PerkinElmer™
instruments.

Low Level Optical Detection using Lock-in Amplifier Techniques

APPLICATION NOTE

AN 1003

Introduction

This note describes a number of techniques that can be used to detect low level optical signals. It starts by considering the problems inherent in the use of DC techniques and how these may be reduced by using AC methods instead. It then discusses a range of different experimental approaches using lock-in amplifiers, pointing out the advantages as well as any disadvantages of each method. Finally, it outlines the important specifications of the mechanical light choppers that are often used as part of such systems.

The note is written primarily for scientists, students and laboratory personnel who have little or no experience with low level light measurements. It is assumed however that readers have some basic knowledge of lock-in amplifiers, but if this is not the case then they may refer to the PerkinElmer Instruments (Signal Recovery) Technical Notes TN1000 "What is a lock-in amplifier?" and TN1001 "Specifying Lock-in amplifiers". Further references given at the end of this note.

The DC Approach

In the simplest form of light measurement, a suitable current meter measures the DC current generated in an optical detector as a result of the incidence of a steady state light source. Such a detection system has its use in applications such as camera light meters, sensors for switching on or off outdoor lighting fixtures or other applications where high levels of light are detected or measured. At much lower light levels, errors will begin to appear as the measurement becomes more susceptible to random events and noise from various sources.

Figure 1 illustrates a DC technique for measuring low light levels in a typical experiment. The output from the detector is taken to a current to voltage converter, implemented using a low-drift operational amplifier. The voltage output from the amplifier is then measured using a conventional voltmeter (not shown). An offset control is used to compensate for the detector's DC leakage current.

This approach has some merit in that it can be used in situations where the "photodiode and current meter"

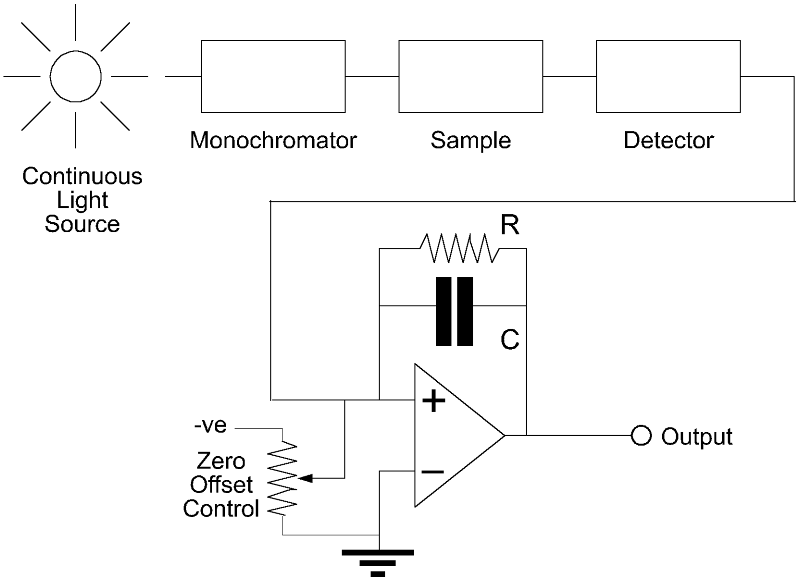


Figure 1, DC Measurement System for Low Light Levels

approach doesn't provide adequate results. Although low-cost and simple, it has a number of disadvantages which limit its usefulness. If the offset control is not adjusted correctly, then the DC signal from the detector due to leakage current will give a non-zero output even with no optical input. Another problem is that there is no way of separating the output signal caused by the wanted input signal from that due to stray light entering the detector. Discerning the signal of interest from these sources of error can be a real challenge. Even when the offset control is correctly adjusted, subsequent readings will still be subject to drift as temperature changes affect the leakage current.

The Modulated Light Approach

The most widely used method of measuring a low level optical signal is to apply a modulation to the light source and then recover the signal at the modulation frequency. The modulation can be of any periodic form, but sinusoidal and square waves are most commonly used. It is generated either by direct application of the output of signal generator to a light source, such as a laser diode, or by using some form of light chopper to periodically interrupt a continuous light source. In either case, an AC signal is generated at the detector output which allows the experimenter to use any one of a variety of AC measurement techniques and, as a result, greatly reduces some of the problems which plague the DC method.

In figure 2, the optical signal generated by a laser is modulated at the frequency output by the signal generator. The output of the detector is therefore now the unwanted DC signal caused by the thermal leakage and an AC signal at the same frequency as the modulation. The signal then passes to a tuned amplifier, which consists of a signal filter and amplifier stage. The filter is set to a bandpass mode, which limits the bandwidth of the measuring system to those frequencies close to the modulation frequency, and its output is then measured using an AC voltmeter.

Although still relatively inexpensive, the lower limit of light detection using this method represents a significant improvement when compared to the DC system. With careful choice of modulation frequency, the lower detection limit may increase by more than an order of magnitude over the DC method. The second advantage is that some stray light can fall on the detector and not influence the voltmeter reading. Still, there are some shortcomings in this method. The minimum signal that can be detected is primarily determined by the selectivity of the detection system, which in this case is set by the Q-factor of the filter. For example, with a band pass filter of Q equal to ten and a modulation frequency of 1 kHz, the signal bandwidth would be 100 Hz. Thus, noise components 50 Hz on both sides of the center frequency of 1 kHz could still make a relatively large contribution to the output. If these same noise voltages were large enough, an error in the measurement would occur since the AC voltmeter would measure not only the 1 kHz modulation signal, but the noise as well. One possible solution is to further limit the bandwidth by increasing the Q of the filter. However, there is a practical limit to the ultimate selectivity of a tuned amplifier. At Q's of 100 for example, it becomes difficult to implement analog filters of sufficient frequency stability, possibly resulting in the pass band of the tuned amplifier shifting away from the wanted frequency. Once this happens, the output signal-to-noise ratio will degrade, requiring the experimenter to retune the filter frequency.

Another problem is that tuned amplifiers are not the best instruments to use in the "front end" of an experiment. Many filters are not optimized for the best noise performance and a low noise preamp ahead of a tuned amplifier is almost always recommended.

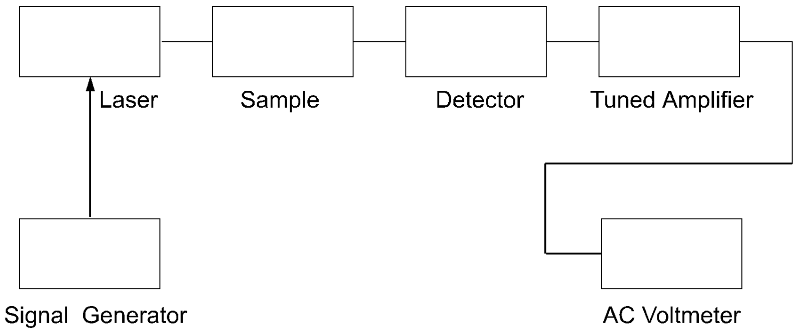


Figure 2, AC Measurement System using Tuned Amplifier

However, for applications not requiring the ultimate in signal recovery performance, the AC filter method may still be preferred over more sophisticated techniques. PerkinElmer Instruments (Signal Recovery) make the model 7310 noise-rejecting voltmeter which is an instrument ideally suited to such use, consisting of a tunable band-pass filter followed by precision AC voltmeter all in one box. Since the filter is implemented using digital circuitry, it does not suffer from the frequency drift problems of analog designs, whilst the front-end amplifier stage is of the same high quality as used in PerkinElmer lock-in amplifiers.

The Lock-In Amplifier Method

A much better approach to the AC detection method is to use a lock-in amplifier to measure the AC signal from the detector. Like the tuned amplifier approach previously outlined, the lock-in amplifier uses a frequency-selective technique. However, when using a lock-in, a much smaller bandwidth can be easily achieved without the inherent frequency-drift problems associated with the tuned amplifier. One can think of a lock-in amplifier as a specialized AC voltmeter, which measures only the amplitude of signals at a frequency equal to the applied reference frequency.[1]

Once set up in the experiment, the lock-in amplifier will display the measured input on a panel meter or make it available over a computer interface. Furthermore, it will provide a DC output voltage which is proportional to the AC voltage appearing at its input, which can be used for such purposes as driving a strip chart recorder or serve as the input to another instrument.

Figure 3 illustrates a basic optical detection setup using a mechanical light chopper and a lock-in amplifier. The light chopper consists of a motor, speed control mechanism, and a rotating blade or chopper wheel. In some cases, all three of these components are in one assembly. In other choppers, the control unit may be in a separate housing. The chopper wheel is a rotating metal disk which contains one or more sets of equally spaced apertures which allow the light source to pass through or be blocked altogether. The number of apertures and the wheel rotation speed determine the chopping frequency. Since the rotation of the blade causes the optical signal path to be interrupted, the light source that stimulates the experiment is in the form of an AC excitation. One could visualize this excitation as an optical equivalent of a square wave, although this is only true if the aperture size is large compared to the beam diameter. The signal appearing at the detector output may or may not be a good representation of the optical stimulation since factors such as detector response time and cable capacitance must be considered.

In addition to modulating the light source, the chopper also provides a synchronous reference signal capable of driving the reference channel of a lock-in amplifier. This reference output voltage is a square wave, usually in the order of a few volts peak to peak.

The optical signal stimulating the experiment and thus falling on the optical detector generates an electrical current which can be measured by the lock-in. Any

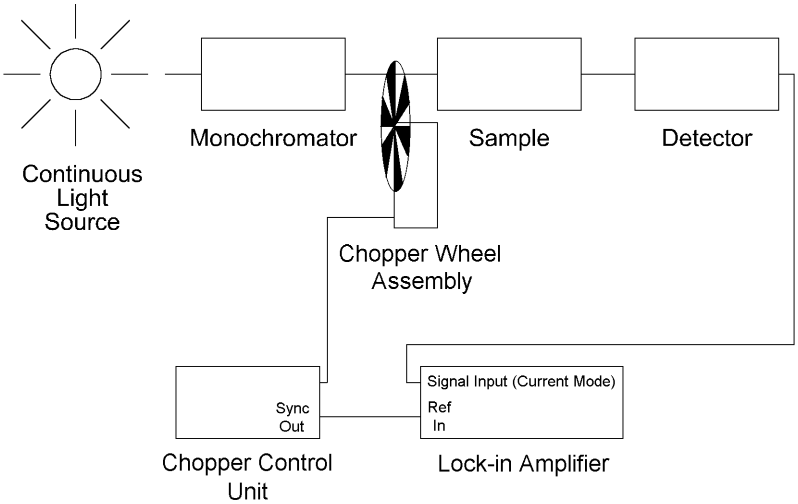


Figure 3, AC Measurement System using a Lock-in Amplifier and Mechanical Chopper

---

[1] The lock-in amplifier will respond to spectral noise voltages very close to the reference frequency as well. Such noise voltages at the input will appear as random fluctuations on the lock-in's output.

discrete frequencies or noise voltages not equal to the reference frequency will be rejected by the lock-in amplifier. The end result is a much lower limit on signals which can be measured. In fact, it's possible that the signal of interest may be completely obscured by noise if one were to view the detector output with an oscilloscope. Again, stray light falling on the detector is usually not a problem as long the magnitude is insufficient to saturate the detector. However, the user still needs to insure that stray light does not enter into the experiment via the chopped light path.

Source Compensation - Ratiometric Spectroscopy

Although the use of a lock-in amplifier dramatically enhances the ability to measure a signal buried in noise, there can be sources of measurement errors other than noise and background voltages. In optical measurements, an often troublesome source of error can be attributed to variations in light source intensity, since the output of many light sources vary over time. Moreover, the efficiency of a scanning monochromator may vary as a function of wavelength. If, in the previous example, the output of the lock-in were to change, the experimenter would not be able to discern between changes in the optical properties of the sample or source variations. This is a common problem that can only be addressed by introducing a second detection path which measures the optical output of the excitation source and by using a ratiometric technique to normalize for source fluctuations.

In figure 4, the optical output from the monochromator is split off and sent to a separate detector and preamplifier (not shown). This generates a DC voltage, the magnitude of which is determined by the intensity of the source as well as the relative efficiency of the monochromator. This optical path is usually referred to as the "normalizing signal" or "optical normalizing path".

It was mentioned earlier that the lock-in generates a DC voltage at its output as part of the detection process. In this configuration, a second DC voltage is now available which represents only the optical signal from the monochromator. By calculating the ratio of the DC output of the lock-in amplifier to the DC voltage generated as a result of the normalizing beam, a third DC voltage is generated which is proportional to only those changes due to properties in the sample path. The block labeled "Ratiometer" may be an analog circuit, or more likely a digital system that calculates the ratio of the two DC voltages and provides an output in some digital form. The neutral density filter is used to adjust the level of the normalizing beam for the appropriate nominal input voltage to the "B" input of the ratiometer. When using most lock-in amplifiers manufactured since the late 1980s, a separate ratiometer is usually not necessary. Such instruments have built-in auxiliary analog to digital converters (ADCs) whose inputs are accessible on the rear panel of the instrument. For example, one could apply a DC voltage from the preamp output to one of the rear panel ADCs (typically **ADC1**), then invoke the lock-in amplifier's ratio mode. The lock-in front panel will then display the ratio of the measured "X" value to the DC level applied to the rear panel ADC1 input.

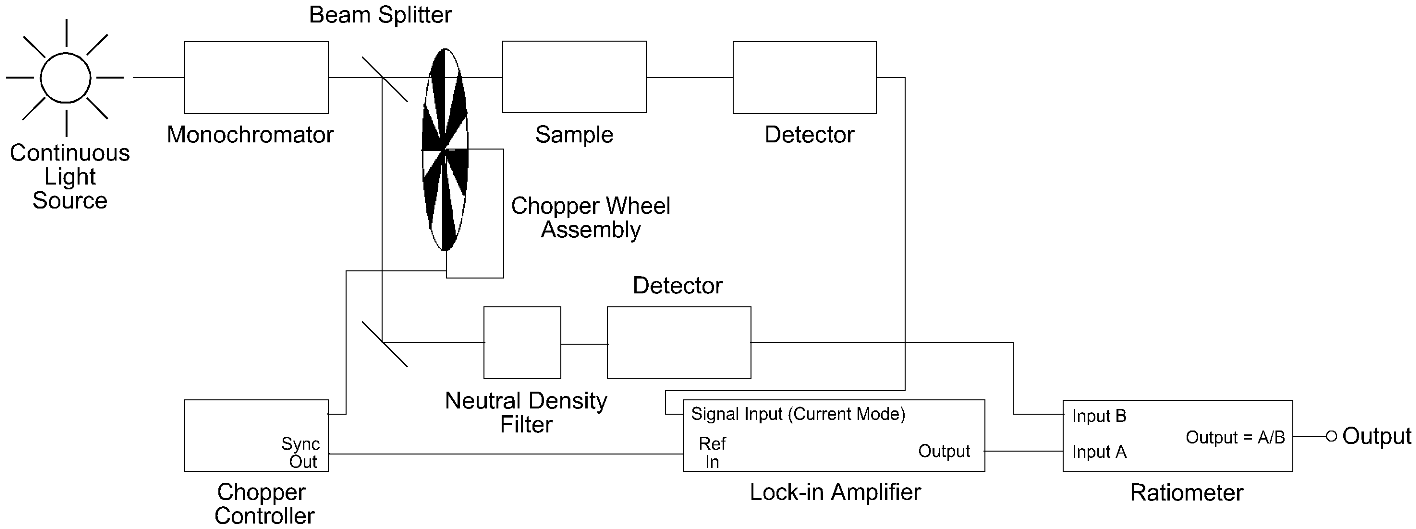


Figure 4, AC Measurement System using a Lock-in Amplifier, Mechanical Chopper and DC Source Compensation

Again referring to figure 4, note that it is essential not to allow stray light to fall on the detector in the normalizing path. Also, there may still be a source of error due to any mismatch in the performance of the two photodetectors.

Source Compensation Using Two Lock-Ins

An improved version of the ratiometer approach is shown in figure 5. Basically, the difference is that both the normalizing and signal beams are chopped, and the two beams are recombined into a single detector. This eliminates any error due to mismatching of optical detectors. Although one could use two separate light choppers, a more practical and economical approach is to use a dual beam chopper such as the PerkinElmer Instruments Model 651-1 which has the capability of chopping two light beams simultaneously. Since the Model 651-1 uses a dual aperture blade, two reference signals are available; one for the outer set of apertures, the other for the inner set of apertures.

As shown in Figure 5, a second lock-in amplifier, #2, is used to detect the normalizing beam. The second lock-in's output is used for the denominator of the ratio calculation. Since the magnitude of the signal in the normalizing beam is usually quite large, a low cost instrument will almost always suffice for this path. The output of the lock-in used in the normalizing path is fed into the rear panel A-D converter 1 of the signal path lock-in, #1, which is configured for the ratio mode.

Another approach, which is perfectly acceptable, is to take output readings from both lock-ins into a computer, and have it perform the ratio calculation.

This system generally provides the best solution to a low level optical experiment.

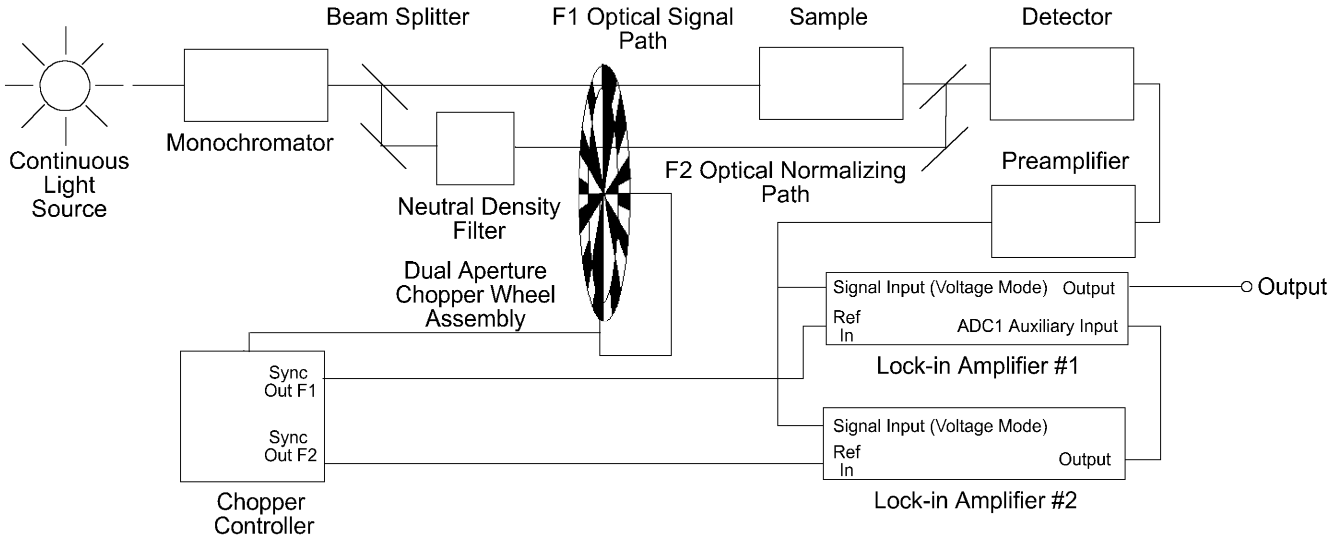


Figure 5, AC Measurement System using two Lock-in Amplifiers, Dual-Beam Mechanical Chopper and AC Source Compensation

Dual Reference Lock-In Amplifiers

Since cost is always a consideration when setting up a new experiment, one should consider the purchase of a lock-in amplifier which has a dual reference capability. Such a lock-in can detect two signals simultaneously, and as a result, only one lock-in is needed for a ratiometric experiment. The PerkinElmer Instruments Models 7260, 7265, and 7280 all have dual reference capabilities.

Figure 6 illustrates how the single PerkinElmer Instruments Model 7265 can be used in a ratio experiment. As in the case of the two lock-in approach, the output from the monochromator is split off and the Model 651-1 Optical Chopper is used to chop the light source at the two chopping frequencies. The chopping frequency, F, is controlled by the Model 7265s internal oscillator, which means that the outer set of apertures is synchronized with the internal oscillator of the Model 7265. The chopper also generates a reference signal, this time at F/10, synchronous with the inner set of apertures. This signal is fed back to the reference input connector of the Model 7265. The Model 7265 now has the two required reference signals, one at frequency F corresponding to the signal channel path and one at F/10 relating to the optical normalizing path.

The Model 7265 can now measure and display the amplitude of both signals appearing at its input connector. In the dual reference mode, two complete sets of output signals are available; X_1, Y_1, X_2, Y_2, MAG_1, MAG_2, etc. Any of these outputs may be displayed on the front panel. In a ratio experiment, the user may prefer to perform the ratio function using the 7265's firmware simply by taking advantage of its "user equations" menu. Once the user equation is setup, the result of the ratio calculation can be displayed on the front panel, accessed by a host computer, or the user can specify that a DC voltage proportional to the ratio be available on a rear panel BNC connector.

It is important to note that when using the dual reference mode, there may be other features of the lock-in used which may not be available. For example, in the Model 7265, the dual reference capability is limited to frequencies below 20 kHz. Moreover, one of the reference frequencies must be derived from the internal oscillator of the 7265 (a requirement satisfied by a chopper which can be externally synchronized). Also when using the dual reference mode, output time constants less than 5 ms are not available. These restrictions usually have little or no impact on a chopped light experiment, but the user should still be aware of any performance differences when operating in dual reference mode.

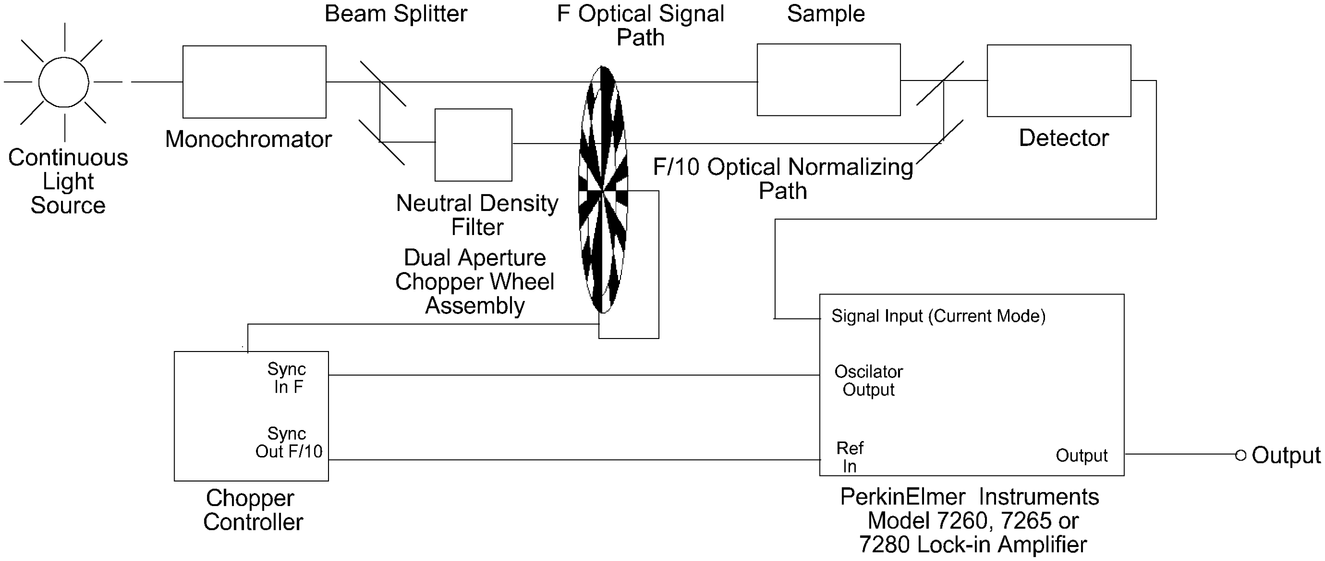


Figure 6, AC Measurement System using Dual-Reference Lock-in Amplifier, Dual-Beam Mechanical Chopper and AC Source Compensation

Mechanical Light Choppers

The experimenter is often faced with the task of determining which light chopper is best suited for a particular experiment. Part of the problem in selecting a chopper is interpreting what each specification means and how it will impact a particular experiment. In this section, some of the more pertinent specifications will be explained and defined.

Frequency Range

The chopping frequency is variable to allow the user the ability to both select a frequency which is optimum for the detector as well as avoid troublesome frequencies.

It's usually a good idea to chop at frequencies above the 1/f noise level (typically 100 Hz) unless there is a more important criterion calling for a lower chopping frequency. In addition, a chopping frequency near the power line frequency or any harmonic of it should be avoided. The PerkinElmer Instruments Models 7265 and 7280 both have a built in FFT display which can aid in selecting a chopping frequency. For choppers using a dual aperture blade, two sets of frequency ranges may be specified since at any given wheel rotation speed, one has the ability to chop at two different frequencies.

External Frequency Control

In addition to a frequency control on the chopper itself, the frequency of most choppers can be controlled externally. In some choppers this is done by the application of a DC voltage. Other choppers, including all the PerkinElmer Instruments models, are controlled by applying an external reference frequency signal. If the dual reference capability of PerkinElmer Instruments lock-ins is to be taken advantage of, it is essential that a chopper of the latter type be used.

Most modern lock-in amplifiers incorporate an internal oscillator, the output of which can be connected to the chopper's reference frequency input. If this is done, then changing the oscillator frequency also changes the frequency of the modulation generated by the chopper. If the lock-in is operated under computer control then the oscillator frequency can be set by the program, allowing for example, with suitable software, automatic selection of an operating frequency where any interfering signals are smallest. Another use of this technique is to prolong the chopper's motor life by reducing its speed whenever measurements are not being taken.

Jitter

Jitter is the short term variation in the period of one chopper cycle to the next. Its effect is to add noise to a measurement. The source of jitter is twofold; one is the mechanical imperfections in the chopper blade, the other is from the speed control electronics and motor combination.

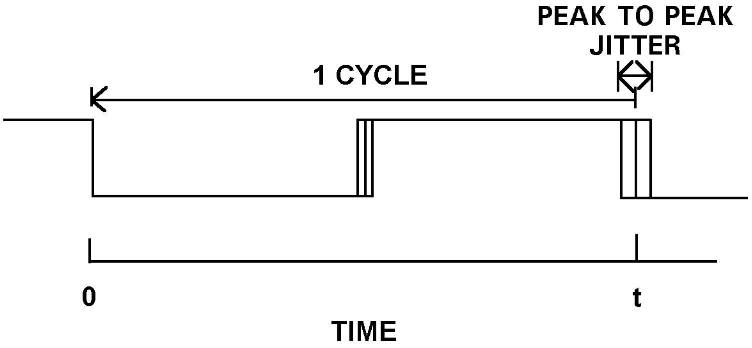
Figure 7 illustrates graphically how jitter manifests itself. Jitter can be expressed in either degree rms values or peak-to-peak units as a percent.

A difficulty may arise when comparing two chopper jitter specifications where the two different values are specified. For example, one chopper might be specified to exhibit 0.5 % peak-to-peak jitter. This is to be compared to another manufacturer who might publish a jitter specification of 0.5 degree rms under similar operating conditions.

Naturally, a comparison must be made in the same mathematical units. The first step is to convert the peak-to-peak percent specification to degree rms units. The 0.5% peak-to-peak specification refers to the percentage of a complete wheel rotation or 360 degrees. In this case, the peak-to-peak jitter is (.005 X 360) or 1.8 degrees. The calculated 1.8 degrees is still in peak-to-peak units, so it is necessary to convert to rms values. Peak-to-peak values are 2.8 times larger than rms values. In this case, it is necessary to divide the calculated 1.8 degrees by 2.8 in order to arrive at a rms value. In this case, a conversion to rms will yield 1.8/2.8 = 0.64 degrees rms. In this case, the two choppers have a very similar jitter specification.

Although jitter specifications are almost always specified by chopper manufacturers, the effect of blade jitter is usually too small to have any significant impact except in those cases where extremely small signals are to be measured.

Other factors to consider when choosing a chopper are mechanical configuration, beam size to be chopped, and how one wishes to externally control the speed.



Further Information

This application note is an introduction to the techniques used in low level light measurements. Additional information may be found in other PerkinElmer Instruments (Signal Recovery) publications, which may be obtained from your local PerkinElmer Instruments (Signal Recovery) office or representative, or by download from our website at **www.signalrecovery.com**

TN 1000 What is a Lock-in Amplifier?
TN 1001 Specifying a Lock-in Amplifier
TN 1002 The Analog Lock-in Amplifier
TN 1003 The Digital Lock-in Amplifier
TN 1004 How to Use Noise Figure Contours

AN 1000 Dual-Channel Absorption Measurement with Source Intensity Compensation
AN 1001 Input Offset Reduction using the Model 7260/7220 Synchronous Oscillator/Demodulator Monitor Output
AN 1002 Using the Model 7220 and 7265 Lock-in Amplifiers with software written for the SR830
AN 1004 Multiplexed Measurements using the 7220, 7265 and 7280 Lock-in Amplifiers

Staff at these offices will be happy to answer any questions you may have.

PerkinElmer™
instruments.

SIGNAL RECOVERY

801 SOUTH ILLINOIS AVENUE
OAK RIDGE
TN 37831-2011
USA
Phone: +1 423 483 2121
Fax: +1 423 483-0396

SORBUS HOUSE
MULBERRY BUSINESS PARK
WOKINGHAM, BERKS RG41 2GY
UNITED KINGDOM
Phone: +44 (0)118 977 3003
Fax: +44 (0)118 977 3493

E-mail: info_sigrecovery@perkinelmer.com **Web Site: www.signalrecovery.com**