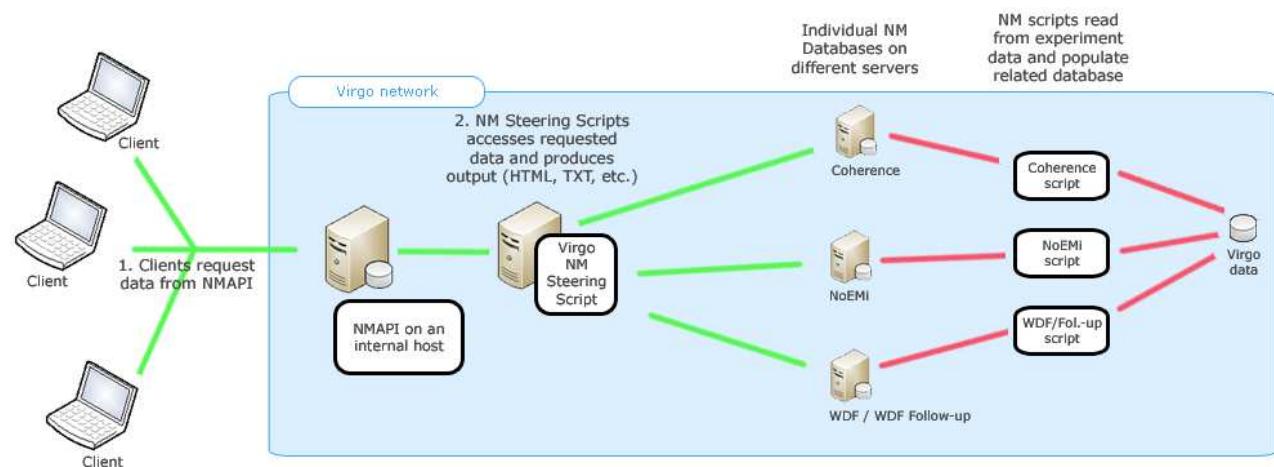


Figure 1. A simple representation of the NMAPI architecture. The noise analysis algorithms produce results that are archived in MySQL databases on different servers. A client requests HTML pages from the NMAPI host, which queries the relevant database, retrieving the requested data and producing the corresponding HTML pages.

¹ Channel refers to a time series obtained following conversion of an analogue data stream to a digital data stream.

NMAPI provides a framework into which different noise monitors can be integrated and then configured, enabling users with little knowledge of web development or web programming languages and standards, to interface their scripts to an Internet audience. 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. This mode of producing results dynamically means that, not only are users able to produce highly-configurable results, but storage requirements are negligible, given that files are created on-the-fly and only the summary plots are stored on disk. For example, in a first version of the Coherence tool the plots showing the coherence between channels, available to users, were saved to disk. With the NMAPI solution it was possible to reduce disk space usage by 98%.

Noise Monitor Administrators use the tool to build HTML forms, specific to a single Noise Monitor, which may then in turn be used by authenticated users to launch the Steering Script related to that Noise Monitor. The Steering Script receives the arguments passed to it by the HTML form POST array and produces the relevant results as required, e.g. text-format datasets or plots. In addition, each Noise Monitor provides a summary page, configurable by the related Administrator, which provides general information, which may be amended by standard users in terms of both date and related channel. NMAPI also provides an in-built debugging system, which can be used to monitor and adjust Steering Scripts and HTML forms as required. In general, NMAPI is designed to be as flexible as possible. It enables Administrators to concentrate their time and effort on providing a first-class script, rather than having to worry about how to launch it via a web interface. The degree of potential customisation available means that it is possible to provide script launch forms that are appropriate to each individual Noise Monitor. In Figure 1 a simple representation of the NMAPI architecture is displayed.

3. Noise monitors

Before VSR4 began, we integrated the following monitors into the NMAPI framework:

- *Wavelet Detection Filter (WDF)*: WDF finds triggers ² associated to transient signal events, which could potentially be due to noise, in the detector data. In particular, it analyses data in the time domain, where a whitening [9] procedure is applied and, following a wavelet transform (using different banks of wavelets), it looks for an excess of power with respect to background noise due to transient signals. It identifies the triggers and assigns a start time for the event, calculates its signal-to-noise ratio, frequency content and duration [10]. This is done online on the DF signal and on a set of selected auxiliary channels. All of the parameters that characterise the events are stored in a MySQL database.
- *Noise Events Miner (NoEMi)*: NoEMi is the Virgo-dedicated software for noise line monitoring and identification. Based on the algorithms implemented for the continuous wave (CW) search, it analyses, on a daily basis, the GW channel and a subset of the auxiliary channels, identifying the noise lines in the various channels and looking for coincident lines between the Dark Fringe and the auxiliary channels. A line tracker algorithm tracks the lines over time, making the follow-up of the non-stationary lines easier. A detailed description of the NoEMi software is given in [13]. Three Noise Monitors have been developed using the NoEMi output data, and have been integrated into the NMAPI:
 - *NoEMi Peakmaps*: the first step of the NoEMi process is the identification of the peaks from the power spectral density of each channel. The peak maps are stored in a dedicated database, from which they can easily be queried and displayed thanks to the NMAPI infrastructure.

² We define a trigger as an event caused by a generic transient signal and which can be identified by features such as the event start time, its duration, its spectral content and its signal-to-noise ratio.

- *LinesDB*: identified spectral lines are archived into the NoEMi lines database, which stores all of the information relating to the lines reconstructed by the NoEMi line tracker algorithm. An interface that allows users to easily query information from the lines database (LinesDB) is part of the NMAPI tool suite and is described in more detail in Section 4.
- *NoEMi Spectra*: NoEMi also stores the daily-averaged frequency spectra of the calibrated data. The spectra have a resolution of 10 mHz. The NMAPI allows users to access the spectra in a given time interval and calculate the resulting average, comparing it with other time intervals.
- *Coherence*: estimates the averaged (over 15 minutes) coherence between the DF signal and all of the (approximately 1000) auxiliary channels. It runs periodically (two or three times per hour) and archives results in a MySQL database. The NMAPI framework makes it possible to retrieve data from the database via a web interface or to request coherence plots between the DF and a selected acquired channel, producing them on-the-fly. This script can also be called by NoEMi to further investigate the coincidence between lines (as explained in the following section).

4. 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 NoEMi data-taking periods, and is linked to a metadata table, which is filled with user-defined information, such as the type of instrument used in measurement and general information relating to the line, once the source of the disturbance is understood.

The LinesDB interface allows users to easily search lists of archived lines that meet specific criteria, for instance lines found in a given time or frequency interval. It also makes it possible to set thresholds on dynamic parameters [13] and even on the lines coincident with a subset of the auxiliary channels. It is also possible to use the metadata as additional filtering criteria, for example making it possible to distinguish between 'known' (i.e. lines for which a metadata description is available) and still 'unknown' lines, or to select lines containing specific descriptions.

Figure 2 shows the web page, including the interface used to query the lines database, with an example query (in this example the search looks for the list of identified 'violin modes', the mirror suspension resonances). Figure 3 presents the result of the query. The line list is formatted in a table which shows, for each line, the mean values of the dynamic parameters, the list of the most coincident auxiliary channels (constantly updated by NoEMi) and the line description (part of the line metadata). The list of coincident auxiliary channels is itself a link to the Coherence Noise Monitor. By clicking on an auxiliary channel name, the Coherence script is launched, which queries the Coherence database and displays the coherence between the Dark Fringe and the selected auxiliary channel in the time and frequency ranges of the line.

5. How NMAPI works

An example of how NMAPI can help in noise hunting and how the links between the different noise monitors operate is presented here.

In this example, a user examines the LinesDB summary page, which contains a list of all of the lines identified and archived by NoEMi (see Figure 4). An inspection of the results shows a line of particular interest (for example the 18.6 Hz). A look at the line plot in Figure 5 confirms that the line is worth examining in further detail, it being a non-stationary line, which shows a step down in the frequency after 30 days.

The user studies the history of the disturbances in the Dark Fringe channel and the coincident auxiliary channels versus time, using the calendar tool available in the NoEMi PeakMaps

LinesDB

Enter required LinesDB script launch criteria

Downloads the NoEMi lines from the database, and lists them.

Select:

- channel (Pr_B1_ACp or h_4096Hz)
- time and frequency interval
- period (plot 2-hours- or daily- updated lines)
- presence (fraction of "how often the line has been seen in the run")
- Line id's, if known
- Auxiliary channel filter (filter lines coincident with one or more channels)
- known, unknown or any lines
- database name

Channel	V1:Pr_B1_ACp	CHOB
frequency	0	to 50
time	VSR4	to2 VSR4
period	7200	
presence	0.1	to3 1
line id's	any	
aux. channel filter	any	
known?	unknown	
plot	yes	
verbose	2	
db	Lines_db_10mHz	
metadata clause	comment like \'%violin suspension resonance\'	
> CLEAR CRITERIA		> LAUNCH SCRIPT

Figure 2. The web interface used to query the lines database. Among the query parameters it is possible to choose between 'known' and 'unknown' lines, to define the frequency and time ranges, as well as to use filters based on the available metadata information.

Mean Freq. (Hz)	Freq. Range (Hz)	First/Last Seen - Presence	Mean Persist.	Mean CR	log(Mean Ampli)	Aux. channels	Comment on source
2749.995	2749.795-2750.024	2011-06-02_22/2011-09-06 - 1.00	0.4	10.4	-13.3	Em_MABDMC02(28.3%) Em_MABDWE01(26.3%) Em_MABDNE01(21.9%) Em_MABDCE01(21.5%)	violin suspension resonance (6th harmonic)
2760.015	2759.990-2760.057	2011-06-02_22/2011-09-06 - 0.98	0.2	8.6	-13.5		violin suspension resonance (6th harmonic)
2761.345	2761.315-2761.373	2011-06-02_22/2011-09-06 - 0.97	0.2	8.8	-13.5		violin suspension resonance (6th harmonic)

Figure 3. A LinesDB query result. For a description of the displayed parameters (Persistency, CR, amplitude, etc.) see [13].

summary pages, in order to choose a day of interest. Via the NM script interface, the user launches the steering script, obtaining a detailed peak-map or line plot for a specific channel (Figure 6). The user confirms the results by looking at the Coherence tool (Figure 7), which displays the coherence between the Dark Fringe and the selected auxiliary channel in the given time and frequency ranges. Once the source of the disturbance is understood (in this example, the 18.6 Hz line was caused by the motor of an air conditioning machine in the Virgo Central

Mean Freq. (Hz)	Freq. Range (Hz)	First/Last Seen - Presence	Mean Persist.	Mean CR	log(Mean Amplit)	Aux. channels	Comment on source
17.004	16.994-17.052	2011-04-25/2011-09-05_22 - 1.00	1.0	133.8	-8.9		Global Control (Gc_MICH) - Calibration Line
18.612	18.501-18.721	2011-04-25/2011-09-05_22 - 0.98	0.5	26.5	-10.6	Em_SETODE01(98.1%) Em_AC_E1B(97.2%) Em_SE_CryoT(96.7%) Em_SETCSW101(96.1%) Em_SEBDC01(96.1%) Em_SETCSN102(94.2%) Em_SE_E1B_04(92.2%) Em_SE_LB_04(92.1%) Em_SE_BnewN(92.0%) Em_ACBDCE01(91.4%) Em_SEBDBL03(84.0%) Em_SEBDC08(82.0%) Em_SEBDC06(72.2%) Em_ACTCSN1(57.9%)	

Figure 4. List of spectral lines identified by NoEMi

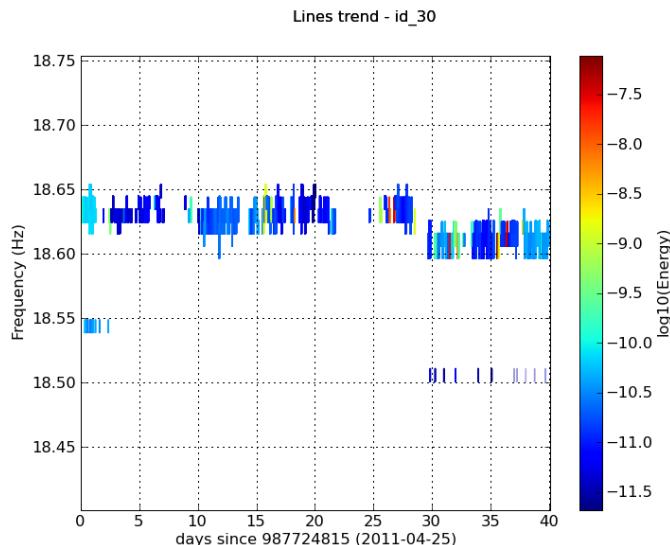


Figure 5. Wandering line at 18.6Hz. It has a step down in the frequency after 30 days

building, which was producing seismic vibrations of the floor that subsequently entered the data), using the LinesDB interface, the user can insert related metadata, adding a description to the line information and providing qualitative information. This information might regard, for instance, which sub-system of the interferometer caused the disturbance, how the line was measured, which mitigation actions were undertaken, and so on.

6. A real-life example: the VSR4 Vela bump

As already mentioned, the NM infrastructure was first used in the last Virgo science run, VSR4. Despite the short run duration (3 months), the framework proved to be a useful instrument in the detection of noise disturbances and helped to provide fast feedback to scientists, in order to help them to identify and mitigate noise sources.

The best example of noise monitoring and hunting is of a broad disturbance detected by the NoEMi tool within the first few days of the run. The disturbance affected the ITF sensitivity at the expected GW emission frequency of the Vela pulsar (22.4 Hz), hence the name 'Vela bump'.

Thanks to the frequency resolution of the NoEMi databases, we observed that the disturbance

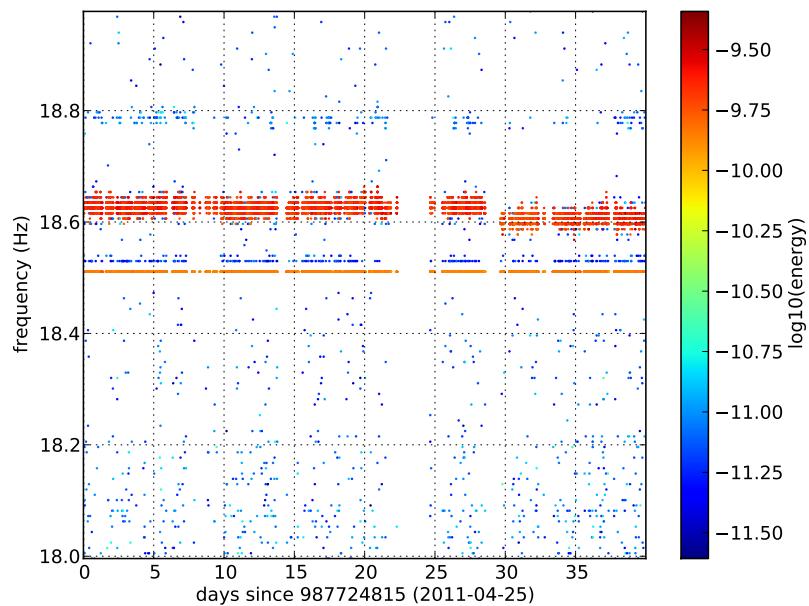


Figure 6. Correlation with auxiliary channels

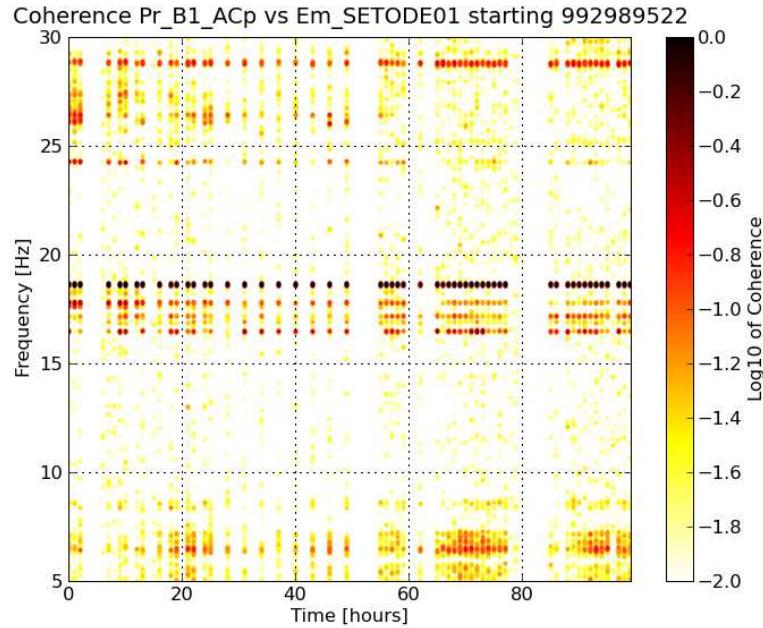


Figure 7. Coherence plot: coherence values between DF signal and one seismic monitoring signal in a frequency-time map

consisted of a dense comb of lines (see Figure 8), and, after deeper investigation, the source of the lines was understood: they were generated by the non-linear coupling of a set of calibration and control lines (sinusoidal signals injected into the interferometer for calibration and control

purposes). The noise was moved away from the Vela pulsar frequency by shifting the frequencies of the calibration lines. The effect of the mitigation is visible in Figure 9.

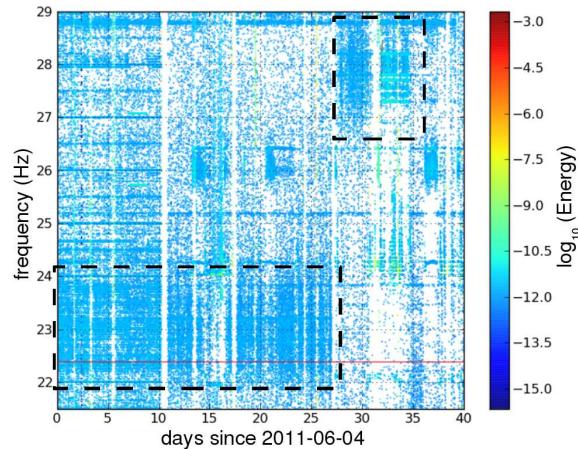


Figure 8. Time-frequency plot of the peak maps at the Vela frequency region. The noise bump was highlighted in the dashed rectangles before and after the change of the frequencies of the calibration lines.

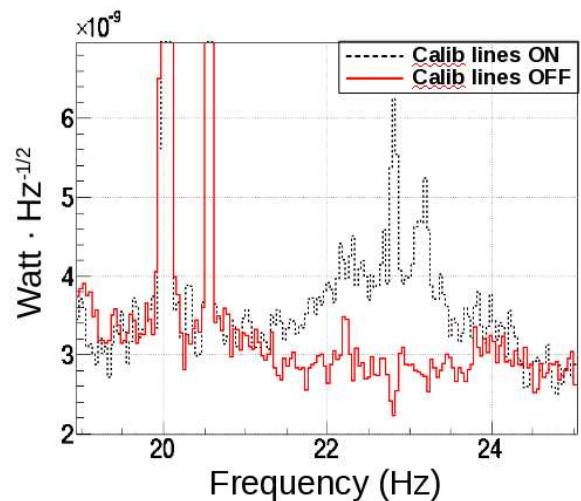


Figure 9. Effect of the calibration signal switch off on the noise power spectral density.

More details on the Vela bump are given in [13].

7. NMAPI evolution

Over the next short- and long-term periods, several developments and upgrades of NMAPI are planned. These include minor modifications, to render NMAPI ever-simpler to use from a user perspective, as well as more complex and detailed developments, designed with the improvement of NMAPI back-end operations in mind. Here we look at each of the upgrades individually.

- *Interface developments.* While NMAPI enables Noise Monitor Administrators to create bespoke script-launch forms, we have seen during testing and usage phases, that there are some occasions upon which users really need to be able to be even more flexible than usual when attempting to produce datasets and results. In order to meet this requirement, the possibility to enter conditional script syntax directly to an HTML textarea, will be provided.
- *Database developments.* In terms of the NMAPI database itself, the possibility to tag data (as VSR3, VSR4, etc.) in an extensible and modular format, will be added.
- *Improvement of cross-application linkages and communication.* NMAPI already incorporates linkages with another Virgo PHP environment application in the form of the Channels Database [14], a source of regularly updated information on channels available within the Virgo Data Acquisition system. The aim is to increase the inter-operability and communication between applications within this environment and NMAPI via the use of a dedicated connection-handling database (CDB) [15].
- *Use of additional data sources and result cross-correlation.* Discussions have taken place regarding the use of NMAPI to interrogate data produced by other interferometers (GEO, LIGO). In the event of additional data sources being used by a central NMAPI installation, a tagging system, enabling data to be recognised by given criteria, would be fundamentally important. In addition, questions relating to data location, input-output and connectivity issues, as well as usage of reduced datasets would also have to be addressed. Integration of

data and results produced by other similar detectors will also facilitate cross-correlation of advanced detector results.

- *Distributed NMAPI.* With Advanced Virgo [16] and LIGO [17] in mind and significant increases in channel examination foreseen for several of the Noise Monitors already interfaced to NMAPI, it will be necessary to move to a distributed version of the application. At present, Steering Scripts are managed by a PHP semaphore and launched by NMAPI directly on the NMAPI local host, as and when conditions allow. However, given increased usage and larger amounts of data to process, the restriction to the use of a single host could become a serious limit. Therefore, a move to a distributed system, D-NMAPI [18], is foreseen.

8. Conclusion

The NMAPI framework, into which the noise monitoring tools were integrated during the last Virgo scientific run, has been described. Online monitoring is fundamental for noise detector characterisation, in order to be able to act promptly on the interferometer and cure possible problems, as well as to assist in the development of data-cleaning strategies for the astrophysical detection groups. An example of how NMAPI was successfully used during VSR4 to identify an excess of noise in the region of the Virgo sensitivity in which the gravitational signal emitted by the Vela pulsar could be detected, has also been presented. Thanks to this it was possible to identify the noise source and to remove the problem, leading to an improved sensitivity in that region in the VSR4 data-taking period.

We plan to further enrich the NMAPI framework, in order to allow for a heavier computational load, by distributing the requested scripts and using a database cluster to collect the processed data of the Advanced generation of interferometric detectors.

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