ALMA Memo #507

ALMA First LO Reference : Elimination of Large Phase Fluctuations due to lightwave polarization effects

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1. Abstract

The ALMA 1st LO reference is sent from the central Array Operations Site Technical Building to each of 64 antennas over optical fiber. Two high-coherence and phase-locked lightwaves are transmitted that are separated by a variable frequency ranging from 27-142 GHz. The round-trip stabilized fiber optic distribution system has been previously described in this memo series [1-3,13].

In August of 2003, a first generation version of the line length correction system was tested on a prototype ALMA antenna. These were the first systematic measurements of the system on the moving structure. During these measurements we noticed an undesirable and unexpected phase fluctuation which was correlated with the antenna azimuth and elevation position. Those tests are described in an internal test report [4]. Further tests and meetings took place in an effort to resolve this issue [5-8]. In addition, an ALMA memo was written describing a theoretical treatment of the measured phase fluctuation [9], supporting the measurement results which showed that the phase fluctuation was due to the *absolute* polarization change (caused by the fiber movement) of the two lightwaves, and that the phase fluctuation magnitude was inversely proportional to the degree of polarization alignment of the two lightwaves. To put it another way, if the state-of-polarizations (SOPs) of the two lightwaves were different at the receiver end, then any movement of the fiber would cause a phase change.

The purpose of this memo is to summarize the main points from the references listed above, and additionally to describe more recent measurements that utilize improvements to the 1st LO reference baseline design. This is mainly an experimental report, there is a related theoretical study as well [14].

2. Review of Previous Work

The ATF (ALMA Antenna Test Facility) tests were conducted on the US prototype antenna. The test results are fully documented, including detailed schematics of the experimental setup and apparatus [4]. The most significant result was that there was a spurious RF phase fluctuation that appeared to be due to the position of the fiber mounted on the antenna. The antenna was at various times moved in azimuth and elevation, and the phase fluctuations were repeatable and position dependent. The test setup that was used for these tests is shown in Fig. 1. A plot of the phase fluctuation versus antenna azimuth position is shown in Fig. 2.

The fluctuation occurred whether the line length corrector was operating or not operating. The phase and amplitude vary in a way that is strongly but imperfectly correlated. The amplitude variation was expected and is due in large part to the

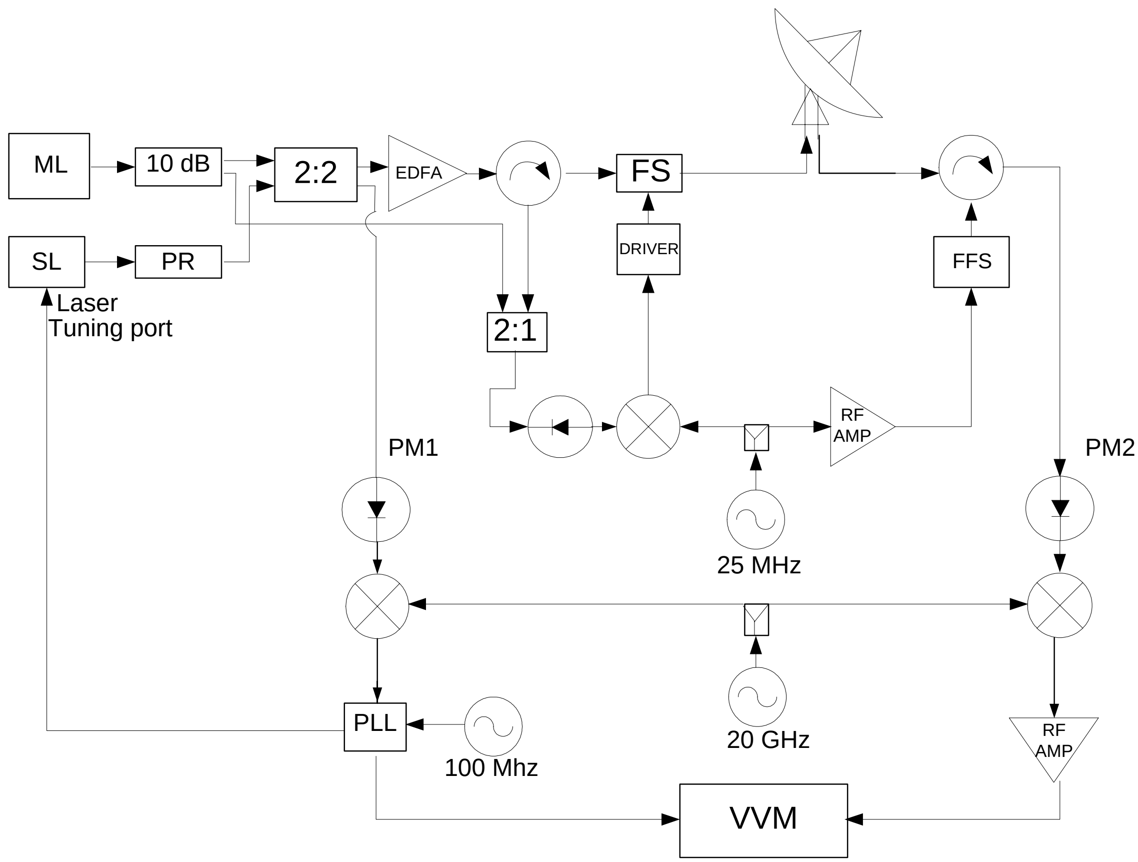

Figure 1: Line length correction previous test setup – Note that the antenna cable wraps are traversed twice.

polarization sensitivity of the photomixer responsitivity. Phase variation was expected with the correction OFF just due to the effective fiber length change, but that type of phase error should be small and correctable. This phase variation was not corrected by the line-length correction system. There were similar phase variations when the antenna was moved in elevation. Many tests were conducted, with various levels of phase change. Roughly speaking, the measurement showed 10-37 degrees of phase change at the 20 GHz measurement frequency for large scale movements of the antenna in azimuth or elevation.

Further measurements in the lab confirmed the following:

1. The effect measured on the antennas was repeatable in the lab.
2. The effect was well correlated with polarization changes in the fiber.
3. The effect was worse the more misaligned the two lightwave SOPs became.
4. The polarization misalignment could take place in the buried fiber sections or in the moving fiber sections.

The effect of the polarization alignment was included in the test reports [4-7] written during this time, but it was not realized that the optical circulators were the largest contributor to the polarization misalignment.

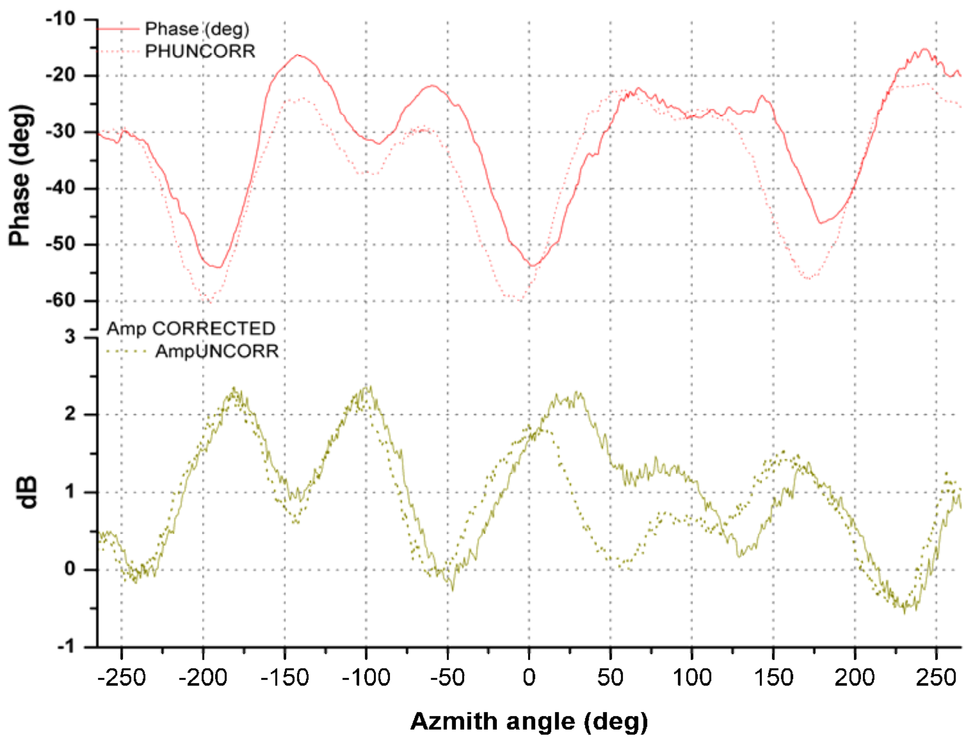

Figure 2 - Phase fluctuation of the 20 GHz beatnote versus azimuth position (red trace–top). The solid line is with the line length correction ON and the dashed line is with the correction OFF. The phase artifact is not affected by the correction, and has some correlation with the variation of the beatnote amplitude (bottom trace).

3. Effect of Optical Circulators

The test setup shown in Fig. 3 was used to measure the State-of-Polarization dispersion (SOPD) of the optical circulator that we had been using in our tests. A tunable laser feeds a polarization rotator and a free-space polarizer, which then goes to the circulator. A polarimeter measures the SOP of the transmitted light. By sweeping the laser wavelength, we can discern the effect of the circulator on the transmitted SOP as a function of wavelength. Also, by rotating the free-space polarizer, we were able to test this effect as a function of the input polarization.

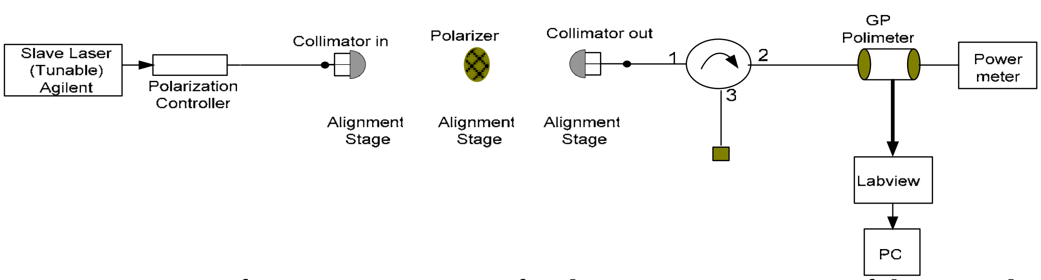

Figure 3: Test setup for measuring State-of-Polarization-Dispersion of the optical circulator

The test result is shown in Fig. 4. The polarimeter measures the Stokes parameters (s0, s1, s2, s3) – which completely specify the total power (s0) and arbitrary general elliptical polarization of the lightwave (s1,s2,s3). For this measurement, the wavelength was swept from 1549.1 to 1550.5 nm. This range exceeds the maximum separation of the two laser comprising the LO reference beatnote (142 GHz is approximately 1.2 nm wavelength separation at 1550 nm). The following parameter is plotted:

$$S_T(\lambda)=\sqrt{\left(s_1(\lambda)-s_1(\lambda_0)\right)^2+\left(s_2(\lambda)-s_2(\lambda_0)\right)^2+\left(s_3(\lambda)-s_3(\lambda_0)\right)^2} \quad (1)$$

which is the root sum of squares of the difference between the measured Stokes parameters and the initial value of the Stokes parameters. Each of the Stokes parameters can vary from {-1..1} so the S_T parameter can range from zero to two. Zero corresponds to a match of the initial polarization, and two corresponds to the point at which the polarization has become completely orthogonal to the initial polarization (maximum SOPD). From the figure it is clearly seen that, depending on the input SOP, the output SOP can become nearly completely orthogonal over a wavelength range of only 0.7 nm, which corresponds to about 88 GHz. Thus, the two-lightwave beatnote could enter the device in perfect polarization alignment, and leave it with completely orthogonal polarizations. For our measurements which were done at 20 GHz the effect was somewhat smaller than this but nevertheless caused very significant polarization misalignment.

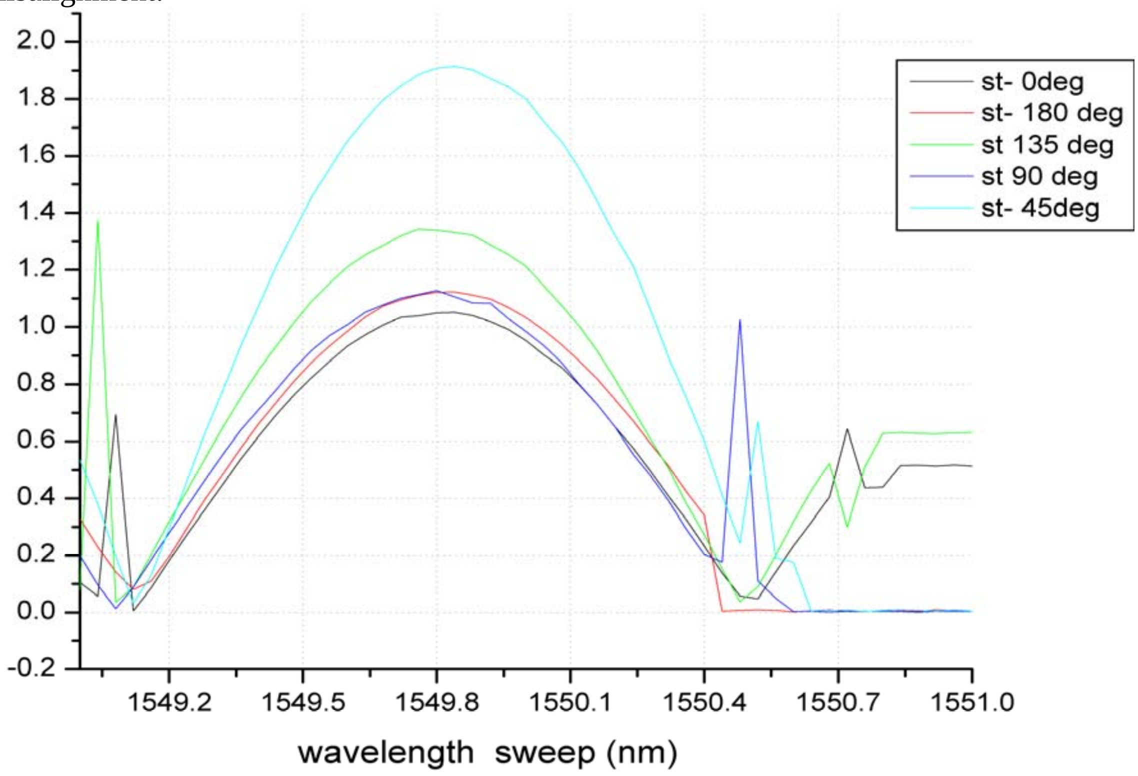

Figure 4: Test Result of State-of-Polarization-Dispersion of Optical Circulator. The vertical axis is S_T (see Eq(1) above). Each trace corresponds to a specific input polarization angle as shown in the key. Peaks and jumps occurring outside the 1549.1-1550.4 range are artifacts of the data acquisition and should be ignored.

The reason for the high SOPD of the optical circulator is made clear by examination of the principle behind the operation of a polarization-independent optical circulator. Fig. 5 below shows a sketch from US Patent #4,650,289 "Optical Circulator – Polarization Independent Input Type" Mar 17, 1987. Light entering Port A is split at polarizing beamsplitter P1, and in both paths undergoes two 45 degree rotations via a Faraday Rotator (FR) and a birefringent wave plate (OA). The light recombines and goes to port B. Light entering port B is similarly split, but on the return path the Faraday rotation and the birefringent rotation are in opposite directions (Faraday rotation is non-reciprocal). Thus the polarizations are unaffected on the return path and light is transmitted from port B to port C. That is how the optical isolation is achieved, and closer examination is require to see why Sate-of-Polarization Dispersion occurs. Assume that the input light at port A is linear and splits in equal amounts to the two split paths. At port B the light is recombined. If the two paths have a path difference of a quarter-wave, then the light at port B will be circularly polarized instead of linearly polarized. So the beam path difference causes a polarization change, and this change must clearly be wavelength dependent. The response is different when the input polarization is varied because as the split ratio becomes more unequal, there is less effect due to the beam path difference. In fact, if the light were polarized so that 100% of the light went on one path, the SOPD from this effect should be zero. However, with 1-m fiber pigtails, the light incident on the first beamsplitter is likely to be elliptically polarized and it is not surprising therefore that we did not find a polarization angle at which the effect went close to zero.

What amount of beam path difference would cause the amount of SOPD that we have measured? If complete orthogonality occurs when the beam path difference changes form one wavelength to another by a half-wave, then the formula is:

$$\Delta L = \frac{1}{2} * \left[\frac{\lambda_1 * \lambda_2}{\lambda_2 - \lambda_1} \right] \quad (2).$$

We measured orthogonal polarization at difference of 0.7 nm, so that yields ΔL =1.7mm, or about 5.6 psec. This is equivalent to the PMD of the device, and represents a very high value. It is necessary to use devices with much lower PMD to eliminate the undesired phase shift effect that we have measured.

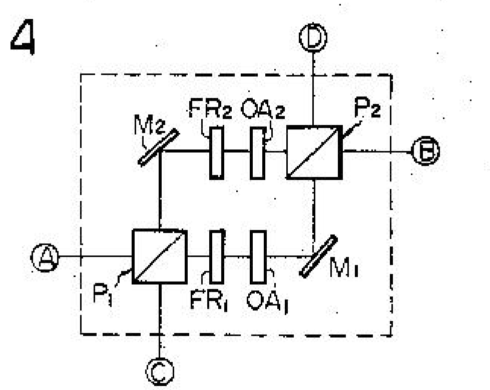

Figure 5 - US Patent #4,650,289 "Optical Circulator – Polarization Independent Input Type" Mar 17, 1987

Measurement of the Phase Fluctuation with Polarizations Aligned and Optical Circulators Removed

The fiber optic circulators were in the system to facilitate the return of the round-trip signal and to diplex the outgoing and returning lightwaves. The large phase fluctuations that we had been observing were present whether the line correction system was operating or not. However, in both cases we used the same test setup incorporating the circulators, simply because it was built into our test apparatus. Therefore, when the effect of the optical circulators was realized, we designed the following test to measure the phase fluctuation without the circulators present. The test incorporates a polarizer at the beginning of the transmission, and light travels as before through a moving fiber section. The rest of the setup is similar to what is described in the test reports [4,6], with a 20 GHz phase-locked beatnote detected before and after transmission, then downconverted and phase compared in a vector voltmeter, see Fig. 6. The polarizer guarantees alignment of the two lightwaves going into the moving section of fiber.

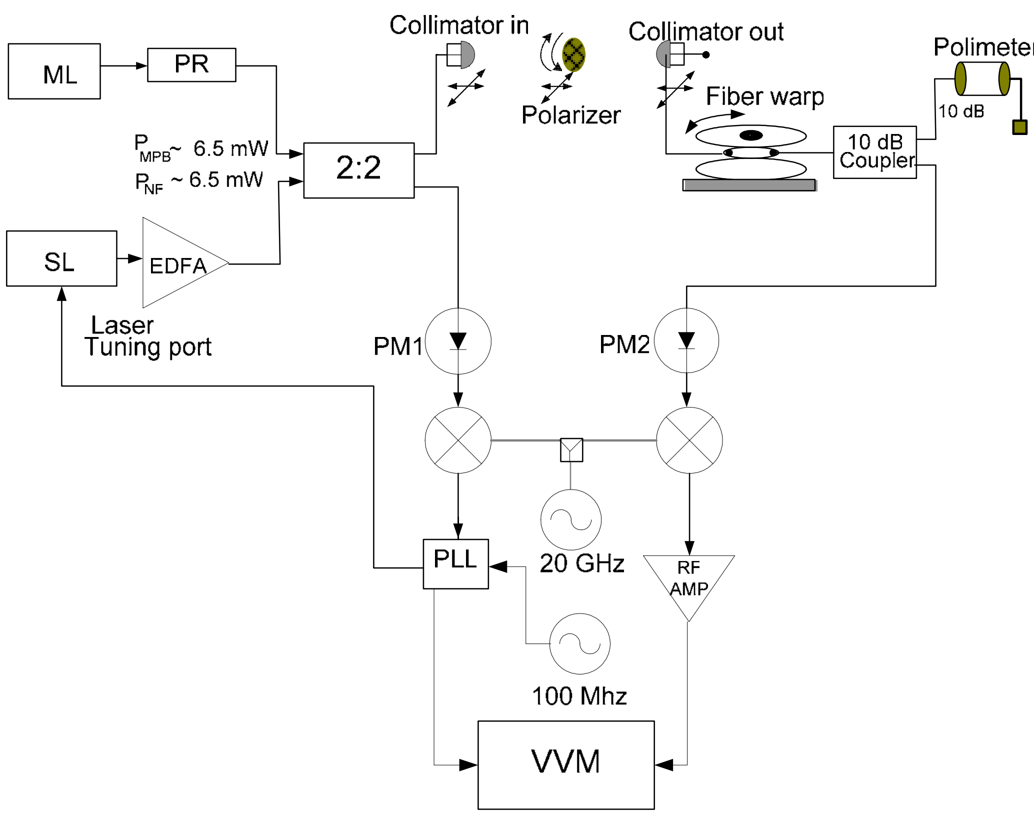

Figure 6 - Test setup for measurement of phase fluctuation due to fiber movement, using two lightwaves with polarization alignment enforced by use of a free-space polarizer. There are no circulators in the receiving system.

The result of this test is shown in Fig. 7. The test shows the phase before, during, and after the movement of the fiber drum through a 300 degree rotation. The movement is then repeated in the reverse direction. The phase fluctuation is now very small, in fact it is difficult to say if there is any fluctuation at all. The RMS phase fluctuation of about 0.4 deg (16 microns or 80 fsec) that is systematic obscures any smaller effects. On the other hand, there is clearly a polarization change that is associated with the movement of the wrap.

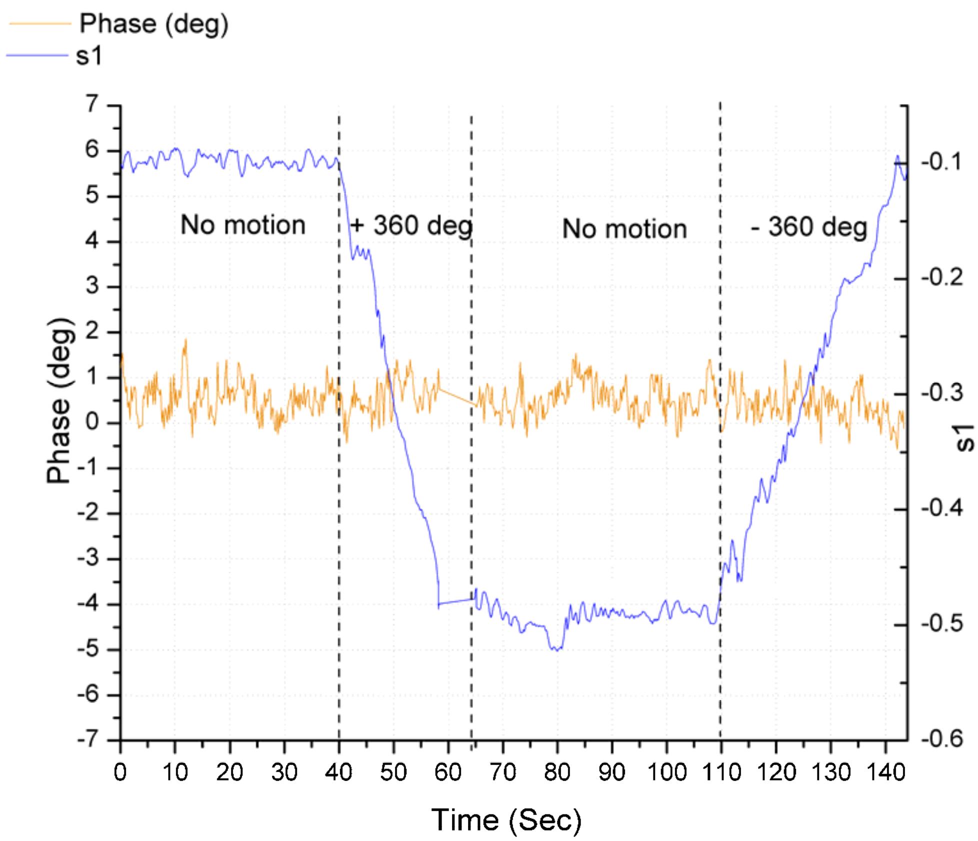

Figure 7: Results of test setup Figure #6 The phase fluctuation resulted by moving the fiber by +360 azimuth rotation and back by -360 deg while recording the change in the polarization due to the fiber move. The Master and slave lasers are fully aligned in this test results.

Ideally, this test would be repeated by adding a fiber spool in series with and before the moving section of fiber. However, without the line correction system in place, the phase changes too quickly due to the thermal drift of the spool, and any change taking place in the phase due to the moving fiber is obscured. However, we expect the long fiber preceding the moving section will cause the two lightwave polarizations to become misaligned (by introducing SOPD, smaller than the circulator but still potentially significant). This, when coupled with the polarization change induced by the moving section, might be enough to cause a significant phase change.

To determine the level of polarization misalignment that might be expected from the buried fiber, we ran a series of tests on the buried fiber installation at the VLA site [10]. The reference contains a lot of data and experimental description that will not be fully covered here. In principle, however, the measurement was similar to the test of the SOPD of the circulator as shown in Figure 3. The circulator is in this case replaced by a length of buried fiber (either 29 km or 58 km -determined by what was available to measure at the site). Unlike the circulator measurement, in this case we did not have a means of orienting the input polarization. The test setup for this experiment is shown in Figure 8. For purposes of comparison, the test was also conducted using a 30 km spool of fiber.

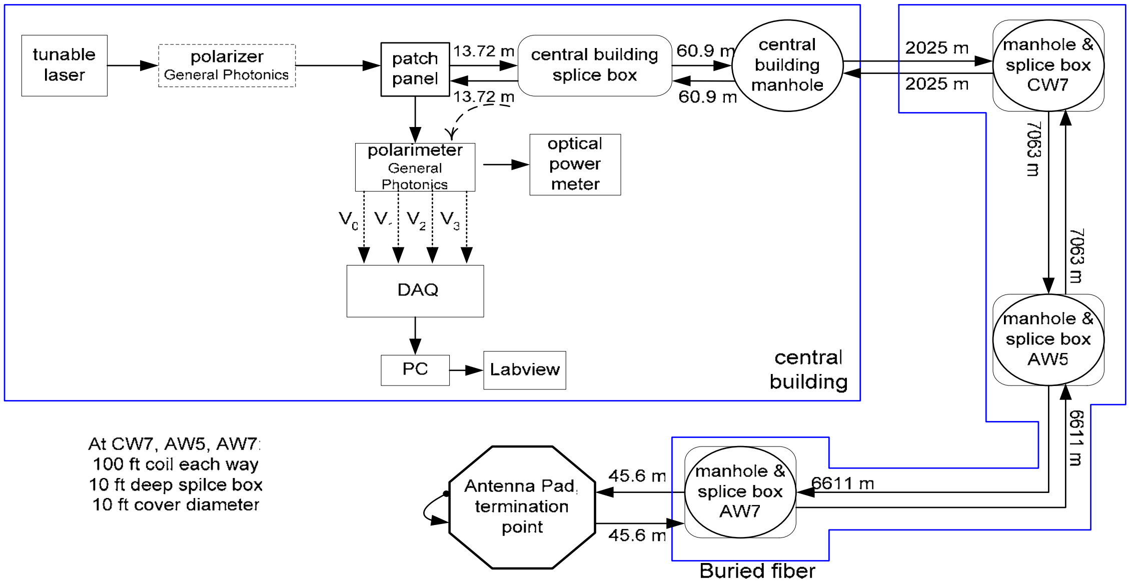

Figure 8: Test setup for measuring the variation of the polarization of the laser light traveling through the buried fiber cable of the EVLA site while scanning the wavelength of a tunable laser source

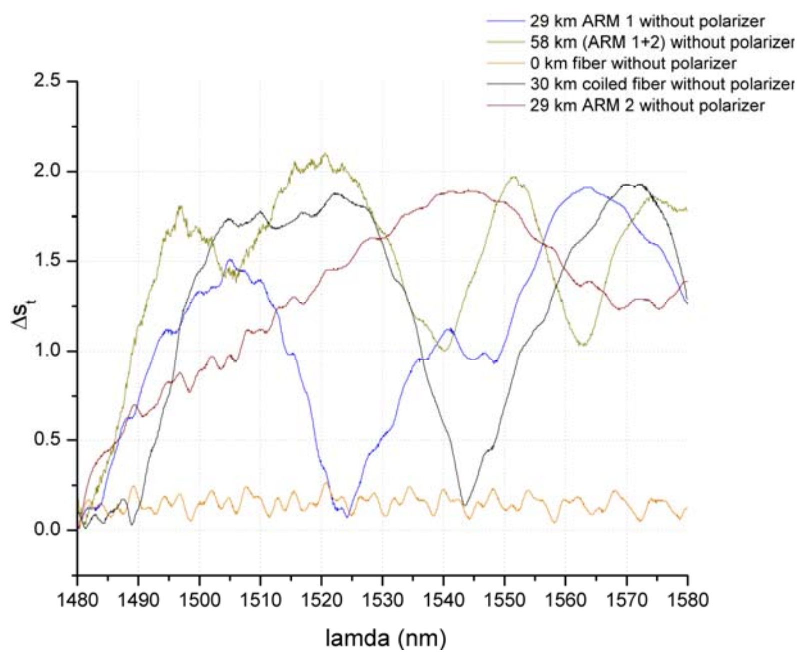

Figure 9: Relative polarization change (from initial value) for various fibers-under-test as wavelength is scanned from 1480 to 1580 nm. The vertical axis is S_T -see Eq(1).

The data in Fig. 9 show that there is a large variation between the various samples, even the two 29 km sections that were in the same fiber cable. The fiber spool variation was not markedly greater or smaller than the buried fiber sections of similar length. The bottom curve shows the polarization variation of a length of fiber that was just the sum of the pigtail lengths from the laser to the polarimeter, about 2-m. The periodicity of several cycles of variation every 10 nm is partly due to the polarimeter and partly due to the laser source. The wavelength was scanned from 1480 to 1580 nm. The SOPD is represented again by the S_T parameter as defined in Eq. 1. The SOPD range is as before from zero to two, with two representing orthogonality from the output SOP at 1480 nm.

Although the polarization variation can be quite large, it is not so large over the ALMA 1st LO reference maximum frequency of 142 GHz or 1.2 nm in wavelength separation. The maximum possible SOPD between two wavelengths separated by 1.2 nm is what we are interested in. To get this, the data is re-plotted in Fig. 10, but instead of having the S_T parameter normalized to the initial output SOP as before, it is instead normalized to the output SOP of the wavelength that is 1.2 nm preceding it. This is described as follows:

$$S_T(\lambda) = \sqrt{\left(s_1(\lambda) - s_1(\lambda - 1.2nm)\right)^2 + \left(s_2(\lambda) - s_2(\lambda - 1.2nm)\right)^2 + \left(s_3(\lambda) - s_3(\lambda - 1.2nm)\right)^2} \quad (3)$$

The plot of the SOPD as defined by Eq. 3 is shown in Fig. 10. The maximum value of the S_T parameter is 0.3 for the 29 km sections and about 0.37 for the 58 km measurement. Since the maximum fiber length for ALMA is about 18 km, it is reasonable to assume that the ALMA SOPD will be no greater than 0.3.

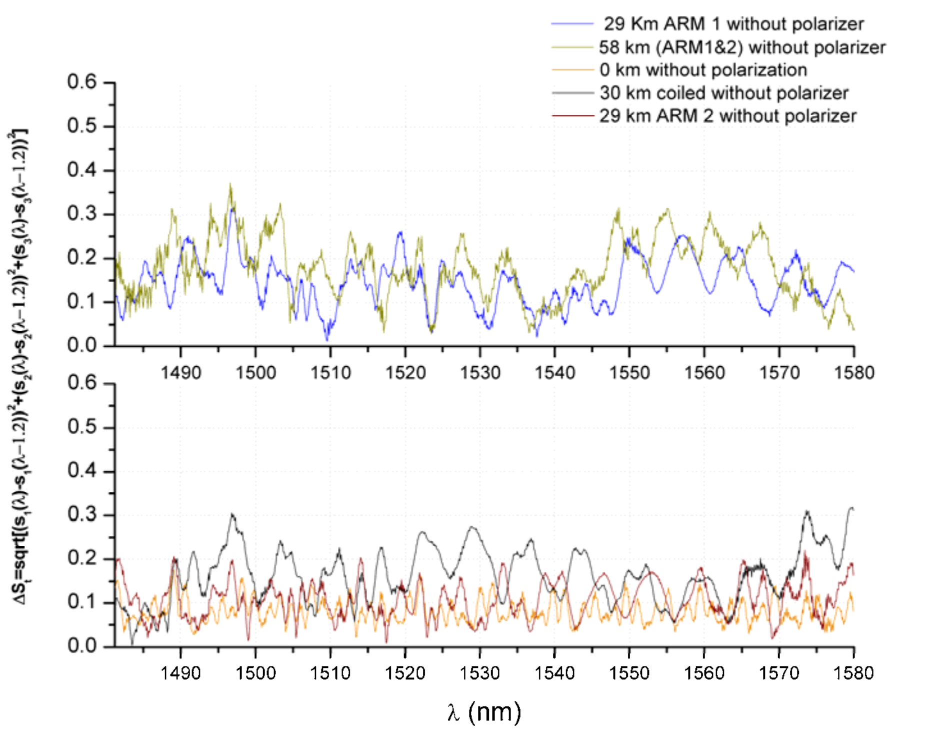

Figure 10 : The 1.2nm-variation in S_T (as described by Eq3). The S_T parameter is normalized to the output SOP of the wavelength that is 1.2 nm preceding it

Measurement of the Phase Fluctuation with Polarizations Misaligned by the maximum amount expected to be introduced by the Buried Fiber Section

The test setup shown in Fig. 6 was again used, but with the polarizer removed. This time, the polarizations were intentionally misaligned by measuring the polarization of the master and slave laser in turn with the polarimeter after the moving section of fiber. The polarization rotator following the master laser was adjusted so that a polarization difference of S_T equal to 0.2 was setup. Then the measurement proceeded in the same way as before. The result is shown in Fig. 11.

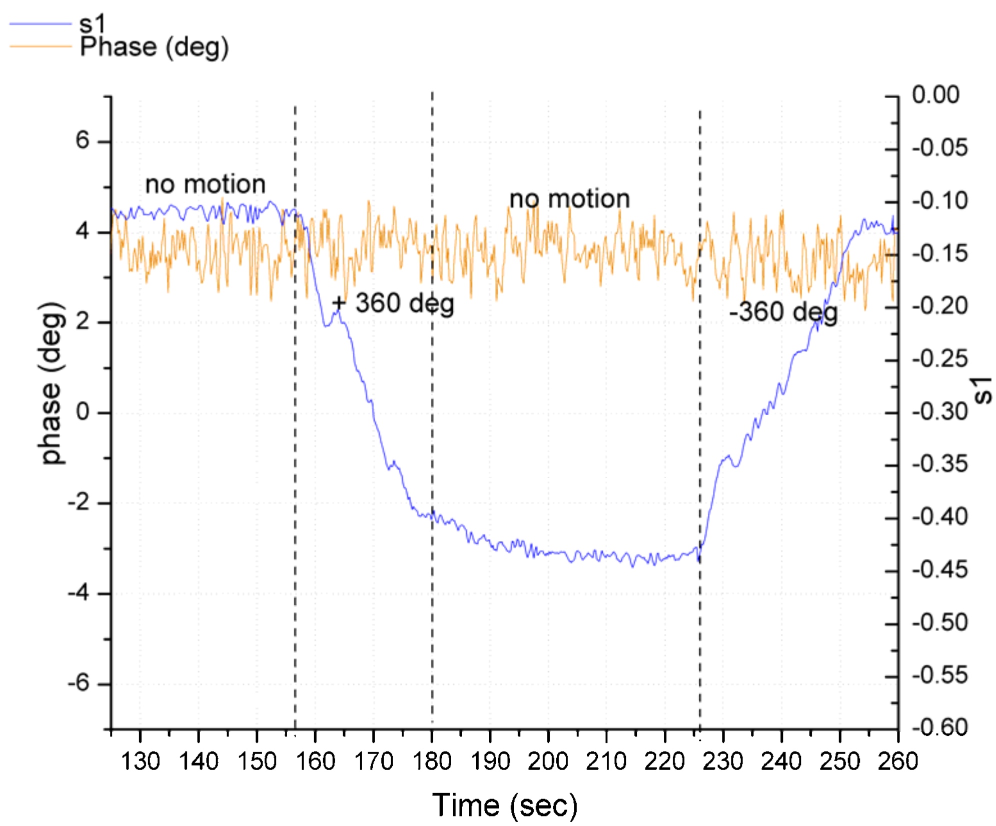

Figure 11 - Results of test setup Figure #6 (with the polarizer is removed & the Master and slave are misaligned by St= 0.2) .The phase fluctuation resulted by moving the fiber by +360 azimuth rotation and back by -360

Note that there is no discernible phase change. One of the Stokes parameters is plotted to show that the 360 degree motion of the fiber wrap is causing a large change in polarization but not in the recovered phase. The resolution of this measurement is again about 80 fsec. The conclusion to this point in the testing program is that:
A measurement system that does not incorporate optical circulators, and which contains a polarization misalignment corresponding to the worst expected behavior of the buried fiber was tested. The result was that the phase change versus wrap motion was too small to measure even for a large 360 degree rotation of the wrap.

4. 1st LO Reference: Faraday Mirror Implementation

The test results described to this point have indicated satisfactory performance, if not to the ALMA spec level, at least down to the level that we could measure, without optical circulators. The next step was to realize a system implementation that did not use these devices. The return of the master laser signal has to be done in such a way that there is a high immunity to reflections. This can be done by using a Faraday Mirror at the far end of the fiber to reflect the light in the orthogonal polarization [11]. In this way, the polarization is still free to vary along the fiber but the reflected light is orthogonal to the transmitted light at every point in the fiber. The outgoing and returning light can then be diplexed by using a polarization beamsplitter at the near end of the fiber. This results in a system that has less SOPD and thus less possibility of phase change due to fiber motion.

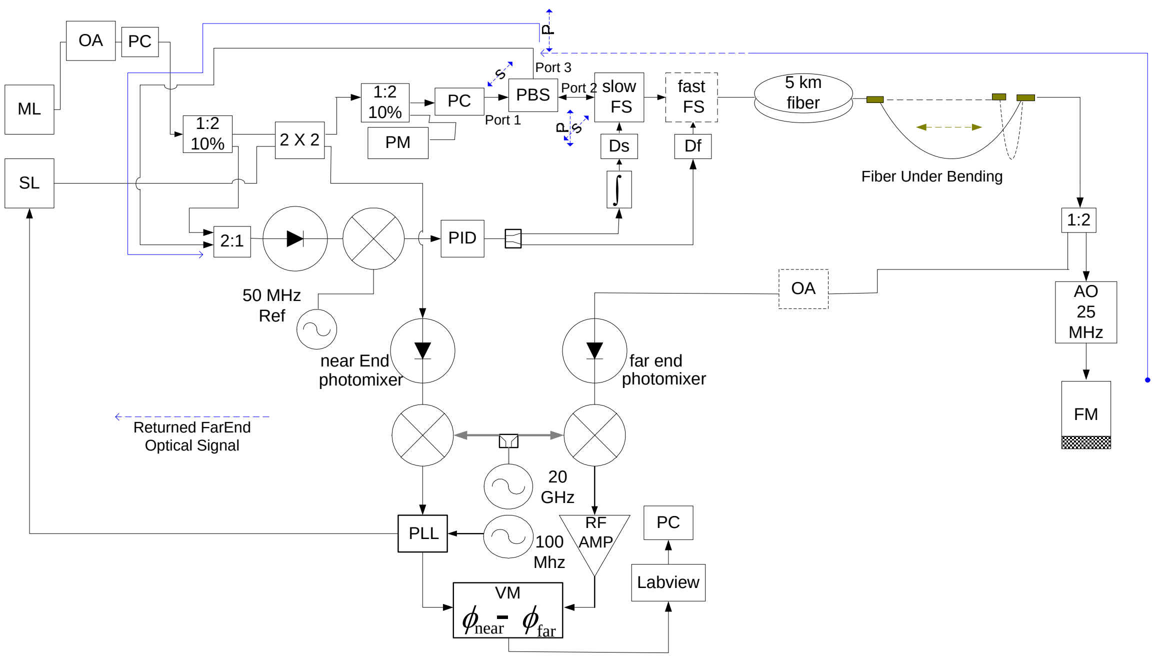

Figure 12 - Farady Mirror test setup for the line length correction system without the use of an optical circulator. Instead we used the combination of PBS and faraday mirror to rout the light signal back to the near end as shown in the blue line

As shown in Fig. 12, the two lightwaves are phase-locked at the first 2x2 fiber coupler, by means of a "Near-End" photomixer generating the 20 GHz beatnote. This beatnote is offset locked by two RF references at 19.9 GHz and 100 MHz An Optical Amplifier was used just after the Master Laser to provide a decent signal-to-noise for the measurement, but it also will contribute uncorrected phase drift to the measurement. The magnitude of this phase drift has not been studied but for ALMA a special low-phase drift optical amplifier will be used. After the optical amplifier, there is a polarization rotator (PC) used for aligning the polarization of the master laser to the slave laser. This test used a cascade of two commercially available piezo fiber stretchers. The first had a stroke of about 25 microns and bandwidth of 1 kHz, and the second had a stroke of 5 mm and a bandwidth of a few Hz, with a driver voltage range of 20 V. A second PC is used to align the two lasers to the correct orientation at the input of the polarization beamsplitter(PBS). The PBS serves the same function as the optical circulators used in our previous work: the outgoing light passes through the assembly and the returning (round-trip) light is reflected to the third port. The output light from port 3 then passes through the fiber stretcher assembly and a 5 km fiber spool and an assembly that simulates simple movements of the fiber. (At the “far-end” there is a 3-dB coupler, so that half of the light goes to the turnaround assembly and half goes to the far-end photomixer. The turnaround assembly consists of the fiber-frequency shifter and a faraday-rotating mirror. The fiber-frequency-shifter contains an acousto-optic cell, and the light receives twice the frequency shift in this type of reciprocal arrangement [11]. The far-end photomixer phase is measured against the near-end phase by means of an offset mixer and a vector voltmeter, as in the earlier measurements shown in Fig. 1 and Fig. 2. All of the RF references are locked to the same 10 MHZ instrument reference. The dotted box around the optical amplifier (OA) in the setup indicates that we have done some of the measurement with an optical amplifier at the “far end.” The need for an optical amplifier at the far end is likely in the ALMA so that the optical power budget can be met. The main issue that we need to examine is how much phase drift does an optical amplifier add to the overall phase variation since the OA is located outside the optical phase correction path.

5. Test results of Faraday Mirror Implementation Baseline test

A baseline test was first conducted in which a 1-m length of fiber was used instead of the spool of fiber and the section of bended fiber. As indicated in Fig. 13, the orange line represents the difference in phase of the 20 GHz beatnote, and the brown line represents the slow stretcher control voltage that is driving the stretcher to compensate for the change taken place by the length of the fiber under test. The test was run for 1-hr while the correction is on and 27 min while the correction is off. In this test we wanted to get the maximum resolution in phase drift that the test setup could provide. From Fig. 13, the calculated RMS phase drift was 0.53 deg at 20 GHz which corresponds to 74 fsec with the correction on, but the maximum p-p variation is 1.55 deg which corresponds to 215 fs at 20 GHz. The maximum drift in the phase with the correction OFF was 7.5 deg over 27 min.

Test of length correction under condition: no fiber movement

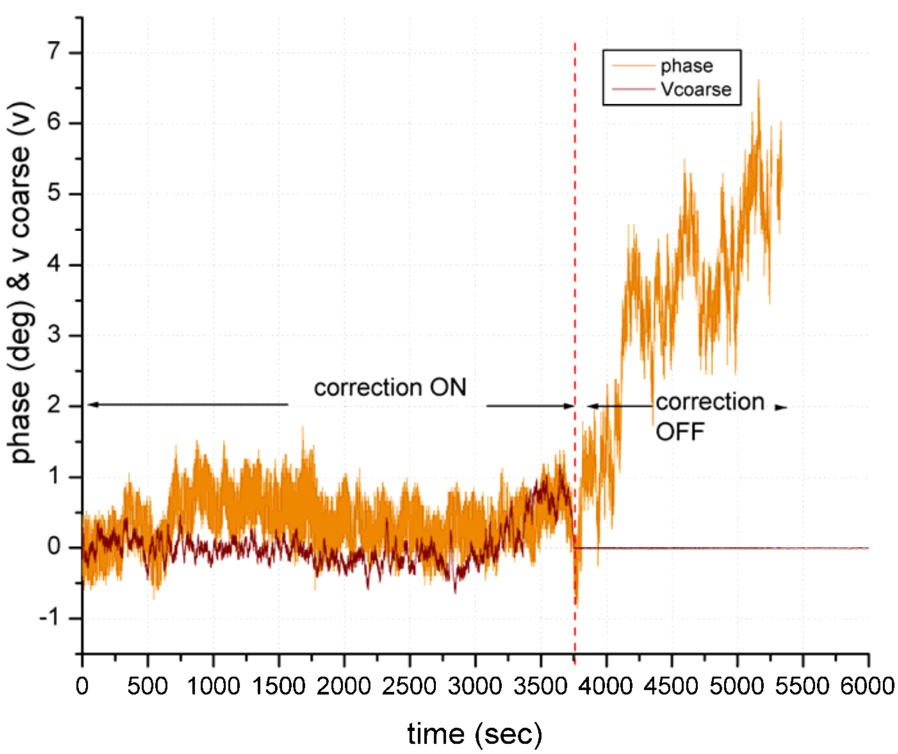

Figure 13: Plot of phase drift for a baseline test in which 1-m of fiber is inserted between the stretcher and the far end without using an OA at the far-end (Fig. 12).

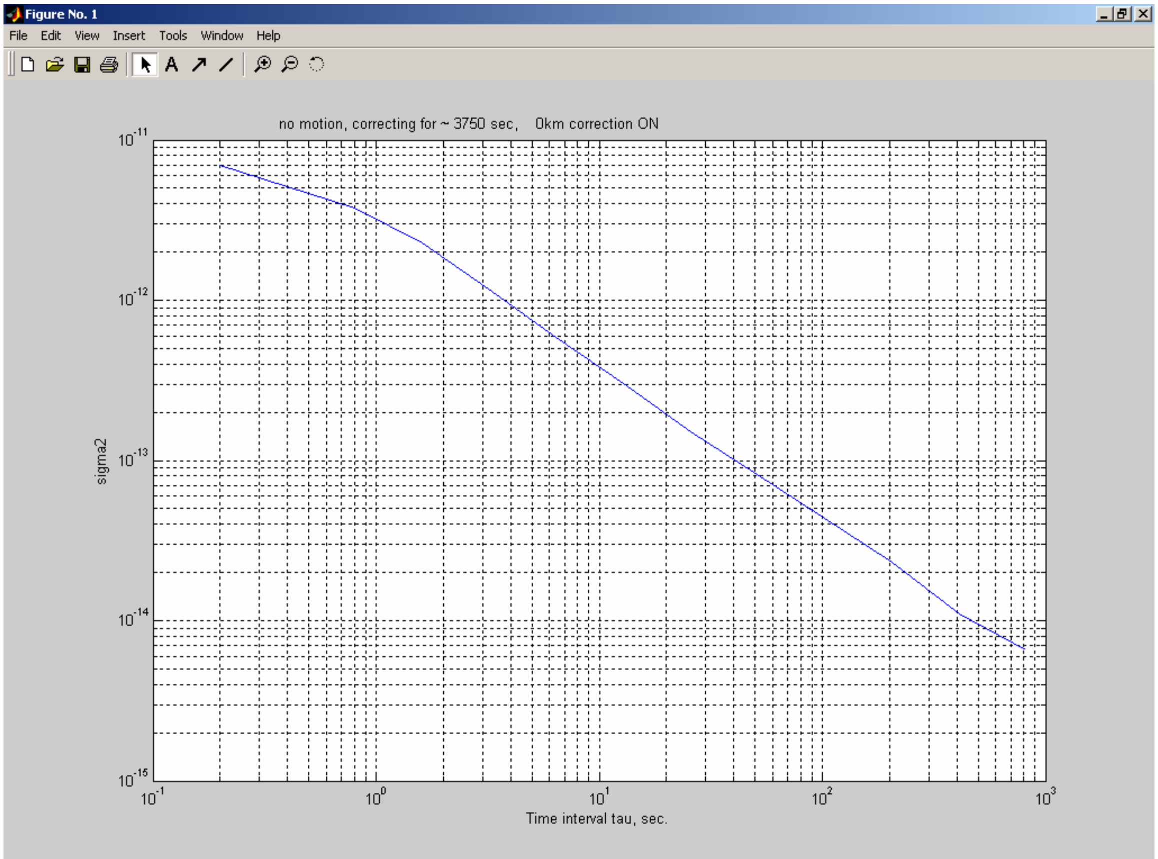

Figure 14: The measurement of the Allan variance of the phase in figure 13 (1m fiber length), for a reference frequency of 20 GHz and sampling time of 0.2 sec.

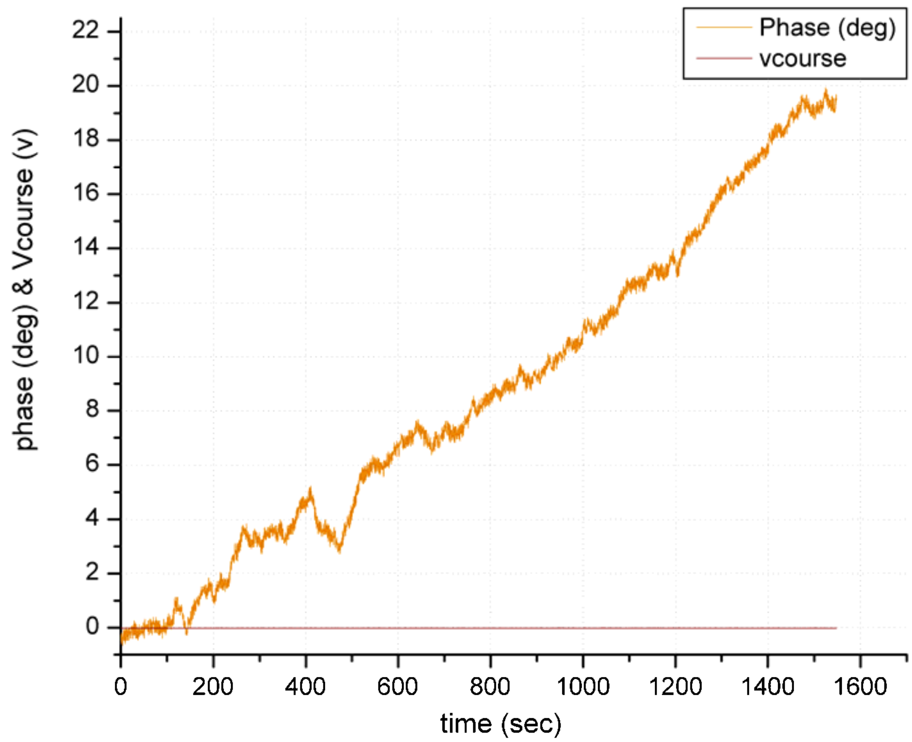

Figure 15: Test of the phase incurred on 5 km of fiber at 20 GHz with the correction system off and no movement of the fiber.

Fig. 15 shows the 20 GHz phase difference for a 5 km length of fiber under the condition that the fiber is not moving. This figure clearly shows the phase drift in the 20 GHz phase due to the fiber length change mainly due to temperature effect on the 5 km of fiber. The slope is ~ 0.77 deg phase/sec which equates with phase change of 0.032mm/sec. Assuming a Coefficient of Thermal Expansion of 10^{-5} for the fiber, this implies an average temperature change of 0.2 deg/min during the measurement.

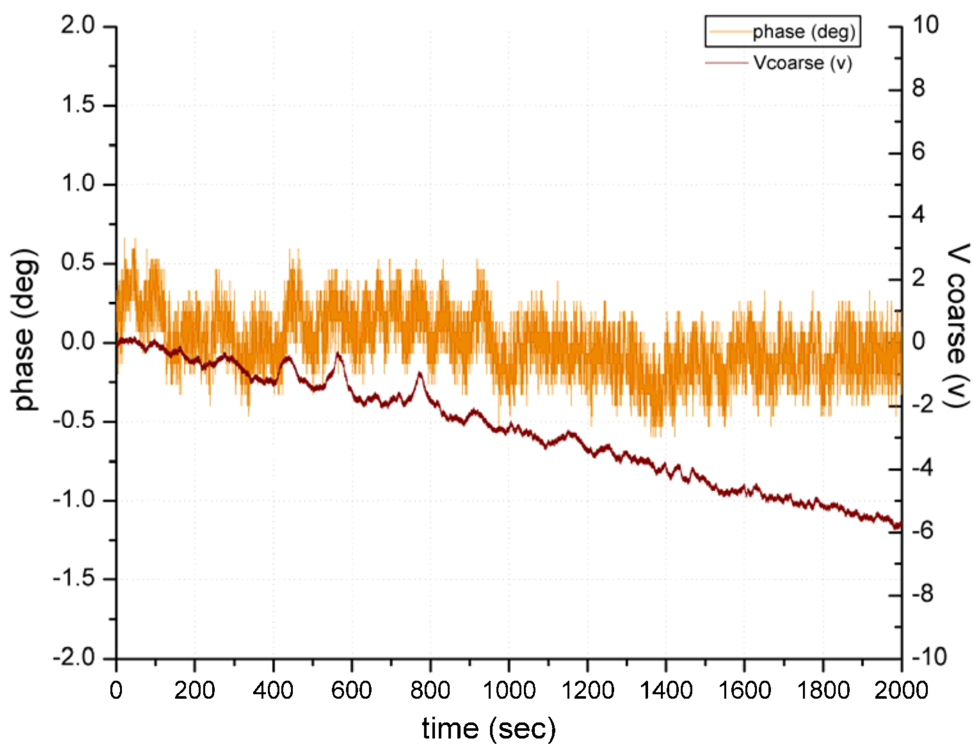

Figure 16: Test of the phase incurred on 5 km of fiber at 20 GHz with the correction system on and no movement of the fiber.

In Fig. 16, the phase of the 20Ghz was measured for 2000 sec while the correction is on , The residual RMS phase in this case is 0.241 degrees (33.4fs). The peak to peak phase drift for the 2000 sec time was~ 1.4deg which corresponds to 194 fs. The coarse voltage changed by ~ 6.6 volts which is equivalent to 1.009~ 1 mm of fiber stretch.

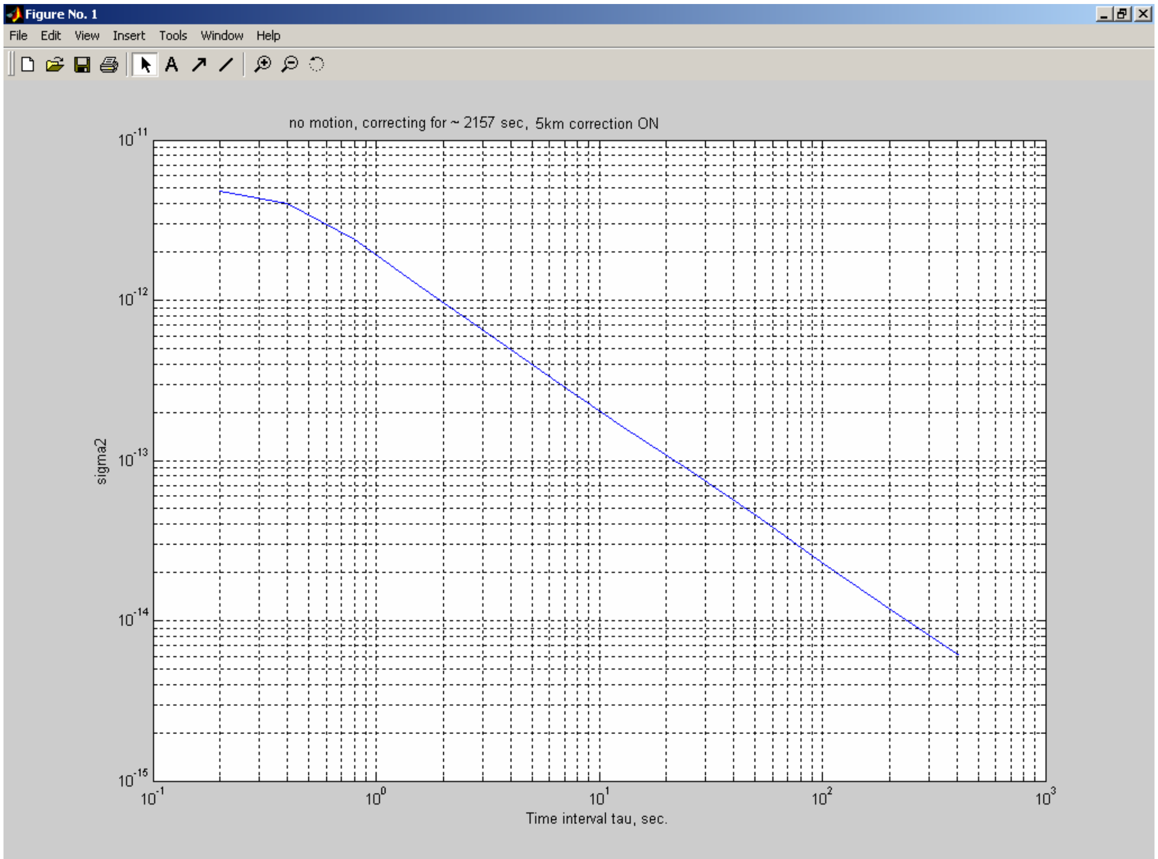

Figure 17: the measurement of the Allan variance of the phase in figure 16(5 km fiber length) , for a reference frequency of 20 GHz and sampling time of 0.2 sec.

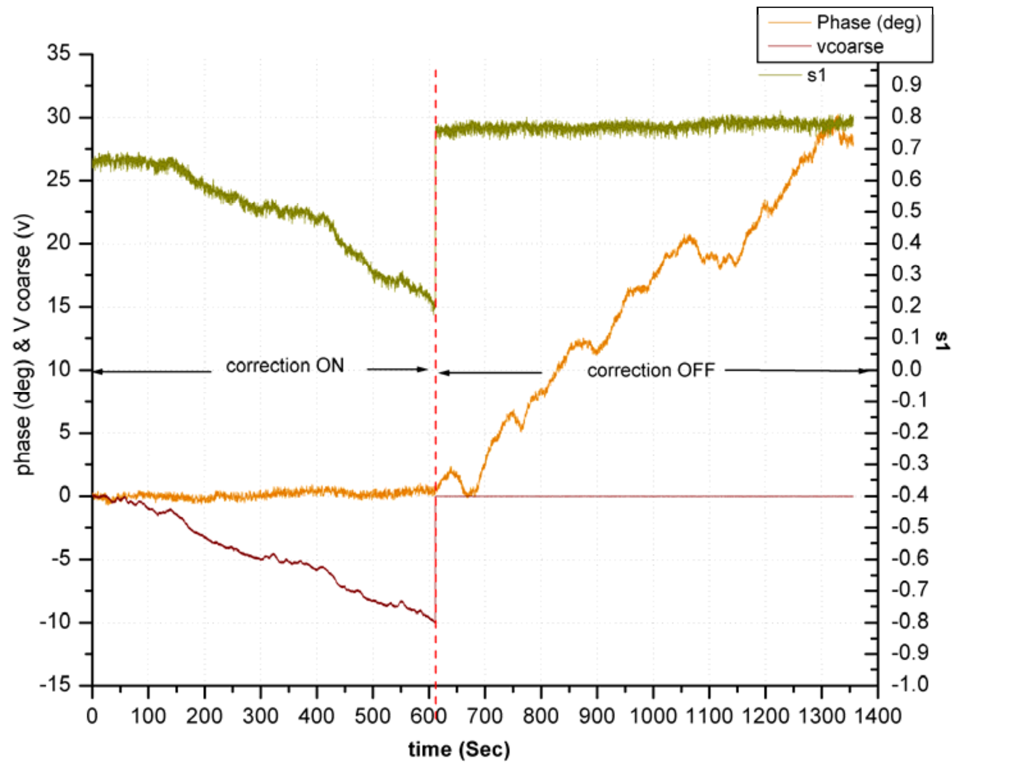

Figure 18: Test of the phase incurred on 10 km of fiber at 20 GHz with the correction system on and off (no movement of the fiber).

In Fig. 18 the test repeated for a 10 km length of fiber, with the correction on for 600 sec and OFF for 700sec. The green line represents one of the polarization Stoke's parameters (s1) which shows the polarization change in the fiber. A zoomed view of the part with the correction "on" is illustrated in Figure 19.

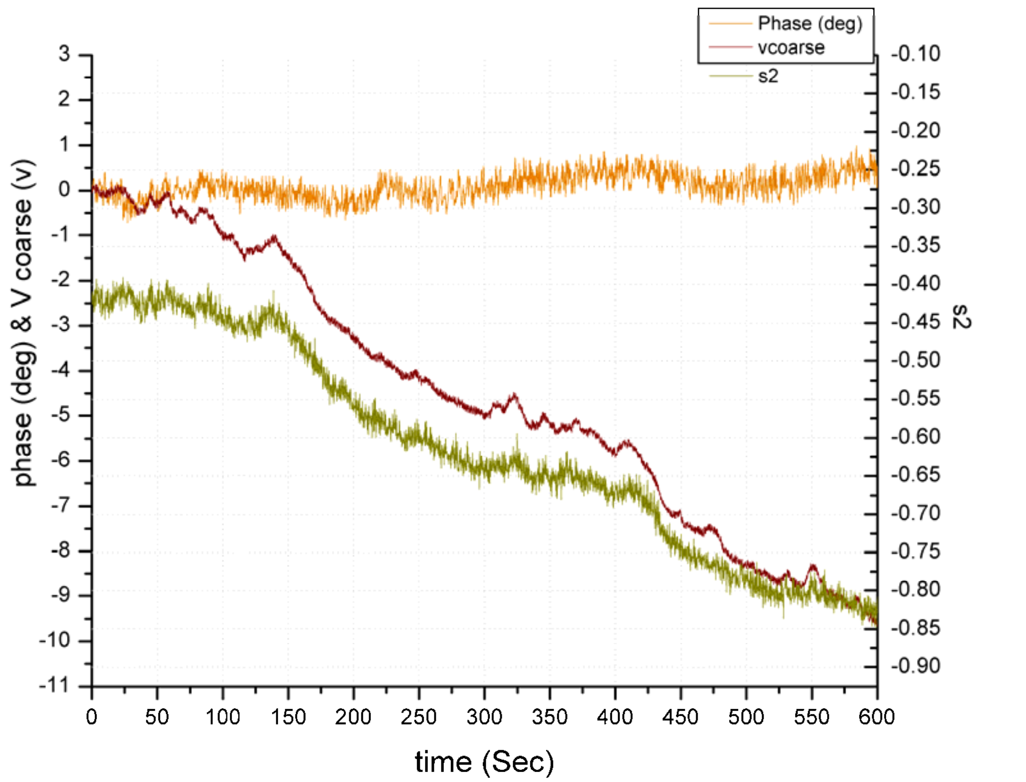

Figure 19: Test of the phase incurred on 10 km of fiber at 20 GHz (no movement of the fiber). This is a zoomed section of the previous plot.

The first significant thing in Fig. 18 and 19 is the obvious correlation between the polarization and the coarse correction voltage. This occurs because the fiber stretcher causes not only a length change in the fiber, but also a birefringence change that in turn causes a polarization change. This is undesirable given the results of our previous measurements, clearly we want to minimize any time variable polarization changes. It may be possible to use a fiber maintaining coarse fiber stretcher to eliminate this effect.

For the 10 km section, the rms phase change with the correction on was 0.3 degrees (41.6 fs) and the peak-to-peak total drift over 600 seconds was 1.7 degrees (236 fs) .

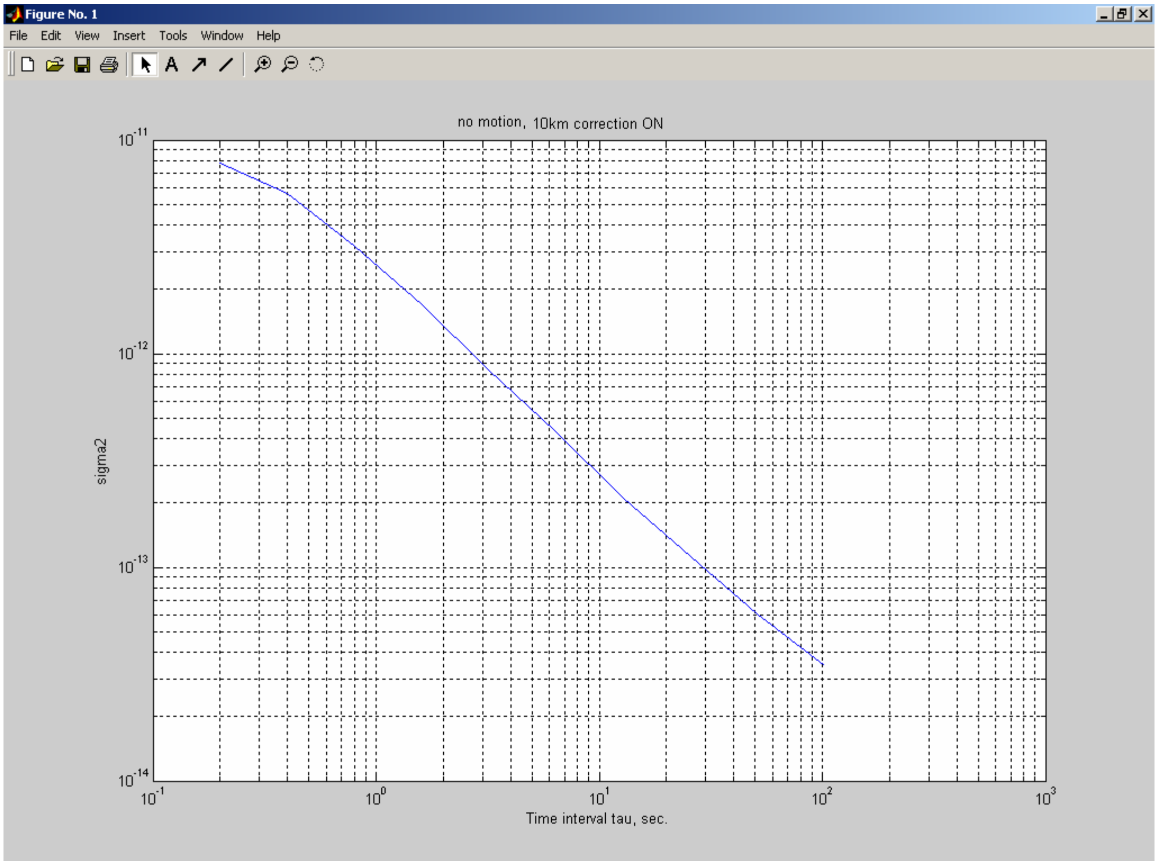

Figure 20: the measurement of the Allan variance of the phase in figure 19(10 km, for a reference frequency of 20 GHz and sampling time of 0.2 sec.

Test of Length Correction with Fiber Movement: Bending

Bending was applied to the fiber in a very controlled manner and reasonably slow and controlled speed. Ideally we would like to see the system correcting for all possible fiber movements including a sudden or rapid motion. But we have learned from testing that the system is very sensitive to sudden and very fast motion of any part of the fiber. For this reason, it will be necessary to consider and evaluate different fiber movements and different fiber wrap configurations. Three test results are shown for the case of the fiber bending:

- 5 km with the correction off
- 5 km with the correction on
- 10 km with the correction on and off in sequence

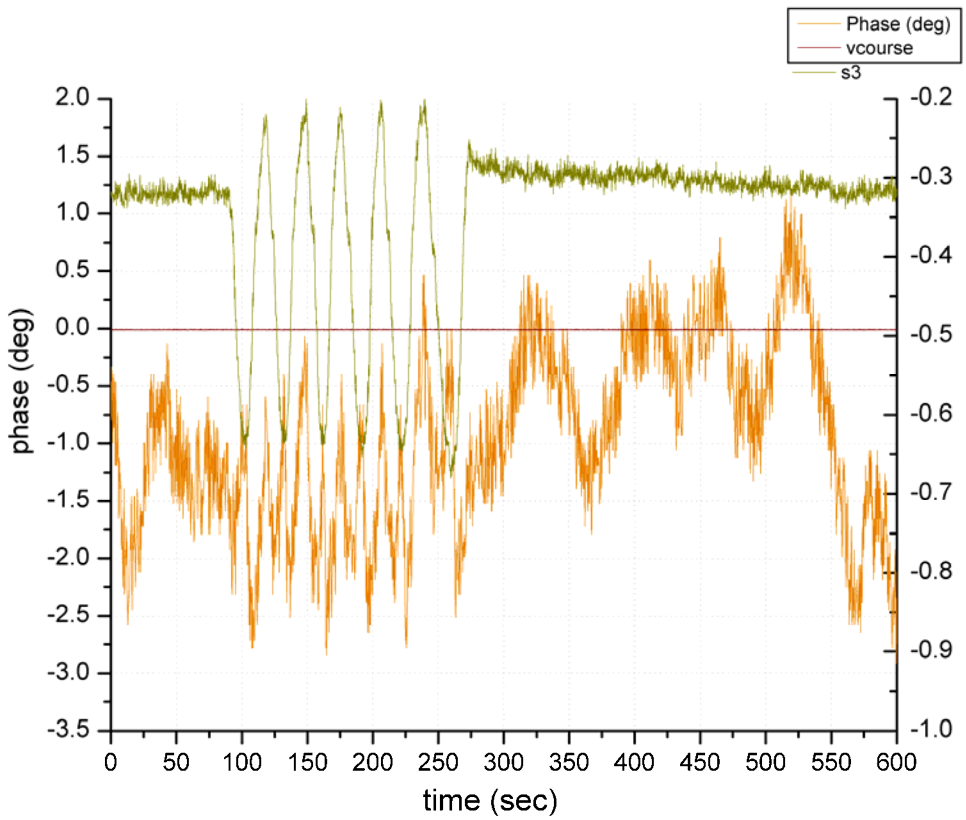

Figure 21: 5 km correction is **OFF** all the time. From 100 to 275 sec the fiber was bent and unbent multiple times, the bend radius was changing from 2.5 inch to 26 inch. From 275 to 600 sec, the bending is stopped.

Fig. 21 shows the phase change while bending 20 meter of fiber after 5 km of distance, with the correction is off. It is very clear to see the impact of bending the fiber on the polarization. In this case only one of the Stoke's parameters (s3 in this case) was plotted. The steady and repeatable change ofs ~ 0.85 in s3 correlates with the change in the 20 GHz phase of about (average p-p) 1.98 deg peak-to-peak. The fiber bending occurs only from 100 sec to 275 sec. From 275 sec to 600 the phase was fluctuating due to the 5 km of fiber.

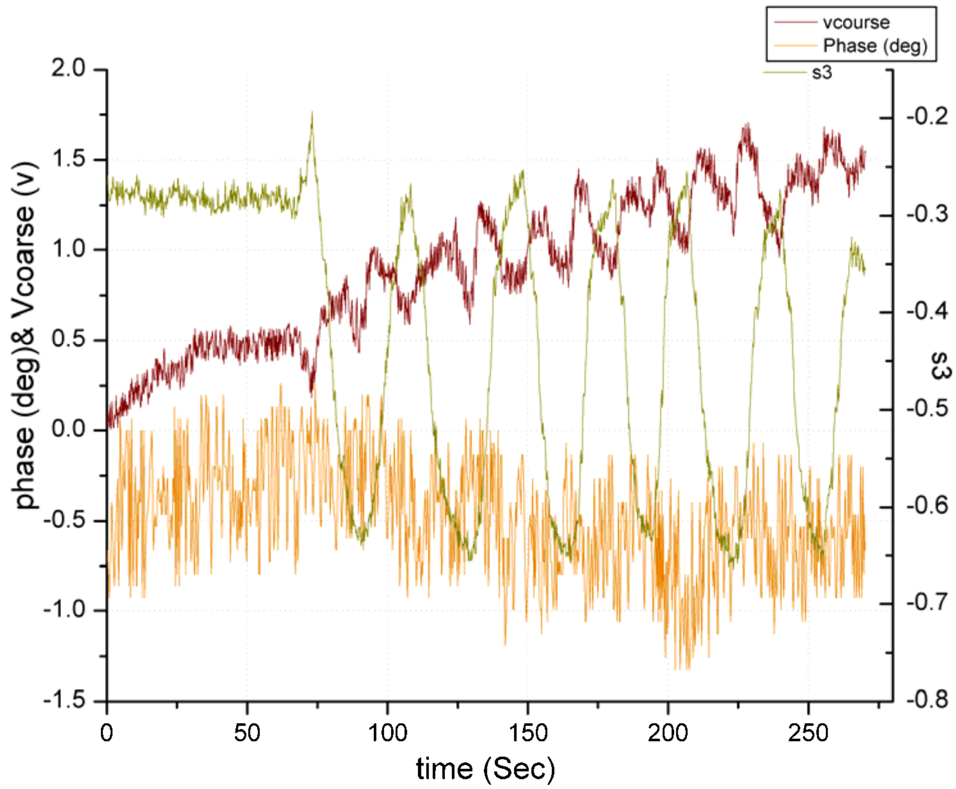

Figure 22: 5 km correction is ON all the time. From 0 to 75 sec the fiber is not moving (or bent). From 75 to 270 the fiber is bent multiple times, the bend radius was changing from 2.5 inch to 26 inch

Fig. 22 shows the corrected 20 GHz phase (in orange) while applying the same bending to the fiber. The brown line represents the change in the control voltage that is driving the slow stretcher. **The phase change due to the fiber motion is clearly suppressed in this measurement. This is obviously a large improvement over Fig. 2.** The important information - how much residual phase change is caused by the bending? – is difficult to determine due to the fact that it is lower than the rms residual phase noise level. Further analysis or measurement might yield a functional relation between the bending and the phase change after correction.

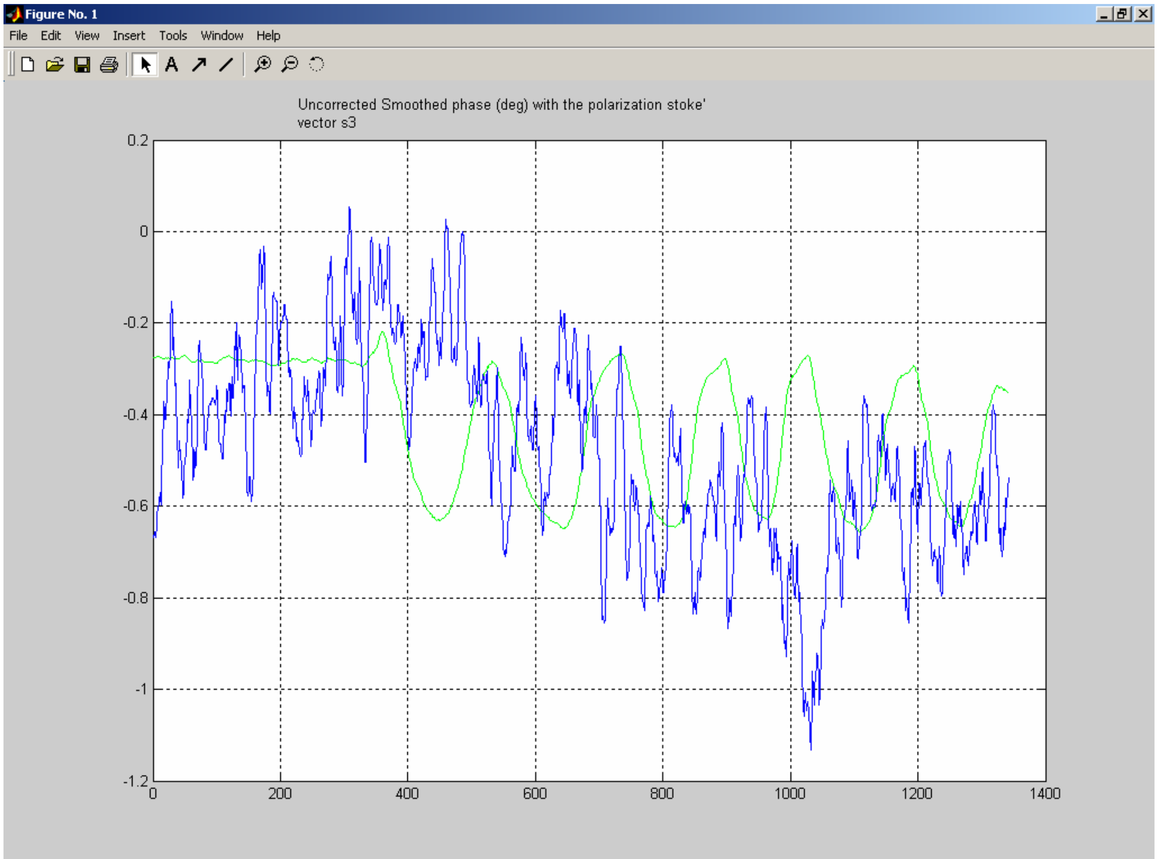

Figure 23: Smoothed version of the data in figure 22. The blue line represents the smoothed phase while bending (from data point 280 to 1360) and the green line represent the smoothed version of s3. The y axis represents the phase (deg) and polarization normalized value (unit less). The x axis represents the sample point.

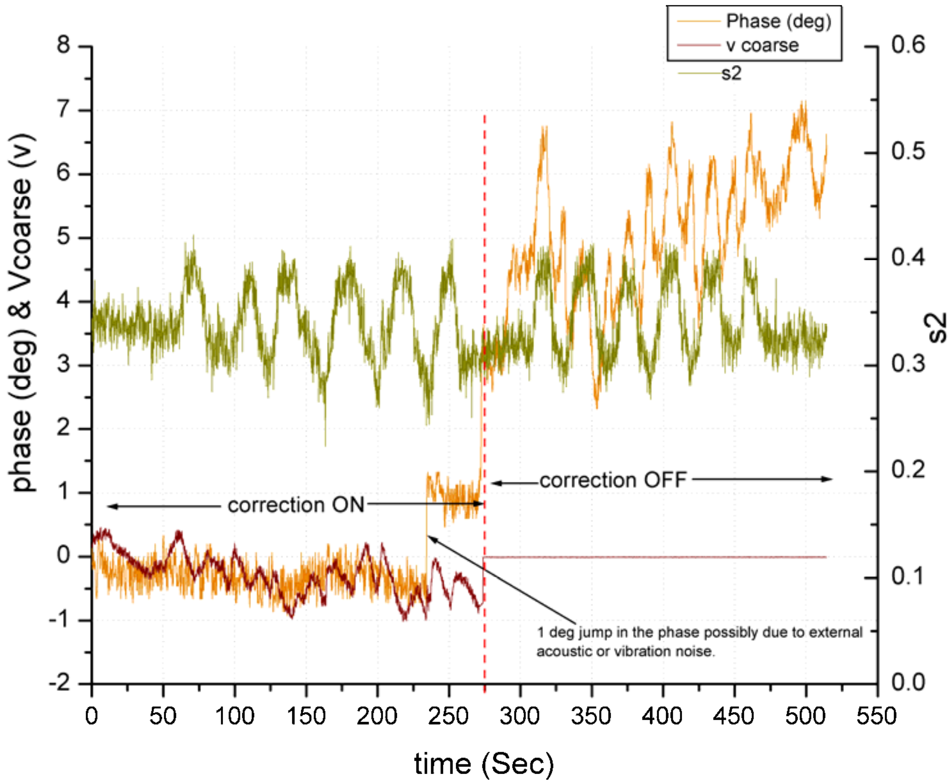

Figure 24: 10 km correction is on and undergoes cyclical bending from 0 to 275 sec., then the correction is turned off from 275 sec to 525sec. The bend radius was changing from 2.5 inch to 26 inches.

Figure 24 shows that in case of 10 km of fiber, the maximum phase variation while bending the fiber with the phase correction ON was less than 0.7 deg (97 fs). However while applying the bending to the fiber while the correction is off (from 275 sec to 525 sec) the 20 GHz phase changes by 4.5 deg.

Test of Length Correction with Fiber Movement: Twisting

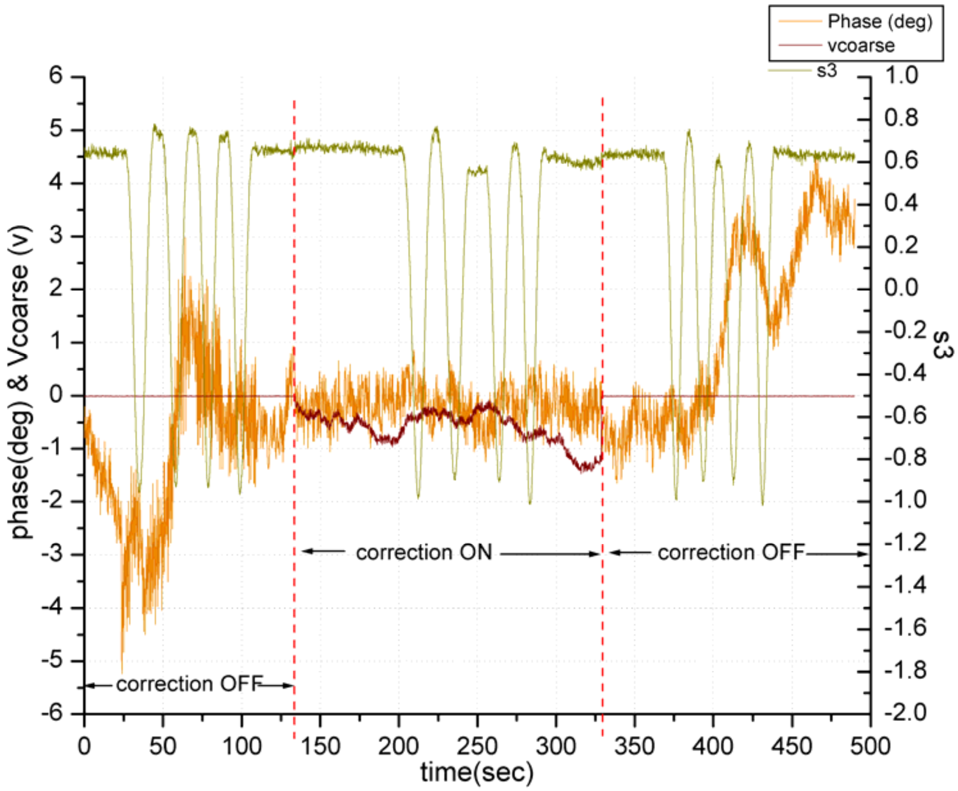

Figure 25: 5 Km with twisting ½ inch of fiber from 0 to + 360 deg and then back from +360 to 0 deg . The correction is OFF from 0 to 130 sec, then the correction is ON from125 sec to 327sec, and finally correction is OFF from 327sec to 490 sec.

Figure 25 shows the phase variations while twisting ½ inch of fiber after 5 km length of fiber, the maximum phase variation while twisting the fiber with the phase correction is OFF was ~ 7.1 deg (from 0 to 130 sec) and 6 deg (from 350 to 500sec) . However while applying the twisting to the fiber while the correction is ON (from 130 to 325 sec) the 20 GHz phase changes by 0.9 deg.

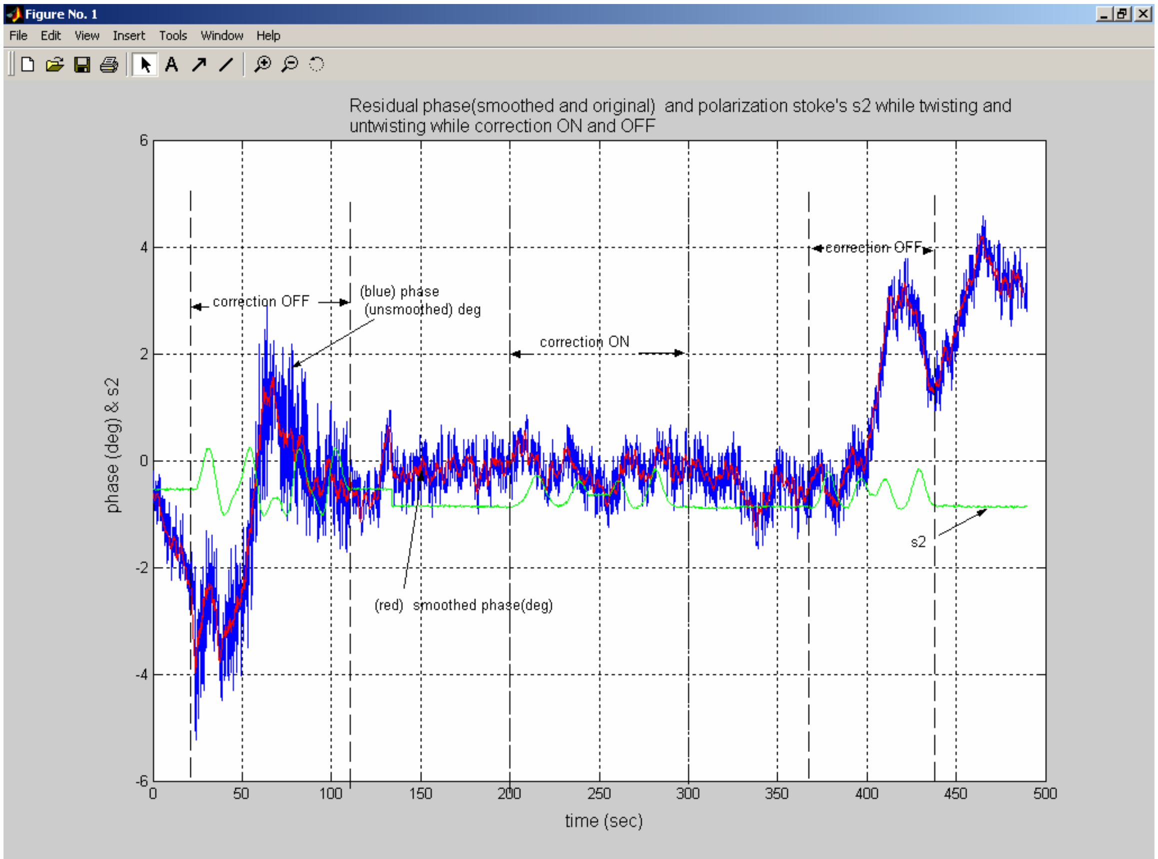

Figure 26: Smoothed version of the data in figure 25. The blue line represents the unsmoothed phase measurements while twisting, the red line represents the smoothed version of the phase and the green line represents the smoothed version of s2. The y axis represents the phase (deg) and polarization stoke's vector s2 value (unit less). The x axis represents the time in sec. Twisting by from 0 to 360 deg and untwisting (360 deg to 0) is done in three sections, 1st while the correction is off (0 sec – 110 sec) then Correction is on (200 sec to 300) and finally the correction is off from (360 sec to 440sec) .

6. Phase drift due to the Optical Amplifier

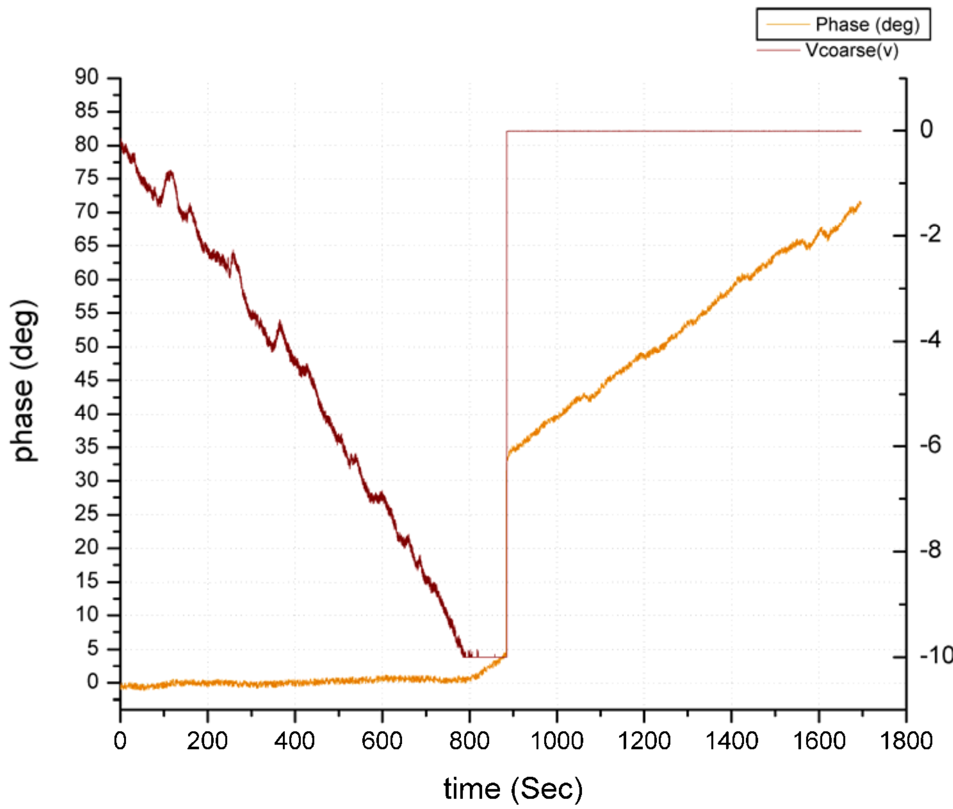

Figure 27: Test of the phase incurred on 5 km of fiber at 20 GHz with the correction system on (from 0 sec to 800 sec) and off from (800 sec to 1700 sec) with an OA located just before the far-end photomixer (refer to figure 12). No movement of the fiber has been applied.

Figure 27 represents the phase change of the 20 GHz beatnote for 5 km fiber distance while inserting an OA before the photomixer at the far-end. To better see the difference in the phase changes due to the OA, the Correction On section is plotted in Figure 28 below.

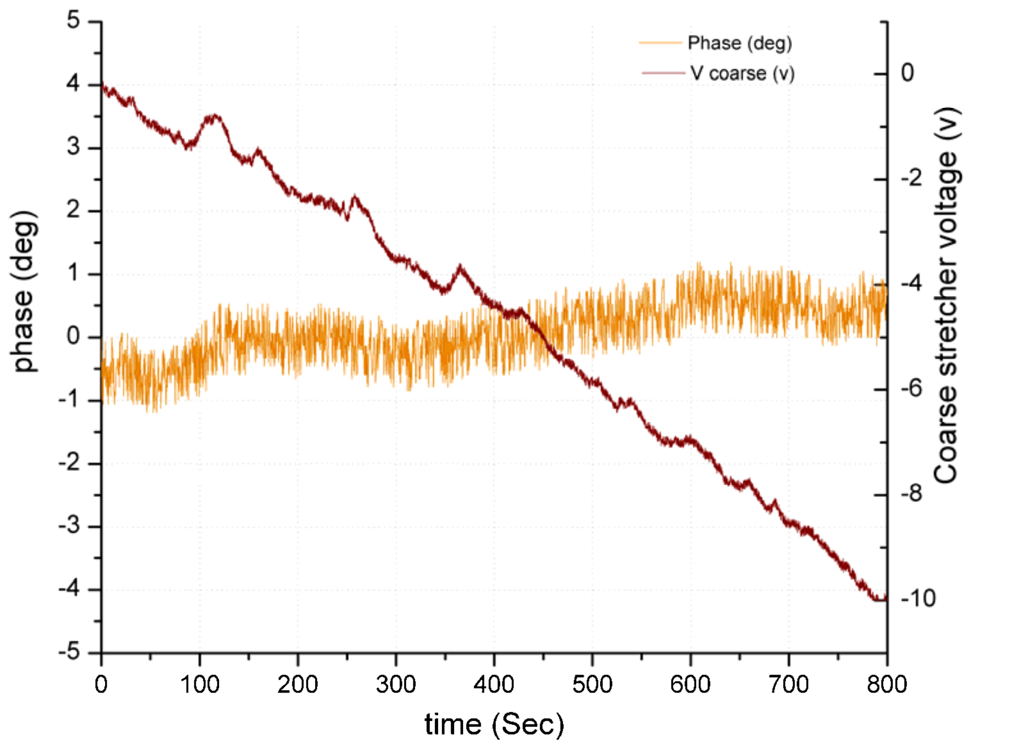

Figure 28: Test of the phase incurred on 5 km of fiber at 20 GHz with the correction system on (from 0 sec to 800 sec) with an OA located just before the far-end photomixer (refer to figure 12). No movement of the fiber has been applied.

From Figure 28 above, the maximum phase change while the correction is on was ~ 2.3 deg which corresponds to 319.4 fs. By comparing the results to Figure 16 (without an OA at the far-end), the RMS phase change is 0.455 deg (63.2 fs), yet the maximum phase change was 1.4 deg (194 fs) for 2000 sec. The OA at the far end (located outside the zone of the fiber correction loop) seems to have added ~ 0.9 deg of phase drift (125 fs) to the overall 20 GHz beatnote phase at the far end. The OA that was used in this test was from JDS model#ONA2017 , it was turned on for several hours before this particular measurement was taken. We have noticed that the OA adds much more phase drift at the 1st 1 hr of operation due to warm up and stabilization. Several other measurements (not included in this memo) were performed on other OAs that had shown larger drift in the phase of the far-end 20 GHz beatnote.

7. Line length correction using phase locked 108 GHz

As shown in Fig. 29, the master and slave laser are combined in a polarization-maintaining coupler (PMF), so their polarizations are aligned. One branch of the coupler provides the output, while the other feeds a photomixer that recovers the difference frequency. (Not shown is the fact that 4 separate photomixers are needed to cover the whole 27-142 GHz frequency range. These are connected as required, along with matching harmonic mixers, by optical and electrical switches.) The microwave reference and harmonic mixer are used to down-convert the signal to 125 MHz. A conventional phase detector and Type II loop integrator then drive a voltage controlled oscillator near 100 MHz, which in turn drives a fiber-frequency shifter (FFS). The FFS is a commercial device modified to provide low acoustic delay of 100 nsec. To avoid having the slave laser drift beyond the range of the FSS (about 30 MHz), an additional slow loop drives a piezo-element that adjusts the frequency of the laser.

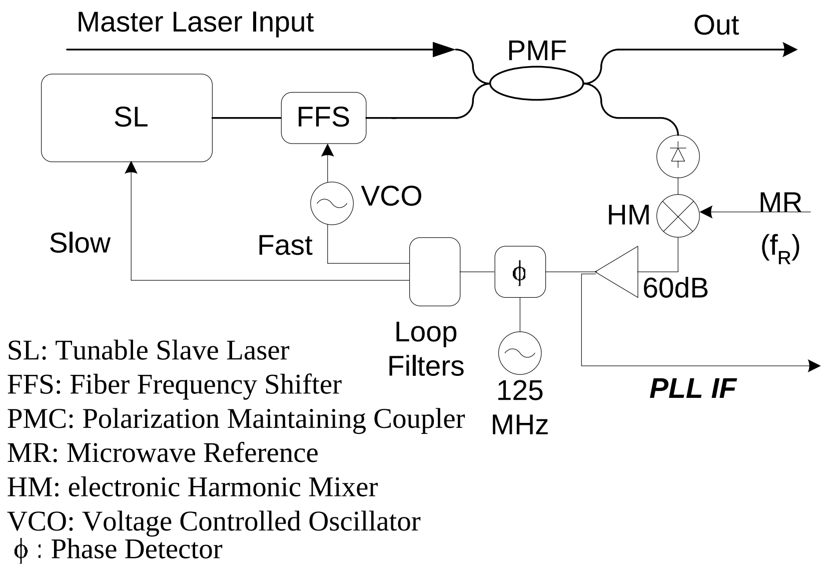

Figure 29 Schematic of the laser synthesizer**.**

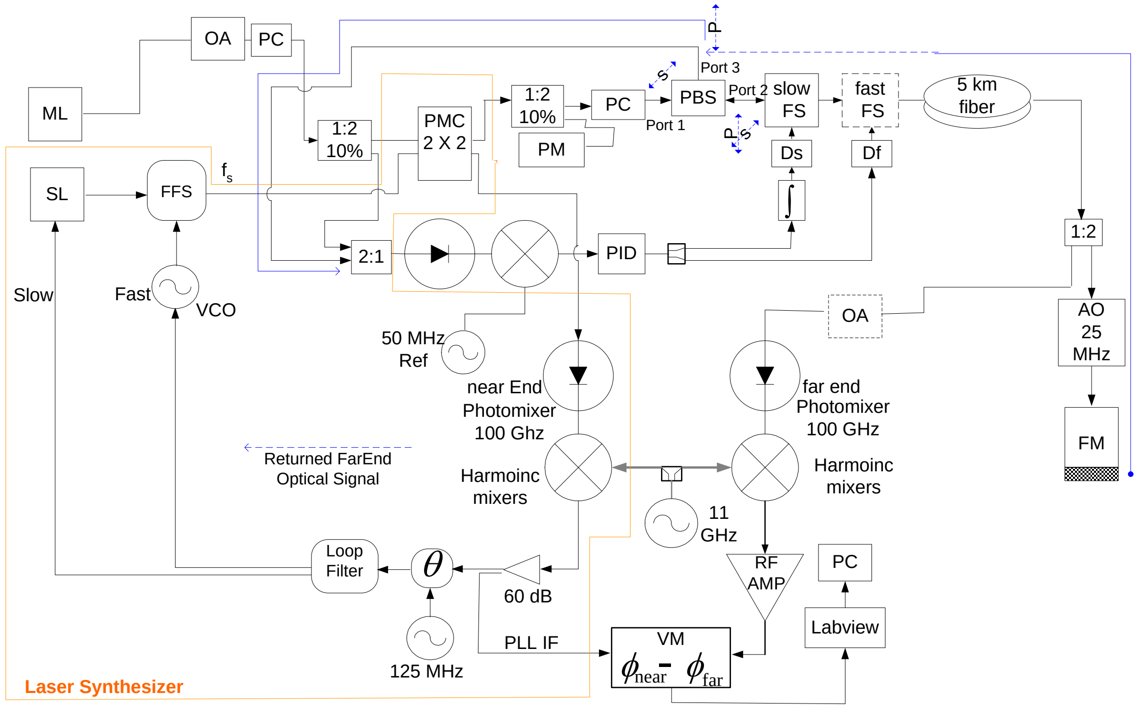

Figure 30: Schematic of the Line length correction at 108 GHz reference

Line length correction for 10 km of fiber

Figure 30 above shows the test setup for correcting 10 km without moving the fiber. The test setup is simply is a combination of two sections; the 1st is the generation of the 108 GHz microwave signal output using the synthesizer shown in figure 29, and the 2nd is the phase correction system as it has been illustrated earlier in Fig. 12 without the use of the fiber moving fixture.

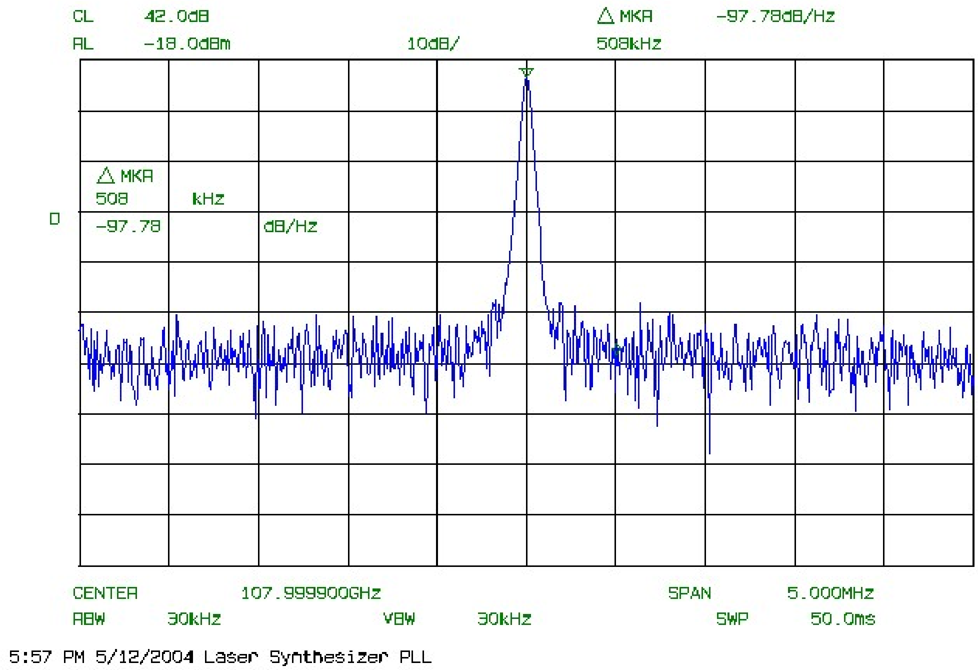

Figure 31: Laser Synthesizer Output at 108 GHz (after photomixer). The measurement noise floor at -97 dBc/Hz limits the measurement above 200 kHz.

Figure 31 shows a test result for an assembly using this technique to phase lock the slave laser at 108 GHz difference frequency. The output shown in Fig. 4 was measured at the laser synthesizer output by a W-band (75-110 GHz) waveguide photomixer and a spectrum analyzer outfitted with harmonic mixers for W-band operation. The RMS phase noise from 3 kHz to 3 MHz is 34 fsec for this measurement. This is thought to be mainly from the microwave reference, which was a laboratory instrument. Later measurements will include a custom-designed low phase-noise microwave reference.

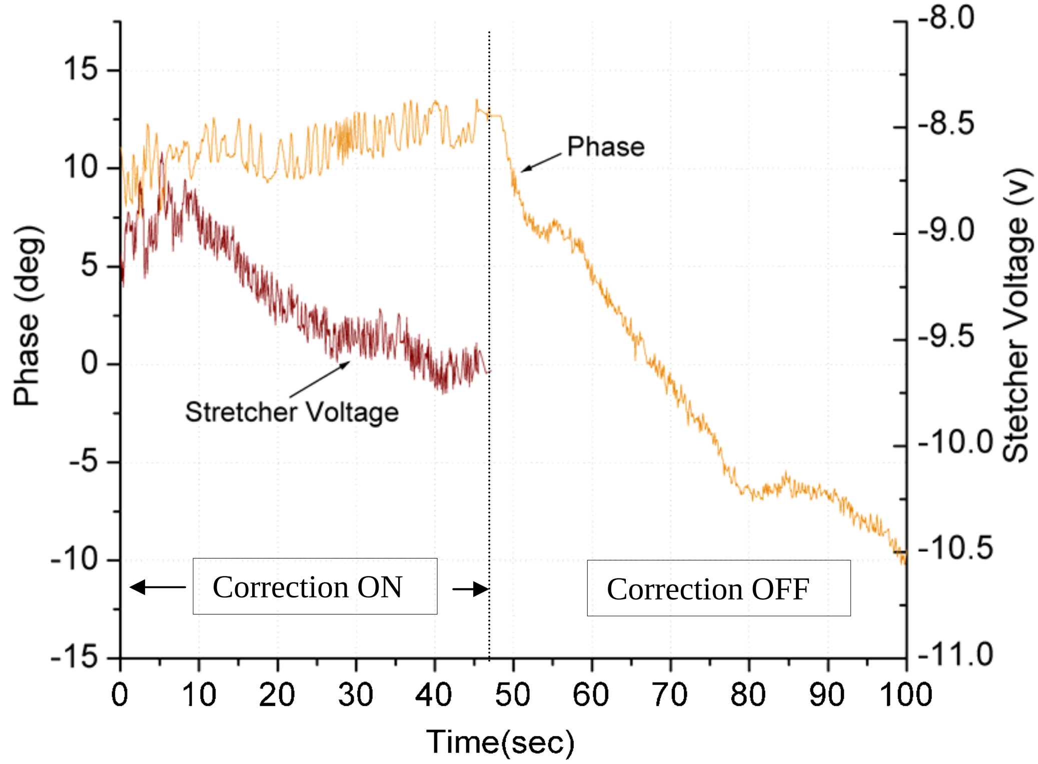

Figure 32 108GHz locked beatnote phase measurement over 10km while correcting for 47 sec and un-correcting for 53 sec.

Figure 32 shows the 108 GHz phase variation over 10 km spool of fiber. The 1st 47 sec of the test the correction was on. The stretcher voltage changed from ~ 9.0 volts to 9.75 volts which correspond to ~ 0.1125 mm of fiber. The master laser was manually locked and that was one of the limitations that didn't permit us from correcting for longer time. The correction was off from 47sec to 100 sec. Maximum phase variation with correction ON= 6.09 deg (156 fs). The RMS phase with correction on is 1.2 deg at 108 GHz which corresponds to 33 fs.

8. Conclusions

The measurements and analysis contained here indicate a history of improvement, but still the need for further improvement, and more accurate measurement under more realistic conditions. For this reason, the measurements were interrupted in Sept 2004 to prepare full prototypes of the laser synthesizer and line corrector for use in the ALMA Systems Integration tests. These test will allow phase drift measurement at higher frequencies with greater resolution.

1. The *large* phase fluctuations have been eliminated which was due to the optical circulator
2. The best fiber wrap configuration still needs to be determined. Two wrap configurations will be tested in SI tests, a bend-only and a twist-only.
3. More testing is needed to determine the effect of the optical amplifier on the phase drift of the beatnote at the far-end, and how to minimize it or eliminate it.
4. The tests to-date have not demonstrated that the system can stay on a fringe with the fiber moving. All tests to date have failed in this regard. A suitable low-perturbation moving fiber wrap must be demonstrated, also another design alternatives need to be considered to minimize or eliminate fringe skipping. Two techniques for achieving this have been identified and will be incorporated in the prototype line length corrector [15,16].

Considerable risk and development remains. A backup plan should be fully studied.

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