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Pentek, Inc.
One Park Way, Upper Saddle River, NJ 07458
Tel: (201) 818-5900 • Fax: (201) 818-5904
email: pipeline@pentek.com
http://www.pentek.com

Looking at Gravitational Events of Cosmic Origin

The Laser Interferometer Gravitational-Wave Observatory (LIGO) is aimed at observing gravitational waves of cosmic origin. LIGO will search for gravitational waves created in supernova collapses of stellar cores that form neutron stars and black holes, collisions and consolidations of neutron stars and black holes, and the remnants of gravitational radiation created by the birth of the universe. LIGO uses laser interferometers to measure gravitational waves that originated hundreds of millions of light years from earth and is a joint project between the scientists at the California Institute of Technology (Caltech), the Massachusetts Institute of Technology (MIT) and several other collaborating institutions. The project is sponsored by the National Science Foundation (NSF).

Facilities

The major LIGO facilities consist of vacuum systems at two widely separated locations, in Hanford, Washington and Livingston, Louisiana. Both vacuum systems are L-shaped with 4 km (2.5-mile) arms that enclose laser interferometer beams. The beams originate and are detected at the vertex of the L (corner station) and are reflected from the ends of the L (end stations).

At the Washington site, additional mirrors are placed at the midpoints of the arms (mid stations) to establish half-length interferometers. The entire system, comprised of three interferometers, a full-length and a half-length at Washington and a full-length at Louisiana, operates as a single gravitational-wave detector. If a gravitational-wave signal is detected by the full-length interferometer, the half-length instrument provides a quick validation, if its output is equal to one-half the output of the full-length interferometer. Further verification is offered by the other facility's interferometer, when its output is a signal of equal amplitude but not necessarily the same phase. Figure 1 is an aerial photograph of the facility in Hanford, WA.

Figure 1. Aerial View of the LIGO Washington Facility

Instrumentation

The scientific objectives of LIGO include research in the fundamental physics of gravitation as well as in astronomy and astrophysics. Possible advances include:

- Tests of the general theory of relativity
- Direct measurement of the propagation speed of gravitational waves
- Direct observation of the dynamics of black holes

The gravitational waves are expected to distort the 4-kilometer mirror spacing by about one thousandth of a Fermi (one thousandth of a Fermi is equal to 10^{-18} meter).

These waves were first predicted by Einstein's theory of relativity in 1916, when the technology necessary for their detection did not exist.

Analog strain signals from the interferometers are digitized and recorded continuously for offsite analysis. Ancillary signals monitoring the state of the instrument, the facility and the environment are also archived continuously. Data is analyzed for bursts, periodic sources and a stochastic background of gravitational waves.

The Interferometers

As shown in Figure 2, the laser interferometer utilizes a prestabilized Nd:YAG laser with roughly ten watts of power. Its output is passed through a "mode cleaner" that is used to further ➤

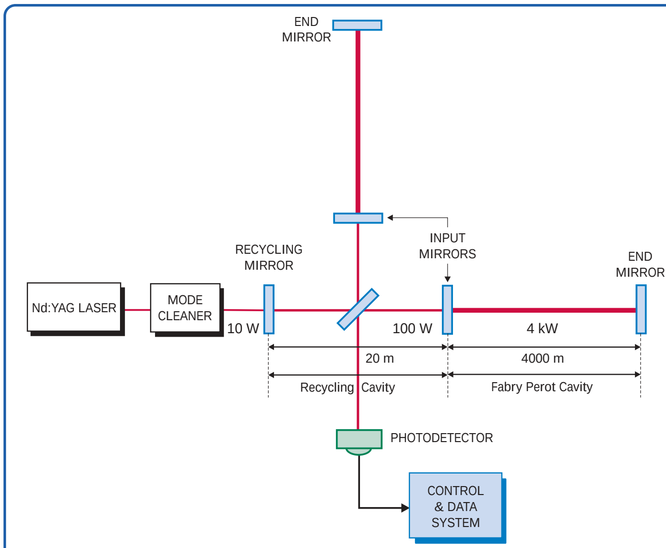

Figure 2. The LIGO Interferometer

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stabilize its amplitude and frequency, and is then injected into the interferometer. The power in the cavity formed by the recycling mirror, beam splitter and input mirrors is approximately 100 Watts. The split beam is coupled through an input test mass into each 4-km long Fabry Perot cavity. The cavities serve to recirculate the light so that there is a power buildup to around 4 kW. This creates enough contrast to detect a gravitational-wave signal when the two beams interfere.

Some of the unusual requirements imposed on the system include:

- A control system to stabilize the laser frequency to better than 1 part in 10^{21}.
- Reflecting mirrors that are among the best optics in the world, with typical RMS deviations from a perfect surface of less than 0.8nm (10^{-9} meter).
- Active reduction of seismic noise through seismic isolation.

Three noise sources determine the performance of the system. At high frequencies, i.e. 100 Hz and above, the system is limited by shot noise that basically comes from counting the photons in the cavities. In the medium frequency band, between 40 and 100 Hz, the limiting noise is thermal noise of the piano wires used to suspend the test masses and thermal noise of the mirrors. Below 40 Hz, system performance is limited by seismic noise. Seismic isolation comes from isolation stacks at the middle of the L and at the end of each arm. These reduce seismic noise by a factor of 10^6. The sensitivity band of the LIGO detectors is from 40 Hz to 8 kHz and anything in this band that is not an identifiable glitch is a gravitational wave candidate.

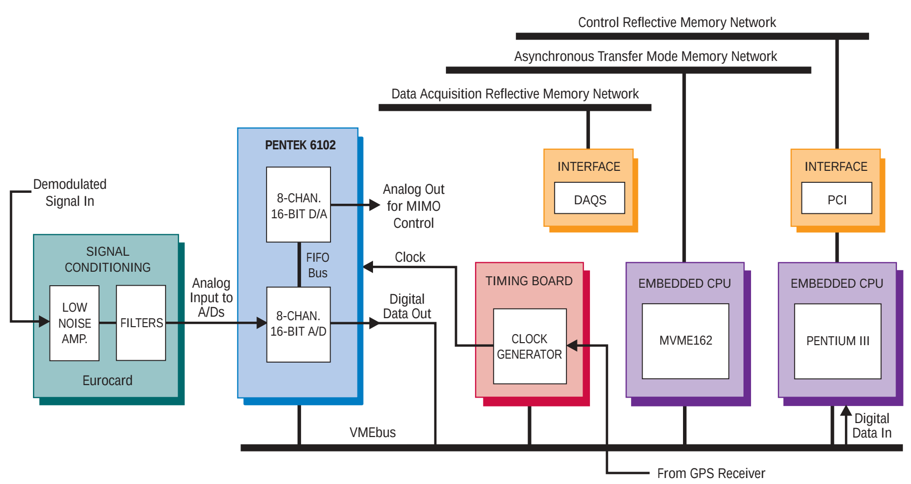


Figure 3. Typical Data Acquisition and Control System Diagram

Data Acquisition and Control

The LIGO Control and Data System (CDS) is a highly integrated data acquisition and control system. Control of the interferometers requires many Multiple Input Multiple Output (MIMO) control loops closed both locally and across the 4-km interferometer arm lengths. In addition to providing the closed loop control, the control systems front end processors act as data collection units for the data acquisition system.

Data collected is time-stamped to an accuracy of 1 µsec and is made available to online analysis tools. The data is also stored at the Center for Advanced Computing Research at Caltech and is made available to the LIGO science collaboration institutions for off-line analysis. Continuous data rates exceed 5 MB/sec per interferometer. Both control and data acquisition systems use VME hardware and VxWorks® operating systems.

A typical signal conditioning and processing path is shown in Figure 3. The photodetector signal is band-pass filtered and demodulated. The demodulated output is amplified by a very low noise amplifier, low-pass filtered and then passed through whitening and anti-alias filters. The signal is then digitized by a Pentek Model 6102 8-channel, 16-bit, simultaneous sampling A/D and D/A converter. The A/D outputs provide the data information, while the outputs of the D/A are used as the control signals for the MIMO control system. Approximately 75 Model 6102's are used in the three interferometers to collect data and to implement all the control systems.

Processors in the VME systems include Motorola MVME162 for slow (<10 Hz) control systems and operator communications, and Pentium III processors for real-time DSP applications to 16 kHz. Timing clocks are derived from the Global Positioning System (GPS) and are distributed to the system through LIGO custom timing boards. The signal conditioning modules are also custom-developed by LIGO and are housed in 6U Eurocard enclosures for optimum noise performance.

Three networks are provided for communication among the various processors: the CDS asynchronous transfer mode network; the Data Acquisition reflective memory network; and the Control reflective memory network.

Typical Data Analysis

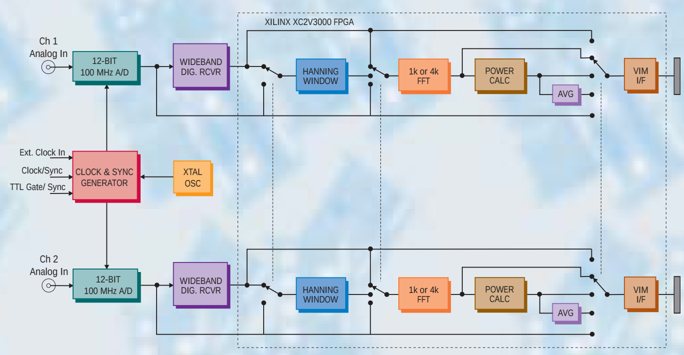
One type of gravitational radiation expected is that attributed to bursting episodes in the universe. The first run with data collected took place in January 2002, when all three LIGO detectors ran simultaneously for the first time. Offline data analysis is done by the LIGO Data Analysis System (LDAS), which will search for burst-type gravitational radiation among other data.

Burst sources emit gravitational radiation that lasts just a few cycles within the frequency band of LIGO. They generally come with little or no indication of their waveforms. Among such anticipated sources are supernova explosions that can emit significant energy that would be hard to miss. ➤

Dual Channel Wideband FFT Receiver VIM Module

[From page 4]

butterfly stages for the 1024- or 4096-point algorithms, respectively. Several advanced noise reduction techniques employed in the algorithms deliver a spurious-free dynamic range for the FFT calculation of better than 90 dB.



Model 6235 with the Optional GateFlow FFT Processing

The FFT output points are reordered (deinterleaved) and may be either delivered as complex I & Q values or routed through a sum-of-squares power calculator.

An averager permits averaging up to four outputs in the single channel mode or two outputs in the dual channel mode prior to delivering them to the main processor through the VIM interface.

Using the A/D input mode with a sampling clock of 100 MHz, both channels of the 6235 can easily perform FFT calculations in real time with no data loss for either option. In this case, as much as 50% overlap processing is also possible. When used, the Hanning window and output power calculation do not impact the FFT speed.

Benefits

Calculation times for the 1024- and 4096-point FFTs are less than 2.5 µsec and 10 µsec respectively, with the Xilinx XC2V3000 FPGAs. These times beat software FFTs implemented in C6000 DSPs or PowerPCs by an order of magnitude.

This capability in a VIM module means that you can also have it in a one-slot VME configuration that includes a processor board, such as the Model 4294 quad PowerPC board. Furthermore, the processor is unburdened from performing the FFT through software and its full power can be dedicated to other tasks.

Finally, you can obtain these benefits without becoming an expert in FPGA programming. Since it's all done for you by Pentek, you can complete your system much faster and significantly reduce your time-to-market. ❑

However, such an event occurs only once every 35 years. To see events of this type more often, we have to survey a large volume of the universe or maintain very high sensitivity.

The LIGO LDAS is comprised of a number of PCs each with 1 GHz processor and 1 GB RAM. This clustered configuration runs Linux and includes a number of additional multiprocessor PCs that serve as "master" and data-conditioning nodes, along with two quad-processor SUN units that serve as data and database servers. The whole system offers a little over 1 terabyte of storage. Its primary mission is to run the algorithms optimized to look for specific astrophysical signatures. Another SUN unit is used for analyzing ancillary data.

Burst search has the task of analyzing a possibly very weak signal, distinguishing it from detector noise, and interpreting it as an astrophysical event. The following presents some highlights of this process:

- Data is brought in from the field sites to the LDAS.

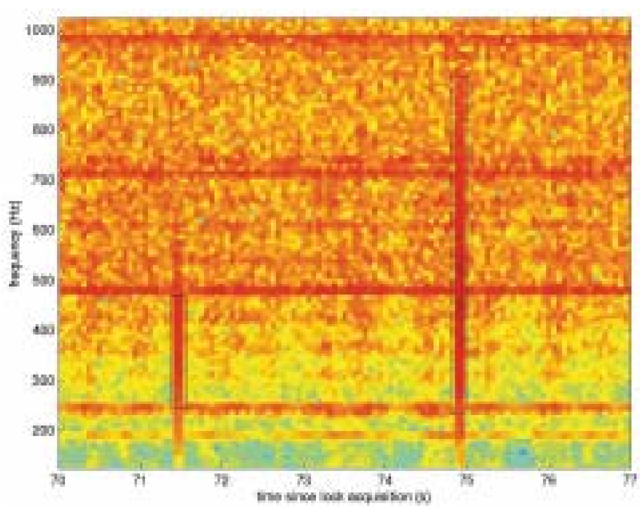


Figure 4. Offline Analysis of Burst-type Data

- Burst algorithms are executed on the system to identify possible candidate events. Algorithms are based on simple time domain filters or time-frequency analysis of the FFTs of the time-domain detector data. One of the ways to identify events is whenever the total power of the data in a frequency band of interest exceeds the noise power, or by looking at the clustering of "loud" events, as in the time-frequency plane shown in Figure 4. Two clusters of "loud" events in this plane are identified with the two thin, black rectangular boxes lying vertically at left and right in the figure. The horizontal stripes are harmonics of the 60 Hz power lines.
- At the same time, transient algorithms are executed on the ancillary data. This data is expected to have much reduced coupling or none to the gravitational data. Thus, they define events that can be used to veto the useful data, if significant correlation is indicated. ❑

Product Focus

Model 6235

Model 6235 is a dual wideband receiver VIM-2 module that includes 12-bit 100 MHz A/Ds and a Virtex-II FPGA.

Dual Channel Wideband Receiver Features GateFlow™

The Model 6235 is now available with FFT-preprogrammed FPGAs

Model 6235 dual wideband digital receiver includes two complete acquisition and digital receiver channels in a VIM-2 mezzanine module for all VIM-compatible platforms, such as the Pentek DSP and PowerPC VME boards.

For standard 6235 units, the Virtex-II FPGA contains factory-programmed code to implement control, initialization, mode selection and data formatting functions. However, much of the FPGA remains available for custom signal processing algorithms.

Extended versions of the standard FPGA functions are now available. These include real-time FFT (Fast Fourier Transform) algorithms for implementing either a 1024- or a 4096-point FFT. With either option installed, all existing operational modes of the standard 6235 remain intact. Either one of these FFT options may be installed in a unit.

GateFlow is Pentek's family of extendable FPGA products. The GateFlow product line includes the *GateFlow FPGA Design Kit* to ease algorithm development and the *GateFlow Installed Cores* featuring Pentek's streamlined FFT algorithm.

FFT Operation

The block diagram on page 3 shows the signal flow paths and processing blocks for both FFT options. The switches are programmable multiplexers controlled through the VIM interface and should be set identically to take advantage of symmetrical pipelined processing.

The FFT can process output samples from the A/D or the digital receiver. Optionally, a Hanning window may be applied to the selected FFT input source.

The FFT block utilizes a complex, radix-4 algorithm with five or six ➤

PENTEK
Pentek, Inc.
One Park Way
Upper Saddle River, NJ 07458-2311

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