MEASURING THE PROPAGATION TIME OF COAXIAL CABLES USED WITH GPS RECEIVERS

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ABSTRACT

Time comparisons by means of GPS are now widely used. The calibration of the receiver delay and the delay in the associated coaxial cables is very important to reach accuracies better than 10 ns.

This paper describes and compares two methods: one using pulses of short rise times and one using interferometry of frequencies in the vicinity of the nominal frequency used. The results of the tests are described. Uncertainties < than 1 ns were attained for a cable length of 100 m at the 75 MHz IF frequency of the NBS designed GPS receivers.

1.0 Introduction

The comparison of time scales by means of GPS receivers and by means of other PRN modulated signals such as the method realized by Prof. Hartl reaches the uncertainty level of 1 to 10 ns. The delays in transmitters and receivers can be measured during the manufacturing process. Cable delays, however, are dependent on the local situation; the distance of antenna to receiver or transmitter may extend to 150 m. Sometimes the propagation time of the cable can be measured before the installation, or the cable can be removed for measurement. In this case there is access to both ends of the cable, which makes the measurement easier.

Two methods for accurate determination of the propagation time will be described and a third proposed. Also, a solution is given for the case of an already installed cable. The first method uses pulses with short rise times. the second uses a set of frequencies in the vicinity of the nominal frequency and the third incorporates a bi-phase modulator.

2.0 Delay Determination with Pulses of Short Rise Times

The velocity of a signal in a cable is known to be V_p, and equals C x $(\mu_r \varepsilon_r)^{1/2}$, where C is the speed of light (3 x 10^8 m/s), μ_r is the relative permeability (1 for a non-magnetic medium), and ε_r is the relative permittivity ($\approx$ 2.25 for solid polyethylene). For a typical coaxial cable $V_p = 2 \times 10^8$ m/s. The propagation time of a signal is $1/V_p = 5 \times 10^{-9}$ s/m or 5 ns per meter. Thus, the simplest way of determining the propagation delay of a coaxial cable is to measure its length and multiply it by 5 ns. An uncertainty of < 5% will be attained.

In practise cables do have losses. The series resistance, R, increases by the square root of the frequency due to skin effect, the parallel conductance (dielectric loss) also increases with $f^{1/2}$, the parallel capacitance is frequency independent, but the the series inductance decreases from 1 KHz to 100 KHz. The latter leads to a decrease in characteristic impedance and a lower phase velocity by a factor of up to 4 at 1 KHz with respect to 100 KHz. For frequencies > 1 MHz up to 1 or 2 GHz, the V_p given above of 2×10^8 is correct, but the attenuation is frequency dependent by $f^{1/2}$. This dependence leads to distortion of a voltage step or pulse. The corners of pulses are rounded because of the larger attenuation of the high frequency components of the voltage step. This leads to a problem when using pulses for the determination of the propagation delay of a cable: what should be taken as the detection point or trigger point of the propagated pulse? And what correction has to be applied for the slower rise time in order to arrive at the correct group delay of the cable for modulated sine waves?

In the literature (1) an expression for the waveform of a propagated pulse is given:

$$M(t) = \text{erfc}\ [0.032\ w(f_c t^{-1/2}],$$

where: w = the attenuation in dB at the used cable frequency, f_c,
t = time after the real delay, and
erfc = complementary errorr function (a mathematical function).

Figure 1 presents this in graphical form.

If the trigger level of the stop input of the time interval counter used to make the measurements is at 10% of the amplitude of the input pulse, then the correction to be subtracted from the measurements can be read from Fig. 1,

1 ns for a cable with 10 dB loss at 100 MHz,
3 ns " " " " 20 dB " " " ",
12 ns " " " " 40 dB " " " ",
and so on.

The real delay is the extrapolated value at zero amplitude, thus the total delay measured is corrected for the delay at the stop trigger amplitude.

On an oscilloscope, pulses show the above form (Fig. 2 and 3). The 250 mV input step is shown, together with the output voltage step. The horizontal scale is 10 ns and 50 ns per division for cables of 100m and 260 m respectively. The loss of the 100 m RG 223 cable is 4.2 dB at 10 MHz; for the 260 m RG 58/U cable this is 11.4 dB at 10 MHz and 40 dB at 100 MHz.

The delay of the 100 m RG223 cable was measured with a time interval counter (HP5370) at different stop trigger levels; the start trigger level was fixed at +0.20 V (in Fig. 2 and 3 the bottom line is 0 Volts, the center line is + 0.20 Volts). A stop level of 0.23 volts (approx. 40% of the input step) gave a reading of 523.7 ns, 0.13 volts (approx. 20%) gave 514.7 ns and at the minimum possible level of 0.08 volts (approx. 0%) the reading was 512.3 ns. These values will be compared to the results of the next method.

3.0 Propagation Time Measurement by Means of Interferometry

3.1 Measurement Principle

The principle of this type of measurement is shown in Figure 4. The phase difference of the output signal and the input signal to the cable is measured by means of a phase detector. We use a double balanced mixer as a phase detector. Its output voltage, V_d, can be characterized as:

$$V_d = K_d \cos(\Phi_{in} - \Phi_{out}),$$

where K_d is the sensitivity of the detector and Φ_{in} and Φ_{out} are the relative phases of the input signal and output signal of the cable.

If the input signal $V_i(t) = A \cos\omega t$ (A is the maximum amplitude of the sine wave, ω is the angular frequency), then at the output the signal is:

$$V_o(t) = Ae^{-ax}\cos(\omega(t-t_p)),$$

where e^{-ax} is the attenuation factor, t_p is the propagation time of the sine wave through the cable.

Combining the input and output signal in the phase detector, we obtain:

$$V_d = K_d\cos[\omega t-\omega\{t-t_p\}] = K_d\cos(\omega t_p).$$

The output of the phase detector is zero if $\omega t_p = \pi/2$ or $3\pi/2$ or any multiple of π added, so that, in general, if

$$t_p = \pi/2 + n\pi \quad \text{or} \quad \omega t_p = (2n-1)\pi/2.$$

Thus $t_p = (2n-1)/4 f_n$, where f_n is the frequency of the nth order zero. When the frequency is changed from zero to higher frequencies, then, at the lowest frequency for which V_d is zero there is a $\pi/2$ phase change in the cable, which means a quarter of a wavelength for the frequency. When the frequency is increased, V_d will become positive, passing a maximum and then going back to zero at $3\pi/2$, following the cosine curve of the phase detector characteristic. So "negative going" zeros can be distinguished from "positive going" zeros.

Zeros of the same polarity have phase differences of 2π radians. If the output of the phase detector has a bias, then the zeros are displaced: The frequency differences for consecutive positive and negative going zeros are unequal; but the frequency differences for zeros of the same polarity will not suffer from the phase detector offsets. This will be demonstrated later. Usually the propagation time around one frequency is of interest. When a filter is inserted in the signal flow we are also limited to the bandwidth of that filter. How then can the propagation time be determined in the described way if the value of n is not known?

Let us take a frequency, f_n in the vicinity of the center frequency of interest for which a zero occurs. Then:

$$t_{pn} = (2n-1)/4 f_n.$$

For the next higher "zero" frequency, f_m: $t_{pfm} = (2m-1)/4 f_m$ because f_m is the next higher "zero" frequency $m = (n+1)$ so: $t_{p(n+1)} = (2n+1)/4 f_{(n+1)}$. The cable

properties for f_n and f_m are supposed to be equal, so $t_{pn} = t_{pm} = t_p$; when this is worked out it is found that $t_p = 1/[2(f_m-f_n)]$ for $m = n + 1$. As can be seen, the value of n need not be known, the only thing is to be sure that f_m is the next higher "zero" frequency above f_n. However, if the phase detector offset is to be avoided, f_m should be the next higher "zero" frequency of the <u>same polarity</u> as th f_n "zero" frequency.
In that case the average propagation time becomes:

$$t_p = 1/[f_m-f_n] \text{ for } m = n+2.$$

3.2 The Realized Measurement

The two inputs to the mixer are buffered to isolate the non-linear input impedance from the coaxial line; otherwise multiple reflections may occur and displace the "zero frequencies. At the far end a very low VSWR should exist. A DC coupled amplifier increases the sensitivity of the phase detector and gives a better "zero" frequency resolution.

A wide band signal splitter drives the cable under test and the buffered LO input of the phase detector. The signal source is of good spectral purity: "zeros" are displaced if frequencies other than the wanted are present. Ground loops arising from multiple grounding must be avoided, otherwise isolation transformers should be used.

The minimum difference between the frequencies, f_n and f_m decreases with the length of the cable, i.e., if the allowed bandwidth is 10% of f_n, then the cable should be longer than 10 half wavelengths.

Figure 6 shows the measurement results of the 100 m RG 223 coaxial cable. The influence of the phse detector offset is clearly visible. The results of the "equal polarity zero" frequencies show a precision of 1 ns or less. The averaged delay between 69.4 MHz and 80.1 MHz is 513.0 ns. Also, the result using a voltage step gives the same answer within 1 ns.

4.0 Delay Determination with Bi-phase Modulated Carrier

There are commercially available group delay measuring instrumants which have the option of measuring the total group delay in a cable, which is its propagation delay. However, for PRN bi-phase modulated systems the best method for accurate delay measurement is the use of a bi-phase modulated carrier. The delay in a wide band double balanced mixer used as a bi-phase modulator can be much power than 1 ns. In this way a GPS receiver or the Hartl demodulator can be tested by a simulation of the normally received signal.

A PRN code generator is installed close to the receiver and connected to the carrier generator and bi-phase modulator by means of coaxial cable (Fig. 7). The delay for the PRN code of this cable can be determined by the described method 2 or in practise by first installing the carrier generator next to the receiver with a minimum length coaxial cable. Then the long coaxial cable is inserted. The extra delay between the PRN generator output and the receiver is the delay of the long coaxial cable. Then the carrier generator and modulator are positioned at the location of the antenna, while being connected to the PRN code generator by means of the calibrated long coaxial cable. Now the delay of the antenna cable or IF cable can be determined. The uncertainty is dependent on the receiver and its input carrier to noise ratio, on the order of 1 ns.

5.0 Delay Determination of Installed Cables

An installed cable can be measured by the method described under 2.0 or 3.0 when two additional cable are available (Fig. 8). If the cable to be measured is "A" and its delay T_a, and the additional cables and their associated delys are "B" and "C" and t_b and t_c respectively, then t_a can be calculated from the sums of the individual delays:

$$t_a = 0.5[(t_a+t_b)-(t_a+t_c)+(t_b+t_c)],$$

where (t_b+t_c), etc. is measured by interconnecting the cable "B" and "C", etc. at the far end.

When additional cables are not available, then, by shorting the far end of the cable, and inverted pulse will be sent back to the beginning and the (double) delay time will be measured by a time interval counter with the appropriate setting of the trigger levels and a correction applied for the pulse distortion as described in 2.0 (Fig. 9).

The method described in 3.0 might also be usable if a directional couple for the frequency range of interest is added. The propagation delay of the cable is half the measured value.

6.0 conclusion

From the results presented the conclusion can be drawn that the determination of propagation delays in coaxial cables is possible to an uncertainty of 1 ns by applying the appropriate methods described.

7.0 References

(1) K.F. Sander and G.A.L. Reed: Transmission and Propagation of Electromagnetic Waves, Cambridge University Press 1978, ISBN 0521 21924 8.

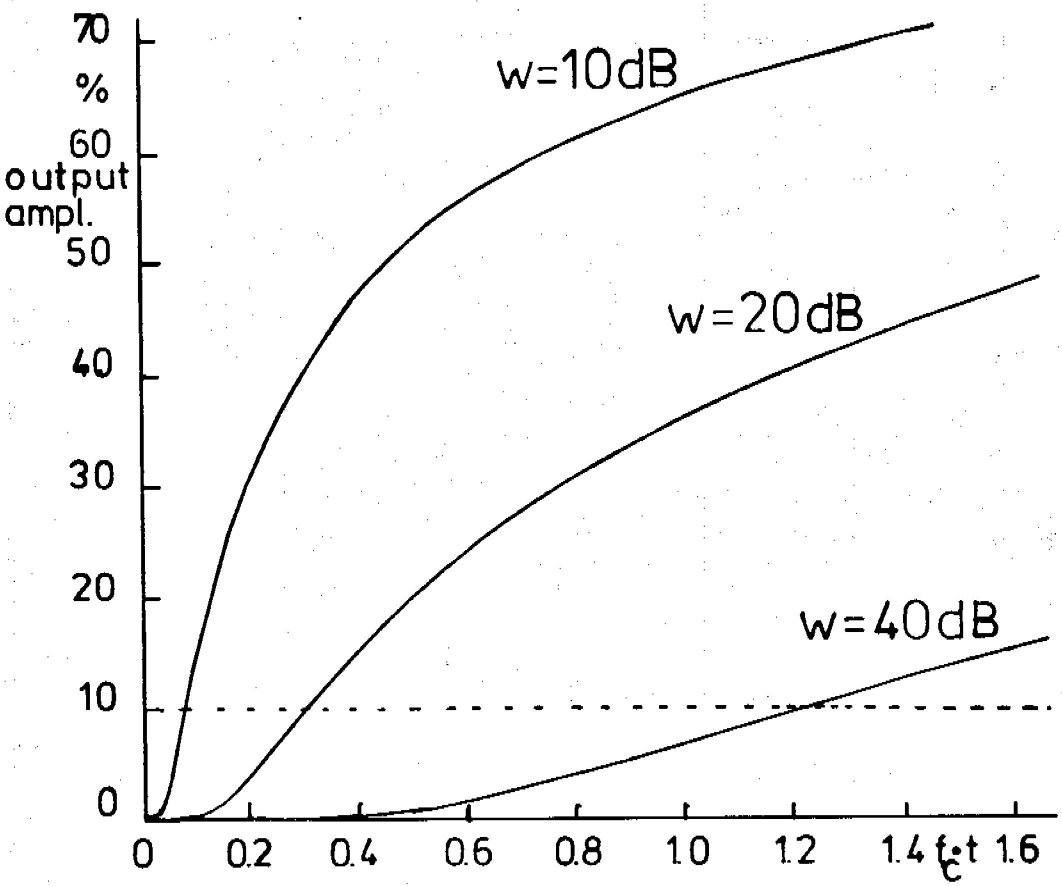

Fig. 1. Response of a coaxial cable to a voltage step for different values of attenuation.

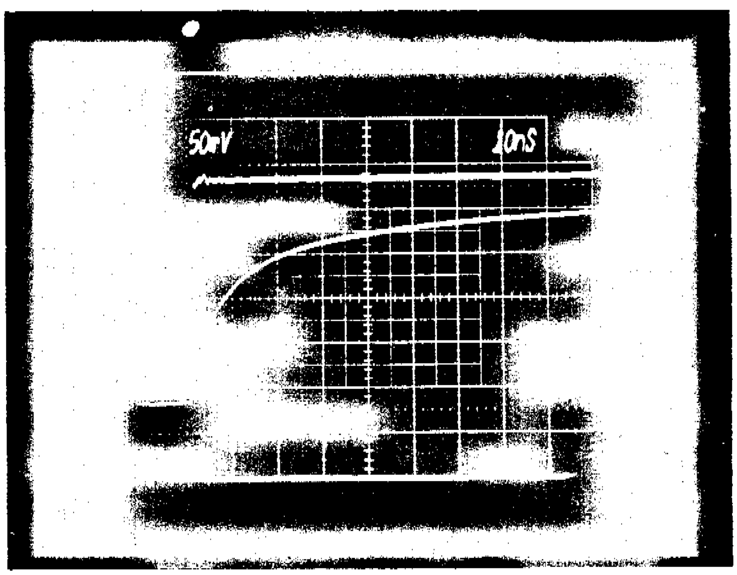

Fig. 2. Response of 100 m RG 223 cable to a 250 mV voltage step with 25 ps rise time.

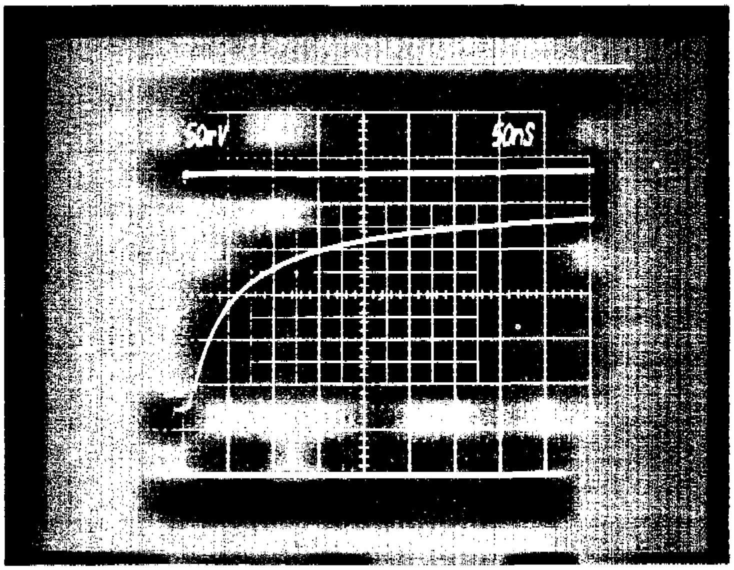

Fig. 3.Response of 260 m RG 58/U cable to a 250 mV voltage step with 25 ps rise time.

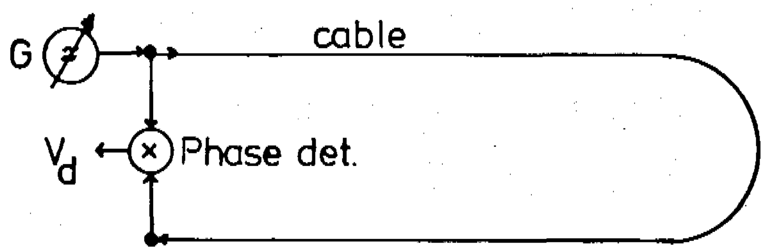

Fig. 4.Principle of interferometric propagation time measurement.

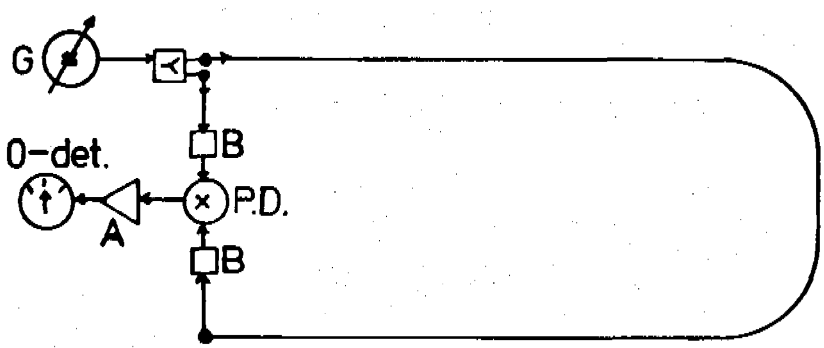

Fig. 5.Interferometric delay measurement set-up.

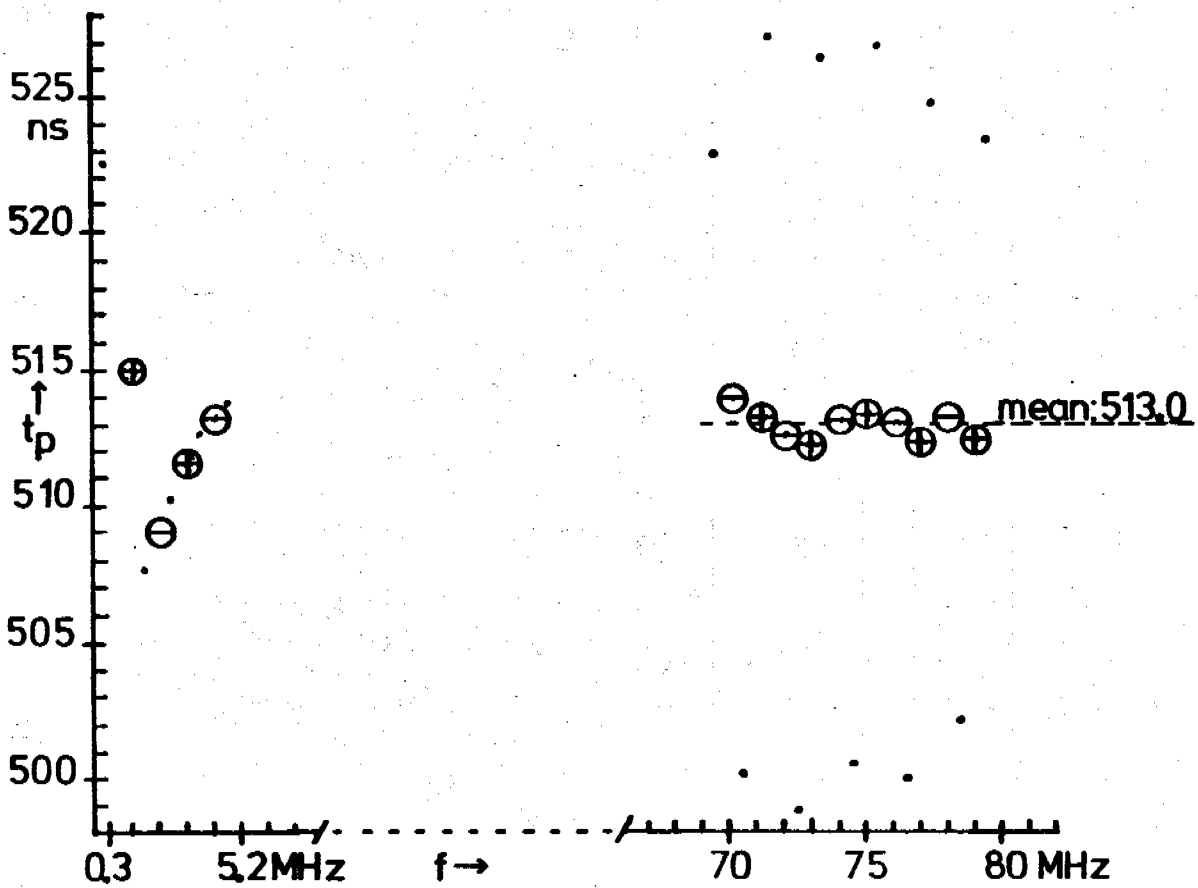

Fig. 6.Results interferometric delay measurement of 100 m RG 223 cable as a function of "zero" frequency.

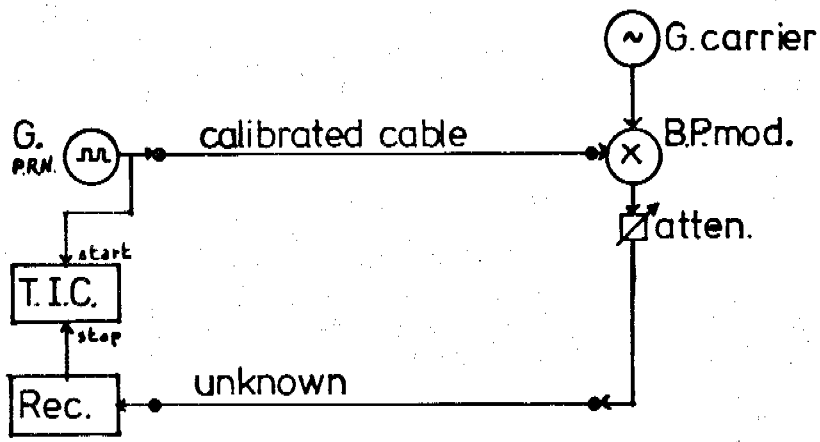

Fig. 7. Bi-phase modulated delay measurement

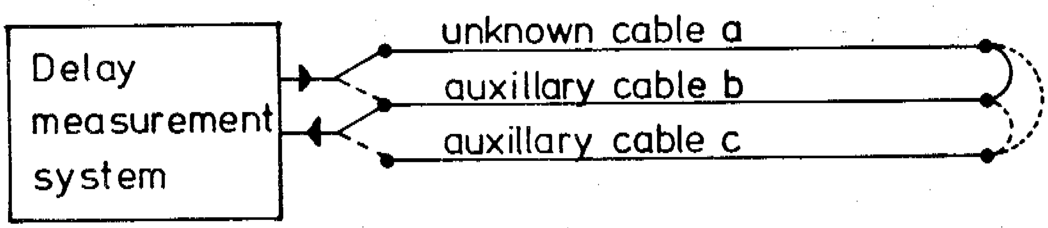

Fig. 8. Delay measurement with auxilliary cables

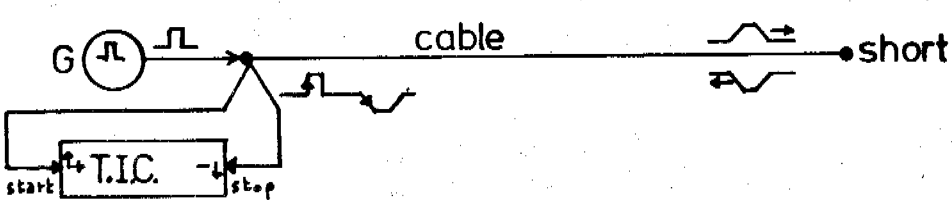

Fig. 9. Delay measurement using reflectrometry.

QUESTIONS AND ANSWERS

DAVID SHAFFER, INTERFEROMETRICS:
To find the resonant condition, feed a signal in one end with a signal generator and a counter and tap off right where you go into the cable with a spectrum analyzer. Watch the spike, and as you tune, the spike will go down at resonance of the cable. I've used that to measure two meter long cables to sub-centimeter electrical length.

MR.DE JONG:
Yes, that is a good suggestion, but one problem is that the system is not terminated at the right impedance. There is some extra, small, capacitance due to your testing connection. There is a problem in evaluating that.

LAUREN RUEGER, JOHNS HOPKINS:
Have you taken into account the temperature variation of your cables when making this measurement?

MR. DE JONG:
The measurement was done very quickly, so we didn't see temperature influence. This measurement is very useful to measure that influence. I didn't use it for this purpose in these measurements.

MR. RUEGER:
I have two sets of cables that are two hundred feet long each. I have measured diurnal variations of about a nanosecond if they are laid on top of the roof, so I had to bury them in the building.

MR. DE JONG:
Yes, I think that I recall that it would be about .003% could be the influence of temperature on the length.

GERNOT WINKLER, NAVAL OBSERVATORY:
In your conclusion would you agree that in making the measurement you should use that method that agrees most closely to the application?

MR. DE JONG:
Certainly.

MR. WINKLER:
For instance, one disadvantage of this method is that one cannot easily use the same frequency for both the application and the measurement.

MR. DE JONG:
If the cable is long enough, you can come very close.