Forecast:

A 'Fourier' Future

The Relaxation Times

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TeachSpin's Hat-Trick

Fourier Methods | UltraSonics | Pulse Counter/Interval Timer

TeachSpin will be displaying three new initiatives at its exhibition at the 2012 APS 'March' Meeting to be held in Boston, February 27 to 29. This newsletter is intended to whet your appetite for these three new offerings, and to invite you to see them in action. The items making their debut are: a combination we call ***Fourier Methods,*** an ensemble of experiments in ***Ultrasonics***, and a new ***Pulse Counter/Interval Timer*** with computer-interface capability.

FOURIER METHODS

In collaboration with Stanford Research Systems (SRS, Inc.), TeachSpin announces a combination of a high-performance Fourier analyzer (the SRS770) and a TeachSpin 'physics package' of apparatus, experiments, and a self-paced curriculum. Together, they form an ideal system for students to use in learning about 'Fourier thinking' as an alternative way to analyze physical systems. This whole suite of electronic modules and physics experiments is designed to show off the power of Fourier transforms as tools for picturing and understanding physical systems.

The SRS770 wave analyzer (shown in the photo) digitizes input voltage signals with 16-bit precision at a 256 kHz rate, and it includes anti-aliasing filters to permit the real-time acquisition of Fourier transforms in the 0-100 kHz range. Any sub-range of the spectrum can be viewed at resolutions down to milli-Hertz. The sensitivity and dynamic range are such that sub-μVolt signals can be displayed with ease, as well as Volt-level signals with signal-to-noise ratios over 30,000:1.

The only additional instruments required to perform these experiments are a digital oscilloscope and any ordinary signal generator. The photo above also shows three 'hardware' experiments from TeachSpin: a cylindrical Acoustic Resonator, the Fluxgate Magnetometer in its solenoid, and the mechanical Coupled-Oscillator system. Not shown is an instrument-case full of our 'Electronic Modules', which are devised to make possible a host of investigations on the Fourier content of signals.

We are confident that the simultaneous use of a 'scope and the FFT analyzer, viewing the same signal, is the best way to give students intuition for how 'time-domain' and 'frequency-domain' views of a signal are related. One of our Electronic Modules is a voltage-controlled oscillator (VCO), which can be frequency-modulated by an external voltage. Fig. 2 shows the 770's view of the spectrum of this VCO's output, when it is set for a 50-kHz center frequency, with a 1-kHz modulation frequency. This spectrum shows the existence of sidebands, and the frequency 'real estate' required by a modulated signal. It also shows that Volt-level signals can be detected standing > 90 dB above the noise floor of the instrument.

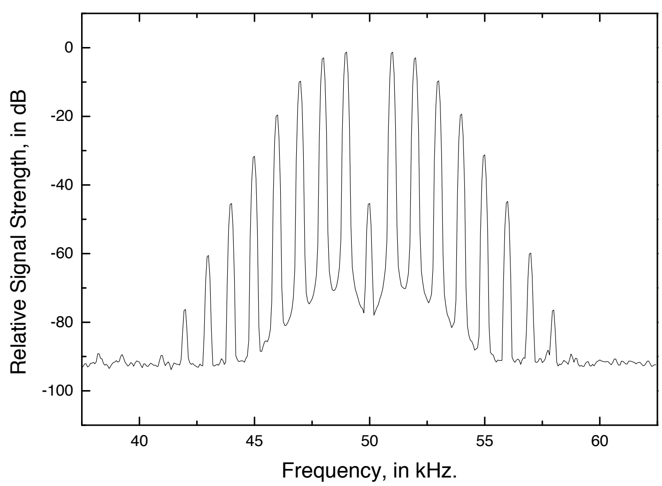

Fig. 2: Spectrum of frequency-modulated oscillator. Vertical scale is logarithmic, covering 90 dB of dynamic range an amplitude ratio of 30,000:1.

As an example of one of our Electronic Modules, let's consider the LCR-circuit that can be excited by steady sinusoids, by unit-step waveforms, or by the white-noise generator that is built into the SRS770. Exciting this one circuit, in turn, by these three signals, students can learn a great deal about the properties of resonant systems. After some point-by-point measurement of the LCR-circuit's transfer function using sinusoids, they will be impressed to excite its time-domain transient response using a voltage-step waveform, and then seeing the Fourier transform of this transient give the entire spectrum, complete with phase characteristics, *all at once* in a single shot – see Fig. 3.

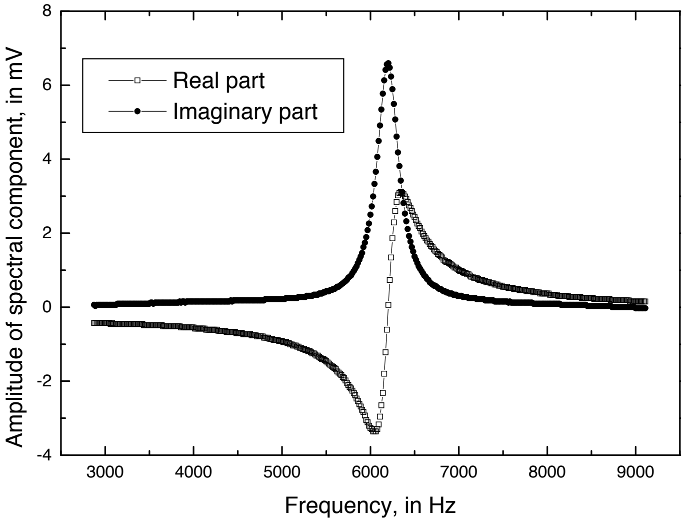

Fig. 3: Real and the imaginary parts of the Fourier transform of an LCR-resonant circuit, excited by a single voltage step and recorded in a single acquisition of duration 64 ms. The spectrum shows the dispersive, and the absorptive, behavior of the resonant system.

Because frequency-mixing technologies are so important across the board in experimental physics, our Electronic Modules include an electronic multiplier, as well as two kinds of mixers. When combined with a 'local oscillator' from a signal generator, a signal in any frequency range can be down-shifted into the 0-100 kHz band. Fig. 4 shows a view of part of the AM-radio spectrum, as received in Buffalo, NY. Our modules include all the parts, and all the instructions, to make the audio content of this AM transmission audible through a speaker.

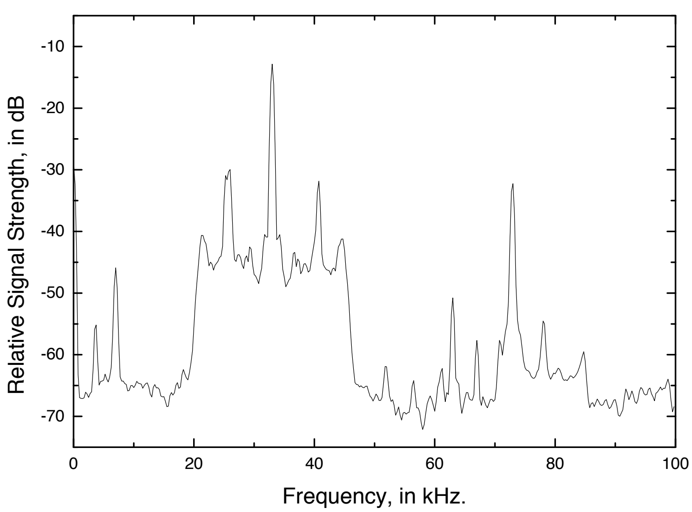

Fig. 4: Power spectrum arising from the down-conversion of radio signals. A local oscillator, set to 1113 kHz, is mixed with signals from an antenna, revealing the down-conversion of a station's frequency of 1080 kHz to a 33-kHz beat note. The sidebands to either side of the down-converted carrier reveal the program content of the AM transmission.

The SRS770 includes a high-gain front end making it capable of detecting very weak signals. And because it disperses those signals by frequency content, and permits time-averaging, it is also capable of detecting weak signals that are deeply-buried in noise. Our Electronic Modules include a signal-under-noise experiment, in which weak sinusoidal signals are overlaid with analog white noise. Fig. 5 shows how such weak signals can be detected by spectral resolution, without the need for a 'reference signal' that a lock-in amplifier would require.

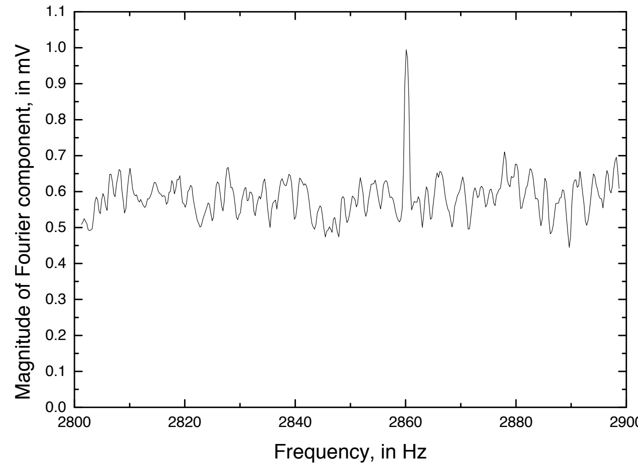

Fig. 5: Power spectral density of white noise, showing the presence of a monochromatic signal under the noise. The noise, filtered to the 0-100 kHz bandwidth, has an rms value of 173 mV, and has a 0.83 mV sinusoidal signal contained within it. The spectrum, viewed over a band 97.5 Hz wide, and averaged for 15 seconds, reveals the signal emerging from its burial under noise, and locates it in frequency space.

The noise source in the Modules, and the noise source within the SRS770, can both be quantified for spectral noise density, so students will finally be able to use an instrument whose output is calibrated in those mysterious units, Volts/√Hz. They'll be able to see that the units for measuring the amplitude of spectral peaks (in Volts) and the level of noise floors (in V/√Hz) are incommensurate, and also see that spending more acquisition time will enhance the degree to which a mono-chromatic signal stands up above the white-noise floor.

Because 'Fourier methods' are a set of mental skills transferable to many areas of physics and technology, we have included a set of experiments and projects which showcase the applicability of Fourier analysis:

- an acoustic resonator, to permit the study of acoustic modes – including finding them *all at once* by white-noise excitation.
- a fluxgate magnetometer, with a frequency-domain view into its operation, and the ability to detect microTesla dc ***and ac*** magnetic fields.
- an electronic analog-computer system which creates the Lorenz attractor, so students can see what chaos looks like, in the time and frequency domains.
- a unique mechanical coupled-oscillator system, allowing the detection of two resonant modes, and a view of how their mode frequencies can be tuned through an 'avoided crossing'.

Fig. 6: The echoscope set-up

- inputs for bringing in microphone, and line-input audio signals, so students can see the real-time spectra of sounds they are hearing.

Physicists acquire Fourier-thinking skills in a variety of ways, and apply these skills in many sub-fields of physics. Advanced-lab instructors might want to share, with their theorist colleagues as well as those teaching mechanics, waves & optics and mathematical physics, the capabilities of this Fourier Methods package so that they too can see, and demonstrate for their students, how Fourier analysis works in action.

UltraSonics

TeachSpin's collaboration with the German company, GAMPT mbH (www.gampt.de), will add to TeachSpin's repertoire not only the elegant GAMPT ultrasonics apparatus, but also TeachSpin-developed curriculum and student manuals which focus on the physics of wave propagation, transferable experimental skills, self-discovery experiments, and student projects for independent study.

We suspect that when you first read 'ultrasonics', you immediately thought of medical applications: ultrasonic imaging of the fetus, of breast tumors, blood flow measurements from Doppler frequency shifts, and, perhaps, procedures for shattering kidney stones with focused high-power ultrasonic waves.

Yes, this equipment will certainly give your students the opportunity to study medical diagnostic and treatment techniques. But with the same hardware students can investigate, experimentally, an important field of physics, which has been neglected in most of our upper-division laboratory courses. Let's take a brief first look at a few of the many possibilities that TeachSpin will now be offering.

The parameters of interest in ultrasonic measurements are frequency, wavelength, propagation velocity, acoustic impedance, and absorption coefficient. The frequency is determined by the electronic oscillator which drives piezoelectric transducers that, in turn create an ultrasonic compression wave. But these transducers can also serve as ultrasonic receivers (or microphones), converting ultrasonic energy into electrical signals. GAMPT has carefully crafted various types of electronics and transducers, both pulsed and continuous-wave, which are customized for various ultrasonic experiments. All of these units will be available through TeachSpin. In this newsletter, we would like to introduce two of these units: 'Echoscope GAMPT-scan', a pulse unit, and 'Wave Generator SC 500', a variable-frequency continuous-wave system.

The 'echoscope', shown in Figure 6, may be the most versatile unit, especially with the 1, 2, and 4 MHz transducers that can serve as both transmitter and receiver.

Ultrasonic waves, like electromagnetic waves, exhibit reflections from material boundaries when there is a discontinuity of the acoustic impedance at the boundary. An example of this is shown in Figure 6, where we are injecting an ultrasonic compression wave into a stack consisting of an acrylic cylinder of height 41.3 mm on top of an aluminum block that is 24.2 mm high. The sound waves encounter two significant boundaries: first, at the acrylic-aluminum interface, and then at the aluminum-air end. The single transducer on top creates the short ultrasonic driving pulse, and also acts as the receiver to detect the time-delayed ultrasonic echoes. The first impedance discontinuity encountered by the acoustic wave (the acrylic-aluminum interface) causes a reflected compression wave which travels back to the transducer.

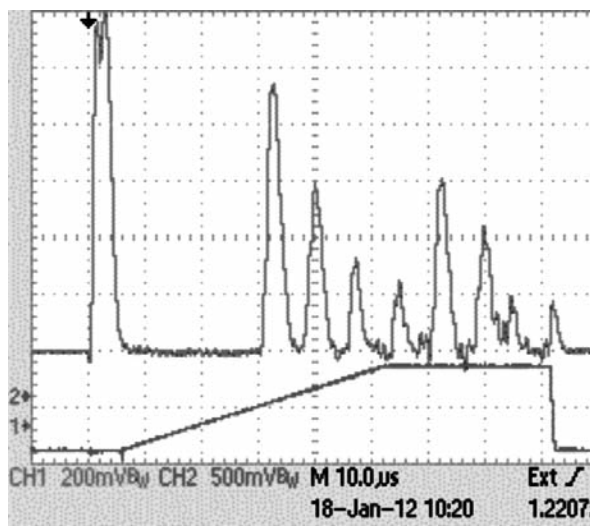

Fig. 7: Ultrasonic echoes on a 10 µs/div time base

The first 'echo', shown in Figure 7, is the signal from that reflection. The round-trip travel time is 30 µs, so the velocity of this 1 MHz wave is 2 x 41.3 mm/30 µs or or 2750 m/s. But at this same interface between the two materials, some of the wave is transmitted into the aluminum. Next, it reflects back from the aluminum-air interface and returns through both the aluminum and the acrylic. This echo travels an additional 48.4 mm. See if you can show, from the 'scope trace, that the velocity of the sound wave in this 6061 aluminum alloy is about 6000 m/s. Why are there additional echo signals? Can you account for them?

Figure 8 shows a water tank with a rectangular acrylic slab of 10 mm thickness obliquely immersed in it. In this experiment, two transducers are used, one to inject an ultrasonic compression pulse into the tank and a second one to receive the ultrasonic waves that propagate to the opposite side. The oscilloscope signals are shown in Figure 9.

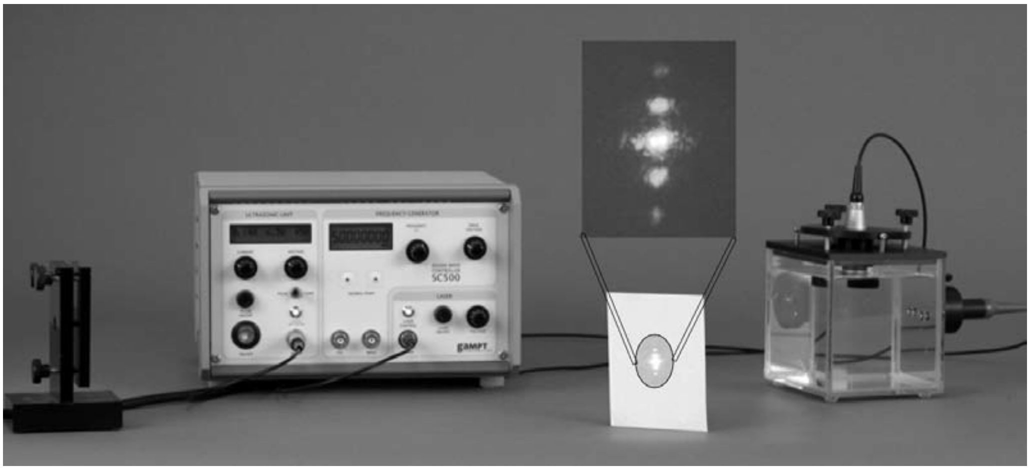

Fig. 10: Debye-Sears set-up.

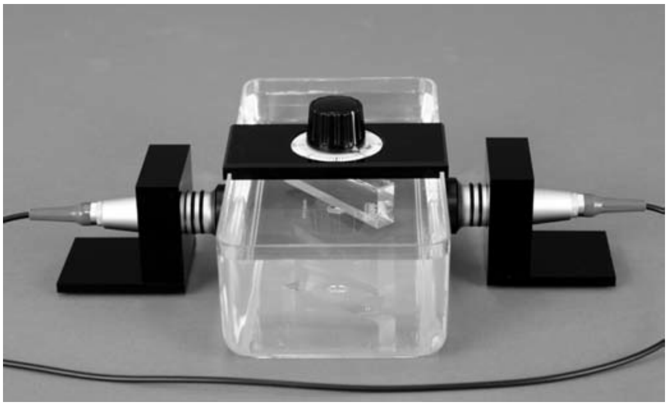

Fig. 8: Transmission Ultrasonics

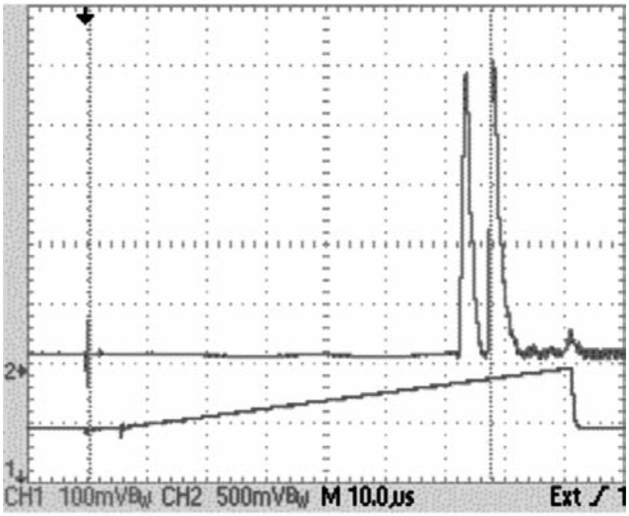

Fig. 9: Pulse transmission signals on a 10 µs/div time base

Notice that two pulses are picked up at the receiver. The reason for the two signals is the creation, at the first water-acrylic interface, of ***two kinds of waves*** in the acrylic slab: a longitudinal (compression) wave, and a transverse (shear) wave. In the solid medium, this shear wave propagates at a significantly lower velocity than the compression wave. However, a shear wave will not propagate in a liquid. Thus, the shear wave in the solid, encountering the interface at an oblique angle, launches only a compression wave in the liquid, which then travels to the receiver. This setup can be used to determine the velocity of both the compression and shear waves in the solid, and the critical angle for total internal reflection, as well as the velocity of sound and the attenuation coefficient for compression waves propagating in the liquid. In geophysics, compression and shear waves moving through the earth are called p-waves and s-waves.

Figure 10 shows the experimental set-up to explore the Debye-Sears effect, the diffraction of light from a 3-d acoustic grating created by an ultrasonic standing wave. The SC500 is a variable (1–20 MHz) high-power, continuous-wave, signal generator with a built-in power supply for operating a solid-state laser. The broadband ultrasonic transducer is mounted on the top of the water-filled cell, in a support structure which allows the student to optimize the standing wave in the water. The laser is mounted on the side of the cell so that its horizontal light beam will be diffracted by the acoustic standing wave. The sound pressure field generates periodic changes in the index of refraction which act as a ‘grating’.

The mirror on the left is used simply to extend the path length of the light beam, which is then projected on the flat screen. The insert in Figure 10 clearly shows the diffraction pattern of the green laser beam by a 5 MHz ultrasonic standing wave. This experiment not only demonstrates the fascinating and highly applicable acousto-optic effect, but can also can be used to measure the wavelength of sound in an optically transparent medium as a function of frequency.

These few examples were chosen, frankly, both to whet your appetite and to remind you of an area of physics you may not have considered for a long time, if ever! We could easily have devoted this entire newsletter to ultrasonics, but, as you can see, we are introducing two other exciting new products.

Before leaving ultrasonics, let us list just a few of the topics to which ultrasonic physics relates – geophysics, non-destructive testing, hidden defects in materials, non-invasive flow measurement, piezoelectricity, acousto-optics and consumer products such as ultrasonic cleaners, humidifiers, liquid level indicators, ultrasonic welding, distance measurement, and last, but certainly not least, medical physics applications. So many ways to broaden the range of your students’ experience!

Are you surprised by the scope of this subject? We were!

TWO-SLIT'S NEW PULSE COUNTER/INTERVAL TIMER

TeachSpin's 'Two-Slit Interference, One Photon at a Time' has become a classic demonstration of the 'essential quantum paradox' and an experiment in single-photon detection. Now, we've improved its electronics with a new Pulse Counter/Interval Timer unit which makes possible a whole new set of investigations in the ***statistics of random-event processes.***

Our new counter/interval timer unit will:

- discriminate pulse events from a noise background, for pulses of amplitude 10 mV to > 1 Volt;
- correctly count 'events per unit time', with 0.1, 1.0, or 10-second counting intervals;
- alternatively, measure the ***time interval between*** a pulse and its successor pulse, to 1-μs resolution;
- *and* write data files of unlimited length (via Hyper Terminal, in a host computer) of successive counts per unit time, or intervals between successive counts.

An electronic discriminator, designed to detect even low-level analog pulses standing up above a noise background, is built into the counter/timer unit. The discriminator's threshold level can be adjusted continuously and linearly over a range of about 10 mV to several Volts. A monitor output gives a view of exactly what input pulses are meeting the discriminator's threshold criterion. Figure 11 shows the discriminator in action.

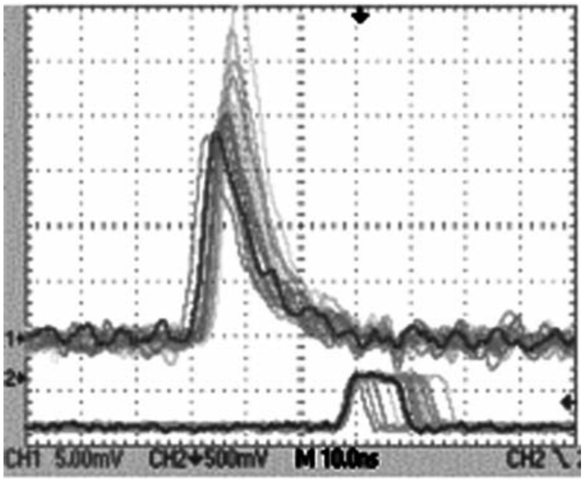

Fig. 11: Oscilloscope traces obtained at 10 ns/div Upper trace: analog input to the discriminator; Lower trace: pulses at monitor output of discriminator. The 'scope is set to trigger on the lower-trace events, so the upper trace displays all (but only) the pulses which have activated the discriminator.

The discriminator's output is a set of standardized pulses, each of which arises from a PMT pulse meeting an electronic criterion. But the time of occurrence of those events ought to obey the laws of a Poisson process – they are expected to occur uncorrelated with each other, and randomly in time, but still at some average rate. Most any counter will do for measuring ***just the average*** of the count rate in the study of single-photon events. However, for studying ***fluctuations*** in count rates, and therefore the ***statistical properties*** of random events, a long series of such counts is needed. For example, suppose we are counting the photons that arrive when the Two-Slit apparatus is set to monitor the intensity at the top of the 'central fringe' of an interference pattern. If we adjust the source intensity to give an average rate of about 1000 counts per second, what will we find if we do many repeated individual measurements? The answer is shown in Fig. 12, which is a scatter plot of the pulse counts for 1200 successive 1-second trials.

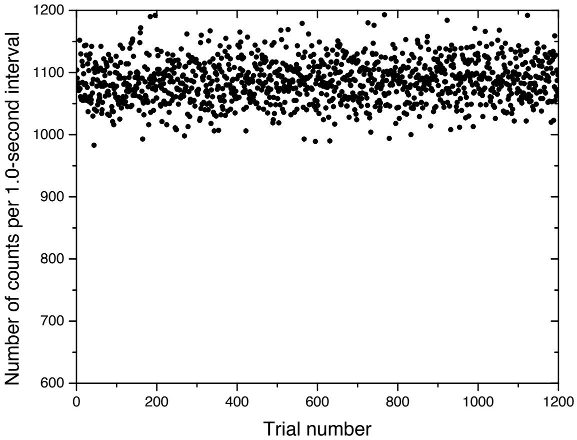

Fig. 12: Scatter plot of the number of photon events detected in 1-second gate times, plotted as a function of observation number, for 1200 successive observations.

The data display statistical fluctuations about the mean of 1086 counts/second and students can process the data files from our new counter to study these fluctuations. Questions they should explore include:

- What is the standard deviation of the count rate?
- How does that result depend on the (variable) average count rate?
- What does the chi-squared test have to say about the data in Fig. 12?
- What is the ***histogram*** of the data in Fig. 12? (See Fig. 13.) Is this distribution Gaussian, and does it have the width expected from Poisson statistics?

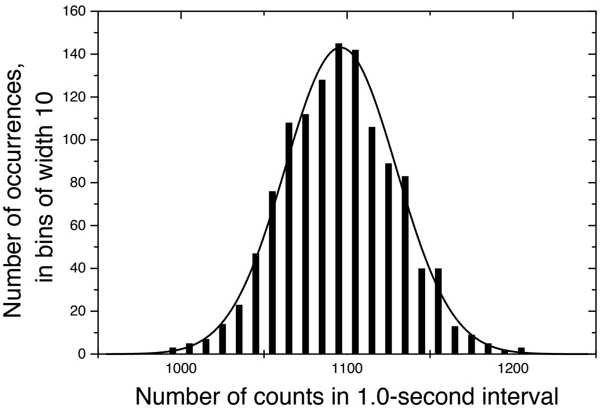

Fig. 13: Histogram of the data of Fig. 12, showing the Gaussian distribution expected from the central-limit theorem

Back to the plot in Fig. 12: it shows counts arriving at an average rate of about 10^3/s, which means that counts are arriving at *average* time interval of 10^{-3} s or 1 ms.

But, if that ***time interval*** between a pulse and its first successor is measured repeatedly, what individual values will

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Two New Collaborations with Many New 'Toys'

result? And what *distribution* of values will result from a repeated series of such measurements? Do you know what ***histogram*** those values will have?

Our new counter/timer can be configured to measure such a time interval, and to do so repeatedly, and to write the results to a file, easily giving a sample of (say) 5000 time-interval measurements. In such a sample, we found (for example) nearly 1000 occurrences of time intervals in the 1-200 μs range. The histogram of all 5000 measured intervals is shown in Fig. 14.

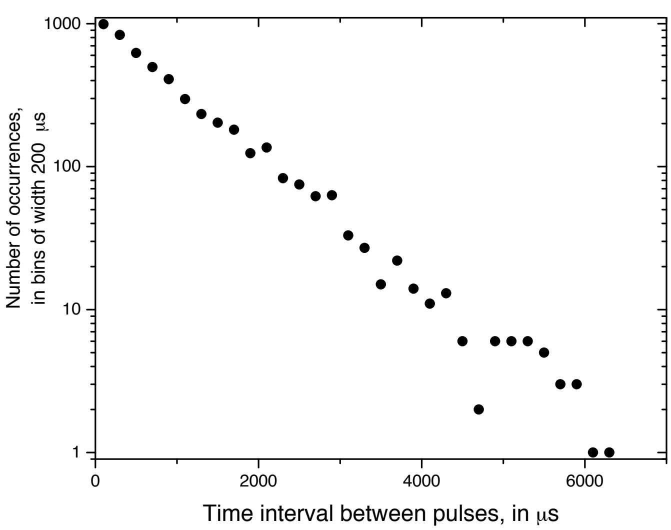

Fig. 14: Semi-log plot of the histogram showing the distribution of 5000 measurements of time intervals between a photon event and its first successor; horizontal axis in microseconds.

The histogram is ***not*** Gaussian, but ***exponential***, in character. The mean interval implied by this distribution is 0.910 ms, to be compared with the value 0.921 ms expected from the average count rate from Fig. 12. But the histogram does not have a peak at that value; in fact, ***the shortest time intervals are the most probable. Surprised?***

Note too, that the degree to which the distribution matches the expected exponential is a test of the random-event hypothesis: any correlation between photon-detection events, or any periodicity in their arrival, would show up directly in this plot.

There are many other sources of electronic events, some highly (but not perfectly) regular, others nearly (or wholly) random, and all of them susceptible to statistical study. You might think of a not-quite-perfect clock, or a Geiger counter, as sources of such events. The pre-requisite for such statistical studies is a large sample of data, and we've now made that as easy, and straight-forward, as possible to obtain. We've paid attention to transparency of operation of our new counter/timer, ensuring (for example) that data can be taken *by hand* for a first mode of understanding of what's going on. We feel sure that students would do best to take a first (small) data set manually, so that they understand the process of abstraction and aggregation that lies between a list of data and the histogram derived from it.

Returning to the Two-Slit experiment, we want students to be able to see that the photon events they're detecting, whether at an interference maximum or a minimum, still display all the statistical properties expected for events that are random and uncorrelated, but nevertheless occurring at a well-defined mean rate. And this invites an even deeper look into the essential quantum mystery.

Finally, we expect that this counter/timer will have uses far beyond the Two-Slit experiment. We invite you to come up with some of them.