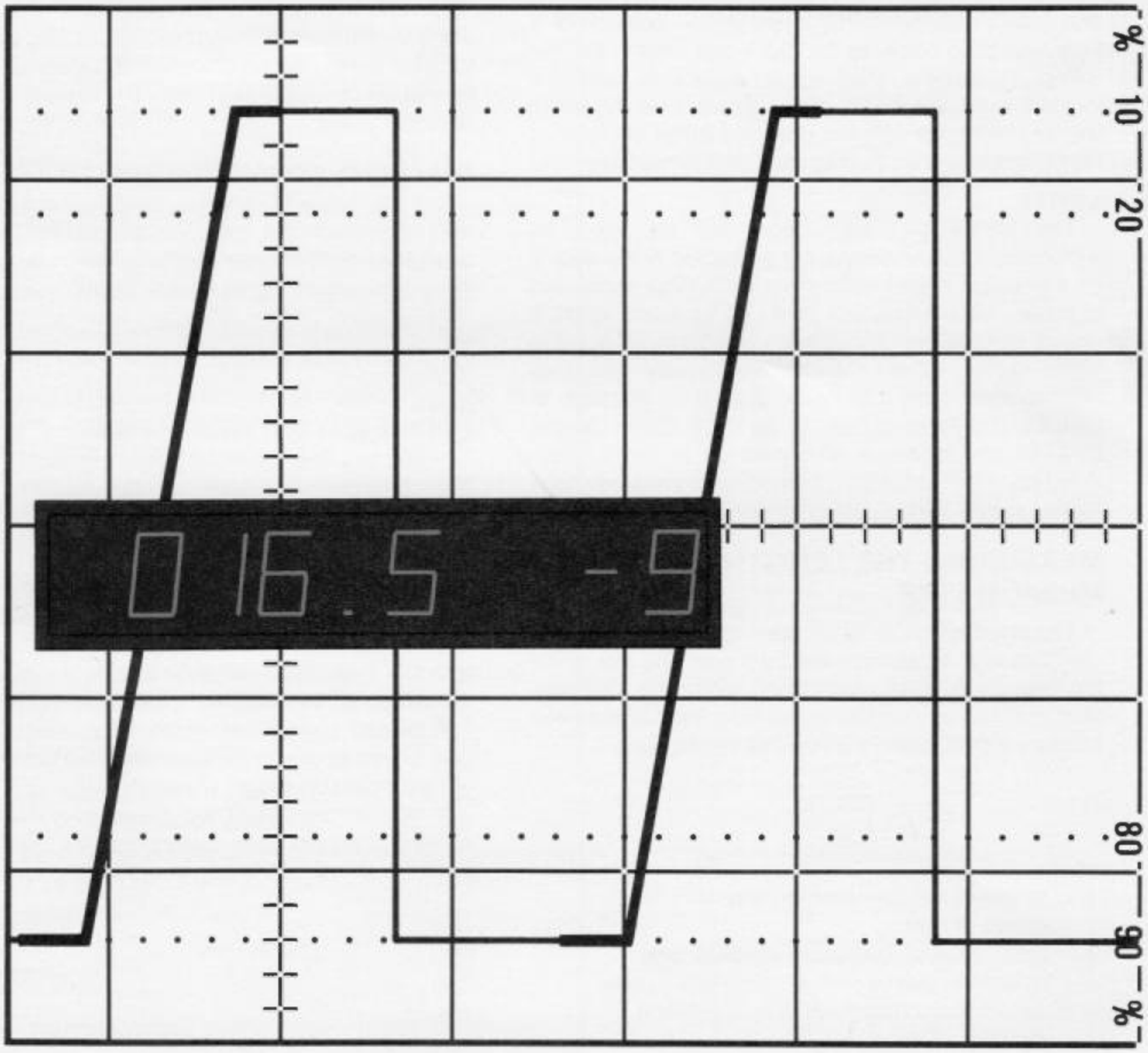
APPLICATION NOTE 185-2

TRANSMISSION LINE MATCHING AND LENGTH MEASUREMENTS USING DUAL-DELAYED SWEEP IN THE MICROPROCESSOR CONTROLLED OSCILLOSCOPE .... MODEL 1722A



HEWLETT PACKARD

INTRODUCTION

Among the more unusual applications utilizing the 1722A are transmission line matching and length measurements. 275 MHz bandwidth with high impedance coupling which permits the injection of energetic pulses, dual-delayed sweep which permits convenient transmission line matching to within 10 ps of electrical propagation delay, and time base accuracy which permits length measurements to within 0.5% are the features of the 1722A that make these applications feasible.

TECHNIQUE

The technique for both transmission line matching and length measurements employs the injection of a very energetic pulse, up to 100 V p-p amplitude. The reflected pulse is then either compared with the incident pulse for length measurements on the same line or compared with the reflected pulse on another transmission line for propagation delay matching.

LIMITS

The length of transmission line that can be either measured or matched is a function of the quality of line being tested. Using RG58 coaxial cable and injecting a 50 V incident pulse of sufficient width, it should be possible to measure up to 18 miles of cable within 0.7% before attenuation seriously interferes with measurement capability. It is also possible to match a test transmission line up to 18 miles in length to a known reference within 10 ps of propagation delay since the reflected pulses can be compared on the fastest sweep speeds using trigger delay techniques.

MEASURING THE LENGTH OF A TRANSMISSION LINE

The physical length of an open or shorted transmission line can be determined by measuring the round trip time for a pulse propagating along the transmission line, i.e., by measuring the time interval between incident and reflected pulses. The relationship

$$l = \frac{ct}{2\sqrt{\epsilon_r}} \qquad (1)$$

where

l = length of the transmission line

c = speed of light

t = time interval between incident and reflected pulses

ϵ_r = dielectric constant of the insulation material

translates the time interval directly into the length of the transmission line.

TECHNIQUE

To determine the length of a test transmission line, given its dielectric constant, a pulse is injected into the transmission line and the time interval between the beginning of the leading edges of the incident and reflected pulses is measured (refer to figure 1 for hook-up). This time interval is used in equation 1 to evaluate the length of the line.

With dual-delayed sweep both the incident and reflected pulses can be observed simultaneously; therefore, it is an easy matter to overlap these pulses to determine accurately the time interval between them. To facilitate the measurement both channels A and B can be connected with a short BNC cable which allows independent attenuator control over each of the displayed pulses in the delayed sweep mode. The small difference between the arrival of the incident pulse at channels A and B input connectors can be eliminated from the time interval measurement with the side panel zero adjustment. Further, the leading edge of the incident pulse can be changed with variable transition time pulse generators to match the leading edge of the reflected pulse.

PRACTICAL CONSIDERATIONS

It is advisable to obtain a sample of the test transmission line cut to a known length and to measure the dielectric constant experimentally, which, by rearrangement of equation 1, can be calculated from

$$\epsilon_r = \left(\frac{c\,t_1}{2\,l_1}\right)^2 \qquad (2)$$

where

t_1 = measured time interval between incident and reflected pulses on the sample

l_1 = measured length of the sample

The minimum length of polyethylene transmission line for a sample line which introduces less than 1% error in the determination of the dielectric constant is about 4 meters, if the error in the measurement of the length of the sample is less than 0.1% or 4 mm. For twisted pair transmission lines, longer samples may be necessary to minimize the effect of the number of twists per unit length variation.

In lieu of calculating the dielectric constant of the sample, a simpler ratio method can be used to determine the length of the transmission line, i.e.,

$$l_2 = \frac{l_1\,t_2}{t_1} \qquad (3)$$

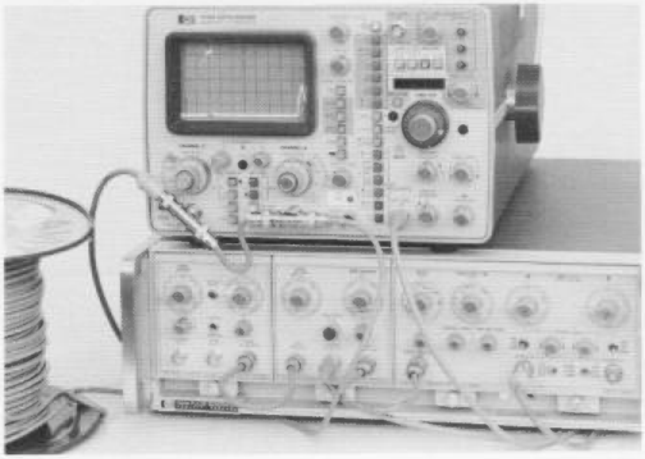
where

l_2 = length of test line

t_2 = time interval between incident and reflected pulses on test line

The error in the length of the test line is found from the absolute time base accuracy (from the data sheet or instrument manual) and the error in measuring the sample length (continued page 4).

CABLE LENGTH MEASUREMENTS



Cable Length Measurement Test Setup

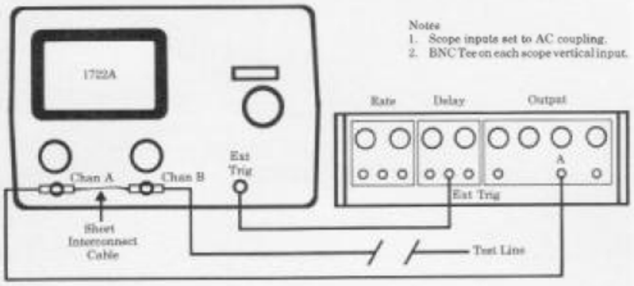


Figure 1a. Test setup. Connect channel A and channel B together with a short length of 50Ω cable and BNC Tee's on each input. The pulse generator output is connected to channel A and the transmission line is connected to channel B. The 1722A is triggered externally by the pulse generator for trigger delay flexibility. The propagation delay difference caused by the 50Ω cable between channels A and B can be eliminated using the 1722A side panel Zero Adjustment.

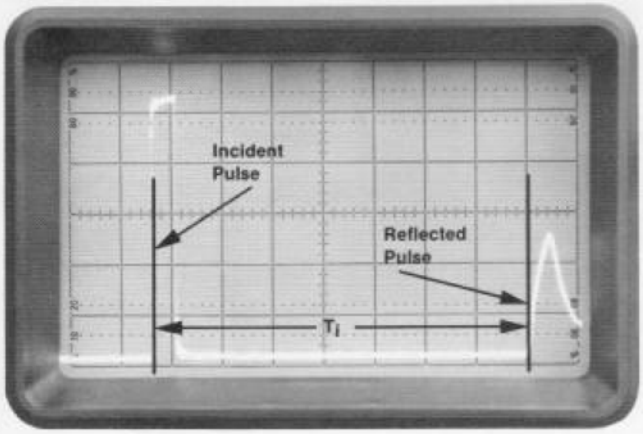


Figure 1b. For maximum accuracy, the time interval between incident and reflected pulses is measured as close to the beginning of the pulse transition as possible. The CRT display is of a single channel main sweep with the time interval occupying as much of the main sweep as possible for viewing.

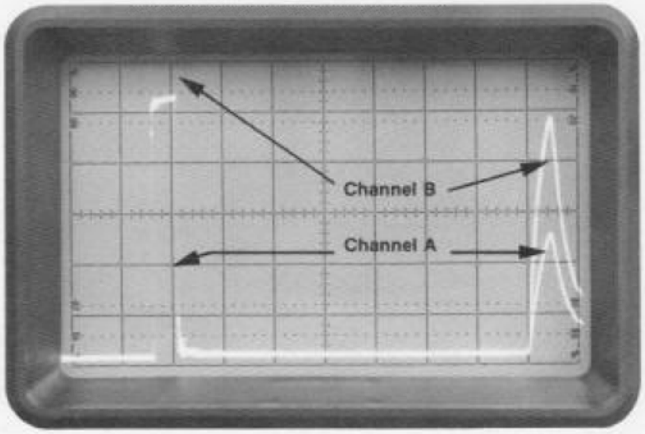


Figure 1c. Use the alternate mode to provide maximum amplitude adjustment of both incident and reflected pulses. The incident pulse on channel B cannot be seen because the pulse is amplified beyond the display area to provide a high amplitude reflected pulse.

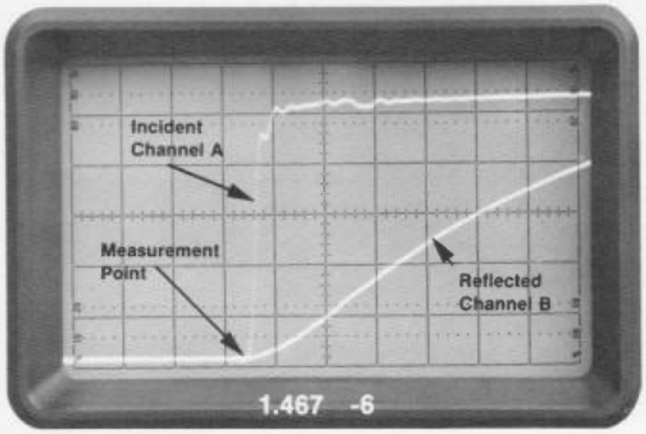


Figure 1d. In the delayed sweep mode, both incident and reflected pulses are displayed with time interval of 1.467 -6 displayed on LED's.

(4) $$d\,l_2 = \frac{l_1\,t_2}{t_1}\left(\frac{d\,l_1}{l_1} + \frac{d\,t_1}{t_1} + \frac{d\,t_2}{t_2}\right)$$

By either the dielectric constant or ratio method the error in length, dl_2, can be calculated from equation 4.

The amplitude of the reflected pulse is another important aspect of transmission line length measurements. As the length of the transmission line increases, the bandwidth of the line decreases and consequently the amplitude of the reflected pulse decreases. The amplitude of the reflected pulse, therefore, not only depends upon the incident pulse amplitude but also on its width. This can be expressed as

(5) $$\frac{dB}{l} = \frac{\propto}{\sqrt{\Delta t}}$$

where

$dB =$ attenuation

$\Delta t =$ incident pulse width

$\propto =$ a quality constant of the transmission line which depends on the inherent loss in the line

$l =$ length of sample line

$\propto$ can be calculated from our sample of test transmission line, i.e.,

(6) $$\propto = \frac{dB\,\sqrt{\Delta t}}{l}$$

to aid in calculating the length of the cable, or the necessary incident pulse width for detecting a discontinuity in the test cable or its length.

Using the pulse injection method provides information about the nature of discontinuities in the transmission line, that is, an open is indicated by a reflected pulse with the same polarity as the incident pulse; a short is indicated by a reflected pulse with opposite polarity. Therefore, dual-delayed sweep using the configuration in figure 1 allows channel B to be inverted when the transmission line is shorted for easy comparison between the incident and reflected pulse.

For further practical considerations, the injected pulse should be delayed from the trigger signal so that the leading edge of the incident pulse can be observed in the delayed sweep mode, the main sweep on the oscilloscope should be as fast as possible to see both incident and reflected pulses, the period of the pulse generator should be at least 10% greater than the time interval between incident and reflected pulses.

AN EXAMPLE:

Sample Cable Parameters

Known length: $l_1 = 9.000 \pm 0.006$ m

Measured time interval: $t_1 = 91.12 \pm 0.655$ ns

Test Cable Parameters

Measured time interval: $t_2 = 1.472 \pm 0.008 \times 10^{-6}$s

RATIO METHOD

From equation 3, cable length is given by:

$$l_2 = \frac{(9.000\text{ m})\ (1.472 \times 10^{-6})\text{s}}{91.12 \times 10^{-9}\text{s}}$$

$$l_2 = 145.391\text{ m}$$

From equation 12, error in the measured length is given by:

$$dl_2 = \pm 145.391\text{ m}\left[\frac{0.006\text{ m}}{9.000\text{ m}} + \frac{0.008 \times 10^{-6}\text{s}}{1.472 \times 10^{-6}\text{s}} + \frac{0.655 \times 10^{-9}\text{s}}{91.12 \times 10^{-9}\text{s}}\right]$$

$$dl_2 = \pm 1.932\text{ m}$$

DIELECTRIC CONSTANT METHOD

From equation 2, the dielectric constant is given by:

$$\epsilon_r = \frac{(2.997925 \times 10^8\text{ m/s})^2\ \ (91.12 \times 10^{-9}\text{s})^2}{4(9.000\text{ m})^2}$$

$$\epsilon_r = 2.30316$$

From equation 15, dielectric constant error is given by:

$$d\epsilon_r = 2.30316\ \left[\frac{0.655 \times 10^{-9}\text{s}}{91.12 \times 10^{-9}\text{s}} + \frac{0.006\text{ m}}{9.000\text{ m}}\right]$$

$$d\epsilon_r = \pm 0.01809$$

From equation 1, cable length is given by:

$$l_2 = \frac{(2.997925 \times 10^8\text{ m/s})\ \ (1.472 \times 10^{-6}\text{s})}{2\sqrt{2.30316}}$$

$$l_2 = 145.391\text{ m}$$

From equation 12, error in measured length is given by:

$$dl_2 = \pm 145.391\text{ m}\left[\frac{0.008 \times 10^{-6}}{1.472 \times 10^{-6}} + \frac{0.01809}{2.30316}\right]$$

$$dl_2 = \pm 1.932\text{ m}$$

TRANSMISSION LINE MATCHING

The technique for matching two cables in propagation delay (figure 2) is much the same as for length measurements with the notable exception that, for convenience, two synchronous pulse generators should be used, one for each line. Again, any time difference between the incident pulses can be eliminated with the side panel zero adjust.

Since only the reflected pulses are of interest, the injected pulse should be advanced from the trigger signal so that only the reflected pulses are displayed at the fastest sweep speed possible.

If the time interval displayed on the LED readout is zero, at 20 ns/div main sweep, and both reflected pulses are overlapped, then the match between the transmission lines is within 10 ps of each other regardless of the actual length of the transmission line, within practical limits.

OPERATING HINTS

The TDR technique is greatly aided by a few operating hints:

LENGTH MEASUREMENTS

1. Use the fastest main sweep possible that displays both incident and reflected pulses.
2. Expand the reflected pulse as much as possible in both horizontal and vertical axes for maximum definition of the reflected pulse.
3. Measure the time interval between incident and reflected pulses at the very beginning of the leading edges.
4. Use as wide an incident pulse as possible for location of the reflections and then decrease the width of the pulse for fastest reflection rise time.
5. Use high impedance input with ac coupling on both channels for best position control.

CABLE MATCHING

1. Use fastest main sweep possible while looking only at the reflected pulse.
2. Use applicable rules stated in length measurement for location and maximum definition of the reflected pulse.

REMARKS

This application note illustrates only two of the many applications that are easier to perform and more accurate with the 1722A. Dual-delayed sweep is the most important feature used in these applications; therefore, any oscilloscope with dual-delayed sweep, such as the 1712A, can be used for line matching and length measurements. However, be sure that the time base accuracy and bandwidth specifications are sufficient for the measurement requirements.

The pulse generator system used in these examples is the 1900A mainframe, 1906A rate generator, 1908A delay generator, and 1916A output generator. However, any pulse generator with fast transition times (preferably <2.5 ns), variable width, repetition rate, and amplitude, both trigger delay and advance, and dual outputs, can be used for these applications.

For an in-depth discussion of time base accuracy and its contribution to measurement error refer to Application Note 185.

THE MATH

The phase velocity of traveling waves of voltage or current propagating along a parallel and straight transmission line, with all the space between conductors filled with a material of dielectric constant, ϵ, and of magnetic permeability, μ, is given by

$$\nu_\psi = \frac{c}{\sqrt{\mu\epsilon}} \qquad (7)$$

If we define $\mu\epsilon = \epsilon_r$ and note that $\nu_\psi = \frac{l}{t}$ where l = distance traveled and t = duration of travel, then

$$l = \frac{ct}{\sqrt{\epsilon_r}} \qquad (8)$$

On the 1722A, we measure the duration of a two way trip for the incident pulse; therefore,

$$l = \frac{ct}{2\sqrt{\epsilon_r}} \qquad (9)$$

THE RATIO METHOD

If l_1 = the known length of a sample transmission line, t_1 = propagation delay for a two way trip for an incident pulse applied to the sample line, and t_2 = propagation delay for a two way trip for an incident pulse applied to a test line and the sample and test lines have the same dielectric constant, then l_2, the length of the test line, is related to l_1, t_1 and t_2 by

$$l_2 = \frac{l_1 t_2}{t_1} \qquad (10)$$

The error in the measurement, dl_2, is given by

$$dl_2 = \frac{\partial}{\partial l_1}\left[\frac{l_1 t_2}{t_1}\right] dl_1 + \frac{\partial}{\partial t_r}\left[\frac{l_1 t_2}{t_1}\right] dt_2 + \frac{\partial}{\partial t_1}\left[\frac{l_1 t_2}{t_1}\right] dt_1 \qquad (11)$$

$$= \pm \frac{l_1 t_2}{t_1}\left[\frac{dl_1}{l_1} + \frac{dt_2}{t_2} + \frac{dt_1}{t_1}\right] \qquad (12)$$

where

dl_1 = uncertainty in actual length of sample line

and

dt_1, dt_2 are from time base specifications as described in AN 185.

THE DIELECTRIC CONSTANT METHOD

If ϵ_r is known, then the length, l_2, of the test line can be calculated from

$$l_2 = \frac{ct_2}{2\sqrt{\epsilon_r}}$$

The error in the measurement of l_2 is given by

$$dl_2 = \frac{ct_2}{2\sqrt{\epsilon_r}}\left(\frac{dt_2}{t_2}\right) \qquad (13)$$

If ϵ_r is measured, then the error in this measurement must be included in the error of the length of the cable; i.e.,

$$dl_2 = \frac{ct_2}{2\sqrt{\epsilon_r}}\left[\frac{dt_2}{t_2} + \frac{d\epsilon_r}{\epsilon_r}\right] \qquad (14)$$

Now, $\epsilon_r = \left(\frac{ct_1}{2l_1}\right)^2$, so

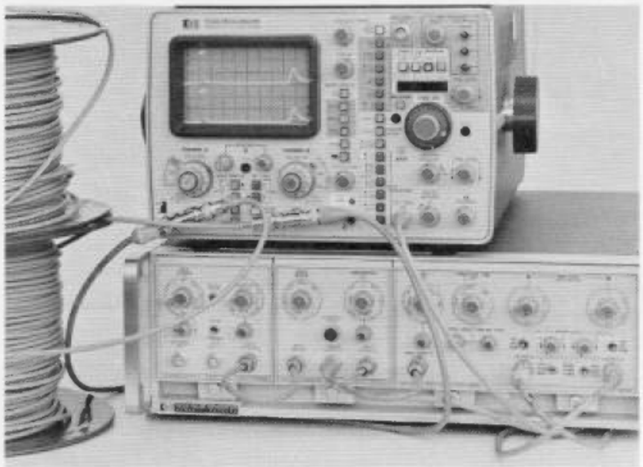
$$d\epsilon_r = \left(\frac{ct_1}{2l_1}\right)^2\left[\frac{dt_1}{t_1} + \frac{dl_1}{l_1}\right] \qquad (15)$$

by substitution,

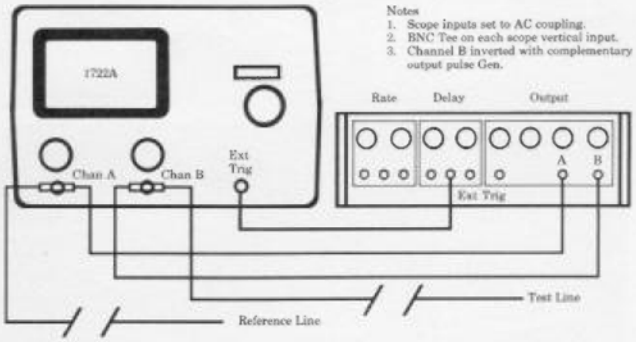
$$dl_2 = \frac{l_1 t_2}{t_1}\left[\frac{dl_1}{l_1} + \frac{dt_2}{t_2} + \frac{dt_1}{t_1}\right]$$

, i.e., the same error derived for the ratio method.

CABLE LENGTH MATCHING



Cable Matching Test Setup



Notes
1. Scope inputs set to AC coupling.
2. BNC Tee on each scope vertical input.
3. Channel B inverted with complementary output pulse Gen.

Figure 2a. Test setup. The reference line is connected to channel A and the test line is connected to channel B with BNC Tee's. The two pulse generator outputs are connected to each channel (in this case, the outputs are complementary so channel B is inverted on the scope). The 1722A is triggered externally from the pulse generator for both trigger delay and advance flexibility.

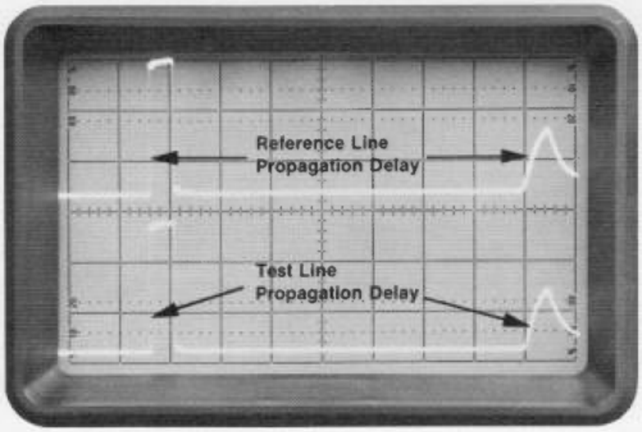


Figure 2b. When the time interval between the incident and reflected pulses on both the reference and test lines are equal the lines are matched.

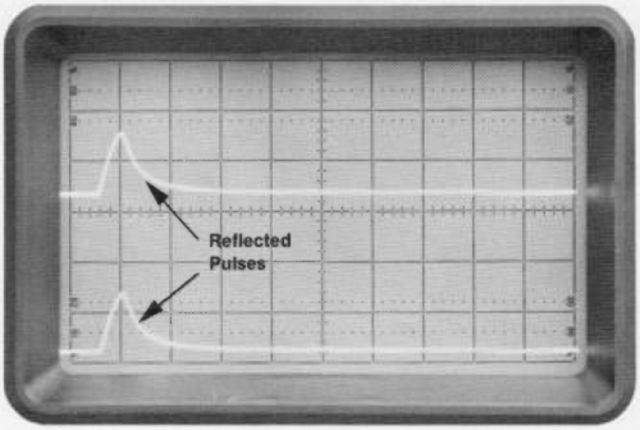


Figure 2c. For increased resolution, the pulse generator supplies a trigger after the incident pulse (trigger advance) to permit extreme expansion of the reflected pulses for maximum accuracy and resolution. This photo shows a very close match condition.

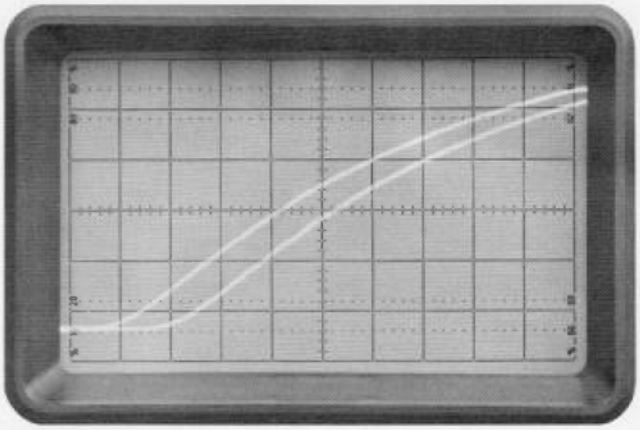


Figure 2d. After amplitude and position adjustment of the reflected pulses, the 1722A is placed in the delayed sweep mode. The separation of the traces shows the propagation delay difference between the lines which is displayed on the LED's.

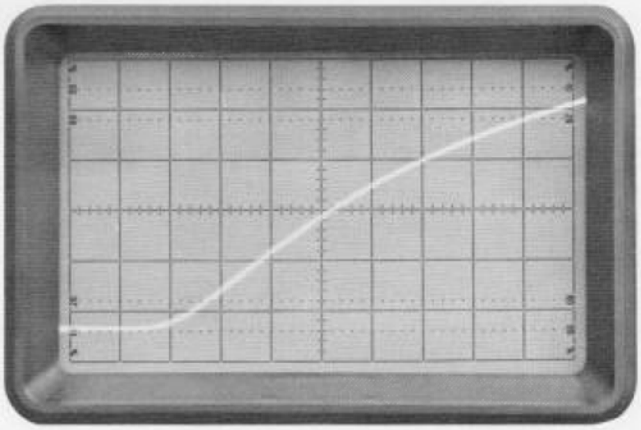


Figure 2e. A matched condition occurs when the reflected waveforms overlap. In this case, the cables are each approximately 145 metres (475 feet) long and are matched within 3.2 mm (1/8 inch) of each other.

Application Note(s) in the 185 series with the primary instrument(s) used in parenthesis.

185 Waveform Parameter Measurements Using the Microprocessor Controlled Oscilloscope (1722A).

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