Measurement of Acoustic Properties of Rooms Using Audio Analyzer R&S® UPV

Application Note

Products:

| R&S®UPV |

| R&S®UPV66

| R&S®UPV-K1

Acoustic properties like reverberation time and early reflections are important for test rooms as well as for speech intelligibility and music performance in assembly rooms and concert halls. This application note explains the basics behind these properties and offers an application program for their measurement.

ROHDE&SCHWARZ

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1 Sound Propagation and Room Acoustics

1.1 Sound Theory

1.1.1 Sound Pressure and Sound Velocity

Sound can be viewed as the AC component of air pressure. For example for a sine tone, the air pressure can be described as

$$p(t) = p_0 + \hat{p} * \sin(2 * \pi * f * t)$$

Where p_0 is the static atmospheric pressure and $\hat{p}$ is the amplitude of the sound pressure.

According to the physical laws for gases, changes in the air pressure are associated with changes in the mass density. A change in mass density is associated with a movement of air. The speed of air particles caused by the changing air pressure is called particle velocity $v(t)$.

1.1.2 Acoustic Wave

Since the compliance and mass of the gas introduce a phase shift on the sound pressure and velocity with increasing distance from a sound source, the sound propagates as a wave. At a fixed point in time, the phase of the sound depends on the distance from the sound source. The distance which corresponds to a phase shift of $2 * \pi$ is called wavelength λ. The speed c with which the wave propagates is called sound velocity.

$$c = \lambda * f$$

The sound velocity should not be confused with the particle velocity. With usual sound levels, the particle velocity is much smaller than the sound velocity.

The ratio between sound pressure and sound velocity is called specific acoustic impedance. It depends on the physical properties of the gas and on the shape of the propagating wave which in turn depends on the shape and type of the sound source. For example, a large moving diaphragm causes a plane wave at least for higher frequencies and in the vicinity of the diaphragm. A small opening can cause a spherical or semi-spherical wave, depending on whether it is in more or less free space or on a hard wall.

1.1.3 Sound Intensity

The power which is transported by an acoustic wave per unit area is called sound intensity I. The sound intensity can be calculated from the RMS values of sound pressure and particle velocity as

$$I = \widetilde{p} * \widetilde{v}$$

1.1.4 Radiation of a Point Source

If the dimensions of a sound source are small compared to the wavelength and there are no obstacles around, the sound propagates as a spherical wave in all directions. Under the condition that the losses in the sound propagation can be neglected, all spherical shells around the sound source are penetrated by the same amount of power: the radiated power of the source. As the surface of the spherical shells is proportional to the square of their radius, the sound intensity decays with the square of the radius:

$$I \sim \frac{1}{r^2}$$

The sound pressure is approximately inversely proportional to the distance form the sound source:

$$\widetilde{p} \sim \frac{1}{r}$$

1.2 Reflection and Absorption

1.2.1 Reflection on a Plane Surface

If an acoustic wave hits a hard flat surface, it is reflected back into the room due to the large difference in the acoustic impedance between the air and the material of the hard surface. Just like in optics, the trajectory of the reflected wave lies in the same plane as the trajectory of the incident wave and the surface normal. The angle between the trajectory of the reflected wave and the surface is the same as the angle between the trajectory of the incident wave and the surface.

1.2.2 Absorption on Surfaces

Real surfaces absorb a portion of the energy of the incident sound wave. Absorption is usually depending on the frequency. The absorption coefficient is the ratio between the intensity I_i of the incident wave and the intensity difference between incident and reflected wave:

$$\alpha = \frac{(I_i - I_r)}{I_i}$$

An open window in a room has more or less 100% absorption ($\alpha = 1$) at least for frequencies where the wavelength is small compared to the dimensions of the window.

Fabric absorbs acoustic energy due to the sound velocity which moves filaments in the fabric. As the particle velocity is zero on the surface of a hard wall, fabric mounted on hard walls absorb only high frequencies where a quarter wavelength is within the fabric layer, because sound velocity reaches a maximum at a quarter wavelength distance from the hard surface. Absorption of fabric layers can be extended to lower frequencies if the fabric is mounted in a distance from the hard reflecting wall. For example a curtain hanging in plaits at a certain distance from a wall or window glass can act as absorber for medium and high frequencies.

Low frequencies can best be absorbed by resonance absorbers. One form of resonance absorbers are wooden panels mounted in a distance from the hard surface of the wall. They resonate at a frequency determined by there mass and by the stiffness of the suspension and the air layer between panel and wall. Another form of resonant absorbers are Helmholtz resonators which consist of the stiffness of air in a cavity and the mass of air in one or more opening(s) from this cavity to open air. Such a construction can be found in perforated panel mounted in a certain distance in front of a wall.

1.2.3   Sound Attenuation During Propagation

Sound propagation in gases is not entirely lossless. Depending on the size of a room, dissipation of acoustic energy during propagation may have an influence on the diffuse sound field and therefore on the reverberation time. The dissipation is linked to sound velocity. Therefore it is higher for high frequencies than for low frequencies.

α_L denotes the attenuation of acoustic waves per traveled distance in dB/m. It depends on the frequency and on properties of the medium like humidity.

1.3   Early Reflections

A sound impulse starts from a sound source traveling at equal speed in all directions. In different distance from the sound source at different directions, the impulse hits a hard surface of a wall or other obstacle in the room and is reflected. At a certain point of observation, the direct sound traveling the shortest distance from the source to the point of observation arrives first. One after the other, reflections arrive from different directions, delayed according to the additional distance the impulse had to travel due to its detour. If the sound intensity at the point of observation is plotted over time, a so-called reflectogram is obtained.

The pattern of reflections arriving at a certain point of observation in the room depends on the position of the sound source as well as on the point of observation. The reflectogram should be investigated for a certain sound path, e.g. from one musician's place to another musician's place to find our how well they can hear each other's performance, or from a musician's place to the place of the conductor or to a place in the audience.

For a good common music performance it is important that the reflectogram from one musician's place to another's should have as much energy as possible as early as possible. For a good impression of a music performance in the audience it is more important to have energy evenly distributed over time to a large number of reflections, as opposed to a few prominent reflections.

1.4 Diffuse Sound Field

1.4.1 Stationary condition

When the source starts radiating sound, the acoustic wave will propagate across the room, get reflected at boundary areas with a certain absorption, and the reflected waves will be reflected again, with the amplitude decreasing with each reflection. After a certain time the room will be flooded with sound incident from random directions at any point in the room after multiple reflections. In the stationary state a level of the diffuse field will be reached where the total power absorbed at the boundary areas and dissipated during propagation equals the sound power radiated by the sound source.

1.4.2 Reverberation Time

When the diffuse sound field is in a stationary state, and the sound source is switched off, the total acoustic energy in the room decays by absorption at boundary layers and dissipation during propagation. The absolute value of lost power, which represents the change of energy in the sound field per time unit, is proportional to the energy present in the sound field. This leads to a simple differential equation. The solution of the differential equation is an exponential decay of the energy which is equivalent to an exponential decay of sound energy and sound pressure and a linear decay of sound pressure level.

The reverberation time is defined as the time in which the sound pressure level of the diffuse sound field decays by 60 dB. Due to the linear decay of the sound pressure level, the reverberation time is independent of the absolute level.

With V being the volume of a room, S its surface area, $\overline{\alpha}$ the average absorption coefficient of the walls and α_L the coefficient for sound dissipation in the air, the reverberation can be calculated as

$$T_R/s \approx \frac{0.16 * V/m^3}{\overline{\alpha} * S/m^2 + 0.46 * \alpha_L / \frac{dB}{m} * V/m^3}$$

This equation is called Sabine's law. If the dissipation in air can be neglected, Eyring's law can be applied:

$$T_R/s \approx \frac{0.16 * V/m^3}{-\ln(1-\overline{\alpha}) * S/m^2}$$

1.4.3 Critical Distance

As set forth in section 1.1.4, the sound pressure generated by a point source in distance r decays approximately with $1/r$. The sound pressure of the diffuse field is approximately constant in the whole room. The total level generated by a point source in a reverberating room is shown by the red curve in the following diagram. The distance at which the sound pressure of the direct sound has the same magnitude as the sound pressure of the diffuse field, is called critical distance r_c. Closer to the source than r_c, the direct sound dominates. Further away than r_c the diffuse field dominates.

At the critical distance, the sound pressure level is 3 dB above the general level of the diffuse field.
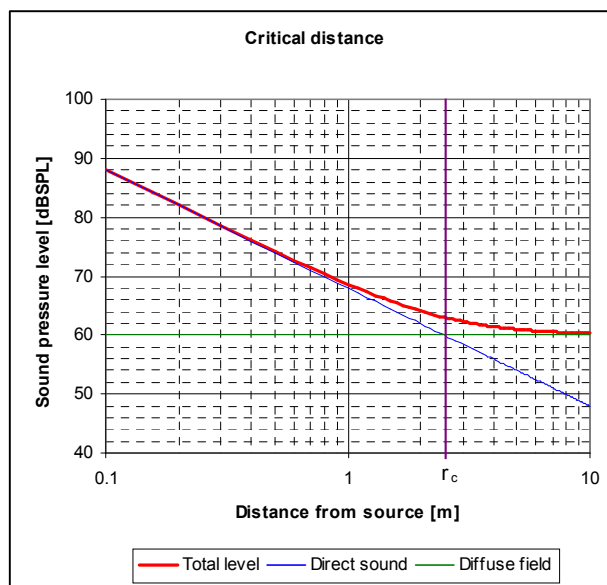

Figure 1: Sound pressure depending on the distance form the source, and critical distance

If the sound dissipation in the air can be neglected, the critical distance can be calculated from the volume of the room and the reverberation time as

$$r_C/m \approx \sqrt{\frac{V/m^3}{T_R/s}}$$

2 Measurement Principle

2.1 Reverberation Time

Reverberation time can be measured by generating a stationary diffuse sound field and measuring the slope of its decay after the sound source has been switched off.

As the decay of energy follows an exponential law, the sound pressure level as the logarithm of the sound pressure, plotted over time, decays approximately linearly. The slope of a linear approximation of the level decaying over time can be used to calculate the reverberation time.

Reverberation time is an integral property of a room which is more or less independent of the place of the observer in the room. Therefore the placement of the sound source and the measurement microphone has little influence on the result. The distance of the measurement microphone from the sound source must be much larger than the critical distance, in order to pick up only diffuse sound, and the sound source should radiate more or less as a point source without directivity. Both the sound source and the microphone should be placed far away from acoustic obstacles.

As periodic signals produce standing waves in reverberating rooms, random noise should be used as test signal. Absorption and therefore also the reverberation time depends strongly on the signal frequency. For assessment of room acoustics the dependence of the reverberation time on the frequency is of interest. Therefore bandpass-filtered noise like 1/3 octave noise or octave noise should be used. The level of the diffuse sound field is limited by the power capabilities of the sound source. To achieve a good dynamic range even in presence of noise in the room, a bandpass filter with the same frequency range as the test signal should be used on the measurement side.

2.2 Reflectogram

The easiest way to measure a reflectogram is to send an impulse from the sound source and record the sound pressure at the microphone over time. For a good signal-to-noise ratio a train of impulses can be used for which the microphone signal is averaged synchronously.

2.3 Critical Distance

For determination of the critical distance, a selective RMS measurement with long integration time is required to measure the octave or 1/3-octave level depending on the distance form the sound source. For rooms with a small critical distance, the sound source must be small enough to allow the measurement at close distance.

3 The Application Program

3.1 Installing the Software

3.1.1 Prerequisites

Running the application program requires option key UPV-K1. The VB.NET IDE (development environment) is not required for running the installed program. Firmware version 3.0 or later should be installed on the UPV.

3.1.2 Required File

Copy the installer "1GA61.msi" to a location on the UPV hard disk, e.g. "D:\R&S Software\Application Notes".

3.1.3 Installation

Start the installer "1GA61.msi" and follow the instructions on the screen.

3.2 Measurement Setup

3.2.1 Loudspeaker

There are special omnidirectional sound sources offered which are equipped with speaker chassis all around a regular body. In many cases sources made up by four or five speakers radiating in different directions or just one small speaker can be used as well.

3.2.2 Microphone

The microphone should have an omnidirectional directivity. Frequency response is uncritical because absolute level has no influence on the results.

A battery powered electret microphone can be directly connected to UPV Analyzer input 1. If necessary use appropriate adapters for the microphone connector. A measurement microphone usually needs a power supply inserted between the preamplifier on which the microphone cartridge is mounted, and the analyzer input.

3.2.3 Connections

Connect a suitable active speaker or speaker with power amplifier to generator output 1.

Connect an omnidirectional microphone to analyzer input 1.

3.3 Starting the Software

The installer creates shortcuts "1GA61 Room Acoustics" on the desktop and in folder "R&S UPV Applications" in the programs menu.

It is possible to assign one of the quick launch buttons in the UPV toolbar for starting the application program.
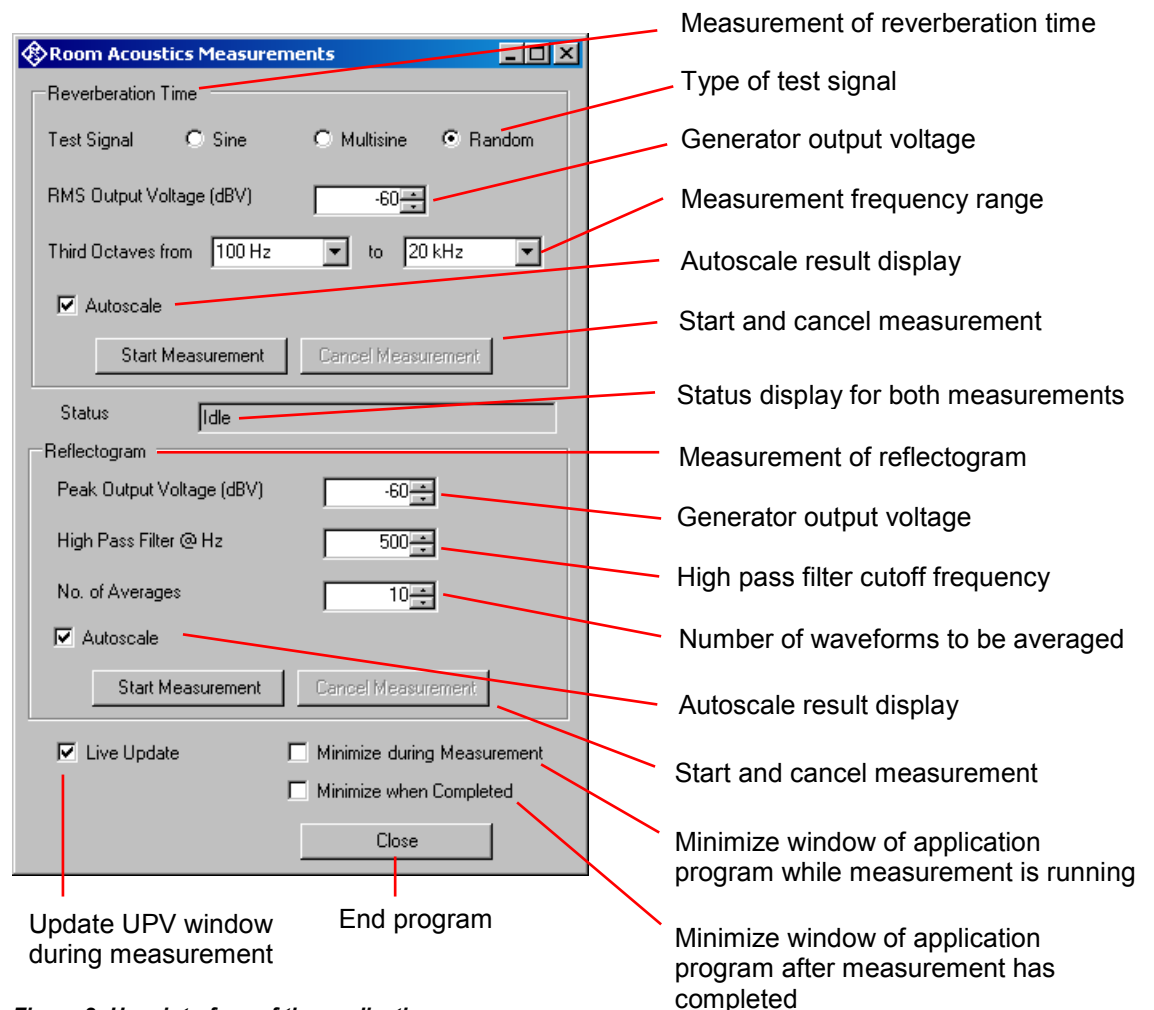
3.4 User Interface

Figure 2: User interface of the application program

3.4.1 Test Signal Type

Random signal is recommended. The other signal types are for evaluation purpose.

3.4.2 RMS Generator Output Voltage

The voltage entered here is the actual RMS value of the 3rd octave signal. The peak output of the generator is limited and depends on the crest factor of the signal and the bandwidth ratio of the filtered to the unfiltered signal.

If the peak generator output voltage resulting from the settings exceeds the capability of the generator output, a message is displayed and the measurement is aborted.

3.4.3 Measurement Frequency Range

The loudspeaker frequency range and the microphone frequency range must include the selected measurement frequency range.

3.4.4 Autoscale Result Display

The sweep graph which shows reverberation time over frequency after the measurement is complete is automatically scaled according to the maximum value when this checkbox is checked.

3.4.5 Status Display

Shows the progress during the measurement. With reverberation time measurement, the current center frequency is displayed. With reflectogram measurement, the average count is displayed.

3.4.6 Peak Output Voltage

Amplitude of the impulses at the generator output.

3.4.7 High Pass Filter

For improvement of the signal-to-noise ration, the analyzer input signal is high pass filtered. This parameter sets the cutoff frequency of the high pass filter.

3.4.8 Number of Averages

The algorithm acquires the specified number of waveforms and averages them sample by sample. This also serves to increase the signal-to-noise ratio.

3.4.9 Autoscale Result Display

The waveform graph which shows the averaged reflectogram after the measurement is complete is automatically scaled according to the maximum value when this checkbox is checked.

3.4.10 Live Update

Allows to watch the level over time during reverberation time measurement and the acquired waveforms before averaging during reflectogram measurement.

3.4.11 Minimize during Measurement and / or when Completed

The window of the application program is minimized at the described condition in order to put the UPV window on top of the screen content.

3.5 Sample Results

The following graphs have been generated using the hardcopy function of the UPV "Source" was set in the config panel to "Active Graphics", and a printer-friendly graphics profile has been loaded for "File".
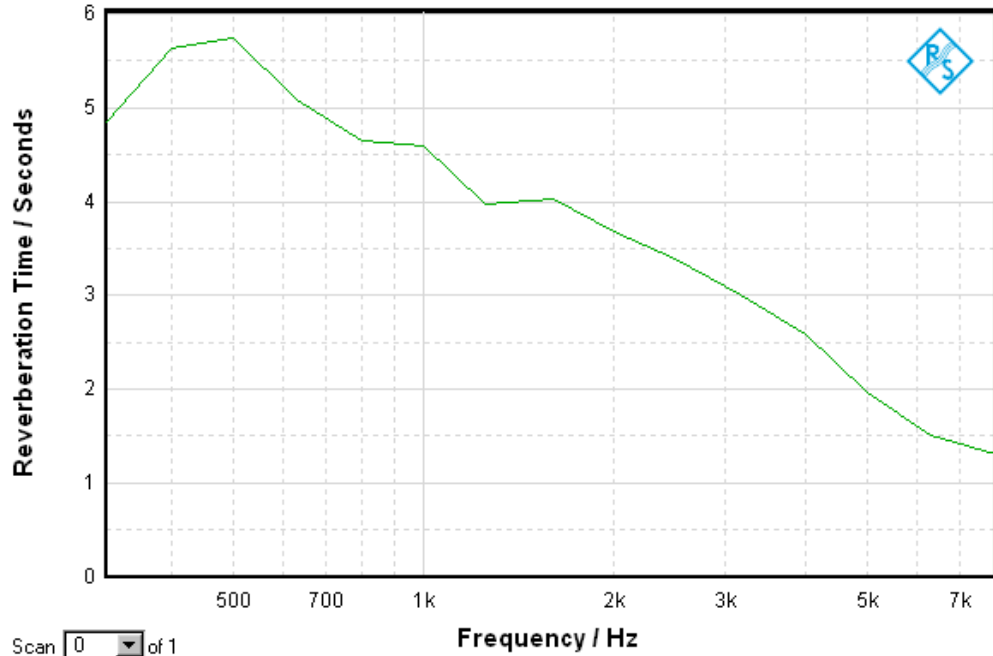

Figure 3: Example result of reverberation time over frequency

Figure 3 shows the reverberation time over frequency in an empty staircase almost without any absorbing surfaces.

An example of a reflectogram taken in a typical medium-sized office room is shown in figure 4. The first and highest peak is associated with the direct sound from the speaker which is placed in about 4 m distance from the microphone. The subsequent peaks are caused by the walls which are closest to the speaker and to the microphone, and by side walls half way between speaker and microphone. Smaller peaks occurring after 70 ms delay are caused by multiple reflections or by surfaces which are farther away from microphone and speaker.
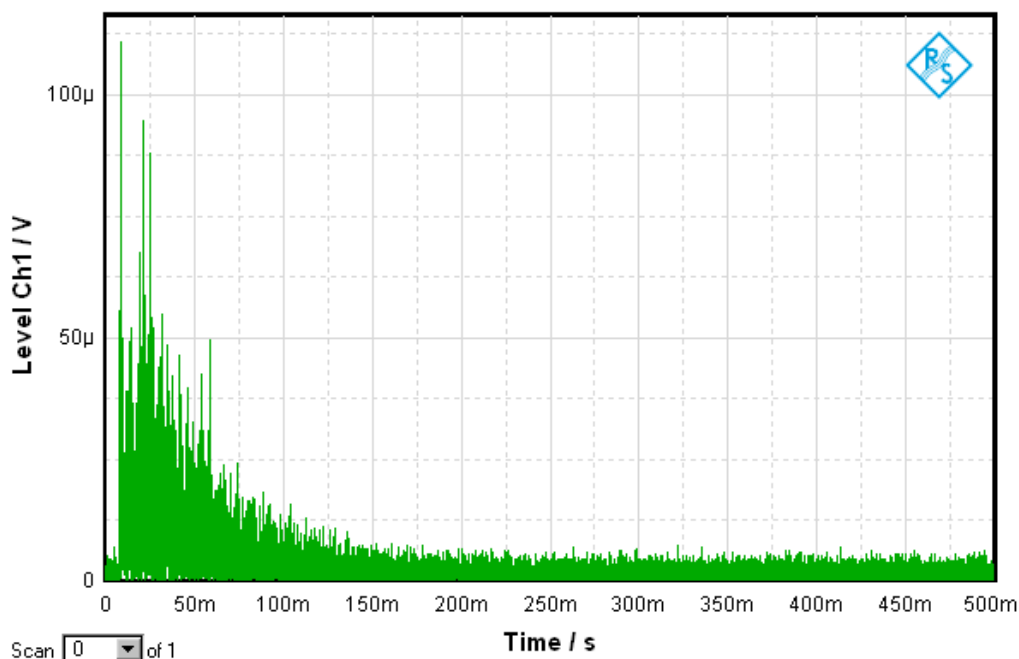

Figure 4: Example reflectogram

3.6 Working with the Source Code

3.6.1 Loading the Source Code to the IDE

- Download "1GA61_VB2003.zip", "1GA61_VB2005.zip" or "1GA61_VB2008.zip" according to the version of the VB.Net IDE installed on the UPV
- Unzip the file to the VB.Net projects folder on the UPV hard disk
- Open file "RoomAcoustics.sln" from the VB.Net IDE

3.6.2 Running the Program in the Debugger

When running measurements, the program loads setup files "Reverb.set", "Reverb_Result.set", "Reflectogram.set" and "Dirac_2s.ARB" from the program folder "C:\Program Files\Rohde&Schwarz\1GA61" of the application to the UPV firmware. If the program folder has not been created by installing the application program, it has to be created manually, and the files have to be copied there.

The program can be started in the debugger from the VB.NET IDE with menu item "Debug → Start" of the IDE menu or with the "run" button in the IDE tool bar (with green triangle).

3.6.3 Modifying the Program

The user interface and program code can be modified and enhanced in the editor according to special requirements.

Open the solution explorer in the IDE, right-click on "Form1.vb" and Click "View Designer" or "View Code", respectively.

To add a new control to the user interface in the designer, select a control from the toolbox on the left side of the IDE window and drag it onto the window of the application program in the designer. Edit the appearance of the control in the "Properties" window. Double-click the new control in the designer and enter code in the source code editor which is to be executed upon actuation of this control.

4 Literature

[1]   Jürgen Meyer: "Acoustics and the Performance of Music: Manual for Acousticians, Audio Engineers, Musicians, Architects and Musical Instrument Makers", Springer, 5th Edition 2009

[2]   H. Kuttruff: "Raumakustik", in "Taschenbuch der Technischen Akustik", edited by M. Heckl and H.A. Müller, Springer, 2nd Edition 1994

[3]   M.Zollner, E. Zwicker: "Elektroakustik", Springer, 3rd Edition 1993

5 Ordering Information

Ordering Information		
Type of instrument		
Description	**Instrument type**	**Ordering number**
Audio Analyzer	R&S®UPV or R&S®UPV66	1146.2003.02 1146.2003.66
Universal Sequence Controller	R&S®UPV-K1	1401.7009.02

About Rohde & Schwarz

Rohde & Schwarz is an independent group of companies specializing in electronics. It is a leading supplier of solutions in the fields of test and measurement, broadcasting, radiomonitoring and radiolocation, as well as secure communications. Established more than 75 years ago, Rohde & Schwarz has a global presence and a dedicated service network in over 70 countries. Company headquarters are in Munich, Germany.

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