Phase Stability of ATA Fiber Optic Cables

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I. Introduction

The instrumental phase stability of the ATA will be almost entirely a function of the stability of the runs of single-mode fiber optic cables that carry the wideband RF signal band (0.5 to 11.2 GHz) back to the central processing facility. In a more conventional interferometric array, errors in the frequency distribution and elements of the LO system are major contributors to variations in the instrumental phase, but in the architecture of the ATA there are no local oscillators at the antennas, and the local oscillators in the central facility will be derived from a single synthesizer with distribution in a closely-controlled environment; thus the phase errors introduced by the LO system should be negligible.

The single mode fibers will almost certainly consist of the standard SMF 28 fiber. Single-mode fiber is too fragile, however, to be directly exposed to the environment outside of specially-protected areas, so the long runs out to the array elements and up the front end modules will necessarily be made with fibers packaged into cables. Most of the length of these cables will be run in buried conduit. The length of the runs will not be known until a configuration for the array has been decided, but we can estimate that the runs will be no more than 1000 meters based on the constraints of the site, making the reasonable assumption that the central facility will be more or less centrally located within the array. These runs will be very similar to those used in the present BIMA with a burial depth of about 0.5 meter. The exact cable runs up the antennas are also not known, but for elements of diameter 6 meters, we can estimate these aboveground cable runs will be about 10 meters.

If the ATA is equipped with a cross-correlator, as expected, this device can be used to generate data sets from which the instrumental phases of each array element can be determined [1]. These phases can then be applied to "phase up" the array for beamforming applications. We would like to have the instrumental phase stability be such that we do not need to "phase up" at inconveniently short intervals – at the least we would like the instrumental phases to stay within tolerance for periods comparable to an hour. For most applications an RMS phase error over the array of ~0.1 radians, corresponding to a gain loss of \leq "1%, should be more than adequate.

At the time this analysis was first prepared, it was expected that 1310 nm light would be used in the single-mode fibers. However economics have now led the ATA to adopt 1550 nm lasers. Although it seems unlikely that this change will invalidate the results described below, the project needs to perform measurements to verify this expectation.

II. Thermal Coefficient of Delay

The Thermal Coefficient of Delay (TCD) is the fractional change in delay through a cable with temperature and is typically given in units of parts-per-million per degree Kelvin (PPM/K). The construction of single-mode fiber-optic cables strongly effects their TCD values. The TCD also depends weakly on the temperature of the cable. Table 1 shows the TCD (in PPM/K) for several varieties of fiber-optic cables.

Type of Cable	TCD	Ref	Comment
Tight buffered	57	2	at about 15 °C
Gore FON 1002	11	3	over –65 to 25 °C
Bare SMF 28	7.9	3	over –65 to 25 °C
Loose tube (gel-filled)	6.6	4	at 20 °C
OCC "Ultra-Fox"	5.1	5	over 20 to 25 °C
Bare "spectran" fiber	5.1	3	over –65 to 25 °C
Sumitomo low TCD	0.4	4	at 20 °C

Table 1

The "tight-buffered" cable is the familiar Kevlar-strengthed cable in common laboratory use. It is sturdy, but has by far the worst TCD of any of the cables. For comparison, RG"223/U coaxial cable has a TCD of about 50 PPM/K at ~20"°C [4]. Most long runs of fiber-optic lines use gel-filled, "loose tube" cable assemblies, which exhibit a low value of TCD, comparable to that of bare fiber. For some applications, the loose-tube construction is not sufficiently robust; Optical Cable Corporation and W.L. Gore Associates have both developed "firm buffered" cable assemblies that share the low TCD of loose-tube cables but are much more rugged. Naturally, they are also more expensive, but for short runs, e.g. through an antenna cable wrap, the cost is likely to be minor compared to other elements of the fiber optic system. Finally, Sumitomo has devised a coated fiber with extremely low TCD (zero at 5"°C [6]), but this type of cable is expensive, and is rumored to have awkward mechanical and environmental properties.

III. Temperature Variations at Hat Creek

The ATA will be constructed at the Hat Creek Observatory located north of Mount Lassen in northern California. Figure 1 shows the statistics of the diurnal temperature swings at Hat Creek compiled from the weather station at the site [7]. The 98th percentile of the distribution is 23.7^{to}C. For buried cables, the diurnal (and annual) temperature variations are the main concern, since more rapid fluctuations do not penetrate to the buried cables. The shorter cable runs up the antennas, however, will respond to more rapid changes in the air temperature; the most rapid swings usually occur in the early morning and are typically no more than 4 to 5^{to}C/hour [8].



Tmax - Tmin (Daily)

A simple model can be used to estimate the swing of temperatures expected for a buried cable. For a sinusoidal temperature variation at the surface with period P, the variation dies away exponentially with scale depth $(aP/\pi)^{0.5}$, where **a** is the thermal diffusivity of the soil [9]. For canonical "dry sandy soil" the thermal diffusivity is roughly 2"×"10⁻⁷ m² s⁻¹ and with P"="1 day, the scale depth is 7.4 cm. At a plausible depth for the ATA buried fiber runs of 0.5 m, the diurnal temperature swing will be reduced by a factor **exp**(-50/7.4)"="1.2"×"10⁻³. The 98th percentile variation at 0.5 m depth will then be a mere 0.028"°C peak to peak.

IV. Phase Variation Due to the Fiber Optic Cable Runs

To estimate the effect of temperature variations on the phase stability of the ATA, I adopt a length for the buried run of 1 km and an observing frequency of 10 GHz. With an index of refraction of 1.47, the amount of delay in the buried run is then $4.9^{"}\mu$ sec. With the expected peak-to-peak diurnal variation at 0.5 m depth of $0.028^{"}$ C, the phase variation in loose-tube cables will then be 3.3 degrees of phase, with a maximum rate of change of 0.4 degrees of phase per hour. These phase variations are so small that they can probably be ignored for most purposes. In particular, it will probably not be necessary to equalize the length of all the buried cable runs in order to improve cancellation between the delay variations for different antennas.

For the exposed runs up the antenna, I adopt a length of 10 m, corresponding to a total phase of 3.1"×"10³ radians. If loose-tube fiber proves to have the mechanical properties required to go up the antenna and through the cable wraps, then the result will be a phase variation at 10 GHz of 1.2 degrees of phase per °C. It may be possible to insulate this fiber run enough to reduce the maximum rate of change of temperature below that of the air, but even if this is not possible the maximum expected rate of change of the phase is only 5.8 degrees of phase per hour, a good part of which should cancel out between antennas since they all share much the same environment. If the array were "phased up" every hour or so, then the worst case would be a distribution of phases with a spread of ~6 degrees of phase, corresponding to an RMS phase variation (for a uniform distribution) of 1.7 degrees and a negligible loss in the gain of the array beam. The total diurnal peak to peak change in phase due to the exposed run would be ~28 degrees of phase, corresponding to about 2% loss if the errors were uniformly distributed, so it might be possible to "phase up" rather infrequently. If loose-tube cable is not sturdy enough for the antenna run, one of the two ruggedized fibers that show low TCD can be used with essentially the same performance. Standard "tightbuffered" fibers would probably not be advisable – the large TCD would result in phase changes of order 50 degrees of phase per hour. Some of this rapid change should cancel out between antennas, but considerable loss in gain (of order 5%) might be expected unless "phasing up" were done rather frequently.

The Submillimeter Array has conducted tests [10] of the phase stability of loose-tube SMF-28 fiber in two kinds of cable wraps: a three-turn helical twister with a nominal diameter of 30 inches, and a torsional-mode twister. Both configurations would be suitable for the ATA¹. For a total azimuth range of 540 degrees and a frequency of 10 GHz, the SMA data imply a peak-to-peak phase variation due to the twister of 1.3 degrees for the helical design, with a linear dependence on angle, and 0.3 to 0.6 degrees for the torsional design, which exhibited non-linear (possible quadratic) function of phase with angle. The corresponding RMS values are less than 0.4 degrees for either, so this source of phase error is likely to be acceptably small.

The cable runs inside the central laboratory will be exposed to temperature variations about five times less rapid and ten times smaller than on the exposed runs at the antennas, Since these runs can almost certainly be implemented with loose-tube cables, these laboratory runs should contribute negligibly to the overall phase variations.

References

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¹ However, the SMA test memorandum [10] notes: "the torsion wrap configuration has been shown to be very sensitive to axial alignment and to fiber tension. Bending of the fiber within the rotating segments appears to seriously degrade the performance. The phase stability is a non-linear, possibly square-law, function of the maximum angle of rotation and although 540 degrees can be accommodated with a 1300 mm wrap, stability is considerably improved if the maximum angle of rotation is reduced to 350 or 400 degrees."