ALMA Memo #443

ALMA LO Distribution Round Trip Phase Correction

2002-Nov-14

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1 Abstract

The ALMA requires a coherent local oscillator at each antenna. Due to the long distribution length from central building to each of the antennas, the fiber optic path to each antenna must be stabilized to meet the ALMA specification. A round trip phase correction technique has been adopted to meet these specifications, and that technique is described here. Also, a summary of various techniques that have been used at other installations is given. Results reported here are given for tests completed through April, 2002. Further tests are planned and will be reported at a later date.

2 ALMA LO Distribution System Description

2.1 Basic Description

The ALMA Local Oscillator (LO) References are sent from the central Building to each of the antennas via optical fiber. The baseline plan calls for a high frequency reference sent as the difference between two wavelengths separated by a frequency in the range of 27-142 GHz. Lower frequency references are sent on a separate optical wavelength but on the same fiber. The high frequency reference serves as the reference frequency for the first LO which is integrated into the Front End Assembly. Thus phase drift that is accumulated by variation of the phase path length from the central building to the antenna is written directly onto the first LO. In addition, phase noise on the reference frequency will also affect the first LO. The first LO is one of several low-phase-noise electronic oscillator assemblies followed by an active-multiplier chain assembly. This entire assembly is phase locked to the output of the photonic reference photomixer. The total phase noise of the first LO is a combination of the intrinsic phase noise of the electronic oscillator assembly outside the loop bandwidth with the photonic reference noise within the loop bandwidth. This phase noise is multiplied to higher frequencies for some bands. The phase noise and the phase drift of the photonic reference are thus both critical parameters in the overall performance of the first LO. The round trip phase correction described here is a technique that removes the effect of phase drift in the fiber.

2.2 ALMA Phase Drift Specification

The ALMA Project Book (updated Jan 2002) lists the requirement on the phase drift of the fiber as 0.09 degrees at 119 GHz, which is 0.6 microns or 2.1 fsec. The 0.6 micron specification is less than half of a wavelength at the 1.55 micron optical carrier wavelength. For the longest fiber length contemplated for ALMA (25 km), 0.6 microns implies a fractional fiber length stability of 2.4e-11.

The following section will review the state-of-the-art in phase transfer by fiber, revealing that the ALMA phase drift specification requires an order of magnitude improvement over the most advanced systems that have been previously built. Although the phase drift specification as currently stated has the same specification regardless of the length of the fiber, it is expected that in any implementation of the fiber path length stabilization, there will be a component of phase drift that is proportional to the fiber path length.

2.3 Calculation of expected fiber phase drift without correction

The fiber drift has two components, drift due to the above ground fiber which is exposed to diurnal temperature fluctuations, and drift due to the buried fiber which has much lower temperature fluctuation. Several sources have reported on the phase vs. temperature coefficient of single-mode fiber [1-3], which is approximately 8 ppm per degree C for bare single mode fiber. Other reports have measured cabled fiber of various types [4], with temperature coefficients ranging from 10 ppm-60 ppm per degree C. For purposes of estimating the maximum likely propagation delay due to temperature for the ALMA fiber, we will assume a worst case value of 15 ppm per degree C. This is likely to be an upper value on the cabled fiber. In ALMA memo #314 [5], the predicted maximum diurnal temperature variation is .006 deg K for fiber buried to a depth of 1-meter. The above ground maximum diurnal temperature change is 30 deg K. These values were used along with a fiber temperature coefficient of 15 ppm/deg C to predict the expected fiber uncorrected path length changes [6]. That result used a longest fiber path length change of 25km. However, in the latest ALMA configuration planning, the so-called Y+ configuration is expected to have a longest baseline of 20 km [7], so the longest distance from the central building to an antenna will be about 10km. We will assume a longest fiber path length of 15 km to account for curves and spurs in the fiber routing, and recalculate the result from[2] :

Expected Fiber Path Length Change per day	
Elapsed Time	1 day
Length change, 15km buried	1.3 mm
Length change, 25m above ground	11.2 mm
Total length change	12.5 mm

This will be again recalculated using a shorter time scale of one hour. The underground temperature fluctuation in one hour should not exceed 1.6mK, and the above ground temperature change should not exceed about 5 K per hour [Ref. 5, Fig. 9]. We then get:

Expected Fiber Path Length Change per hour	
Elapsed Time	1 hour
Length change, 15km buried	.36 mm
Length change, 25m above ground	1.9 mm
Total length change	2.26 mm

In either case, the fiber path length change is dominated by the above ground sections. From previous work [8] it has been found that a large phase drift component was added by sections of fiber in and near fiber manholes. For ALMA, care must be taken to minimize the above ground fiber run lengths and to insulate the fiber manholes so as to reduce the amount of compensation required in the round trip phase correction.

3 Prior work in phase transfer by fiber

The Smithsonian Astrophysical Observatory operates the Submillimeter Array (SMA) on Mauna Kea. This is a six element interferometer with a similar frequency coverage as ALMA [9]. In light of the above discussion, it is somewhat surprising that the SMA does not use an active fiber correction. The longest baseline for the SMA is less than one km. In addition, the fiber that they use for distribution is a special, expensive, fiber with extremely low temperature coefficient of phase. The secondary coating of the fiber is made from a liquid crystal polymer with a negative thermal expansion coefficient which compensates the positive expansion coefficient of the silica glass core [10]. This fiber has a temperature coefficient that is in general less than 1 ppm/deg C, but at the mean ambient underground temperature on Mauna Kea (5.5C) it is less than .03 ppm/C for small deviations. Using this fiber, and a special torsionally controlled azimuth fiber wrap, the SMA hopes to achieve phase drift of less than 10 microns per hour. This special fiber was discontinued by Sumitomo and is now reportedly manufactured by Furukawa. However, it would be of limited use for ALMA since the cost would likely be prohibitive and the phase drift would still be much larger than the ALMA goal.

Several groups have done some version of a round trip phase correction based on a microwave reference modulated onto an optical carrier. Previous work at NRAO includes a round trip phase measurement scheme using the microwave reference technique [11]. Using a 500 MHz modulation, and simple inexpensive components, the technique was used to measure phase with resolution below 1 psec. A similar technique has been used at Jet Propulsion Lab (JPL) and National Astronomical Observatory of Japan (NAOJ) using more expensive components such as a narrow linewidth laser for transmission and an optical modulator [12,13]. The JPL work was a reference frequency distribution for the Cassini-Deep Space Network experiments. The highest frequency used in the experiment is 32 GHz and the longest fiber length is 16 km. In this case an optical wavelength of 1310 nm was used and the modulation frequency was 1 GHz. The signal is detected, frequency shifted, and retransmitted at the antenna end. The returned signal is detected, phase compared to the outgoing signal and then used to drive a temperature controlled spool of fiber so that the round trip phase is unchanging. This system has resulted in phase stability of approximately 100 fsec on time scales from a few minutes to a few hours. The NAOJ work was similar, except a 1.4 GHz microwave carrier was used and 100fsec phase drift was measured over only 100m of fiber. Neither of these techniques would meet the ALMA specification. Also, on shorter time scales, changes in fiber length due to antenna motion or cable wrap perturbation would be corrected very slowly (tens of seconds) by either of these techniques.

There is also a commercial company that sells products meant to send coherent timing signals by fiber. A paper that is available on their web site describes their measurement/correction system that is based on comparing the phase of a microwave modulated reference signal over fiber [14]. Their system achieved an RMS phase stability of 650 fsec.

Both the EVLA and CARMA (Combined Array for Research in Millimeter Astronomy) have plans to do real-time measurement of the fiber round trip path delays [15,16]. These measurement systems will be similar to the NAOJ and JPL systems, except that the phase correction is not applied to the fiber but rather in the backend. In both cases, the ultimate phase accuracy falls well short of the needs of ALMA.

4 ALMA Round Trip Correction by Optical Interferometry

4.1 Description of the Technique

The methods described above all use microwave modulation of a lightwave on fiber, and the phase comparison is done after photodetection and recovery of the microwave carrier. The ultimate resolution of the technique is proportional to the signal to noise ratio in the phase comparison electronics, and to the phase comparison frequency. To achieve high resolution, ALMA chose to do this phase comparison directly at the optical wavelength, where the frequency is approximately 10^5 higher (at 200 THz) than in the other techniques. Phase comparison of an unmodulated lightwave is done by using a fiber-optic Michelson interferometer. To do the phase comparison with higher signal-to-noise, we put a small frequency shift on the lightwave at the far end. In this way, the photodetection of the reference light with the returned light can be AC-coupled. The basic test setup is shown in Figure 1.

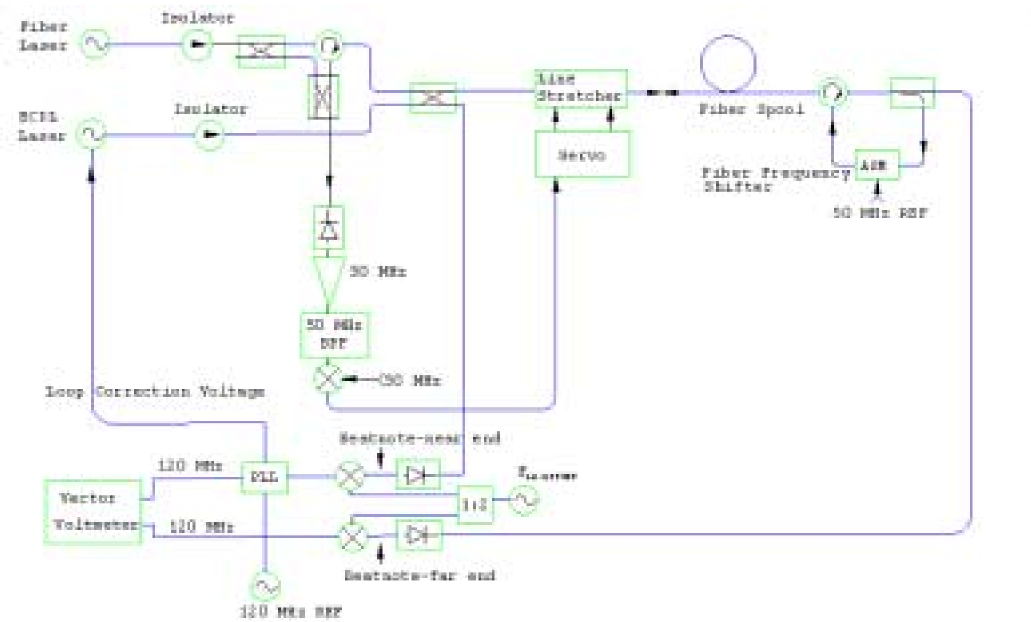


Figure 1 - Setup for measurement of the phase measurement of the LO reference while using a length correction based on the round-trip phase measurement of an optical wavelength supplied by the master laser.

This technique requires a laser of exceptionally long coherence length, greater than twice the maximum fiber distance from the central building to an antenna. This is very rare in a commercial laser but we did find one that was available in the 1550-nm band that we have used for prototype tests. The setup shown in Figure 1 depicts two lasers separated by the desired LO difference frequency and phase-locked to a microwave reference (labeled $F_{LO\text{-}OFFSET}$). One laser is a fiber-ring laser which exhibits a high degree of spectral purity and stability [17], the second laser is an external-cavity-diode laser. The fiber laser is both the master laser for the optical phase lock and the phase standard for the fiber length measurement. A spool of fiber of arbitrary length is used to simulate the path from the central building to the antenna. At each end of the fiber is a photodetector for detection of the beatnote frequencies, which are downconverted and phase compared by a vector voltmeter. At the far end of the fiber, a portion of the light is coupled off, frequency shifted by 50 MHz, and returned over the 1-km fiber. The returning light is combined with the fiber laser at the source end, creating a fiber interferometer. The phase difference is measured, and a correction is applied to the fiber line stretcher.

We have used two typed of fiber line stretchers: A piezoelectrically stretched fiber with a stretch range of about 50 microns, and a bandwidth of aabout 5 kHZ, and an air gap stretcher with a range of tens of millimeters and a bandwidth of about 1 Hz. When operated in series, these combined to form a robust wide-range stretcher that was fast enough to track the fastest variations in fiber phase. More recently we have replaced the air-gap stretcher with a second piezo-fiber stretcher which has a range of 5 mm and a bandwidth of 10 Hz. The system performance was not compromised and the mechanical air gap assembly was eliminated.

In the only previous reference describing phase transfer by fiber with a correction based on comparison of optical wavelengths, the round trip phase cancellation was successful but the experiment was only made over 25-m of fiber [18]. An interesting aspect of this experiment was that Bragg cells were used to shift the frequency of the light traveling through the fiber rather than shifting the phase by use of fiber stretchers. In the ALMA application, this could also be done by using fiber optic frequency shifters instead of fiber stretchers. This would be slightly more expensive but would give greater immunity of the Michelson interferometer to cycle skipping due to perturbations of the fiber that are either too fast or too large for the correction system to handle. Ultimately, the response speed of the length correction will be limited by the length of the fiber. The time delay of the round trip can be as long as 250 μsec, which means that the correction cannot be run at bandwidth faster than about 1 kHz. Thus, vibration induced phase errors must be minimized (kept below about 0.8 μm – half of a fringe) if they have frequency components above 1kHz. These might be induced by such things as motion of the antenna, motors, fans, air flow, or the refrigerator crosshead.

4.2 Master Laser Requirement

The Master Laser is the key component for doing correction of the phase drift of the fibers in the LO distribution. However, the successful implementation of the method requires a master laser that is both frequency stable and highly coherent. The high coherence is necessary for the phase comparison to be done on an optical fringe at the round-trip distance. The frequency stability of the master laser is important because the round trip correction will impart a phase error proportional to the laser fractional frequency stability. For instance, for a 20 kHz frequency drift of the 200 THz master laser (which would be exceptionally good), the fractional frequency stability is 10^{-10}. Thus the line length correction would be good to 100 nm for a 1 km fiber and 2 microns for a 20 km fiber. ALMA’s requirements for a master laser have been written and sent to industry and research groups as a Request-for-Proposals (ALMA EDM Document BEND-50.03.08.00-001-A-SPE). The current status is that proposals have been received and are currently being evaluated.

4.3 Measurement Results

The next few sections detail some of the measurements that have been made with this type of round trip phase correction using the instrumentation shown in Figure 1. All of the data represent measurements done with the original mechanical air gap stretcher. Currently tests are underway with the new 5mm piezo stretcher, but that data is not yet available. Also, all of the measurements included below were done with the MPB fiber laser, and thus has residual phase drift left after the correction which is due to the frequency instability of the laser. Future work will be concentrated on doing similar measurements with a much ore highly stabilized laser in order to evaluate if there are any other effects that contribute to the residual phase drift.

4.3.1 11.1 GHz beatnote with 1 km of fiber:

In the first test, we used 1-km of fiber and a beatnote frequency of 11.1 GHz. The phase of the detected difference frequency before and after transmission through the fiber was compared. Figure 2 shows the result of this phase comparison with the phase correction turned on and then off over an 8-minute period. The red trace is the phase difference at

11.1 GHz, the bottom trace is the magnitude of the slow correction with a scale as indicated. The corrected portion is very flat, with an RMS of about 0.06-degrees. The uncorrected portion shows the phase drifting at a rate of several degrees per minute.

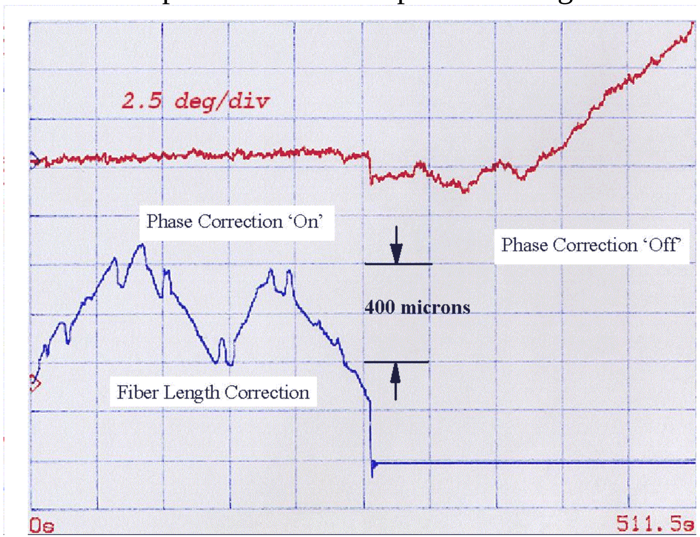
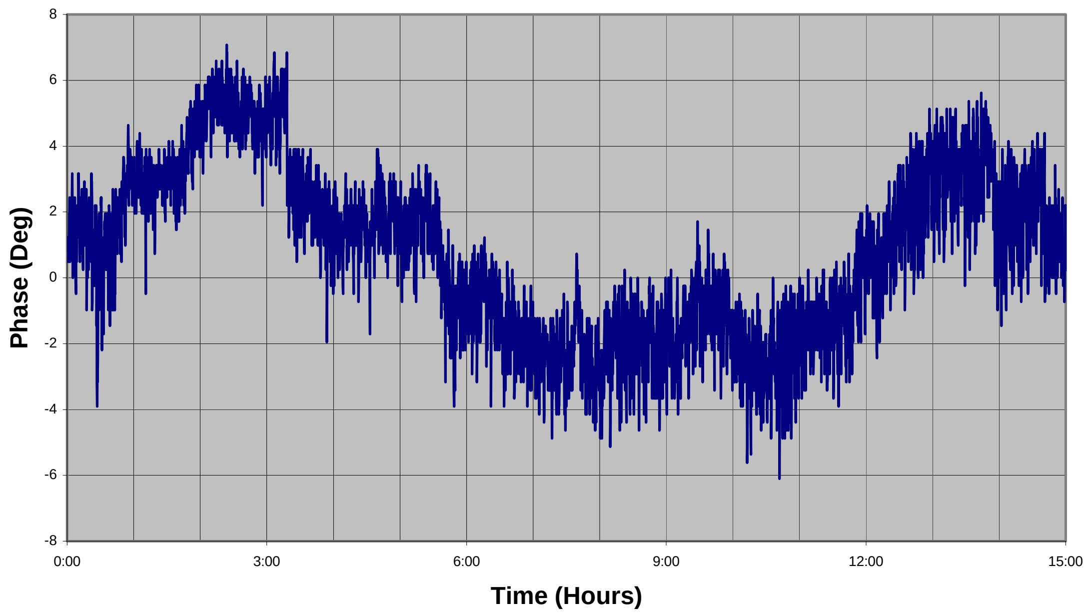


Figure 2: Comparison of Phase Difference between 11.1 GHz phase-locked beatnote before and after being transmitted through a 1-km single mode fiber: with correction 'on' and 'off'. Bottom trace is the movement of the slow fiber length corrector

The corrected phase drift is quite small, less than 0.25 deg per minute. At the time this was attributed to drifts due to the electronic components and cables used in the test setup.

4.3.2 Beatnote frequency of 25 GHz and 1 km of fiber.

The measurement was made over a 15-hour period to observe long term trends. The fiber was on a spool on a laboratory bench. The phase is seen to drift through about ten degrees peak-to-peak over a 9 hour period. It was during extended tests like these that we realized that wavelength fluctuations of the master laser would cause a corresponding fiber length change leading to phase drift. The master laser that we used for these tests has a wavelength drift of roughly 10 MHz per hour according to the manufacturer. This is about 0.1 ppm per hour of fractional frequency deviation. The fiber length change associated with this should be the same fractional amount, 100 microns for a 1-km fiber. This is 3 degrees of phase (at 25 GHz) of expected phase change per hour. The phase drift that is shown in Figure 3 is consistent with this explanation. The frequency drift of the master laser needs to be improved by several orders of magnitude in order to result in a round-trip phase correction system that will meet ALMA specifications. Until a much more stable master laser is available, it is difficult to measure more precisely to see if there are other effects present that will also affect the phase measurement. In other words, it is not possible to prove that this technique will work without a more stable master laser.



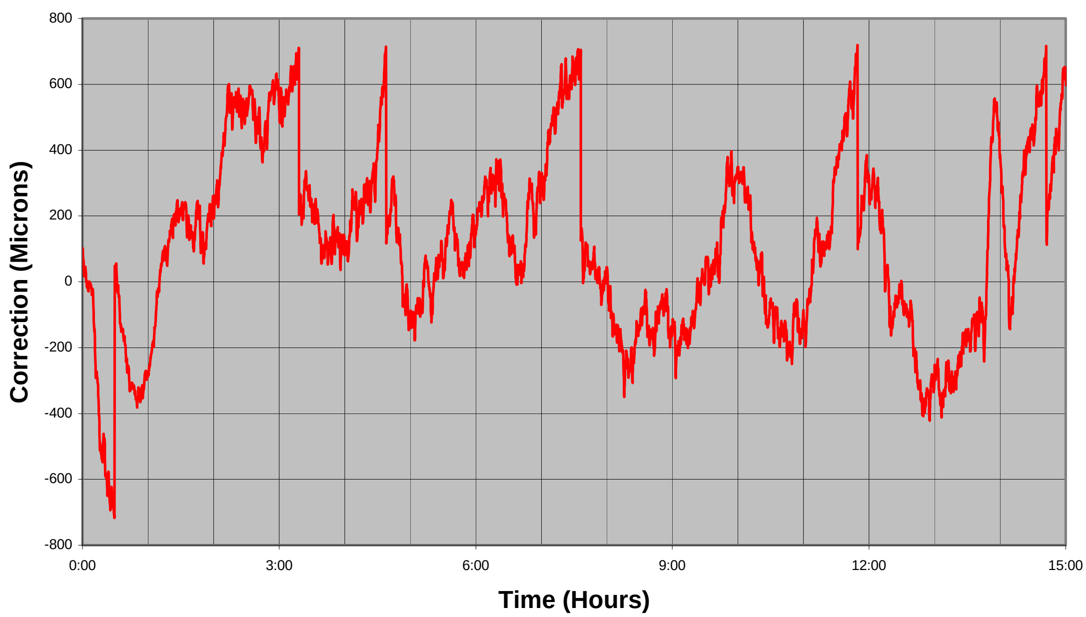


Figure 3 Upper : Phase in Degrees Lower : Correction distance in Microns. Plotted aginst time. RF phase is measured at 25 GHz for 1 km of fiber. The bottom plot includes several resets of the air gap stretcher as the LVDT sensor reached its limit.

4.3.3 25 GHz beatnote, 10 km of fiber, 4 hour test

Figure 4 is the result of an experiment in which the fiber length was increased to 10 km (the beatnote frequency was still 25 GHz). The green trace is the phase difference between the near and far end of the fiber. There are large phase jumps at 1.5 and 2 hours which correspond to times when the air gap stretcher had reached the end of its range and was reset. The corresponding jumps in the air gap position are shown by the red trace. The blue trace represents the result of post-processing the data to remove the large jumps from the data. This represents the phase drift with the correction system 'on' if the stretcher were able to cover a wider range. Incidentally, the limit to the stretcher range in this case was the LVDT sensor rather than a mechanical limit on the moving mechanism. The range shown here is about 1mm, but with the newer wide-range piezo stretcher we have a range of at least 5 mm. Note that the phase drift over the five hour period progressed linearly over about 50 degrees in 3 hours, or about 17 degrees per hour. This is consistent with the previous experiment with 1-km of fiber, as phase drifts roughly ten times as fast here. Also note that the air gap position is uncorrelated to the phase drift. This indicates that the correction itself is not inducing the residual phase error. Also, though not plotted, the local room temperature is not correlated with the phase drift. In attributing the master laser frequency drift to be the cause of the phase drift, one might expect that the local temperature would be proportional to both the master laser frequency drift and the residual phase drift. However, the optical fiber cavity that determines the output frequency of the master laser is itself in a tightly temperature controlled box and is therefore not directly on the local room temperature.

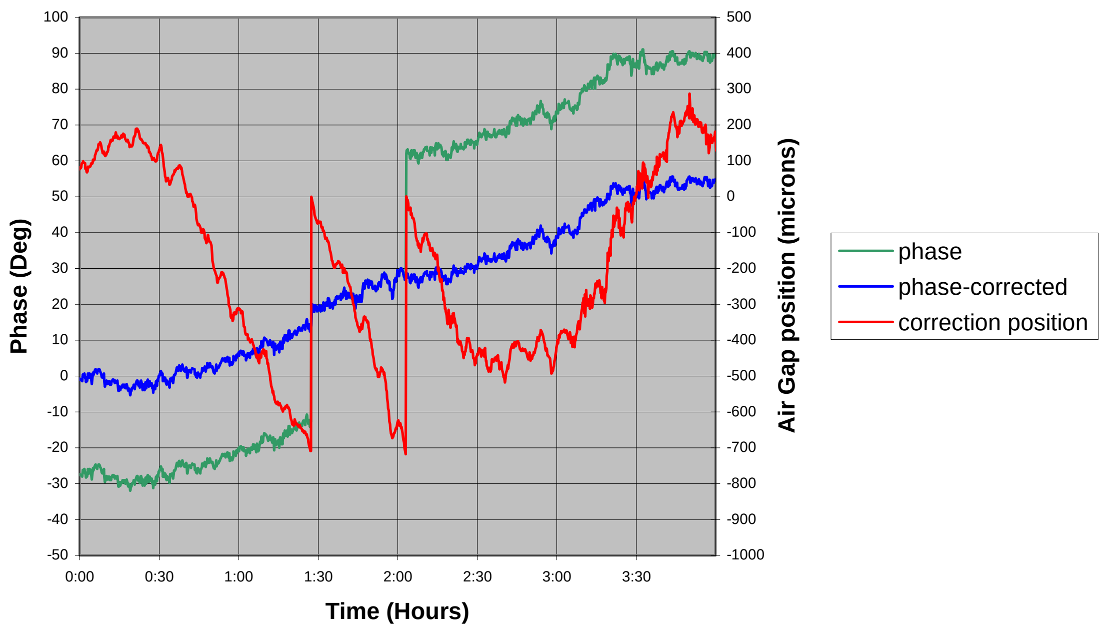


Figure 4 - Phase and air gap correction position versus time for a 4 hour test of the round-trip phase correction at 25 GHz with 10km of fiber.

4.3.4 25 GHz beatnote, 10km of fiber, 64 hour test

This test is a repeat of the previous test but was run for 64 hours instead of four hours. A number of additional effects can be seen in Figure 5. The green trace is the phase as measured from the vector voltmeter, and the red trace is the air gap position. The dominant feature in both cases is the reset that occurs when the air gap reaches the end of its range. The air gap is then set to a mid range value and the phase has a discrete jump which looks like a staircase versus time. The second feature which appears in the phase is the wraparound from +180 degrees to –180 degrees. In post-processing the data, we removed both of these effects and the result is shown in the blue trace. Note that the phase drift is about 150 degrees peak-to-peak over the first forty hours of the test and 450 degrees over the final 24 hours of the test. The last 24 hours has a rate of change of phase very similar to that displayed in the four-hour test of Figure 4. It is interesting to note that there is a very noticeable diurnal effect on the air gap position, which represents the amount of the fiber compensation. This is to be expected since the fiber path length change should be directly proportional to temperature. The red trace clearly shows that the fiber is expanding for about half of the day and compressing for the second half of the day. The diurnal effect is not seen in the phase drift data. There may be a diurnal effect on the blue trace but if it is there it is hidden by the major effect which we attribute to the drift of the master laser frequency.

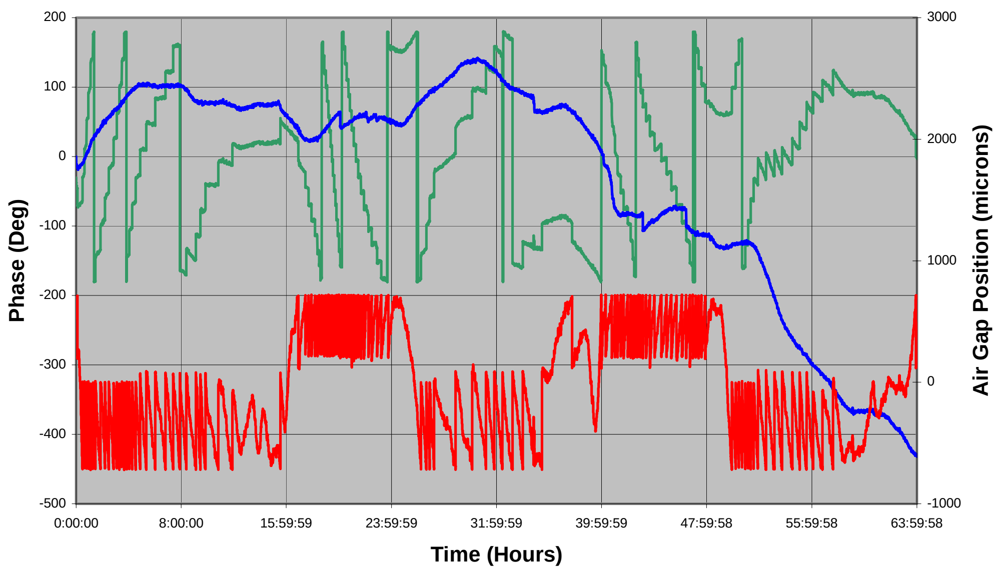


Figure 5 - 25 GHz, 10 km test of round trip phase correction. Green trace is uncorrected phase, Blue trace is corrected phase, Red trace is air gap correction position.

4.3.5 Fiber phase: no round trip correction; 25 GHz, 10 km of fiber.

In this test the round trip phase correction was turned off. In Figure 6, the blue trace shows the phase comparison at 25 GHz between either end of the fiber, and the green trace is the temperature measured in close proximity to the 10 km spool of fiber. It can easily be seen that there is good correlation between the phase difference and the temperature. Using the peak excursions between 12 and 24 hours, there are 3530 degrees of phase change per degree K. This total phase change at 25 GHz is equivalent to 118 mm, so the effective temperature coefficient of the spooled fiber is 11.8 ppm per degree C. This is quite close to but slightly higher than has been measured for single mode fiber by other groups [1-3], but there may be some additional effect due to the spooling of the fiber that explains the discrepancy. The same setup was used but the 10 km spool was replaced by a short fiber patchcord to see if there was any instrumental bias to the measurement. The phase drift of the measuring instrument in this case was 160 microns per degree C. This indicates that at least for the previous plots shown in Figure 1-5, the drift of the measuring instrument is small compared to the phase drift being measured. However, the drift of the measuring instrument is still large in terms of the overall ALMA phase drift specification. This is a concern because many of the components used in this test will be similar to the ones that we plan to use for ALMA. Thus, in future tests, we plan to take greater care by carefully temperature control on the measuring instrument.

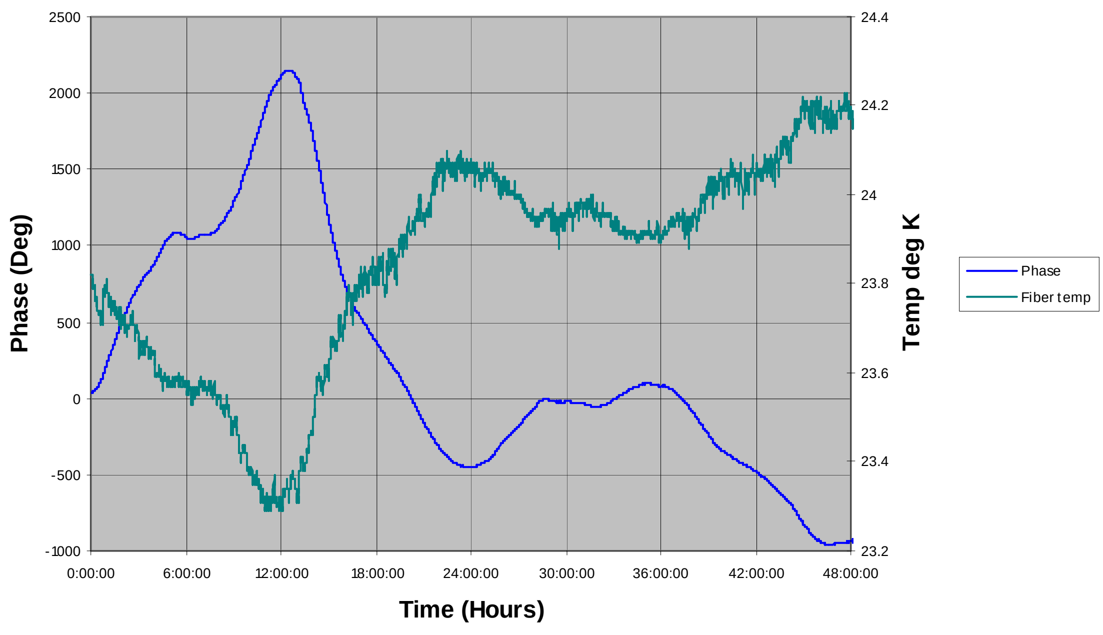


Figure 6 - 25 GHz, 10 km test without active phase correction

5 Conclusion

The ALMA Round Trip Phase Correction System has been described. This is the baseline system which has been chosen to meet the extremely challenging ALMA Phase Drift Specifications. It has been noted that the ALMA specifications are more ambitious than any known system that has been built to-date for phase transfer by fiber. Measurement results have been presented that show that although the phase correction can be achieved on an optical fringe, the stability of the best available master laser obscures whether or not the technique will work. Further testing is necessary using a more stable master laser.

6 References

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