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Time domain analysis using network analysers: some good practice tips

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Editor's foreword

This report reproduces a text originally issued as a Research Note[1] within the National RF and Microwave Standards Division of NPL which, at the time (1997), was based at DERA in Malvern. The decision to issue this text as an ANAMET Report, and distribute it to the ANAMET membership, was made by the ANAMET Steering Committee during its most recent meeting in August 1999.

Time Domain Network Analysis (TDNA) is rapidly becoming a popular topic within ANAMET, so it was felt that the report would be of considerable interest. I hope you and/or your colleagues find it a useful document. I would like to thank Drs Renwick, Szwarnowski, Bannister and Mr Ide - the authors of the original Research Note.

Nick Ridler
Chairman of ANAMET

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SUMMARY

The report provides guidelines on setting up a network analyser to obtain an accurate time-domain response of a known or unknown microwave network. Results taken from a Hewlett Packard 8510C network analyser demonstrate the effects on the time-domain output of changing the number of frequency calibration points, the frequency range and applying windowing functions. The technique of gating the time-domain data to focus on particular phenomena is described and the effectiveness of gating the time-domain data of interest by selection of a suitable gate shape and width is illustrated.

The work presented in this report was funded by the National Measurement System Policy Unit of the UK government's Department of Trade and Industry.

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1 E K Renwick, S Szwarnowski, D J Bannister and J P Ide, "Time Domain Analysis using Network Analysers: Report on Best Practice", *National RF and Microwave Standards Research Note No 118*, August 1997.

1. INTRODUCTION

Time-domain measurements display the location of impedance discontinuities of a microwave network as a function of time or distance. Common applications of time-domain methods include the location of faults within a microwave network and the identification of individual component responses within a circuit.

Modern network analysers are generally frequency-domain instruments, which stimulate the network-under-test with a frequency-stepped RF signal. To carry out measurements in the time-domain, a frequency-domain calibration is first carried out, and network S-parameters are measured in the frequency-domain. The frequency-domain measurements are then converted to the time-domain by applying an inverse Fourier transform to the data. Automatic network analyser (ANA) manufacturers generally build such functionality (at least as an option) into their ANAs.

In this report, guidelines on how best to set up an ANA for effective time-domain measurements are given. The report is illustrated using results obtained with a Hewlett Packard 8510C ANA. For this work, reflection measurements in time bandpass mode were considered and the network-under-test comprised a 12.5 cm long, 50 Ω airline terminated with a lowband load. It is assumed that the reader is familiar with frequency-domain measurements using ANAs.

2. RELATIONSHIP BETWEEN FREQUENCY AND TIME-DOMAINS

Fourier analysis [1] mathematically relates the description of a signal as a function of frequency $X(f)$ and as a function of time $x(t)$.

Where an ANA has been used to measure the S-parameters of a circuit as a function of frequency $S(f)$, these can be transformed to a function of time $s(t)$ by applying the inverse Fourier transform:

$$s(t) = \int_{-\infty}^{\infty} S(f) e^{j2\pi ft} df \qquad (1)$$

Although equation (1) is exact, for practical implementation on an ANA, the transform needs to be recast to deal with a finite number of data points over the limited frequency bandwidth of the ANA.

To carry out the transform, the ANA must be calibrated at regularly spaced frequency points in the frequency-domain. Suppose that the ANA is calibrated at N frequency points, $f_o, f_1, \ldots f_m, f_{m+1}, \ldots f_{N-1}$.

Let the measured S-parameter of interest in the frequency-domain at frequency f_m be $S(f_m)$. The "discrete" version of (1) used to compute the time-domain response is:

$$s(t_n) = \frac{1}{N}\sum_{k=0}^{N-1} S(f_m)e^{\frac{j2\pi nk}{N}} \qquad (2)$$

Details of this implementation of the inverse discrete Fourier transform can be found in reference [2].

3. SETTING THE FREQUENCY RANGE AND THE NUMBER OF DATA POINTS

Notice that the time-domain response, $s(t_n)$, has period N, thus:

$$.......s(t_{n-N}) = s(t_N) = s(t_{n+N}) =......... \qquad (3)$$

To map out one complete period of $s(t_n)$, it is conventional to vary n from 0 to N-1. On varying n from 0 to N-1, equation (2) expresses the time-domain response of the network at times t_n, where, if $f_{min}=f_0$ and $f_{max}=f_{N-1}$,

$$t_n = 0\ ,\ \frac{1}{(f_{\max}-f_{\min})}\ ,\ \frac{2}{(f_{\max}-f_{\min})}\ ,\ ....\frac{N-1}{(f_{\max}-f_{\min})} \qquad (4)$$

Consequently, the maximum range that can be viewed in the time-domain is:

$$Range = \frac{N-1}{(f_{\max}-f_{\min})} \equiv \frac{1}{\Delta f} \qquad (5)$$

where Δf is the frequency spacing. To maximise the range, for a fixed upper and lower frequency, as many points as possible should be measured in the frequency-domain.

Referring to equation (3), the time-domain response of the network is periodically extended when n varies outside 0 to N-1. Consequently, if the range on the ANA display is greater than the range calculated from equation (5), repetition of the time-domain response occurs. This is illustrated by the 51-point plot in figure 1, which shows the major peak at 1.00 ns repeated at 3.76 ns and -1.76 ns. The plots in figure 1 were constructed using f_{min}=45 MHz and f_{max}=18 GHz therefore to generate a valid time response over the displayed range (-2 to 4 ns), the number of sampled frequency points needs to be at least 201 from equation (5).

Increasing the number of data points, in addition to extending the range, can improve the definition of the time-domain response. In figure 1, for example, the recurrent peaks in the 51-point plot (t = -1.76, 1.00 and 3.76 ns) have different amplitudes, yet each peak is constructed from identical frequency data. There is therefore an insufficient number of points to correctly identify the peak maxima. However, on increasing the number of points from 51 to 201, the major peak at ~1 ns and similarly the subsidiary peak at ~0 ns, are mapped out in finer detail allowing their peak amplitudes to be determined more exactly. Moreover, additional features are visible between 0.1 ns and 0.3 ns in the 201 point plot.

In some instances, raising the sampling rate gives only a marginally better reconstruction of the time response, as demonstrated in figure 2. The 101 and 801 point plots are almost identical. The responses in the 801 point plot are however rounded off more smoothly enabling the peak amplitudes to be pinpointed more accurately.

The responses at t = -0.01, 0.78 and 0.99 ns correspond to the ANA test port to airline connection, the airline to load connection and the lowband load element, respectively.

It can also be deduced from equation (4) that the separation between adjacent points in the time-domain response is inversely proportional to the frequency range. This means that the minimum resolution is given by:

$$Resolution\ (ns)\ \alpha\ \frac{1}{[f_{\max}(GHz)\ -\ f_{\min}(GHz)]} \qquad (6)$$

The effect of frequency range on resolution is shown in figure 3. Maintaining the lowest frequency, f_{min}, at 45 MHz and 801 frequency data points, the upper frequency limit, f_{max}, was set to 2, 10, 14 and 18 GHz. With the upper frequency set to 2 GHz, the responses of the two airline connections appear at approximately -0.1 ns and 0.8 ns. As this upper frequency limit increases, these responses become significantly narrower. Accordingly, the ability to resolve the two responses increases and the airline connections can be located more readily.

Notice that on extending the upper frequency from 2 GHz to 18 GHz, there is a dramatic increase in the amplitude of the trace peak corresponding to the lowband load element. To explain this observation, consider the frequency response of the load (figure 7, dashed line). Up to 8 GHz the load gives a reflection coefficient below 0.006 while above 8 GHz the reflection coefficient rises sharply and levels off at approximately 0.05 at 16 GHz. Consequently, in the time-domain, the terminating load is effectively invisible until the frequency span embraces frequencies higher than 8 GHz and as the upper frequency rises to 10, 14 and 18 GHz, the amplitude of the reflection from the lowband load increases.

4. WINDOWING

As discussed earlier, in section 2, to obtain the exact time response of a network, the frequency measurements would have to be taken over a continuous and infinite number of frequencies. In practice, however, frequency data can only be sampled over part of the circuit's response function. This truncation of the frequency-domain data at the start and stop frequencies produces ripples, commonly referred to as 'ringing', in the time-domain output.

The frequency data can be regarded as being 'windowed' or 'weighted' by a unit function with transitions at the start and stop frequencies. By varying the shape of this windowing function, it is possible to control the level of the 'ringing' in the time-domain output. In general, window functions are symmetrical, smoothly varying functions which taper from unity to zero or near zero. Reference [3] catalogues some widely used window functions.

A windowing function which suppresses the ringing also has the effect of increasing somewhat the width of the principal maxima in the time-domain spectra. Suppressing the ringing in the time-domain output is therefore made at the expense of reducing the effective resolution.

Three frequency data weighting ('windowing') functions are available on the HP8510C; minimum, normal and maximum. The effect of each window function on the resultant time-domain output is demonstrated in figure 4. The application of the minimum window function (that is, the rectangular window function) to the frequency data yields, in the time-domain output, the highest level of ringing but the narrowest principal maxima. In contrast, the maximum window function gives the least degree of ringing but the widest principal peaks. The normal window displays a moderate level of ringing and peak broadening.

The resolution of a time-domain measurement is determined by the full width at half maximum (FWHM) of the time-domain response peaks. The FWHM is dependent on the windowing function applied to the frequency data and the frequency span and can be calculated from the following approximate formula:

$$FWHM \approx K \cdot \frac{1.2}{f_{max} - f_{min}} \qquad (7)$$

where K=1, 1.6 and 2.4 for a minimum, normal and maximum window respectively [4].

Referring to figure 4, it is interesting to note that the amplitude of the load response is also dependent on the applied windowing function. To explain this observation, refer to figure 7 (dashed line) which shows the frequency response of the load. By windowing the frequency response of an item, the relative amounts of the high and low frequency components that are included in the inverse discrete Fourier transform averaging process are altered. As the lowband load exhibits a large response at high frequencies, the peak amplitude of the load in the time domain is a sensitive function of the choice of window.

5. GATING

'Gating' is a technique used to remove unwanted responses from the time-domain data. This facility allows the frequency response of components to be viewed individually and is particularly useful in removing the effects of auxiliary elements such as connectors, adaptors and flanges.

The 'gate' is centred on the item or items of interest then the gate width is set to eliminate the unwanted responses. As the gate span decreases, the amount of information contained within the gate reduces. In figure 5, the gate is centred on the terminating load response at 0.99 ns. Notice that as the gate span reduces from 616 ps to 286 ps, the response of the airline connection at 0.78 ps is heavily attenuated.

While maintaining the ANA's default gate shape, the effect of the gate span on the frequency response was examined and the results are presented in figure 7. On converting to the frequency-domain, the ungated time response generates a frequency response with high frequency ripple. This fast ripple is a consequence of interacting reflections from the load element and the test port. A gate span of 616 ps is sufficiently wide to allow the responses of both the load element and the load's connector through. The interference between reflections from the load element and connector creates a frequency response which displays low frequency ripple. With a gate span of 306 ps, the load response is effectively isolated and on transforming this data, the load response is seen to be a smoothly varying function of frequency.

The gated data is converted back into the frequency-domain to enable the frequency response of the selected discontinuities to be ascertained. However, on transforming the gated time-domain data, ringing is introduced into the frequency response. In a similar manner to windowing, this ringing can be suppressed by applying an appropriate weighting function (gate shape) to the time-domain data prior to the conversion.

Four different gate shapes are available on the HP8510C; minimum, normal, wide and maximum. The isolation of responses using the maximum gate yields the highest level of ringing on the transformed data. In order to decrease progressively the level of ringing in the frequency response, the gates should be applied in the following order: maximum, wide, normal and minimum.

The effectiveness of each gate in isolating the load response is demonstrated in figure 6. The maximum gate has the fastest rolloff rate and allows the greatest amount of time information through at the extremes of the gate span. Consequently, the load element response is poorly isolated from the response of the load connector when the maximum gate is applied. In contrast, the information contained in the wings of the gated time response is significantly attenuated by the minimum gate. For this particular case, the load element response is suitably isolated when the minimum gate is used.

6. PRACTICAL CONSIDERATIONS

In carrying out time-domain measurements using the HP8510C, it is important to note that the time at which a discontinuity is located corresponds to the time it has taken the incident signal to reach the discontinuity plus the time taken for the reflected signal to return, that is, the round-trip time, T_{RT}. For example, in figure 2, the lowband load is shown as being located 0.984 ns from the reference plane. In reality, the load is situated (0.984/2) ns from the reference plane.

For practical purposes, it may be advantageous to express the location of a discontinuity in units of distance rather than time. The electrical length, L_e, to a discontinuity may be determined from:

$$L_e = \frac{T_{RT}}{2} \cdot c \qquad (8A)$$

where c is the speed of electromagnetic radiation in vacuum. Alternatively, the physical length, L_p, to a discontinuity may be found from:

$$L_p = \frac{T_{RT}}{2} \cdot v \qquad (8B)$$

where v is the velocity of the electromagnetic radiation in the relevant transmission medium.

The time taken to perform a measurement is a function of the number of frequency data points and the averaging applied to the frequency data. Consequently, in circumstances where measurement time is an important consideration, the minimum number of points required to cover the desired range should, where possible, be established using equation (5). The averaging factor should be chosen such that there is an acceptable signal to noise ratio in the frequency domain. It may be necessary to opt for different averaging factor values in calibration and in measurement of the network-under-test. An averaging factor of 128 on the HP8510C updates the frequency information at a reasonable speed and is suitable for moderately noisy signals.

7. GENERAL RECOMMENDATIONS

The choice of calibration frequencies is, for a time-domain study, essentially determined by three factors; resolution requirements, the time range of the measurement and the frequency bandwidth of the network-under-test.

The resolution in the time-domain response is inversely proportional to the frequency range. A band-limited item should, where possible, be measured over its bandwidth while a broadband device should be measured over as wide a frequency range as the HP8510C test set will allow. Where the frequency response of the circuit is not known, preliminary frequency measurements should be carried out to determine if the circuit is broadband or band-limited.

Having set the start and stop frequencies of the measurement and knowing the electrical (or physical) length of the circuit, the number of frequency data points needed to examine the entire circuit in the time-domain follows from equations (5) and (8). Where there is no available information on the length of the circuit, the electrical length and hence the appropriate number of calibration data points must be established through an initial frequency domain study.

It is generally good practice to apply each window function in turn to the frequency data and to observe the resultant time-domain response. If, on switching between the three windowing functions, only the peak amplitudes and widths change, then this is a good indication that the time output is valid. If, however, on changing between window functions, the number of trace peaks reduce, it is likely that this loss of detail is an artifact of the windowing. A circuit with closely spaced discontinuities is best examined using the 'maximum' window since this window optimises resolution whereas a circuit which displays low amplitude responses is best observed with a 'minimum' window as this window minimises the level of ringing.

On taking measurements using one set of calibration frequencies, it is possible that the resolution in the time-domain is inadequate to detect all the discontinuities. The first course of action is to select the maximum window function. If the discontinuities are still indistinguishable, the frequency span, f_{max}-f_{min}, must be increased by changing the ANA test set.

Once in the time-domain, it may be helpful to isolate a response using the gating facility so that the gated response may be analysed in the frequency-domain. It is recommended that each of the four gate shapes be applied in turn to the time-domain response of interest. The gate shape which isolates the response most effectively from neighbouring responses should be selected.

Whenever possible, the position of the various discontinuities on the ANA display should be verified with the estimated positions of the network discontinuities to ensure that the time-domain data is a reasonable representation of the circuit. If the level of confidence in the results is low (particularly if the electrical length of the item is unknown), a new set of calibration frequencies should be selected and the measurements repeated.

8. REFERENCES

[1] BRIGHAM, E.O. *The Fast Fourier Transform and its Applications*, Prentice-Hall, 1988.

[2] PRESS, W.H., FLANNERY, B.P., TEUKOLSKY, S. A. and VETTERLING, W. T. *Numerical Recipes*, Cambridge University Press, 1988.

[3] HARRIS, F. J. On the use of Windows for Harmonic Analysis with the Discrete Fourier Transform. *Proc. IEEE,* 1978, **66,** 51-83.

[4] HEWLETT-PACKARD CO., *HP8510C Network Analyser Manual*, 1991.

Figure 1. TIME DOMAIN RESPONSE OF AIRLINE TERMINATED IN LOWBAND LOAD .v. NUMBER OF MEASUREMENT POINTS

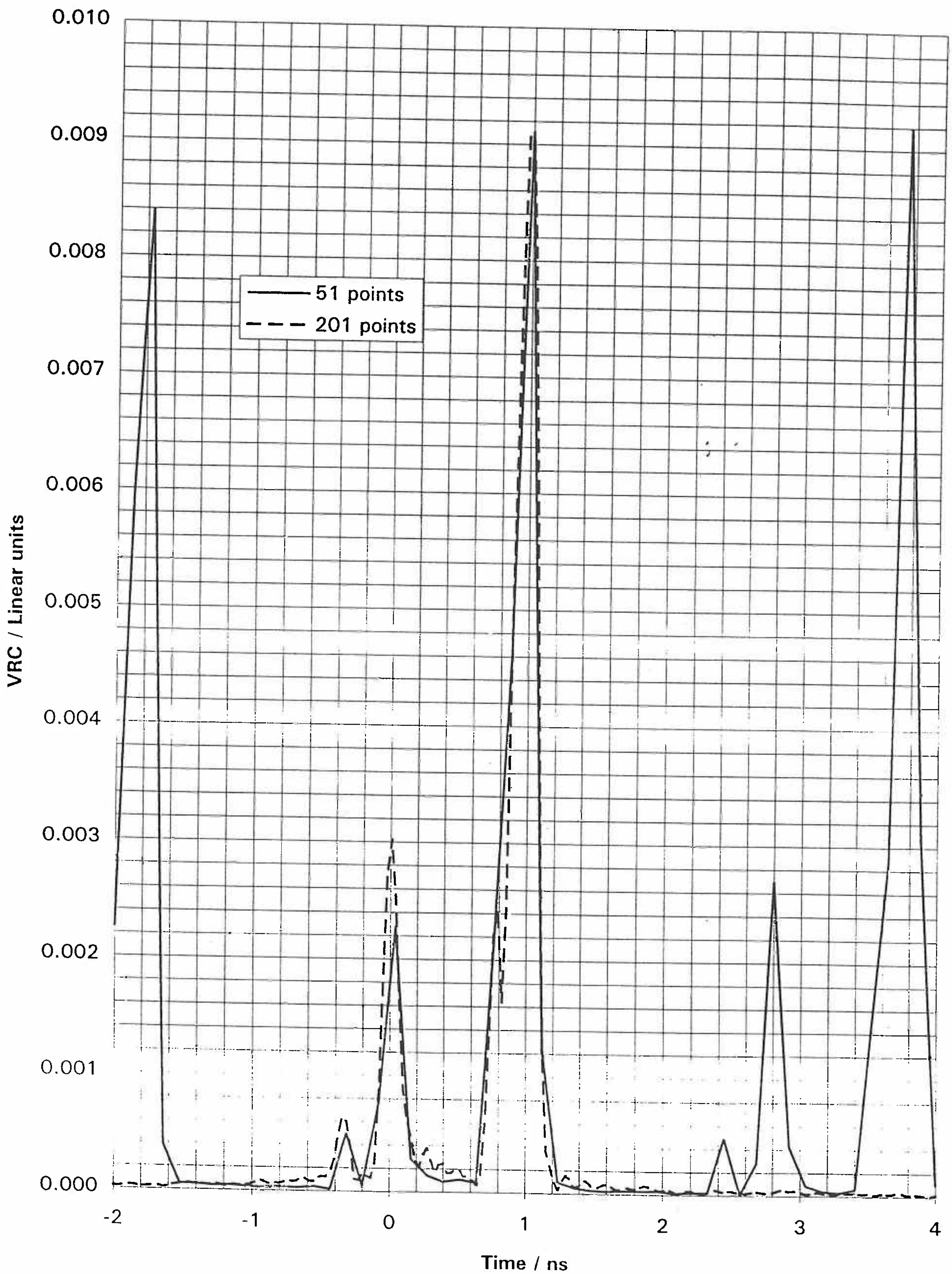

Figure 2. TIME DOMAIN RESPONSE OF AIRLINE TERMINATED IN LOWBAND LOAD .v. NUMBER OF MEASUREMENT POINTS

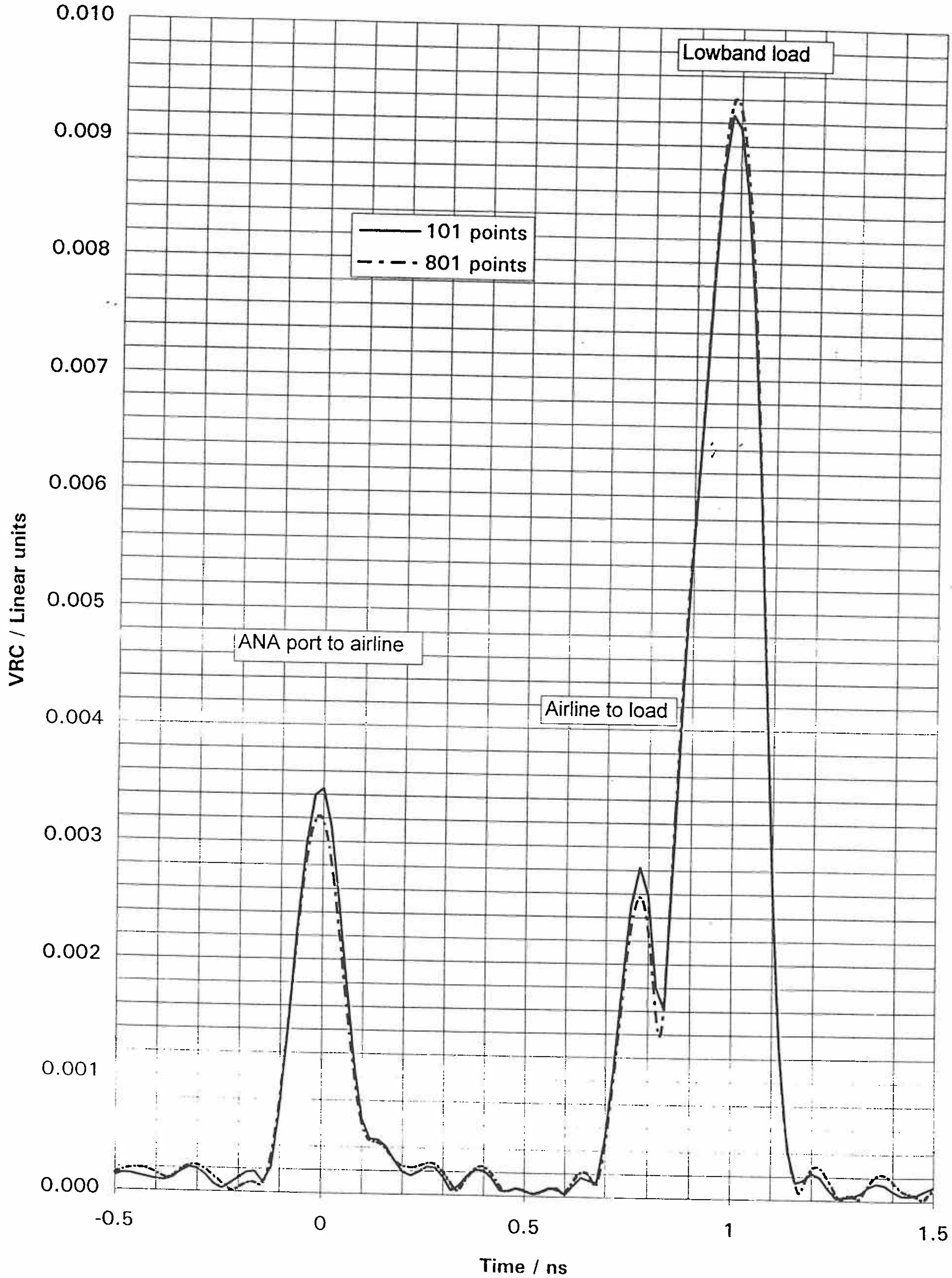

Figure 3. TIME DOMAIN RESPONSE OF AIRLINE TERMINATED IN LOWBAND LOAD .v. UPPER FREQUENCY MAXIMUM

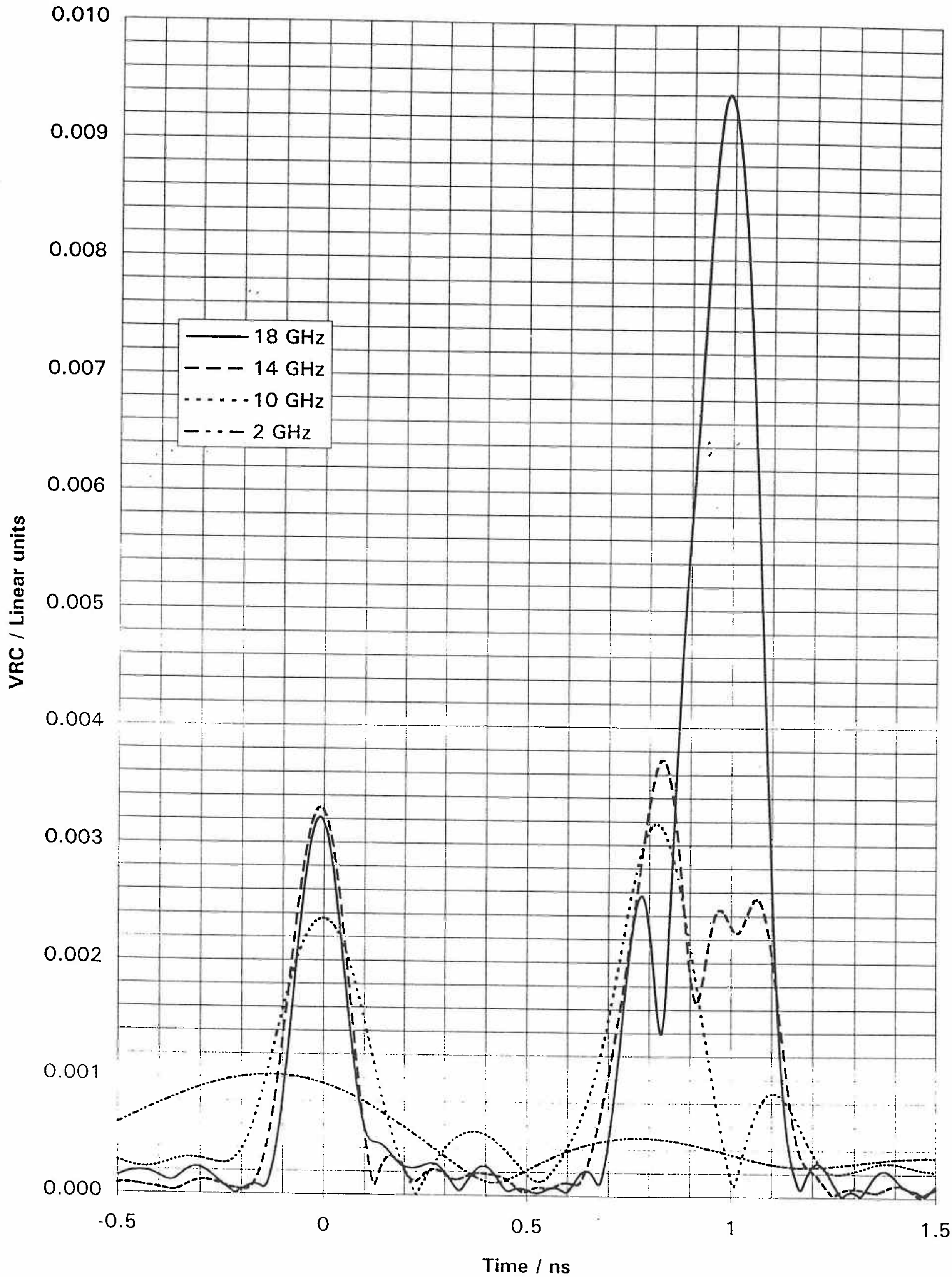

Figure 4. TIME DOMAIN RESPONSE OF AIRLINE TERMINATED IN LOWBAND LOAD .v. WINDOW TYPE

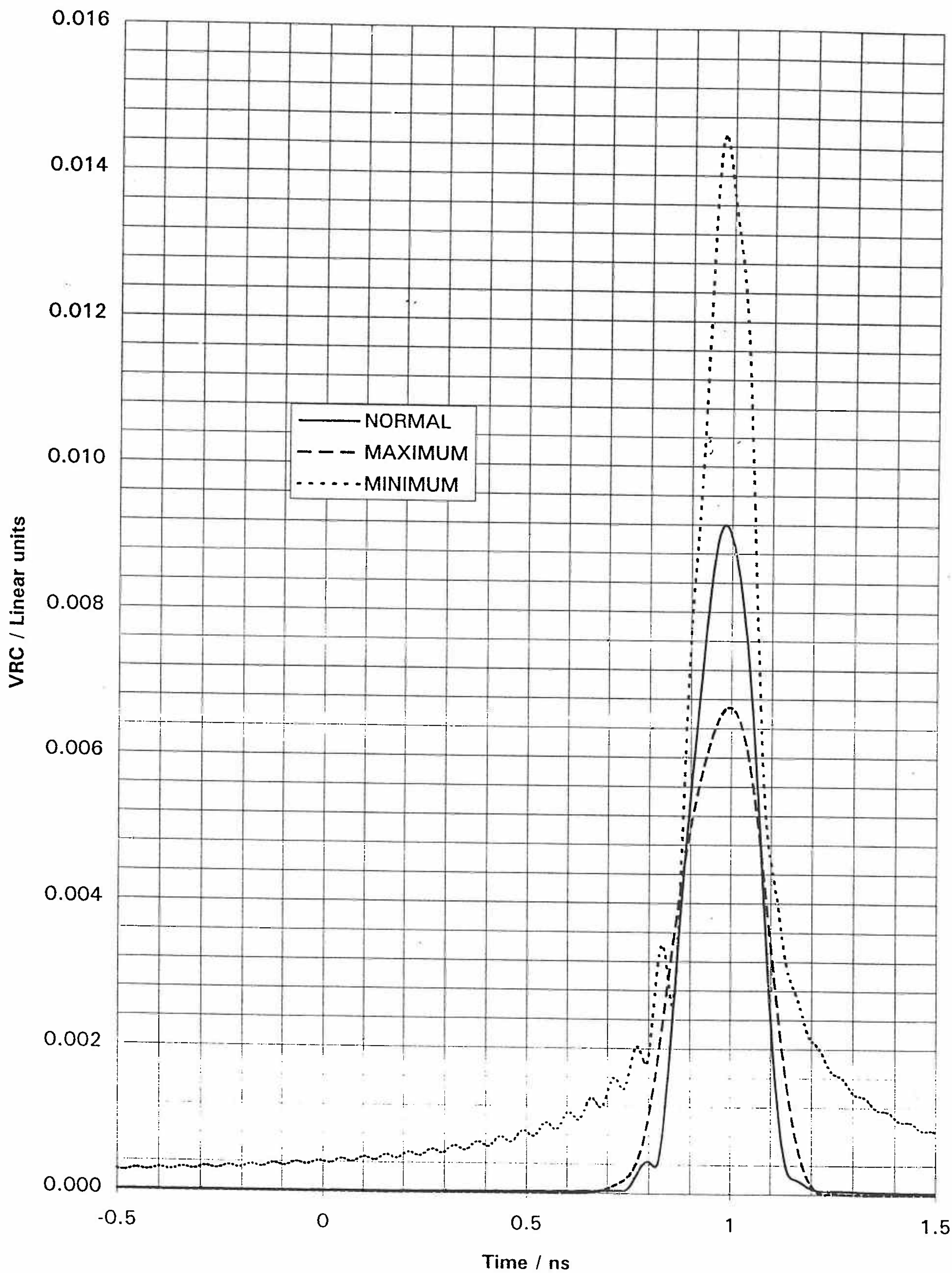

Figure 5. TIME DOMAIN RESPONSE OF AIRLINE TERMINATED IN MATCHED LOAD .v. GATE SPAN

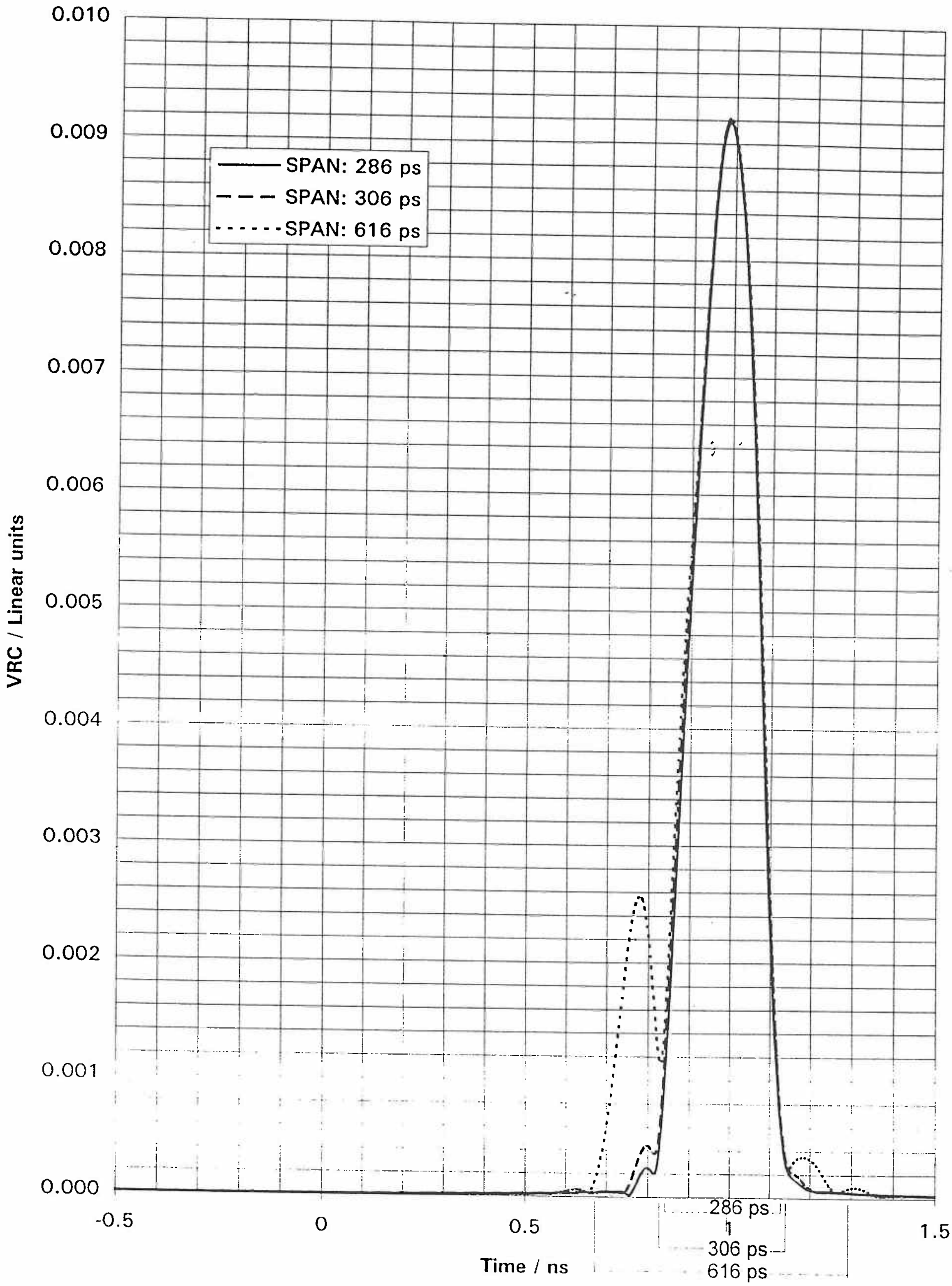

Figure 6. TIME DOMAIN RESPONSE OF AIRLINE TERMINATED IN MATCHED LOAD .v. GATE SHAPE

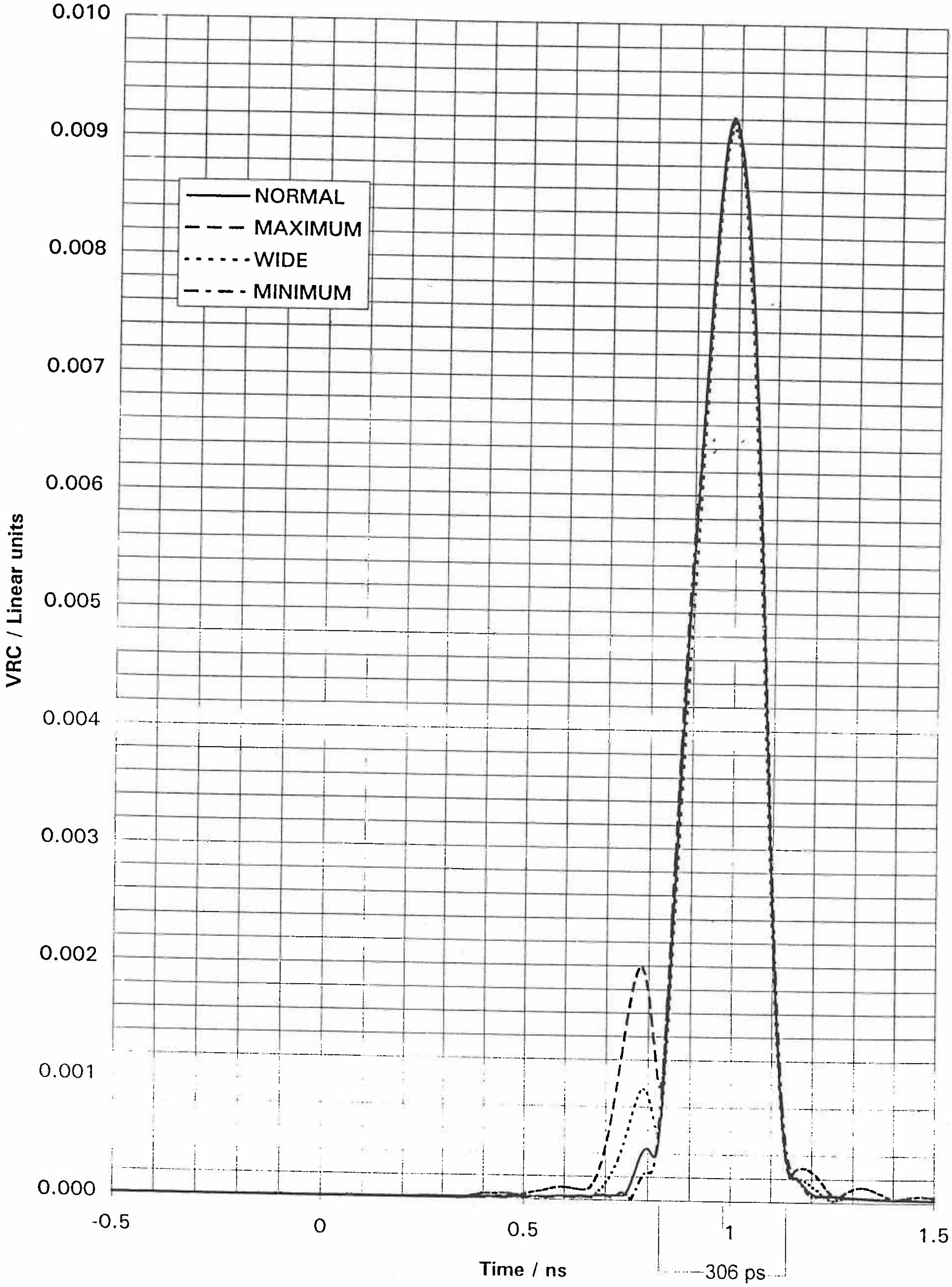

Figure 7. **EFFECTS OF TIME DOMAIN GATING TRANSFORMED BACK INTO FREQUENCY DOMAIN**