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Thermal Coefficient of Delay for Various Coaxial and Fiber-Optic Cables

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This article presents data on the thermal coefficient of delay for various coaxial and fiber-optic cables, as measured by the Frequency and Timing Systems Engineering Group and the Time and Frequency Systems Research Group. The measured pressure coefficient of delay is also given for the air-dielectric coaxial cables. The article includes a description of the measurement method and a description of each of the cables and its use at JPL and in the DSN. An improvement in frequency and phase stability by a factor of ten is possible with the use of fiber optics.

I. Introduction

Highly stable frequency and timing reference signals generated by atomic frequency standards enable the NASA/JPL Deep Space Network (DSN) to make precise measurements of relative time and position. These measurements are used to locate spacecraft and guide them to their destinations. They are also used to support radio science, radio and radar astronomy, very long baseline interferometry, and geodynamics.

Within a Deep Space Communications Complex (DSCC), high-stability distribution systems are used to distribute the frequency and timing reference signals derived from the frequency standard to the subsystems that use them. These distribution systems use coaxial or fiber-optic cables as the transmission medium. Delay changes in these cables are often the major contributor to the phase and frequency instability of the distributed reference signals.

Detailed data on delay stability of cables is generally not available from manufacturers. Since this information is needed to design frequency and timing distribution systems, the Time and Frequency Systems Research Group and the Frequency and Timing Systems Engineering Group have measured the thermal coefficient of delay (TCD) and the pressure coefficient of delay (PCD) for various coaxial and fiber-optic cables. This article presents the results of these measurements. A key finding is that an improvement in frequency and phase stability by a factor of ten is possible, compatible with anticipated requirements on the DSN for supporting gravitational-wave experiments and connected-element interferometry.

II. Background

Delay changes degrade the phase and frequency stability of a signal transmitted through a transmission line [1]. When the temperature of a transmission line changes, the result is a corresponding delay change through the transmission line. A pressure change in an air-dielectric transmission line results in an additional delay change, since a dielectric constant change results from a pressure change.

The TCD is a measure of delay change in a signal path that results from a temperature change. Its value is often given in parts per million per deg Celsius (ppm/deg C), which is the change in delay divided by the total delay normalized to 1 million units. In equation form it is

$$\mathrm{TCD} = \frac{\Delta t(10^6)}{t\Delta T} \tag{1}$$

where Δt is the change in delay through a signal path, t is the nominal delay through the signal path, and ΔT is the change in temperature. Similarly, the pressure coefficient of delay (PCD) is a measure of delay change in a signal path that results from a pressure change. Like TCD, the value of PCD is often given in ppm/psi.

In practice, phase measurements can be made with much higher resolution and accuracy than direct delay measurements. Therefore, to obtain the data presented in this article, phase changes were measured and converted to delay changes. Since phase delay has a linear relationship to time delay, Eq. (1) can be rewitten in terms of phase as

$$\mathrm{TCD} = \frac{\Delta\Theta(10^6)}{\Theta\Delta T} \tag{2}$$

where $\Delta\Theta$ is the change in phase delay through a signal path, and Θ is the nominal phase delay through the signal path.

The TCD and PCD of various cables have been measured, and the data presented in this article will enable designers to identify a cable with suitable stability performance for a particular application.

III. Measurement Method

Figure 1 shows a block diagram of the measurement system. A reference signal is separated by an RF power splitter into two signals. One of these signals is passed through the cable under test, and the other signal is used as a reference. The signal at the output of the cable under test drives one port of an RF phase detector. The reference signal from the RF power splitter passes through a manual RF phase shifter and drives the other port of the RF phase detector. A lowpass filter on the output of the RF phase detector eliminates the RF signals, leaving only the DC component, which is measured with a DC voltmeter. A temperature-controlled test chamber contains the cable under test.

The phase detector's sensitivity is measured in volts per deg phase, and must be calibrated before measurements can be made. For most phase detectors, the output voltage vs. phase curve, commonly called the S-curve, is sinusoidal if the proper input signal levels are applied. When this is the case, it is only necessary to measure the peak voltage out of the phase detector in order to calibrate it. The peak voltage is obtained by adjusting the manual phase shifter for 0 deg or 180 deg phase difference between the signals at the phase detector input ports. In terms of the peak voltage, the slope of the S-curve, in volts per deg phase, near zero volts (90 deg) is

$$K_\Theta \approx \frac{\pi V_p}{180} \tag{3}$$

where V_p is the peak voltage out of the RF phase detector. If the phase detector curve is not sinusoidal, it is necessary to determine the slope of the curve by other means.

The measurements are made with the phase difference between the signals applied to the phase detector set near 90 deg. This is where the output of the phase detector is near zero volts. For these measurements, the phase detector output voltage vs. phase change is assumed to be linear in this region. However, the total phase-delay change in the cable under test should be no more than ±30 deg over the test temperature range. This keeps errors due to the nonlinearity of the S-curve to less than 5 percent. A lower test frequency permits testing very long cables without exceeding a 30-deg phase-delay change over the test temperature range.

To make the measurement, the temperature of the test chamber is set to a nominal value, usually 25 deg C. The manual phase shifter is adjusted to obtain a 90-deg phase difference between the signals at the ports of the RF phase detector. For this phase difference, the output voltage from the RF phase detector is near zero. Once this zero-volt reference is established, the temperature in the test chamber is changed in steps. For each temperature change in the test chamber, the voltage out of the phase detector changes, indicating a phase (delay) change. The value of the phase-delay change is

$$\Delta\Theta = \frac{\Delta E}{K_\Theta} \tag{4}$$

where ΔE is the change in voltage due to a temperature change.

When the voltage change stabilizes, its new value is recorded and the temperature in the test chamber is stepped to a new value. This can take from 20 min to 1 hr per step. The temperature is normally changed in steps of 5 deg C. This usually results in a large enough phase change to be accurately measured. Yet the phase change is not so large that it results in significant error due to the nonlinearity of the phase-detector curve.

From Eqs. (2), (3), and (4), the TCD in terms of the known and measured parameters is

$$\text{TCD} = \frac{\Delta E(10^6)(3 \times 10^8)\alpha}{2 f l \pi V_p \Delta T} \tag{5}$$

where α is the propagation constant for the cable, f is the measurement frequency used, l is the physical length of the cable, and ΔT is the change in temperature of the transmission line.

A plot of the phase detector output vs. time and temperature for a 39.6-m length of RG-223/U cable is shown in Fig. 2. Each step in phase was the result of a temperature step of 5 deg C in the test chamber. The total temperature range is from 35 deg C at the bottom of the plot to 15 deg C at the top of the plot. The vertical scale shows 50 mV per major division (50 mV/div), and the horizontal scale shows time in 1 hr per major division (1 hr/div). The phase detector's peak output V_p was measured at 1.06 V. The propagation factor α for the cable is given by the manufacturer as 0.659. A 100-MHz test frequency was used. Using the example of the step between 30 deg C and 25 deg C, shown enclosed in dotted lines at the left side of Fig. 2, the change in voltage E is $1.2(5 \times 10^{-2}) = 6 \times 10^{-2}$. Evaluating Eq. (5) for this change in delay using the above information,

$$\text{TCD} = \frac{(6 \times 10^{-2})(10^6)(3 \times 10^8)(0.659)}{2(10^8)(39.6)\pi(1.06)5}$$

$$= 90\text{ppm/deg C at 27.5 deg C}$$

which is the average temperature of this step.

IV. Results

The cables that have been measured in the Frequency Standards Laboratory (FSL) at JPL are loose-tube single-mode fiber-optic cable, low-TCD fiber-optic cable, and metal-based coaxial cables RG-223/U, SF-214, F242-VV-2400-AOB, F645-EIA-5160-AO, HCC-12-50J, 64-500, and 64-875. Each of these cables and its application at JPL and in the DSN is described in this section. The TCD for each cable is given and the PCD is given for those cables that are normally pressurized.

Loose-tube single-mode fiber-optic cable is used between Deep Space Stations (DSSs) at the Goldstone DSCC. These cables, supplied by several manufacturers, use Corning single-mode fiber and are very similar in design. Figure 3 depicts the general cable design. The performance characteristics are virtually identical for all of the manufacturers, and are given in Table 1 [2, 3, 4]. A graph of TCD with respect to temperature is shown in Fig. 4, which compares this type of cable to low-TCD optical fiber and the best coaxial cable (64-875).

A new optical fiber with a very low TCD has been tested in the FSL. This fiber is manufactured by Sumitomo Electric, and cables containing four fibers of this type are now being procured. They will be tested for distribution of several types of signals in the DSN, including frequency references, time references, local oscillator signals, and intermediate frequency (IF) signals. Table 2 lists the physical and performance characteristics of this new fiber [5]. Figure 5 shows a graph of its TCD with respect to temperature.

RG-223/U is a general-purpose coaxial cable in common use at JPL and in the DSN. It is manufactured by a number of companies, including Times Wire and Cable. Table 3 lists its important physical and performance characteristics, and Fig. 6 shows a graph of its TCD with respect to temperature [6].

SF-214 is also a general-purpose cable in common use at JPL and in the DSN. This cable is manufactured by Times Wire and Cable. It has lower loss than RG-223, and is used where this characteristic is important. It is also used in the antenna wrap-ups in the DSN where the cable must be flexed. Table 4 lists the important physical and performance characteristics of SF-214, and Fig. 7 shows a graph of its TCD with respect to temperature [6].

F242-VV-2400-AOB is a 3/8-in.-diameter coaxial cable with a corrugated outer conductor for flexibility. It is used in the FSL for test applications where the cable must have low TCD and be flexible to accommodate various test configurations. It is manufactured by Flexco Microwave. Table 5 lists its important physical and performance characteristics [7], and Fig. 8 shows a graph of its TCD with respect to temperature.

F645-EIA-5160-AO is a 1-in.-diameter coaxial cable with a corrugated outer conductor, manufactured by

Flexco Microwave. It was tested for possible use in the DSN. Table 6 lists its important physical and performance characteristics [7], and Fig. 9 shows a graph of its TCD with respect to temperature. The PCD of F645 cable with respect to air pressure is shown in Fig. 10.

HCC-12-50J is a 1/2-in.-diameter hardline cable used in the FSL where delay stability is critical but the cable is not flexed. It is manufactured by Cablewave Systems. Table 7 lists its important physical and performance characteristics [8] and Fig. 11 shows a graph of its TCD with respect to temperature.

Two pressurized hardline air-dielectric cables, 64-500 and 64-875, are used in the DSN where the lowest TCD and low attenuation are needed. The 64-875, a 7/8-in.-diameter cable, has better delay stability and lower attenuation than the 64-500 cable, which has a 1/2-in. diameter. However, the 64-875 cable is considerably more expensive and harder to work with. These two cables were manufactured by Prodelin, which was sold to Cablewave, who now manufactures them. Cablewave has informed the cable Cognizant Operations Engineer (COE) that they will stop manufacturing these cables in the near future. Table 8 lists the important physical and performance characteristics for 64-500 cable, and Figs. 12 and 13 show graphs of its TCD and PCD. Table 9 lists the important physical and performance characteristics of 64-875 [9], and Figs. 14 and 15 show graphs of its TCD and PCD.

V. Conclusion

Several fiber-optic cables and coaxial cables used at JPL and in the DSN have been measured to determine their TCD. The PCD of the air-dielectric cables was also measured. The plots of TCD and PCD given here are meant to guide the user in choosing a coaxial or fiber-optic cable for use in applications requiring high delay stability. Many of the technical parameters needed to make tradeoff decisions are given. The costs of these cables as given in the tables are to be taken as a guide only. For very large quantities, e.g., tens of kilometers, the costs are tied largely to material costs and market conditions, and the cost of short lengths of cable may be three to four times the large-quantity cost. In the normal operating range of temperatures from 15 to 35 deg C, the new low-TCD fiber-optic cable with superior delay stability permits signals to be transmitted with unprecedented frequency and phase stability. For instance, compared to the best coaxial cable at 25 deg C, the use of low-TCD fiber would improve the frequency and phase stability of a transmitted signal by more than ten times.

Acknowledgment

The authors wish to thank Al Kirk for developing the procedure used to measure the cable delay stability vs. temperature given in this article.

References

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[9] "General Catalog 1776," Prodelin, 1976. Information now available from Cablewave Systems, 60 Dodge Avenue, North Haven, Connecticut 06473.

Table 1. Physical and performance characteristics of loose-tube, single-mode, fiber-optic cable

Cutoff wavelength	1130 to 1270 nm
Core concentricity	$< 1\mu m$
Cladding diameter	125 $\pm 3\mu m$
Coating diameter	250 $\pm 15\mu m$
Core diameter	8.7μm
Spot size	10μm
Dispersion of 1285- to 1350-nm wavelength	< 3.5 psec/nm-km
Optical loss, maximum	0.5 dB/km
RF bandwidth	> 100 GHz-km
Number of fibers	18 and 24
Nominal weight	165 kg/km
Maximum diameter	15.1 mm
Temperature range	-40 to $+70$ deg C
Maximum tensile rating	
During installation	2700 N
Long-term after installation	600 N
Minimum bend radius	
During installation	300 mm
Free bend, installed	150 mm
Crush resistance, long-term installed	50 N/cm
Maximum vertical rise	175 m
Price	$0.25/fiber-meter to $0.35/fiber-meter

Table 2. Physical and performance characteristics of low-TCD, single-mode optical fiber cable

Cutoff wavelength	1260 nm
Core concentricity	$< 0.1\mu m$
Cladding diameter	125.4μm
Coating diameter	815.0μm
Spot size	9.6μm
Zero-dispersion wavelength	1305 nm
Zero-dispersion slope	< 0.083 psec/nm-km
Optical loss, maximum	0.32 dB/km
RF bandwidth	> 100 Ghz-km
Price	$\approx$ $4/fiber-meter

Table 3. Physical and performance characteristics of RG-223/U coaxial cable

Inner conductor	Silver-covered copper; outside diameter 0.035 in.
Dielectric	Solid polyethylene; outside diameter 0.116 in.
Outer conductor	Two shielding braids, silver-covered copper
Jacket material	Black polyvinylchloride
Cable outside diameter	3/16 in.
Minimum bend radius	1.0 in.
Weight	0.034 lbs/ft
Impedance	50 ohms
Nominal capacitance	30.8 pf/ft
Maximum operating temperature range	−40 to +80 deg C
Maximum operating voltage	1900 volts RMS
Propagation constant	0.659
Nominal loss characteristics, dB/100 ft	
10 MHz — 1.35	
50 MHz — 3.0	
100 MHz — 4.3	
200 MHz — 6.0	
400 MHz — 8.8	
1 GHz — 16.5	
3 GHz — 36.0	
5 GHz — 51.0	
10 GHz — 85.0	
Price, < 300 meters	≈ $4.50/m

Table 4. Physical and performance characteristics of SF-214 coaxial cable

Inner conductor		Seven strands of 0.0296-in. silver-covered copper; outside diameter 0.089 in.
Dielectric		Solid polyethylene; outside diameter 0.285 in.
Outer conductor		Silver-covered copper, braided flat round composites
Jacket material		Black polyvinylchloride
Cable outside diameter		0.450 in.
Minimum bend radius		2.0 in.
Weight		0.144 lbs/ft
Impedance		50 ohms
Cutoff frequency		13.7 GHz
Nominal capacitance		30.8 pf/ft
Maximum operating temperature range		−55 to +80 deg C
Maximum operating voltage		5000 volts RMS
Propagation constant		0.659
Minimum recommended bend radius		2.0 in.
Nominal loss characteristics, dB/100 ft		
10 MHz	Not available	
50 MHz	Not available	
100 MHz	2.0	
200 MHz	2.9	
400 MHz	4.1	
1 GHz	7.0	
3 GHz	13.0	
5 GHz	18.0	
10 GHz	27.0	
Price, < 300 meters		≈ $20/m

Table 5. Physical and performance characteristics of F242-VV-2400-AOB coaxial cable

Inner conductor		Silver-covered copper; outside diameter 0.081 in.
Dielectric		Air; spline polytetrafluoroethylene spacer; outside diameter 0.200 in.
Outer conductor		Soldered strip-wound (corrugated) silver-covered copper; outside diameter 0.330 in.
Jacket material		Fluorinated ethylene propylene
Cable outside diameter		3/8 in.
Minimum bend radius		1.0 in.
Weight		Not available
Impedance		50 ohms
Cutoff frequency		20 GHz
Nominal capacitance		Not available
Maximum operating temperature range		−55 to +200 deg C
Maximum operating voltage		5000 volts RMS
Propagation constant		0.80
Nominal loss characteristics, dB/100 ft		
10 MHz	Not available	
50 MHz	Not available	
100 MHz	2.5	
200 MHz	4.0	
400 MHz	6.0	
1 GHz	8.5	
3 GHz	15.0	
5 GHz	19.5	
10 GHz	37.0	
Price, < 1 km		≈ $102/m
> 5 km		≈ $30/m

Table 6. Physical and performance characteristics of F645-EIA-5160-AO coaxial cable

Inner conductor	Stranded silver-covered copper
Dielectric	Air; spline polytetrafluoroethylene spacer
Outer conductor	Soldered strip-wound (corrugated) silver-covered copper; outside diameter 1.025 in.
Jacket material	Fluorinated ethylene propylene
Cable outside diameter	1.065 in.
Minimum bend radius	5.5 in.
Weight	Not available
Impedance	50 ohms
Cutoff frequency	6 GHz
Nominal capacitance	Not available
Maximum operating temperature range	−55 to +200 deg C
Maximum operating voltage	5000 volts RMS
Propagation constant	0.79
Nominal loss characteristics, dB/100 ft	
10 MHz — Not available	
50 MHz — Not available	
100 MHz — 0.60	
200 MHz — 0.95	
400 MHz — 1.50	
1 GHz — 2.70	
3 GHz — 5.0	
5 GHz — 6.80	
10 GHz — 10.0	
Price, < 1 km	≈ \$148/m
> 5 km	≈ \$40/m

Table 7. Physical and performance characteristics of HCC-12-50J coaxial cable

Inner conductor	Copper-clad aluminum; outside diameter 0.155 in.
Dielectric	Air; spiral polyethylene spacer; outside diameter 0.338 in.
Outer conductor	Corrugated copper; outside diameter 0.484 in.
Jacket material	Black polyethylene
Cable outside diameter	0.618 in.
Minimum bend radius	5 in.
Weight	0.16 lbs/ft
Impedance	50 ohms
Cutoff frequency	11.3 GHz
Nominal capacitance	Not available
Maximum operating temperature range	−55 to +80 deg C
Maximum operating voltage	Not available
Propagation constant	0.915
Nominal loss characteristics, dB/100 ft	
10 MHz 0.26	
50 MHz 0.59	
100 MHz 0.85	
200 MHz 1.3	
400 MHz 1.8	
1 GHz 2.9	
3 GHz 5.0	
5 GHz 7.0	
10 GHz 10.0	
Price, > 5 km	≈ $12/m

Table 8. Physical and performance characteristics of 64-500 pressurized hardline air-dielectric cable

Inner conductor	Copper-clad aluminum; outside diameter 0.167 in.
Dielectric	Air; six polyethylene tubes; outside diameter 0.456 in.
Outer conductor	Aluminum; outside diameter 0.530 in.
Jacket material	Black polyethylene
Cable outside diameter	0.550 in.
Minimum bend radius	5 in.
Weight	0.22 lbs/ft
Impedance	50 ohms
Cutoff frequency	Not available
Nominal capacitance	Not available
Maximum operating temperature range	−55 to +80 deg C
Maximum operating voltage	3.4 volts RMS
Propagation constant	0.855
Nominal loss characteristics, dB/100 ft	
10 MHz 0.24	
50 MHz 0.53	
100 MHz 0.75	
200 MHz 1.1	
400 MHz 1.5	
1 GHz 2.4	
3 GHz 4.6	
5 GHz 6.4	
10 GHz 10.0	
Price, < 1 km	≈ \$35/m
> 5 km	≈ \$10/m

Table 9. Physical and performance characteristics of 64-875 pressurized hardline air-dielectric cable

Inner conductor		Copper-clad aluminum; outside diameter 0.311 in.
Dielectric		Air; six polyethylene tubes; outside diameter 0.837 in.
Outer conductor		Aluminum; outside diameter 0.953 in.
Jacket material		Black polyethylene
Cable outside diameter		1.023 in.
Minimum bend radius		10 in.
Weight		0.46 lbs/ft
Impedance		50 ohms
Cutoff frequency		Not available
Nominal capacitance		Not available
Maximum operating temperature range		−55 to +80 deg C
Maximum operating voltage		6.0 volts RMS
Propagation constant		0.855
Nominal loss characteristics, dB/100 ft		
10 MHz	0.13	
50 MHz	0.30	
100 MHz	0.43	
200 MHz	0.6	
400 MHz	0.86	
1 GHz	1.4	
3 GHz	2.7	
5 GHz	4.0	
10 GHz	Not available	
Price, < 1 km		≈ $66/m
> 5 km		≈ $18/m

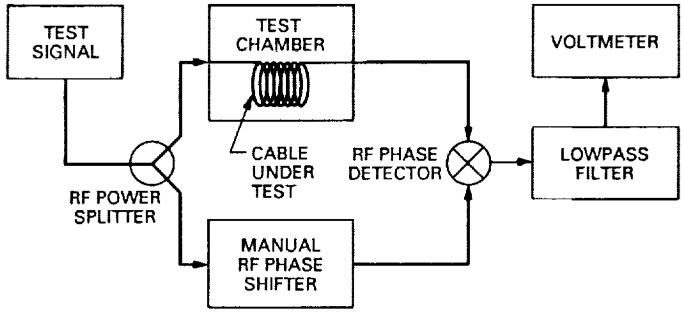

Fig. 1. Block diagram of the system used to measure cable thermal coefficient of delay (TCD) and pressure coefficient of delay (PCD).

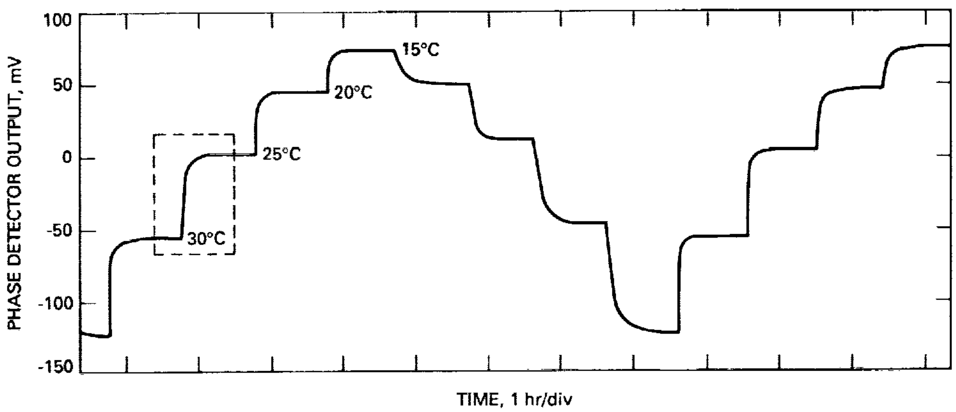

Fig. 2. Example of recorded data for RG-223/U coaxial cable.

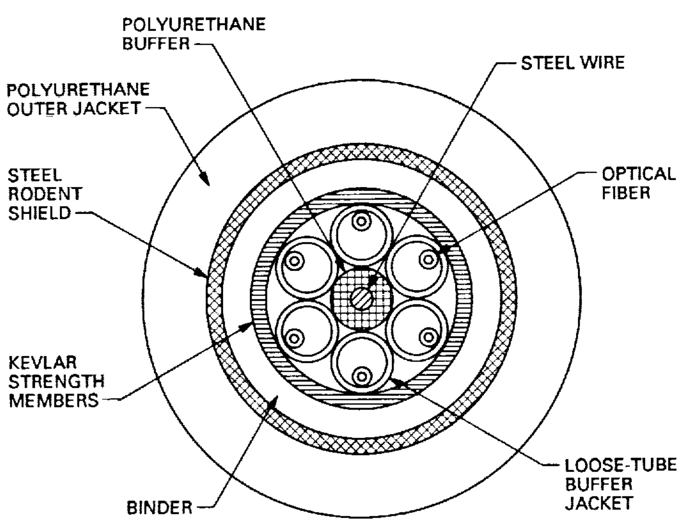

Fig. 3. Construction of a typical loose-tube fiber-optic cable.

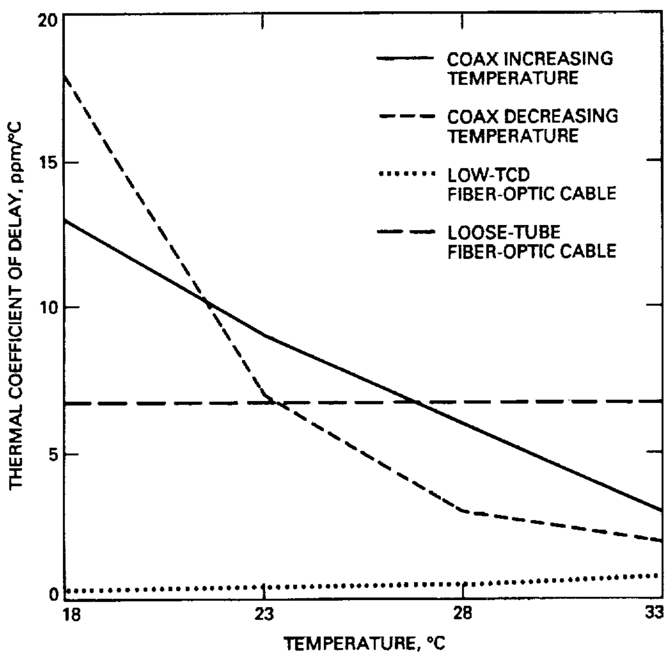

Fig. 4. A comparison of the measured TCD of loose-tube, single-mode, fiber-optic cable, the best coaxial cable (64-875), and low-TCD fiber-optic cable.

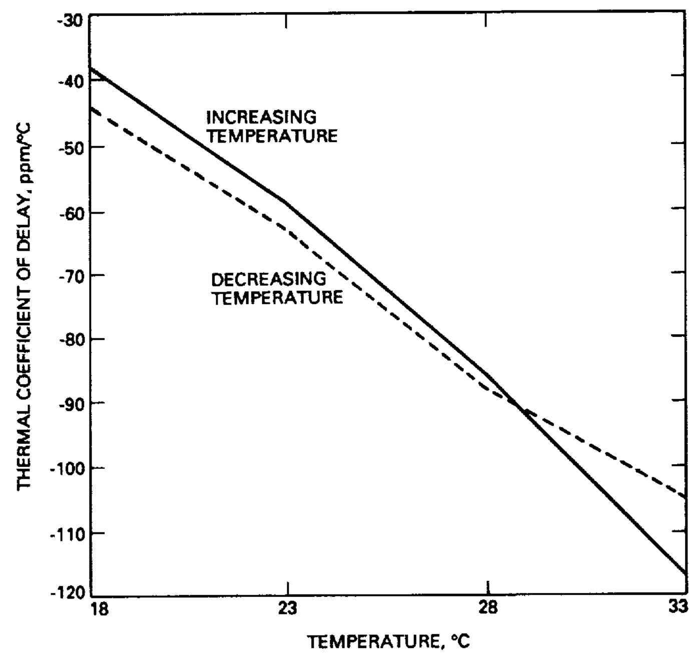

Fig. 6. Measured TCD of RG-223/U coaxial cable.

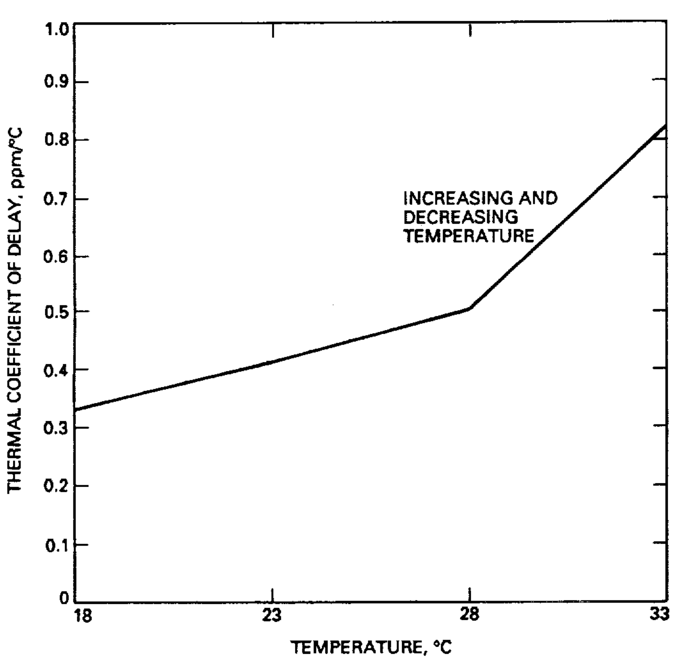

Fig. 5. Measured TCD of Sumitomo Electric optical fiber.

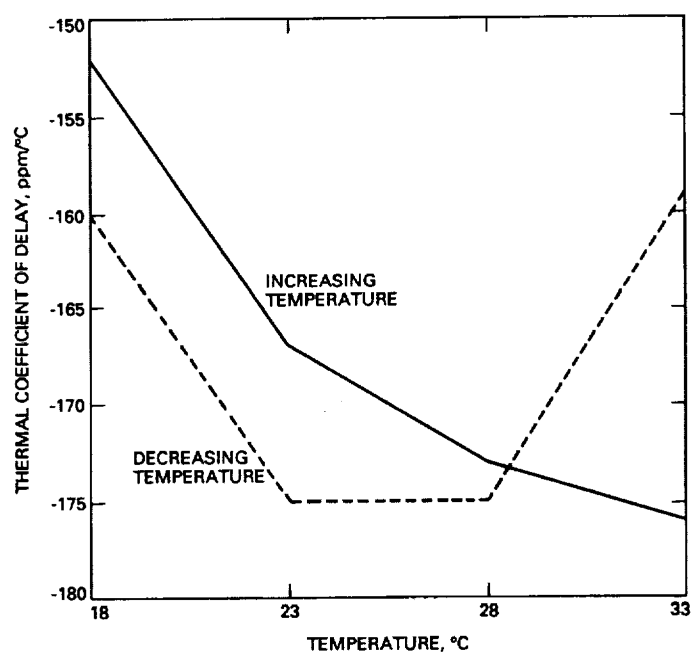

Fig. 7. Measured TCD of SF-214 coaxial cable.

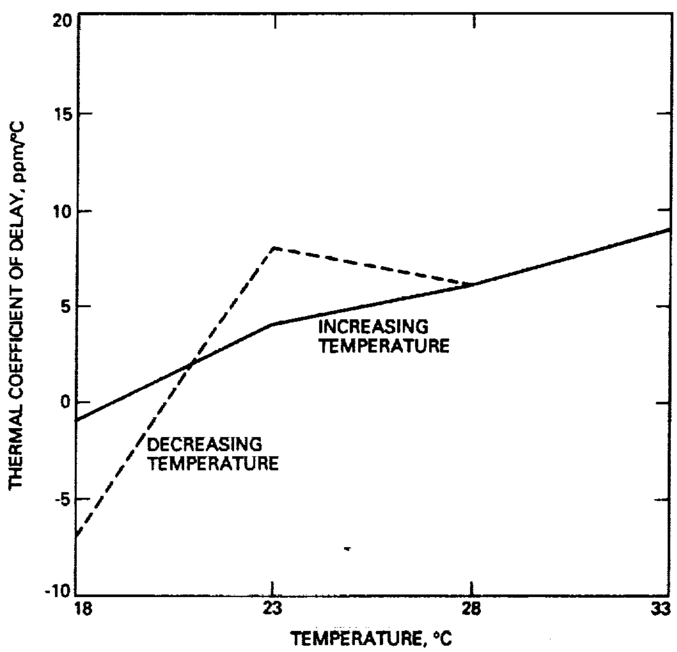

Fig. 8. Measured TCD of F242 coaxial cable.

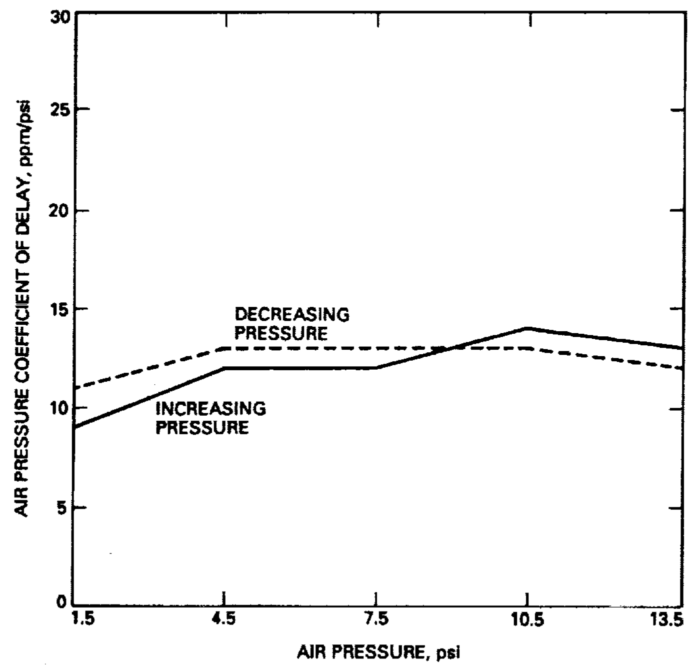

Fig. 10. Measured PCD of F645 coaxial cable.

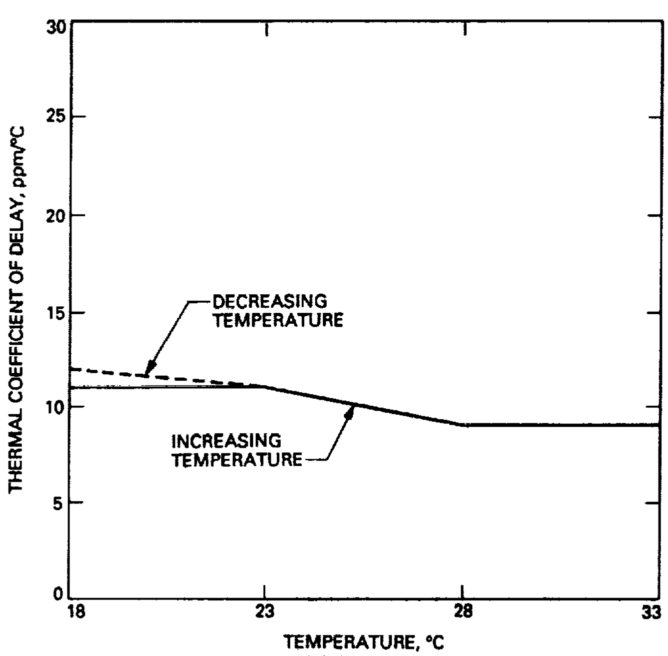

Fig. 9. Measured TCD of F645 coaxial cable.

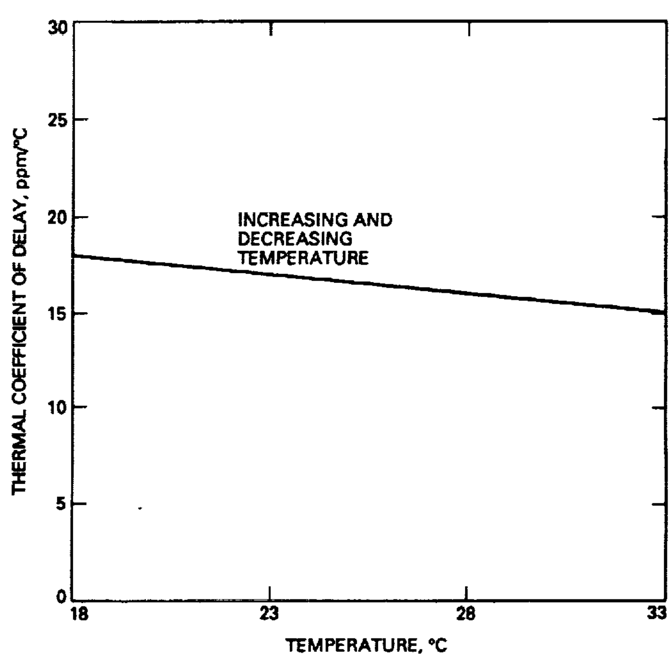

Fig. 11. Measured TCD of HCC-12-50J coaxial cable.

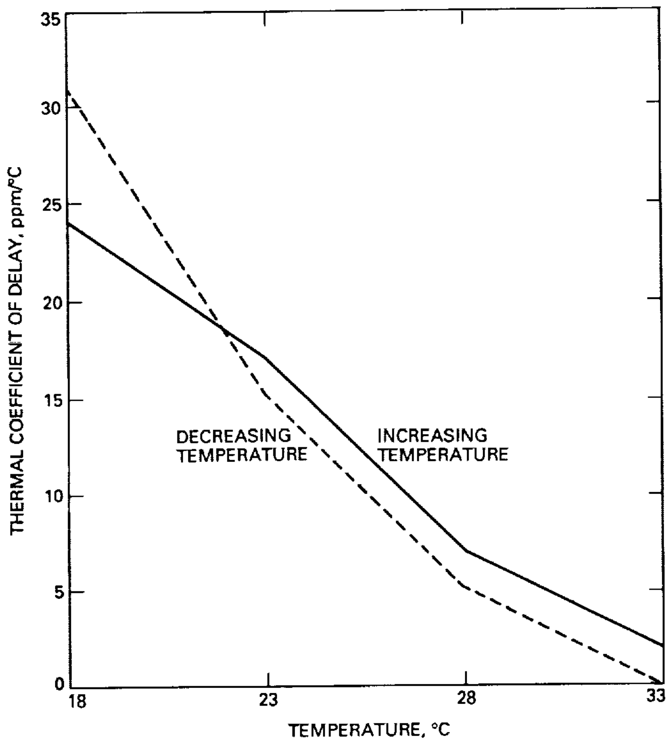

Fig. 12. Measured TCD of 64-500 coaxial cable.

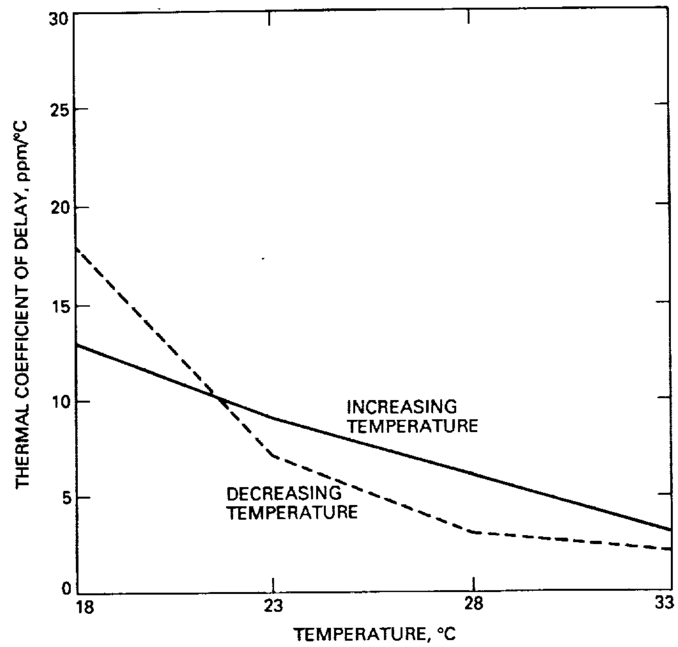

Fig. 14. Measured TCD of 64-875 coaxial cable.

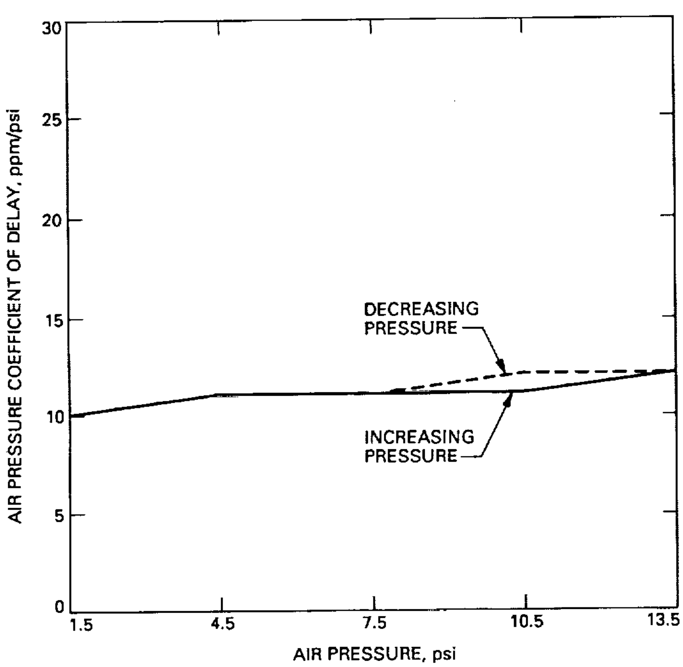

Fig. 13. Measured PCD of 64-500 coaxial cable.

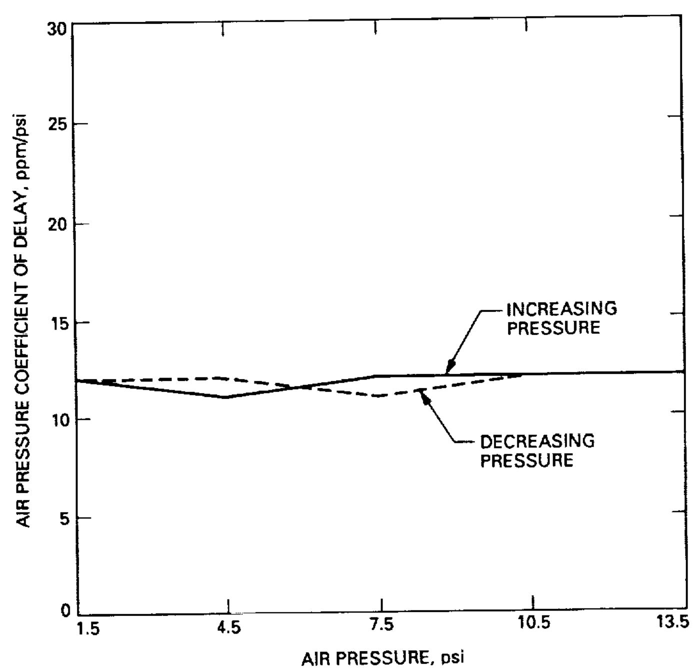

Fig. 15. Measured PCD of 64-875 coaxial cable.