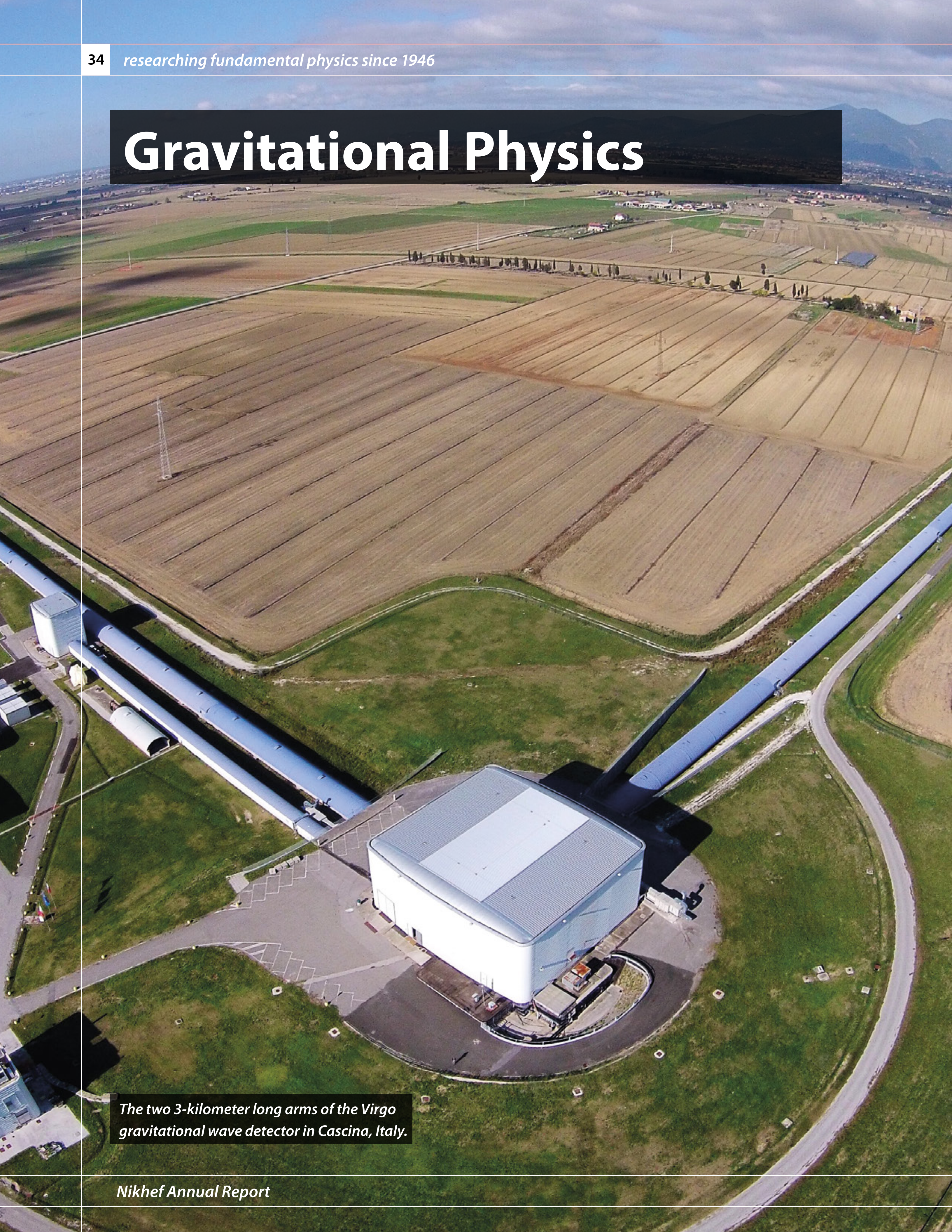
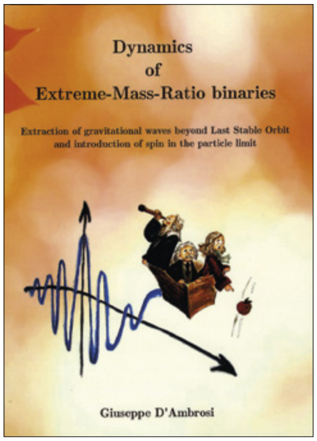
Gravitational Physics



The two 3-kilometer long arms of the Virgo gravitational wave detector in Cascina, Italy.



Giuseppe D'Ambrosi
21 April 2016

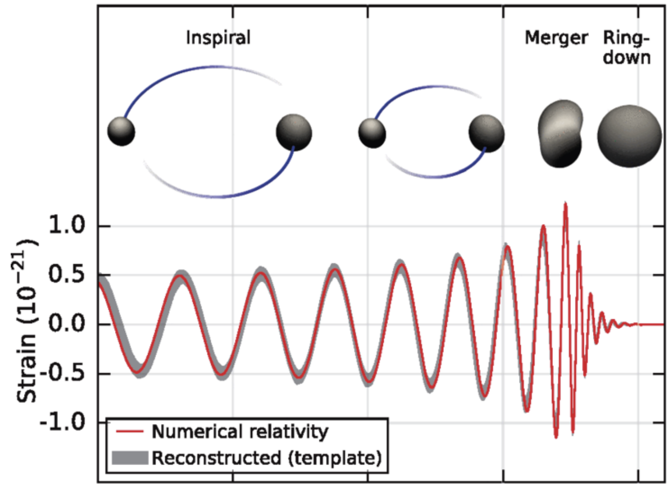


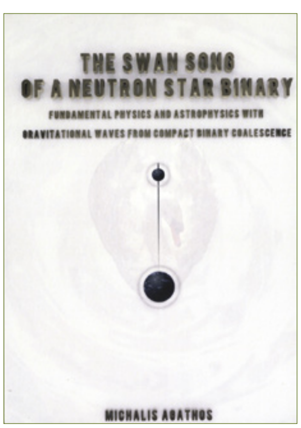
Figure 1: Estimated gravitational-wave strain amplitude from GW150914 projected onto H1. This shows the full bandwidth of the waveforms. The inset images show numerical relativity models of the black hole horizons as the black holes coalesce.

Management
prof.dr. J. van den Brand

The first direct detection of gravitational waves (GWs) with LIGO happened on 14 September 2015, and was named GW150914. The event was identified as extremely promising already on the day itself, and shortly afterwards its significance was established to be > 5.1σ. Follow-up analyses revealed that it had most likely resulted from the merger of two black holes of 36 and 29 solar masses, respectively; no less than 3 solar masses worth of energy was emitted in gravitational waves, making this the most powerful event ever observed by mankind. Also at the detectors, it was sufficiently loud to be visible by eye in the raw data. The detection represented several scientific breakthroughs at once: apart from being the first direct GW detection, it provided the first direct evidence of the existence of black holes; it was also the first observation of a binary black hole merger, and it finally gave us access to the genuinely strong-field dynamics of pure spacetime. A second clear detection came on 26 December 2015, called GW151226, involving black holes of 14 and 8 solar masses, respectively.

Data analysis

The Nikhef group played an important role in the analyses, in a variety of ways. Jo van den Brand was a member of the Detection Committee, which had been charged with checking all aspects of the process that led to the discovery of GW150914, from the instrumentation (including the possibility of malicious tampering) to the final data analysis products. Chris Van Den Broeck was Virgo Data Analysis Coordinator, in which role he helped organise the joint LIGO-Virgo analysis activities, together with his counterpart in the US. Furthermore, during the preceding 5 years, Nikhef had been spearheading the development of methods for testing general relativity (GR) using GW signals from merger events, which could now be applied to real detections. Finally, Gijs Nelemans helped in interpreting the events from an astrophysics point of view: the unexpectedly high masses of the black holes in GW150914 implied that they had formed in a low-metallicity environment.



Michalis Agathos
20 December 2016

GW150914 was what is known as a 'golden event', meaning one whose total mass was such that the merger occurred at a frequency where the detectors are the most sensitive. The process whereby two black holes coalesce is illustrated in Fig. 1. It starts with two black holes spiraling towards each other as orbital kinetic energy and angular momentum are radiated away in gravitational waves. At some point a last stable orbit is reached, and the black holes plunge towards each other and merge to form a single, highly excited black hole. The latter will shed its excitations ('ringdown'), and finally settles down into a dormant state. The early inspiral is understood perturbatively through the so-called post-Newtonian formalism, in which *e.g.* the GW phase can be written as an expansion in powers of v/c (with v the characteristic velocity and c the speed of light). In earlier kinds of observations (*e.g.* radio observations of binary neutron stars), only the leading-order post-Newtonian contribution could be measured with any kind of accuracy; already with GW150914, for the first time bounds could be put on potential violations of GR in high-order post-Newtonian coefficients. Moreover, observables related to the pre-merger and merger-ringdown regimes could be constrained. GW150914 and GW151226 yielded complementary information: the former revealed the strongly non-linear behaviour of spacetime near merger, while the latter, with its much longer inspiral signal in

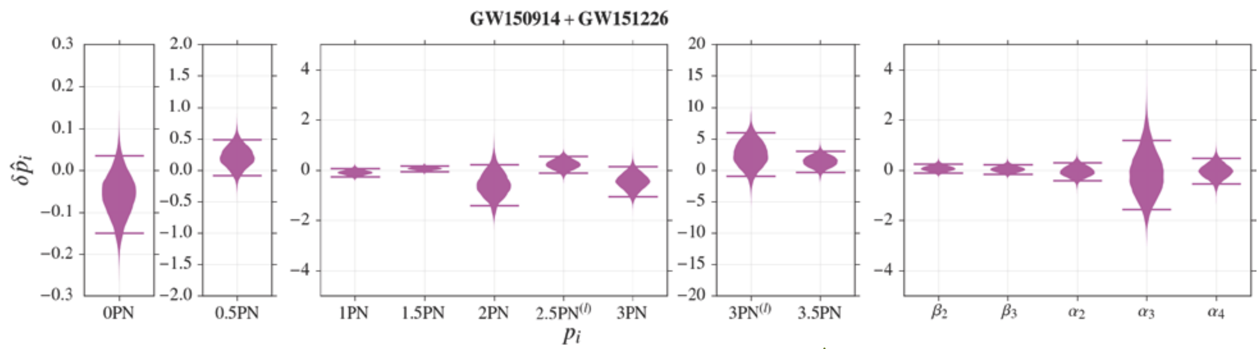


Figure 2: Posterior density distributions and 90% credible intervals for relative deviations $\delta\hat{p}_i$ in the PN parameters p_i (where l denotes the logarithmic correction), as well as intermediate parameters β_i and merger-ringdown parameters α_i. The figure shows combined posteriors from GW150914 and GW151226.

the sensitive frequency band, enabled precision tests of the inspiral of binary objects. One of the most important post-Newtonian parameters is the one at $(v/c)^3$ beyond leading order, which incorporates the dynamical self-interaction of spacetime. This coefficient has now been constrained to 10%; towards the end of the decade, as information from a growing number of detections can be combined, this uncertainty will likely shrink to the 1% level. These results will be part of the PhD thesis of Nikhef student Jeroen Meidam; see also Fig. 2.

Another Nikhef result (by PhD student Michalis Agathos) was a bound on the mass of the graviton. A non-zero value of this mass would be noticeable in a classical gravitational wave: the higher-frequency components would be traveling slightly faster than the low-frequency ones, and both slower than the speed of light. This effect is cumulative over the huge distance (in this case 1.3 billion lightyears) that the wave has to travel from source to detector, so that a sharp measurement can be made. This led to the strongest dynamical bound on the graviton mass yet obtained: $m_g < 1.2 \times 10^{-22}$ eV/c^2, the first ultra-high precision result to come from gravitational wave astrophysics. The paper summarizing these and other tests of GR that were performed was the most cited research publication of the LIGO-Virgo Collaboration for 2016, second only to the two detection papers themselves.

Meanwhile the group is looking towards the future. It seems likely that binary neutron star coalescences will be detected in the next few years. During late inspiral, the tidal field from one star will induce deformation in the other, which affects the orbital motion; this in turn gets imprinted upon the GW signal and can be measured. How deformable a neutron star will be, is set by the equation of state, which is the main open problem in nuclear astrophysics: theoretical predictions for pressure as a function of density vary by as much as an order of magnitude. As had already been shown before by the Nikhef group in simulations, the observation of multiple binary neutron coalescences will allow us to distinguish between a stiff, intermediate, and soft equation of state.

In 2016, this research moved from proof-of-principle to more practical considerations. Though theoreticians are providing increasingly accurate waveforms with inclusion of tidal effects, these are too slow to generate on a computer, and in pure form are not yet useful in data analysis. A solution is reduced order modelling, a waveform decomposition which retains most of the physics and discards the rest, with a loss of accuracy that is much smaller than the measurement uncertainty. As shown by Nikhef researchers, this reduces the time needed to perform an analysis from more than a year to a couple of weeks, rendering the problem computationally feasible. The same technique will also be needed in tests of GR with binary black holes; it is plausible that O(100) binary black hole coalescences will be observed in the next few years, which would again strain our computational resources.

Binary coalescences provide a unique opportunity to study relativistic compact objects. The celebrated no-hair theorem states that the geometry of a stationary black hole is determined solely by its mass and spin (and possibly electric charge, though the latter is expected to be zero for astrophysical black holes). This reflects itself in the fact that the different vibration modes in the ringdown process (which can be described as linear perturbations of a stationary black hole) have characteristic frequencies and damping times which only depend on mass and spin. The Nikhef group is preparing to put this to the test in upcoming GW observations. Another exciting possibility which we want to explore in the near future is GW echoes. Motivated by Hawking's information paradox, it has been argued that black hole horizons get modified to *firewalls*. If so, the part of the gravitational radiation that is ingoing and would normally be swallowed by the black hole can instead be reflected outward; in practice what one gets is repeated GW bursts, or echoes, with decreasing amplitude. Even if the characteristic length scale of the corrections is at the Planck scale, the echoes will be loud enough to in principle be measured.

Apart from binary coalescences, fast-spinning, single neutron stars with small deformations (in the order of 0.1 mm) can also be sources of detectable gravitational waves. These are weak but long-duration signals, allowing for long integration times so that they can be extracted from the data. Detecting such radiation would yield additional information about neutron stars, notably the structure of the crust. Many neutron stars will be part of a binary system, where the other component is an ordinary star. The binary motion causes Doppler modulation in what would otherwise have been a monochromatic signal, which considerably complicates the data analysis. To address this, the Nikhef group has been developing *Polynomial Search*, whose computer code is now mature, and can produce upper limits on signal strengths in case of non-detection. An all-sky search on data from LIGO's first science run is in preparation.

Instrumentation contributions to the Advanced Virgo detector

The upgrade of Virgo to a second generation gravitational wave detector, the Advanced Virgo project, was brought to completion in 2016. The upgrade has involved the majority of the detector subsystems, with Nikhef giving a decisive contribution to many of them.

Advanced Virgo will operate with increased laser power circulating in the interferometer arm cavities (from 20 kW to 700 kW), which allows reducing the photon shot noise by more than one order of magnitude. Practical implementation requires to compensate the thermally induced distortion and the optical defects in the input optics (*i.e.* the power recycling mirror and input test masses). Such those aberrations would in fact spoil the matching between the laser and the power recycling cavity, *e.g.* the power sent to the interferometer beamsplitter, preventing to reach the aimed shot noise figure. A complex adaptive optics system, called Thermal Compensation System (TCS), has therefore been realised for Virgo, based on different types of wavefront sensors and non-contacting thermal actuators, to statically and dynamically correct the aberrations.

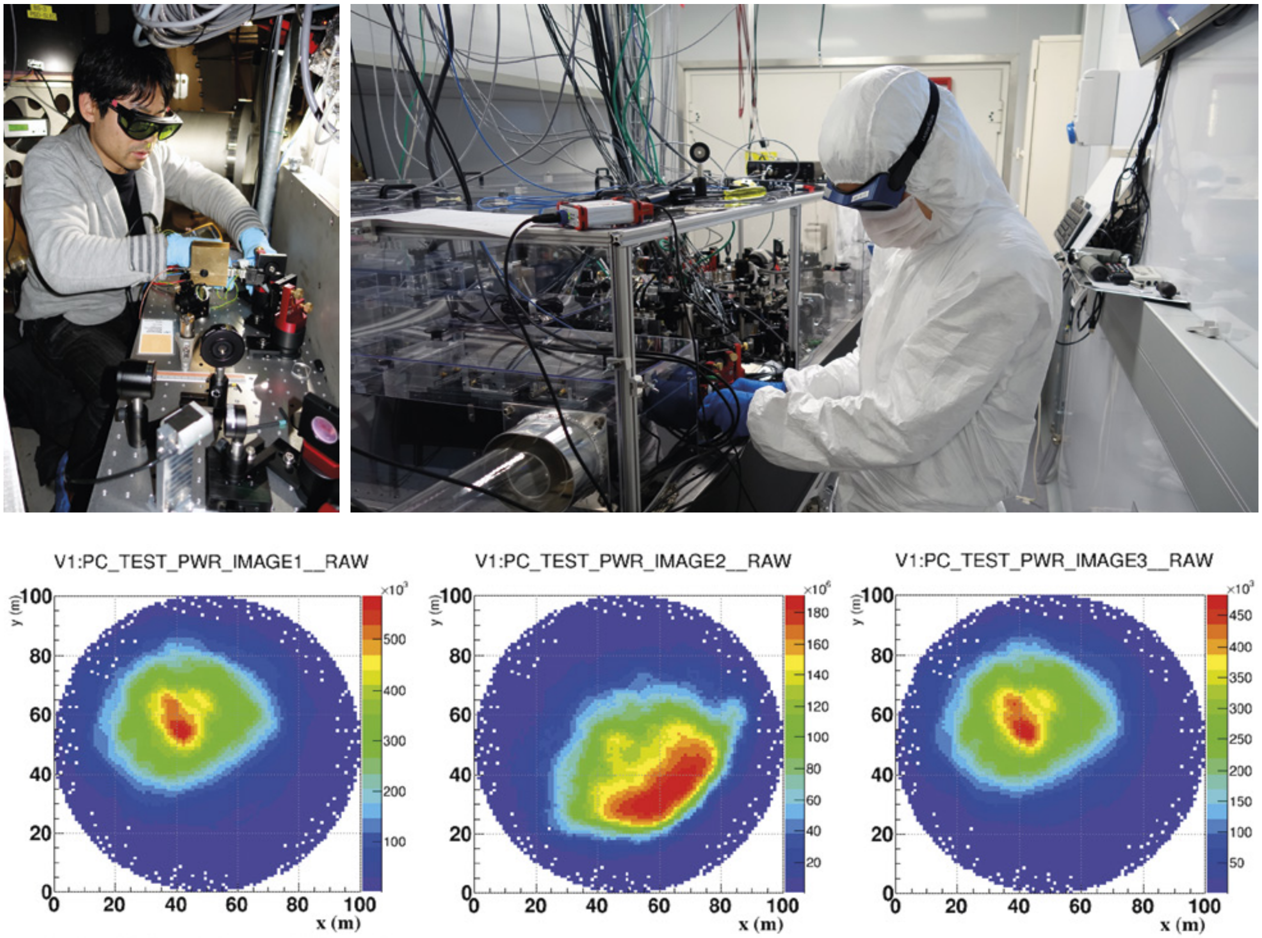


Figure 3: Top left panel: Kazuhiro Agatsuma (postdoc) installing the phase camera PC2 at the power recycling cavity pick-off port. Top right panel: Laura van der Schaaf (PhD student) installing the reference phase camera in the Laser Room. Bottom panel: PRC beam intensity profiles as measured by PC2 with PRC locked; the scan shows from left to right the 6 MHz lower sideband, the carrier and the 6 MHz upper sideband.

Among the TCS wavefront sensors, the most peculiar ones are the three Phase Cameras developed and realised at Nikhef which allow to compare, with sub-nanometer level resolution, the wavefront of the input laser beam with that of the beam circulating in the interferometer. The last one carries imprinted the input optics aberrations that then are measured and can corrected by means of the TCS actuators. In the second half of 2016 the three phase cameras have been installed and integrated into the detector, and they are now already providing crucial reference signals during the commissioning of the machine (see an example in Fig. 3).

Nikhef also designed and produced the optical sensors, shot noise limited DC and RF quadrant photodetectors, used in the angular alignment system of Virgo to maintain the relative orientation of all suspended optical elements within the required few nano-radians accuracy. Nikhef's instrument makers have also designed and produced dedicated high vacuum compatible galvo scanners needed to center the beam on the RF quadrants for the differential wavefront sensing. All these components are in service on the Virgo auxiliary optical benches since mid-2016.

In Advanced Virgo the decision was taken to have all auxiliary optical benches in vacuum and vibration isolated in order to reduce the seismic noise coupling to the angular alignment sensor signals and the coupling to the interferometer output through the light scattered by the sensors themselves and by their associated pick-off telescopes. This required five multistage seismic attenuation systems (so-called MultiSAS) to be designed and built at Nikhef. All MultiSAS units, each of them providing more than six orders of magnitude vibration isolation in all six degrees of freedom, have been integrated into the detector and the two of them located behind the interferometer end mirrors are fully operational since Summer 2016. The remaining three units, now temporarily disabled, are planned to also be operational during the first observation run.

The cryogenic vacuum links, the major infrastructure upgrade of the detector, also designed at Nikhef, have proven, in their first year of continuous operation started at the end of 2015, to be very effective in reducing the residual gas pressure in the interferometer arms (the largest vacuum system in Europe with its nearly 6,000 m^3 volume) well below the water vapour limit. Reaching vacuum pressures below 10^{-9} mbar is of paramount importance for the successful operation of Advanced Virgo, the sensitivity of which would otherwise be limited by the phase noise caused by the random scattering of the laser beam from the residual gas molecules.

While the full commissioning phase of Advanced Virgo has started, with the initial goal of participating with the two Advanced LIGO detectors in the first joint Observation Run in April 2017, a mid-term further upgrade of the interferometer has been planned. Besides the addition of a frequency independent squeezer for the reduction of the quantum noise, a Newtonian noise cancellation system will be implemented. Newtonian noise, caused by seismic noise inducing mass density fluctuations in the surroundings of the detector test masses, cannot be shielded and can only be mitigated by subtraction techniques by using the measured seismic fields as input. Nikhef is deeply involved in this endeavour which can be considered a pathfinding experiment for such a technology towards the third generation detectors such as Einstein Telescope. In this framework, on August 2016 a Nikhef team has made a survey of the Virgo area to characterise the seismic environment of the detector. An array of cable-less, autonomous seismic sensors, developed by the institute spin-off company InnoSeis B.V., was deployed and the local main seismic noise sources were investigated; the seismic wave propagation characteristics of the area were measured and, by means of inversion algorithms a soil density profile was reconstructed. The gained knowledge is now being used to estimate, through elastodynamic based simulations, the Newtonian noise level of the detector site, and will be used to design the sensor array for the cancellation system.

Still related to Newtonian noise, even if more projected towards Einstein Telescope, is the development of novel MEMS-based seismic sensors that incorporate Nikhef proprietary technology. Large arrays of several thousands of ultralow noise seismic sensors will be needed in third generation gravitational wave detectors for the suppression of Newtonian noise. For this reason, MEMS technology, suitable for cost effective large scale manufacturing, is very attractive. Several sensor prototypes have been produced in collaboration with the MESA+ laboratory of Twente University and nano-g level resolutions, suitable for these applications, have been achieved in the Nikhef laboratory by using conventional discrete components conditioning electronics. Since the fall of 2016 the design of a companion ASIC has been started with the aim of further improving the resolution, reducing the form factor, and lowering production cost and power consumption.

Rubicon grant Michalis Agathos

Michalis Agathos obtained funding in the framework of the Rubicon programme of NWO for his proposal *"Exploring Gravity With Gravitational Waves"*. For a period of 24 months, he will conduct research at the University of Cambridge. With Rubicon, NWO creates an opportunity for scientist who have recently gained their PhD to acquire research experience at internationally renowned institutes abroad. *"The recent discovery of gravitational waves marks the kick-off for a new era of physics. The researcher will combine state-of-the-art methods to test general relativity and alternative theories of gravity against signals detected from colliding black holes and neutron stars."*

Dutch-German impulse for gravitational wave research

In April 2016, Nikhef and the German Albert-Einstein Institute (AEI) signed a declaration in the presence of Dutch Prime Minister Mark Rutte to strengthen scientific and technological cooperation in the area of gravitational wave research. The signing took place during the Hannover Messe 2016, the world's largest technology trade fair. Nikhef and AEI intend to develop a joint vision on new (third generation) detectors for gravitational waves. One of the most promising projects is the Einstein Telescope. Joint research into a possible location for a future detector in Europe will form a key part of the cooperation. One of the ways this takes place is in the form of feasibility studies, looking at sites in the Dutch-German border area in South-Limburg and North Rhine-Westphalia.

Mark Beker
Innoseis

Mark Beker, director of Innoseis, founded the company together with Jo van den Brand in 2013 as a Nikhef spin-off. Before that, he had completed his PhD at Nikhef on gravitational wave detector research, for which he received the FOM valorisation chapter prize in 2014.

"Nikhef has been very important for our start-up in establishing relations with industry. Cooperation between the institute, industry and the start-up produces synergy. Nikhef offers networking, knowledge and credibility. Shell offers industrial knowledge and finances. The start-up is the source of innovation."

"We produce seismic detectors that are smaller, lighter and cheaper than our competitors'. From the start, there has been a long-standing collaboration with Shell. They bought a hundred of our sensors and use them for testing their geophysical models. Moreover, we work together with an oil and gas company in Eastern Europe that has borrowed a network of sensors for tests. In the end, we would like to develop networks of over 100,000 sensors that will really enable us to look underground."

"Another use of the sensors is in the detection of earthquakes. Moreover, we are also discussing their use with defense and police authorities; they would like to be able to tell whether someone walks in certain areas. Also the location of explosions could be determined by the sensors."

"Finally, the work on the sensors can also have a strong feedback on the work for gravitational wave detectors."

Gravitational waves and damping vibrations

Eric Hennes
Mechanical Technology

By Laetis Kuipers

As a Physics Engineer in Nikhef's Mechanical Technology Department, Eric Hennes is closely involved in the development of various technical-mechanical instruments for the European gravitational wave detector Virgo. "My specialty lies in vibration isolation," he explains, "a technique that enables us to prevent 'noise' from being measured together with relevant signals. We do this by damping environmental vibrations and seismic movements that interfere with the detection of gravitational waves. To achieve this, our team at Nikhef has developed the suspension of six auxiliary optical systems that previously were directly connected to the ground. It's one of Virgo's improvements that were needed to reach the required sensitivity of 'Advanced' Virgo. And now we are waiting for this system to become operational in a few months' time."

"I must say," Eric continues, "that I can hardly wait for the moment when, together with our colleagues from LIGO and Virgo, we will measure new events. Something that we hope to see is gravitational waves from the merging of neutron stars. What makes our work in this field so very exciting is that it signals the beginning of a completely new type of astronomy. We currently have two LIGO detectors in the USA that have captured gravitational waves, but imagine how much more we could see when we have three detectors. We can then use triangular measurements to determine the location of the sources of the gravitational waves. And with Virgo upgraded to the best possible standards, I expect the new constellation to work significantly better, perhaps even ten times better. This surely is a prospect to relish."

"Physics has always been my passion, and next to my work in the Mechanical Technology Department I am closely involved in Nikhef's outreach projects. I worked in academic education for much of my earlier professional career, and I very much like sharing my knowledge and experience with others. My main drive for the coming years is the development of the Einstein Telescope (ET), Virgo's large-scale underground successor. Following the first detections of gravitational waves, the realisation of this telescope has come a step closer. Nikhef is heavily involved in ET, particularly in its site selection, presently focused on the province of Limburg. As you can see: there are many more future prospects to relish."