Thermal and mechanical tests of loose-tube and military tactical fiber-optic cables

A. Navarrini, R. Plambeck and E. Fields

Radio Astronomy Lab, University of California, Berkeley

November 20th, 2003

CARMA

Combined Array for Research in Millimeter-Wave Astronomy

Thermal and mechanical tests of loose-tube and military tactical fiber-optic cables

Abstract

We report on comparative tests of two types of fiber-optic cables, a loose-tube currently in use at BIMA, and a much more flexible tight-buffer military tactical one. A 1310 nm signal AM modulated at 3 GHz was sent through two fibers within the same cable and the phase and the phase difference variations were monitored when: 1) cycling the temperature of the cables in a thermal chamber; 2) moving or bending the cables. The measurements show that the loose-tube cables are largely to be preferred for their lower differential phase change between parallel fibers caused by temperature variation and mechanical stresses.

1 Introduction

The millimeter wavelength local oscillators on each CARMA receiver will be phaselocked to a ≈1.2 GHz reference signal sent via a fiberoptic link to each antenna. A linelength measurement system is used to track and correct for changes in electrical length of fiber-optic cables due to temperature changes and/or bending. The system is based on a laser transmitter sending a reference signal (1100-1260 MHz) from the lab to the antennas through a fiber. A fraction of the signal is coupled back to the lab and the roundtrip phase is measured and used to derive the one way time delay through the fiber. A disadvantage is that the echo signal returns to the lab on a separate fiber, which might have different electrical delay if the fiber bundle is heated or cooled rapidly or if the cable is flexed in the azimuth and elevation twisters at the telescope. This phase difference $\delta\varphi$ leads to an error $\delta\varphi/2$ in the calculation of the reference signal phase at the receiver. The aim of the tests described in this memo is to measure the magnitude of $\delta\varphi$ due to typical temperature variations and mechanical stresses experienced by the optical cables during operation of the interferometer and to determine its contribution to the instrumental phase errors. Two different fiber-optic cable types have been tested: a loose-tube and a military tactical both encasing 12 single-mode fibers, as well as a loose tube cable with 6 single-mode fibers (SMF-28) from Corning Optical Cable.

The fiber optic cable in use at BIMA is a loose-tube type from Alcoa Fujikura where the fibers are contained in a buffer tube with an inner diameter that is considerably larger than the fiber itself. The interior of the plastic tube is flooded with water blocking gel and covered by a polyethylene outer cable jacket. Each single-mode fiber consists of a core/cladding with diameter 9/125 μm and a 250 μm coating. While the singlemode cables have operated reliably on the BIMA antennas for several years, a number of *multimode* cables have failed due to cracked outer jackets, whereas the multimode cables had PVC jackets.

New tight-buffer cables from Optical Cable Corporation offering superior mechanical protection provided by multiple fiber buffers and external polyurethane jacket have therefore been considered for use with SZA. These cables are based on military technology and are tougher and more flexible than loose tube type. The military tactical cable we have tested is based on 9/125 μm diameter core/cladding fiber surrounded by a 500 μm acrylate coating covered by 900 μm diameter hard elastomeric tight-buffer. In

both loose-tube and military tactical cables, Kevlar aramid yarn is used for protection of the fibers against mechanical loads and for reduction of the tensile force.
The main characteristics of the two cables are summarized in Table 1.

	Loose-Tube Cable -All Dielectric Uniflex- Alcoa Fujikura	*Military Tactical Cable -D-Series- Optical Cable Corporation*
Cable Length [ft]	117	76
Fiber type	Single Mode	Single Mode
N. of fibers	12	12
Attenuation 1,300 nm [dB/km]	0.4	0.4
Core/Cladding Diameter [μm]	9/125	9/125
Coating Diameter [μm]	250	500
Buffer Material	-	Hard Elastometric Tight Buffer
Temperature Range	-40^{0}C to +70^{0}C	-55^{0}C to +85^{0}C
Cable Diameter [in]	0.307	0.26
Outer Jacket Material	Polyethylene	Polyurethane
Weight [kg/km]	50	51
Tensile Load Rating, short-term [N]	2700	2100
Tensile Load Rating, long-term [N]	890	700
Minimum Bend Radius, installation [in]	6	4
Minimum Bend Radius, post-installation [in]	3	2

Table 1: Main characteristics of tested Loose-Tube and Military Tactical cables.

1 Experimental Setup

The thermal and mechanical properties of each cable have been derived by measuring the absolute and differential phase of two selected fibers using the experimental setup shown in Fig.(2). A 3 GHz RF signal is sent from the HP 8753A Network Analyzer to the Ortel 3541C-020 Fiberoptic Transmitter, based on a 1310 nm laser. The 3 GHz AM modulated optical signal out of the transmitter is split by a -10 dB optical directional coupler and sent in two single mode fibers of the cable under test. The cable is rolled up in a bundle (≈5 in radius) and located inside a thermal chamber whose temperature can be varied and monitored. The two fibers at the output of the thermal chamber enter two identical optical receivers (Discovery Semiconductor DSC50S photodiodes) that convert the modulated optical signals back to RF. The signals are finally sent to the A and B channels of the network analyzer. Data acquisition and control from/to the network analyzer, the temperature sensor, and the temperature control of the thermal chamber is based on a National Instruments Labview software platform in a computer interfaced to the instruments with GPIB.

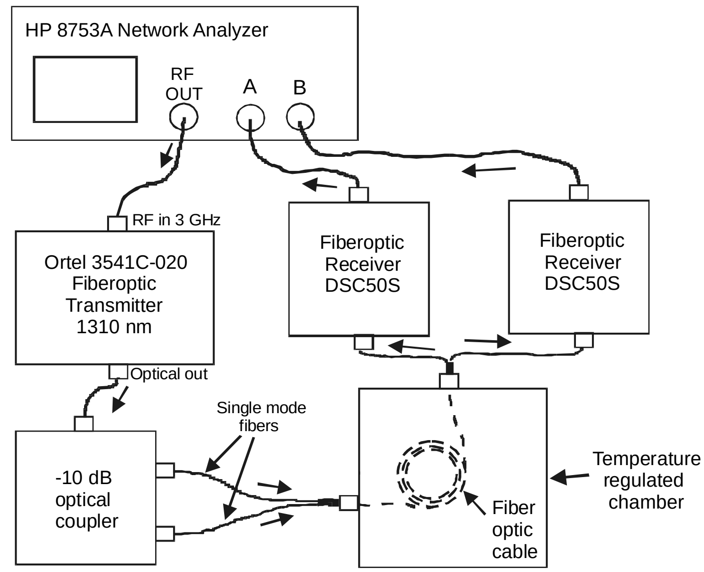


Fig. (1): Test setup to measure the absolute and differential phase variations due to fibers length change when cycling the temperature of the cable in a thermal chamber.

2 Experimental Results

2.1 Thermal Tests

The thermal tests of each cable consisted in varying the temperature of the thermal chamber between ≈25^0 C to ≈40^0 C and back to ≈25^0 C while monitoring the phases of two fibers versus time. The temperature of the thermal chamber was kept constant for one hour or more before and after each thermal step to allow proper thermalization of the cable. A linear ramp rate of 2 ^{0}C/min was used during the steps. The thermal tests concern the loose-tube and the military tactical cables encasing 12 fibers as well as a 53 ft long loose-tube cable encasing 6 single-mode fibers.

2.1.1: Loose-Tube Optical Cable – 12 fibers

Results of measurement of the L=117 ft long loose-tube optical cable encasing 12 single mode fibers are shown in Fig.(3). The upper left panel displays the temperature versus time inside the thermal chamber as measured by a temperature probe (Fluke 80TK Thermocouple Module). The bottom panels of Fig.(3) show the measured phase of the two fibers versus time. The phase of each fiber tracks closely the temperature variation in the chamber and changes of approximately $\Delta\varphi$=22 deg for a temperature variation of ΔT =15^0 C. This gives $\Delta\varphi/\Delta T$ =[φ(37^{0}C)- φ(22^{0}C)]/ ΔT≈1.5 deg/^{0}C at 3 GHz. The difference of the phases between the two fibers is shown on the right panel in the upper part of Fig. 3. The phase difference $\delta\varphi$ tracks approximately the temperature variations and jumps ≈0.1 deg with the 15 ^{0}C temperature step. This gives $\delta\varphi/\Delta T$≈0.007 deg/^{0} C at 3 GHz. We interpret the short and deep decrease measured in the phase difference after the second temperature step (around 14800 sec) as due to fact that the two fibers cool down at different rates.

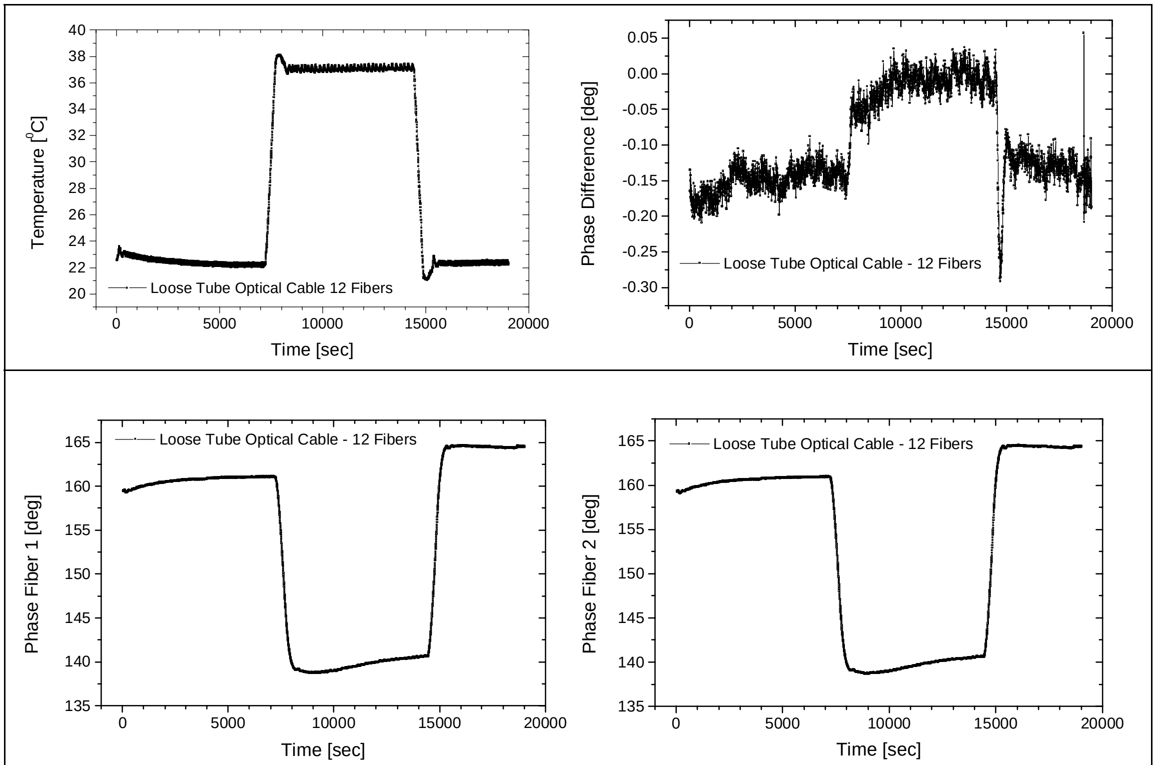


Fig.(3): Thermal test of Loose-Tube Optical Cable encasing 12 single-mode fibers. Top left): Temperature in the thermal chamber. Top right): Phase difference between the two fibers. Bottom left): Phase of fiber 1. Bottom right): Phase of fiber 2.

2.1.2: Loose-Tube Optical Cable – 6 fibers

Results of measurement of the 55 ft long loose-tube optical cable encasing 6 fibers are shown in Fig.(4). The upper left panel shows the temperature measured in the thermal chamber versus time. The optical cable was located inside a plastic conduit wrapped on a spool inside the thermal chamber, thus the time taken for the fibers to reach the thermal equilibrium was much longer than in the previous measurement. This is evident in the lower panels of Fig. (4), showing the slow variation of the phases of the two fibers versus time after the temperature step. The phase of each fiber tracks the temperature variation in the chamber giving approximately $\Delta\varphi/\Delta T = [\varphi(37^0C) - \varphi(22^0C)]/\Delta T \approx 11$ deg/15^0 C≈0.7 deg/^{0} C. The phase difference also tracks approximately the temperature variations with $\delta\varphi/\Delta T \approx 0.08$ deg/15^0 C≈0.005 deg/^{0} C.

2.1.3 Military Tactical Cable

The 76 ft long military tactical cable was tested two times, once using two fibers physically close to each other inside the optical cable, another time using two fibers in opposite sides with respect the center of the cable. Experimental results are similar in both cases. Only the results for two close fibers are shown (see Fig.(5)). The phase variation of each fiber is: $\Delta\varphi/\Delta T = [\varphi(37^0C) - \varphi(22^0C)]/\Delta T \approx 23$ deg/15^0 C≈1.5 deg/^{0} C, while the differential phase change between two fibers is $\delta\varphi/\Delta T \approx 0.6$ deg/15^0 C≈0.04 deg/^{0} C.

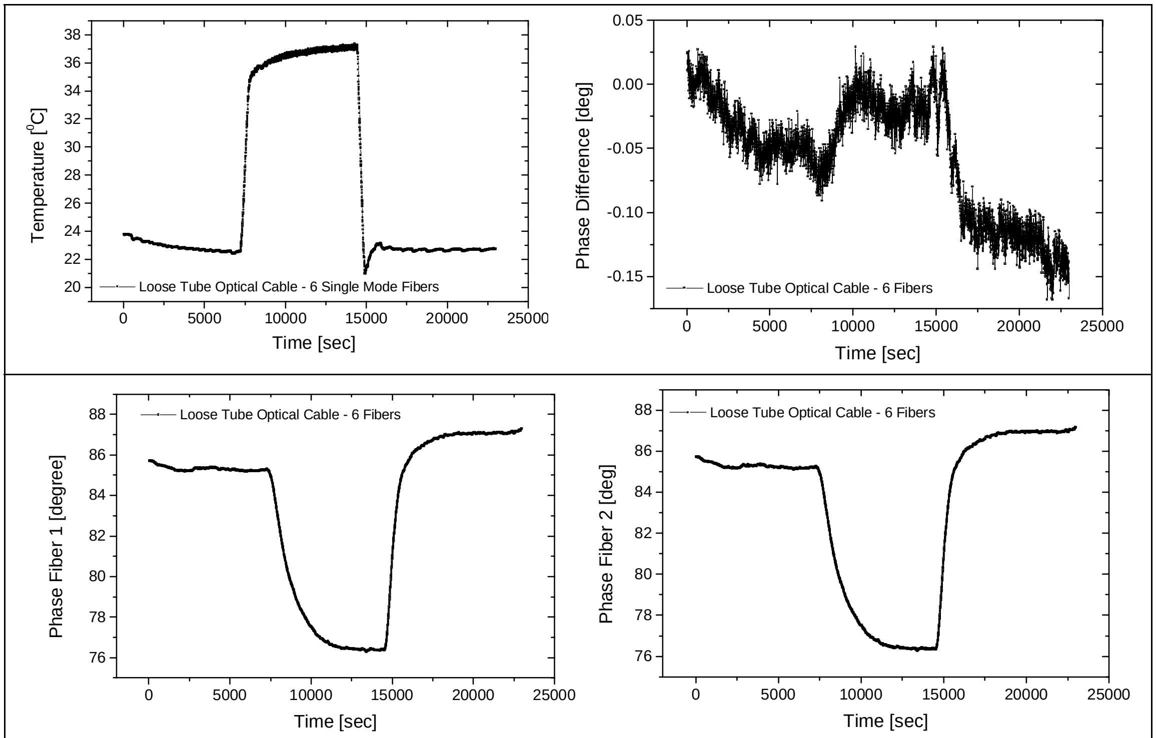


Fig.(4): Thermal test of 53 feet long Loose-Tube Optical Cable encasing 6 single-mode fibers. Top left): Temperature in the thermal chamber. Top right): Phase difference between the two fibers. Bottom left): Phase of fiber 1. Bottom right): Phase of fiber 2.

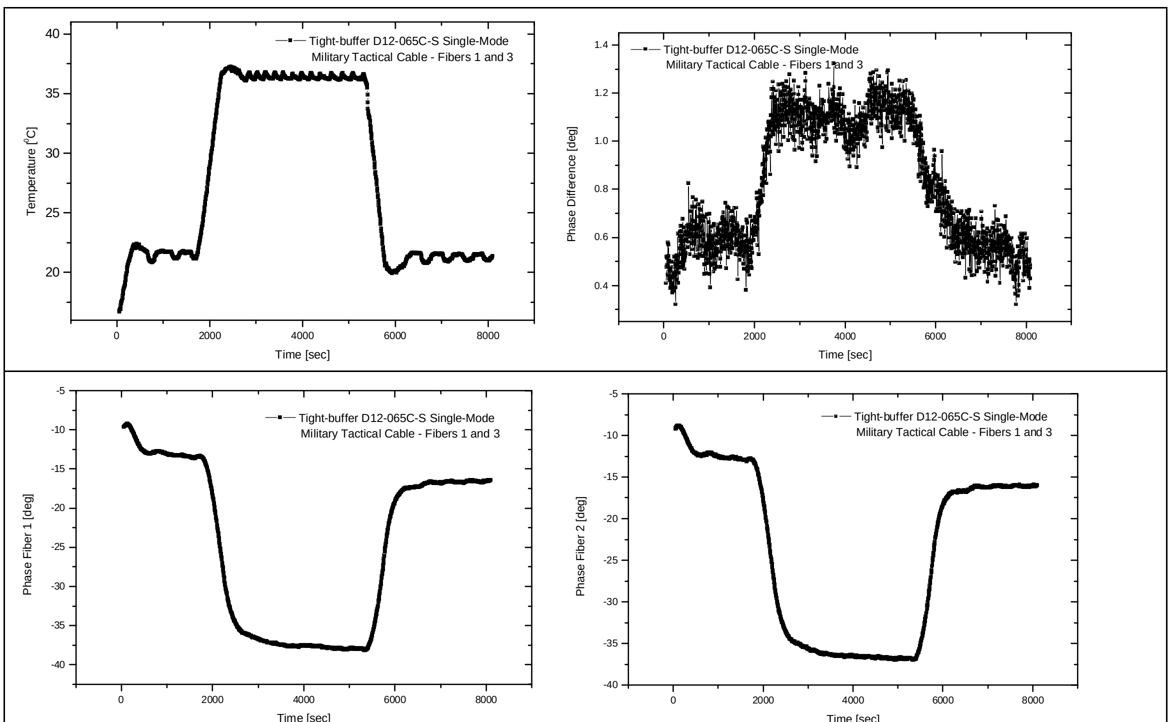


Fig.(5): Thermal test of Military Tactical Cable: two close fibers. Top left): Temperature in the thermal chamber. Top right): Phase difference between the two fibers. Bottom left): Phase of fiber 1. Bottom right): Phase of fiber 2.

2.1.4 Summary and discussion of results

The phase φ of the signal at frequency ν propagating through the fiber of length *L* is

$$\varphi=2\pi\, n\, L\, \nu/c \qquad (1)$$

where *n*=1.4677 [1] is the group refractive index of the fiber at 1310 nm, and *c* is the speed of light in vacuum. When the temperature of the fiber is changed by ΔT, the propagation time through the fibers changes, and the phase varies by $\Delta\varphi$ due to variations of the refractive index and of the length of the fiber:

$$\Delta\varphi/\varphi=\Delta n/n+\Delta L/L=(\Delta n/\Delta T)\,\Delta T/n + \alpha\,\Delta T \qquad (2)$$

Empirical data for Corning SMF-28 fibers [2] having similar properties to those used in the Alcoa Fujikura loose-tube cable we have tested, indicate that the dependence of the group refractive index on temperature is $(\Delta n/\Delta T) \approx 1.2\ 10^{-5}\ /^{0}C$, while the coefficient of thermal expansion is approximately $\alpha \approx 5.6\ 10^{-7}\ /^{0}C$. Using these numbers in eq.(2) we evaluate the expected phase variation $\Delta\varphi$ due to a temperature step $\Delta T=15\ ^{0}C$ for the L=117 ft long cable: the expected $\Delta\varphi$ is 24.69 deg, in good agreement with the experimental result $\Delta\varphi$=22 deg. The main contribution ($\approx$94%) to the phase variation is due to the dependence of the refractive index on temperature and accounts for a phase change of 23.11 deg, while only 1.58 deg are due to the thermal expansion of the fiber. The expected phase variation $\Delta\varphi$ for the 55 ft long Corning Optical Cable encasing 6 fibers due to 15 ^{0}C temperature variation is 11.6 deg in excellent agreement with the experimental result $\Delta\varphi \approx 11$ deg.

A measure of delay change in the signal path that results from a temperature change is given by the Thermal Coefficient of Delay (TCD) and is given in units of parts-per-million per degree Celsius:

$$TCD=\Delta t\ (10^{6})/(t\ \Delta T) \qquad (3)$$

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. Unlike the cable length dependent $\Delta\varphi$, the thermal coefficient of delay characterize an intrinsic properties of the transmission line. Since phase has a linear relationship with time, phase changes $\Delta\varphi$ are measured and converted to delay changes, so that the TCD is calculated using the following:

$$TCD=\Delta\varphi\ (10^{6})/(\varphi\ \Delta T) \qquad (4)$$

A summary of the results of thermal tests is given in Table 2. The third column gives the measured values of phase variation at 3 GHz per degree C, while the TCD is indicated in the fourth column. The value of TCD for loose-tube cable is in good agreement with that of $\approx$6.6 ppm/^{0} C measured from Lutes and Diener [3]. The fifth column gives the measured phase variation at 3 GHz per degree C between two fibers, while the last column is the corresponding differential TCD. Currently on the BIMA antennas approximately 100 feet of fiber-optic cable is exposed to the ambient air temperature; this is the length of the umbilical cable from the nearest underground pit to the antenna pad, plus the cable run through the azimuth and elevation twisters. The propagation delay through this length of fiber is of the order of 150 nsec. For a TCD of 7.9 ppm/^{0} C, the corresponding phase shift of a local oscillator at 230 GHz is approximately 100 deg/^{0} C. The differential phase shift through the fiber leads to an error of about 0.25 deg/^{0} C in the phase correction derived from the linelength measurement. The corresponding numbers for a military tactical cable are much worse – a phase change of 150 deg/^{0} C and a phase error after linelength correction of 2 deg/^{0} C.

Table 2

Optical cable type	Length [ft]	$\Delta\varphi/\Delta T$ (3 GHz) [deg/^{0}C]	TCD [ppm/^{0}C]	$\delta\varphi/\Delta T$ (3 GHz) [deg/^{0}C]	Δ TCD [ppm/^{0}C]
Loose-Tube 12 Fibers	117	1.5	7.96	0.007	0.037
Loose-Tube 6 Fibers	55	0.7	7.90	0.005	0.056
Military Tactical 12 Fibers	76	1.5	12.25	0.04	0.33

2.2 Mechanical Tests

The mechanical tests consisted in monitoring the phase and the phase difference (at 3 GHz) of two fibers versus time when moving and flexing the cable. The following cycle was repeated two times in all tests: 1) one cable of the bundle lifted by 3 inches; 2) bending the cable of r=6 inches; 3) bending of r=3 inches. These three "under stress" positions have been maintained for several seconds and alternated each time to rest positions. Only the loose-tube and military tactical cables with 12 fibers have been tested. The military tactical cable was tested two times, once using two fibers physically close inside the cable, another time using two far fibers, in opposite positions with respect to the cable center.

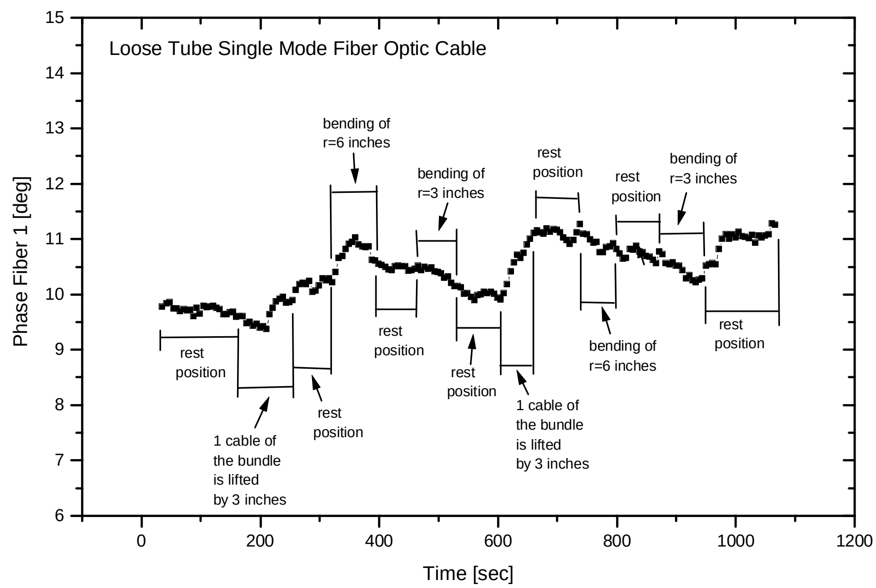
Results of measurement of loose-tube optical cable are shown in Fig.(6). The top panel is a plot of the phase variation of one of the two fibers versus time, while the bottom panel gives the phase difference between two fibers. The type of mechanical stress and the time during which it was applied to the cable is indicated on the same figures. The observed phase variations are unrelated to the applied mechanical stresses, and probably depend on the temperature changes occurring during the test. Even during the strongest stress, which is a bending of the cable with 3 inches radius (the minimum applicable during post-installation), no change in phase or phase difference are observed. Loose-tube cables are therefore insensitive to mechanical stresses to a level that does not allow any measurable effect using our setup.

Test results of military tactical cable using two far fibers are shown in Fig.(7). The same vertical scales as in Fig.(6) are used. The top panel is a plot of the phase of one fiber versus time that clearly shows the effects due to the various mechanical stresses that were applied. Different values of phase changes are obtained when applying the same stress during the two cycles period. An order of magnitude for the phase jump due to a bending of r=3 inches is about 5 degrees. The plot of phase difference between the fibers versus time shows similar jumps due to applied stresses (see bottom panel of Fig.(7)), and a step as high as 2.5 deg is observed during the r=3 inches bending. For a similar variation of phase difference to be due to thermal effects would require a temperature change of more than 60^{0}C for the 76 ft long cable.

Test results of the military tactical cable using two close fibers are shown in Fig.(8). The top panel is a plot of the phase versus time for one of the fiber, while the bottom panel is a plot of the phase difference. Although the phase steps have similar magnitude as for the two far fiber case, the phase difference shows smaller variations.

3 Conclusions

Two different types of fiber-optic cables, a loose-tube from Alcoa Fujikura, and a military tactical one from Optical Cable Corporation, have been tested for their thermal and mechanical properties in order to assess their suitability for use on CARMA. The tests consisted in cycling the temperature of the cables in a thermal chamber and moving/bending the cables of given radius while monitoring the phase and the phase difference between two fibers of an AM modulated signal. When a loose-tube optical cable approximately 100 feet long is used, the uncompensated phase difference between two fibers is of the order of 8 degrees at 230 GHz for an outdoor temperature change of 15^0C and the error in the linelength correction is 4 degrees. We conclude that loose-tube cables introduce only minor errors during typical operation of the interferometer and that they are largely to be preferred to military tactical ones for their lower differential phase changes caused by temperature variation and mechanical stresses.



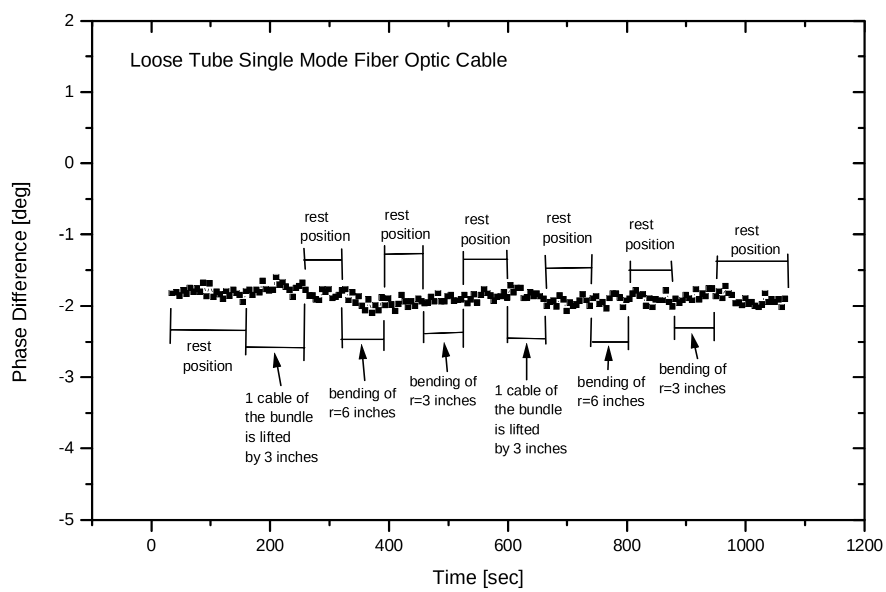


Fig.(6): Bending test of loose-tube optical cable. Top): Phase of fiber 1 versus time. Bottom): Phase difference between two fibers versus time.

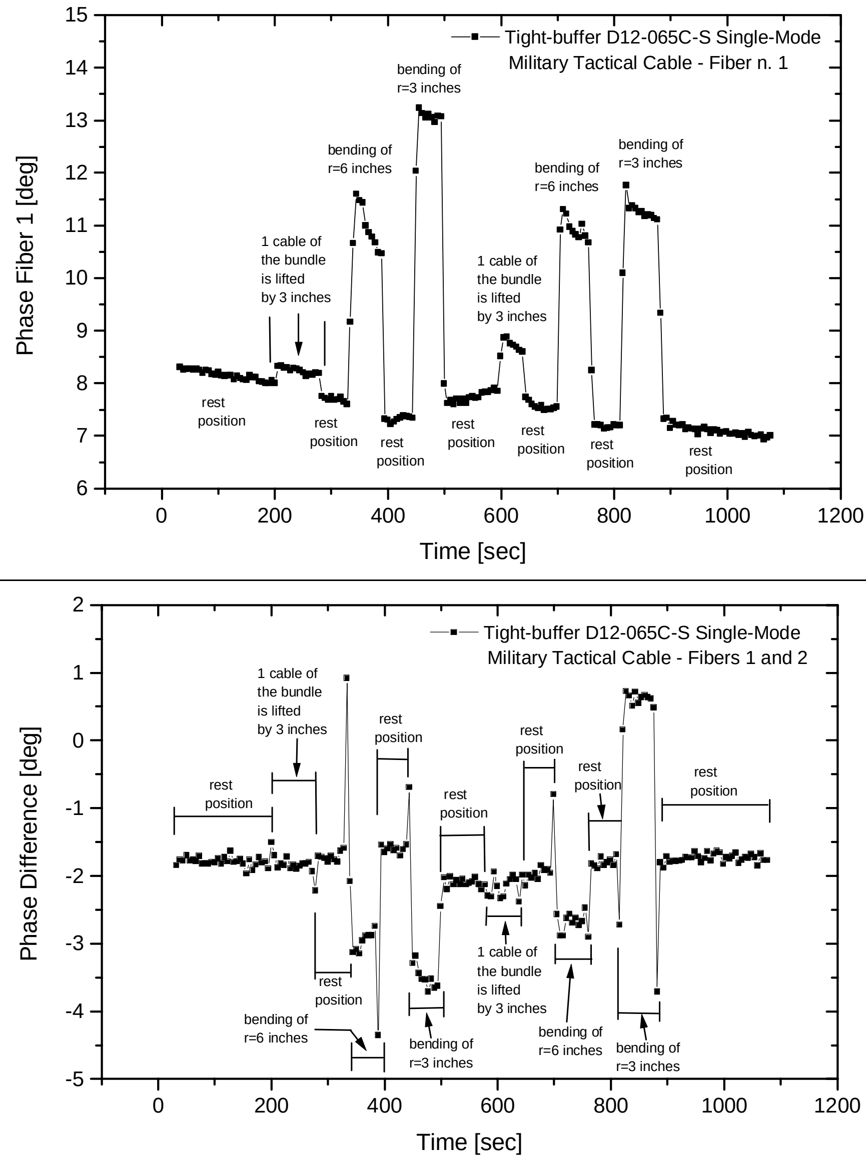


Fig.(7): Bending test of Military Tactical Optical Cable: two fibers in opposite sides of the cable. Top): Phase of fiber 1 versus time; Bottom): Phase difference between the two fibers versus time.

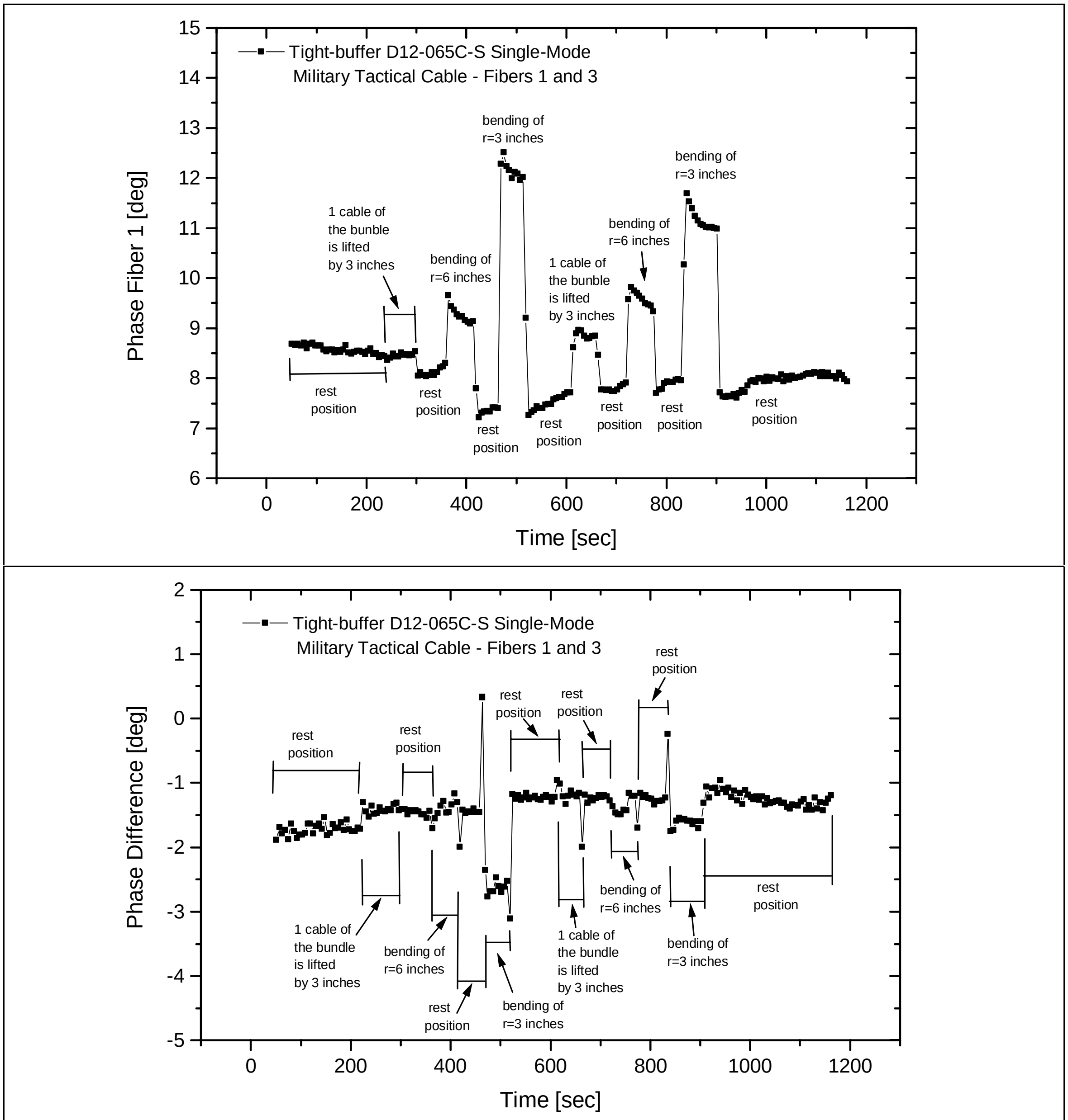


Fig.(8): Bending test of Military Tactical Optical Cable: two close fibers. Top): Phase of fiber 1 versus time; Bottom): Phase difference between the two fibers versus time.

References

[1] Corning SMF-28 Optical Fiber Product Information.

[2] Vastag M., Corning GuideLines Magazine, Winter 2000.

[3] Lutes, G. and Diener, W., *Thermal Coefficient of Delay for Various Coaxial and Fiber Optic Cables*, TDA Progress Report 42-99, Jet Propulsion Laboratory, Pasadena, 1989.
http://tmo.jpl.nasa.gov/tmo/progress_report/42-99/99E.PDF