Laser Focus World

# Digital lock-in amplifiers minimize noise and distortion

**A broader spectrum of electronic signals can be recovered from noisy backgrounds with modern lock-in amplifier technology.**

*By James L. Scott*

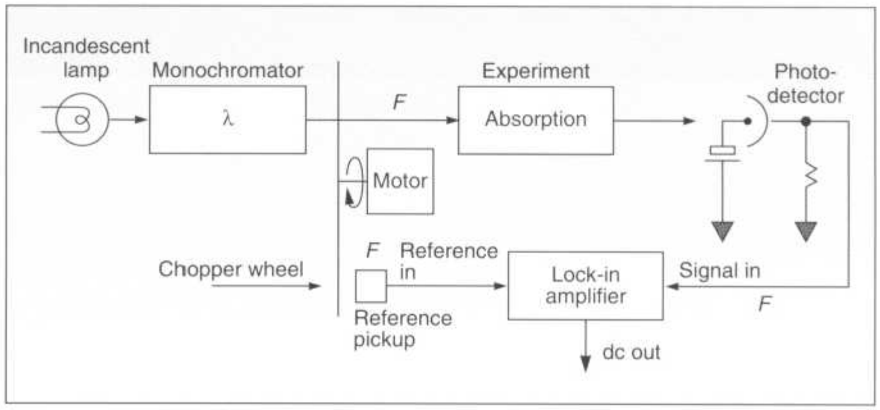


*FIGURE 1. Typical lock-in system has chopper that modulates signal at frequency F and lock-in that demodulates signal back to dc.*

The lock-in amplifier is a very sensitive, frequency-selective ac voltmeter. It receives a signal at a specific frequency *F*, which presumably is obscured by interference, along with a second synchronizing reference-frequency input that must be coherent with the signal frequency. The lock-in responds to the fundamental component at the frequency of interest, while discriminating against the other components present at the input: dc, discrete frequency interference (for example, integer multiples of 60 Hz), harmonics of the measurement frequency (2*F*, 3*F*, 4*F*, 5*F*, and so forth), and random noise.

From a systems point of view, the lock-in acts as the demodulator in a modulator/demodulator scheme (see Fig. 1). The rotating, slotted, optical-chopper wheel converts the steady light beam to a source pulsed at frequency *F*. The lock-in recovers the weak, noise-ridden signal from the photodetector, using a reference input derived from the chopper to synchronize the demodulation.

Lock-in amplifier technology has been mature for more than a decade, with evolutionary products appearing from time to time. Until recently, the main advance has been the introduction of digitally controlled analog instruments, which has put a number of reasonably high-performance instruments on the market, ranging from $3000 to $6000. These lock-ins (EG&G/Princeton Applied Research 5209 and 5210, ITHACO/NF 3961B and 3962A, and Stanford Research Systems SR 510 and 530) all feature on-board microprocessors with GPIB and RS-232 interfaces to host computers.

The notable exception to this evolutionary trend is the advent of commercial digital-signal-processing (DSP) based products this past year. The digital lock-in performs signal demodulation by purely digital means rather than by analog circuitry.

### What's a lock-in amplifier?

A classical analog lock-in amplifier works on the principle of signal mixing, wherein the input spectrum is multiplied by the reference frequency, resulting in a down-shifting of all input-frequency components by an amount, *F*. This is accomplished in a circuit referred to as a phase-sensitive detector (PSD). This process converts the measurement signal to exactly dc, while all other components emerge from the PSD as frequency-shifted ac waveforms. A simple resistor-capacitor low-pass filter with user-selectable time constant is used to remove the ac interference, while passing a dc level to the output that is proportional to the rms fundamental component at the ac signal frequency selected by the reference input. Thus, the lock-in amplifier converts dirty ac into relatively clean dc, which is then either presented directly on an analog meter, digital voltmeter, chart recorder, or oscilloscope, or is digitized for display, recording, or further signal processing.

A high-performance analog lock-in typically operates over the frequency range from 0.5 Hz to 200 kHz. Full-scale sensitivity generally ranges from 100 nV to 1 V. Practical overall system sensitivity down to 1 nV, or 10 fA full scale, is achievable, but only by insert-

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## Signal analyzers embrace optoelectronic technology

Signal analysis has always been the backbone of communications and data-acquisition technology. But as communications and data-acquisition technologies continue to push the limits of speed and purity, the demands on signal-analysis and processing techniques grow ever more stringent. The need for speed has even driven the technology beyond the realm of electronics and into the frontiers of optoelectronics. The contribution of fiberoptics to this evolution has been phenomonal.

This month's Technology Guide features three articles on both electronic and optoelectronic (OE) signal-analysis technology. James Scott of ITHACO Inc. (Ithaca, NY) presents an overview of recent developments in lock-in amplifier technology, comparing variations on lock-in design and performance (see this page).

Jim Stimple of Hewlett-Packard's Signal Analysis Division (Rohnert Park, CA) describes a novel double-pass monochromator for the new HP71450A and HP71451A optical spectrum analyzers. The compact, rugged optical design achieves the same dynamic range as a full-sized double monochromator (see p. 121).

A. M. Prokhorov, M. Ya. Schelev, and S. Nebeker, representing a joint venture between Cordin Co. (Salt Lake City, UT) and the General Physics Institute (Moscow, USSR) discuss their newly developed Proschen streak cameras. These are useful in applications requiring fast temporal resolution of signals (see p. 125).

The instruments available to designers for characterizing lightwave signals, components, and systems include optical time-domain reflectometers (OTDRs), reflectometers, optical signal analyzers, optical spectrum analyzers, interferometers, and high-speed (20-GHz) oscilloscopes. These instruments can help locate faults within fiber links, test the fidelity of modulated lightwave signals, or characterize the optical purity of diode lasers.

With an OE converter, which converts optical signals into electrical ones, many lightwave components can also be tested with conventional electronic signal-analysis equipment. However, the performance of electronic signal-analysis instruments based on conventional analog circuitry is limited because of the noise and distortion created by intrinsic nonlinearities in the electronic components. Digital circuitry and processing eliminates noise and distortion due to these nonlinearities.

Stanford Research Systems (Sunnyvale, CA), for example, recently introduced a lock-in amplifier (the SR850) in which the conventional demodulator, low-pass filter, and dc amplifier are replaced by a single digital-signal-processing (DSP) chip (see photo). The result is an unparalleled 0.001° phase distortion, more than 100 dB of dynamic reserve without front-end signal filtering, and zero output drift and gain error. The frequency range (bandwidth) of this instrument is 1 mHz to 100 kHz. Such performance is simply not possible with analog circuitry.

Another benefit of DSP is the purity with which waveforms can be analyzed. Fast Fourier-transform spectrum analyzers can digitally sample periodic waveforms and evaluate them in the frequency domain with a wide array of mathematical tests for such things as total harmonic distortion and power spectral density.

Using DSP, ideal waveforms can be generated as well, because the signals are literally calculated electronically. The sinusoidal internal reference signal of Stanford Research Systems' SR850 is synthesized in this way.

Finally, many of the same conveniences associated with computers, such as miniaturization, menu-driven display functions, disk-drive data storage, digital data interfaces, and printer ports, have also emerged in state-of-the-art signal-analysis instrumentation. There are even board-level signal-analysis instruments, such as ITHACO's Model 3981, that plug directly into the expansion slots of an IBM PC, transforming the PC into a low-cost signal analyzer. Indeed, the variety of electronic and OE signal-analysis equipment is almost as vast as the spectra of signals to be analyzed. □

*Thomas V. Higgins*

STANFORD RESEARCH SYSTEMS

*Digital-signal-processing lock-in amplifier is a complete data-acquisition system offering better performance than conventional analog lock-ins.*

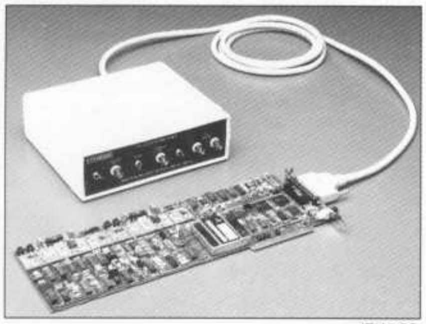
ing the appropriate low-noise current or voltage preamp ahead of the normal lock-in signal input. Under some circumstances, a lock-in amplifier can deliver a dynamic reserve (ratio of an interfering waveform to full-scale sensitivity) of 1 million:1 (120 dB).

Besides measuring ac voltage, the lock-in amplifier often is designed with the ability to measure current, spectral-noise density in the vicinity of the measurement frequency, harmonics (2*F*, 3*F*, and so forth), external dc inputs, and ratio. It may include analog output, digital I/O, and oscillator output functions.

### Alternatives to lock-ins

Several instruments provide measurements similar to those made by the lock-in amplifier—the narrowband filter, spectrum analyzer, and boxcar averager. Often one must decide whether a lock-in or one of these other instruments best suits a particular application.

***Narrowband filters.*** Before the advent of lock-in amplifiers, measurements of signal and noise were more commonly made using a bandpass filter followed by a true rms voltmeter. Measurements of this sort are still performed today in circumstances where operational simplicity, low cost, and absolute calibration are the predominant considerations. Filters have a number of disadvantages compared to lock-in amplifiers. Among these are limited selectivity to dis-



ITHACO

*FIGURE 2. Dual-phase plug-in lock-in amplifier for an AT-class computer transforms PC into a signal analyzer.*

criminate against interference near the signal in frequency, susceptibility to error from signal or filter frequency drift, inability to measure signal and noise simultaneously, and lack of phase measurement capability.

***Spectrum analyzers.*** The original spectrum-analyzer designs consisted of a narrowband filter, the center frequency of which could sweep over a range to produce a plot of amplitude versus frequency. The heights of peaks measured the amplitude of discrete frequency components present in the input spectrum. The curve of the baseline offset above zero yielded the spectral noise-density profile. Modern designs rely on the digitization of the input into a series of samples followed by fast Fourier-transform processing to accomplish the same result in a much more efficient manner. Both lock-in amplifiers and spectrum analyzers can make simultaneous signal and noise measurements. The lock-in is much faster and more accurate, as well as being much more selective when making single-frequency measurements.

***Boxcar averagers.*** The boxcar averager resembles a lock-in amplifier in that it accepts a dirty repetitive signal-input waveform and requires a clean coherent reference-frequency input to synchronize its operation. It differs in that the detection process involves sampling a particular portion of the waveform with a precisely timed narrow-aperture window. By accumulating a large enough number of such samples and averaging the sum, one can impose the desired degree of signal smoothing. One can obtain a waveshape by sampling with varying time delays. The boxcar excels at tasks such as measuring the peak height for low-duty-cycle pulse trains and determining decay-time constants.

## Board-level lock-ins

Several new circuit-board lock-in products have come to market in the past few years. These lock-ins supply surprisingly high performance at typically less than $2000. The Model 3981 dual-phase PC plug-in lock-in amplifier from ITHACO (Ithaca, NY) embodies the PC instrument concept, with up to four independent Model 3981 lock-ins operable within a single AT-class computer (see Fig. 2). The driver software interfaces to any MS-DOS language for OEM, test, and repetitive-analysis systems. Optionally, an operator can use a virtual panel user program to control the lock-in in a manner similar to a bench-top unit.

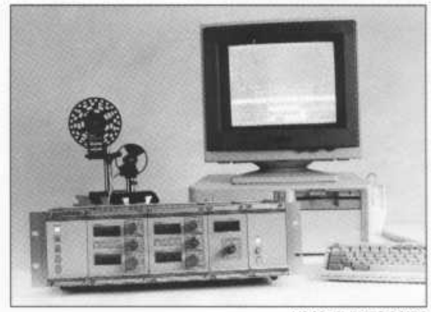
The Model 3981 delivers respectable performance with regard to dynamic reserve (50 dB), sensitivity (10 μV or 100 pA), frequency range (5 Hz–20 kHz), and self noise (25 $nV/Hz^{1/2}$), along with high precision and accuracy from self-calibration features.

The other new board-level lock-in, Model 410 two-phase single-board lock-in amplifier from HMS Elektronik (Leverkusen, FRG), is designed as a fixed-parameter function block for installation in OEM equipment. The design concept yields performance comparable to research-grade instruments with regard to gain and offset stability, sensitivity (1 μV or 1 pA full scale), frequency (1 Hz to 100 kHz), and dynamic reserve (100 dB).

Jupiter Microsystems (Livingston, UK) manufactures a series of board-level lock-in amplifiers that either stand alone or are programmable via an RS-232 interface. Available features include 12-bit A/D conversion of lock-in outputs or multiplexed external analog inputs, operation of lock-in with signal isolation to withstand common mode voltages up to several hundred volts and low distortion, quadrature, and internal oscillators. Frequency of operation ranges from 10 Hz to 100 kHz. The dynamic reserve is greater than 50 dB.

## Modular lock-in amplifiers

HMS Elektronik manufactures the Dynatrac 500 Series lock-in amplifier, which features a selection of plug-together modules (see Fig. 3). These include several lock-ins to cover various frequency ranges, a GPIB interface, and a chopper controller. The company has available various configurations, for example a dual lock-in, dual-beam arrangement that includes software and control outputs to operate system optical components such as the light source and monochromator.



HMS ELEKTRONIK

*FIGURE 3. Dynatrac 500 lock-in amplifier features a selection of plug-together modules, including several lock-ins to cover various frequency ranges, a GPIB interface, and a chopper controller.*

## Multimegahertz lock-ins

Conventional lock-in technology historically has been limited to frequencies less than 200 kHz. To get to higher measurement frequencies, a mixing technique must be used to shift both the signal and the reference frequency down to a range that could be handled by an ordinary lock-in PSD demodulator. Two new mix-down-type multimegahertz instruments have become available recently.

The Model PAR 100 lock-in extender/enhancer from Palo Alto Research (Palo Alto, CA) operates up to 12.5 MHz (25-MHz option available) using its internal oscillator and operates up to 50 MHz with an externally supplied reference input (see Fig. 4). The PAR Model 100 boasts a large number of operating modes to cover the full spectrum of measurements that a sophisticated user might want to make. It works either as a down-shifting front end to a separate, conventional lock-in, or as a complete, self-contained lock-in amplifier.

The HMS Model 531 10-MHz down converter, in contrast, is extremely simple. It accepts high-frequency sig-

PALO ALTO RESEARCH

*FIGURE 4. Lock-in extender/enhancer operates up to 12.5 MHz and works either as a down-shifting front end to a separate, conventional lock-in, or as a complete, self-contained lock-in amplifier.*

nal and reference inputs and shifts them down to 20 kHz. Three toggle switches select for single-ended or transformer input, 0- or 40-dB gain, and *F*, *2F*, or *3F* detection. The Model 531 can be used in conjunction with any conventional lock-in amplifier or packaged with other HMS 500 Series components to make up a complete high-frequency lock-in amplifier.

### Digital lock-in amplifiers

Stanford Research Systems (Sunnyvale, CA) elects to term its newly introduced digital lock-in amplifier a DSP lock-in to avoid confusion with earlier microprocessor-controlled analog instruments. Nonetheless, there exists a 20-year history of one-of-a-kind lock-ins employing software multiplication to achieve phase-sensitive detection that are referred to in the literature as "digital lock-ins."

EG&G/PRINCETON APPLIED RESEARCH

*FIGURE 5. Lock-in amplifier covering 1 mHz to 1 MHz has a flat-panel display with multiple layers of selectable screens to provide control of data readout, acquisition, and manipulation. In analog mode, the 5302 uses conventional PSD demodulation circuitry; when operating in its low-frequency mode, it switches over to digital signal processing.*

The DSP replaces the PSD demodulator, low-pass filters, and dc amplifier circuits found in analog designs. This brings about an unprecedented improvement in specifications, including 0.001° phase resolution, zero output drift, greater than 100-dB dynamic reserve without input-signal conditioning filters, 96-dB harmonic rejection, ultralow output noise, and a frequency range extending from 100 kHz down to 1 mHz. The SR850 sports a highly readable CRT with virtual panel, strip chart, bar graph, and polar plot displays (see "Signal analyzers embrace optoelectronic technology," p. 2).

According to EG&G/Princeton Applied Research (Princeton, NJ), its top-of-the-line Model 5302 lock-in amplifier represents the latest advances in conventional microprocessor-controlled analog lock-in design wedded to digital lock-in operation in the low-to-ultralow frequency realm (see Fig. 5). This allows it to cover the widest spectrum of any instrument—0.001 Hz to 1 MHz. A large flat-panel display with multiple layers of selectable screens provides control of data readout, acquisition, and manipulation. When operating in analog mode, which spans from 2 Hz to 1 MHz, the 5302 employs conventional PSD demodulation circuitry. When operating in its low-frequency mode covering 20 Hz down to 0.001 Hz, the 5302 switches over to DSP signal processing. It then functions in a manner similar to that described for the Stanford SR850, with demodulation being accomplished in software by synchronous multiplication of the input by a sine function. □

***Before the advent of lock-in amplifiers, measurements of signal and noise were more commonly made using a bandpass filter followed by a true rms voltmeter.***