BIMA Memoranda Series

Report from First Hat Creek Fiber-Optic Test

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Abstract

A fiber-optic link for the distribution of LO and IF signals was successfully installed and tested on antenna #3 at Hat Creek. The links performed to specification; there was no measurable degradation of system performance over the standard coax cable system. Appendix A presents and costs a plan for upgrading the entire array to fiber-optic LO and IF distribution.

1 Introduction

During the week of September 16 to 20, 1991, a fiber-optic link for distribution of LO and IF signals was installed and tested on antenna #3 at Hat Creek Observatory. Two days were spent installing equipment and adjusting power levels. Cable length measurements were successfully made using the existing cable length hardware and software on the night of Sept. 17th. The first fringes were detected with the optical fiber link on the Orion SiO masers on the following day. During that day, the software was modified and new delay offsets were found. From late afternoon on the 18th until the morning of the 19th, 3-element interferometer observations and cable length measurements were made using the 100 meters of standard single-mode fibers. From late afternoon of the 19th until the morning of the 20th, 3-element interferometer observations and cable length measurements were made using the 100 meters of phase-stable single-mode fibers. On Sept. 20, the fiber-optic link was disassembled and the normal system restored.

2 Installation

The array was in a North-South configuration, with antenna 1 at 260N, antenna 2 at 40E, and antenna 3 at 320N. The fiber-optic link was established with antenna 3; normal coax cable links were maintained to antennas 1 and 2.

2.1 Fiber-Optic Link

Fiber-optic transmitter and receiver units were installed in the control room and on the receiver plate. In the control room, we tapped the 10 MHz reference signal and the 700 MHz LO signal in the IF/LO box just before the 4-way coupler. The 700 and 10 MHz signals were put into a combiner and input to the rf port on the laser transmitter (Figure 1). Fiber-optic cable was run from the control room, stretched out on the N-S runway, and run up to the backend of the antenna. The cable was fed through the axis cable run to the receiver plate. On the receiver plate, the optical signal was converted to rf and passed to a two-way splitter and filter to recover the 10MHz and 700 MHz signals (Figure 2).

The 700 MHz echo and the receiver IF were feed through a computer controlled switch to the laser transmitter allowing us to select the IF or echo signal as desired. The laser signal was carried back to the control room in a second fiber in the cable and fed into the optical receiver unit. The rf signal from the receiver was fed into an amplifier and splitter, and back into the normal system. The IF was fed into the delay box at the anzac coupler, bypassing the equalizer circuit for the normal IF cable (Figure 3). The power levels were adjusted to match levels expected by the normal system.

2.2 Fiber-Optic Cable

Two 100-m lengths of fiber-optic cable were used in the experiments. One cable consisted of multiple strands of standard single-mode fibers, two of which had connectors (JDS Angle Polished Connectors). The second cable consisted of 6 thermally phase-stable fibers produced by Sumitomo Inc., three of which had connectors. In all experiments, connectors were attached to the fibers by splicing on roughly 5 meter lengths of standard single mode fiber with JDS Angle Polished Connectors. The transmitter/isolator units had 3-m of standard fiber and the receiver units had 1.5-m of standard fiber. In total, it is estimated that 30-m of standard single mode fiber was in the system during the tests of the thermally delay stable fiber, half in the lab and half at the antenna feed. During tests with the standard cable, there was an extra 5-m jumper on the LO and an extra 10-m jumper on the IF at the receiver end.

2.3 Fringe Detection

After the equipment was installed, approximately one day was spend adjusting and measuring power levels into and out of the equipment. The amplifier before the laser transmitter was removed and pads placed at various points in the system. Once proper power level were obtained, the X-band oscillator locked successfully to the LO signal. Since the antenna delay was not known, observations of the Orion SiO maser were attempted first. Fringes were detected on the first integration. The phases on baselines involving antenna 3 wrapped too rapidly to show coherence but the maser lines showed clearly in amplitude (Figure 4).

After some fiddling with the software to allow short delay lengths, broadband fringes were detected on Venus and 3C273. In general, the LO lock appeared to be as stable as for the standard coax LO cable. The systems temperatures on antenna #3 were roughly 40% higher with the optical fiber link than with the standard coax cable; We attribute this to saturation within the fiber optic link system.

3 Thermal Stability Analysis

From 0100 UT 19 Sept to 1800 UT 19 Sept, the array was run in standard interferometer mode with the standard single mode fiber connected to antenna 3. Strong point source calibrators were monitored with a coherent integration time of 1 minute; The cable lengths were measured and recorded once a minute. The sky was clear throughout although the integrated column abundance of water vapor was greater than 15 mm. The following day, the phase-stable fiber was installed on antenna #3 and the observations were repeated as on the first day. The conditions were similar.

3.1 Delay Measurements

Results of the cable length measurements for all antennas and both days are shown in Figure 5 and 6. The horizontal axis is time in hours since 0 UT, while the vertical axis shows the air temperature in the lower panel, and the delay change in the upper panel. The delay is expressed as a differential change in length in ppm on the right scale, and in change in radians per kilometer at a frequency of 100 GHz on the left scale.

On both days, the outside air temperature exhibited variation from a peak of 35°C before sunset to a minimum of 10°C just before sunrise. The change in delay of the fiber-optic cable accurately tracked the instantaneous changes in air temperature. This is most clearly illustrated near 0300 UT on September 19, when a sudden temperature warming was mirrored in the delay. There is no doubt that this behavior is a direct result of placing the optic-fiber cable fully exposed on the runway rather than in the underground conduits along with the coax.

In contrast, the delay behavior of the coax cables exhibits a simple sinusoidal variation which seems to lag the air temperature by about one hour. This difference suggest that the coax is responding to temperature changes in the conduit which are classic propagating thermal waves forced by the diurnal solar cycle. Furthermore, the distinct difference between the response of the coax and the air temperature variations suggests that the exposed portion of the coax contributes little to the total delay change.

The difference between the two coax cables can be attributed to the difference in path-length of the coax within the conduit for the two antennas: antenna 2 was at pad 40E (about 100 meters from the pit) while antenna 1 was located at pad 260N (just outside the pit).

3.2 Fiber-Optic Thermal Coefficient of Delay

The correlation between the delay of the fiber-optic cable, and the air temperature shown in Figure 5 and 6 suggests that we can use these measurements to estimate the thermal coefficient of delay (TCD) of the optic-fiber itself. Figure 7 shows a plot of delay vs air temperature for both fiber-optic cables. Straight lines have been fit to different segments of the data, and the slope of the fit is simply the TCD in units of ppm/°C, assuming that the air temperature is an indication of the temperature of the cable. This is not always a valid assumption however, especially during the day when the cable is exposed to direct solar radiation. The black polyvinyl coating of the fiber-optic cable, increases its absorption to solar radiation, hence increasing its temperature above that of the ambient air.

The three different fits in each plot correspond to data taken before sunset, at night, and after sunrise. It is clear that before sunset, while the cable is cooling down, and after sunrise, while the cable is warming up, the cable temperature is different than the air temperature. This may be entirely due to the direct exposure to solar radiation. During these times, the slope (and thus the TCD) is greater than that measured at night. It is the lowest of the three values which provides the best estimate of the TCD of the cable, but even this may be an upper limit for the delay-stable fiber since standard fiber was in the circuit during these measurements.

Our best estimate or the TCD of Sumitomo's phase-stable fiber and the regular fiber is 0.5 ppm/°C 6.0 ppm/°C respectively. These values are also consistent with independent measurements by Lutes and Diener[1] They measured the TCD of Sumitomo's cable to be in the range 0.3–0.5 ppm/°C and the TCD of loose-tube fiber at about 7.0 ppm/°C. In contrast the TCD of the coax is 25-70 ppm/°C, assuming that it is the same as the cable being used in the new delay boxes.

4 Sensitivity to Bending and Flexure

The object of this test was to see if the fiber-optic cable length was changed by bending or moving the cable. In the first test, the cable was manually moved and bent as continuous measurements of the cable length were being made. In the second test, a 1.5-hour file consisting of 6 minute observations of a variety of sources was executed and the cable lengths measured and recorded every 30 seconds. The cable was generally found to not be very sensitive to changes, although the length did sometimes jump when major bends were made. When the length did jump, it was a temporary change and the cable quickly returned to its former value. The general conclusion is that antenna movement, and the ensuing changes in the cable wraps, will not affect the stability of the LO.

5 Interferometer Measurements

Standard interferometer measurements of 3C454, PK0420, and 3C273 were made during the nights of September 19th and 20th to test the stability of the LO lock and the phase coherence of the LO lock. Although the coherence was marginal in the afternoon and early evening, it became reasonable during the night. LO lock was maintained by the computer throughout both nights. Due to the weather, the best data were collected in the early morning on PK0420.

Comparing data for PK0420 with and without the fiber-optic link, the gain in Jy/K on baseline 1-3, the shortest baseline, was 224 $\pm$ 20 (corrected for saturation) with the fiber-optic link and 220 $\pm$ 25 with the standard coax cable. Thus, the short timescale coherence of the system with fiber-optic link is good.

6 Conclusions

1. Fiber-Optic links can be used to carry LO and IF signals to and from the antennas on the current interferometer with no degradation of performance. The X-band and mm oscillator locks are not adversely affected. The effects of cable movement appear to be no worse than those for standard coax cable.

2. The current line length hardware and software can be used to measure and correct temperature dependent phase variations in the fiber-optic link with no changes.

3. The Sumitomo delay stable fiber shows approximately an order of magnitude less temperature sensitivity than standard single-mode fiber. Even the standard single mode fiber shows a factor of 3-10 less temperature sensitivity than the current coax cable. If the delay-stable fiber is run to a 1 km station underground (assume a 3°C diurnal temperature variation),

[1] Lutes, G., and Diener, W., "Thermal Coefficient of Delay for Various Coaxial and Fiber-Optic Cables," *TDA Progress Report 42-99*, Nov. 15, 1989, pp. 43-59, JPL, Pasadena, California.

there should be roughly 6 radians peak-to-peak variation in a day; this can be followed quite easily with standard astronomical phase calibration, without the line length measurement system. On the other hand, variations in standard single-mode fiber, which should be roughly 60 radians during a day (0.042 radians/minute), can be followed quite easily with cable length measurements every minute. Hence, the delay-stable fiber can be used effectively up to kilometer lengths with, or without, the cable measurement hardware. In contrast, the standard single-mode fiber requires length measurements even for 100-meter lengths.

A Fiber-Optic Upgrade of the BIMA Array

In light of the success of the fiber-optic link experiment, it is resonable to consider the advantages and disadvantages of upgrading the entire array to use fiber-optic links for all IF and LO signal distribution. This appendix presents the outlines of such a system, its advantages, disadvantages, and costs.

A.1 Proposal

Our proposal is to transmit the X-band LO from the control room to each antenna using an Ortel 10 GHz fiber-optic link. The IF is returned on an Ortel 3 GHz link. The array would be rewired with standard single-mode fiber running through the power conduits. Each antenna would be equipped with a 30-m tail of delay-stable fiber to run from the antenna to the local IF/LO pit. All of the necessary equipment are off-the-shelf items and the technical difficulty in building the links is low. The cable length measurement system would be used to correct for cable length changes.

The advantages of the above system over the current coax system are as follows:

1. Only one X-band oscillator system is needed and it will reside in the temperature-stable computer room in the control building. Thus, problems with the X-band locks should disappear completely.
2. The thermal stability of the LO and IF cables will improve by more than a factor of three, thus making the line length measurement less critical.
3. The IF link will have a bandwidth of roughly 3 GHz as opposed to the expected 1 GHz bandwidth for the coax system in the new array. With this additional bandwidth, it will not be necessary to expand the IF system to deal with large bandwidth dual-receiver or dual-polarization data.
4. Additional delay segments for long baseline work can be added using optical fibers. This is both cheaper and easier for the long delays needed for kilometer length baselines.
5. This is a major step toward lessening our exposure to lightning strikes as it removes two major connections between the antennas and control room.

The main disadvantages of the optical fiber link system is the additional cost and the question of long-term reliability. A detailed estimate of the costs will be presented in the next section. The long-term reliability question resides entirely with the laser transmitter unit. Discussion with technical representatives at Ortel suggest that the mean lifetime of a unit is 100,000 hours (11 years); the laser itself should have a mean lifetime of one million hours (110 years).

A.2 Cost Estimate

Cost estimate for the major components have been obtained from the relevant companies. The plan is to use one 10 GHz transmitter unit in the control room for sending the LO to all antennas. The IF from each antenna will be returned on 3 GHz units. Optical isolators are needed to protect the laser from reflections. A standard single model cable with 4 fibers will be run to each LO/IF pit.

Table 1: Cost breakdown for fiber-optic upgrade for 9 antennas.

Quantity	Item	Price/unit	Total Price
2	10 GHz Transmitter unit	already purchased	
2	6 GHz Photodiodes	already purchased	
9	10 GHz Photodiode units	3,475	31,275
8	3 GHz Transmitter units	5,295	42,360
7	3 GHz Photodiode units	1,760	12,320
8	Optical Isolators	2,650	21,200
1	10-way optical splitter		1,000
0.5 km	Delay-Stable Fiber Cable		10,000
4.0 km	Standard Fiber Cable		12,000
36	Optical fiber connectors (4 pairs/antenna)	180/pair	6,480
9	Misc electronics and power supplies	500/ant	4,500
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	Total Cost		141,135

Table 2: Cost breakdown for fiber-optic upgrade for 6 antennas.

Quantity	Item	Price/unit	Total Price
2	10 GHz Transmitter unit	already purchased	
2	6 GHz Photodiodes	already purchased	
6	10 GHz Photodiode units	3,475	20,850
5	3 GHz Transmitter units	5,295	26,475
4	3 GHz Photodiode units	1,760	7,040
5	Optical Isolators	2,650	13,250
1	10-way optical splitter		1,000
0.5 km	Delay-Stable Fiber Cable		10,000
4.0 km	Standard Fiber Cable		12,000
24	Optical fiber connectors (4 pairs/antenna)	180/pair	4,320
6	Misc electronics and power supplies	500/ant	3,000
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	Total Cost		97,935