Vehicle Diagnostics with Oscilloscope

What is the oscilloscope?

Unlike the voltmeter, with an oscilloscope you can not only see the mean values of the voltage in the circuits measured, but also the change and shape of that voltage through time.

All oscilloscopes have screens on which the waveform is shown. The screen can be a cathode-ray tube type, a liquid crystal display (LCD) or in the form of a computer program. The typical oscilloscope screen is divided into equal spaces (divisions) which allow to visually interpreting the parameters of the signal.

The graphics shown on the monitor are called waveforms. Usually oscilloscopes show only waveforms of the voltage. This form of visualization shows the change of voltage through time.

The divisions marked on the horizontal(x) axis allow for the time parameters to be measured, and the vertical(y) axis allow for the voltage values to be measured.

What purposes have oscilloscopes in auto diagnostics?

The oscilloscope helps us find the problem quicker and easier. Often the problem hasn't recorded an error code (DTC) in the corresponding ECU, a DTC that can be read with a code reader. Usually a DTC is recorded when there is a broken cable or a cable has short circuited to a positive or negative supply. But when a detector or a mechanism has stopped working in some mid position, there is no error recorded. In this case, as when you need to find the reason that caused an error to be recorded – the automobile oscilloscope is your most needed instrument.

With the increase of sensors, actuators and wiring diagrams built in the modern automobiles, the automobile oscilloscope is an instrument which diagnoses irregularities in the automobile faster and easier. The oscilloscope is a irreplaceable tool, when you have to observe output signals from inductive sensors, whose output signals form a impulse sequence, slow-changing analog signals, primary and secondary ignition circuits, intake manifold absolute pressure, starter current waveforms, charging currents and etc.

What types of oscilloscopes are there?

Analog oscilloscope

The ones with a cathode-ray tube screens. They show detailed graphics, and can usually show high frequencies, but are not suited for observing short processes repeated through a long time interval or relatively slow processes like the ones in an automobile.

Digital storage oscilloscope

The observed result from the digital storage oscilloscope is almost identical to the analog, but the signal shown on the DSO can be “frozen still” on the screen, saved on the PC’s hard drive, and used later, or printed. Further more only the current “screen” shown on the monitor can be saved, and a sequence of many screens can later be opened and observed through time as an animation. Any screen saved in the working fail can be printed.

There are two kinds of digital oscilloscopes: independent which are external device, and PC oscilloscopes. The PC-based oscilloscopes are a new type of "oscilloscope" that consists of a specialized signal acquisition board, which can be an external USB or Parallel port device, or an internal add-on PCI or ISA card.

One, dual and multiple-trace oscilloscopes

Depending on the number of measuring inputs, both analog and digital oscilloscopes can be divided into 3 types: one-trace, dual-trace and multiple-trace oscilloscopes.

Universal and specialized oscilloscopes

Depending on their purpose oscilloscopes are divided into 2 groups – universal and specialized. In automobile repair, an ignition analyzer is used to show the spark waveforms for each cylinder. In this way the specialized automobile oscilloscopes are also used for testing injectors, ABS, O2 sensor, quick compression tests, fuel pump, CAN Bus and much more. The Motortester is a specialized automobile oscilloscope.

What’s the universal oscilloscope?

The universal oscilloscope is an electronic measuring device used only for observing electrical voltage through time. The screen of the oscilloscope shows the changes in one or more input signals over time in an X-Y display, allowing for the amplitude and shape of the voltage to be accounted, as well as making phase and frequency measurements of the signal.

In order for the oscilloscope to observe other physical parameters, as well as observing voltages outside its original ranges different types of additional attachments and transformers that convert the given input into voltage are used.

What is the difference between a motortester and a lab scope?

The motortester is one kind of specialized oscilloscope used for auto diagnostics.

The main difference between a motortester and a universal oscilloscope is that the motortester is capable of visualizing short-timed processes like the ignition spark process. This process is exceptionally fast, and the period of repeat of the ignition of sparks in time is many times greater than the time the spark itself exists. This is easily observable when testing the engine in idle speed, when the majority of the measurements are conducted.

For example: if we observe the ignition cycle of a 4 cylinder gasoline engine, and an ignition spark that lasts around 2ms, at 800 RPM, the time period between sparks on a single cylinder would be 150ms. What this means is that the 'length' of the spark would account for around 2% of the actual work cycle, and therefore the burning of the sparks will be seen as very thin lines on the screen of the oscilloscope, and no information about the phases of the ignition would be seen. Because of this many diagnostics are forced to increase the RPM of the engine thus shortening the ignition cycle thus 'saturating' the waveform of the cycle.

The motortester shows all the cylinders simultaneously, and allows for detailed observation of the time period that includes: dwell period, drilling voltage, burn time and turbulence of voltage.

Most motortesters can show the cylinders graphs next to each other, or under one another, excluding the long time periods between sparks, this method is also known as "parade".

Another distinctive feature of the motortester is that it can show its time divisions on its horizontal (x) axis in milliseconds as well as in degrees – up to 720 degrees.

Features that allow PC-based oscilloscopes to be used in auto diagnostics.

Lower cost than a stand-alone oscilloscope, assuming the user already owns a PC.

Easy exporting of data to standard PC software such as spreadsheets and word processors

The software of the device can be directly installed on a PC and upgraded via CD or directly download from the Internet without having to send the device back to its manufacturer.

Use of the PC's disc storage functions, which cost a lot extra when added to a self-contained oscilloscope.

PCs typically have large high-resolution color displays which can be easier to read than the smaller displays found on conventional scopes. Color can be utilized to differentiate waveforms.

PC-based USB oscilloscope get their power supply from a USB port, so no external source is required.

The USB oscilloscope as any other USB device can be turned on/off without having to turn off/on the computer.

How many input channels are needed when conducting measurements in auto diagnostics?

When observing signals from sensors, valves, primary ignition chain, secondary ignition chain etc. no more than one channel is needed. The first kinds of motortesters, which were analog, needed more than one channel in order to show uniform signals simultaneously on the screen, so they could be compared with each other. But whit PS based DSO's this became unnecessary because a standard waveform can be saved on the PC's hard drive and opened at any time for comparison with the currently observed.

Two channels are needed when the sequence in time between 2 signals has to be measured and how many milliseconds are between them. In other words the second channel is used when the phase difference between the 2 signals has to be observed and measured. An example for such a measurement is when simultaneously observing signals from the Crankshaft Position Sensor and the Camshaft Position Sensor.

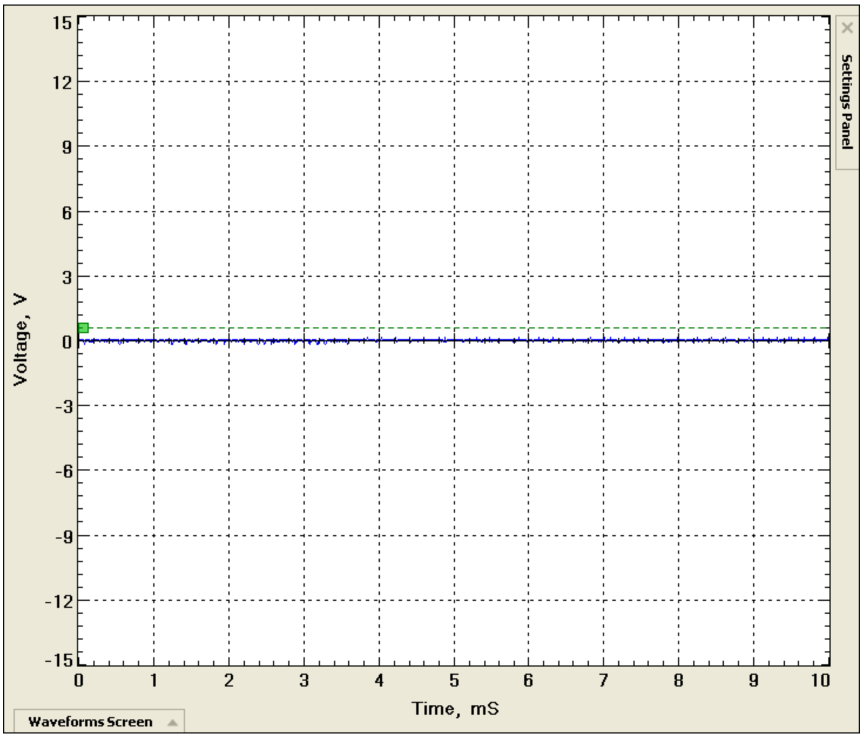
Using more than 2 channels is more convenient in some cases but pointless from a functional point of view.

Where can scope waveforms used for comparison be found?

Most programs that contain automobile technical information have sections whose headlines have “waveform”, “pattern” and “trace” in them. In other words these sections contain sets of standard waveforms. Such programs are **Autodata**, **Vivid Workshop**, and many others that contain technical information about automobiles. When looking at a “waveform” on the screen you must not forget that this is just an ordinary coordinate system like the one everyone has learned about at school. Like any coordinate system it has a horizontal (x) axis and a vertical (y) axis. The vertical axis (height) represents voltage, and the horizontal (width) represents time. The scale of both axes can be changed.

How does one work with an oscilloscope?

All oscilloscopes have a display on which the waveform is shown. The screen can be a cathode-ray tube, a LCD panel; a PC monitor can also be used. Here a typical oscilloscope screen is shown.



Scope display

There are divisions on the screen; they allow the signals parameters to be visually measured.

With the divisions on the horizontal axis **the time** parameters of the signal are measured. The vertical divisions are used to measure the strength of the **voltage.**

The "time" scale can vary from parts of a second to several seconds. The "voltage" scale can vary from several mV to several kV.

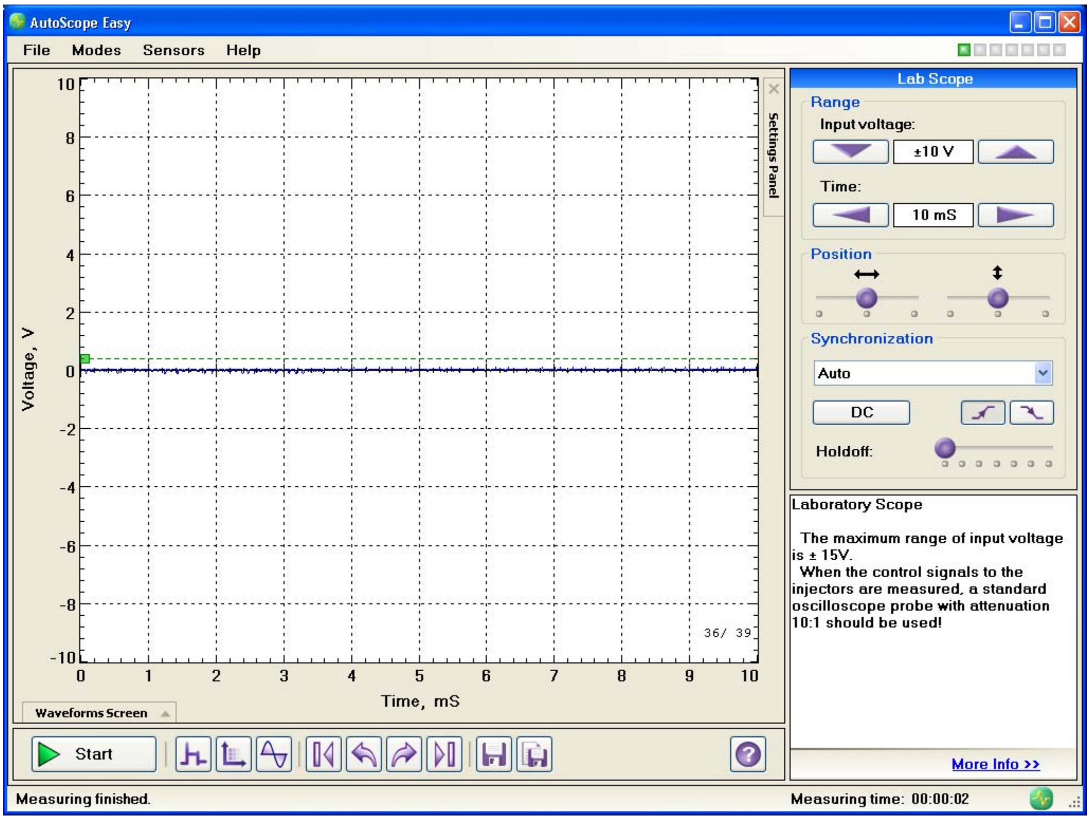
The graphics which are visualized on the screen are called waveforms. An oscilloscope can only observe waveforms produced by an electrical voltage. The screen of the oscilloscope shows the stretched through time image of the electrical fluctuation allowing for the shape and the amplitude of the voltage to be rendered into account, as well as making phase and frequency measurements.

For most of the measurements only 2 probes, such as Multimeter are required. The ground cable of the probe should be connected to the negative side of the car battery or the chassis, and the other cable should be connected to the cable whose signal we want to check.

Basic terminology when working with oscilloscopes

"Zero" line

If no electrical current source is plugged into to the oscilloscope, the waveform is represented by a straight line. This line is called "zero" line because it represents a level corresponding to a 0V voltage at the input of the oscilloscope.

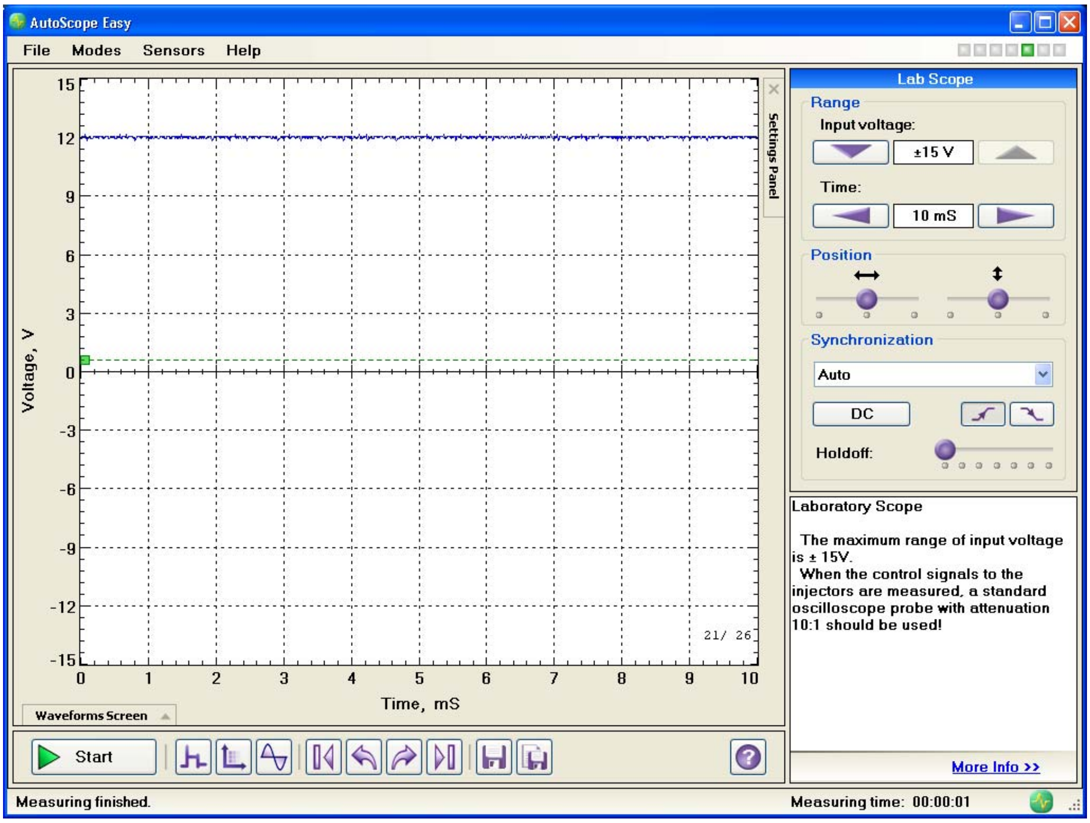


Waveform – there is no signal at the input of the oscilloscope

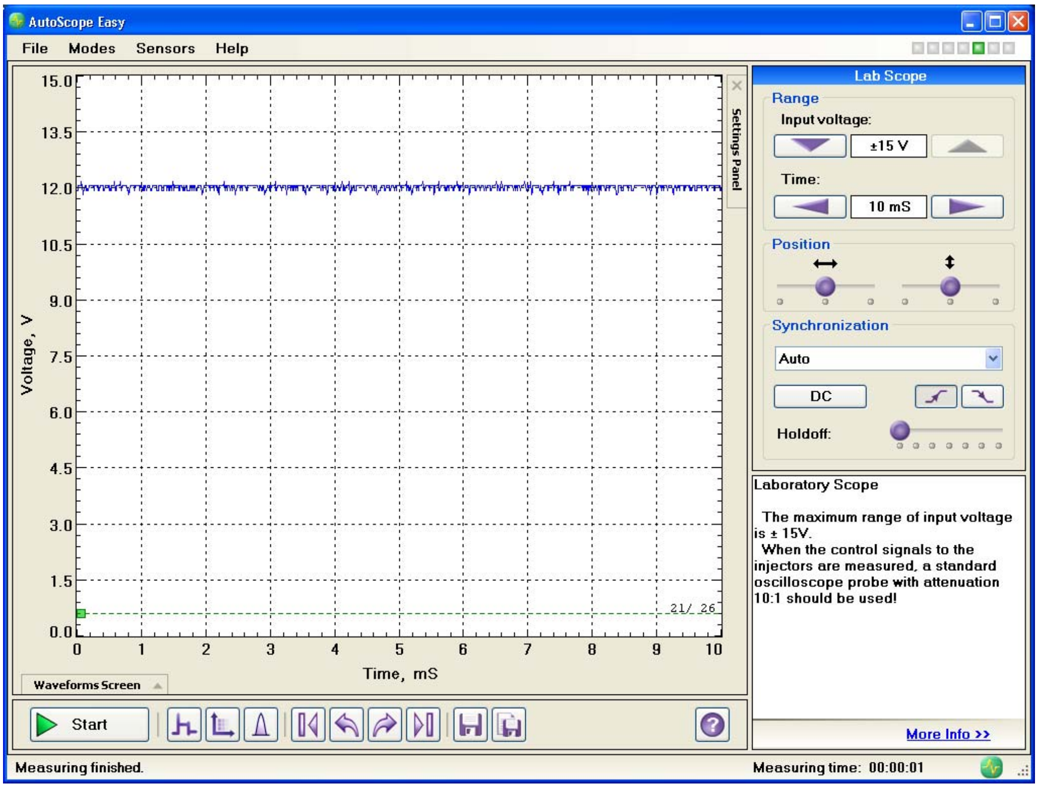
(The blue line is the zero line)

The position of the zero line can be displaced vertically according to the geometrical center of the screen. The need for moving the zero line vertically depends on the type and shape of the signal, as in the cases when using multi-channeled oscilloscope for a better visualization of signals from more than one channel.

When we connect a direct current (DC) supply to the oscilloscope, the waveform we would observe would be a straight line. The line itself would be vertically displaced from the zero line. The difference between the observed waveform and the zero line is proportional to the value of the electric current.



The waveform of a 12V car battery current



The waveform of voltage of the car battery.

(An 'only positive current values' mode has been selected)

The majority of waveforms have a shape different from a straight line.

Vertical Sensitivity

The graph on the screen of the oscilloscope shows the relation between the values of the voltage and time. If the amplitude of the input voltage is greater, a higher range of the vertical amplifier must be set. Depending on the amplitude of the signal, for a better visual result an appropriate vertical amplifier is used. The ability to change the scale of amplification of the signal enables the oscilloscope to show signals with very high amplitudes as well as signals with very low amplitudes. The appropriate value of the amplification depends on the amplitude parameters of the signal observed. The same signal would be shown differently depending on the degree of amplification. A larger range is used when the amplitude of the whole signal needs to be shown. A smaller range is used when, is need to make a detailed observation of the shape and the amplitude parameters of separate sections of the signal. In such cases, when the signal is of higher voltage, only a part of the signal is visible on the screen.

Timebase Controls

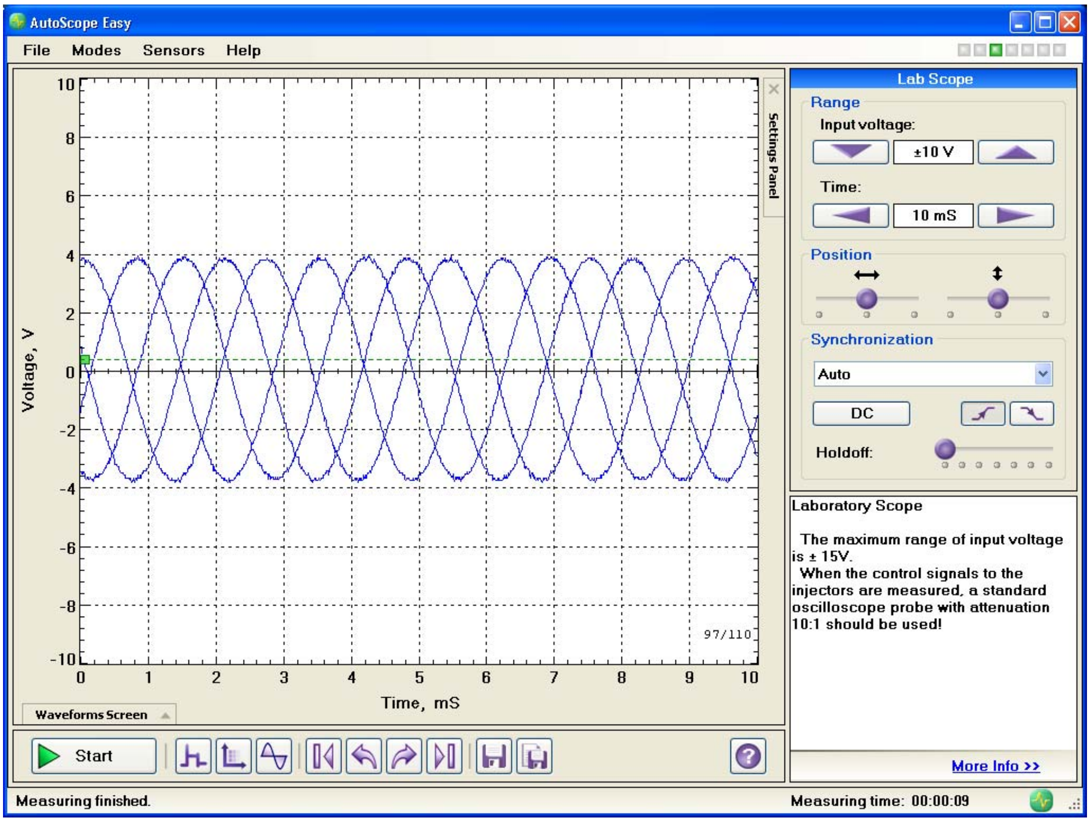
The oscilloscope plots a graph of the voltage left-to-right, starting from the left side of the screen. These select the horizontal speed of the spot as it creates the trace; this process is commonly referred to as the sweep. In all oscilloscopes the sweep speed is selectable and calibrated in units of time per major graticule division. Quite a wide range of sweep speeds is generally provided, from seconds to as fast as picoseconds (in the fastest 'scopes) per division.

As mentioned above the sweep is measured in seconds. In automobile measurements milliseconds are more often used (ms) – 1ms=1/1000 s. The value of the sweep can be changed with the time switch. The same signal is visualized differently depending on the sweep setting selected. A shorter period of time is selected when a detail observation of the shape and time parameters of separate sections of the signal is needed. In such cases a very short time fragment of the signal is shown on the screen. If we need to observe a larger time fragment of the signal (for example when showing individual impulses with irregular shape of the signal or skipping impulses) a bigger sweep is used.

Basic types of sweeps

Sweep trigger controls - Synchronization

Synchronization is needed for stabilizing the image of the signal on the screen. Synchronization provides that the plotting of each separate signal starts from the same point on the screen. The moment, when the plotting of the new screen starts is called a "triggering" moment. Because of this the image shown on the screen does not move or is relatively stable. When there is no synchronization active, which may be a result of a wrong synchronization setting, the signal is seen as mishmash.



The oscilloscope is not synchronized – a mishmash type of display

For a correct synchronization setting the following must be set

- The level control sets the threshold voltage. The threshold voltage is the value of the voltage at which the oscilloscope starts plotting.
- The slope control selects the direction (negative or positive-going).

Types of synchronization:

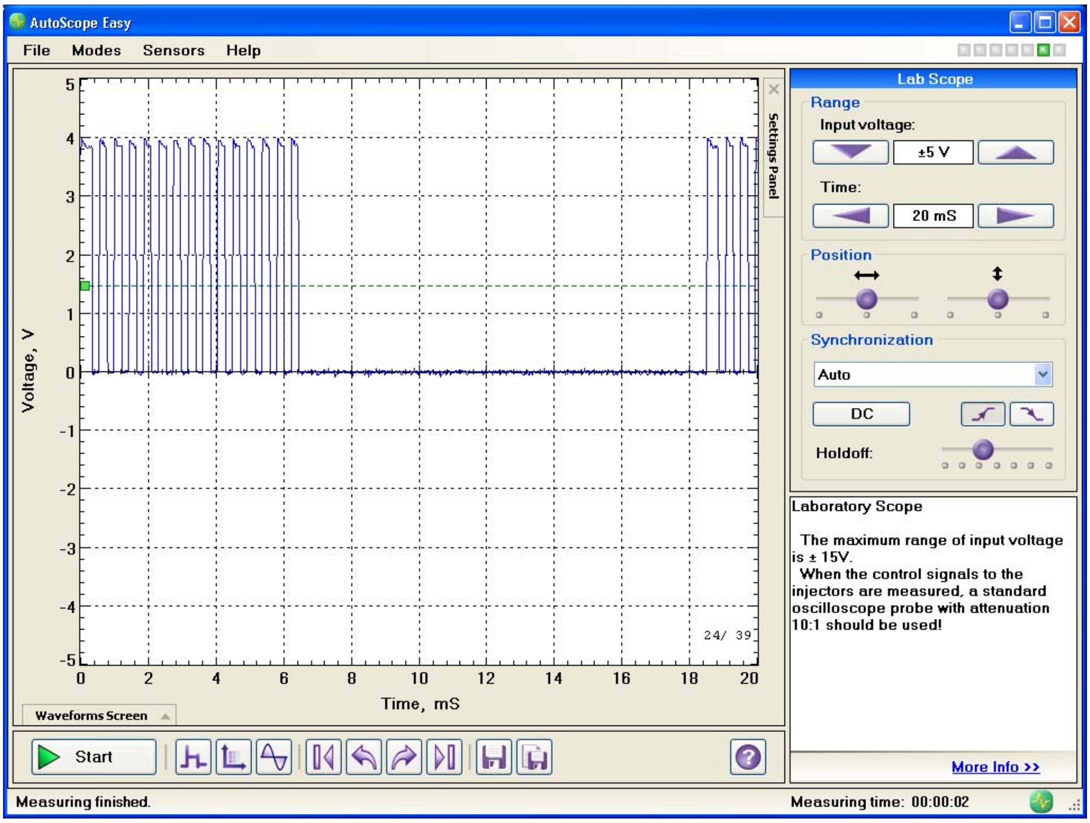
Automatic sweep mode – This mode is used when measuring signals that repeat periodically in time. When using multi-channel oscilloscopes it is necessary to select the signal that will be synchronized. It is also necessary to select the level of synchronization of the signal - falling or increasing front.

Single sweeps – This mode is used when observing signals consisting of impulses with identical shape. The time intervals between the pulses can be identical or can vary. This mode is also used with single impulse on the input signal. We must again select the level of synchronization – falling or increasing front.

External trigger – The oscilloscope has to have an additional input used for external synchronization in order for this mode to be used. Automobile oscilloscopes usually have an ignition synchronization signal connected to that input (#1 Cylinder).

Holdoff control – This function is very useful when complex signals consisting of several frequencies must be observed. In order for these signals to be synchronized on the screen of the oscilloscope, the device must have a "Trigger hold-off" function. On the examples shown below this function is represented by a slider on the control section of the synchronization.

An example of a signal that needs a holdoff setting, in order for the display of the signal to be stable.



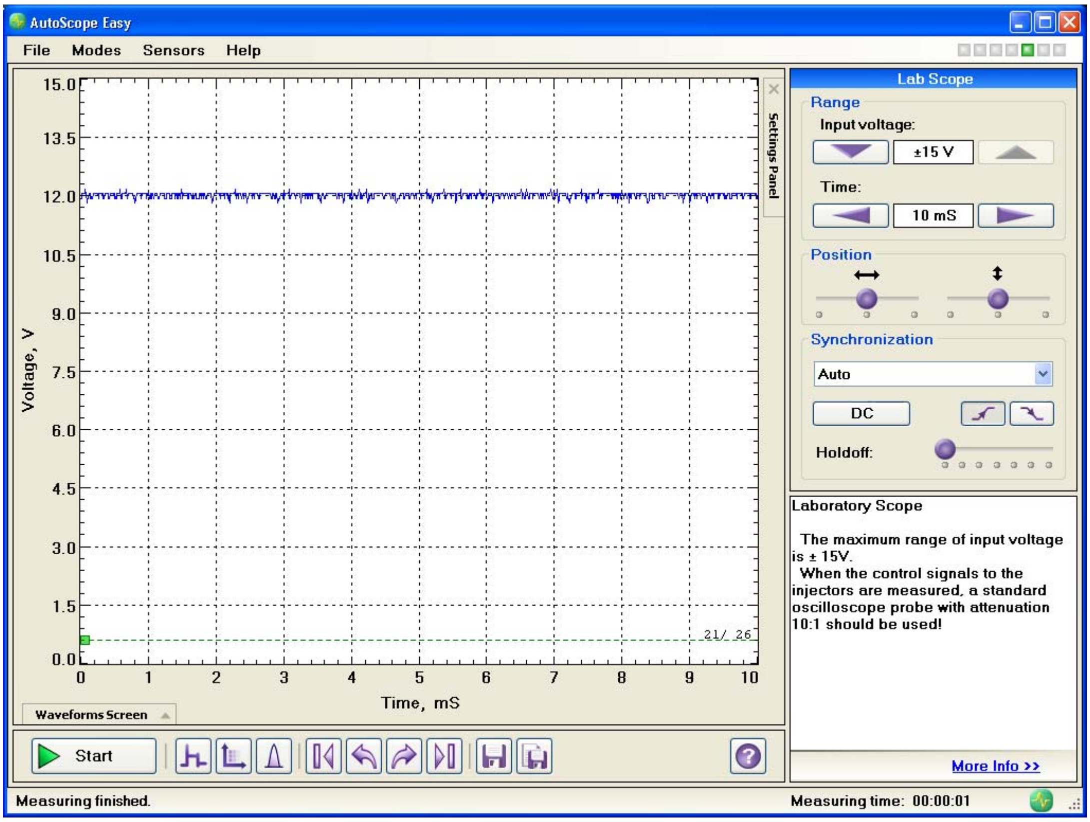
Pre-trigger

This is a method of visualizing the signal on a digital oscilloscope, which helps for the detailed observation of certain parts of the signal before the synchronization of the signal (before the triggering). There is no such concept in analog oscilloscopes. The pre-triggering visualization is possible because during the conversion of the signal to digital data, part of the values is kept in a buffer memory. After the synchronization of the signal the values kept in the buffer memory can be shown on the screen.

What types of electrical signals are there and what are their parameters?

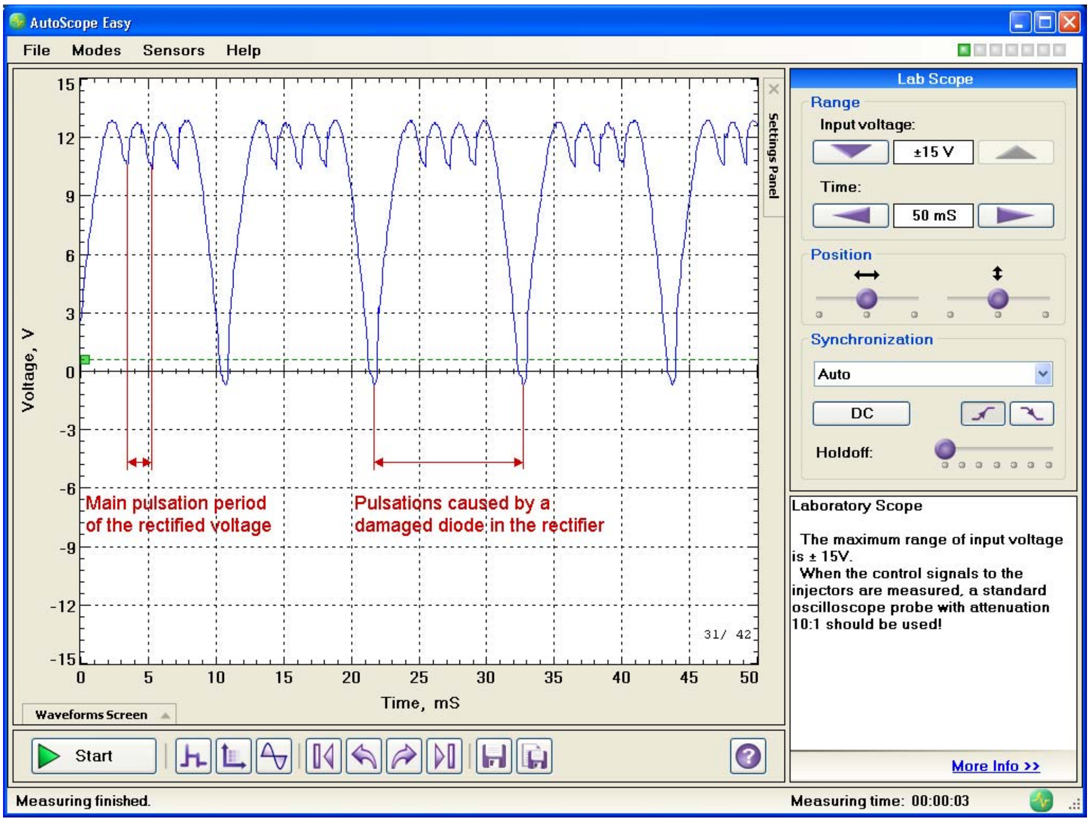
DC and AC

Direct current (DC) is the unidirectional flow of electric charge. It can be positive or it can be negative. Direct current is produced by such sources as batteries and electric machines of the dynamo type. Also may be obtained from an alternating current supply by use of a current-switching arrangement called a rectifier. The picture below shows the current of a car battery.



The wave produced by a car battery

Another example for DC of a much more complex nature is the rectified current of a generator. This current is positive, but it's also pulsating. These pulsations are additionally amplified by the fact that in the shown example below there is a damaged diode in the rectifier bridge.



Example of complex DC voltage

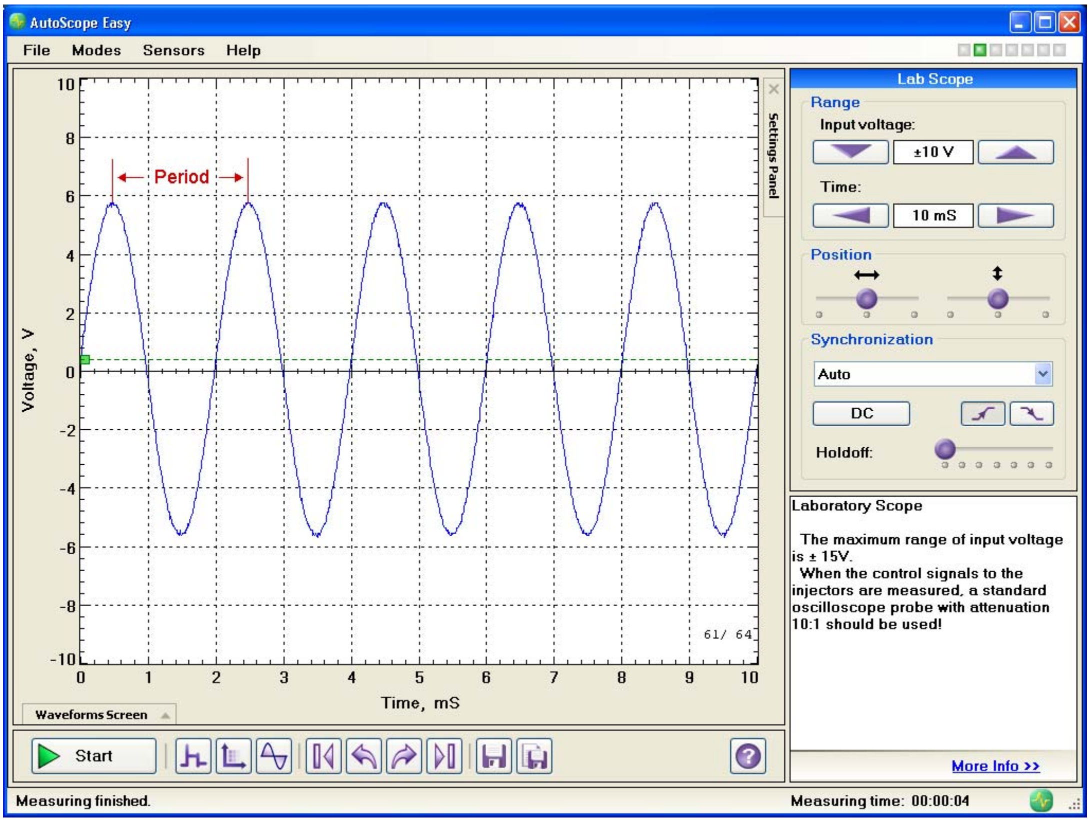
Alternating current (AC) - In AC the movement of electric charge periodically reverses direction. In direct current (DC), the flow of electric charge is only in one direction. The signal varies around 0V. Its momentary value can be both positive and negative. Such voltages are represented by almost all signals from inductive sensors: the CKP sensor, the CMP sensor, the signal from the ABS sensor etc.
The voltage in the electrical circuit is also AC and has sinusoidal shape. All examples viewed in the "Periodical and non-periodical signals" section are also examples for variable signals.

Periodical and non-periodical signals

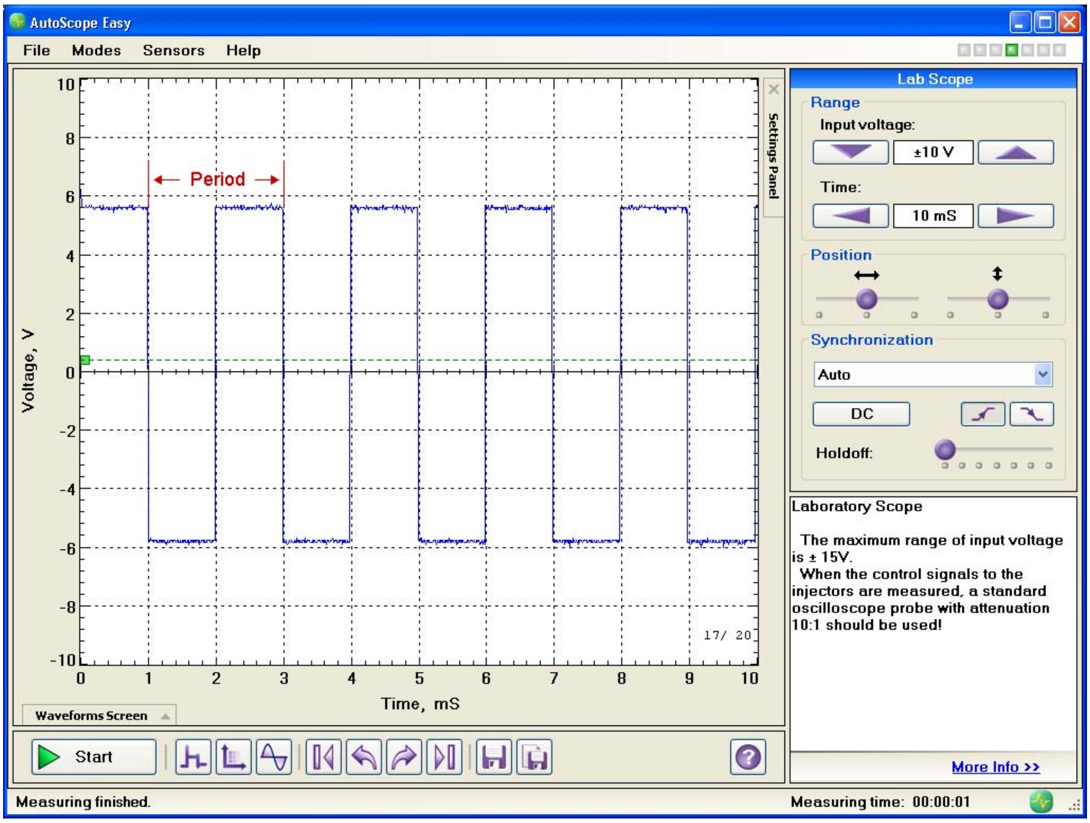
A signal is a periodical one if the values of its voltage pulsations and the shape of these pulsations are identical and are repeated through equal intervals of time.

The time needed for one periodical signal to complete one full cycle is called **period.** The number of periods per second is called the frequency of the signal. If the waveform of the voltage of the periodical signal crosses the 'zero' line the signal is called a varying signal. If the waveform does not cross the 'zero' line the signal is a constant one. Example waveforms of different periodical signals are shown below.

The first signal shown is a sine wave. This signal is characterized by 2 parameters – amplitude and frequency. In the automobile electronics similar to the sine wave signal are the signals generated by inductive speed and position sensors. Similar signals are generated by some crankshaft position sensors (CKP), camshaft position sensors (CMP), vehicle speed sensors (VSS) and others.

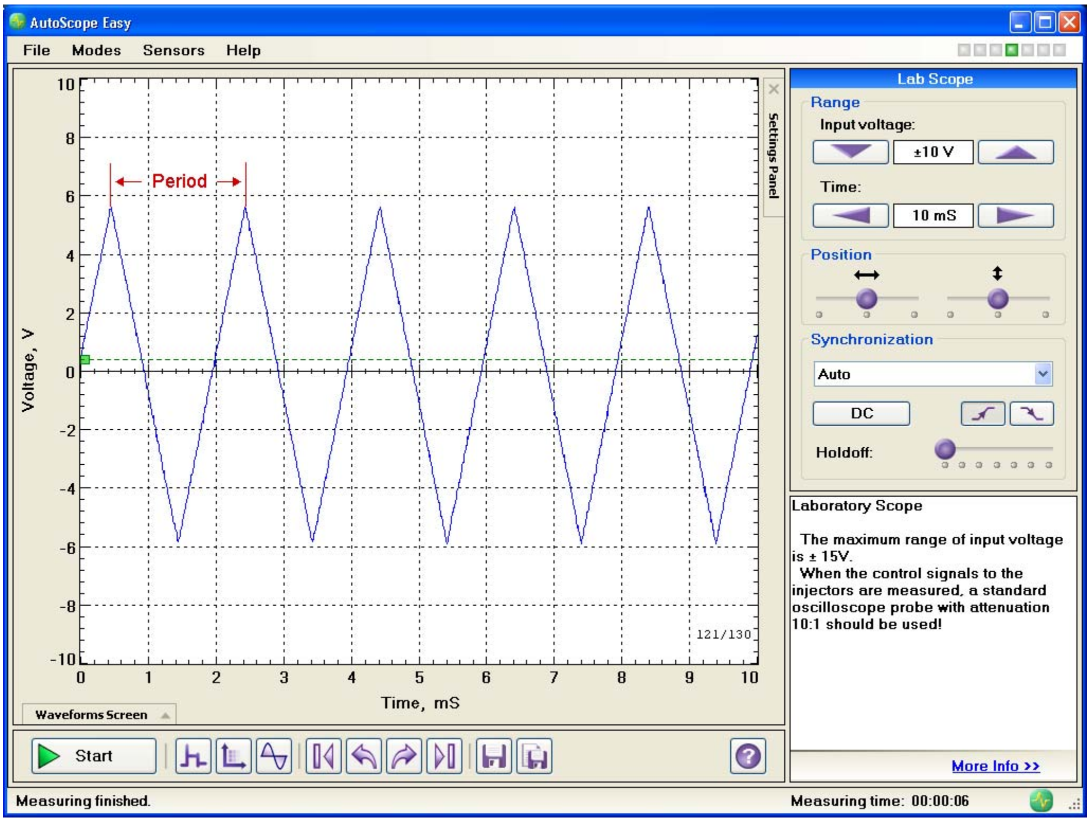


Sine wave periodical signal



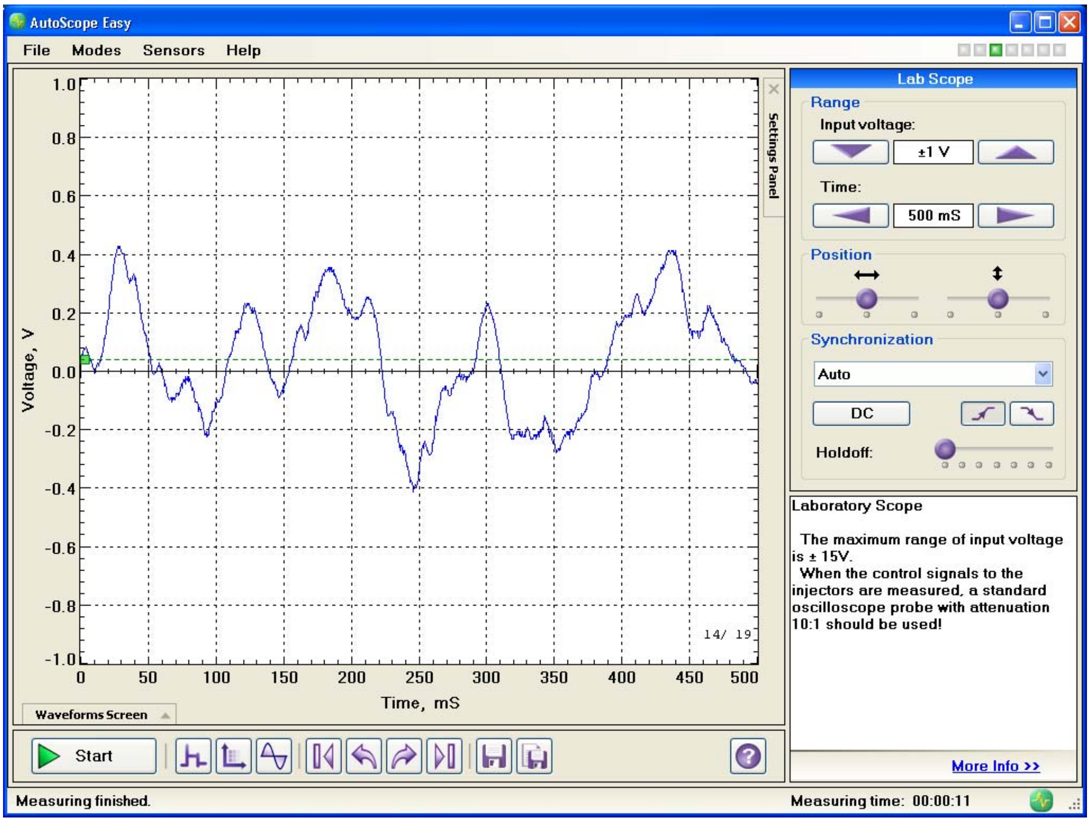
Square periodical signal

The injector control signal is a square one similar to the one shown above. Its impulses repeat periodically.



Triangular periodical signal

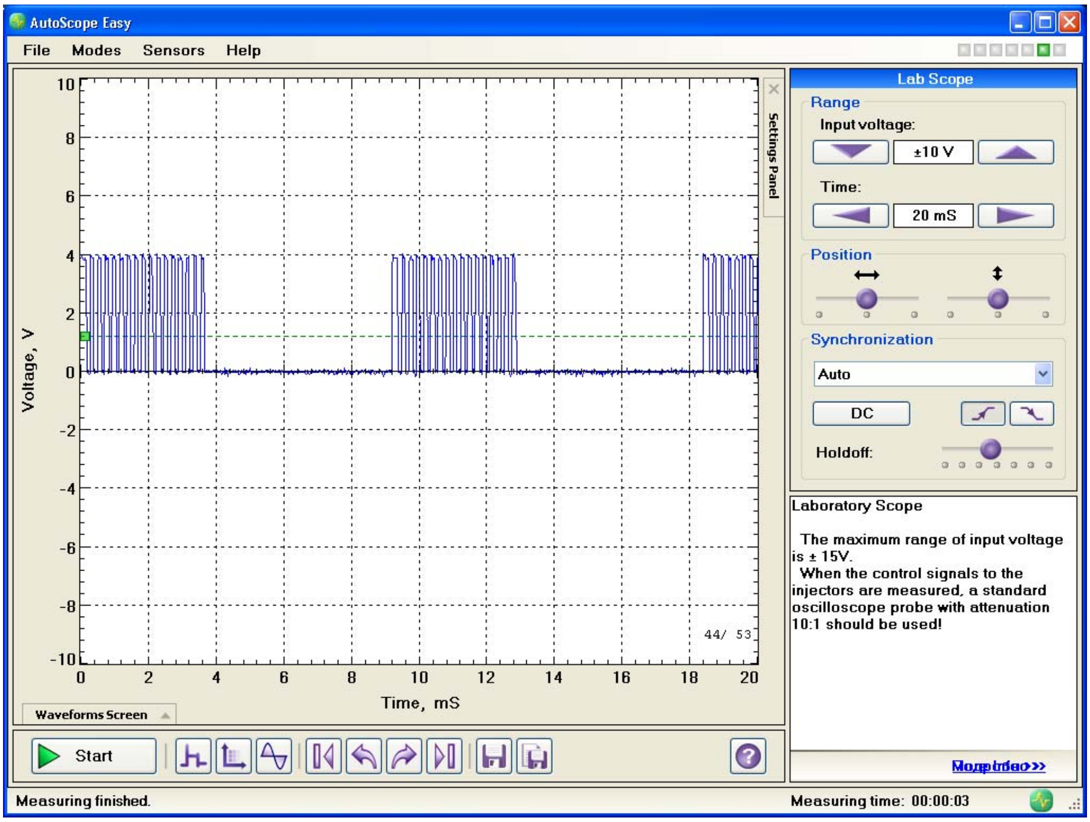
Signals that don't repeat through equal time intervals are called non-periodical.



Non-periodical variable signal

An example for non-periodical signals is the digital data transfer between the cars different controllers. There is another type of non-periodical signals – single signals. This is a kind of signal that is represented by a single impulse, which may never repeat or may repeat after a long interval of time.

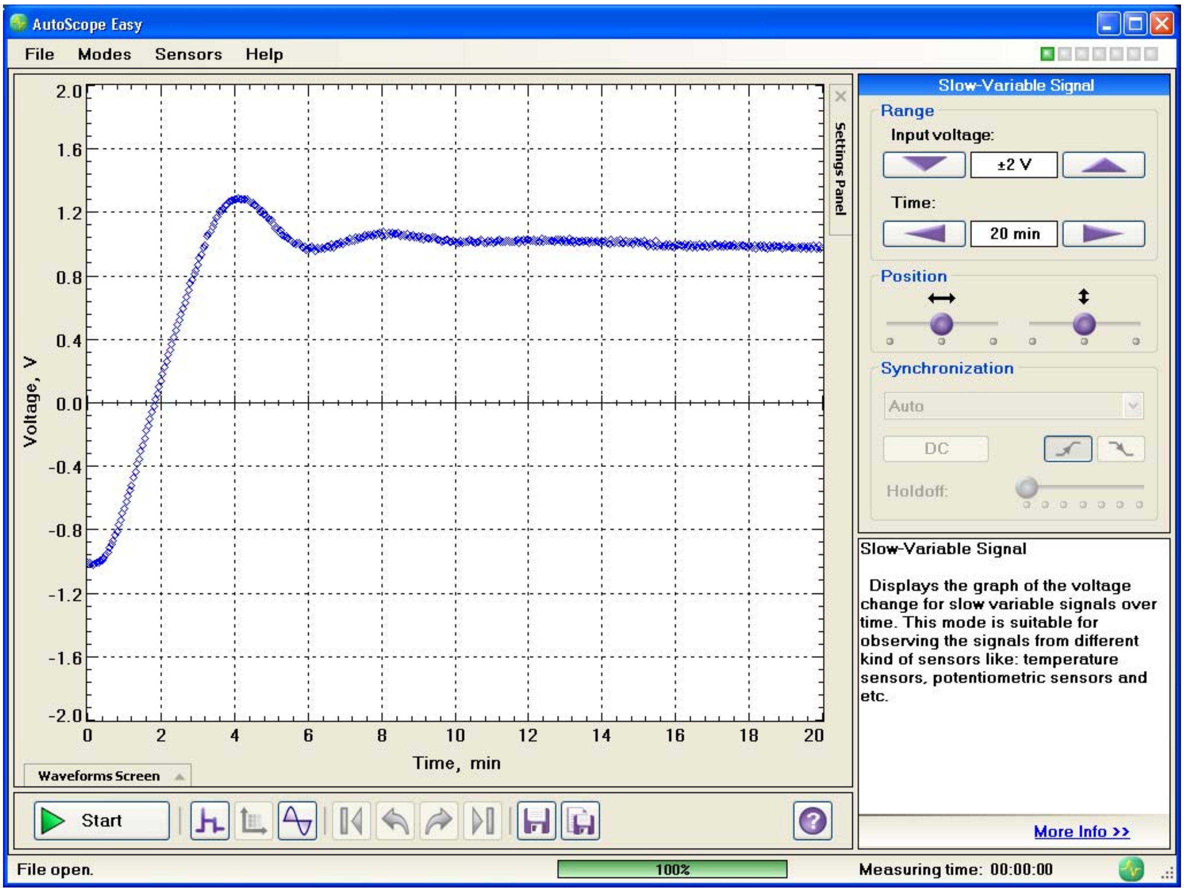
There is another type of complex signals, which can be both periodical and non-periodical. These signals are such that include more than 1 frequency. An example of such a signal is shown in the following picture:



For such a signal to be synchronized on the screen, the oscilloscope needs a specialized function called "**Trigger hold off". (* Look up in the Synchronization section)**

Slow-Variable Signal

One of the biggest advantages of the digital oscilloscope is the ability to show waves of processes with a large period, meaning signals that change slowly through time. An example for such a signal is the waveform on the following picture.



Slow-Variable Signal

Analog and Digital signals

All the signals examined until now are analog signals, they are uninterrupted signals. The values of their voltage changes through time by some rule or randomly. As an example for a complex analog signal the lambda sensor (O2 sensor) signal can be mentioned.

A waveform of digital signals switches between two voltage levels representing the two states of a Boolean value (0 and 1), even though it is an analog voltage waveform, since it is interpreted in terms of only two levels – high and low, on and off. Such voltage levels are called *Logic voltage levels*. In most cases, the logical levels have constant voltage values: +5V and 0V for example.

Digital signals are generated by switches. These switches are represented by transistors switching between "open/closed" states. Sometimes digital signals are generated by mechanical switches, electromechanical relays. An example of digital signals in the automobile electronic is the Hall sensor, the throttle end position sensors; the closed throttle position sensor (CTPS), the wide open throttle (WOT) sensor and the data transfer signals between the different ECUs. As the analog signals digital signals can be periodical and non-periodical.

Frequency

Frequency is the number of occurrences of a repeating event per unit time. The SI unit of frequency is the hertz (Hz), defined as one cycle per second. In the automobile electronics the number of rotations of the engine is measured per minute – (RPM). Using the waveform of the voltage of a periodical signal we can easily calculate the frequency of the signal. In order to do this we need to measure the period of the (the duration of a complete cycle of the signal). The value obtained can be recalculated into frequency using the respective formula.

Let us examine the following example. A sensor generates 1 voltage impulse per crankshaft rotation. The time lapse between 2 impulses is called a period. In the case given 2 consecutive impulses are separated by 7.4 divisions of the screen of the oscilloscope. The scale of the screen used for visualizing this signal is 1 division equal to 100 ms or 1/100 of the second, thus the period of the signal is 0.74 seconds. Knowing the length of the period of the signal we can calculate how many cycles per second are there, hence the frequency of the signal in Hz. When converting period to frequency we need to divide the time period chosen (in our case 1 second) by the length of the period of the signal (in our case 0.74 seconds):

1/0.074 = 13.5 Hz

If in this case we calculate the number of repeated periods per minute we will get the frequency of rotation of the crankshaft in RPM. When converting the period in frequency in RPM we need to divide the time period chosen (60 seconds) by the length of the period of the signal (0.74 seconds)

60/0.74 = 81 RPM

Such calculations can be can be made using all kinds of waveforms with different scales of division, but some oscilloscopes can directly show the results in RPM.

Pulse width

The width of the impulse – this is the time lapse, during which the signal is in active state. The active state is the level of voltage that triggers the executive mechanism. Depending on how the actuator is connected the active state can have different voltage levels: 0V, +5V, +12V. Practically the level can vary around these values. For example: the active state for the injector control signal in most engine control systems has a voltage of 0V, but can practically vary in range from 0V to +2.5V and more.

Duty cycle

The duty cycle is the fraction of time that a system is in an "active" state. For example, in an ideal pulse train (one having rectangular pulses), the duty cycle is the pulse duration divided by the pulse period. For a pulse train in which the pulse duration is 1 µs and the pulse period is 4 µs, the duty cycle is 0.25. The duty cycle of a square wave is 0.5, or 50%. This period is one of the PWM signal parameters (Pulse Width Modulation).

The PWM signal is used to control some executive mechanisms. For example in some engine control systems the PWM signal operates the electromagnetic idle speed valve. Furthermore PWM signal is also generated by some sensors that transform the measured physical parameter into direct correlation with the period of ignition.

What is self-induction?

This concept is not directly connected to the work principle of the oscilloscope, but it is important to understand why when activating the inductive executive sensors on a 12V car voltage we get voltages ranging from 60V to 200V and in the primary ignition chain up to 400V-500V.

Self-induction - This occurs when the current in an inductive circuit changes and the magnetic field cuts the wires; this induced electromotive force opposes the change in current, restricting it if the current is increasing and enhancing it if the current is decreasing.

Self-induction back-voltage - This is back-voltage produced by self-induction. This induced electromotive force opposes the change in current, restricting it if the current is increasing and enhancing it if the current is decreasing.

If the rate of change of the magnetic field in a solenoid (relay solenoid, solenoid injector, ignition coil, inductive sensor for rotation detection) the self-induction back-voltage can reach up to thousands of Volts. The magnitude of the back-voltage mainly depends on the inductiveness of the coil and the rate at which the value of the magnetic field is changing. In electromagnetic executive mechanisms the value of the magnetic field changes the fastest when the field fades away after a quick shutdown of the powering voltage. In some cases the self-induction effect is undesirable and precautions are being made in order to reduce it or to remove it. But some electric circuits are designed to produce the maximum self-induction back-voltage, for example the ignition system of gasoline engine. Some ignition systems can produce a back-voltage of self-induction up to 40kV– 50kV. Such voltages can be easily measured with an automobile oscilloscope by using capacitive pick-up.