ALMA Memo No. 445

ALMA Line Length Correction System: Report on Tests in Japan

Larry D'Addario, Sarmad Al Banna, and Bill Shillue, National Radio Astronomy Observatory (NRAO), Tucson, Arizona, USA;
Masato Ishiguro and Akitoshi Ueda, National Astronomical Observatory of Japan (NAOJ), Mitaka, Tokyo, Japan; and
Ken-Ichi Nakagawa and Mitsuru Musha, University of Electro-Communications (UEC), Chofu-shi, Tokyo, Japan

2003-Feb-03

Abstract. A preliminary version of the ALMA line length correction system, which will stabilize the electrical length of the optical fibers used to distributed the LO reference signals from the center to each antenna, has been constructed in the form of a semi-portable test instrument. The length stabilization technique is dependent on use of a frequency-stable master laser. Such a laser is not yet available, but the University of Electro Communications (UEC) in Japan has a laser with very good long term stability. Therefore the test instrument was brought to Japan and a series of measurements was made using the UEC laser with the goal of verifying the accuracy of the length stabilization technique. The tests allowed us to set an upper limit on the delay variation in the stabilized path of about 70 fsec over 1 hour. It is possible that the system meets the ALMA goal of about 6 fsec delay variation (1.26 μm fiber length variation) over at least 100 sec, but establishing this was beyond the limits of these tests.

1. Introduction

The present design for local oscillator distribution for the ALMA telescope [1] involves the transmission of millimeter wavelength reference signals on long optical fibers, up to 25 km, as the difference between optical frequencies. The effective length of the fiber must be stabilized to about 1 μm. It is planned to accomplish this by forming an optical interferometer over the entire fiber and actively adjusting the length via a servo so as to maintain constant interferometric phase, thus keeping constant the number of optical wavelengths in the fiber. The interferometer is formed at the wavelength of one of the two lasers used to encode the millimeter wavelength reference; this is known as the master laser.

This concept requires that the frequency of the master laser be maintained constant to better than (1 μm)/(25km) = 4e-11. Such stability is required over time intervals of at least 100 sec, and preferably longer. In addition, the short term stability must be sufficient to maintain good coherence over the round-trip path of up to 50 km of fiber, or an interval of about 240 μsec. Such a laser is not currently available.

The NRAO has constructed a test set which includes a line length correction system similar to that planned for ALMA and which allows measurement in the laboratory of the performance of that system over a long fiber, where both ends of the fiber are available in the same room. The University of Electro Communications (UEC) has available a stabilized laser whose long term stability is suitable for the ALMA master laser, and whose short term stability is adequate for fiber lengths up to about 1 km.

For these measurements, the first two authors brought the NRAO test set to Japan for use with the UEC laser during four days of tests in December 2002. A second laser was phase locked by the test set to the UEC laser at a microwave offset frequency f_0 = 26.625 GHz.. The beat note at f_0 was detected in the test set after transmission through the length correction servo and a long fiber. The phase of the beat note signal was then measured by the test set with respect to the microwave reference. Our intention was to use a fiber length as long as the laser coherence permits. At 26 GHz, the desired length stability of 1.0 micron corresponds to a phase stability of .044 degrees.

2. Principles of Test

A simplified block diagram illustrating the basic principles of the test is shown in Figure 1. A tunable laser ("slave laser") is phase locked to the master laser at an offset frequency determined by a microwave synthesizer. The master and slave optical signals are combined onto a single optical fiber, passed through the line length correction (LLC) assembly, then through the long fiber, then through a turn-around assembly, and then to a photodetector. The photodetector output is compared with the microwave reference in a phase detector, and the measured phase difference is recorded.

The turn-around assembly takes a portion of the received light, shifts its frequency slightly, and launches it back toward the LLC on the same fiber. The LLC compares the returned light with the outgoing light at the master laser wavelength and drives a variable delay unit (fiber stretcher) so as to keep the phase difference constant.

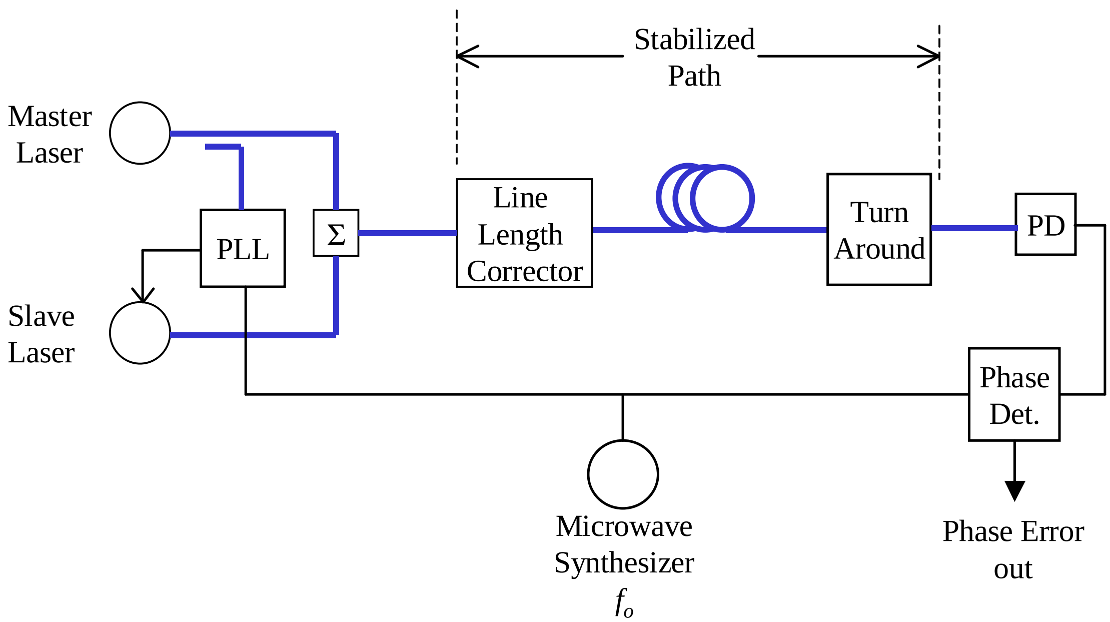

Figure 1: Basic principle of the test.

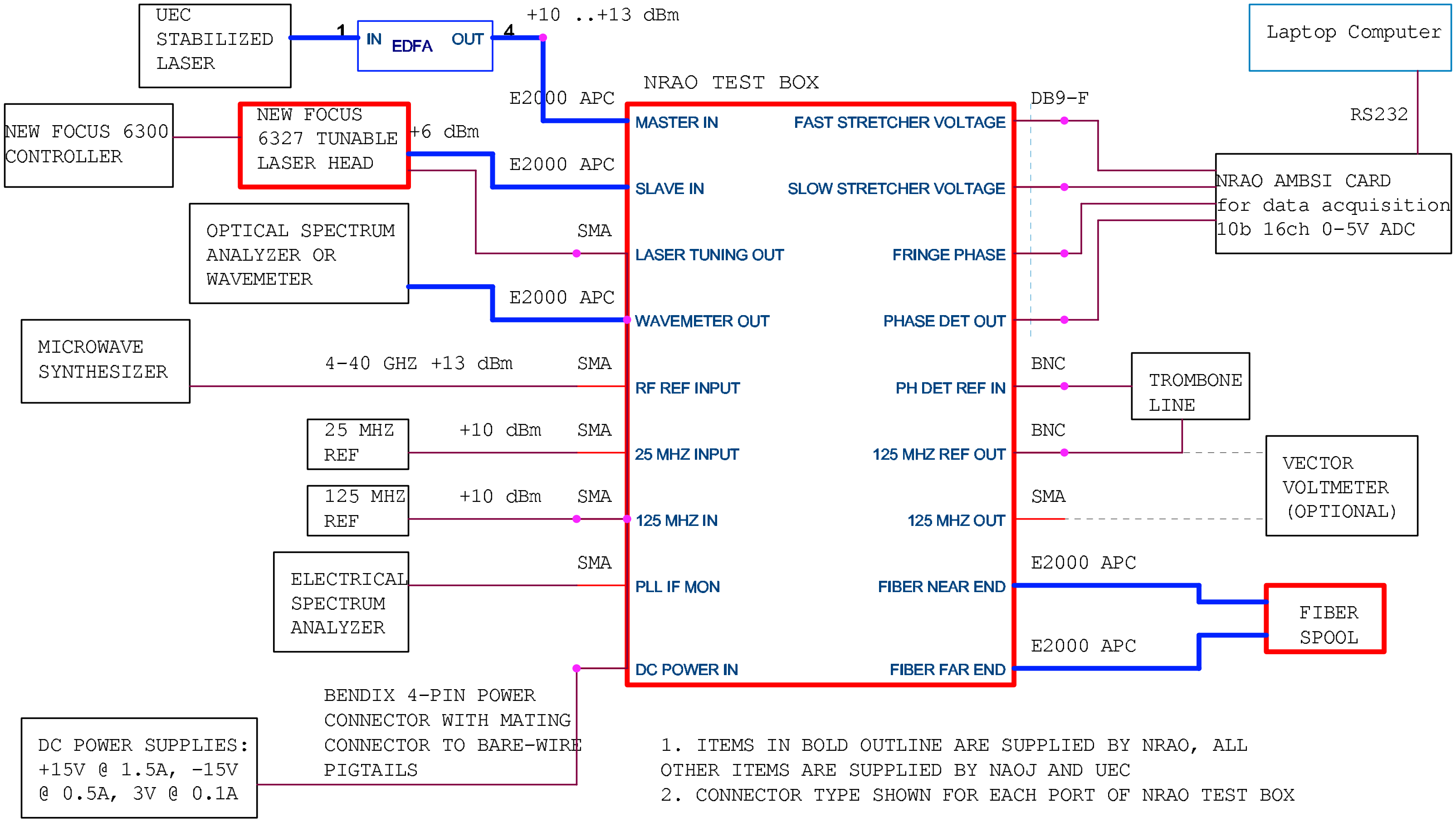

Figure 2: Test setup details, showing interconnections among devices.

3. Description of Test Setup

Figure 2 shows the actual test arrangement.

Most of the test set components are contained in a single rack-mountable box ("NRAO Test Box") of dimensions 173x486x541 mm. The internal block diagram of this box is shown in Figure 3. It contains the slave laser phase locking circuitry, the length correction system, the high frequency photodetector for the beat note, and a phase detector (double balanced mixer). The box implements, in one place, both the central components and the antenna-based components of the ALMA reference transmission system.

Optical signals from the two lasers are brought into the box via Diamond E2000/APC connectors. The slave laser, a New Focus Model 6327H external cavity diode laser, is coarsely tuned to the desired frequency using a New Focus Model 6300 Tunable Laser Controller. To facilitate this, the combined signal from both lasers is brought out via a separate connector ("Wave Meter Out") for connection to an optical spectrum analyzer or wavemeter. The slave laser head has been modified by NRAO to provide a d.c. coupled bias offset input. This is used to provide fine tuning

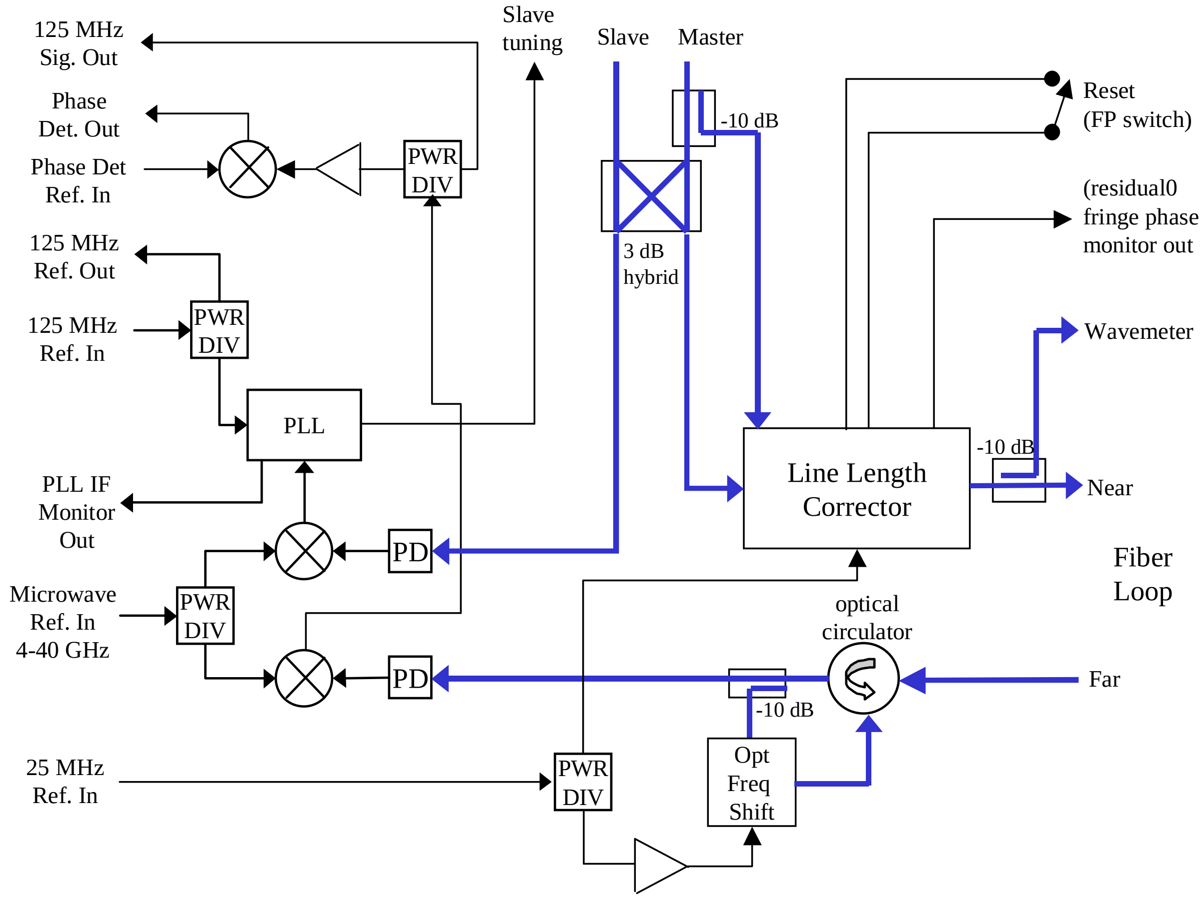

Figure 3: Block diagram of NRAO Test Box.

for phase locking, and is driven by the PLL integrator inside the box.

The UEC master laser [2] achieves very good long-term stability by frequency locking its internal laser (an external cavity diode laser) to a molecular line, namely that of acetylene (C_2H_2) at 1542.3 nm. Low-pressure C_2H_2 is contained in a glass tube that is embedded in a Fabry-Perot cavity. The cavity is first locked to the saturated, doppler-free absorption line of the gas, and then the laser is locked to the cavity. To achieve the cavity-to-gas locking, it is necessary to modulate (or dither) the cavity length slightly. This causes frequency modulation of the laser output at a rate of 1.6 kHz and a deviation of approximately ±250 kHz.. This modulation turned out to be a limiting factor in our tests.

Two RF reference signals are required, the first at frequency f_1 in the range 4 to 40 GHz at +13 dBm, and the second at f_2=125 MHz and +10 dBm. When the PLL is locked, the slave laser frequency will be offset from the master by $f_0 = f_1 + f_2$. These reference signals should have good short term stability, but they need not be phase locked to each other. They were provided by separate Agilent synthesizers. In all of the tests reported here, f_1=26.5 GHz and f_2=125±5 MHz.

The combined signal from the two lasers is passed through a voltage-variable delay with a range of about 5 mm (implemented by two piezo-driven fiber stretchers), and then to an output connector (“Fiber Near End”). A spool of optical fiber then simulates the long transmission path required by the ALMA telescope. The length of fiber can vary from less than 1 m to a maximum that is limited by the master laser’s coherence. After the fiber spool, the signal is returned to the box via another connector (“Fiber Far End”). The system has been tested at the NRAO with up to 10 km of fiber using an MPB model EFL-R98-T fiber laser.

The line length correction (LLC) system operates by driving the variable delay line so as to keep the total phase delay through it and the external fiber equal to an constant number of cycles of the master laser signal. Details of this will be described in the next section.

At the “far” end of the fiber, a photodetector recovers the beat note signal at $f_{0.}$ This signal is mixed with f_1 to obtain 125 MHz, which is then compared in a phase detector with the 125 MHz reference f_2. The phase detector output voltage is low pass filtered and amplified in an op amp with a single-pole RC time constant of 47 µsec and a voltage gain of 9; the filtered signal is available at the front panel for recording. The 125 MHz signal and reference are also brought out on separate connectors so that an external phase detector, such as a vector voltmeter, can be used. The internal phase detector is actually a double-balanced mixer, so it provides maximum sensitivity only when its inputs are in quadrature. This can be adjusted using an external variable-length coaxial line (“trombone line”), or by slightly varying the 125 MHz reference frequency. During all the measurements reported here, the internal mixer was used as the phase detector and its reference was the PLL IF monitor signal rather than the 125 MHz reference from the synthesizer. When the synthesizer is used directly, the noise on the measured phase includes the PLL residual phase error, which is substantial; most of this is cancelled by using the PLL IF as the reference.

Several internal voltages in the test box are available for monitoring at a front panel connector, including:

- line length correction phase detector (residual length error), filtered and amplified
- coarse fiber stretcher control voltage
- fine fiber stretcher control voltage

These signals, along with the filtered phase detector signal, were recorded during the tests using an ALMA AMBSI [3] board and a laptop computer. Special firmware on the AMBSI board, supplied by Andrea Viccari, enabled it to sample a user-selected number of its analog inputs at a user-selected rate and to provide the results as ASCII strings via its serial port. The ADC range is 0 to 5V with 10b resolution. All of the monitor signals were offset and scaled to fit within this range.

4. Length Corrector Details

As shown in Figure 3, the optical signal at the “far” end of the fiber passes through an optical circulator and then a portion of the signal is coupled off and passed through an optical frequency shifter driven by the 25 MHz reference. The frequency-shifted signal is then transmitted in the reverse direction through the fiber via the circulator.

The “Line Length Corrector” block of Figure 3 contains two piezo-driven line stretchers in the two-way signal path, one with a range of about 5 mm and a bandwidth of about 10 Hz, and the other with a range of about 12.5 micron and a bandwidth of several kHz. An optical circulator is used to separate the outgoing and return signals. The return signal is added to a sample of the master laser signal and the result is applied to a low-frequency photodetector, producing a 25 MHz output whose phase variation is the same as that of the two-way optical path. This is compared in a phase detector with the 25 MHz reference, and the resulting phase error signal drives the line stretchers through an analog controller.

A schematic of the controller board is shown in Figure 4. The phase error signal drives the fine line stretcher through a simple integrator. The integrator gain can be adjusted by a front panel pot. The fine line stretcher control signal is further integrated to drive the coarse line stretcher, thus keeping the fine line stretcher near the center of its range. A front panel switch allows the coarse integrator to be reset to zero, setting the line stretcher near the middle of its range for initialization.

5. Test Results

The main test consisted of recording the 26 GHz signal phase for an interval the order of one hour while the fiber length was allowed to vary as a result of temperature changes in the room. One such test is plotted in Figure 5. The external fiber length was 180 meters and the UEC master

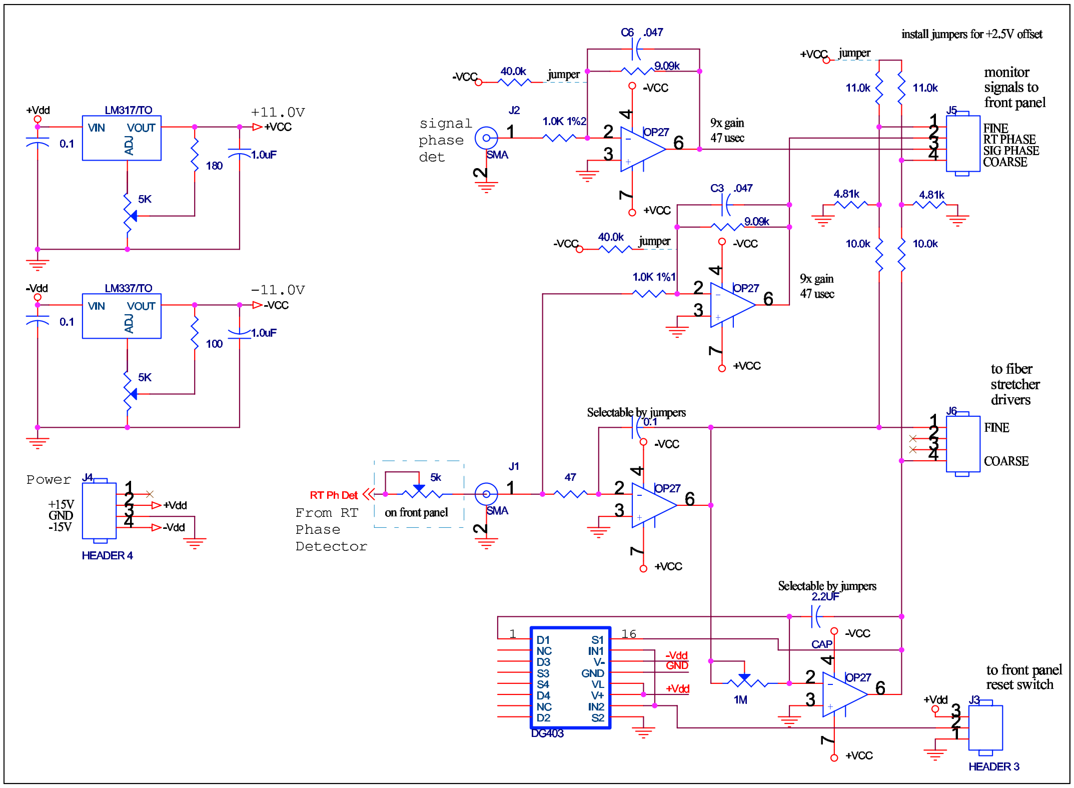

Figure 4: Schematic of controller board for correction loop, including filter/amplifiers for monitoring phase detector signals.

laser was used in its stabilized mode. The upper plot shows the signal phase, which remained stable within the noise for all of the 3300 seconds shown. Also plotted are the residual phase of the line length corrector and the control voltages to the coarse and fine line stretchers. The coarse stretcher range was about 1.1 V, corresponding to 1.1 mm of length change; this is consistent with a temperature change of about 0.5 C for this length of fiber. The temperature measured inside the test box is also plotted, but most of the fiber path was outside this box. The sampling period was 1 sec.

More detailed analysis of the signal phase data in Figure 5 yields the following:

- mean phase = –0.3488 radian
- rms phase = .0431 radian, or 263 fsec of delay at 26.125 GHz
- best fit straight line slope = .0095 rad/3250 sec, or 58 fsec of delay change in 3250 sec.
- rms phase after 50-sample boxcar smoothing = .0109 rad, or 66 fsec of delay.

The noise in this data is clearly not induced by the line length corrector, but we were not able to determine its exact mechanisms. It is partly due to the portion of the slave laser's phase noise not tracked by the PLL. But it is mostly amplitude noise, rather than phase noise, and would have appeared much smaller in the plot if the phase detector had been operated closer to quadrature (0 in the plot); we observed that it is largest when the phase detector is near in-phase or anti-phase.

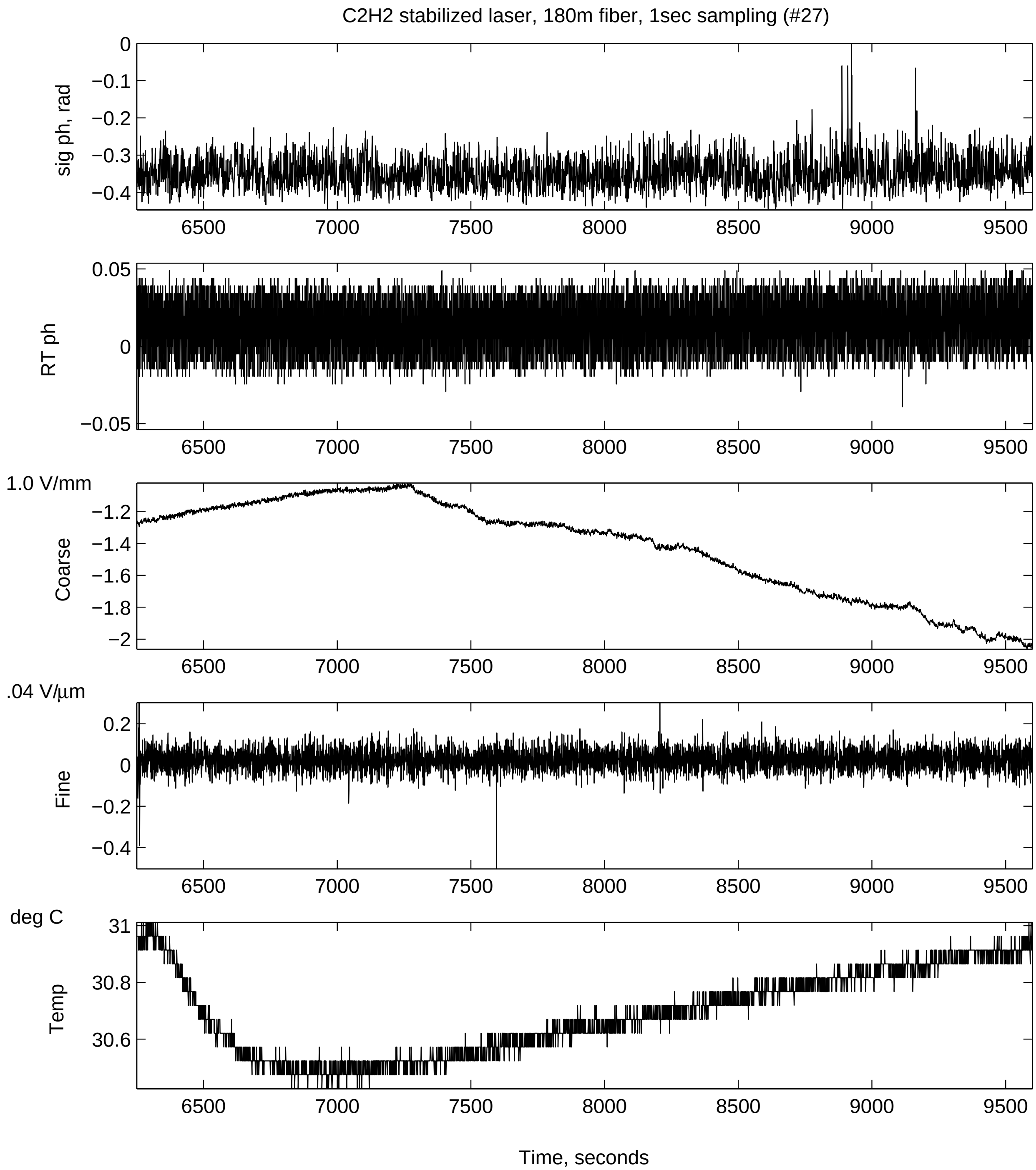

Figure 5 : Measurements using stabilized master laser with 180m of external fiber. Top plot shows phase of 26.625 GHz beat note after transmission through the stabilized fiber path. Second plot is the residual round-trip optical phase error, and the next two plots are the control voltages to the fiber stretchers. The last plot is the temperature on the main component plate inside the test box. Vertical scales are in volts unless otherwise noted. The fiber spool was inside a foam-lined box, and the box cover was opened part way through the test. Nearly one hour of data is shown. The rms signal phase is .0431 radian or 263 fsec; after 50 sec boxcar smoothing, this becomes .0109 radian or 66 fsec.

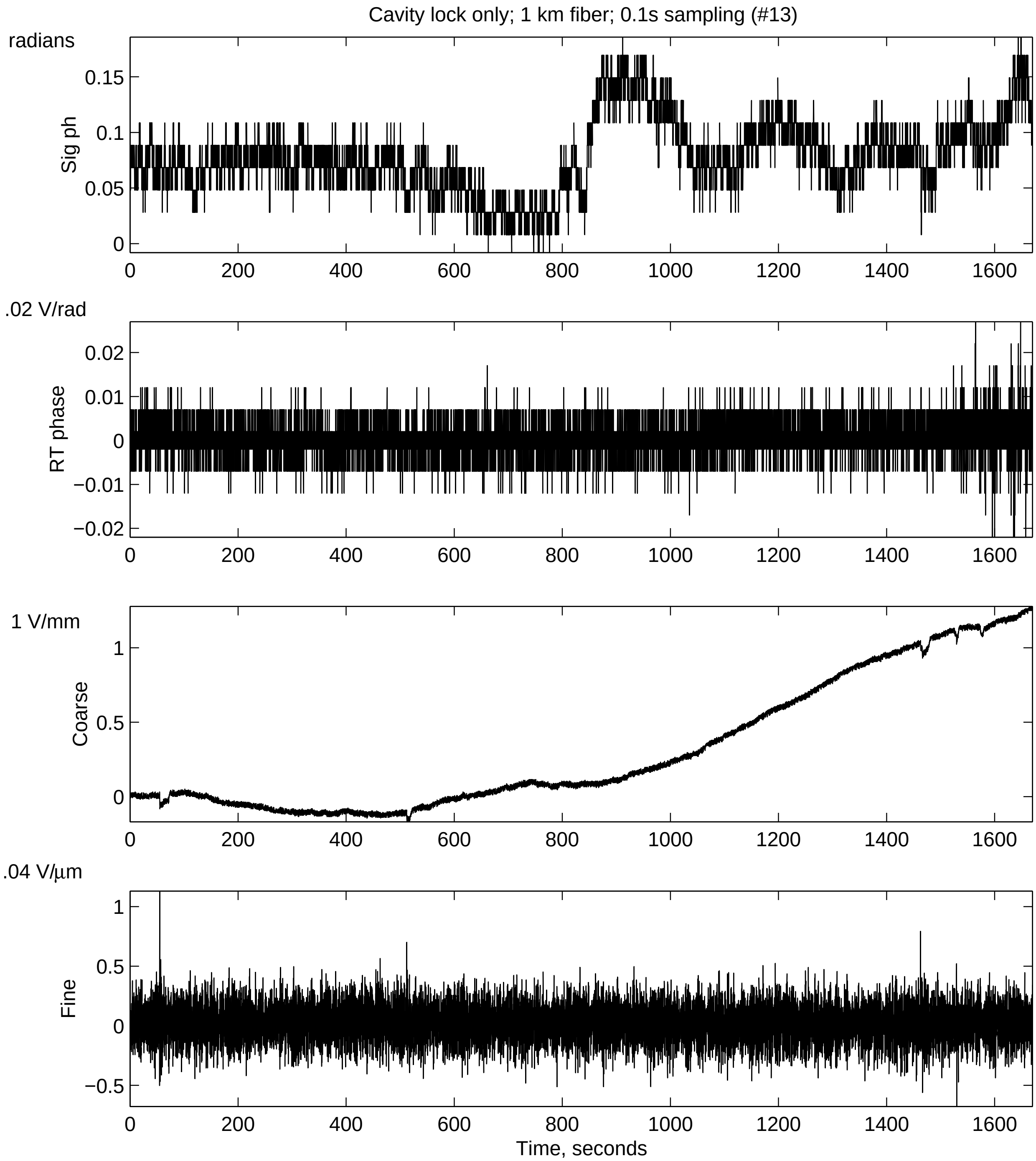

Figure 6: Similar to Fig. 5, but with 1 km of fiber and with the master laser locked to its optical cavity but not to the acetylene cell. It is believed that nearly all of the signal phase variation (704 fsec or 148 μm p-p) results from frequency drift of the laser, but the length correction applied by the coarse stretcher is about 10 times larger and this is easily explained by length variation of the fiber due to a small temperature change.

There may have been excessive intensity noise on one or both lasers. Fourier analysis of the time series shows that it is nearly white noise, with no significant features over the Nyquist bandwidth of 0 to 0.5 Hz.

Therefore, we think that the rms of the smoothed data or the best fit straight line provide a better upper limit to the residual error of the line correction system. That limit seems to be 60 to 70 fsec. This is far from the ALMA goal of about 6 fsec, but it is the best we could do in this test. The actual error may be much lower.

The second plot in Fig. 5 shows the residual round-trip optical phase. This signal is dominated by the 1.6 kHz frequency modulation of the master laser (see additional results below). The correction loop's gain was set as large as possible without oscillation, resulting in an integrator time constant of 50 μsec. We think that the loop gain is limited by the speed of the fine line stretcher, which has not yet been fully characterized (although its manufacturer claims a bandwidth >20 kHz).

We discovered during these tests that the master laser's modulation is a significant limitation. We had expected that the correction loop would be fast enough to track out the 1.6 kHz modulation rate, thus imposing a length modulation on the fiber of $(w/f_{opt})L$, where w is the frequency span of the modulation, f_{opt} is the laser's nominal frequency, and L is the fiber length. For w = 500 kHz and L = 1 km, this is 2.6 μm or 12.3 fsec of delay or 0.115 deg of phase at 26 GHz. Such a small and systematic error could have been averaged out and would not affect the measurements. However, we found that the modulation was only partially tracked by the loop, leading to a residual error in round trip *optical* phase that becomes more than 90 deg for fiber length greater than about 300 m. Since the correction loop's phase detector is a double balanced mixer, the unambiguous range is ±90 deg; the performance gets worse as the residual error approaches this, and it fails when the error exceeds it. We had available spools of fiber of length 180 m, 500 m, 1000 m, and 25 km. Of these, only the 180 m length could be used with the laser modulation on. Figure 6 shows measurements similar to those of Fig. 5, but with 1 km of fiber and with the master laser's modulation off so that it was not stabilized to the C_2H_2 line. This measurement lasted about 30 minutes, and the laser frequency drifted very little even without the stabilization. Noise in both the signal phase and round trip phase data is dominated by the 5 mV quantization of the ADC. The rms signal noise is about .0146 radian or 89 fsec at 26 GHz. The peak-to-peak signal phase variation was 0.118 rad or 704 fsec; if all of this is due to laser frequency drift, as we expect, then the drift was 28.7 MHz peak-peak, and this is reasonable. Meanwhile, the third plot shows that the stretcher length range was 1.45 mm or 6.9 psec, about 10 times as much as the signal delay. Most of this is the intended correction for the change in fiber length, which would be explained by a temperature change of about 0.15 C.

Figure 7 shows the spectrum of the residual round-trip phase as observed on a dynamic signal analyzer. The master laser was stabilized and the fiber length was 180m. The signal analyzed was taken directly from the phase detection mixer (not via the filter and amplifier used for the sampled data) and passed through a wide band (approximately 400 kHz) passive low pass filter. The

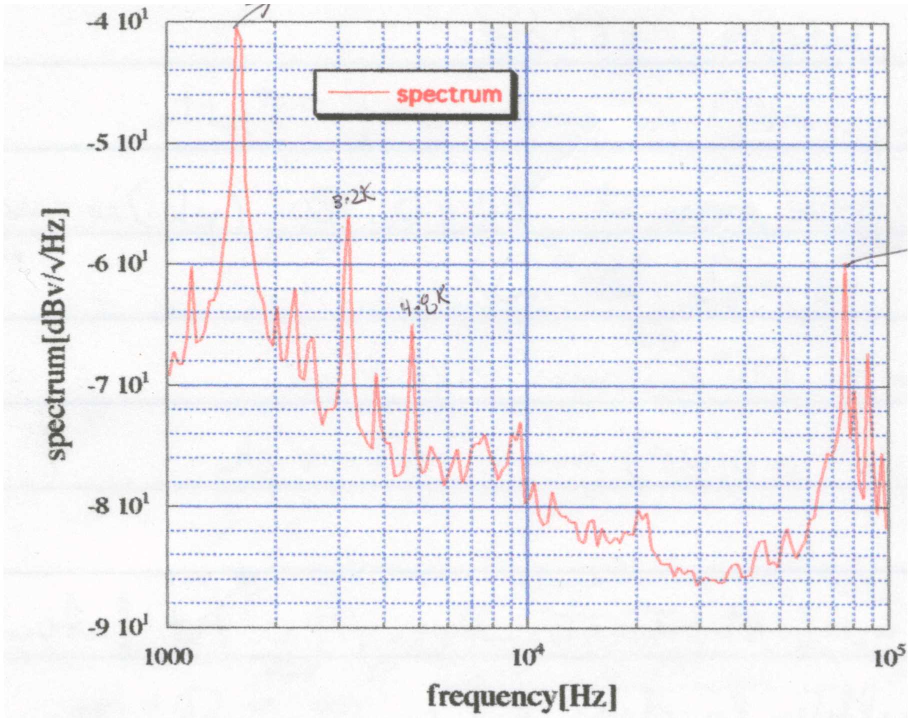

Figure 7: Spectrum of residual round-trip phase error obtained from dynamic signal analyzer. The UEC laser is used, locked to the C2H2 line and the external fiber length is 180m. The scaling is 250 mV/radian. The effect of the 1.6 kHz modulation and its harmonics at 3.2 and 4.8 kHz are clearly visible, as is the 75 kHz modulation due to a low-level oscillation in the laser-to-cavity locking loop.

dominant component is from the 1.6 kHz modulation, as expected; harmonics at 3.2 and 4.8 kHz are visible. Another component at 75 kHz is also from phase modulation of the master laser and is due to a low level oscillation in the its cavity locking loop. This becomes the dominant residual when the gas cell locking is turned off, and it is large enough to limit operation of the correction loop to a few km of fiber.

A small amount of data was obtained at higher sampling rates. Figure 8 shows such a measurement with 1.5 msec sampling period, for a Nyquist bandwidth of 333 Hz. Note that the pre-sampling bandwidth of the signal and round trip phase measurements was about 3 kHz, so components up to this frequency are visible in aliased form, even in Figs. 5 and 6 where the sampling rate is much slower. Figure 9 shows the computed spectra of the signal phase, round trip residual phase, and fine correction. Figure 10 is the 2-sample Allan standard deviation computed from the signal phase data. See the captions of these figures for further discussion.

Considerably more data was recorded during the tests than can be presented here. A brief report with additional annotated plots has been prepared for specialists [4]. Digital photographs taken during the tests are also available [5].

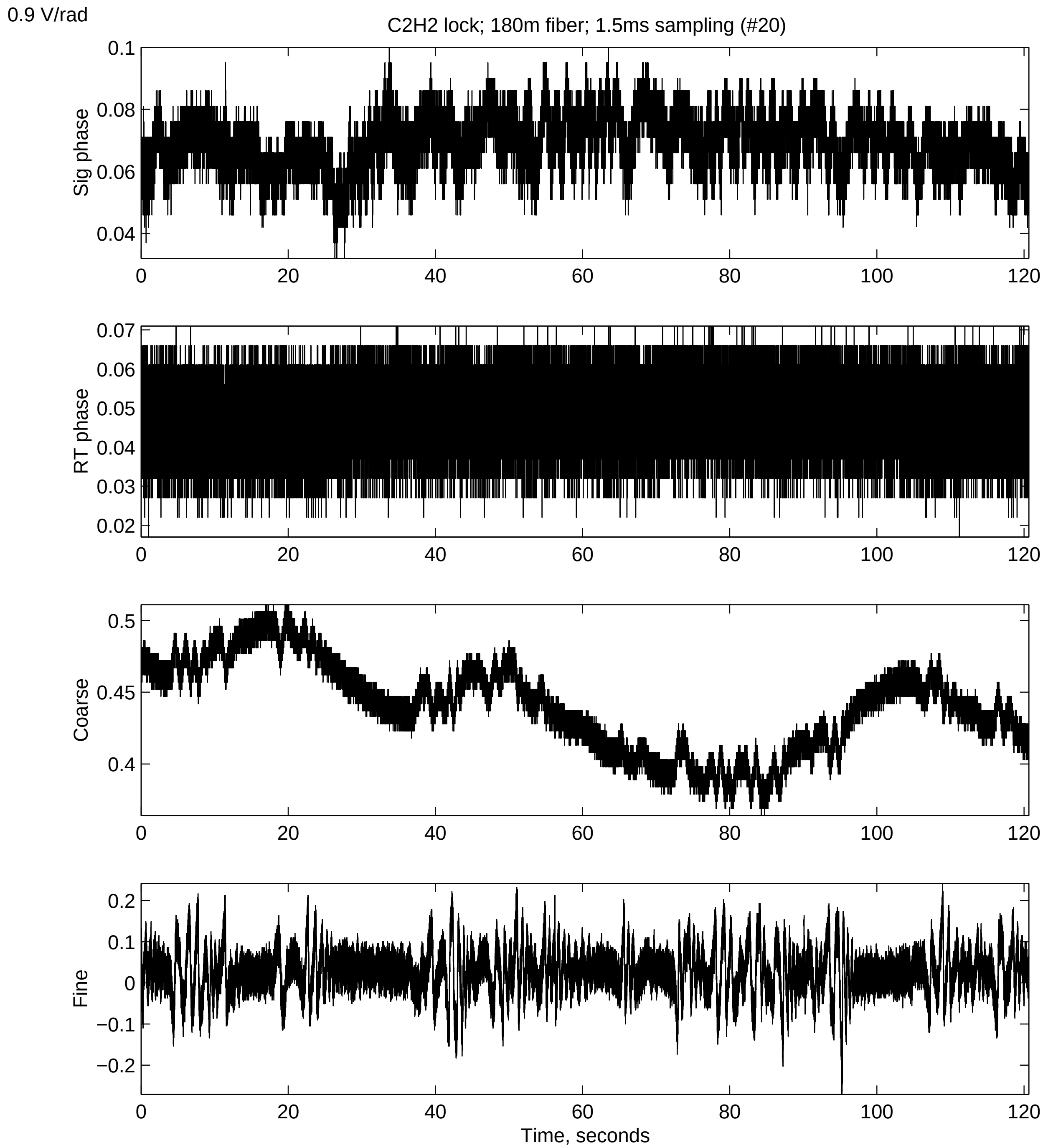

Figure 8: High time resolution measurement, with sampling period 1.5 msec. UEC laser locked to C2H2 line, 180m of external fiber. Features in the fine correction voltage may be vibration responses, perhaps to accidental disturbances. The following figures analyze this data in more detail.

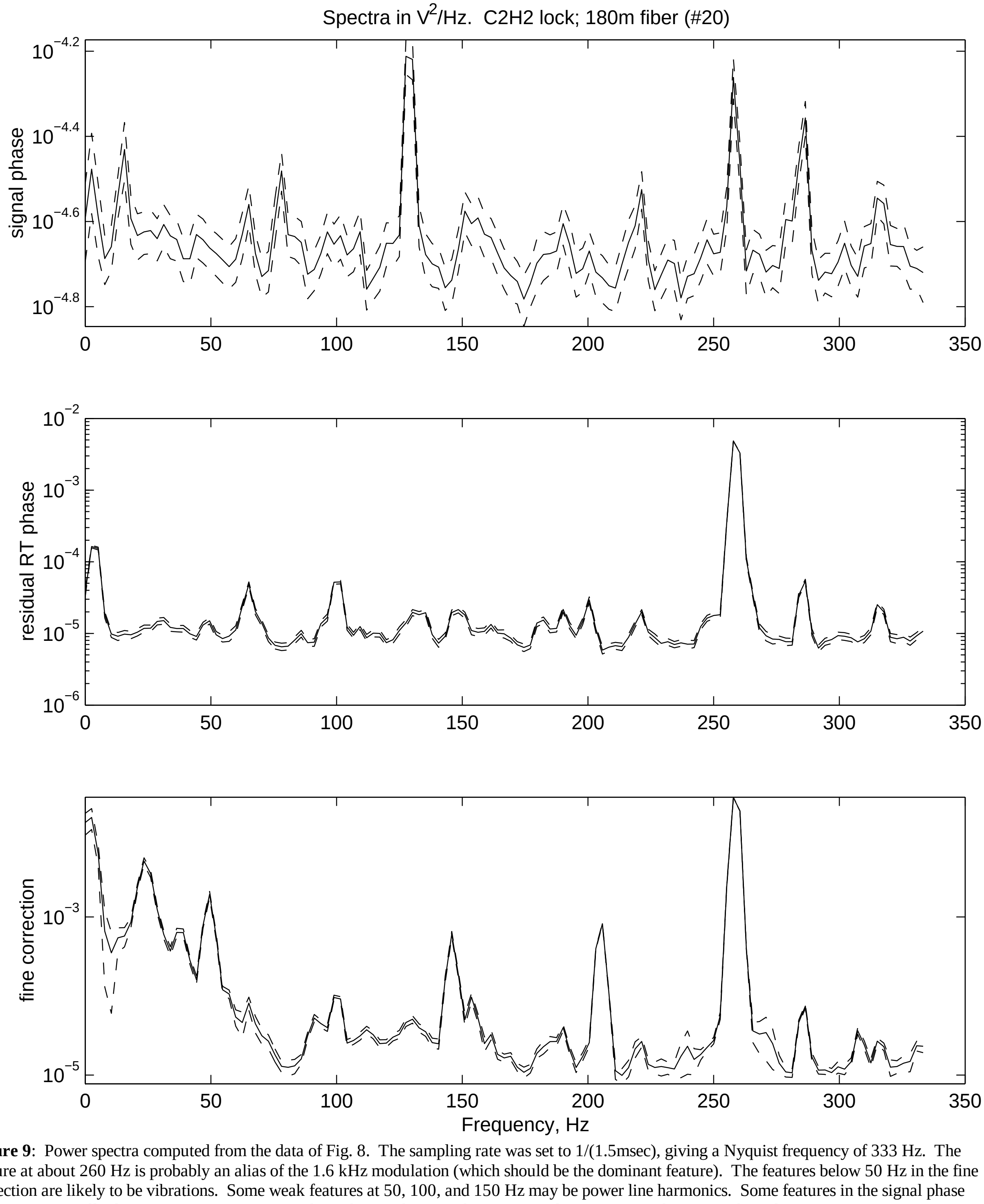

Figure 9: Power spectra computed from the data of Fig. 8. The sampling rate was set to 1/(1.5msec), giving a Nyquist frequency of 333 Hz. The feature at about 260 Hz is probably an alias of the 1.6 kHz modulation (which should be the dominant feature). The features below 50 Hz in the fine correction are likely to be vibrations. Some weak features at 50, 100, and 150 Hz may be power line harmonics. Some features in the signal phase spectrum, especially the one near 130 Hz, are much weaker or absent in the correction loop spectra and are unexplained.

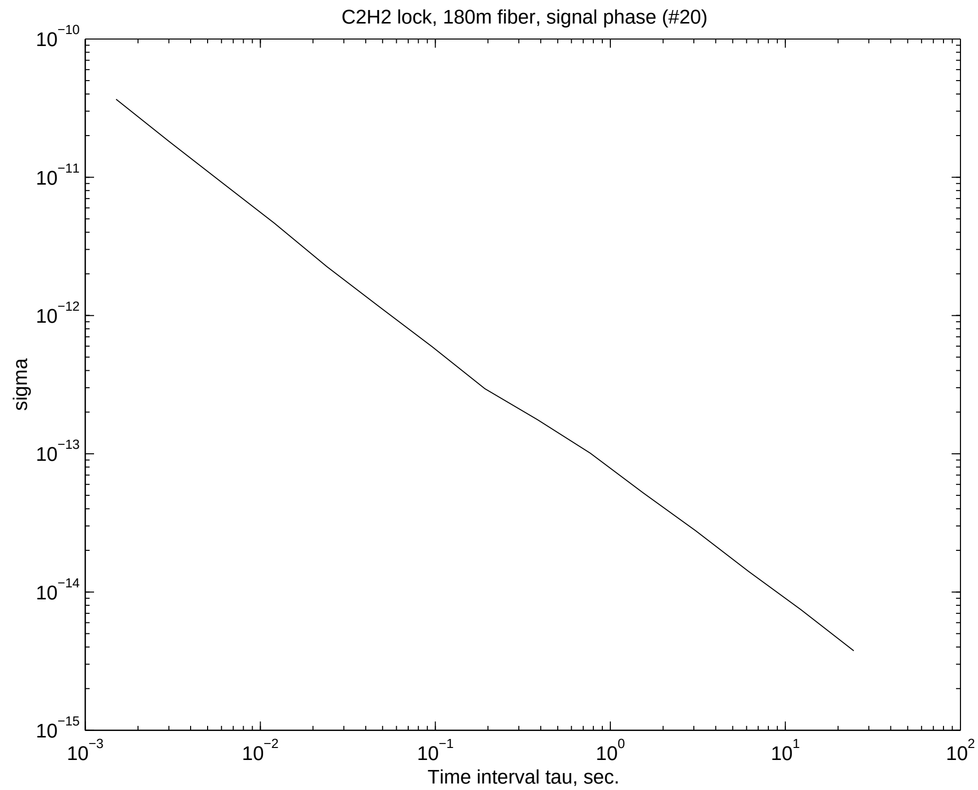

Figure 10: Allan standard deviation of the signal phase data from Fig. 8 at a frequency of 26.625 GHz.

6. Conclusions

Correct operation of the line length correction system has been demonstrated with a wavelength

stabilized master laser. The laser's frequency stability on time scales longer than 1 sec is such that it contributes no measurable error in the fiber length. These measurements were limited to a fiber length of 180 m and a signal frequency near 26 GHz, so it was not possible to determine the performance to the precision required for ALMA. Nevertheless, an upper limit of about 70 fsec was placed on the residual delay error in the stabilized fiber. The results here can be compared with earlier measurements in Tucson [6] which used a longer fiber (10 km) and a master laser with good short term stability (coherence length) but without long term frequency stabilization; those measurements were dominated by the laser's frequency drift.

Further work is planned. A new acetylene-stabilized laser under development at the UEC will be available soon, and it will have dither-free output. Procurement of a prototype master laser meeting all ALMA requirements is underway. Definitive tests should be possible once these devices are available. Meanwhile, the frequency responses of the line stretchers will be fully characterized and the correction loop controller design will be upgraded to obtain larger loop bandwidth. Tests will be made using the fiber ring laser available in Tucson, which has good coherence and short term stability but excessive long-term drift, by attempting to measure and account for the frequency drift.

7. Acknowledgments

The authors thank Denis Urbain for detailed design and construction of the test box and Andrea Vaccari for the special firmware on the AMBSI board that facilitated the data acquisition. The measurements in Japan were carried out with very valuable assistance by Yohei Sato of UEC.

REFERENCES

[1] J. Payne, B. Shillue and A. Vaccari, "Photonic Techniques for Use on the Atacama Large Millimeter Array." ALMA Memo No. 267, June 1999.
[2] K. Nakagawa and A. Onae, "Development of an acetylene optical frequency standard at 1.5 μm and its application." *Proc. SPIE*, vol 4269 p 41 (2001).
[3] M. Brooks, "ALMA monitor and control bus AMBSI-1 standard interface design description." ALMA Computing Memo #13, 2002-Mar-05.
[4] L. D'Addario, "Plots of Data Collected in Line Length Correction Tests, 2002 Dec 18-21," internal report dated 2003-Jan-08. Available on request from mailto:ldaddario@nrao.edu .
[5] S. Al Banna, digital photographs taken during tests. Available through ALMA Electronic Document Management, http://almaedm.tuc.nrao.edu .
[6] B. Shillue, "ALMA LO Distribution Round Trip Phase Correction," ALMA Memo No. 443, 2002-Nov-14.