2.5 Gravitational Waves
The dynamics of spacetime

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General relativity is one of the pillars of modern physics, yet over the past century, empirical access has been limited to situations where gravitational fields are nearly stationary (as in the Solar System), or where they are dynamical but relatively weak (as with radio observations of binary neutron stars). Direct detection of gravitational waves (GW), ripples in the curvature of spacetime that propagate at the speed of light, appears in the foreseeable future the only way to observe the genuinely strong-field dynamics of space-time. The worldwide network of second generation laser interferometric GW detectors, with ten times enhanced sensitivity and a 1000 times larger accessible volume of universe and expected detection rate, is undergoing the commissioning phase towards the first joint data taking planned for 2017. Nikhef is involved in the historical quest of the first GW direct detection by participating in the Advanced Virgo project.

Instrumentation for Advanced Virgo

Nikhef is in charge of the design and production of crucial hardware components for the vacuum, injection, and detection subsystems of Advanced Virgo, an upgrade of the Virgo interferometer with three kilometre long arms located in Cascina near Pisa in Italy. The institute has important responsibilities in the angular alignment of core optics, seismic attenuation systems of Advanced Virgo's optical sensors, cryogenic ultra-high vacuum links, input-mode cleaner dihedron and end mirror suspension (see Fig. 1), and adaptive optics systems such as phase cameras.

Thanks to the deep expertise in vibration isolation technology and skills in high precision mechanics, Nikhef is the leading institution of the Suspended Benches project subsystem. The Nikhef group has conceived and produced six vibration isolation systems for Advanced Virgo: one single-stage six degrees of freedom in-air seismic attenuator, called EIB-SAS for the external injection bench, and five multiple-stage in-vacuum isolators, called MultiSAS (see Fig. 2) for the suspended optical benches.

Figure 2. Panorama of the BOL Clean Room at Nikhef during the assembly of the five MultiSAS units for Advanced Virgo.

Seismic isolation provided by EIB-SAS allows to take full advantage of the beam pointing feedback system located on the external injection bench, to inject the laser beam into the interferometer with the required picoradian level jitter in the detection frequency band. The large attenuation factors provided by the MultiSAS units will ensure that the seismic motion of the angular alignment sensors (and related pickoff telescopes) placed on the suspended benches will not couple to the output of the detector through scattered light. This year all five MultiSAS have been assembled and tested at Nikhef and three of them installed at the Virgo site and pre-commissioned; the installation of the remaining two units is foreseen before summer 2015.

The cryogenic ultrahigh vacuum links (*cryolinks*), allowing a 100-fold improvement in the residual gas pressure in the arm pipes, must be considered the major improvement in the vacuum infrastructure of the detector. The four units, designed at Nikhef, have been produced and transported to the Virgo site last spring. Their

Figure 1. Installation of the new end-mirror suspension in Virgo's Input Mode Cleaner.

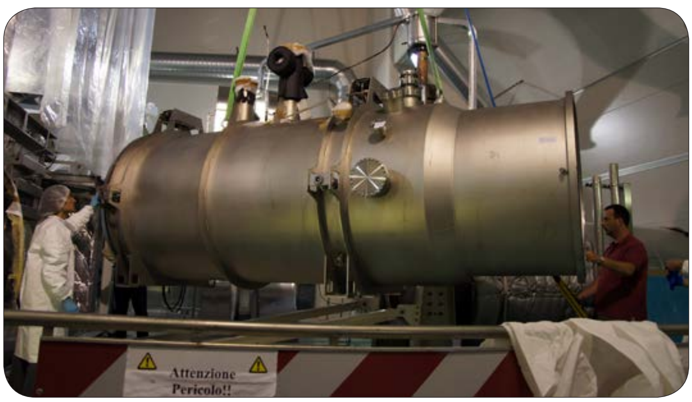

Figure 3. Installation of the first cryolink at Virgo's North End building, summer 2014.

installation (see Fig. 3) and commissioning is ongoing and will last till June 2015.

Prototyping of the phase cameras, developed by the Nikhef group after an intense R&D campaign, was completed in spring 2014. Phase cameras, providing accurate images of the spatial distribution of amplitude and phase of the laser fields (carrier and sidebands) circulating in the power recycling cavity, are instruments of paramount importance for the active compensation of the aberrations of the transmissive optics of the interferometer, which otherwise could compromise the detector stability and would limit the usable optical power. Installation of the three units is foreseen in early 2015.

During the last year Nikhef has also designed and produced all RF and DC quadrant photodiode modules (see Fig. 4) necessary to sense and control the alignment between the optics of the interferometer, and novel vacuum compatible low power galvoscanners needed for the automatic beam centering on the RF quadrant photodiodes used for differential wavefront sensing.

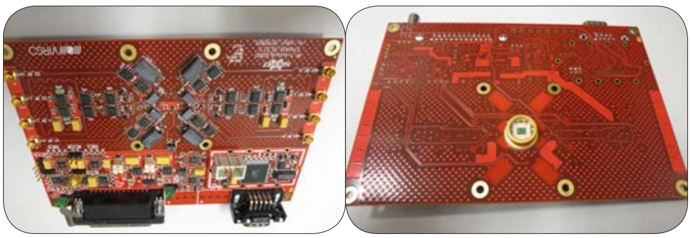

Figure 4. Front- and back-side of the PCB for the linear-alignment front-end systems. The right panel shows the quadrant photo-diode.

Data analysis

The gravitational wave group at Nikhef also carries an extensive research programme in data analysis, under the leadership of Chris Van Den Broeck who was recently appointed as Data Analysis Coordinator by the Virgo Collaboration. Focussing on the coalescence of compact binaries composed of neutron stars (NS) and black holes (BH), considered one of the most probable sources for the first direct detection of GW events, Nikhef has made leading contributions to the LIGO–Virgo effort towards developing software that will extract fundamental physical information from the signal. This comprises the determination of individual component masses and spins, the sky location and orientation of the binary, and the distance to the source, together with the identification and removal of instrumental calibration effects.

The Virgo group at Nikhef has studied a method to use future data from NS–NS coalescenses to characterise the equation of state of a neutron star, one of the most unknown observables in astrophysics, and it has developed a data analysis pipeline, called TIGER (Test Infrastructure for GEneral Relativity), to test the genuinely strong-field dynamics of general relativity in a model-independent way up to $(v/c)^6$ order (see Fig. 5). This latter effort has led to the creation of a new technical sub-group within the LIGO–Virgo collaboration to expedite the activity. This group has brought the TIGER pipeline for binary neutron stars coalescences to maturity by making it robust to unknown instrumental effects (*e.g.* calibration errors), to imperfect knowledge about the signal shape according to general relativity and to unknown astrophysical effects, *e.g.* the neutron star equation of state.

The TIGER framework has been proposed to also test the validity of the No-Hair Theorem when applied to ring downs of coalescing binary black-holes. A preliminary benchmarking has been made on simulated waveforms for ringdowns of massive (500–1000 solar masses) BH–BH binaries which will be seen by the Einstein Telescope. The Nikhef Virgo group is also involved in the search of continuous gravitational waves from fast-spinning neutron stars in binary systems for which it is developing a dedicated data analysis pipeline called Polynomial Search. Such a pipeline was benchmarked among others last summer in a mock-up data challenge.

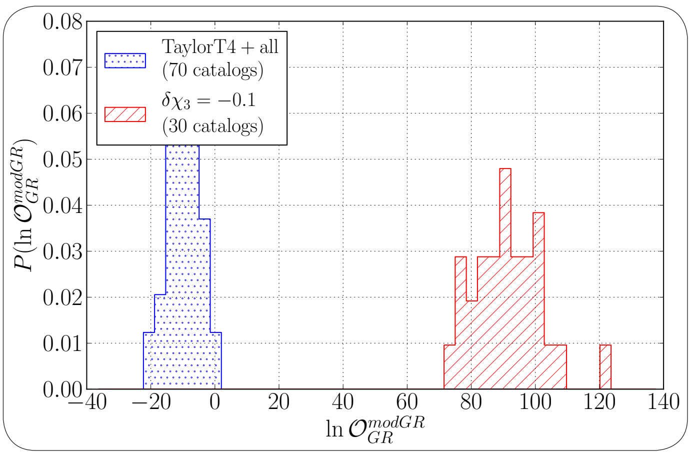

Figure 5. If the strong-field dynamics of spacetime is not as predicted by general relativity (GR), then the TIGER data analysis pipeline will be able to find out by studying gravitational wave signals from coalescing binary neutron stars. Shown are the distributions of TIGER's 'detection statistic' for GR violations, for the case where GR is correct (blue), and assuming a violation of the GR prediction for the self-interaction of spacetime (red).