Notes on cable length measurement systems

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These notes are intended to supplement Alan Rogers's material on phase/delay calibration with some information about current and prospective systems for measuring the electrical length of cables carrying phase cal or LO reference signals.

Required precision

Variations in the one-way electrical length of a cable should be measured with a 1-σ precision of < 1 ps on time scales of seconds to hundreds of seconds. The most temperature-sensitive portions of the electronics can usually be situated in a temperature-controlled (stable to < 1 K on time scales of seconds to tens of minutes) environment that is decoupled from antenna orientation, so it should be safe to relax the spec on temperature sensitivity (by how much?) from the upper limit of 1 ps/K required for cables and electronics in the absence of a calibration system.

Existing cable measurement systems

The Mk4 cable measurement system designed in the 1970s by Alan Rogers and improved by him in the late 1980s employs a 5 MHz reference signal, which is modulated at 5 kHz on the far end of the cable and then returned to the starting point, where its phase relative to the unmodulated 5 MHz is measured with a phase-locked loop and picosecond phase comparator. Modulation of the returned signal is necessary in order to distinguish it from signals reflected at poor cable connections, for instance. The short-term stability of the one-way measurements is typically ~2 ps rms on time scales of seconds to tens of seconds. The temperature sensitivity of the "ground unit" is ~6 ps/K.

Moving the reference frequency upward has the advantage of lessening the precision with which the relative phase in degrees must be measured. The VLBA cable measurement system is similar in design to the Mk4 but is based on a 500 MHz reference. (Does anyone know how well it performs??)

The cable measurement systems at the Kokee Park and NRAO20 antennas use(d) a commercial vector voltmeter in the control room to compare the phase of a 500 MHz reference transmitted up the antenna on optical fiber and a portion of the signal returned from the antenna on a separate fiber. Figure 1 shows typical NRAO20 cable cal data from a 24-hour geodetic session. The fluctuations on hour and shorter time scales are < 1 ps rms. There is no way to tell from this plot alone whether the mild outliers are real length changes or measurement error, of course, or whether any real changes that may occur are on the "up" or "down" cable.

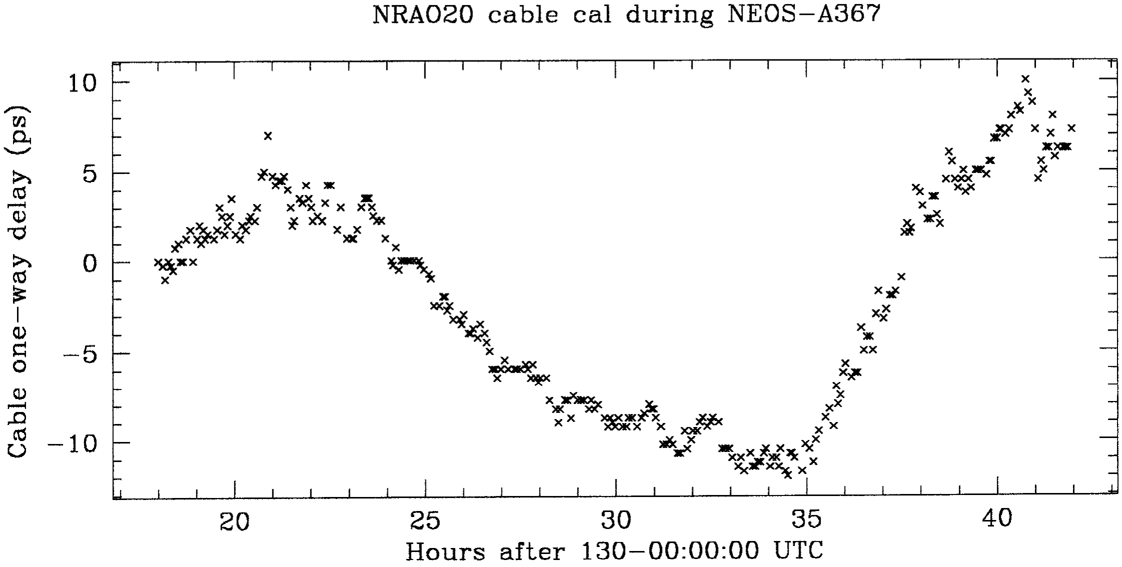

Figure 1. Cable length measured over 24 hours with the NRAO20 cable cal system.

A more precise and stable cable measurement system designed by D'Addario and Stennes (1998) also uses separate optical fibers on the antenna to carry 500 MHz up and down. In the control room the return signal is mixed with an LO offset from 500 MHz by 260 Hz to produce a 260 Hz baseband signal, which is sent to a digital phase detector, where its phase is compared against a 260 Hz reference. Measured short-term noise is < 0.1 ps rms. Figure 2 shows measurements acquired over 2.4 hours on a 14m-diameter antenna at Green Bank while the antenna was slewing repeatedly over > 360° in azimuth. Variations of ~0.2 ps pk-pk can be seen that are attributable to stress-related changes in the length of the 80-m-long portion of the cable on the antenna.

A disadvantage of both the D'Addario and Stennes system and of the NRAO20 system is that two different fibers are used to make the round trip. (Because the up and down frequencies are the same, measurement accuracy can be degraded by crosstalk if there is insufficient directivity in the optical path.) D'Addario and Stennes carried out reciprocity tests to determine how well temperature-induced delay changes tracked between two different fibers in the same multi-fiber bundle. They found that the delays were the same to < 1.2 ps, which was essentially the measurement limit imposed by their equipment, out of a total change of 45 ps. In the real world of cables and connectors exposed to the weather for 10 years, however, an intermittent problem could develop in the return path, say, which could cause short-term variations in the round-trip travel time that are not present in the phase of the reference signal received by the front end.

Systems with yet higher precision and stability have been developed for ALMA (Shillue 2002, Kiuchi and Ishiguro 2005). In these all-optical systems, a laser signal with very long coherence time is sent to the antenna, where it is shifted in frequency by tens of MHz, then returned over the same optical fiber to the control room, where it is beat against the unshifted signal in a Michelson interferometer. The cost of these systems is much greater than the microwave systems described previously, and their precision far exceeds our needs. An advantage they do have, however, is that the same fiber is used for the up and down trips. This feature is also present in the frequency distribution system developed at JPL for the DSN (Calhoun, Sydnor and Diener 2002).

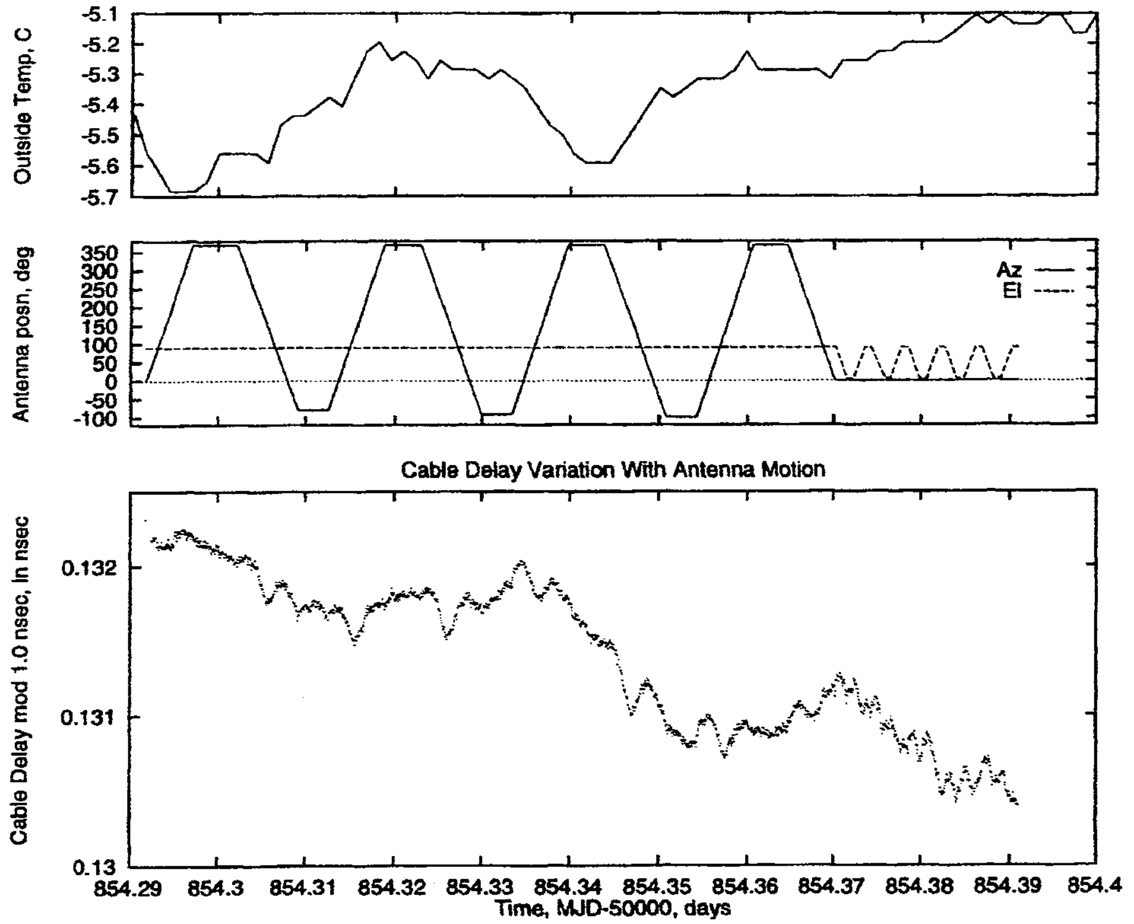

Figure 2. One-way cable delay (calculated by dividing the round trip time by 2) to Green Bank 14m antenna during antenna slews (D'Addario and Stennes 1998). The vertical scale in the lower plot spans 2.5 ps.