Notes on phase/delay stability of cable and electronics

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Brian Corey

The purpose of this note is to explore how phase-stable the cables and analog electronics in a VLBI2010 receiving system are likely to be, in the absence of any phase/delay calibration system.

Required stability

To meet the goal of 4-ps delay precision per observation, variations in instrumental delay from scan to scan should be < 1 ps.

Typical scan-to-scan variations in the temperature of receiver electronics and cables on the outside of the antenna structure are expected to be of order 1 K, so the instrumental delay temperature coefficient should be < 1 ps/K.

Strawman picture of receiving electronics

Assume an antenna 10-20 m in diameter, with a cable run <100 m long from receiver to control room, of which all but 30 m is buried underground. As the antenna moves from source to source, the 30 m of cable on the antenna will be subject both to short-term temperature change, as it is alternately in the sun and in shadow, and to bending or stretching. The receiver electronics may also be subject to temperature change of order 1 K from scan to scan as the receiver orientation changes.

An advantage of housing as much of the electronics as possible in the control room is that the temperature is more easily controlled there. But independent of where the LO and IF electronics is situated, the requirement on the delay stability of the cables carrying the RF or LO reference signals remains the same: < 1 ps.

Thermal stability of cables

Temperature-driven cable delay changes on time scales of seconds to hours will be dominated by variations in the cable section exposed above ground. For a 30-m section with propagation velocity 0.67 c, a limit of 1 ps on delay change corresponds to a fractional cable length change of (1 ps) / [(30 m) / (0.67 c)] = 6.7 ppm, and a corresponding temperature coefficient of 6.7 ppm/K for a 1 K temperature change.

Figure 1 shows the fractional change in propagation delay over temperature for various coaxial cables and for representative single- and multi-mode optical fibers. Table 1 lists temperature delay coefficients for some other cable types measured over various temperature ranges between -30 °C and +40 °C.

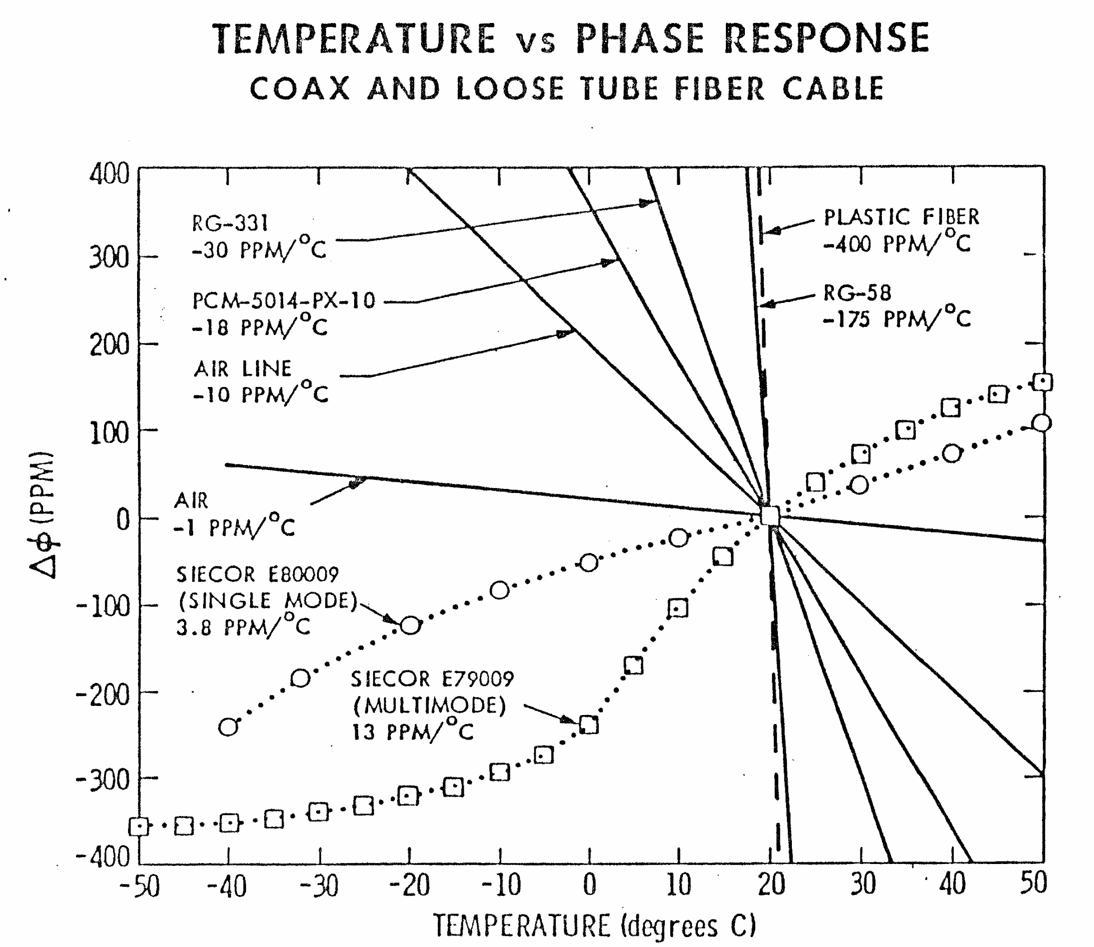

Figure 1. Phase change vs. temperature for selected coaxial and loose-tube fiber cables (from C. Moore, Bendix Field Engineering, 1987).

Table 1. Thermal coefficient of delay for selected coaxial cables and optical fibers

Type of cable or fiber	Temp coef (ppm/K)	Reference	Comments
RG-8A	-85	Moore & Kriss 1987	
RG-214	-60	Andrew Corp. catalog	
RG-223	-40 to -100	Lutes & Diener 1989	Varies with T
Belden 9913	-21	Moore & Kriss 1987	
Andrew FSJ4-50B	-2 to +6	Andrew Corp. catalog	Varies with T
Andrew LDF2-50	-8 to +6	Andrew Corp. catalog	Varies with T
Andrew LDF4-50A	+7 to +16	Andrew Corp. catalog	Varies with T
Bare SMF-28 optical fiber	8	Dreher 2003	
"Loose tube" fiber bundle	8	Navarrini et al. 2003	
"Firm buffered" fiber bundle	5	Dreher 2003	

Phase stability of cables with flexure

Figure 2 illustrates the large changes in cable delay that can occur with antenna motion as a coax cable is flexed. In this example the delay changes by ~25 ps over ~180° in azimuth.

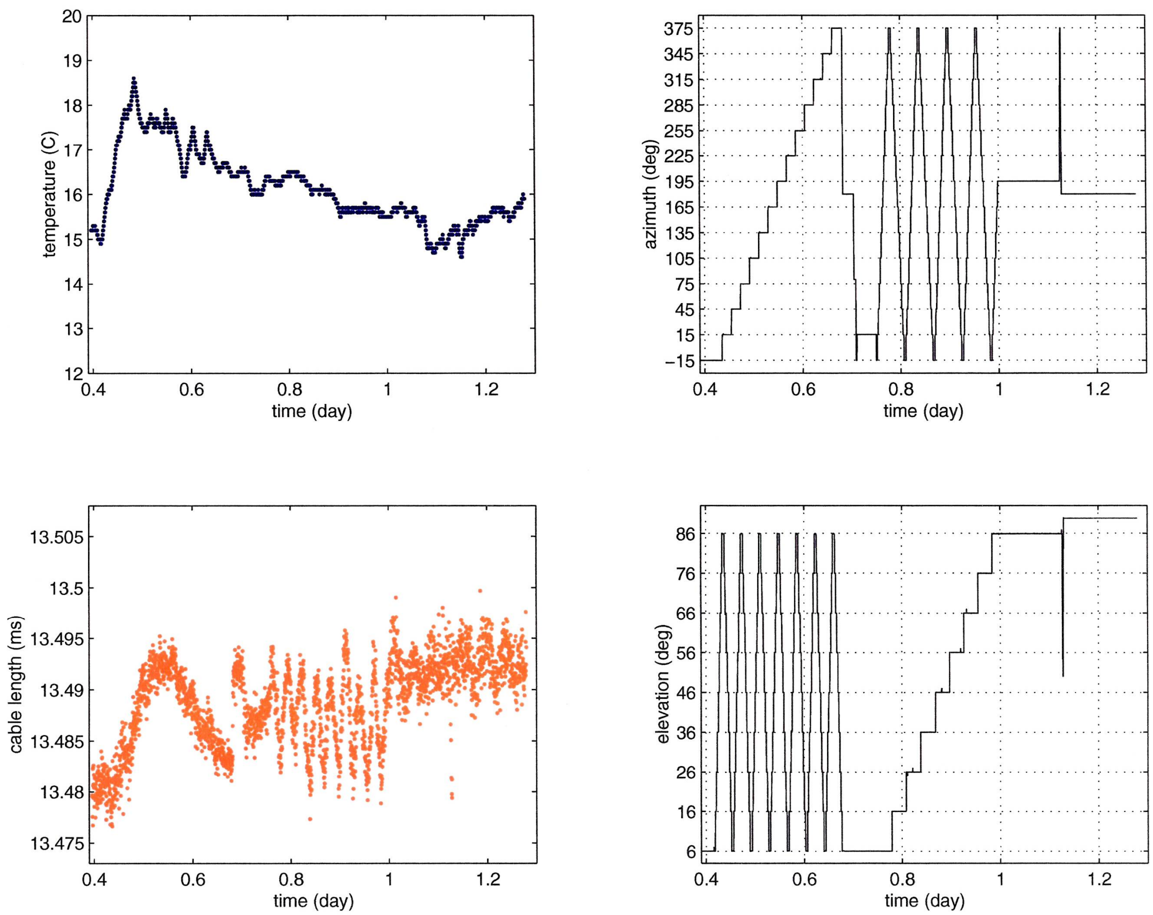

Figure 2. Delay variation with azimuth for an RG-213 cable on Onsala 20m telescope. 10 ms change in "cable length" in lower left plot corresponds to 25 ps one-way delay change.

More modern coax cables have much better phase stability with flexure than most of the older RG-style cables. Andrew Corporation manufactures many types of corrugated cables with very good stability. For instance, the ½-inch-diameter LDF4-50A cable exhibits a phase change of ~5° at 8 GHz when bent into a 360° loop with a 5-inch radius; the equivalent phase delay is 1.7 ps. Gore manufactures cables with even better performance, with phase delay changes of 0.1-0.5 ps in loop tests with a 2.25-inch radius.

Single-mode optical fibers in a "loose tube" cable bundle also exhibit excellent stability. Navarrini et al. (2003) were unable to detect reliably any phase change at 3 GHz, to < 0.5°, when the cable was bent with a radius as small as 3 inches; the corresponding upper limit on the change in phase delay is 0.5 ps. Using a prototype helical cable wrap for the azimuth axis of the Submillimeter Array dishes, Levine (1993) found the delay changed by only ~0.2 ps for a change in azimuth of 270°.

Comments on cable stability

At first blush it appears that optical fiber and some modern coaxial cable designs will meet the phase stability requirements. Even some cable types with marginal thermal stability might be usable if the cable temperature is continually monitored at various points, so that the delay change can be estimated from the known thermal coefficient. Pitfalls of this approach include hysteresis effects (the delay depends not only on T, but also on the sign of dT/dt) and highly nonlinear delay-vs.-T curves for some cables, especially around 25 °C.

But the cable itself is only part of the story. For cables exposed to the outside environment and subject to flexure, there are two other causes of instability that often dominate on short time scales: (1) poor electrical contact at the center pin or outer conductor of a connector, and (2) water, either in a connector or inside the outer conductor of a coax cable. 1 ps corresponds to only 0.2 mm path length in a dielectric-filled coax cable or an optical fiber. Path length changes much larger than this have been observed (too often) to be caused by both effects at existing geodetic antennas.

Stability of analog electronics

Local oscillators and narrowband filters are generally the largest source of thermally driven phase and delay variations.

The S/X-band LOs manufactured by CTI and installed in the 1980s-vintage NASA/CDP receivers exhibited thermal phase sensitivity of ~50 ps/K. This high sensitivity resulted from operating a highly temperature-sensitive step recovery diode outside the phase-locked loop, and from driving it at a low reference frequency of 5 MHz. Better circuit designs and/or higher reference frequencies can reduce the sensitivity to < 1 ps/K. For instance, the 1024/2048 MHz synthesizer designed by Alan Rogers (2006) for a DBE sample clock has phase jitter and stability of < 1 ps rms and < 1 ps/K, respectively.

As a general rule, the narrower the fractional bandwidth of a bandpass filter (or of any electronic device, for that matter), the greater its thermal phase sensitivity. Thompson, Moran and Swenson (2001) show that, for the tubular bandpass filters that are often used at frequencies up to ~1 GHz, the thermal phase sensitivity is approximately 10^{-5} N_{poles} Q radian/K, where N_{poles} is the number of poles in the filter and the filter Q factor is $\nu_0 / \Delta\nu$. For a filter with Q = 2 and N_{poles} = 10, as might be used for an anti-aliasing filter at baseband before the DBE, the sensitivity is ~0.01 °/K, which is negligible. (4 ps of delay corresponds to a phase difference of 19° over 2-15 GHz.) Cavity filters of the sort used above 1 GHz exhibit comparable sensitivity. A cavity filter with Q = 50 and N_{poles} = 10, as might be used to define the final passband in an up/down dual-frequency conversion scheme with tunable 1st LO, should have a sensitivity of ~0.3 °/K.