

# High-Precision Ranging and Range-Rate Measurements over Free-Space-Laser Communication Link

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**Abstract**— We present a high-precision ranging and range-rate measurement system via an optical-ranging or combined ranging-communication link. A complete bench-top optical communication system was built. It included a ground terminal and a space terminal. Ranging and range rate tests were conducted in two configurations. In the communication configuration with 622 data rate, we achieved a two-way range-rate error of 2  $\mu\text{m/s}$ , or a modified Allan deviation of  $9 \times 10^{-15}$  with 10 second averaging time. Ranging and range-rate as a function of Bit Error Rate of the communication link is reported. They are not sensitive to the link error rate. In the single-frequency amplitude modulation mode, we report a two-way range rate error of 0.8  $\mu\text{m/s}$ , or a modified Allan deviation of  $2.6 \times 10^{-15}$  with 10 second averaging time. We identified the major noise sources in the current system as the transmitter modulation injected noise and receiver electronics generated noise. A new improved system will be constructed to further improve the system performance for both operating modes.

**Index Terms**—Space Optical ranging, Doppler range rate, Doppler ranging, space optical navigation, space optical communication, formation fly.

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## I. INTRODUCTION

In spacecraft navigation and tracking, range and range-rate are the most commonly used tracking observables. Currently this is done with Doppler shift of a microwave carrier that provides the spacecraft-Earth relative velocity along the line of sight [1,5]. ESA and NASA Doppler tracking systems rely on two-way coherent radio links at X-band (7.2-8.4 GHz). The average measurement accuracy ranges from 100 to 20  $\mu\text{m/s}$  at 60s integration time. ESA has conducted a study for enhancement of end-to-end accuracy for spacecraft tracking techniques. It sets the target accuracies to 10  $\mu\text{m/s}$  at 60 s integration time for Doppler (two-way) [6].

High-precision Doppler ranging also enables the gravitational science missions such as Gravity Recovery and Climate Experiment (GRACE [7]) and Gravity Recovery and Interior Laboratory (GRAIL). GRAIL is a spacecraft-to-spacecraft tracking mission that was developed to map the structure of the lunar interior by producing a detailed map of the gravity field [4].

One of the primary noise sources with RF Doppler ranging is the plasma (interplanetary and Earth ionosphere). It becomes a performance limitation when Sun-Earth-probe (or SEP angle) is less than 30 degrees [2]. This noise source impacts both interplanetary and low-earth-orbit (LEO) Doppler tracking accuracies. To achieve the NASA and ESA required performance specifications, a dual frequency RF ranging system was needed to calibrate out the plasma caused ranging error [5]. This increased the instrument size and complexity.

To overcome the plasma limit to the signal-to-noise ratio of RF ranging, the ranging measurement can be performed on an optical carrier with a RF subcarrier or with synchronized optical communication links. The Lunar Laser Communication Demonstration (LLCD) has conducted such synchronized laser ranging tests over an optical communication link. LLCD achieved sub-centimeter ranging accuracy [3].

There are several advantages of ranging with the optical carrier. First, plasma scintillation phase noise [5] is one of the fundamental performance noise sources for RF ranging, especially at small Sun-Earth-Probe (SEP) angles [1, 5]. The magnitude of this noise is proportional to square of the wavelength [5]. The optical carrier has a significantly shorter wavelength. This eliminates the effects of the plasma on the noise in optical ranging. Second, the high directionality of the

optical signal (high antenna gain) makes long ranging links feasible. Third, the directionality of optical beam makes optical ranging instrument very small. It makes a Cubesat-compatible high-precision science instrument feasible. Fourth, the clock signal is intrinsic for synchronized optical communication. There is no major hardware upgrade on an optical communication platform with clock recovery hardware already present.

This paper is arranged as follows: First, an introduction gives an overview of our work and the related background. Second, the instrument configurations and corresponding test results are presented. It includes a description of a Dual Mixer Time Difference (DMTD) measurement apparatus. The DMTD provides increased system sensitivity. We also give a description of two ranging operating modes and results: a) laser communication mode, b) single-tone optical amplitude modulation (AM) mode. Third, we show our data analysis and give a performance comparison of the different ranging modes, noise sources, and predicted instrument sensitivity. Last, a technical summary will be presented.

## II. CONFIGURATION AND PERFORMANCE

The ranging measurements were conducted in two different modes: ranging over optical communication (Fig. 5 ), where the recovered data clock is used for ranging and range rate measurement, and ranging over single tone optical amplitude modulation (Fig. 9 ), where the detected RF tone is used for ranging and range-rate measurements. All of clock phase measurements were conducted with the DMTD test apparatus.

We were using as many commercial-off-the-shelf (COTS) parts as possible to lower the cost and shorten the development time. The OC-12 protocol parts are selected for its availability, which has a data rate of 622 Mbps.

### A. DMTD TEST APPARATUS AND PERFORMANCE

All measurements of the frequency stability measurements used the DMTD. The best time-frequency counter on the market has time timing accuracy of  $\sim 10$ ps, which will have an instrument sensitivity level at  $10^{-11}$  for relative accuracy at 1 second averaging time. We require a sensitivity level of better than  $10^{-14}$ . A Dual Mixer Time Difference (DMTD) clock measuring system (see Fig. 1. ) was constructed. A DMTD system is a well-established way to make high-resolution phase measurements on precision frequency sources [10]. Both “Clock under Test” and “Ref Clk” are mixed with an RF signal ( $\Delta$ Frequency Oscillator). The  $\Delta$ Frequency Oscillator has a small frequency offset from “Clock under Test” and “Ref Clk” to generate IF frequencies as the output of the mixer. Two IF signals at the output of the mixers are low pass filtered and amplified before the “Time Interval Counter”. The signal phase is measured as the zero-crossing time difference of the two IF signals.

For the instrument noise floor test (see Fig.2), a single RF source at 622MHz is divided into two and feeds both Sig-Port and Ref-Port. The  $\Delta$ Fre Oscillator frequency is set at 622.001MHz, which gives a 1 KHz IF frequency. The heterodyne mixing gain for signal phase measurement is  $3.11 \times 10^5$  (622MHz/1kHz), which increases the counter sensitivity by 5 orders of magnitude.

The phase data and Allan Deviation of the system are shown in Fig. 3 and Fig. 4 respectively. Fig. 3 is a phase error plot with a sampling rate of 1 KHz. It has a zero-to-peak value of  $\sim 50$ fs. As shown in Fig. 4, the system has achieved a noise floor of  $1.6 \times 10^{-14}$  for the Allan deviation and  $9.3 \times 10^{-16}$  for the modified Allan deviation at a 1 second averaging time.

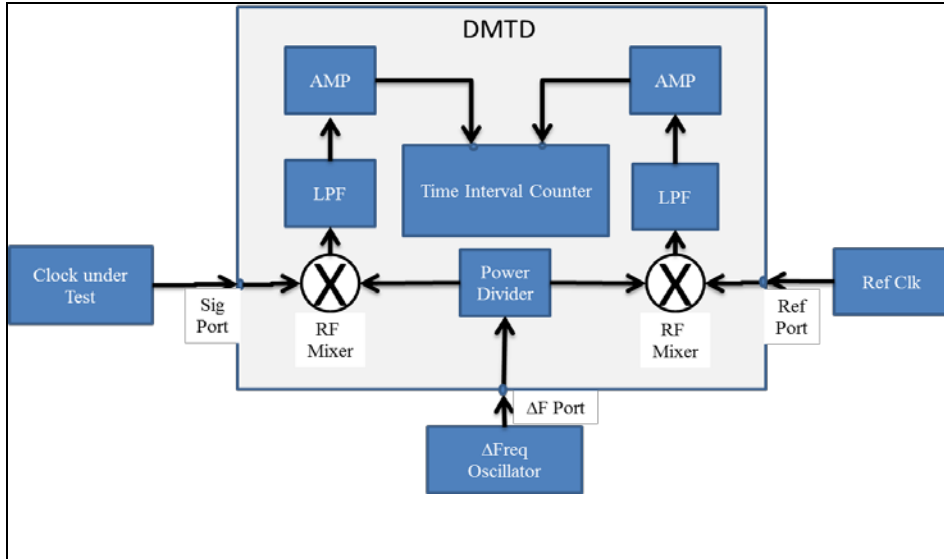


Fig. 1. Dual Mixer Time Difference (DMTD) phase measurement setup. “AMP” (low frequency amplifier for IF frequency).

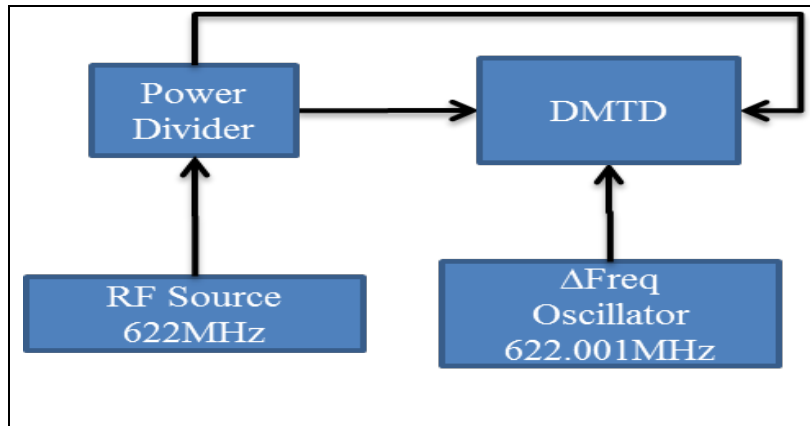


Fig. 2. Dual Mixer Time Difference (DMTD) noise floor test configuration. A frequency offset of 1KHz is used for IF frequency after mixer.

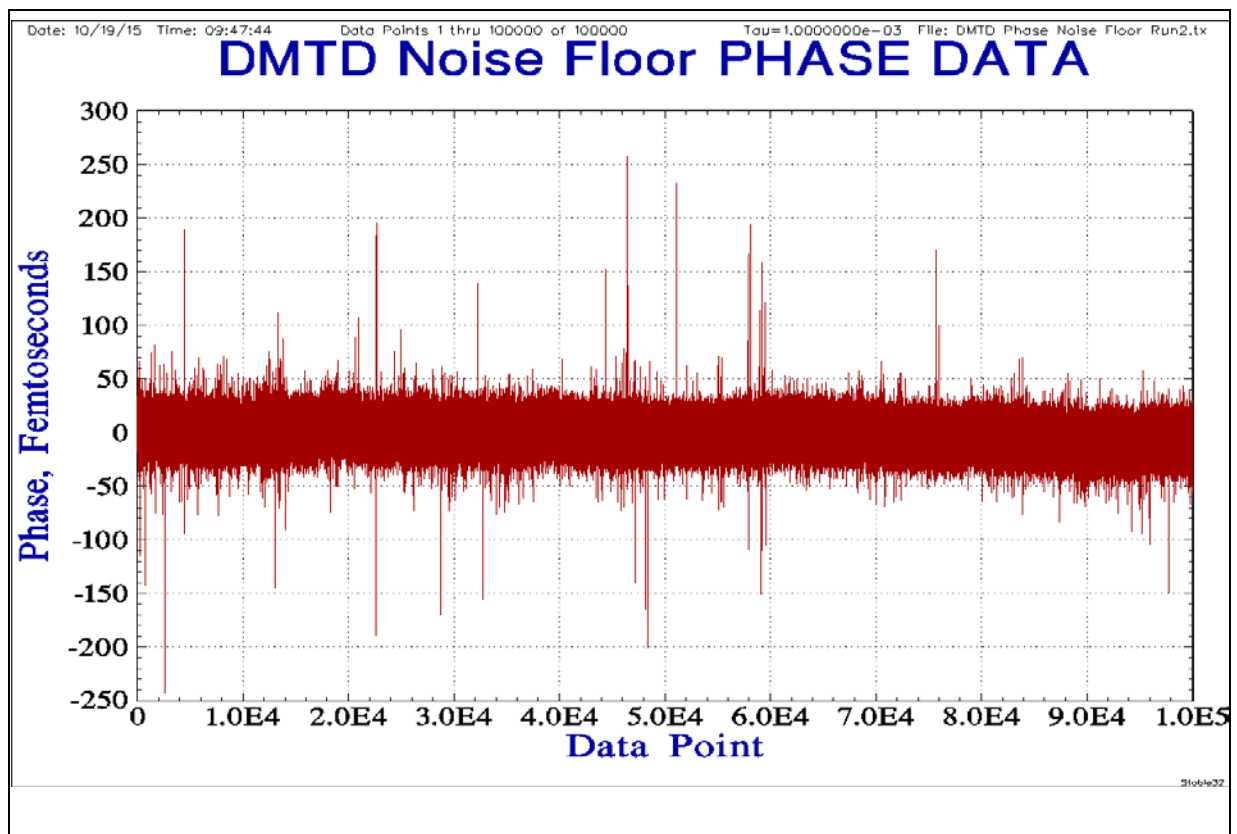


Fig. 3. Dual Mixer Time Difference (DMTD) phase measurement noise floor test results. Sequential phase error with sampling rate of 1KHz

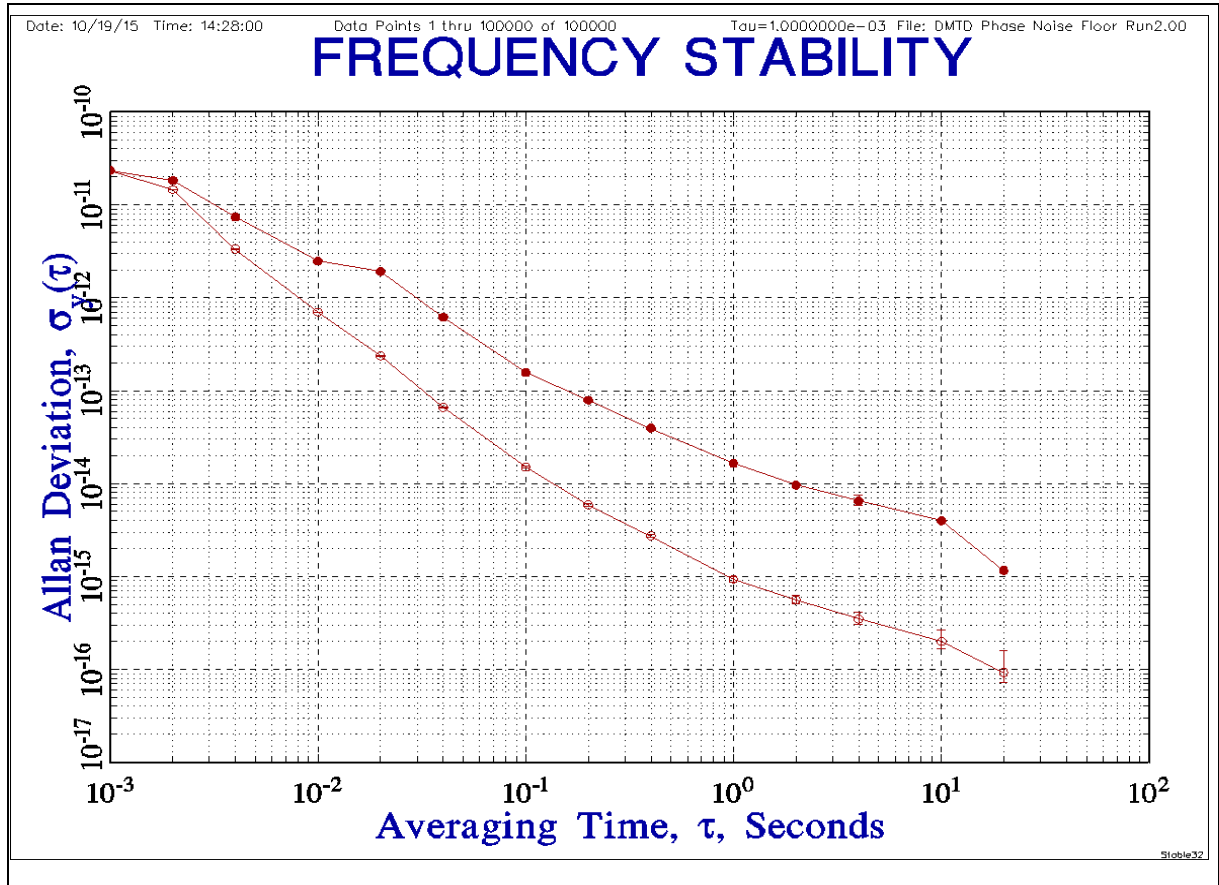


Fig. 4. Dual Mixer Time Difference (DMTD) phase measurement noise floor test results. Allan and Modified Allan deviation as a function of averaging time.

## B. OPTICAL COMMUNICATION MODE RANGING PERFORMANCE

The ranging over optical communication link test configuration is shown in Fig. 5. The system is operating at 622 Mbps (OC-12 rate) with a pseudo-random bit sequence (PRBS)  $2^{31}-1$ . The recovered clock is used for range-rate measurements.

The signal flow (Fig. 5.) is: “RF Source A” generates an RF clock at 622 MHz. It is divided into two signals with a “Power Divider”. One power divider output is used as DMTD reference input for the clock phase measurement. The other output of is driven the pattern generator to generate a PRBS  $2^{31}-1$  pattern at 622 Mbps, followed by a laser transmitter (“SFP Tx”, a commercial OC-12 transmitter with wavelength of 1550 nm). The optical output from the ground transmitter is then connected to the space receiver through an optical attenuator. The space terminal receives the signal, and realigns the data with the clock via the clock data recovery circuit. The realigned data is then looped back to drive the space optical transmitter. Then the optical signal is free-space coupled to the ground optical receiver. The signal is fed to the ground clock data recovery (CDR) circuit, one clock and one data signal are fed to the error detector for bit error rate testing. The other

clock signal is fed the Signal Port of the DMTD for clock phase measurement. A second RF source is generating an RF signal at 622.001MHz to drive the DMTD  $\Delta F$  port.

The range-rate accuracy as a function of BER is tested by varying receiver optical power.

All phase measurements of the recovered clock signal are taken with DMTD with sampling rate of 1 KHz. A typical phase measurement plot is shown in Fig. 6. The standard deviation of the phase amplitude is 0.5 ps, giving a 3-sigma value of 1.5ps.

Fig. 7. is the modified Allan deviations vs. averaging time for different receiver optical powers. The Allan deviations are not changing for all receiver optical powers (-18dBm to -33dBm) until the receiver CDR has a “Loss of Lock” at “-33.17 dBm” receiver power level. Under the “Loss of Lock” condition, the CDR output clock is not locked to the received data clock. At that point, the corresponding Allan deviation is no longer valid (Fig. 7., Trace “-33.17 dBm”).

Fig. 8. is a plot of range-rate accuracy as a function of BER for averaging time of 1second and 10 seconds. Again, the range-rate accuracies are the same for the entire BER rates until the CDR has the “loss of lock”. Range rate accuracies of 25 $\mu$ m/s for 1 second averaging time and 2.1 $\mu$ m/s for 10 second averaging time were achieved.

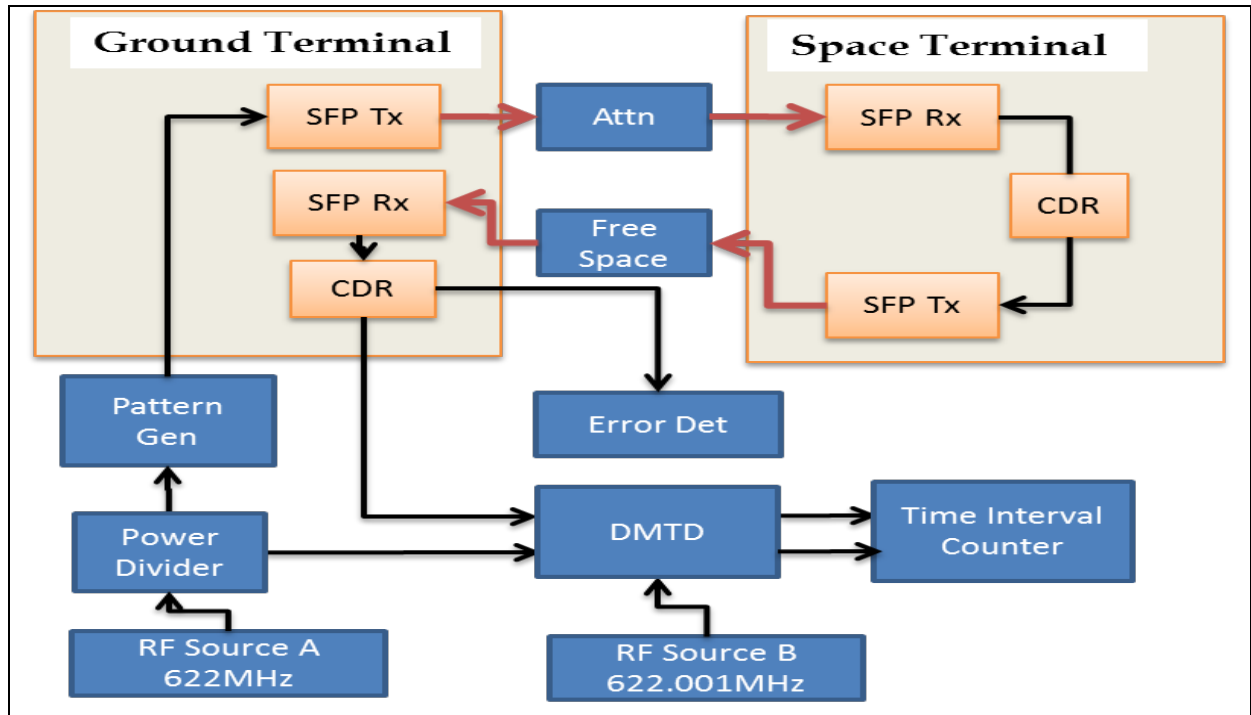


Fig. 5. Ranging over optical communication configuration. “SFP Tx”( Telecom OC-12 optical transmitter), “SFP Rx”(Telecom OC-12 optical receiver;”), “CDR”( clock data recovery circuit), “Attn”( variable optical attenuator), “Free Space”( Optical free space coupling telescope), “Pattern Gen”( communication data pattern generator), “Error Detector”( communication error detector), “Power Divider”( 3 dB RF power divider), “RF Source”( low noise RF frequency synthesizer), “DMTD”( Dual Mixer Time Difference measurement system), “Time Interval Counter”( high precision frequency and time interval counter).

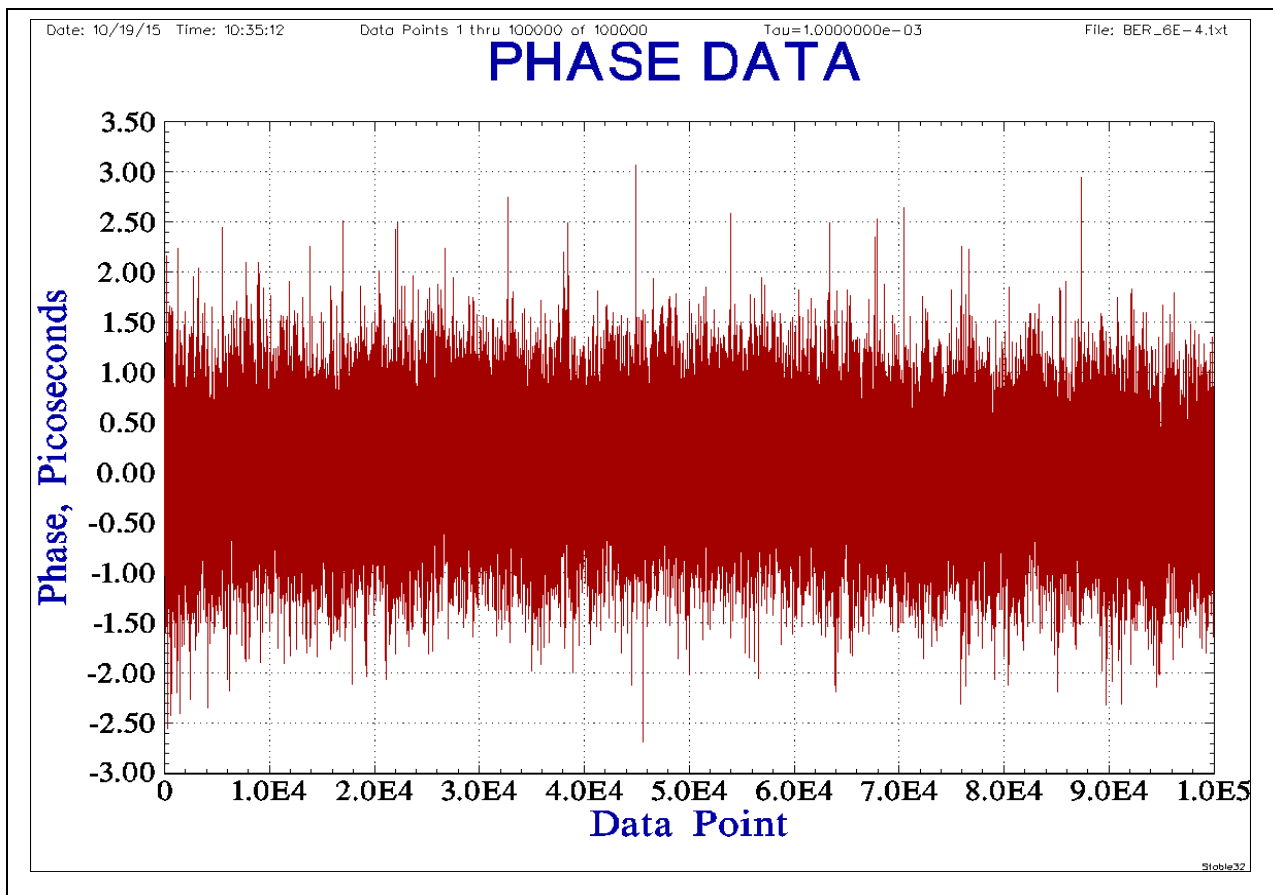


Fig. 6. RF ranging over 622MBPS optical communication: Phase measurements with an averaging time of 0.001s for a BER=6x10<sup>-4</sup> data link performance.

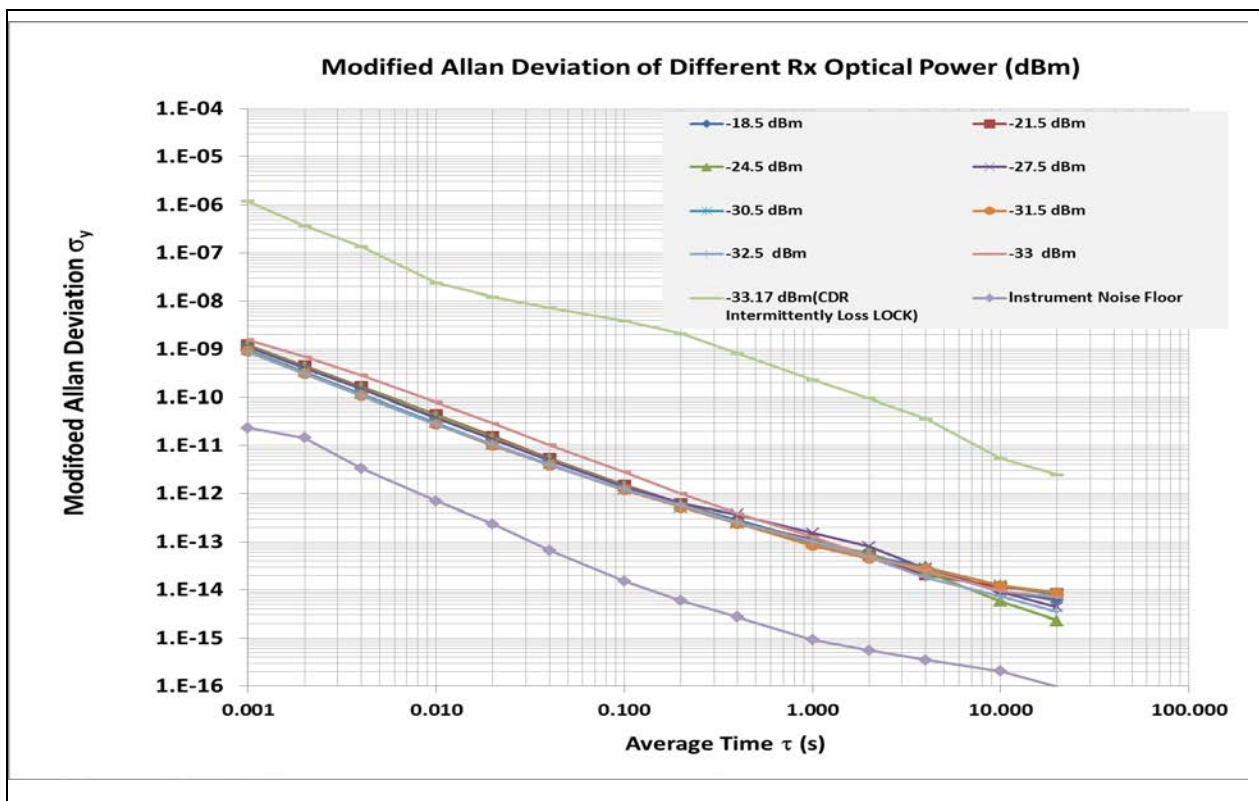


Fig. 7. Modified Allan deviation of RF ranging over 622Mbps optical link for different receiver optical power. Instrument noise floor is also plotted for reference. x-axis is the averaging time of the frequency measurement, y-axis is the Modified Allan deviation

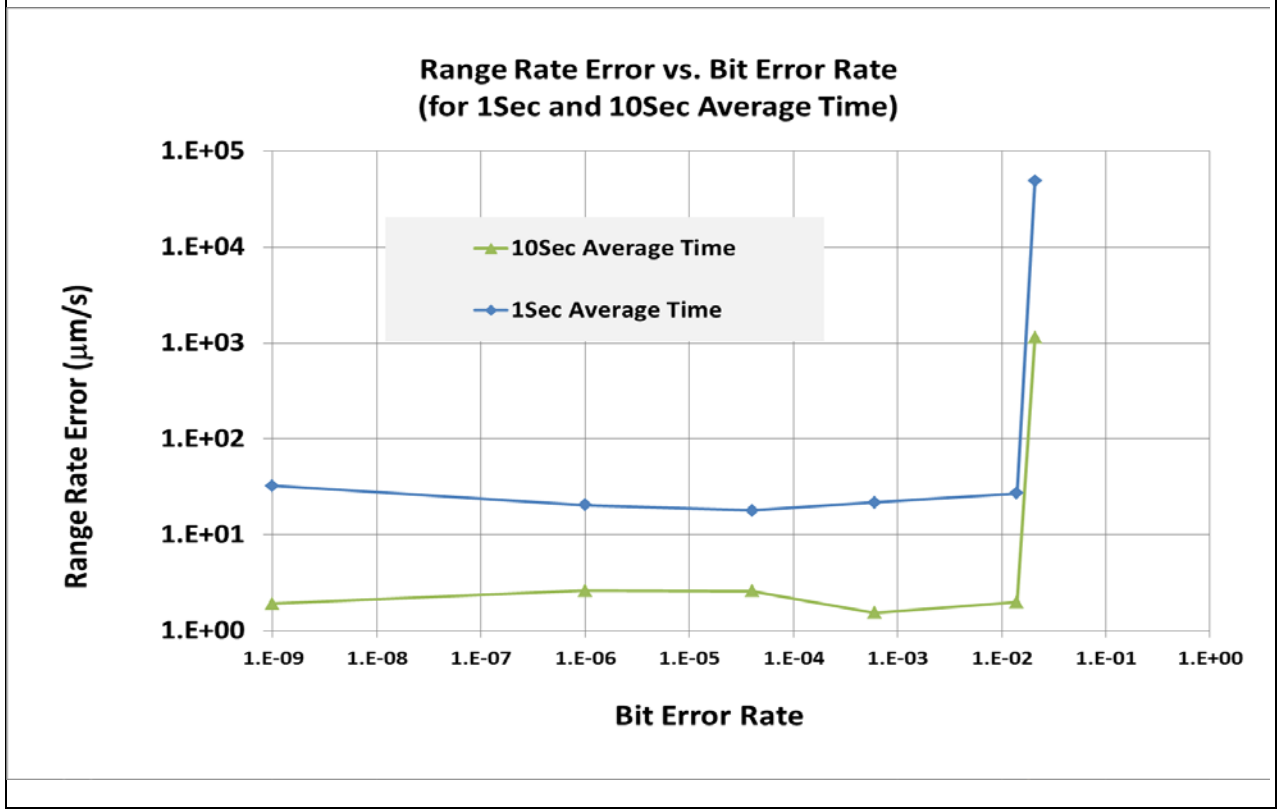


Fig. 8. Range-rate error as a function of receiver optical power. x-axis is the bit error rate (BER) of the communication link, y-axis is the rang rate error in  $\mu\text{m/s}$ . Two traces are shown in the figure for different average time of the frequency measurement (1second and 10 second).

### C. SINGLE TONE MODE RANGING PERFORMANCE

Ranging measurements were also conducted with single tone intensity modulation. Compared to the optical communication clock signal, the single-tone AM modulation will provide improved 622MHz RF signal power since there is no data modulation to introduce spectral broadening. This improves the signal-to-noise ratio for the clock used in the ranging measurement.

Similar to the optical communication ranging configuration, the signal flow (Fig. 9. ) is: "RF Source A" generates an RF clock at 622 MHz. It is divided into two signals with a "Power Divider". One power divider output is used as DMTD reference input for clock phase measurement. The other output drives a laser transmitter. The optical output is reflected back to a receiver by a retro-reflector. The receiver

RF signal is fed to the Signal Port of the DMTD for clock phase measurement. A second RF source is generating an RF signal at 622.001MHz to drive the DMTD  $\Delta F$  port.

Fig. 10. shows the phase measurements of the 622 MHz tone. It has a zero-to-peak value of 300 fs with an averaging time of 0.001s. Fig.10 gives the Allan and modified Allan deviation. Overall, it is factor of 6 away from the instrument noise floor. However, compared to the ranging over communication in Fig. 6. There is a factor of 10 improvements. The main contribution of the improvement is the increased RF signal power at 622 MHz frequency. There is flicker FM noise for averaging times in range of 0.1 s to 1 s. This flicker noise limits the range-rate accuracy for 1 s averaging time at 19.7  $\mu\text{m/s}$ . The signature of this flicker noise is also visible from the phase measurement plot in Fig.10. The range-rate accuracies are 19.7  $\mu\text{m/s}$  and 0.27  $\mu\text{m/s}$  for a 1 second and 10 second averaging time respectively.

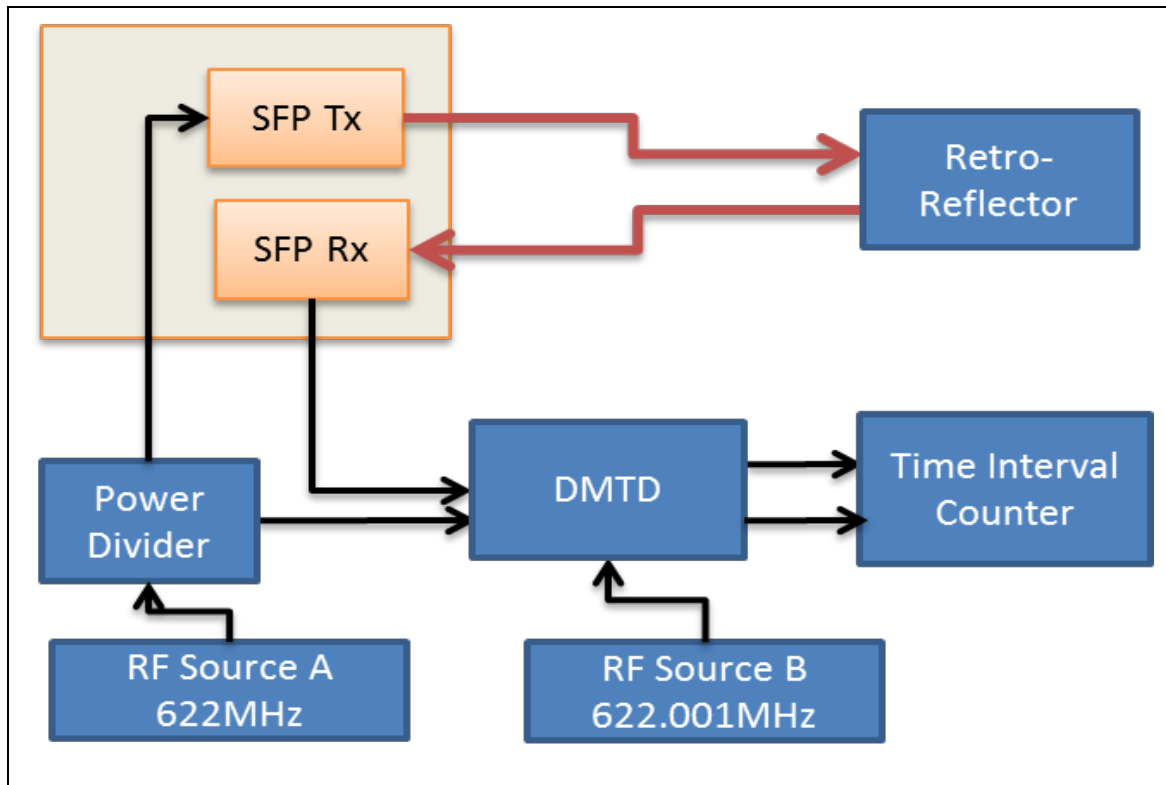


Fig. 9. RF ranging over optical tone modulation configuration. “SFP Tx”( Telecom OC-12 optical transmitter), “SFP Rx” (Telecom OC-12 optical receiver,”), “Retro-Reflector” (optical retro-reflector) “Power Divider” (3 dB RF power divider), “RF Source” (low noise RF frequency synthesizer), “DMTD” (dual mixer time difference measurement system), “Time Interval Counter” (high precision frequency and time interval counter).

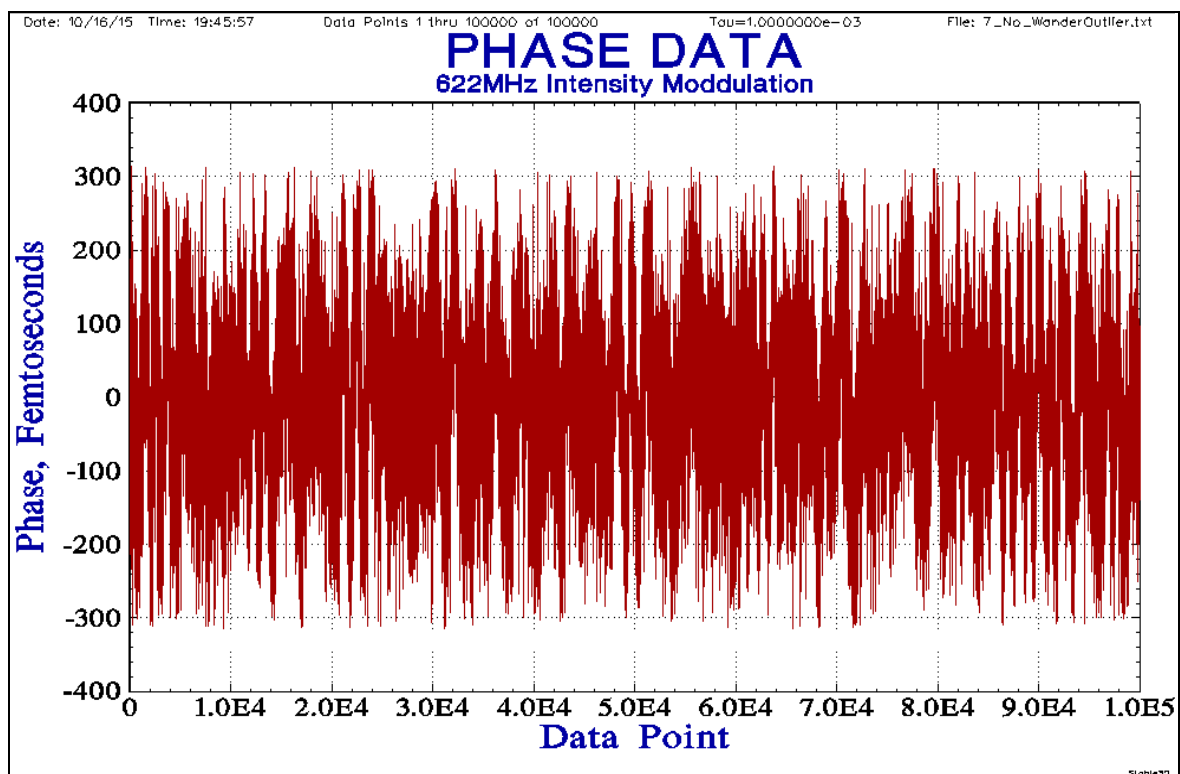


Fig. 10. 622Hz tone amplitude modulation ranging, phase measurements with an averaging time of 0.001s.



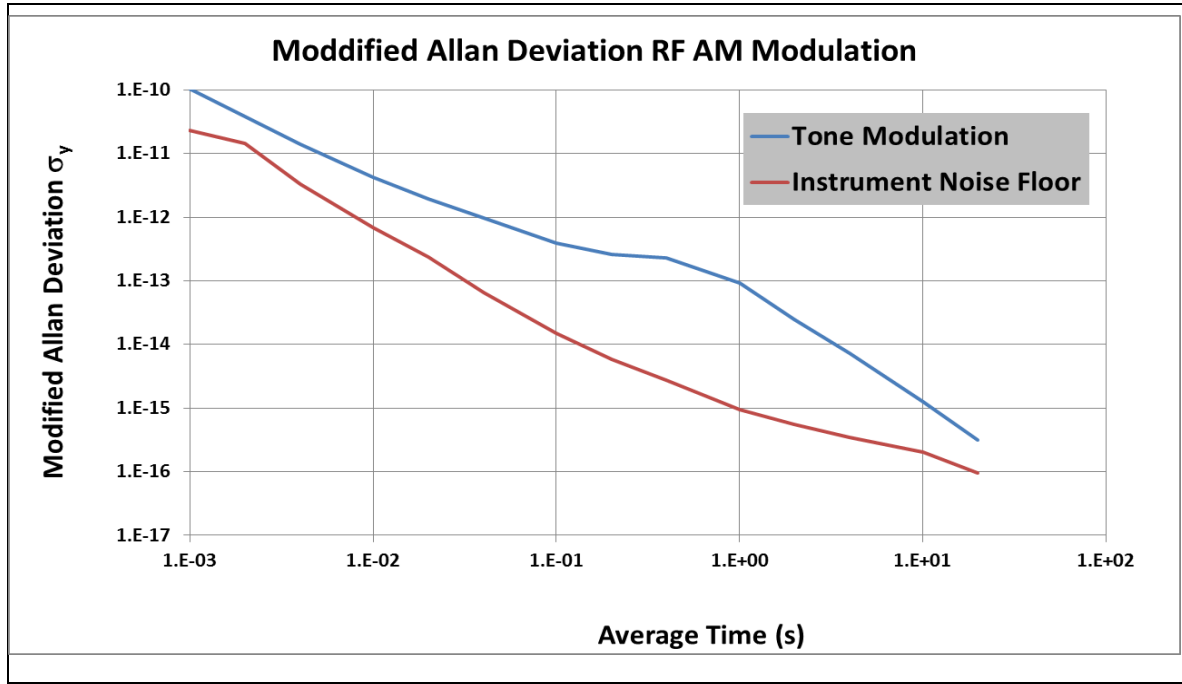


Fig. 11. 622MHz tone amplitude modulation ranging Modified Allan deviation and instrument noise floor.

### III. DISCUSSION

A DMTD system for accurate clock phase measurements has been built. The system exhibits a range rate  $0.28 \mu\text{m/s}$  for 1 second averaging time and  $0.06 \mu\text{m/s}$  noise floor (see TABLE I. ). The range rate measurements over an optical communication link at 622 Mbps for different optical power level (corresponds to different bit error rate) were tested. A range-rate of  $23.1 \mu\text{m/s}$  and  $2.1 \mu\text{m/s}$  for 1 second and 10 seconds averaging time respectively are achieved (see TABLE I. ). The range-rate does not change with the received optical power or bit-error-rate (see Fig. 8. ). This indicates that the shot and thermal noise are not the dominant noise sources. The dominant noise source is electronic noise. This is understandable since all of the optical transmitter and receiver, CDR and corresponding amplifiers are commercial-off-the-shelf parts. To improve the signal-to-noise ratio, single-tone optical amplitude modulation was used. Range-rates of  $19.74 \mu\text{m/s}$  for 1 second averaging time and  $0.27 \mu\text{m/s}$  for 10 seconds averaging time were achieved (see TABLE I. ). Compared to the communication configuration, range-rate results at 10 second averaging time have almost an order of magnitude better performance - improving from  $2.1 \mu\text{m/s}$  to  $0.27 \mu\text{m/s}$ . However, the range-rate at 1 second averaging time improved very little. This is due to the observed flicker FM noise from 0.1 to 1 second averaging time (see Fig. 14. ). The mostly likely cause for this flicker noise is the commercial OC-12 receiver and the RF mixer for frequency down-converting in the DMTD.

For comparison, the phase-noise power-spectral-density in dBc/Hz is calculated from each phase measurement point (see Fig. 13. , Fig. 14. , and Fig. 15. ). We chose a phase noise at 2 Hz Fourier frequency for comparison (see TABLE II. ). This is the point right before the FM flicker noise in the tone modulation is approaching the maximum (see Fig. 14. ). The phase noise is -120 dBc/Hz (instrument), -90 dBc/Hz (tone modulation ), and -80 dBc/Hz (communication link).

The noise increase of communication link compared to the tone modulation is due to spectral spreading from the data modulation, which reduced the power level of the 622 MHz data clock. This is supported with the following test. A test was configured with direct optical loopback at space terminal. So that the optical signal bypasses space receive, transmitter and CDR. Same ranging accuracies were obtained as the fully configured communication link.

The phase noise density increased from -120dBc (RF baseline ) to -90 dBc (tone modulation). Two major sources can contribute to this increase. One is the time delay between the DMTD start and stop times introduced by the reference clock timing error [12. 16,17], the other source is electronic noise from the optical transmitter, receiver and RF mixer. The electronic noise can be further improved with customer made components.

The phase noise is directly proportional to Allan deviation [13, 14, 15]. There is room for further improvement in both ranging modes phase noise. These improvements will increase the range-rate accuracy beyond the current values.

TABLE I. RANGE RATE ACCURACY

Average Time (s)	Range Rate Accuracy ( $\mu\text{m/s}$ )		
	Instrument Noise Floor	622MHz Tone AM Modulation	622MBPS Data Communiation
1	0.28	19.74	23.1
10	0.06	0.27	2.1

TABLE II.

Fourier Frequency (Hz)	Phase Noise Power Spectral Density (dBc/Hz)		
	Instrument Noise Floor	622MHz Tone AM Modulation	622MBPS Data Communiation
2	-120.00	-90.00	-80

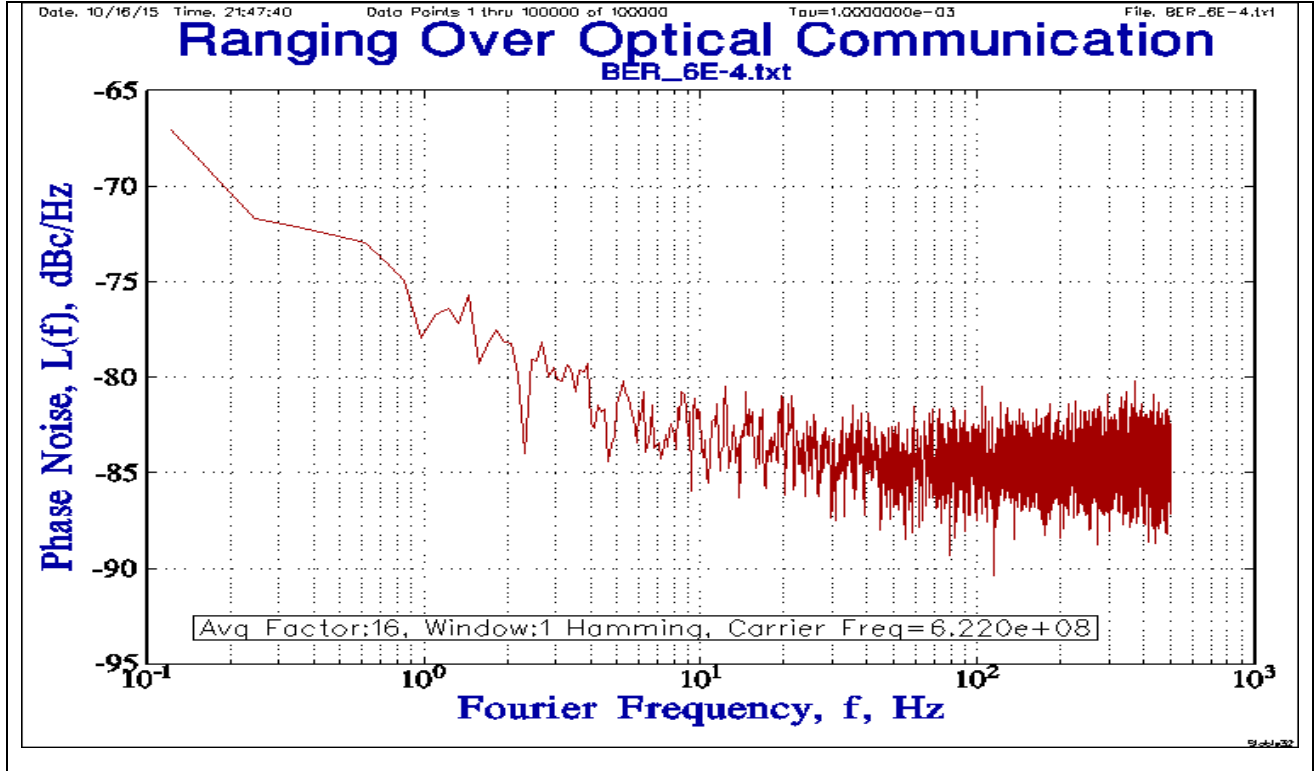


Fig. 12. Single side band phase noise power spectral density of optical communication mode.

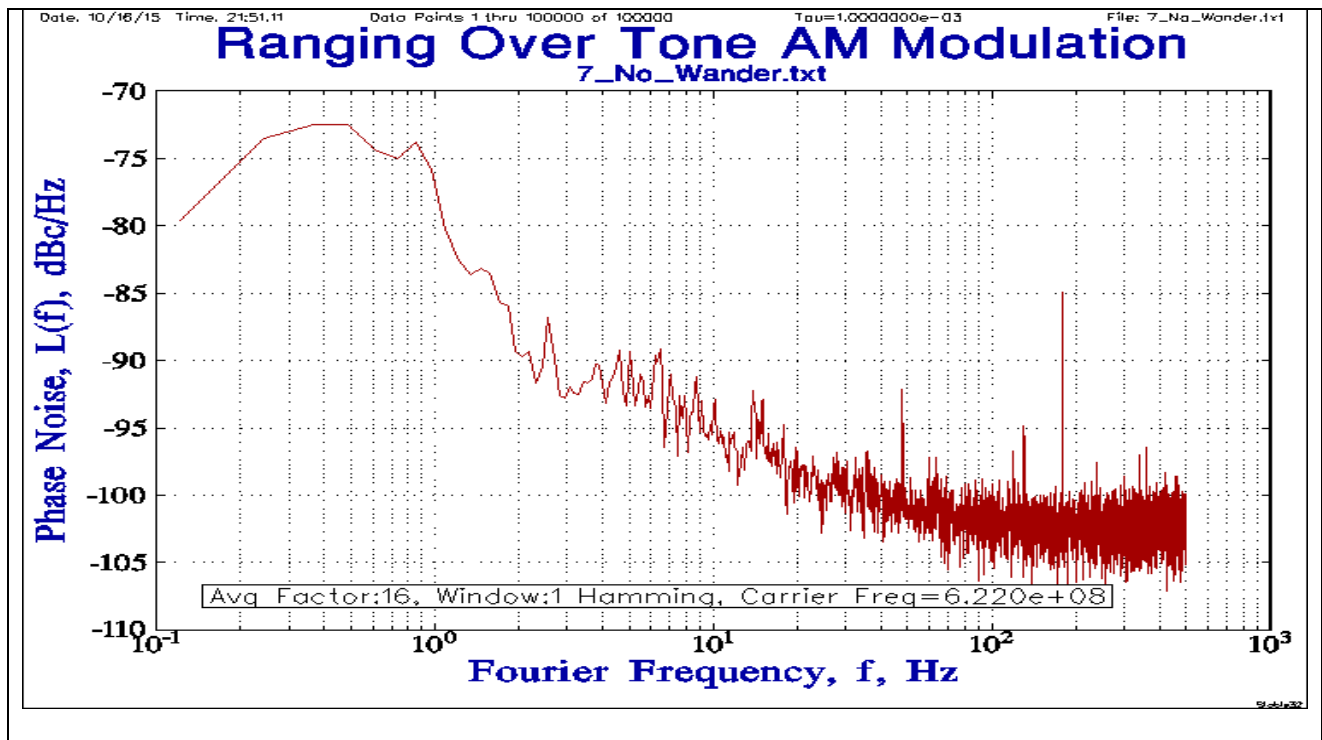


Fig. 13. Single side band phase noise power spectral density of Single Tone amplitude Modulation mode.

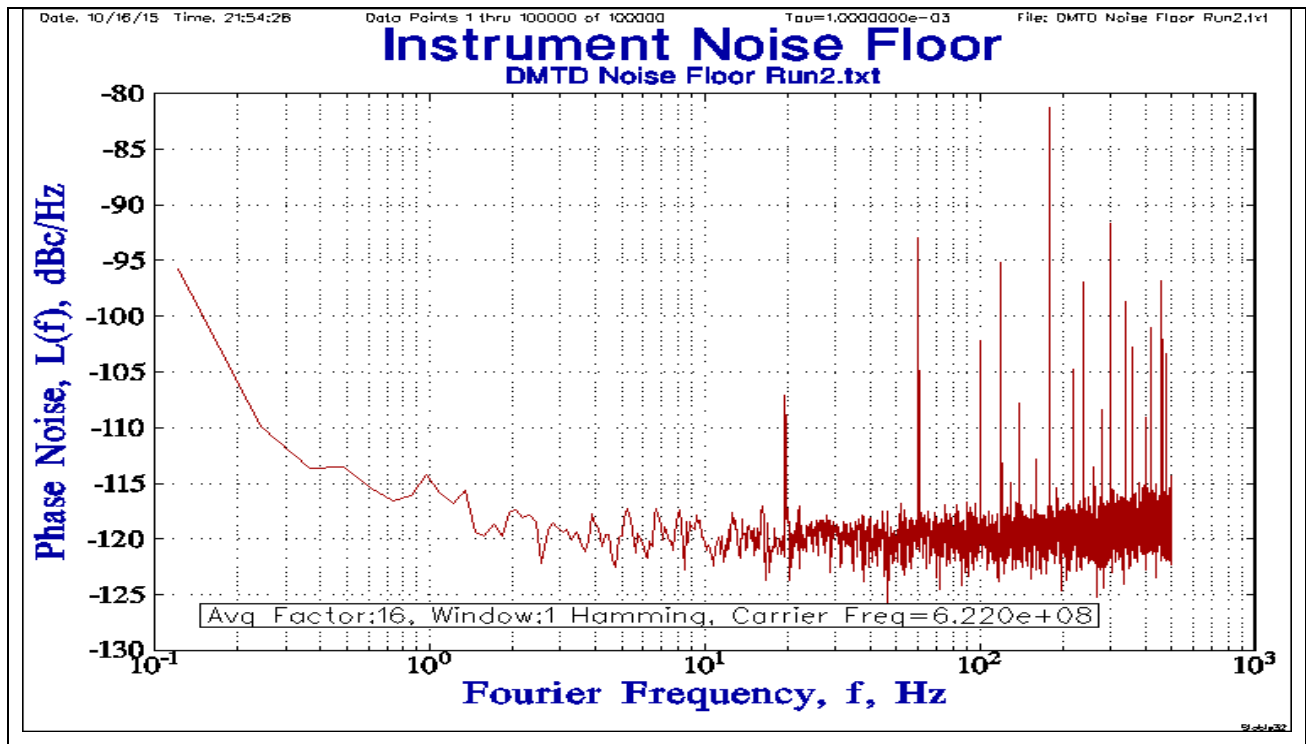


Fig. 14. Single side band phase noise power spectral density of Instrument Noise Floor

#### IV. CONCLUSION

A laboratory test bed laser communication link with mock space and ground terminal transmitter and receiver hardware

was constructed. The link was used to evaluate the range-rate performance by measuring the phase of the recovered data clock. Range-rate accuracies of 23.1  $\mu\text{m/s}$  and 2.1  $\mu\text{m/s}$  for 1 s and 10 s averaging time respectively were achieved. We demonstrated that this range-rate does not change with the BER rate and received optical power for powers as low as -33 dBm. Improvements of the range-rate accuracy from the communication configuration were tested with a single-tone optical amplitude modulation system at 622 MHz. Range-rate accuracies of 19.7  $\mu\text{m/s}$  and 0.27  $\mu\text{m/s}$  for 1 s and 10 s averaging time respectively were achieved. All phase measurements are performed with a DMTD test apparatus which has a measured noise floor of 0.28  $\mu\text{m/s}$  and 0.06  $\mu\text{m/s}$  for 1 s and 10 s averaging time respectively. Both experimental ranging mode performance was limited by the use of commercial-off-the-shelf components from the telecommunication OC-12 family. We are building an improved version of the hardware using custom components to address this.

The achieved range-rate accuracy has significant importance for both space navigation and communication. It enables an almost no-cost, very high-precision ranging service for any free-space optical communication system. This is because the range measurement is conducted with the recovered data clock, which is required in all synchronized optical communication systems. Another important application for our work is high-precision range measurements in science applications, (e.g. gravity-wave measurements of GRAIL and GRACE). These systems use RF signal tones for ranging, where plasma scintillation is a major performance limitation [1]. A special design is required to correct plasma introduced phase noise[5]. Further, it remains a major error source when the Sun-Earth-Probe (SEP) angle is less than 30 degrees [5]. The plasma-induced refractive-index fluctuation is proportional to the square of carrier wavelength [5]. The optical carrier is 4 orders of magnitude shorter wavelength than 10GHz RF carrier. The short optical wavelength eliminates the plasma induced noise issue for optical ranging. High-precision optical ranging has another intrinsic advantage due to the short wavelength. It has very high antenna gain (small beam divergence) compare to RF. This small beam divergence (high antenna gain) can be used in two ways: to decrease the size of the ranging equipment, and/or to increase the ranging distance. This makes optical ranging instruments attractive for deep-space small satellite and cubesat missions. Optical communication ranging provides precise absolute range measurements due to the synchronized operation[3], it provides another dimension of measurement for science missions to explore.

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## BIOGRAPHY



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