TFA Time Frequency Analysis S61

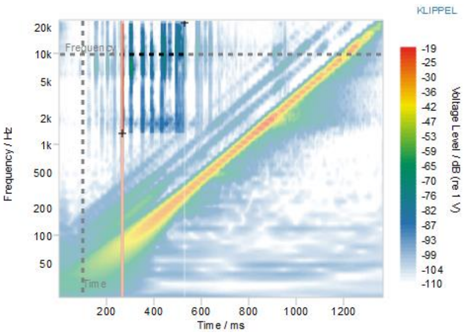
Software of the KLIPPEL Analyzer System (Document Revision 1.6)

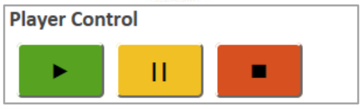
FEATURES

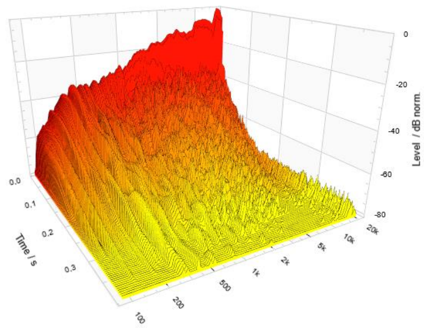
- Spectrogram analysis
- Wavelet transform
- Auditory filter bank
- Short-time Fourier Transform (STFT)
- 3D waterfall plot
- Detailed signal characteristics
- Playback of filtered waveform
- Compatible with *QC 3DL*

APPLICATION

- Defect (Rub & Buzz) analysis and auralization
- Detecting acoustical and mechanical resonators (room modes, rocking modes)
- Visualizing signal distortion







DESCRIPTION

The Time Frequency Analysis (TFA) is a post-processing module that visualizes the characteristics of any audio signal over time and frequency. The processing is based on four different methods (*Wavelet Transform*, *Short Time Fourier Transform*, Cumulative Spectral Decay, *Filter Bank*) and can be applied to waveforms and impulse responses generated by the KLIPPEL Analyzer System or imported from external sources such as audio files. For additional subjective diagnostics, the TFA integrates a dedicated player function for auralizing signal parts that can be directly selected in the spectrogram with variable playback rate.

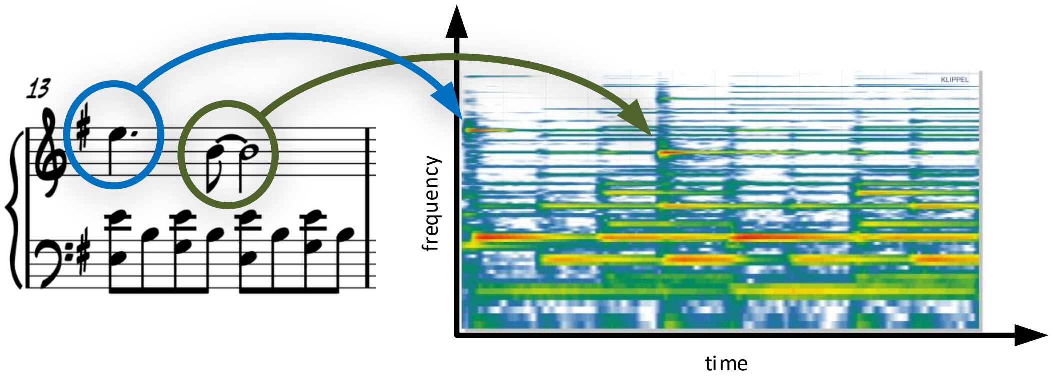
Item number:	1000-920

CONTENT

1 Principle

Time-frequency plots (spectrograms) are a common tool in audio analysis and forensics to monitor the spectral information of audio signals over time in an intuitive way.

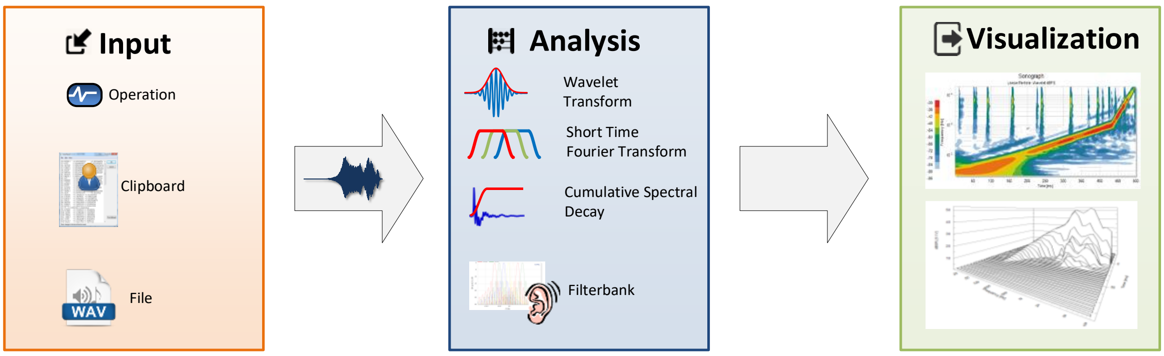
Similar to a music sheet, the spectrogram visualizes which frequencies are present at which time as shown in the music example below.



Applied to audio systems testing these methods provide highly valuable diagnostic information about defects or other abnormal behavior. Particularly when processing responses of sinusoidal test signals such as chirps, the different symptoms in audio reproduction can be identified and separated in the spectrogram.

Another common application is the analysis of impulse responses to visualize the spectral decay over time that helps to identify mechanical or acoustical resonance and calculation of the frequency-dependent reverberation time from room impulses.

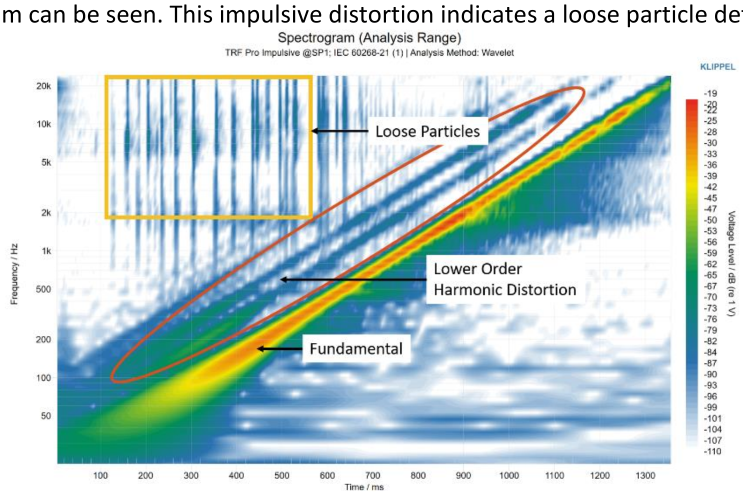
Based on four different methods, the Wavelet Transform (WT), the Short Time Fourier Transform (STFT), the Cumulative Spectral Decay (CSD) or a Bark scaled Filter Bank Analysis (FBA), the TFA decomposes the input signal and visualizes the signal characteristics over frequency and time.



2 Examples

Defect Analysis – Rub & Buzz

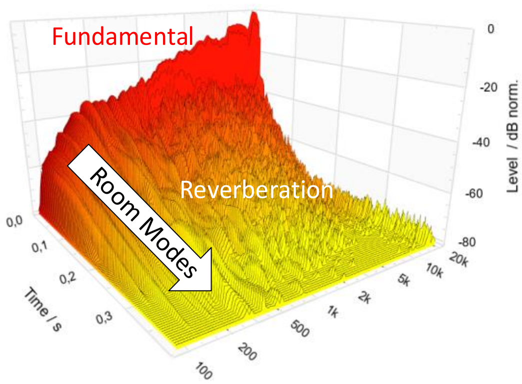
The example below shows the SPL spectrogram of a chirp measurement of a defective drive unit imported from a ***Transfer Function Measurement*** (TRF).
As seen in the picture, the frequency of the fundamental increases logarithmically with time. The “regular” lower-order harmonic distortions appear in the spectrogram above the fundamental as lines which are parallel to the fundamental. In this example the 2nd and 3rd order harmonics are very distinct. From roughly 100 ms to 650 ms vertical lines in the spectrogram can be seen. This impulsive distortion indicates a loose particle defect.



When enabling the playback feature with ***Bandpass Filter*** the distortion can be selected directly in the spectrogram and played back through your default Windows audio device.

Waterfall spectrum - Room Response

The graph shows the waterfall spectrum of a loudspeaker’s impulse response measured in a normal office room. The result is a 3D representation of the ***Spectrogram*** and shows how much the speaker excites the room over time. At low frequencies there are distinct narrow-band resonances in the room that have a low damping and thus a long ringing. At higher frequencies also an influence of the early reflections and the reverberation of the room is visible, but the higher frequencies have higher damping and thus a faster decay.



3 Requirements

3.1 Hardware

Operation	Since the TFA is a post-processing application, no dedicated analyzer hardware is required. However, a KLIPPEL USB license dongle is required to run the TFA on a *Windows* PC.

Playback	In order to use the playback function of the TFA, a playback device is required

3.2 Software

	Running the TFA requires KLIPPEL dB-Lab 212 or higher and a TFA license.

4 Processing Methods

4.1 Wavelet Transform (WT)

The *Wavelet Transform* is an analysis method that correlates a signal with particular basic functions, so called Wavelets. Depending on the frequency, the length of the wavelet varies to optimize the relation between time and frequency resolution for each frequency band.

Basic Wavelet Transform [1]

$$Y^{\psi}(a,b) = \left| \frac{1}{\sqrt{|a|}} \int_{-\infty}^{\infty} x(t)\psi^{*}\left(\frac{t-b}{a}\right) dt \right|^{2}$$

$x(t)$	input signal in time domain
$\psi^{*}\left(\frac{t-b}{a}\right)$	conjugate complex wavelet function (normalized)
a, b	scaling parameters

Complex Gaussian Morlet Mother Wavelet – Time Domain [2] [3]

The analysis uses the complex Gaussian Morlet wavelet which is represented in time domain by

$$\psi(t) = \frac{1}{\sqrt{\pi B}} e^{j\omega_0 t} e^{-\frac{t^2}{B}}$$

and frequency domain by

$$\Psi(\omega) = e^{-(\omega - w_0)^2 \frac{B}{4}}$$

with

$$B = \frac{4}{(\omega_0 BW)^2}$$

B	Bandwidth parameter
ω_0	Wavelet center frequency
BW	Bandwidth in Octaves

4.2 Short Time Fourier Transform (STFT)

The *Short Time Fourier Transform* uses a window function that is shifted successively over a time signal. Calculating the Fourier Transform of each windowed section provides the spectral information at each time interval. Limited by the uncertainty relation the results of this method are a compromise between frequency resolution and time resolution. The signal level over time and frequency is defined by:

$$Y(t,f) = \left| \int_{-\infty}^{\infty} e^{-j2\pi f\tau} x(\tau)\, h(\tau - t) d\tau \right|^{2}$$

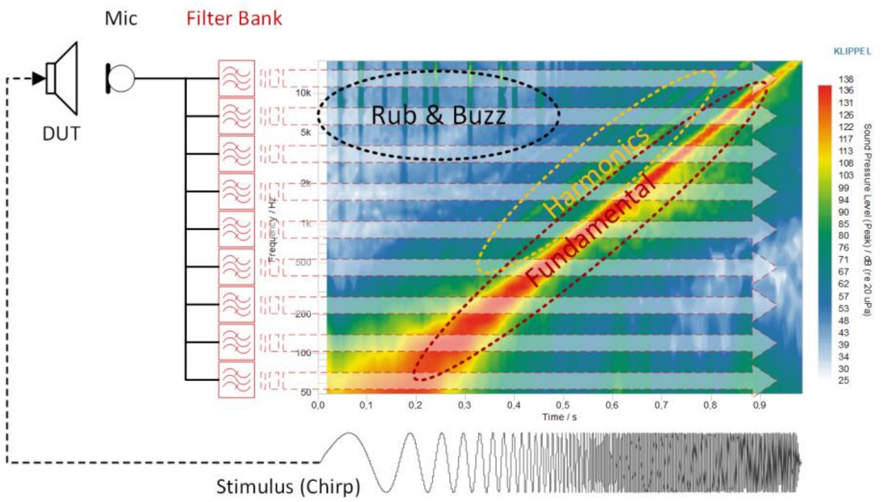
4.3 Cumulative Spectral Decay

The CSD shows the power decay of an impulse response $h(t)$ over time across different frequencies (e.g., octave bands). By using a shifted time window $u(t)$, like the Heaviside step function, CSD determines how quickly the energy diminishes at various frequencies.
This is essential for evaluating room acoustics (reverberation time, room modes) as well as for designing and optimizing audio systems (mech. acoustical resonances).

$$|Y(t,\omega)|^2 = |\mathcal{F}\{u(t-\tau)h(\tau)\}|^2$$

4.4 Filter Bank (FBA)

The Filter Bank Analysis (FBA) separates the spectral components of an input signal using multiple auditory band-pass filters according to *ITU-R BS1387-1* recommendation. The center frequencies are evenly distributed over a Bark frequency scale (roughly logarithmic).
The FBA is able to visualize short-time effects such as impulsive noise or the fluctuation of an amplitude-modulated signal. The time resolution in lower frequencies is the best of all of the other methods.
The figure below shows a schematic example for a typical filter bank use case: the analysis of a defective speaker's response to a chirp signal.



5 Parameters

5.1 Input

Select	The parameter specifies from where the data will be imported.	
	File	Absolute or relative path to a wave file.
	Directory	Absolute or relative path to a directory containing wave files.
	Clipboard	Paste waveform curve from other dB-Lab operations.
	Operation	Import waveforms from other operations of the KLIPPEL Analyzer system
	Imported	Select data which is already imported.
Impulse Response	This option shall be activated when an imported wave file or data imported via clipboard shall be interpreted as an impulse response	
Store File	If checked an imported long wave file will be stored in the attachment.	

5.2 Analysis

Analysis Method	This parameter sets the time-frequency analysis method • None • Wavelet Transform • Short Time Fourier Transform • Cumulative Spectral Decay • Filter Bank
Analysis Resolution & Advanced Mode	The ***Advanced Mode*** checkbox is recommended for users with some experience in the field of time frequency analysis and offers more detailed settings to tune the analysis in the preferred way. When Advanced Mode is inactive (default), many parameters are hidden and three ***Analysis Resolution*** are available as processing templates. • Frequency Priority • Default

	• Time Priority
Transform Normalization	The normalization of the Wavelet Transform and the Short-Time Fourier-Transform can be adjusted to suit the signal to be analyzed: • Periodic Signals • Impulses
Time Resolution Reduction Mode	This parameter is only visible for the wavelet transform and the filter bank since the time resolution of both analysis methods is reduced to limit plot data size. The user may choose between two calculation modes: • RMS • Peak
Time Resolution Spectrogram	The user can choose between four predefined time resolutions or specify a custom time resolution. The predefined time resolutions are: • Coarse (500 ms) • Medium (50 ms) • Fine (5 ms) • QC 3DL Resolution
Analysis Range	There are dedicated parameters for selecting the frequency and time range of the input signal to be analyzed. These values can also be adjusted via cursors • Start Time • End Time • Frequency Minimum • Frequency Maximum
Wavelet Transform	
Bandwidth	Wavelets have a constant octave fraction bandwidth which affects the time resolution of the used wavelets. With a high bandwidth the wavelet will be sensitive for short effects like impulses and defects. Smaller bandwidths (< 1/4) for example are used for detecting resonances. Available bandwidth options as octave fractions: • 1 • 1/2 • 1/3 • 1/4 • 1/6 • 1/8 • 1/10 • 1/12 • 1/16
Short-Time Fourier Transform	
Window Type	Window function which is used for the STFT (e.g.: Hann, Rectangular, Tukey)
Window Time	Length of the time windows
Window Overlap	Overlapping of the windows in percent
Cumulative Spectral Decay	
Window Type	Window function to extend the step function in order to reduce artifacts • Von Hann • Hamming • Triangle
Rise Time	Rise time of the window function from 10 % to 90 %
Calculate T60	Activates the frequency-dependent reverberation time $T_{60}(f)$ calculation.
Automatic Time Range	Sets the processing range for the frequency-dependent reverberation time calculation automatically. Only available if “Calculate T60” is activated.
Filter Bank	
Number of Filters	Number of filters used for the analysis. Available options: • 10 • 20

	• 30 • 40 • 50 • 60 • 70 • 80 • 120

5.3 Display

Log. Freq.	Sets logarithmic frequency axis in all plots.	
Spectrum		
Spectrum Resolution Reduction	If enabled, the resolution of the Input Spectrum and Transfer Function Magnitude windows are reduced. The following target resolutions are available: • R10 (3 pts/oct) • R20 (6 pts/oct) • R40 (12 pts/oct) • R80 (24 pts/oct) • By resolution (custom)	
3D Display		
3D Time Resolution	Sets the time resolution of the 3D Plot window	
Spectrogram		
Result Normalization (Spectrogram)	With this option, the spectrogram level can be normalized to 0 dB	
	None	No normalization
	To Peak	The results will be normalized to the overall peak level of the spectrogram
	To fundamental	Normalizes every individual frequency channel to its peak value.
Result Range	(opt.) displayed level range in dB	
Result Max	(opt.) maximum displayed level in dB	
Color Map	The Color Map defines the color scale used for representing the level over time and frequency in the Spectrogram window. Various pre-defined color maps are available (default: *Jet*).	
Color Map Resolution	This property sets the granularity of color scale used to display the result in the ***Spectrogram*** window • Low • Mid • High • Custom	
Custom Color Map	In addition to the pre-defined color maps a custom color map may be used by selection the ***Color Map*** option ***Custom***. The custom color map is defined as an n×4 matrix. The first column is the spectrogram level associated with the color. The three other columns define the RGB colors. Thus, n corresponds to the number of levels associated with a color.	
Transparency Color	Adjusts the color of the overlay on the ***Spectrogram***'s non-playback area, which excludes specific time and frequency ranges from playback.	
Highlight Max Value	If enabled, the maximum value of the displayed ***Spectrogram*** will be highlighted with black color.	
Time/Frequency Cursor	When cursors are activated two dashed lines are shown in the spectrogram window and the Level at ***Time Cursor*** and ***Level at Frequency Cursor*** plots will be shown. The positions of the cursors correspond to the parameters ***Time Cursor*** and ***Frequency Cursor***.	

5.4 Player

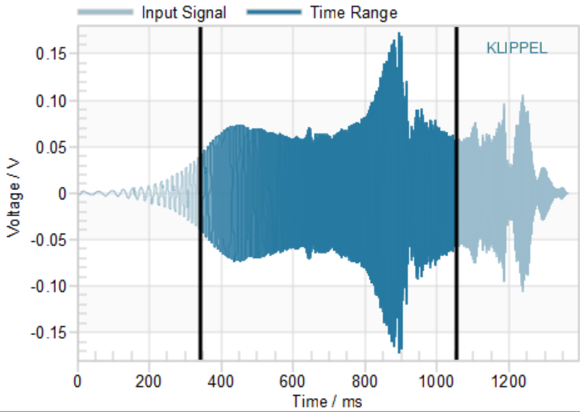
Input Level	Relative level of the input signal's peak value to full-scale digital amplitude in dB.
Normalize Playback	When activated, the input waveform in playback range will be normalized before playback.
Set Playback Level	Sets the input signal's peak value in relation to full-scale digital amplitude in dB.
Playback Rate	The playback rate of a signal may be changed with this parameter affecting speed and pitch.
Number of Loops	The number of times the input waveform will be played back may be specified.
Enable Bandpass Filter	When activated the imported audio signal within the playback range specified in the is band-pass filtered before playback.
Lower/Upper Cutoff Frequency	These parameters determine the lower/upper frequency limit for the playback band-pass filter.
Export	The full or only the selected (and filtered) waveform can be exported to a wave file.

6 Limitations

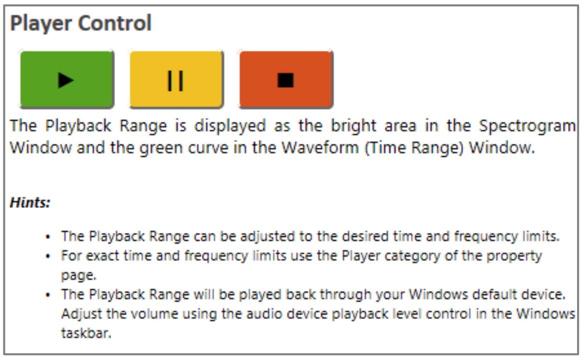
6.1 Setup Parameter Limits

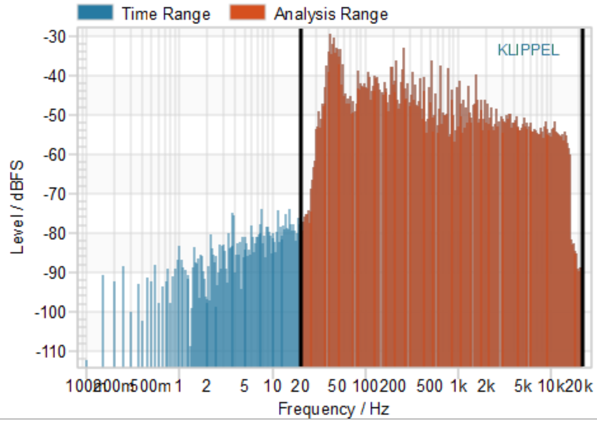
Parameter	Symbol	Min.	Typ.	Max.	Unit
WAV FILE IMPORT					
Sampling Frequency	f_{sample}	6	48	192	kHz
Bit depth		8	16	32	Bits
File Length	t_{signal}	0.01	5	3600	s
INPUT					
File / Directory	Only WAV files are supported.				
Clipboard / Operation	Only signals up to a length of 950000 samples (≈19.79 s @ 48 kHz)				
PLAYER					
Set Playback Level	L_{Playback}	-100	0.0	0.0	dBFS

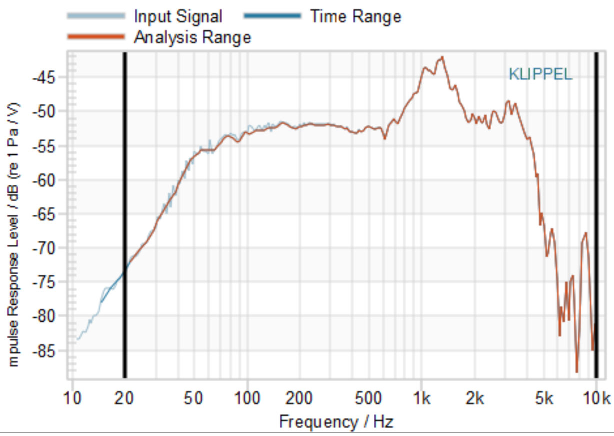
7 Results

Waveform	The Waveform shows the imported signal's waveform. By using the provided cursors, the processing time range can be adjusted. If a long wave file is imported, this window will show the full wave file content as a bar graph. The bar graph shows peak, bottom and root mean square values of time intervals of the imported wave file. A detailed view of the selected processing time range is given in the Waveform (Time Range) window. 

<table>
<tr><td>Player Control</td><td>The Player Control window gives access to the control of the playback functionality.


</td></tr>
<tr><td>Spectrum</td><td>The Spectrum window shows the Fourier transform of the imported waveform. By shifting the cursors, the frequency range of the time-frequency analysis can be modified.


</td></tr>
<tr><td>Transfer Function Magnitude</td><td>This plot shows the transfer function magnitude level in case an impulse response was imported. By shifting the cursors, the frequency range of the time-frequency analysis can be modified.


</td></tr>
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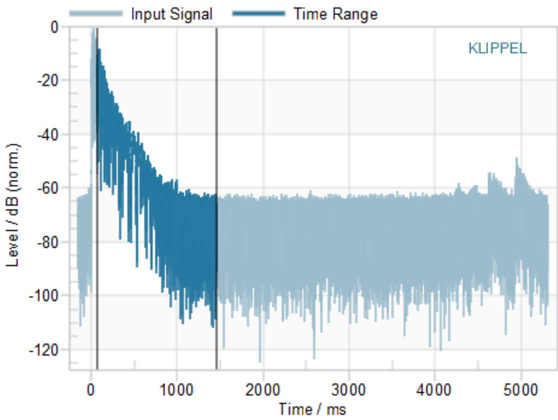
Energy Time Curve

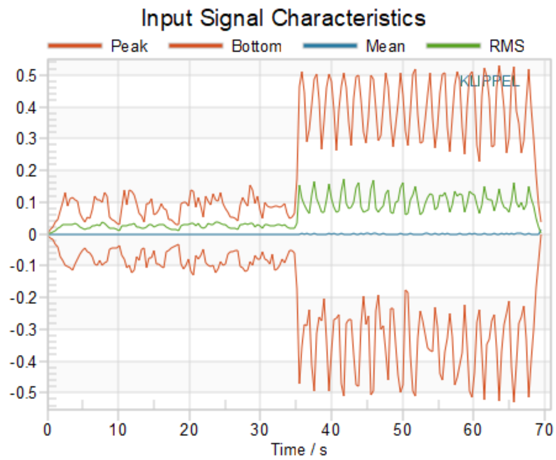
The Energy Time Curve is typically used to analyze impulse responses showing the signal energy decay over time. It is normalized to 0 dB. For example, this can be used to determine the reverberation time of a room impulse response.



If the imported audio signal is not an impulse response, the signal envelope of the selected analysis time range will be displayed.

Input Signal Characteristics

This window shows the standard signal characteristics (e.g., mean, rms, peak, etc.) of the full audio signal over time.



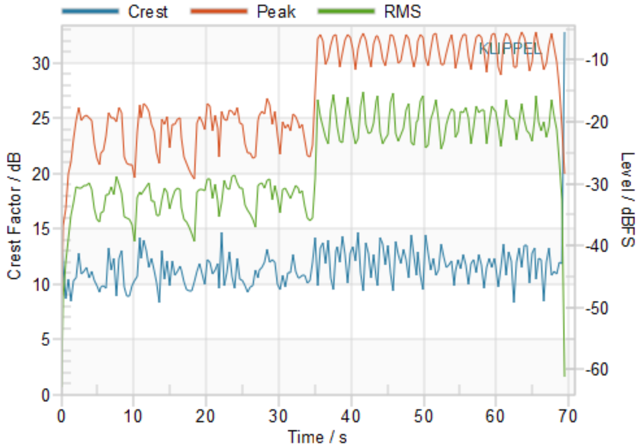
Additionally, accumulated signal characteristics are provided in the *Table Results + Settings* window.

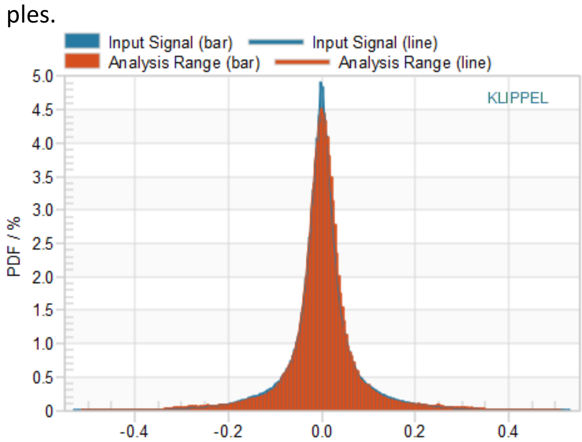
Results + Settings

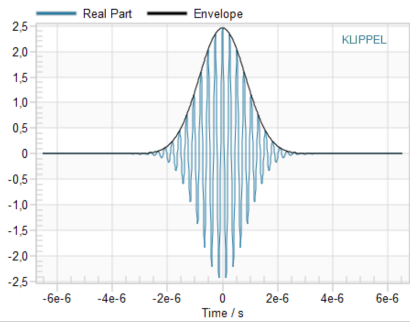
Symbol	Input	Time	Playback	Unit	Comment
Signal Characteristics					
$y_{abs,max}$	0.53	0.51	1		Absolute peak value of signal
y_{peak}	0.53	0.51	1		Peak value of signal
y_{bottom}	-0.53	-0.51	-0.59		Bottom value of signal
y_{rms}	0.077	0.079	0.11		Root Mean Square of signal
y_{mean}	2.5e-05	-8.4e-05	4.7e-05		Mean of signal
Crest Factor	17	16	19	dB	Crest factor of signal
Kurtosis	8.4	8.4	8.2	-	Kurtosis of signal

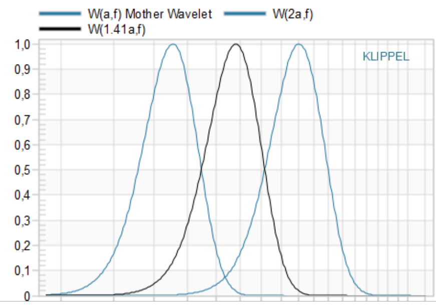
Symbol	Value	Unit	Comment
y(t) Input Waveform			
t_{signal}	69.4	s	Length of the imported signal
$N_{channels}$	2	-	Number of channels
$N_{samples}$	3059638	-	Number of samples
f_{sample}	44.1	kHz	Sampling Frequency
Impulse response	No	-	Imported an impulse response

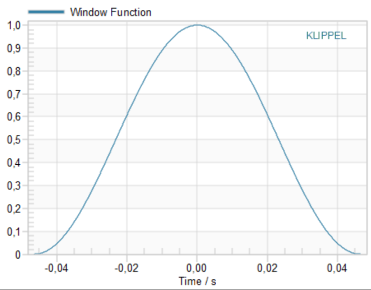
<table>
<tr><td>Input Crest Factor</td><td>The crest factor is the ratio of peak and RMS value of a signal. This graph shows the crest factor of the input signal over time.

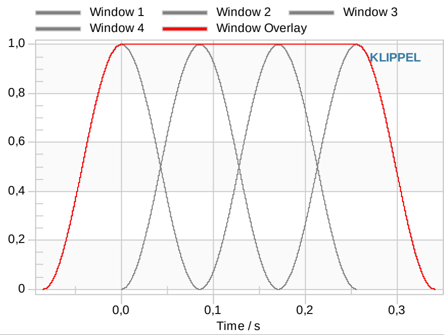

</td></tr>
<tr><td>PDF Probability Density Function</td><td>The graph shows the probability density function of the imported audio signal's samples.


</td></tr>
<tr><td>Wavelet Waveform/Spectrum</td><td>In case the Wavelet transform is used as the analysis method, the waveform and spectrum of the mother wavelet are shown.



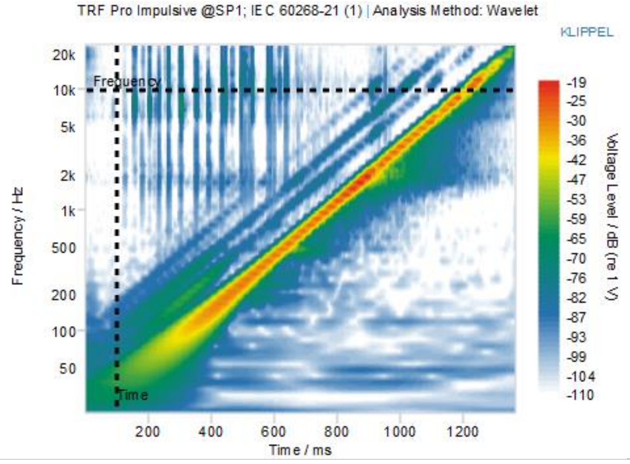

</td></tr>
<tr><td>Window Function & Overlapped Windows STFT</td><td>The left graph shows the window function (e.g., von Hann-Window) which is used for the short time Fourier transform while the graph on the right shows the window overlap over time.




</td></tr>
</table>

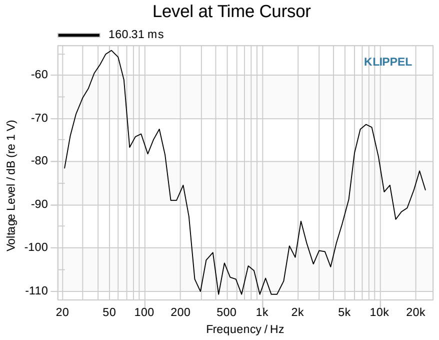
Spectrogram

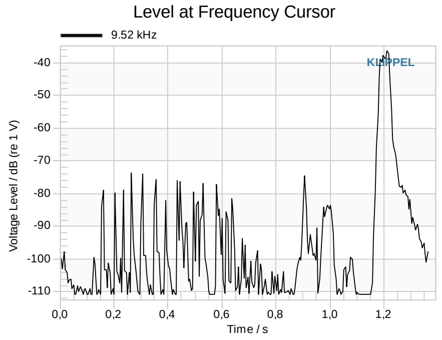
This graph visualizes the signal level over frequency and time. The signal level is represented by a color scale. This is considered the main result window of the TFA module.



Level at Time/Frequency Cursor

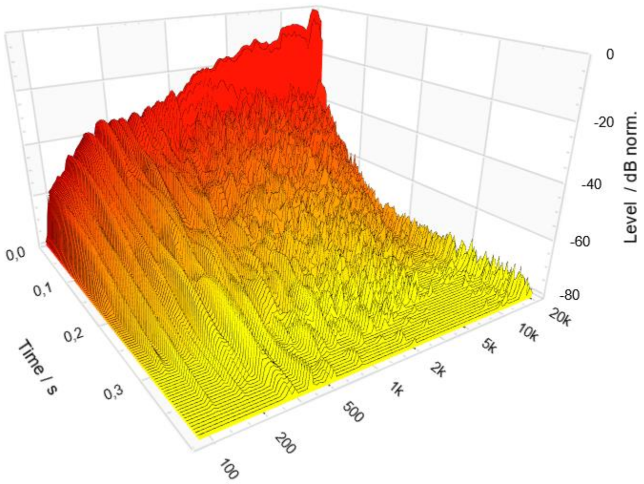
These two plots show the level of the analyzed signal over frequency or time for one specific point in time or frequency. Based on the time and frequency cursors shown in the Spectrogram, they can be interpreted as cross sections.



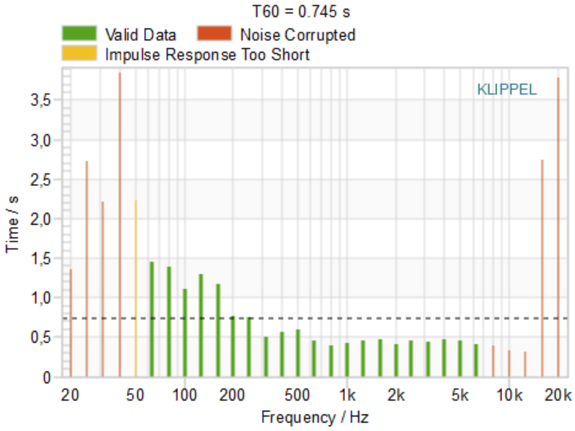


3D Plot

This is a 3D representation of the spectrogram to visualize the level over time.



T60(f) Reverberation Times	It shows the frequency-dependent reverberation times. In case the T60 reverberation time cannot be determined, e.g. when the data is corrupted by noise or the impulse response is too short, the corresponding frequency bands are marked.



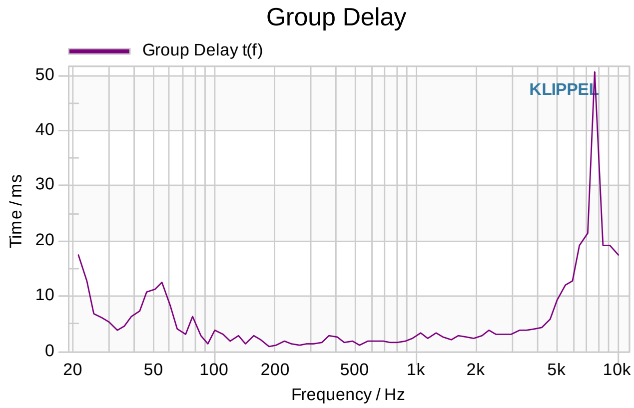
Additionally, a table is provided with all the frequency-dependent reverberation times.

T60(f) Reverberation Times

T_{60} = 0.737 s

f / Hz	$T_{60}(f)$ / s	Info
31.50	5.645	Noise Corrupted
40.00	4.869	Noise Corrupted
50.00	2.487	Noise Corrupted
63.00	1.897	-
80.00	1.305	-
100.00	1.262	-
125.00	0.918	-
160.00	0.783	-
200.00	0.720	-

Group Delay	In signal processing, the group delay is the time delay of the amplitude envelopes of the various frequency components of a signal through a device under test, and is a function of frequency for each component. Delays caused by resonators (e.g., vented boxes) can be evaluated with the group delay. This result is only available for the Wavelet transform and when an impulse response was imported.



8 References

8.1 Related Products	• S6 – Transfer Function (TRF) • S7 – Transfer Function Pro (TRF-Pro) • S63 QC 3DL – Spectrogram 3D Limits
8.2 Standards	• *Rec. ITU-R BS1387-1* - Method for objective measurements of perceived audio quality
8.3 Literature	*[1] P. Goupillaud, J. Morlet and A. Grossmann, "Cycle-Octave and related transforms in seismic signal analysis," Geoexploration, vol. 23, pp. 85-102, April 1984.* *[2] D. B. Keele, "Time-Frequency Display of Electroacoustic Data Using Cycle-Octave Wavelet Transforms," in Audio Engineering Society Convention 99, 1995.* *[3] S. J. Loutridis, "Decomposition of Impulse Responses Using Complex Wavelets," J. Audio Eng. Soc, vol. 53, no. 9, pp. 796-810, September 2005.* *[4] L. Cohen, Time-Frequency Analysis, Prentice Hall PTR, 1995.* *[5] O. Rioul and M. Vetterli, "Wavelets and signal processing," IEEE Signal Processing Magazine, vol. 8, no. 4, pp. 14-38, #oct# 1991.* *[6] S. G. Mallat, "A theory for multiresolution signal decomposition: the wavelet representation," IEEE Transactions on Pattern Analysis and Machine Intelligence, vol. 11, no. 7, pp. 674-693, #jul# 1989.* *[7] W. Klippel, „Physical and Perceptual Evaluation of Electric Guitar Loudspeakers" (download)*

Find explanations for symbols at:

http://www.klippel.de/know-how/literature.html

Last updated: October 16, 2023