Chromatic Dispersion Variations in Ultra-Long-Haul Transmission Systems Arising from Seasonal Soil Temperature Variations

Alexander Walter
TerraWorx, Inc., 595 Shrewsbury Ave., Shrewsbury NJ 07702

Garry Schaefer
USDA/NRCS, National Water and Climate Center, 101 SW Main, Suite 1600, Portland OR 97204

We quantify the expected amount of chromatic dispersion variation in an ultra-long-haul fiber optic transmission system arising from the seasonal soil temperature variations experienced by a buried fiber optic cable. The calculations are based on multi-year nationwide soil temperature measurements conducted by the US Department of Agriculture. The measurements can also be used to predict the system-wide level of temperature-dependent variations of other fiber optic impairments.

Chromatic dispersion is the phenomenon wherein different spectral components of the transmitted laser signal travel at different velocities in the fiber, arriving at different times at the receiver. Depending on system length and bit rate per wavelength, the amount of chromatic dispersion in a system must be carefully managed with dispersion compensators to achieve the right amount of residual dispersion. Too much residual dispersion will degrade Q from inter-symbol interference.

A long-haul fiber optic cable is typically buried at a depth of 2 – 4 feet. An ultra-long-haul transmission system will travel along these fiber optic cables for 7500 km or more. At these depths, daily soil temperature variations are negligible. However, seasonal soil temperature variations are significant, and will vary across North America depending on regional factors such as climate, soil type, moisture content, heat capacity, thermal conductivity, vegetation, and snow cover [Ref. 1].

Previous results [Ref. 2] have shown that the chromatic dispersion of fiber optic cable varies with temperature, and that the thermal coefficient depends on the dispersion slope of the fiber. The thermal coefficient is also related to the λ_0 of the fiber [Ref. 3]. For NZ-DSF, a thermal coefficient of –0.0025 ps/nm/km/ºC was measured. For large core fibers, the thermal coefficient was found to be –0.0038 ps/nm/km/ºC. Over ultra-long-haul distances of 7500 km, this would result in thermal sensitivities of –18.75 ps/nm/ºC for NZ-DSF, and –28.5 ps/nm/ºC for large core fibers.

To estimate the seasonal soil temperature fluctuations, we rely on measurements obtained by the Soil Climate Analysis Network (SCAN), a multi-year program run by the National Water & Climate Center, a part of the US Department of Agriculture's Natural Resources Conservation Service [Ref. 4]. This program gathers a large number of soil and weather parameters on an hourly basis, including soil temperature measurements at depths of 2", 4", 8", 20", and 40". Data encompasses 50 collection sites in the continental USA and Puerto Rico as shown in Figure 1. Some of these sites archive data dating back to 1991 [Ref. 5].

To process the raw data, we first removed the data points that appeared to be in error, as indicated by a code in the raw data such as "99.99", abrupt discontinuities, or by readings beyond a threshold. These erroneous data points were commonly caused by moisture invading the probe, or by problems in the computer hardware collecting the data. Remaining hourly data points were then averaged at each depth for each day, resulting in a composite number representing that day's soil temperature at each depth, for each measurement site. We justify this by noting that the daily fluctuations are small compared to the seasonal fluctuations we are interested in. Each day's soil temperature measurements for each site and each depth were then averaged across the years 1997 – 2000 (subject to data availability) to calculate the expected year-long seasonal variation for each site and each depth.

Seasonal data from a typical cold climate site is shown in Figure 2, and data from a typical warm climate site is shown in Figure 3. The cold climate sites tended to have a greater peak-to-peak variation in soil temperature, with the variation at a 40” depth loosely bounded by 20ºC peak-to-peak. To estimate soil temperatures at other depths, relationships can be derived from the Fourier law for heat conduction [Refs. 1, 6]. Note too how at a given site the phase of the temperature fluctuations changes slightly as the depth increases, but that for a given depth the phase is approximately the same from one site to another.

We assume the fiber optic cable is in thermal equilibrium with the surrounding soil. Over the length of an ultra-long-haul system, different portions of the fiber will experience different peak-to-peak temperature fluctuations, but the phase of the fluctuations should all coincide. Therefore we take 20ºC to be an upper bound on the peak-to-peak seasonal temperature fluctuation experienced by the fiber. Using the thermal coefficients determined by Kato *et al*, we calculate a peak-to-peak seasonal fluctuation in the chromatic dispersion of 375 ps/nm for NZ-DSF and 570 ps/nm for large-core fiber, based on a reference route length of 7500 km. The maximum slew rate of the chromatic dispersion at this depth was approximately 3 ps/nm/day over a two-month period for NZ-DSF, and 4.8 ps/nm/day for large core fiber.

This amount of seasonal chromatic dispersion variation, if left uncompensated, would introduce unacceptable levels of system performance degradations to an ultra-long-haul transmission system. The exact level of degradation depends on route configuration. TerraWorx has designed a Dynamic Dispersion Compensator, which will adaptively adjust in a closed-loop manner the level of chromatic dispersion compensation in order to compensate for the dispersion variations arising from seasonal soil temperature variations. This limits the residual system performance degradations from chromatic dispersion to within a few tenths of a dB.

A. Walter’s e-mail address is
awalter@terraworx.com
G. Schaefer’s e-mail address is
GSchaefer@wcc.nrcs.usda.gov

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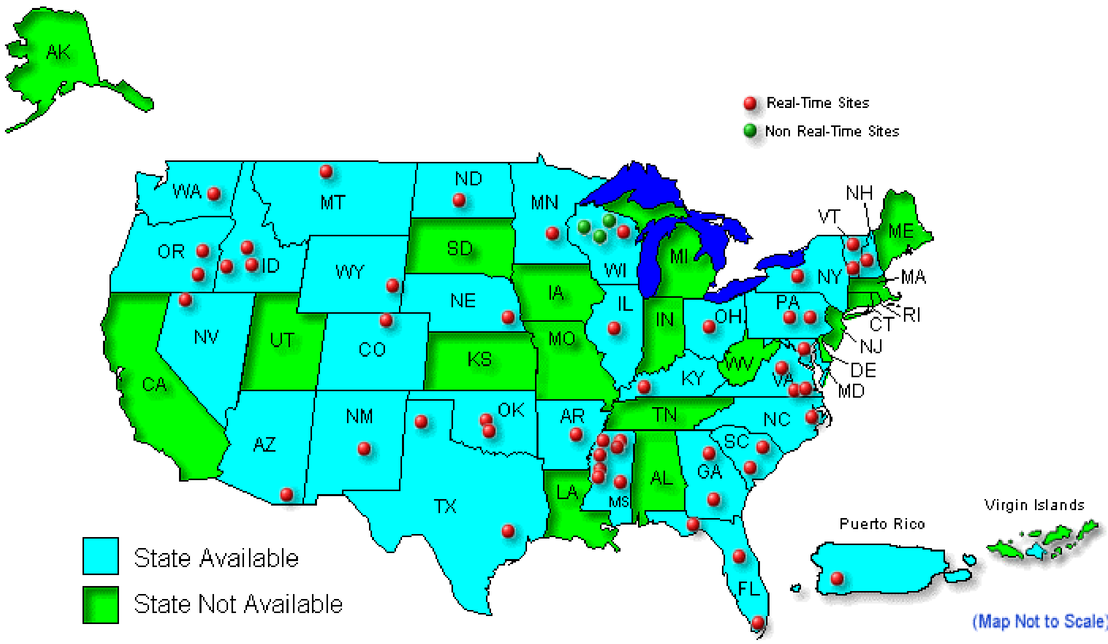

Figure 1. Available SCAN Sites.

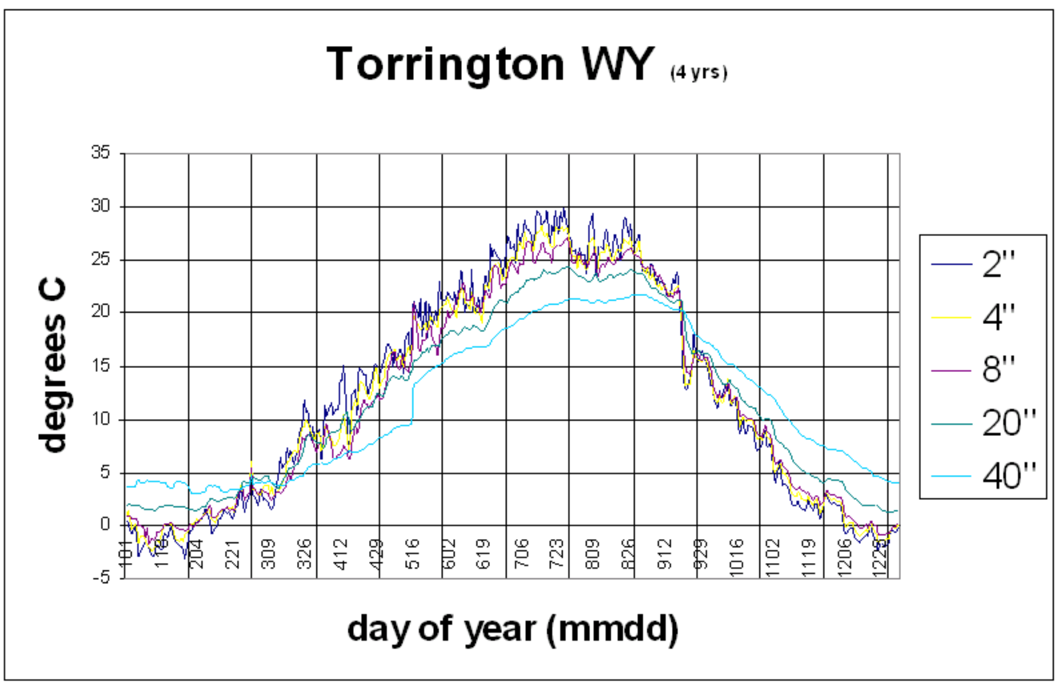

Figure 2. Typical Cold-Climate Profile.

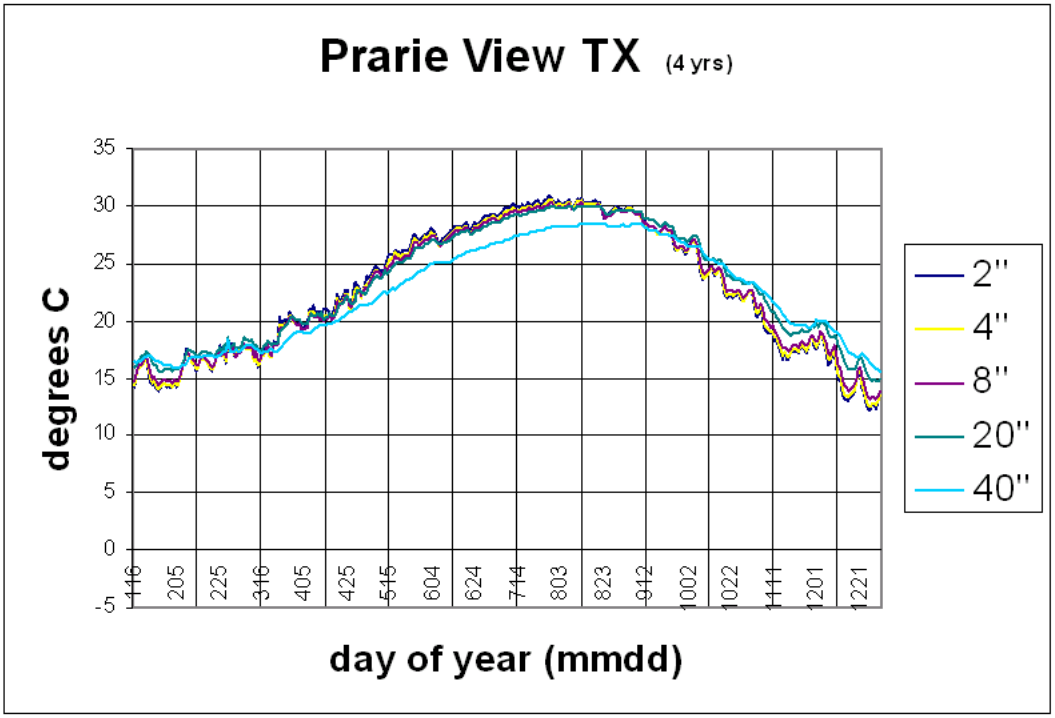

Figure 3. Typical Warm-Climate Profile.