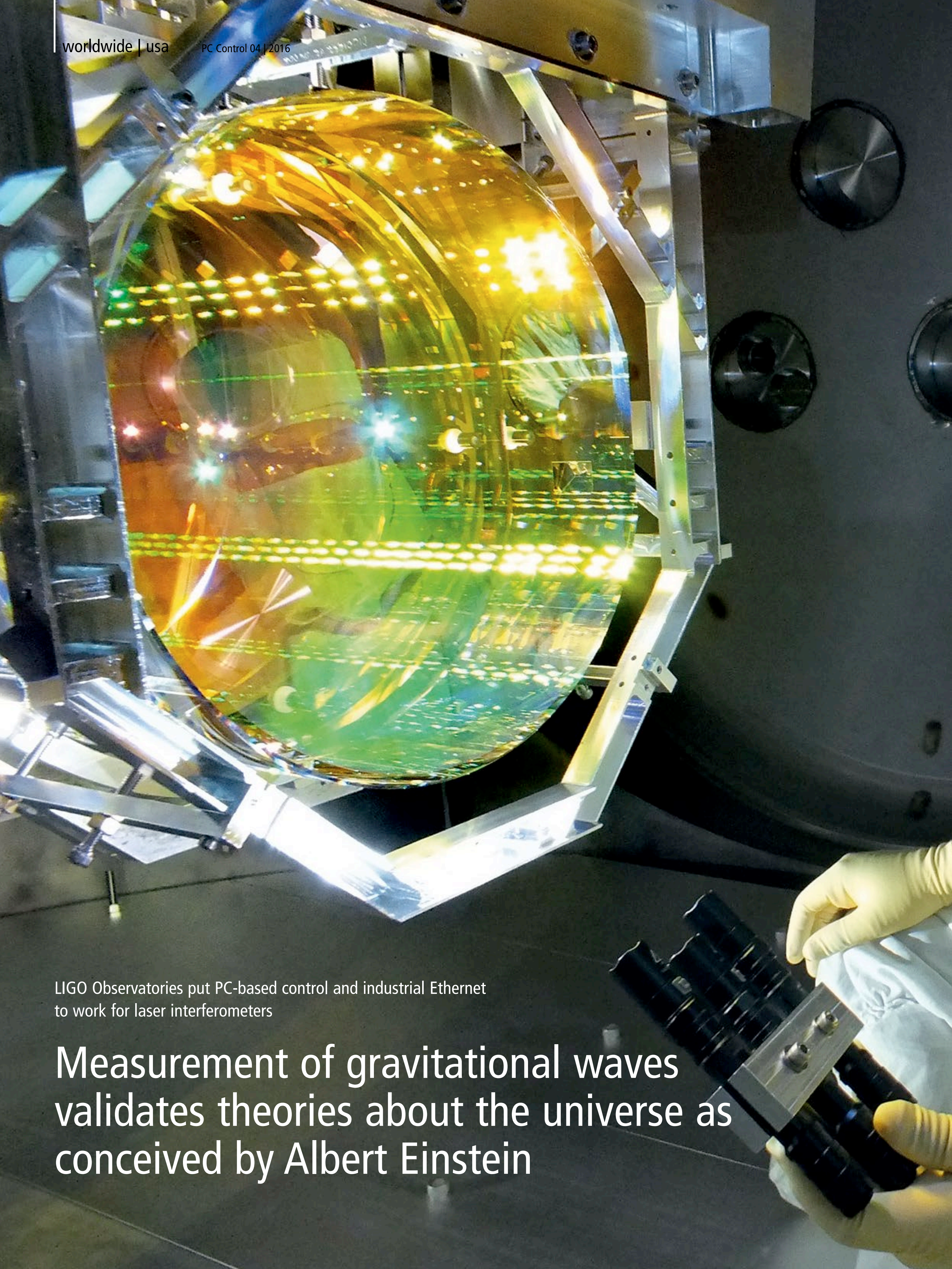


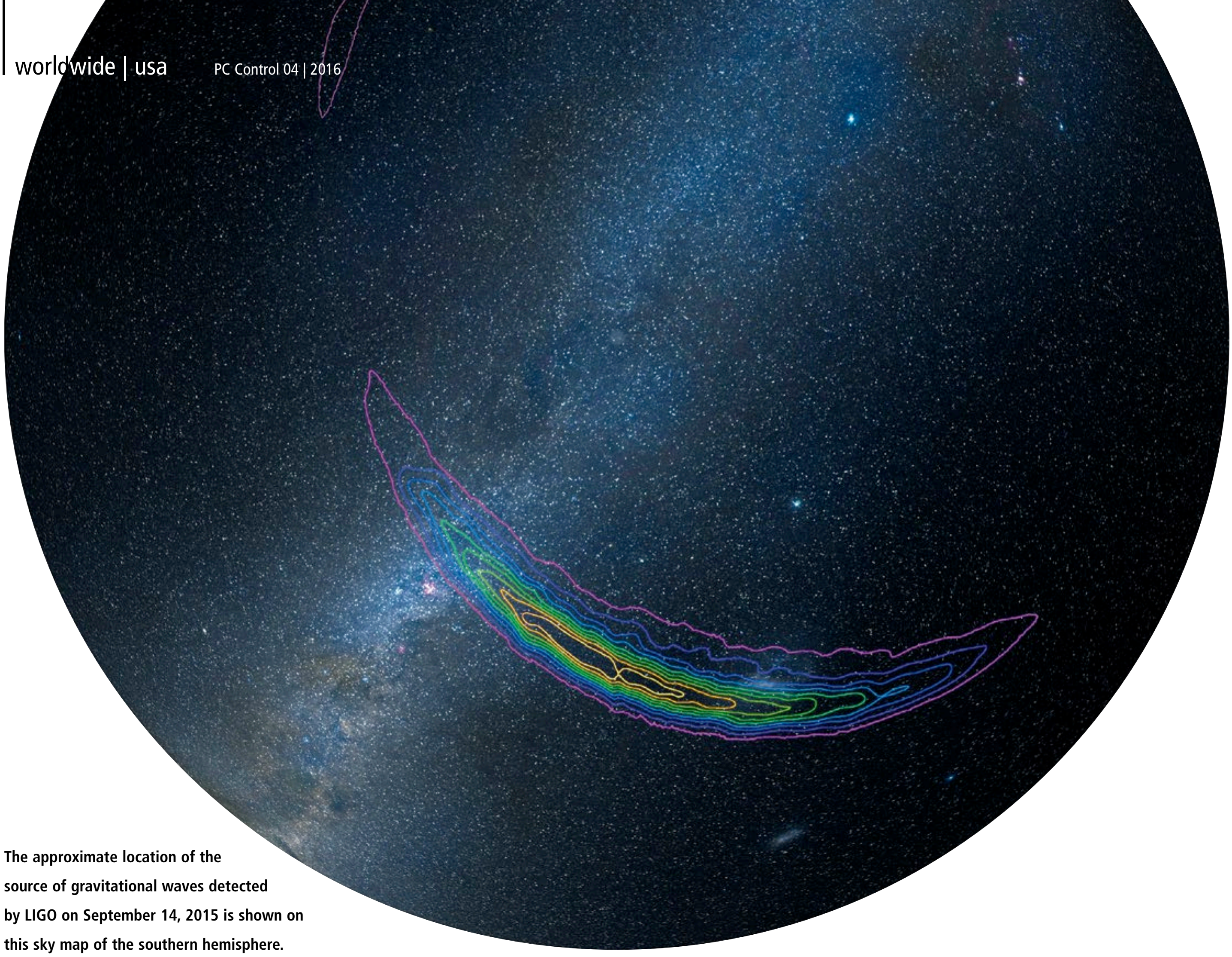
LIGO Observatories put PC-based control and industrial Ethernet to work for laser interferometers

Measurement of gravitational waves validates theories about the universe as conceived by Albert Einstein

A LIGO technician inspects one of the mirrors prior to sealing up the chamber where the laser-interferometer is housed and pumping the vacuum system down

100 years after Albert Einstein's general theory of relativity and his prediction of gravitational waves, LIGO (Laser Interferometer Gravitational Wave Observatory) recently confirmed their existence for the first time. Gravitational waves were first recorded on September 14, 2015 by the twin LIGO detectors based in Hanford, Washington and Livingston, Louisiana. LIGO recorded its second gravitational waves detection on December 26, 2015.

Gravitational waves are ripples in the fabric of space-time, which are emitted by major cosmic events such as merging black holes or by neutron stars. Albert Einstein predicted the existence of gravitational waves as part of the general theory of relativity in 1915, but it was only now that LIGO managed to observe and measure them with highly sensitive interferometric gravitational wave detectors. The first-detected gravitational waves came from a truly mind-boggling source: the cosmic collision of two black holes measuring between 29 and 36 times the size of the sun, which happened at an estimated distance of 1.3 billion light years. The LIGO detectors were able to record gravitational



The approximate location of the source of gravitational waves detected by LIGO on September 14, 2015 is shown on this sky map of the southern hemisphere.

waves created during what were the final 100 milliseconds before the two black holes combined.

Industrial automation in the service of discovery

In the course of the research conducted in the Hanford and Livingston detectors, PC-based controls and EtherCAT are used as high-speed communication system. Daniel Sigg and Richard McCarthy from the Hanford site are two of the specialists that lead the implementation of the automation technology. "The PC-based control technology is used for servo-based laser control at the end stations of the interferometer arms," explains Daniel Sigg, Senior Scientist at LIGO Observatories. "The L-shaped ultra-high vacuum systems, in which the laser-interferometer is housed, are very large and have a leg length of 2 km at Hanford and 4 km at Livingston. Remote control in the applications, including the servo control for stabilizing the laser frequencies, was therefore a critical requirement. We also implemented a highly sophisticated data acquisition system with the aid of EtherCAT."

The monitoring of the research facility is one of the primary responsibilities of the PC-based control system. This includes timing control for the distribution systems, which send a great deal of research data for diagnostics via RS232 or RS485, which is channeled into the higher level EtherCAT system. "We realized this could be done with traditional PLCs, but to simplify the system for those involved in the project, we went with PC-based control," explains Richard McCarthy, Lead Electrical Engineer, LIGO Observatories. The previous automation and I/O system used at LIGO was not modular or flexible enough to accommodate regular system updates and expansion. Equipment for scientific research requires relatively frequent modifications and enhancements, so flexibility of the control technology is a major concern.

The EtherCAT system is used as the integrated fieldbus system for all components, including I/Os, safety technology and stepper motors. LIGO Observatories also developed many of their own EtherCAT devices used for high-end measurement and data analysis. In addition, multi-protocol communication in EtherCAT and TwinCAT 3 automation software ensures measured data is readily available and accessible by all the universities and organizations involved in this massive research project. Daniel Sigg and Richard McCarthy use TwinCAT ADS to create direct interfaces to the visualizations on LIGO control room screens.

Through integration in Microsoft Visual Studio® and the wide range of available programming languages, TwinCAT 3 automation software is flexible by nature and offers numerous programming tools. LIGO Observatories primarily uses Structured Text (ST) for the PC-based automation systems in the interferometer research stations, while other research equipment features code created in C++ or Python.

For monitoring functions, LIGO uses various Beckhoff Panel PCs, including a CP2215 with multi-touch display. These are installed at the vacuum controls for the interferometers and facilitate process monitoring and pump control, among other functions. "The most expensive equipment for us to replace is the vacuum system, so we must constantly monitor the different buildings that house the vacuum systems, cryopumps and ion pumps," McCarthy explains.

Since the arms of the interferometers extend 4 km (2.5 miles), fiber optic networking with noise immunity is required for physical connections to the remote electronic equipment. This is handled via EK1501 EtherCAT Couplers with glass fiber cables, depending on the distance between stations, in multi-mode (max. 2,000 m) or single mode variants (max. 20,000 m). In addition to the fiber optic connection, EL6692 EtherCAT bridge terminals establish real-time data exchange between EtherCAT I/O ring topologies and different masters – a critical consideration for interferometers that extend for kilometers.

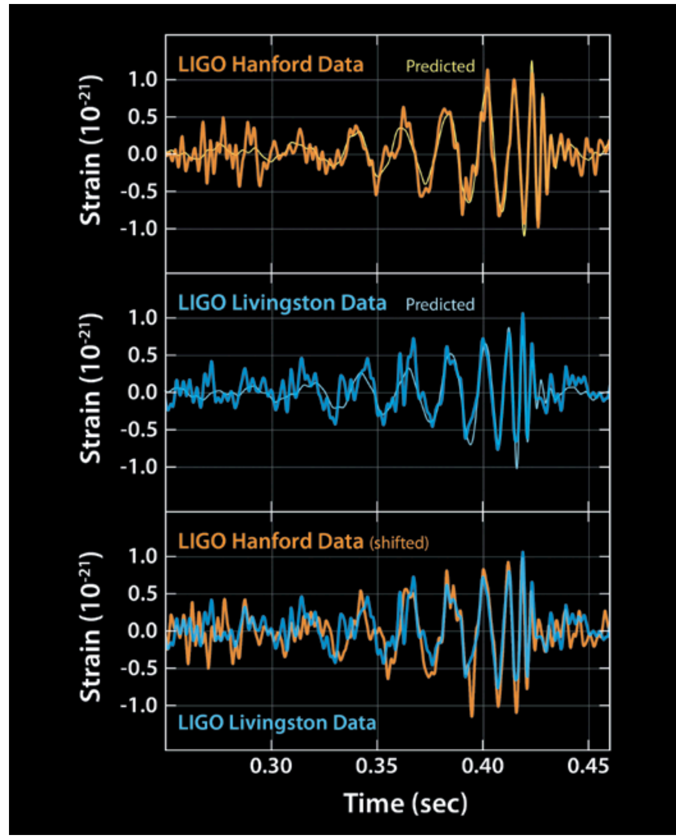
The I/O system is frequently called upon to remotely change gain settings and relays while interfacing with other high-precision measurement electronics that were custom-designed for LIGO. TwinSAFE terminals facilitate a wide range of human and equipment protection measures at the LIGO sites. These are directly connected to Beckhoff CX5020 Embedded PCs. All high-power laser beams must be contained in protected areas to keep personnel safe. If any person or object somehow enters a protected area, TwinSAFE and an emergency stop ensure that all interferometer arms are shut down simultaneously. TwinSAFE also makes it possible for LIGO Observatories staff to safely open laser tables without having to shut any lasers down.

A high precision, low frequency (0.01 Hz) tilt meter is used to measure the tilt of the interferometers. The device is so sensitive, it can detect how much the floors of the observatory buildings sway on days with high winds. Optics equipment tilting out of the acceptable range can be compensated for by other equipment installed in the interferometers. The tilt meter itself is run by a C5210 19-inch rack-mount Industrial PC. This also handles image analysis for the tilt meter, which has a small mirror that reflects a laser in order to detect minute vibrations while a camera records any changes. The camera is synchronized with the EtherCAT I/O system. The EtherCAT Box modules connected to stepper motors make high-precision adjustments to the alignment of the measurement table.

Research equipment designs continue to make waves

Through a focus on the introduction of standardized and flexible systems, this massive and ambitious LIGO Observatories project was finished on-budget and on-schedule. Of course, that isn't to say there were no course corrections along the way. As the scientists and engineers at LIGO fine-tuned their research methodologies and built the lab infrastructure, the PC-based control and EtherCAT equipment had to follow suit. And it did: "We maintain a 10 ms update rate with over 1,000 physical devices and 10,000 input/output variables within TwinCAT software, which is handled by the high-performance PC-based controllers," Sigg concludes.

Future plans for LIGO Observatories include the retrofit of multiple legacy systems at existing sites to modern PC- and EtherCAT-based control technology. Specific targets for retrofit include weather stations, dust monitoring, hydraulic pump control and more.



The plots show the signals of gravitational waves detected by the twin LIGO Observatories at Livingston, Louisiana and Hanford, Washington.

The vacuum control systems developed by LIGO heavily utilize PC-based control and EtherCAT communication technology.

Further information:
www.ligo.caltech.edu
www.beckhoffautomation.com