HAMEG
Spectrum Analyzers

To many, spectrum analysis appears to be a type of "secret knowledge" dominated by only few specialists. One might acquire this impression from reading the available literature on this topic. It is full of theories, integrals, differential equations as far as the eye can see. The practical engineer's central interest, though, basically focuses on two questions: "How does it work and what can I do with it?"

In this article HAMEG has taken the "practical" route to address these questions. We would like to demonstrate that measurements with the spectrum analyzer are not any more difficult than working with an oscilloscope. Properly used, the applications of spectrum analyzers in research and development, quality assurance and electromagnetic compatibility (EMC) are very diversified. In the following we try to reduce theory and mathematics to a necessary minimum.

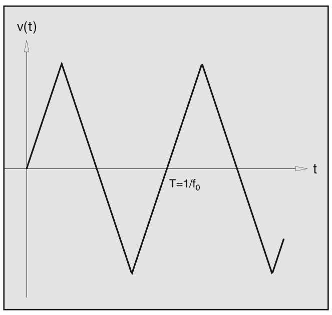
This article will give you a general overview of signal analysis as well as the types of equipments and applications. Examples are taken from practical applications in the field of EMI and frequency response measurement.

Introduction

One reason for the high performance of modern electronics (semiconductor components, microprocessors, oscillators, ...) is the constantly increasing speed of processing. The signal frequencies extend into the classical high frequency range, in this range also spectrum analysis is used. Oscilloscopes and spectrum analyzers both have their specific strengths and weaknesses to be covered in the following paragraphs.

The oscilloscope

The traditional method of analysis of electrical signals is the display of amplitude versus time. Oscilloscopes in their normal Yt operating mode (picture 1) display just this. This type of display versus time is familiar to humans. For this reason, oscilloscopes are also used in digital electronics. The vertical or amplitude scale of oscilloscopes is normally linear, hence oscilloscopes have a fairly low dynamic range (30 dB to 50 dB).



Picture 1: Classical oscilloscope display: amplitude versus time (Yt-operating mode). Signal: triangle.

Oscilloscopes which are used to measure electromagnetic interference must be very fast and feature rise times of a few nano seconds, they are consequently quite expensive.

The spectrum analyzer

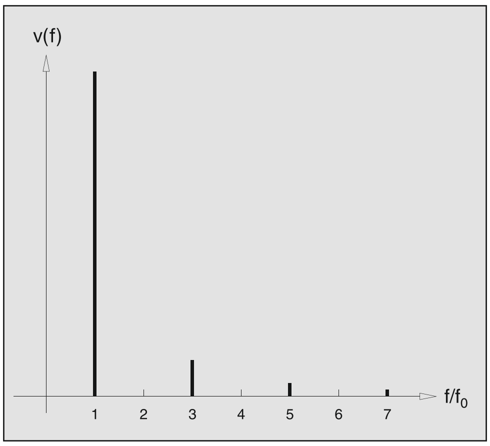
A simple example is the tuning display of any radio receiver. This is in principle a "small" spectrum analyzer. While tuning through a frequency band the field strength meter will display the intensity (power) of the frequency to which the set is tuned. The input signal from the antenna to the radio receiver contains the frequencies of all stations. After manually tuning once through a complete frequency band the result will be a chart of amplitude versus frequency. Spectrum analyzers (picture 2) work on this principle, first employed in World War II in order to obtain a quick broadband overview of enemy activities.

Spectrum analyzers can resolve signal components to very high frequencies (300 GHz). Due to logarithmic signal processing, they feature an extremely high dynamic range (> 80 dB). The input as a rule is 50 Ω, it is very delicate and can be easily destroyed by high signal levels (please observe the maximum input voltage!).

It is therefore advisable, if the signal to be measured is still unknown, to test first whether signal levels might be excessive. It is furthermore recommended to start any measurement with maximum attenuation and the maximum frequency range. It is important to bear in mind that measurements with a standard spectrum analyzer will only display the amplitude of the signals, time and phase information is lost, however in most practical applications this is of no consequence.

Different representations of the same signal

Each periodic signal may be represented versus time or versus frequency. As men-



Picture 2: Spectrum analyzer display: display of amplitude versus frequency (Yf-operating mode). Same signal as in pic. 1.

	Oscilloscope	Spectrum Analyzer
display:	Yt-operating mode (amplitude versus time)	Yf-operating mode (amplitude versus frequency)
x-direction/scale	linear (time)	linear (frequency)
y-direction/scale	linear (amplitude)	logarithmic (amplitude)
frequency range	DC to 12 GHz	0 to 300 GHz (no DC component)
dynamic range	30 to 50 dB	larger than 80 dB
phase information	yes	lost
prices	from a few thousand EURO to 100,000.00 EURO	a few thousand EURO up to 100,000.00 EURO

table 1: comparison oscilloscope/ spectrum analyzer

tioned, these two representations are not of equal quality, because an ordinary spectrum analyzer will only retain the amplitudes of the individual frequency components, time and phase information is lost. Hence the signal representation versus time cannot be reconstructed from the amplitude versus frequency representation of an ordinary spectrum analyzer. The representations in the time and frequency domains are related by the Fourier transform.

time domain ↔ frequency domain

Time function ↔ amplitude spectrum

v(t) ↔ V(f)

This will be detailed in the following paragraph information theory.

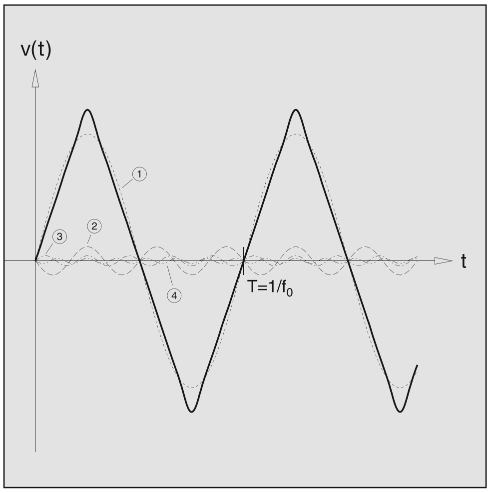
In table 1 the most important features of oscilloscopes and spectrum analyzers are compared. Picture 1 shows a signal versus time and picture 2 shows the same signal versus frequency.

Information theory

Time domain

Jean Joseph Fourier showed in 1808 that each periodic signal may be broken down into a fundamental frequency and its harmonics. In electronics that means: Each periodic signal (square wave, triangle, sawtooth, other waveforms) may be constructed by a sum of sine waves of different amplitude and phase.

In picture 3 the curves 1 to 4 are superimposed in order to obtain a triangle waveform. The fundamental frequency (curve 1) has the same period as the signal. The curves 2 to 4 are called harmonics and are always integer multiples of the fundamental. The more harmonics are taken into consideration, the more the display will come close to a true triangle wave form.



Picture 3: Curve 1 – 4 superimposed form a triangle waveform

Frequency domain

In order to look at the triangle waveform in the frequency domain a real time analyzer may be used. This instrument contains a multitude of band pass filters connected in parallel to its input. If a triangle wave form is applied to the input, only those filters will respond the resonance frequencies of which coincide with the frequencies of the curves 1 to 4. The output voltage of each filter is a measure of the amplitude of the individual frequency.

Table 2 refers to our example:

Curve 1	Frequency	f_0 = 10 kHz	Amplitude = 1
Curve 2	Frequency	$3f_0$ = 30 kHz	Amplitude = 0.111
Curve 3	Frequency	$5f_0$ = 50 kHz	Amplitude = 0.04
Curve 4	Frequency	$7f_0$ = 70 kHz	Amplitude = 0.02

Table 2

Fourier Analysis

As shown the triangle signal may be displayed on an oscilloscope in the time domain (pic. 1) or in the frequency domain (pic. 2) with a spectrum analyzer.

The transformation between the time and frequency domains is done using the Fourier transform. This requires integral calculus. We intentionally renounce on a theoretical mathematical treatment because the spectrum analyzer does the Fourier transform for us.

How to interpret the Y-scale of a spectrum analyzer

The Y-axis in oscilloscopes is linear. Each division corresponds to the same amount.

Example:
1 Div. = 2 V means that a 5 Div. display = 10 V.

In contrast the Y-axis of spectrum analyzers is logarithmic. Hence each division corresponds to the same value in dB.

Example:
1 Div. = 10 dB means that a 5 Div. display = 50 dB.

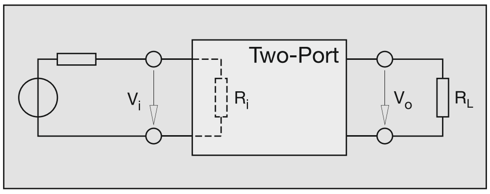
The advantage of a logarithmic scale is the ability to display a very large range on screen.

The designation dB (= decibel) equals 1/10 of the unit Bel. One Bel is the decade logarithm (lg) of the ratio of two powers. It is thus a pure number (see table 3).

Calculation of power in dB

Picture 4 shows a two port: The input voltage is designated V_i, the output voltage is designated V_o. The input resistance R_i is equal to the load resistance R_L. The power amplification of the two-port A_P may be expressed in dB.

$A_P = 10\,\lg\,(P_L/P_i)$ dB   Equation 1



Picture 4: The power amplification Ap of the Two-Port may be expressed in dB.

Voltages expressed in dB

If a voltage (V) is applied to a resistor (R) a power (P) equals V^2/R will be generated.

$P_i = V_i^2/R_i$ and $P_L = V_o^2/R_L$.

If this is inserted in equation 1 we get:
$A = 10\,\lg\,(V_o^2 \times R_i/V_i^2 \times R_L)$

as $R_i = R_L$, it follows:
$A = 10\,\lg\,(V_o^2/V_i^2)$
$A = 10\,\lg\,(V_o/V_i)^2$ or
$A = 2 \times 10\,\lg\,(V_o/V_i)$
$A_V = 20\,\lg\,(V_o/V_i)$ dB   Equation 2

Example of a calculation using dB

Assuming that $V_o = 10$ V, $V_i = 2$ V it follows:

$A_V = V_o/V_i = 10/2 = 5$
Inserted into equation 2:
$A_V = 20\,\lg\,10/2$ dB = +13.96 dB

If for instance an attenuator with -10 dB is followed by an amplifier with +19 dB the amplification of the whole chain is equal to the sum of -10 dB + 19 dB = +9 dB.

Table 3

Decade logarithm (dB-value) and ratio of power		In practice:
0 Bel	$\widehat{=} 10^0 = 1$	signal is transmitted 1:1, i. e. there is neither amplification nor attenuation
1 Bel	equals a ratio of powers of $10^1 = 10$	amplification of the signal by a factor of 10
-1 Bel	equals $10^{-1} = 0.1$	attenuation of the signal by a factor of 0.1
1 dB	equals $10^{0.1} = 1.259$	amplification by a factor of 1.259
3 dB	equals $10^{0.3} = 1.995 \approx 2$	amplification by a factor of 2
10 dB	equals $10^1 = 10$	amplification by a factor of 10
Mathematics: $1\ \text{Bel} = \lg 10^1 = \lg (10^{0.1})^{10} = 10 \lg 10^{0.1}$ Bel 10 dB		

dB based on a reference level (= absolute level)

The unit dB is non-dimensional and expresses only the ratio of two values; e.g. voltages. For the application of absolute levels, reference levels were introduced in technical applications. The customary magnitude 1 mW is based on power output.

0 dBm	≙ 10^{0} mW		=	1 mW
30 dBm	≙ 10^{3} mW	= 1000 mW	=	1 W
-30 dBm	≙ 10^{-3} mW	= 1/1000 mW	=	1 µW

Since the relationship $P = U^2/R$ is valid for any available resistance, one can also express voltages in dBm. For a reference resistance of 50 Ω the results are:

$V_{ref} = \sqrt{50\,\Omega \times 1\,mW} = 224\,mV_{rms}$ Equation 3

as reference voltage.

In order to avoid the uncertainties for the voltage values in dBm (reference resistor 50 Ω, 75 Ω, 600 Ω), it is customary to refer voltage levels to 1 µV. For larger voltages, 1 Volt is employed as reference magnitude.

0 dBµV	≙ 10^{0} µV		=	1 µV
60 dBµV	≙ 10^{3} µV	= 1000 µV	=	1 mV
-60 dBµV	≙ 10^{-3} µV	= 1/1000 µV	=	1 nV

Example: Conversion from reference levels:
0 dBµV ≙ 1 µV ≙ -120 dBV

The following applies:
dBµV is a measure of how much greater a certain voltage is than the reference magnitude (here 1 µV). It makes no special sense, but one could for instance also the express mains voltage in dBµV. (230 V_{eff} in equation 2:

$A_V = 20\,lg\,(230\,V/1\,\mu V)\,dB$
$= 167\,dB\mu V$).

For power, there is a similar validity; here the values in Equation 1 are employed. The reference value ($P_i = P_0$) is 1 mW, for a power output of e.g. 4 mW a value of 6 dBm is computed.

Conversion from dBm to mW

The height of the amplitude (A_p) at the spectrum analyzer is directly displayed in dBm. If you for instance read a value of –47 dBm, then you can convert the power output to mW. Equation 1 is:

$P_L/P_i = 10^{Ap/10}$
$\rightarrow P_L = P_i \times 10^{Ap/10}$
$P_L = 1\,mW \times 10^{-47/10} \rightarrow P_L = 2\,nW$

i.e., if you read a level of - 47 dBm on a spectrum analyzer, then this means – for the corresponding frequency – a power output of 20 nW.

Conversion from dBm to voltage (mV)

In order to be able to convert the power output (reference magnitude 1 mW) into voltages, one must constantly refer to a firmly defined (termination) resistance. The spectrum analyzer has a 50 Ω input.

According to Equation 3:
$V_{ref} = 224\,mV_{rms}$

Transposition of Equation 2:
$A_V = 20\,lg\,V_0/V_{ref}$ dB the following:
$A_V/20 = lg\,V_0/V_{ref}$ or
$10^{AV/20} = 10\,lg\,(V_0/V_{ref}) = V_0/V_{ref}$

$\rightarrow V_A = V_{ref} \times 10^{A_V/20}$

$V_A = 224\,mV \times 10^{-47/20} = 1\,mV$

Conversion dBm – dBµV

From Equation 3 the following:
0 dBm ≙ 1 mW ≙ 224 mV_{eff} (50 Ω)

is employed in Equation 2:
$A_V = 20\,lg\,(224\,mV/1\,\mu V)\,dB = 107\,dB\mu V_{eff}$

This results in the overall relationship:
0 dBm ≙ 1 mW ≙ 224 mV_{eff} ≙ 107 dBµV

Resumed: In order to derive dBµV from dBm add 107 dB to the dBm value. Vice versa in order to derive dBm from dBuV subtract 107 dB. (See table 4.)

How to select a spectrum analyzer

Disregarding price which may reach 100,000 Euro very high performance spectrum analyzers are available. Those are much too expensive for general application. Many measurement tasks can be solved using instruments markedly lower priced. In the following the most important parameters are listed.

Table 4: Level definition with diverse reference magnitudes

Size Reference value	Letter symbols	Level definition	Unit	
Power level Reference value 1 W	$A_{P/W}$	$= 10 \lg (P_L/1\,W)$ dB	dBW	$P_L = 1\,W \cdot 10^{A_{P/W}/10}$
Power level Reference value 1 mW	$A_{P/mW}$	$= 10 \lg (P_L/1\,mW)$ dB	dBm	$P_L = 1\,mW \cdot 10^{A_{P/mW}/10}$
Voltage level Reference value 1 V	$A_{V/V}$	$= 20 \lg (V_O/1\,V)$ dB	dBV	$V_O = 1\,V \cdot 10^{A_{U/V}/20}$
Voltage level Reference value 1 µV	$A_{V/\mu V}$	$= 20 \lg (V_O/1\,\mu V)$ dB	dBµV	$V_O = 1\,\mu V \cdot 10^{A_{U/\mu V}/20}$

Frequency range

This parameter has the most decisive influence on the price. Instruments with an upper limit of 1 GHz allow measurements in most of the amateur bands, in the ISM band (433 MHz), in the frequency range of the D cell phone system, the lower GSM band, in the terrestric radio and TV bands as well as of EMI measurements. Above 1 GHz the cost increases sharply, e.g. a frequency-stabilised YIG (yttrium-iron-garnet) oscillator may be needed for the first mixer stage.

Resolution

Resolution defines the ability of a spectrum analyzer to differentiate between two adjacent signals. This ability will depend on the qualities resp. properties of the IF section, i.e. the bandwidths and slopes of the filters therein (see picture 5). If e.g. the smallest filter bandwidth is 9 kHz the minimum frequency difference between two spectral lines will be also 9 kHz, otherwise they can not be recognized as separate. However, bandwidths ‹ 10 kHz mandate that the oscillators used are of adequate quality. FM signals e.g. require such quality.

Frequency stability

Of course, a spectrum analyzer must feature a much better frequency stability than the signal to be measured. This stability of the whole instrument is dependent on the local oscillator's stability. Longterm and shortterm stability specifications are necessary.

Amplitude accuracy

As a rule the vertical (amplitude) scale of spectrum analyzers is calibrated logarithmic.

Assuming the standard 8 cm display 80 dB of amplitude can be displayed, this is equivalent to a voltage ratio of 1:10,000. The accuracy of amplitude measurements is influenced by the frequency response and the quality of the logarithmic amplifier. Total errors of ± 1 dB may be regarded as excellent.

Dynamic range/compression

The dynamic range of a spectrum analyzer is an important feature and will determine the range of small and high amplitudes which can be displayed.

The maximum level is limited by linearity constraints of the mixer stages which may generate distortions and false signals.

The lowest signal level usable is given by the noise level of the instrument. The noise may be reduced by reducing the filter bandwidth as exemplified by equations 4 and 5, thus increasing the dynamic range.

Input sensitivity

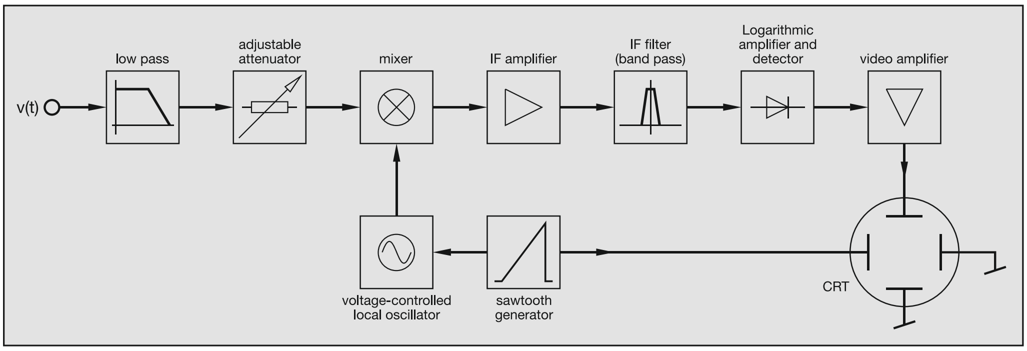
The sensitivity defines the smallest signal measurable and is limited by the noise level. Only signals which stick out from the noise band are measurable. We differentiate between thermal and non-thermal noise.

Thermal noise is given by:

$P_{therm} = K \times T \times B$ Equation 4

P_{therm}: Noise power in watts
K: Boltzmann's constant = 1.38 x 10 exp. – 23 VAs/degr. K
T: absolute temperature
B: Bandwidth in Hz

$B\,(dB) = 10 \lg B_{(IF)}\,(Hz)$ Equation 5



Picture 5: Block diagram of a Spectrum Analyser using the superhet principle.

Equation 4 shows that noise power is directly proportional to bandwidth. Reducing filter bandwidth by a decade step will reduce the noise power by a factor of 10 dB which in turn will mean an increase of sensitivity by 10 dB. All other noise sources are assumed as being non-thermal.

Spectrum analyzers sweep a wide frequency band and are narrow bandwidth measuring instruments as described in the beginning. All signals within the frequency range of a spectrum analyzer are converted to an intermediate frequency and pass an IF filter. The detector following the filter only responds to the noise contained in the filter passband, and only this noise will be displayed. Consequently, maximum sensitivity is achieved by using the smallest filter bandwidth available.

When comparing spectrum analyzers it is important to note that the filter bandwidth is identical.

At room temperature the theoretically achievable sensitivity would be - 134 dBm at 10 kHz bandwidth and a perfectly square filter response. Signals from approx. - 131 dBm should then be just visible, equivalent to a signal-to-noise ratio of 3 dB. Of course, such numbers are unattainable. - 100 dB are quite practical and - 115 dBm may be regarded as the ultimate achievable with any reasonable effort.