HIGH-PERFORMANCE RF OPTICAL LINKS

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Abstract

Transferring a master reference signal across a research campus or even across a region is a key activity for a timing facility. In the past, the U.S. Naval Observatory (USNO) has used techniques ranging from coaxial cables to basic fiber links to transfer 5 MHz Master Clock signals. Recently, USNO installed new fiber runs on its campus, along with newly designed laser modules. Several months of data have now been collected with the new transceivers driving these inter-building fiber links. The modules were also tested in an environmental chamber to evaluate their temperature sensitivities. The laser modules alone show more than a factor of 10 improvement over previous transceivers used at USNO. We are also investigating actively stabilized laser links to further improve our ability to transfer Master Clock signals.

INTRODUCTION

The USNO is the common time reference for the Department of Defense (DoD) and also holds the responsibility for dissemination of this time reference. Currently, our best Precise Time and Time Interval (PTTI) dissemination is by two-way satellite time transfer (TWSTT) and/or GPS carrier phase, with stabilities as good as 10^{-15} over a day of averaging. With the implementation of the Rb fountain ensemble, the USNO Master Clock is expected to operate at the 10^{-16} level in the long term. We therefore require a more precise means of delivering our PTTI products to our external customers. USNO also has clocks in and time transfer needs between three different buildings in Washington, DC and in one building in Colorado Springs, Colorado. Our initial efforts have focused on better ways to connect the clocks in the different buildings at USNO in DC.

IMPROVED HARDWARE FOR UNCOMPENSATED LINKS

Earlier solutions for connecting the clocks between buildings at USNO had various drawbacks. Using temperature-insensitive coaxial cable leaves one susceptible to lightning storms, electrical pickup, and large ground loops between buildings. Earlier fiber links were noisier than our current clock performance and the transmit and receive hardware was very sensitive to environmental effects. In an initial attempt to improve our campus configuration, we searched for better commercial laser solutions. We then tested several vendors' solutions to find the one with the lowest noise and best frequency stability.

The initial goal was to establish a campus link that would provide the performance necessary to transfer signals from hydrogen masers, Rb fountains, and possibly future clocks. To understand the necessary performance, we looked at the typical performance of a hydrogen maser and compared it to the measured performances of our old laser setup, as well as our new laser setup. Figure 1 shows a comparison of the phase noise and Figure 2 shows the Allan deviation.

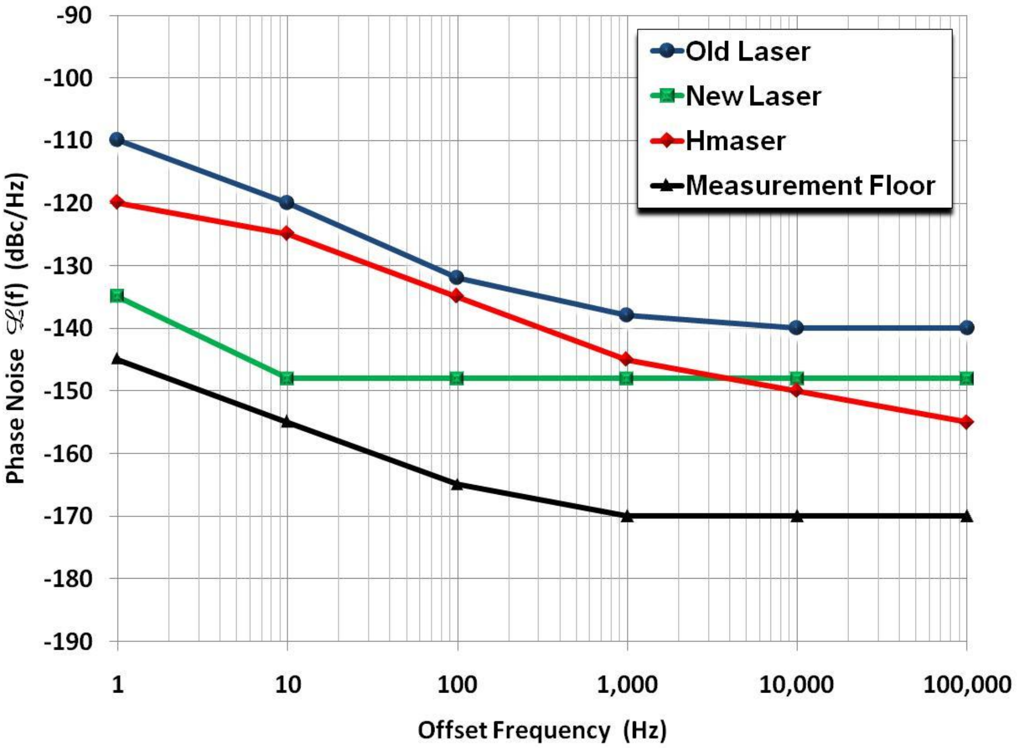


Figure 1. Phase noise of the new and old laser links. Also shown is the typical phase noise of an active hydrogen maser and the noise floor of the measurement system.

The test shown in Figure 1 used a low-noise 5 MHz oscillator to produce the test and reference signals. The test signal was connected to a transmit module, which was in turn connected via fiber to a receive module. The output of the receive module was then connected to a measurement system and compared against the original oscillator signal. The noise floor of the measurement system is also shown in Figures 1 and 2. One can see from Figure 1 that the phase noise of the new laser system is a clear improvement over that of the previous generation.

The test setup for Figure 2 is the same as the setup for Figure 1, but in this case the Allan deviation is shown. The short-term maser performance was estimated by calculating the effect that the 500 Hz bandwidth would have on our maser measurements. One can see here that the new laser is clearly better than the previous system. The table in Figure 3 summarizes the performance tests conducted on the two laser systems. In every parameter we measured, the new system is superior to the older one.

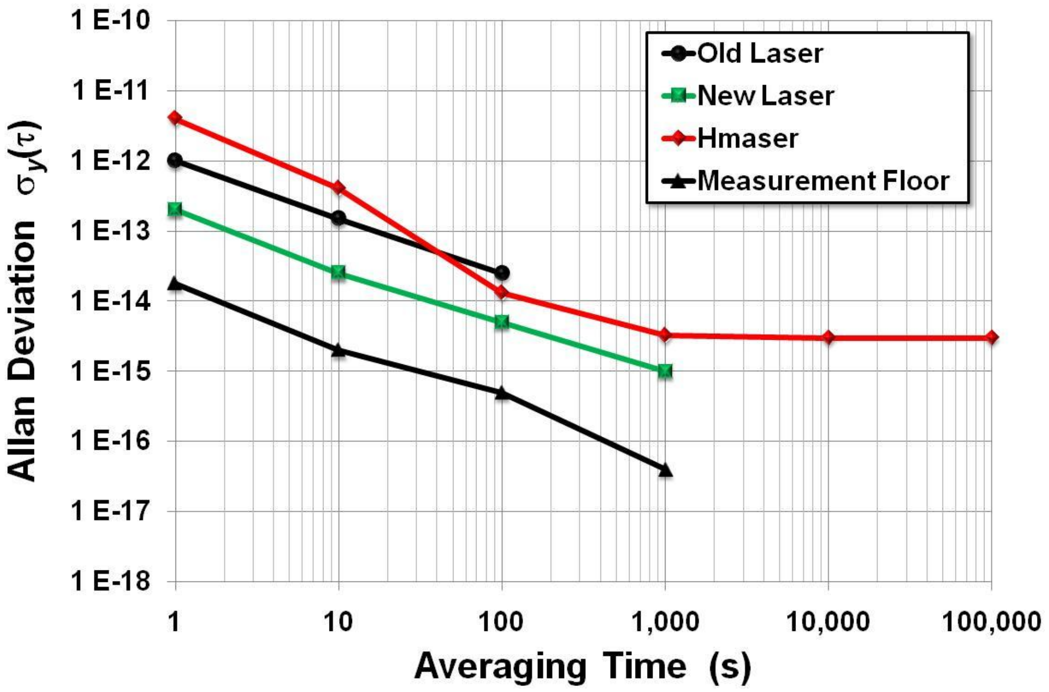
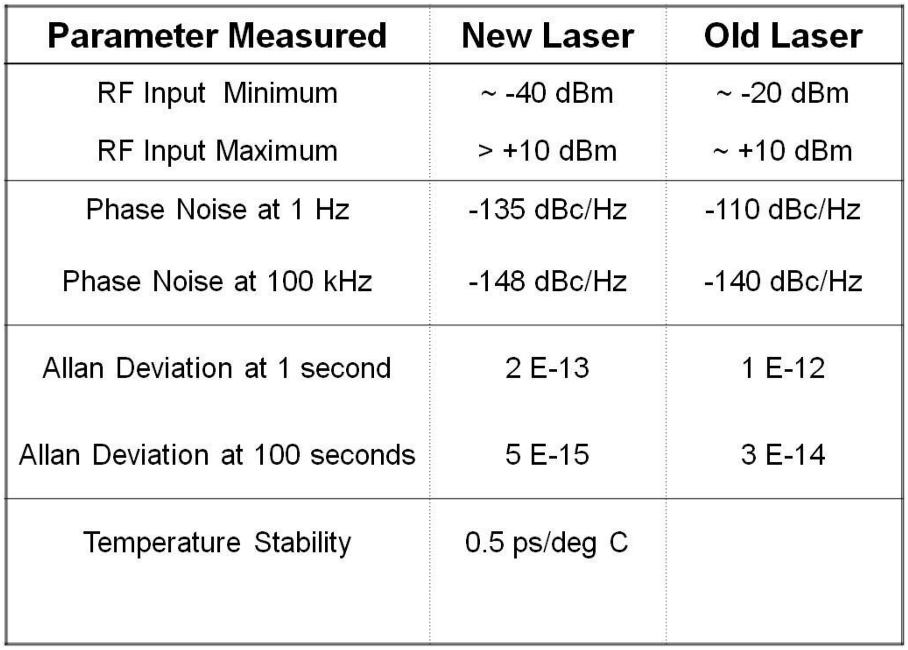


Figure 2. Allan deviation of the new and old laser transceiver systems. Also shown is the measurement system noise floor and the phase noise of an active hydrogen maser (see text for explanation of measurement bandwidth).



Parameter Measured	New Laser	Old Laser
RF Input Minimum	~ -40 dBm	~ -20 dBm
RF Input Maximum	> +10 dBm	~ +10 dBm
Phase Noise at 1 Hz	-135 dBc/Hz	-110 dBc/Hz
Phase Noise at 100 kHz	-148 dBc/Hz	-140 dBc/Hz
Allan Deviation at 1 second	2 E-13	1 E-12
Allan Deviation at 100 seconds	5 E-15	3 E-14
Temperature Stability	0.5 ps/deg C	

Figure 3. Summary of the test results for both the old and new laser transceiver modules. Allan deviations are measured with a 500 Hz bandwidth.

After performing the initial tests described above on the new modules, we installed new single-mode fiber runs between our buildings and conducted an 8-month data collection campaign to study the performance of the laser modules over a 700-foot inter-building connection. We had both standard single mode fiber as well as temperature-compensated single-mode fiber installed. These runs are located in buried conduit and pass under a road between the two buildings. Figure 4 shows the performance of these new fiber links using the same types of new laser modules. Outliers have been left in to give a real-life view of what happened to the links.

There are three different experiments represented in Figures 4 and 5. All tests go from one building to a second building, loop back onto another fiber, and return to the original building where we evaluate the stability of the transfer. One test (blue traces) is run on standard telecommunication fiber and is looped back with an optical interconnect in the second building. The second and third tests are on the temperature-insensitive fiber with either an optical interconnect at the second building (green traces) or a conversion from optical to rf and back to optical (using the new laser transceivers) in the second building (red traces).

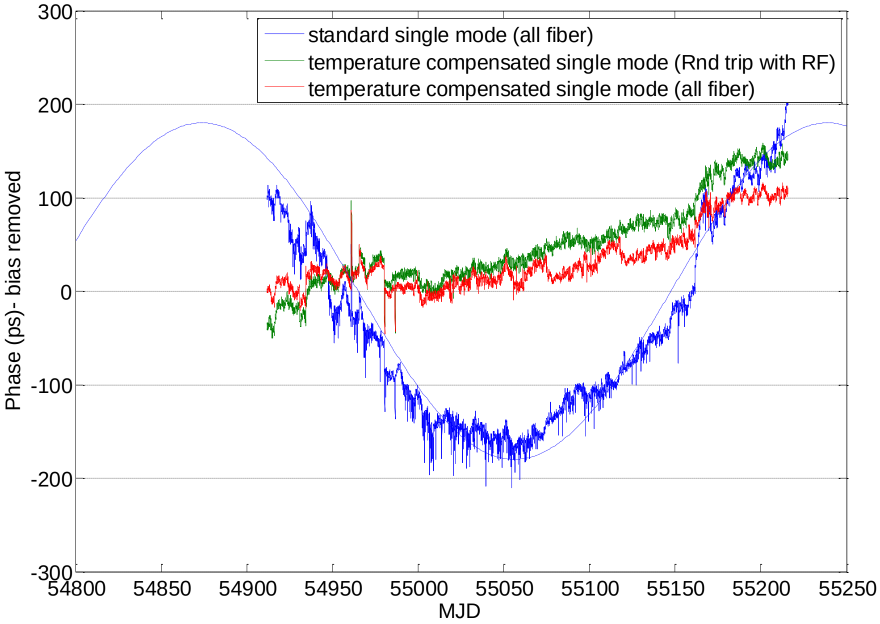


Figure 4. Phase records from inter-building fiber link tests. Each data set uses a 700-ft link that goes out to and back from a second building at USNO. The red and green traces are data from temperature-insensitive fibers and the blue trace is data from standard telecommunication fiber.

The data from Figure 4 were processed to determine the Allan deviations, which are shown in Figure 5. All three tests showed excellent performance with the new laser modules. These tests were conducted using our Master Clock as the reference signal. The link performances are sufficient to transfer typical hydrogen maser and Rb fountain performance over this relatively short distance. The slight degradation of the stability at long times with the standard single-mode fiber is almost certainly due to annual temperature changes in the fibers.

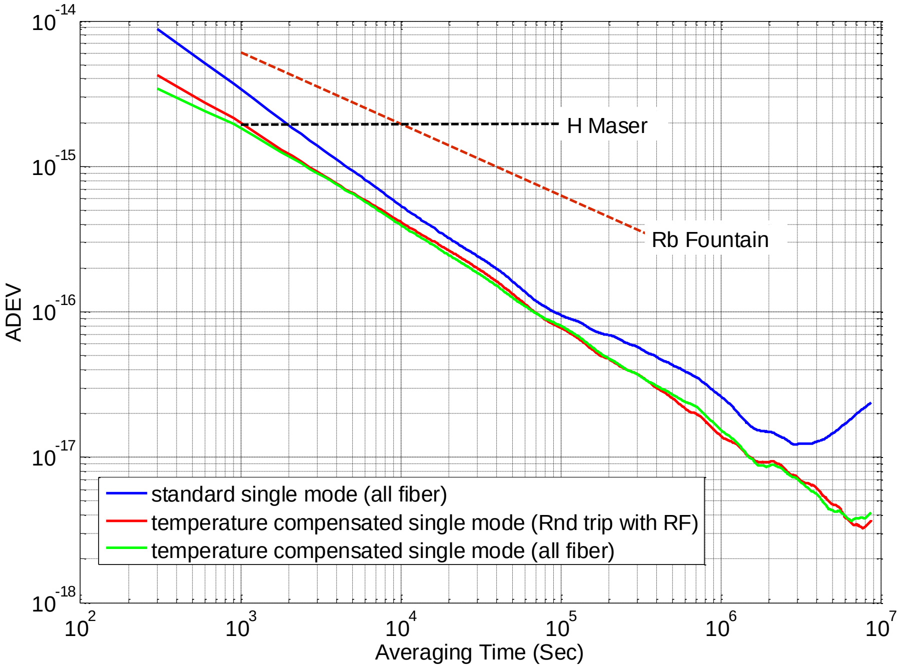


Figure 5. Allan deviation of the phase records in Figure 4. Also included are the typical white frequency noise of a Rb fountain and flicker frequency noise of an active hydrogen maser. Data length is over 8 months.

The new lasers have been integrated in a modular unit that takes 1RU of space. The resulting product is shown in Figure 6. It has hot-swappable transmit and receive modules (up to 6 total) and dual-redundant power supplies that load from the rear of the chassis. This solution provides not only a high-performance unit, but one that is robust and easy to service while it is in operation.

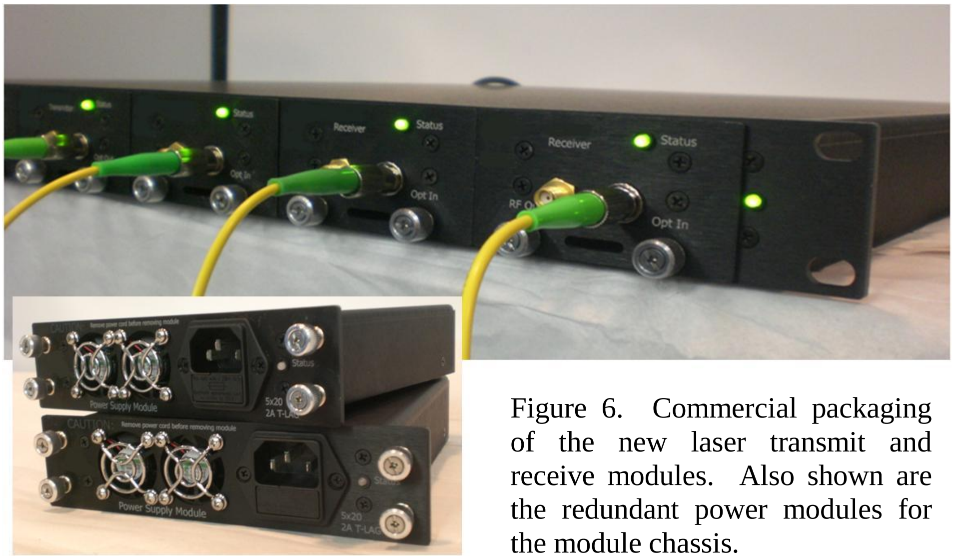


Figure 6. Commercial packaging of the new laser transmit and receive modules. Also shown are the redundant power modules for the module chassis.

ACTIVELY STABILIZED LINKS

Developing fiber timing links with either lower noise or longer length requires that one measures and corrects for the changing link delays. These corrections can be applied while post-processing data, or they can be applied as real-time corrections to the link itself.

Both passive **[1]** and active systems have shown impressive results, and we will be concentrating on actively stabilized systems. A generic scheme for phase-noise cancellation system is shown in Figure 7, in which a signal is sent out over some medium – in our case optical fiber. At the remote end, a portion of that signal is split off and returned to make a comparison with the reference frequency/time after having passed twice through the delay medium. The effects of temperature changes and/or acoustic/mechanical vibrations/disturbances in the fiber/medium are then detected and corrected for by adjusting the phase of the outgoing signal. At the far end, this scheme produces a phase-coherent signal up to the limitations of the compensation system. Actively stabilized systems can be divided into two categories: coherent optical systems that require correction of the phase delay **[2-4]** and amplitude-modulated systems that require stabilization of the group delay **[5]**. There has also been recent success in the transfer of femtosecond frequency combs over compensated systems **[6]**. While the coherent optical systems show better stabilities they require more complex laser systems.

We will be concentrating on amplitude-modulated systems, as they will provide sufficient stability for transfer of the USNO Master Clock performance after operational inclusion of the Rb fountains. Our preliminary system is referenced with a 5 MHz signal and recovers a 5 MHz signal at the remote end of the link. The amplitude modulation on the fiber is at 6.8 GHz for the forward direction and 6.9 GHz on the return.

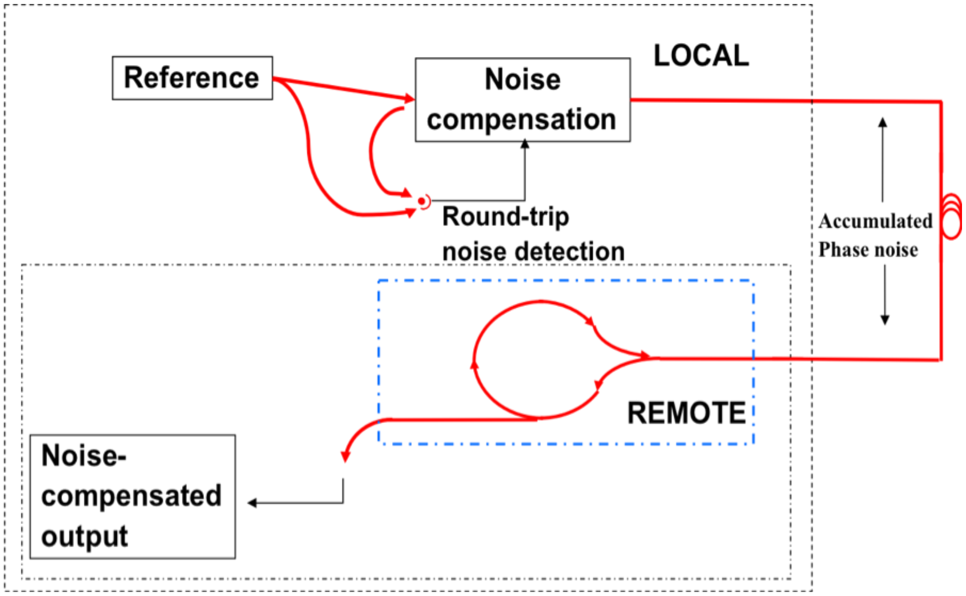


Figure 7. General two-way fiber link with error correction.

SUMMARY

We have developed campus-scale optical-fiber links for use at USNO. During their evaluation period last year, these links were used to deliver the stability of the Rb fountains between buildings for integration times of 1000 and 10^6 seconds. We are currently designing and testing a scheme to do active compensation that will be sufficient for transferring the stability of the fountains for short-term comparisons as well. We are also currently investigating access to fiber and schemes for delivering our PTTI products to customers over urban fibers. Our long-term goal is to establish a 2000-km link between the USNO in Washington, DC and our alternate clock facility at Schriever Air Force Base in Colorado Springs, Colorado.

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