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GATING IN TIME DOMAIN AS A TOOL FOR IMPROVING THE SIGNAL-TO-NOISE RATIO OF BEAM TRANSFER FUNCTION MEASUREMENTS

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ABSTRACT

For the measurement of Beam Transfer Functions the signal-to-noise ratio is of great importance. In order to get a reasonable quality of the measured data one may apply averaging and smoothing. In the following another technique called time gating to improve the quality of the measurement will be described. By this technique the measurement data are Fourier transformed and then modified in time domain. Time gating suppresses signal contributions that are correlated to a time interval when no interesting information is expected. Afterwards an inverse Fourier transform leads to data in frequency domain with an improved signal to noise ratio.

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Gating in time domain as a tool for improving the signal to noise ratio of Beam Transfer Function measurements

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Introduction:

In order to perform Beam Transfer Function (BTF) measurements the beam is excited through a kicker by an external signal and the response to this excitation is measured by a pickup. The exciting signal consists of an electrical noise of a given bandwidth or of a sine wave with a frequency, which is stepped over a certain range. To compare the beam response with the excitation signal a Fast Fourier Transformer (FFT) often implemented as a Chirp-Z transform is used to analyse the response to noise excitation or a Network Analyser (NA) is taken to record the response to stepped frequency excitation. The measured response is the Beam Transfer Function and consists of amplitude and phase data as a function of the exciting frequency.
Since the signals are often noisy it is in general necessary to use a certain number of averages in order to get a reasonable signal. Also smoothing may be applied.
In the following another technique to improve the signal to noise ratio of BTF measurements will be described. It analyses only the information of the beam response that corresponds to a time interval, when the interesting information is expected. In other words the time gating separates the noise correlated with the signal from the non correlated noise.
Examples with signal simulations and longitudinal BTF measurements with beam will be given.

The time gating technique:

The amplitude and phase data of a measurement can be used as input data to perform a Fourier transformation into time domain [Fig. 1a-c]. Looking at the real part of this complex Fourier transform one can determine a time range (sometimes called time gate), which includes the interesting information of the beam response [see gate markers in Fig. 1c]. The width of this "interesting interval" is given by the response time of the beam. The time range outside of this time gate will then mostly consist of signal contributions coming from other sources (noise of pickup amplifiers etc.).
Once one has determined this time gate (carefully!) the inverse Fourier transform back into frequency domain can be performed using only the information included in the specified time range. The procedure is called time gating. It suppresses the signal contributions and noise outside of the interesting time interval by weighting the data in time domain by a special window [1,2] with a width equal to the desired time gate [Fig. 1d]. Using these weighted data for the inverse Fourier transform one obtains a much better signal to noise ratio in frequency domain [Fig. 1e].
Ideally the time gate includes all the information of the beam response and the signal contributions outside of this gate consist only of noise. In this ideal situation the time gating procedure analyses only the information, which includes a special phase correlation and suppresses all non correlated contributions.

Simulations have been done with the NA HP8753B to test the principle of the time gating technique. The calculation of the Fourier transform is an option of this NA.

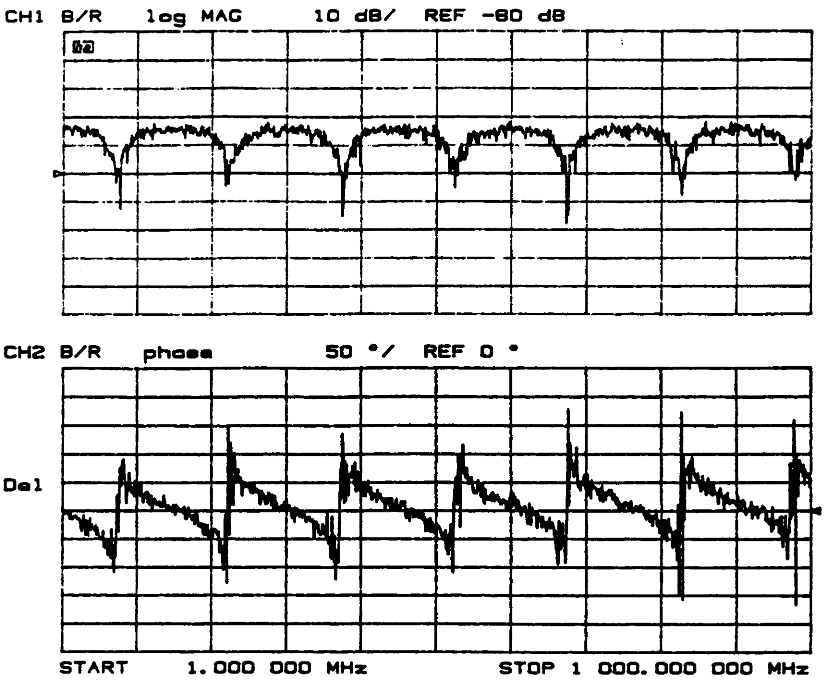


Fig. 1a: *Amplitude in dB (upper) and phase in degree (lower) of a simple notch filter (floating cable) against frequency from 1 MHz to 1 GHz, resolution 1601 points*

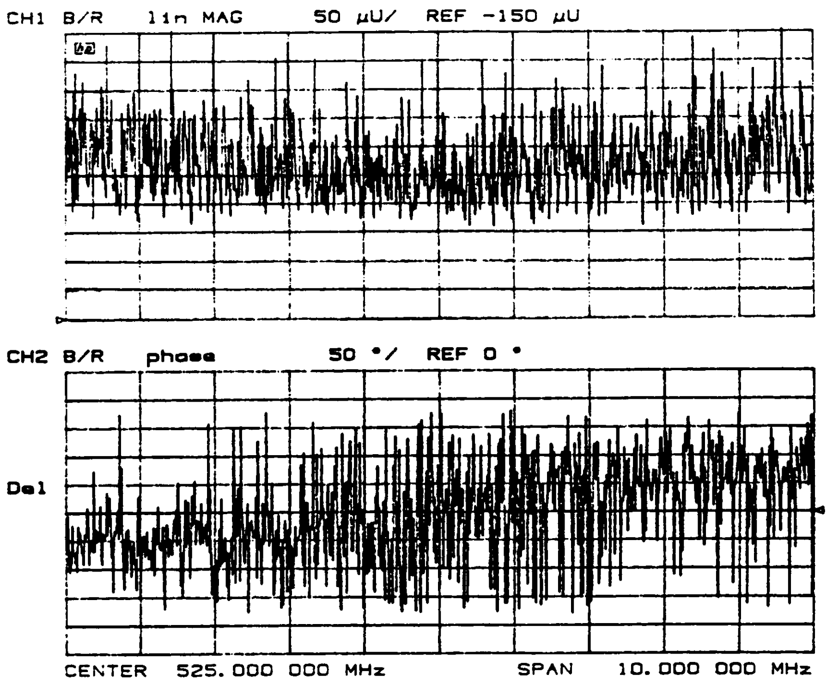


Fig. 1b: *The same signal as shown in Fig. 1a, but amplitude with a linear scale and frequency from 520 MHz to 530 MHz (this frequency interval includes one resonance)*

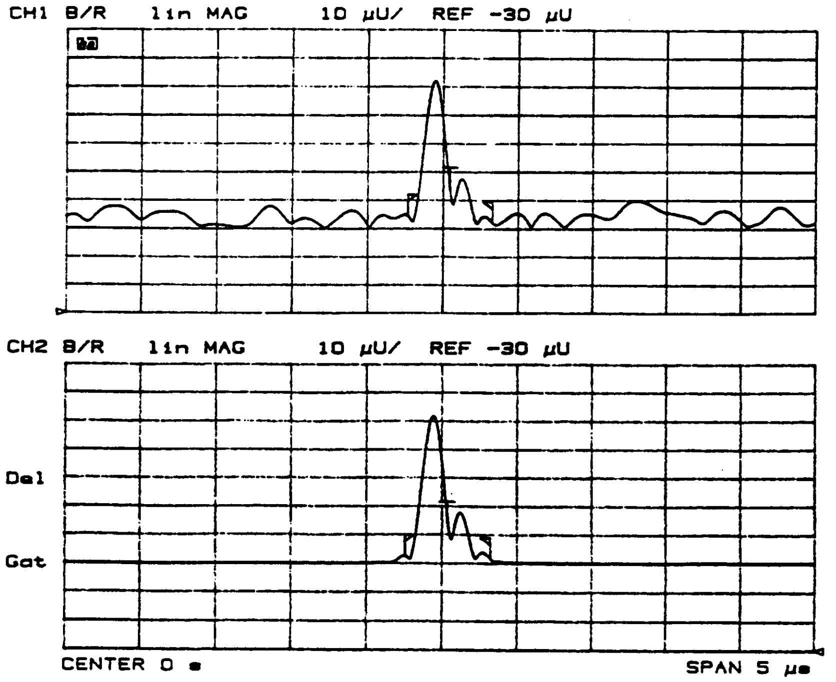
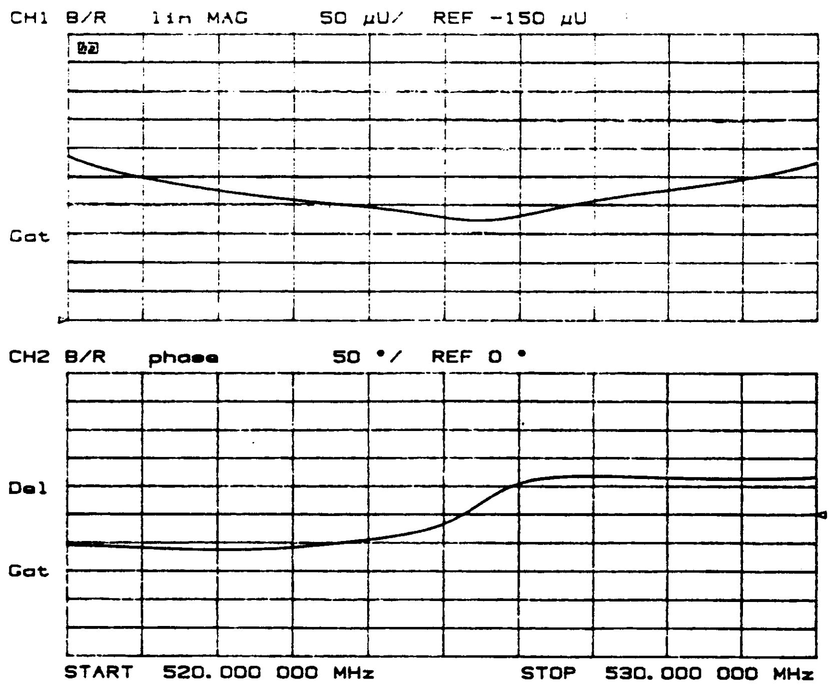


Fig. 1c

Fig. 1d

<u>Fig. 1c,d:</u> *The Fourier transform into time domain of the signal of Fig. 1b, time axis in the range from -5µs to +5µs, without (upper) and with (lower) gating*



<u>Fig. 1e:</u> *The signal of Fig. 1b in frequency domain after time gating*

Fig. 2a shows a longitudinal broad band BTF measured at the CERN Antiproton Ring. The time gating technique described above has been applied to the measured data [Fig. 2b]. The result are the smooth BTF amplitude and phase of Fig. 2c in frequency domain.

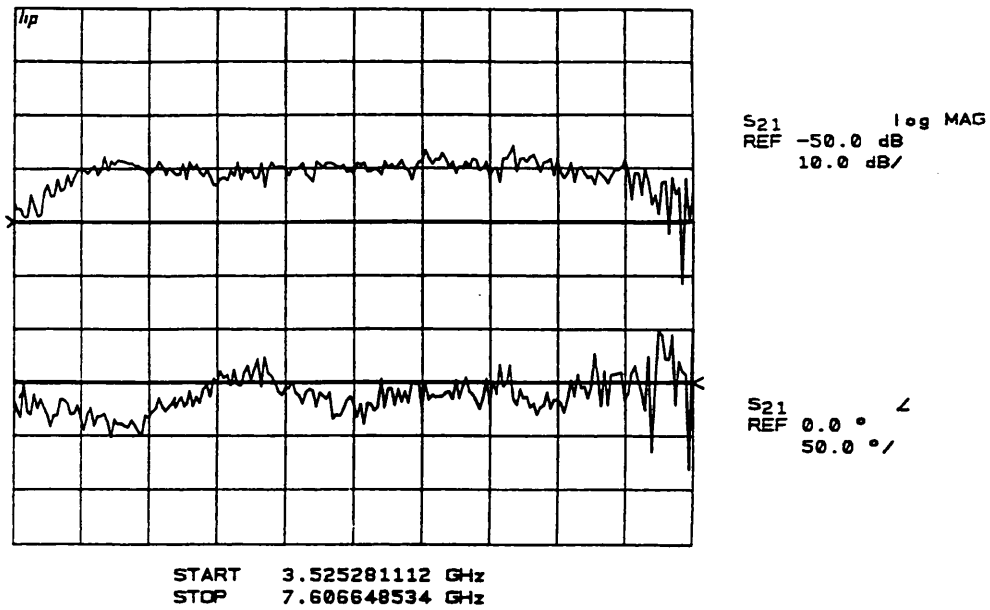


Fig. 2a: *Longitudinal broad band BTF measurement at the CERN Antiproton Ring from 3.5 GHz to 7.6GHz, upper trace: amplitude in 10 dB/div., reference -50 dB, lower trace: phase in 50 degree/div.*

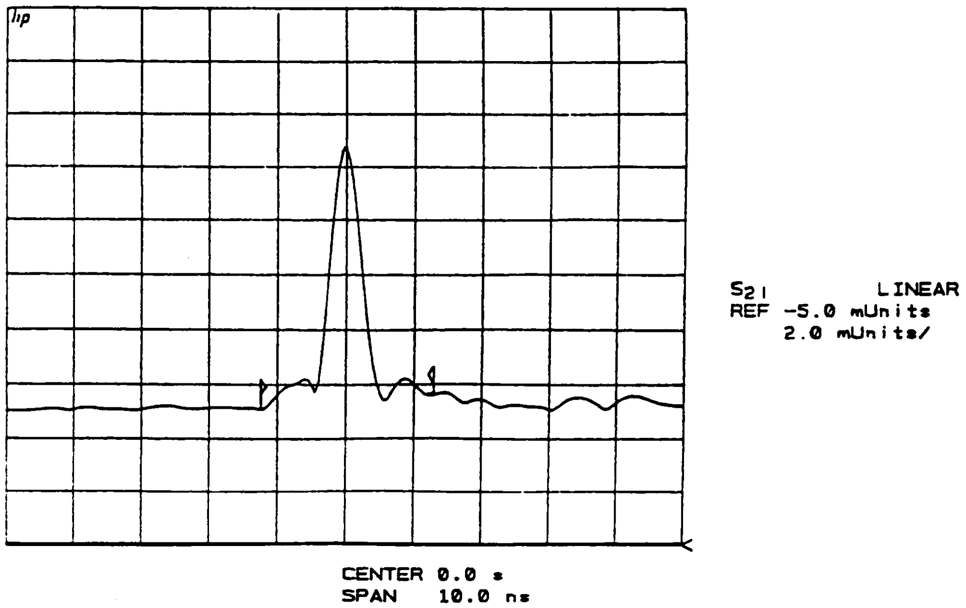


Fig. 2b: *Fourier transform of the signal of Fig. 2a into time domain from -5 ns to +5 ns, span of time gate: 2.5 ns*

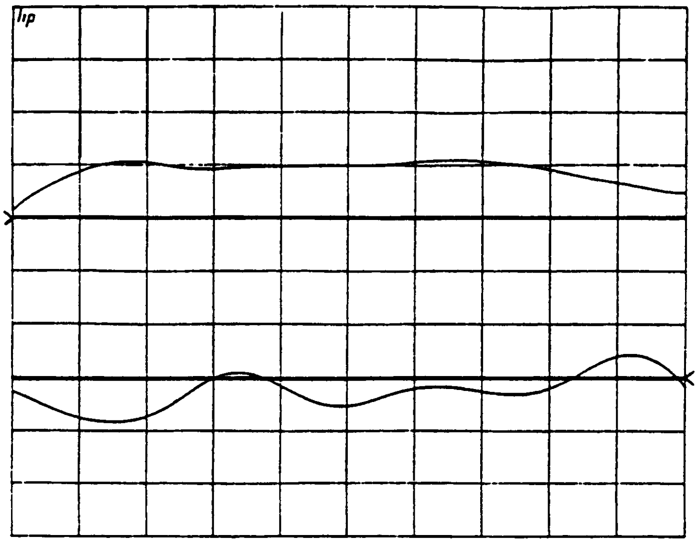
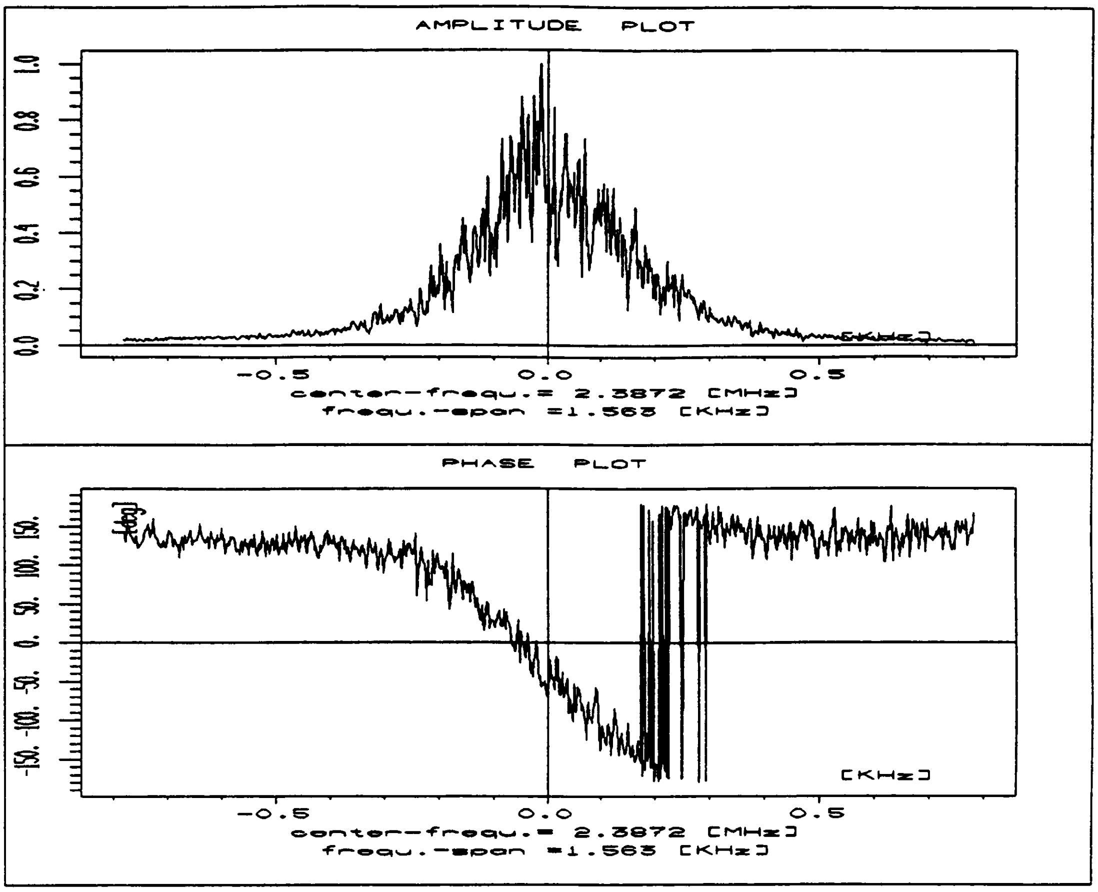
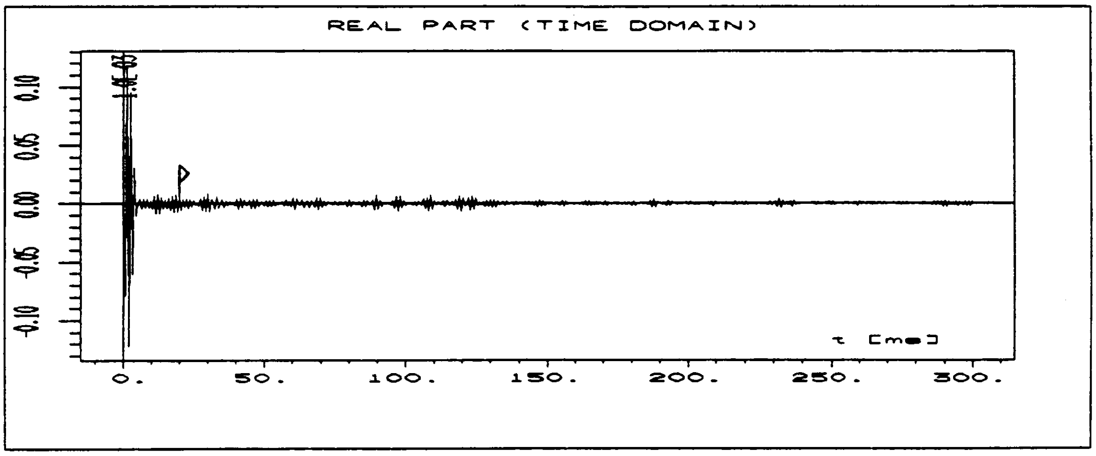


Fig. 2c: *Signal of Fig. 2a after time gating, specified time gate: 2.5 ns*

A longitudinal narrow band BTF measurement with antiprotons at LEAR is shown in Fig. 3a. Because the FFT (HP3562A) used for this measurement is not able to perform a Fourier transformation on the data into time domain, the time domain structure of the signal has been calculated afterwards by software [Fig. 3b]. It is the wellknown time response of a resonator on a (fictive) impulse excitation. The time range above 20 ms consists - in contrast to the signal of Fig. 1a - of noise dominated by the beam behavior. This relatively large time interval includes no information about the coherent part of the beam response, but is most likely due to Schottky noise. It can be explained by a too small frequency spacing of the BTF data in frequency domain. This means that the record length of the FFT data taking was too high.
If the number of samples that are to be taken is fixed, one should not increase the resolution in frequency domain beyond a certain limit. The limit is determined by the length of the time interval of the Fourier transform, when all the information is present. The remaining number of samples should be used for more averaging.
Because the record length of the FFT used here cannot be changed easily, time gating is a good alternative to get rid of the noisy signal contribution. In the measurement shown in Fig. 3c suppressing the noise between 20 ms and the end of the interval by time gating and transforming the gated data back into frequency domain the signal to noise ratio of the measurement is improved by a factor of 25 in power (approximately given by the ratio of the length of the Fourier transform interval to the length of the interesting time range).



<u>*Fig. 3a:*</u> *Longitudinal narrow band BTF measurement at LEAR with antiprotons at the 2. harmonic, amplitude with a linear scale, phase in degree*



<u>*Fig. 3b:*</u> *Fourier transform of the signal of Fig. 3a into time domain, time gate from 20 ms to the end of the Fourier transform interval*

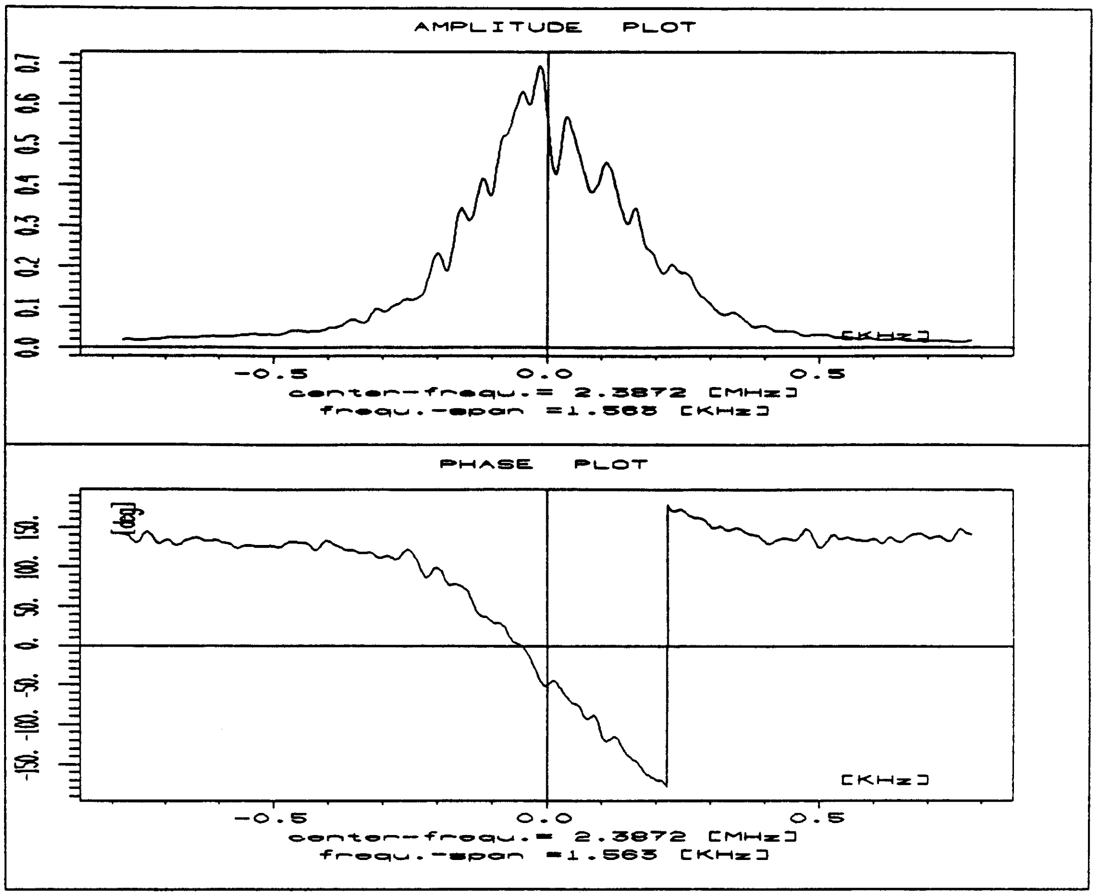


Fig. 3c: *Signal of Fig. 3a after time gating, time gate see Fig. 3b*

Some measurements concerning the influence of the width of the time gate on the suppression of noise in frequency domain are shown in Fig. 4a-f for a width of the gate varying from 100 ns down to 5 ns.

Different resolutions (from 201 to 1601 points) in frequency domain have been used to test the effect on the reduction of noise after time gating, but no change in the quality of the signal in frequency domain has been observed [Fig. 5a-c, compare with Fig. 4e].

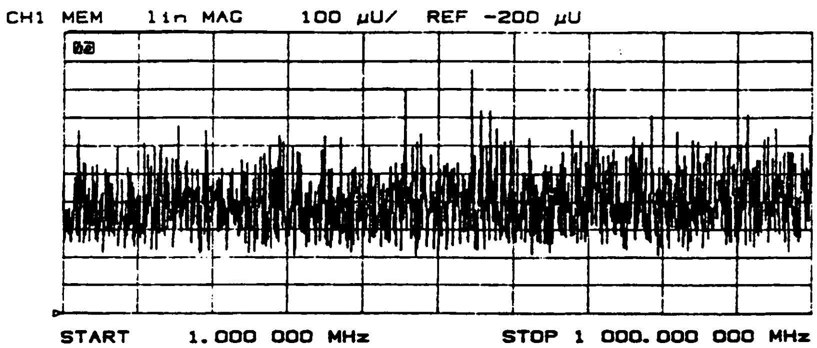


Fig. 4a: *Noise used for time gating tests of Fig. 4b-f with a frequency range from 1 MHz to 1 GHz, amplitude with a linear scale, resolution: 1601 points*

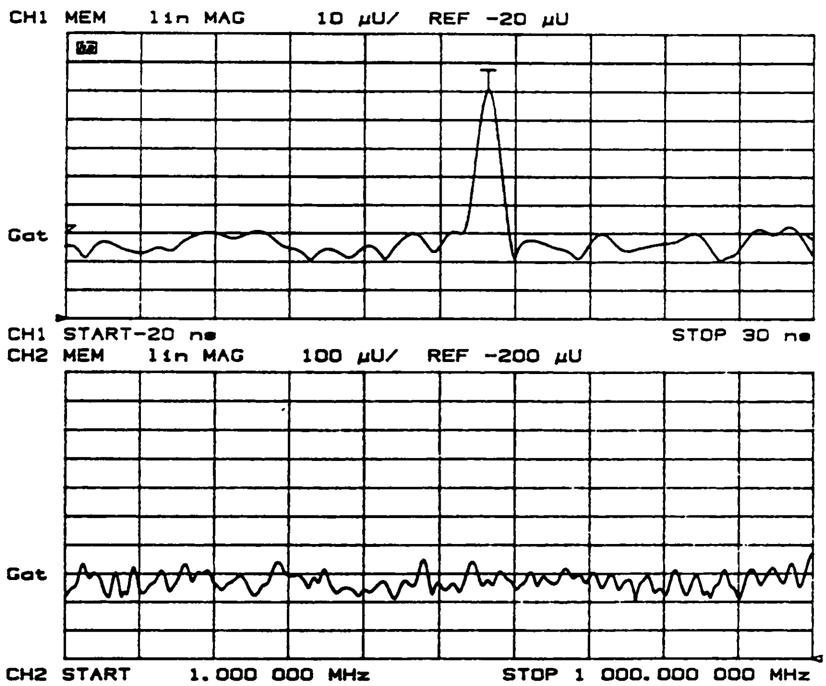
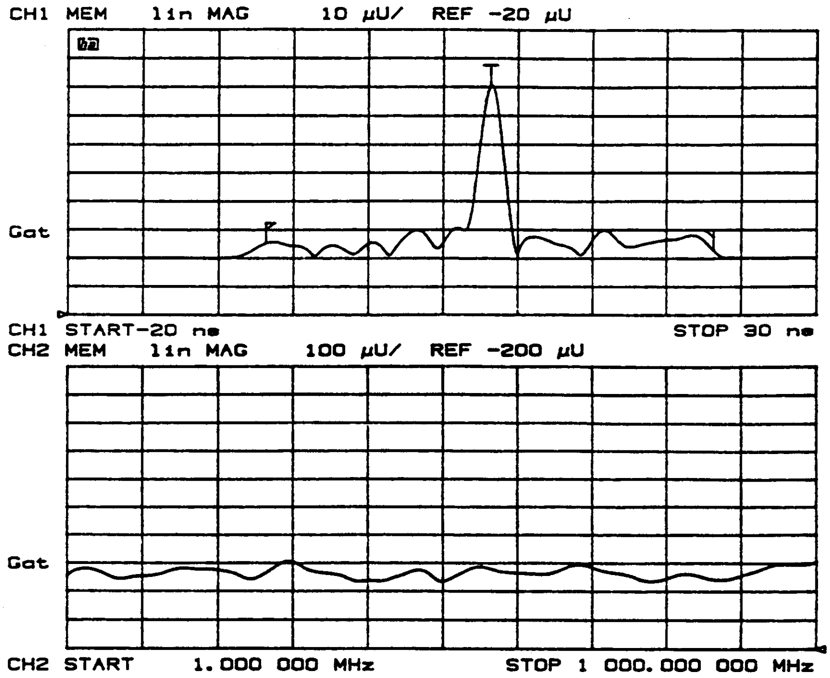
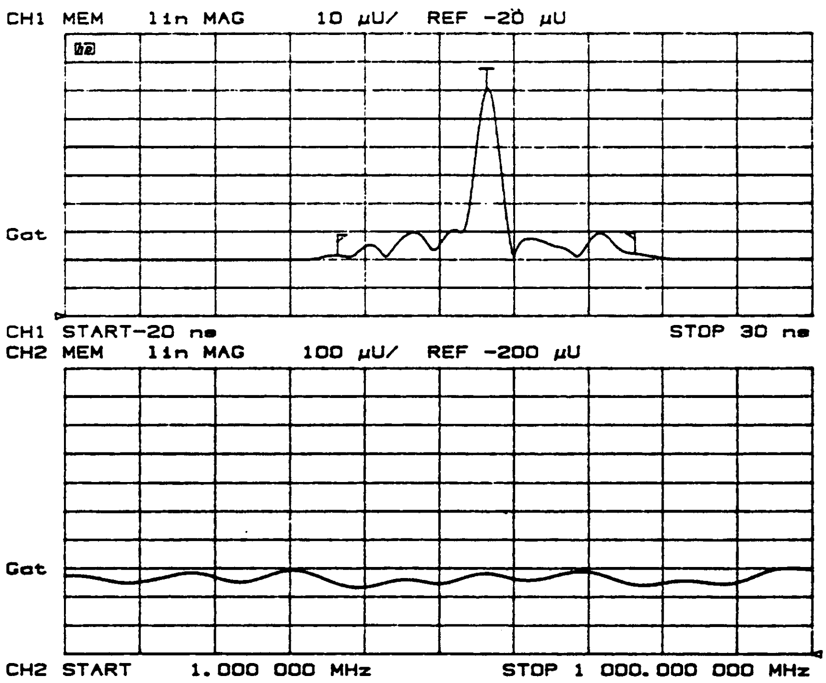


Fig. 4b: *The signal of Fig. 4a after time gating, in time domain (upper) and frequency domain (lower), time axis from -20 ns to +30 ns, frequency axis from 1 MHz to 1 GHz, amplitude with a linear scale, time gate width: 100 ns*



<u>Fig. 4c:</u> *The signal of Fig. 4a after time gating, in time domain (upper) and frequency domain (lower), time axis from -20 ns to +30 ns, frequency axis from 1 MHz to 1 GHz, amplitude with a linear scale, time gate width: 30 ns*



<u>Fig. 4d:</u> *The signal of Fig. 4a after time gating, in time domain (upper) and frequency domain (lower), time axis from -20 ns to +30 ns, frequency axis from 1 MHz to 1 GHz, amplitude with a linear scale, time gate width: 20 ns*

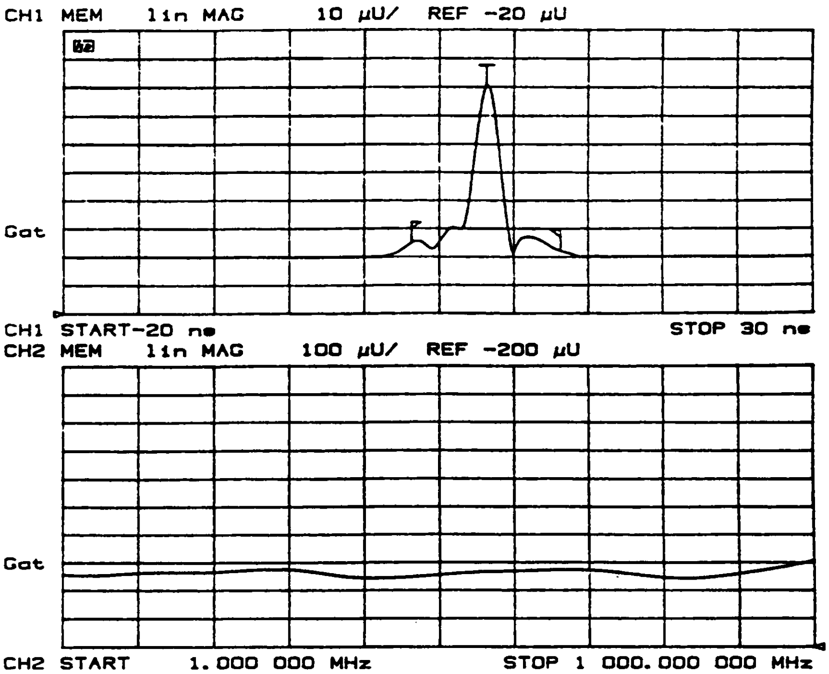


Fig. 4e: *The signal of Fig. 4a after time gating, in time domain (upper) and frequency domain (lower), time axis from -20 ns to +30 ns, frequency axis from 1 MHz to 1 GHz, amplitude with a linear scale, time gate width: 10 ns*

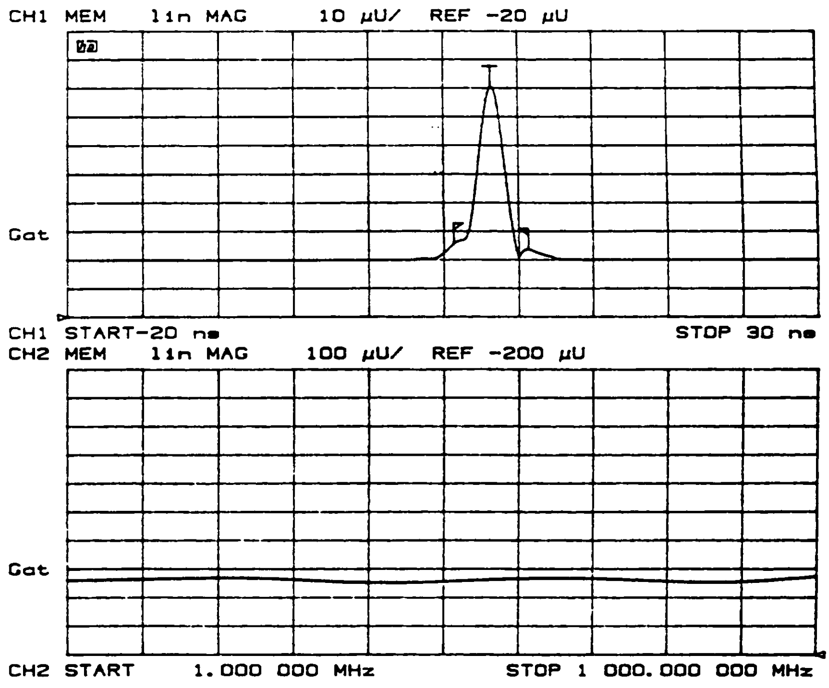


Fig. 4f: *The signal of Fig. 4a after time gating, in time domain (upper) and frequency domain (lower), time axis from -20 ns to +30 ns, frequency axis from 1 MHz to 1 GHz, amplitude with a linear scale, time gate width: 5 ns*

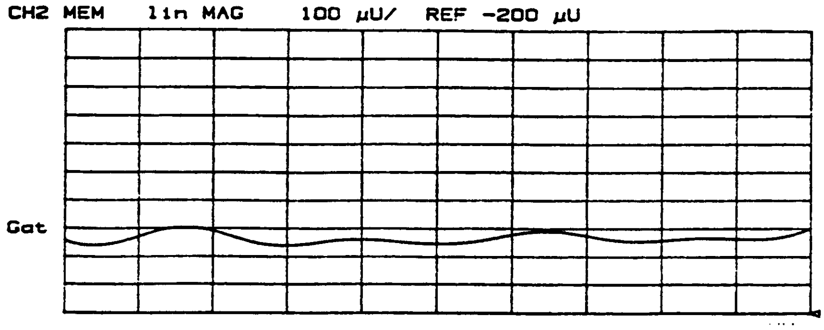


Fig. 5a

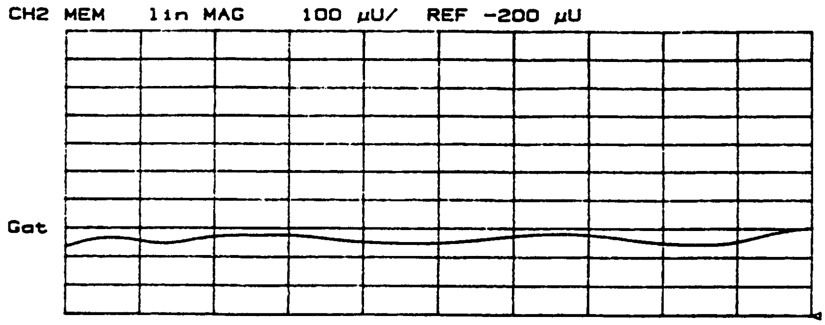


Fig. 5b

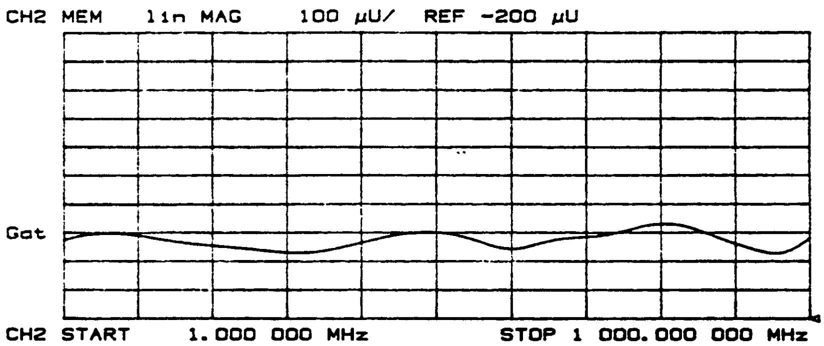


Fig. 5c

<u>Fig. 5a-c:</u> *Noise signal of Fig. 4a in frequency domain after time gating with a time gate width of 10 ns using different resolutions: 801 points (a), 401 points (b), 201 points (c) - compare with Fig. 4e (1601 points)*

Time gating versus averaging and smoothing in frequency domain:

Fig. 6 shows the same simulation signal that has been used for the time gating technique [Fig. 1b] after 50 averagings. By this averaging one gets a better signal to noise ratio, but - as one can see - with less success.

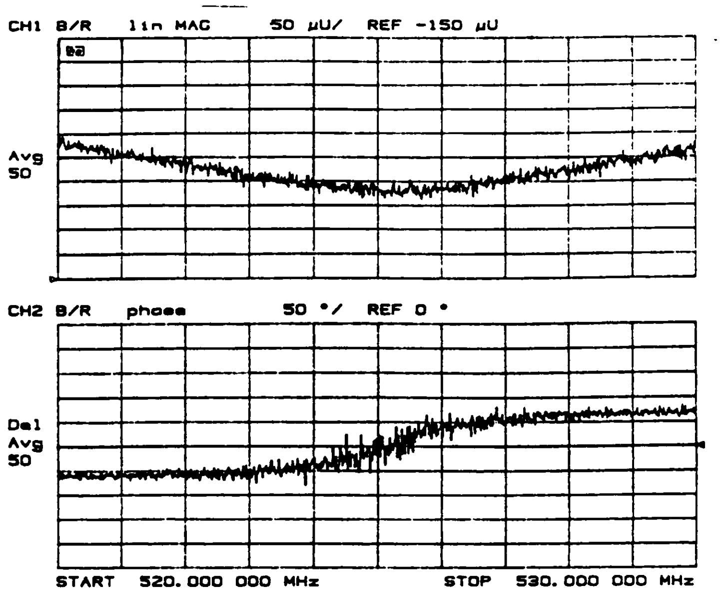


Fig. 6: *Amplitude (upper) and phase (lower) of the signal of Fig. 1b in linear scale after 50 averagings without smoothing*

Time gating uses only the information of a small time interval. Short time intervals correspond to large frequency intervals, which means in the case of time gating that large changes between neighboring data in frequency domain are suppressed. The question is, whether this leads to nearly the same result as smoothing, because nothing else is done by smoothing, too.
The effects of smoothing and time gating have been compared in frequency domain and time domain using the longitudinal BTF measurement data of Fig. 3a. As shown in Fig. 7a smoothing leads to a smaller improvement of the signal to noise ratio than time gating. Looking at the peaks of the traces one can see that smoothing causes a flattening of the peaks, whereas time gating doesn't modify the details of the curves too much.
The good efficiency of time gating is verified by performing a Fourier transformation of data that have been smoothed in frequency domain first [Fig. 7b]. In spite of smoothing a residual noise is present all over the time interval. On the contrary by time gating, signals corresponding to a time longer than 20 ms are completely suppressed. From the fact that the amplitude of the interesting signals of the smoothed data is about half of the one of the time gated data [Fig. 7c] follows that smoothing not only modifies signals that correspond to time intervals that are of no interest, but also signals that consist of information of the beam response.
This shows that smoothing has an effect different from time gating. By smoothing one has less evident control of the data compared to time gating.

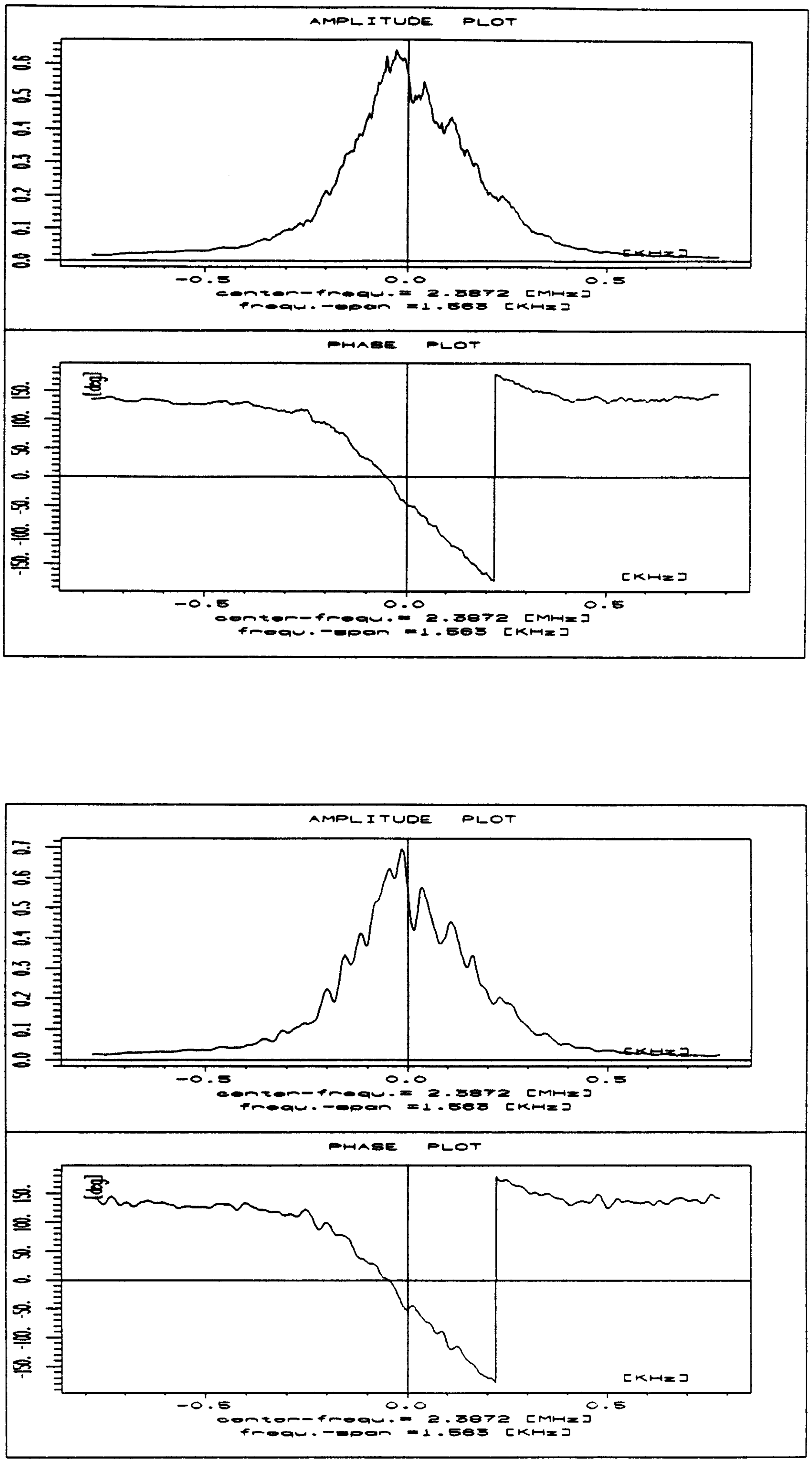


Fig. 7a: *Effect of smoothing compared with the effect of time gating in frequency domain using the signal of Fig. 3a, upper traces: smoothing aperture 2% of span, lower traces: time gate from 20 ms to the end of the time interval*

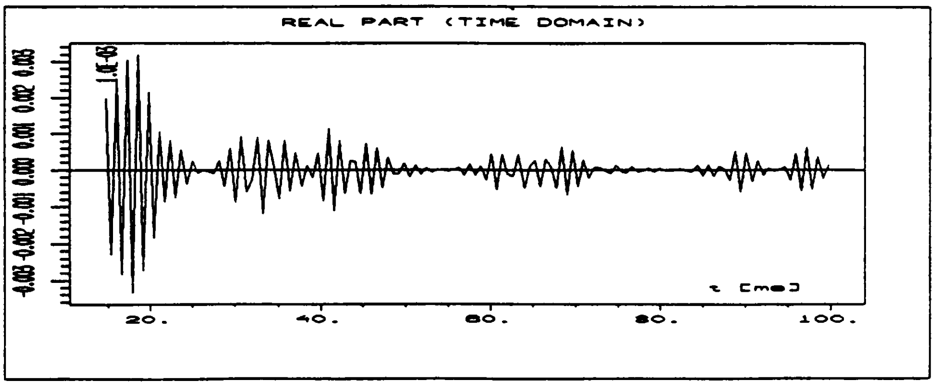


Fig. 7b: *Fourier transform of the smoothed data of Fig. 7a between 15 ms and 100 ms, smoothing aperture: 2% of frequency span*

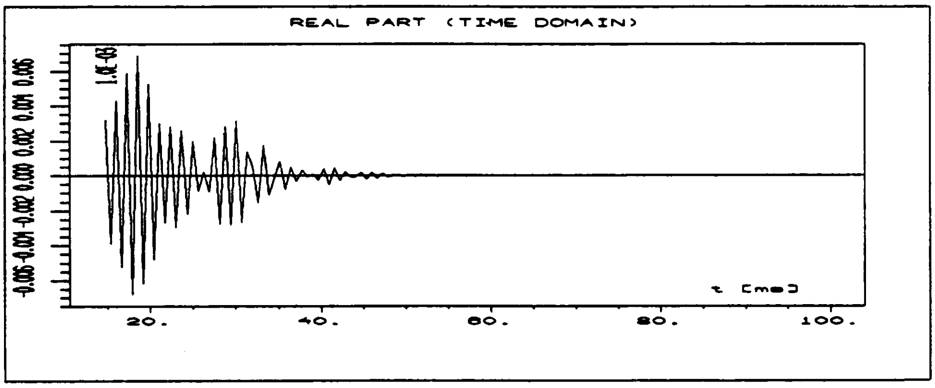


Fig. 7c: *Fourier transform of the time gated data of Fig. 7a between 15 ms and 100 ms, time gate from 20 ms to the end of the Fourier transform interval*

Conclusion:

Using time gating as a tool for BTF measurements one can improve the signal/noise-ratio of the BTF. This technique analyses only the information obtained during a short time interval, when all the relevant information is present, without any modifications of the interesting information. The unnecessary and perturbing signals, which are present during the rest of the time are gated out. By software more than one time gate may be applied, where the gates can include the signal contribution inside or outside of the time intervals. This time gating is therefore a powerful tool to obtain clear BTF signals. The measurements clearly indicate that this method is much more adequate than smoothing on amplitude and phase data in frequency domain and more powerful than averaging.

Acknowledgments:

We should like to thank M. Chanel for his guidance in performing BTF measurements at LEAR.

References:

[1] Carlo Offelli and Dario Petri: "Weighting Effect on the Discrete Time Fourier Transform of Noisy Signals", IEEE Transactions on Instrumentation and Measurements, Vol. 40, No. 6, Dec. 1991

[2] Hewlett Packard: "HP 8753 B Network Analyser, System Operating and Programming Manual", HP Part Number 08753-90122