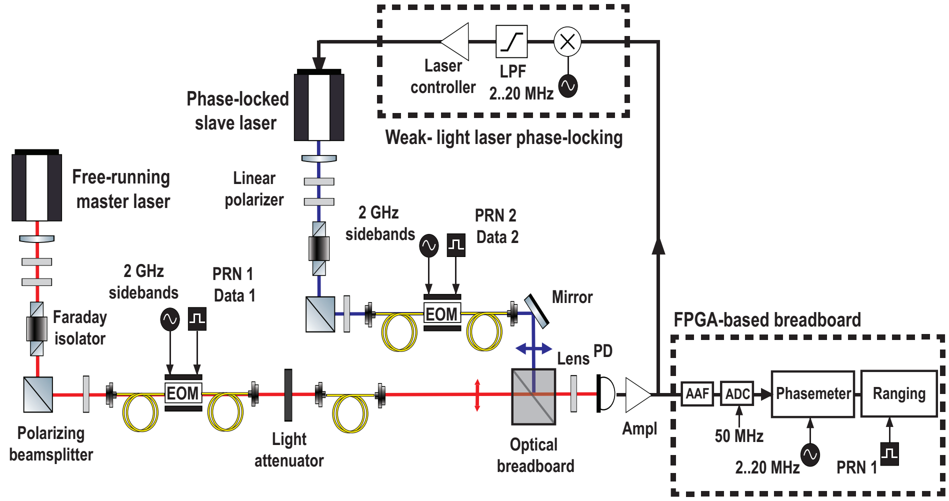

Fig. 5. Simplified schematic of the experimental setup used to test the laser modulation scheme.

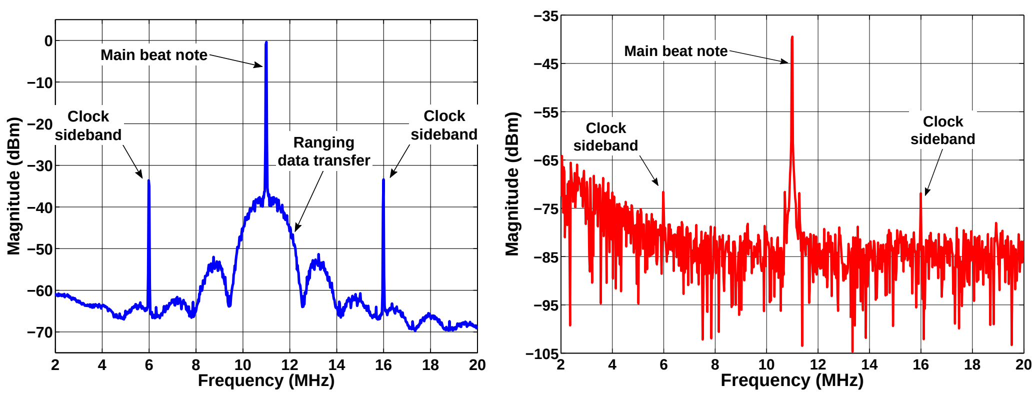

Fig. 6. Spectrum comparison of the beat note for normal-light (left side) and weak-light (right side) environments.

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ditions the PRN modulation appears as sidelobes in the main carrier. An attenuation in the beat note power of 40 dB is observable for the weak-light environment, resulting in a noise floor above the ranging signals. Figure 7 shows the corresponding rms ranging accuracy in meters. The tracked signal is a time-varying PRN code with an equivalent velocity of $\pm 20\,\mathrm{m/s}$. The ranging signal modulated onto the local laser is also time-varying such that it performs a cross-correlation distribution for all possible delays. Under these conditions, experimental results demonstrate a ranging rms noise of 42 cm at 3 Hz for data rates of 24.4 kbps at 1 pW power levels. The raw data transmitted has a bit error rate (BER) of up to 26×10^{-3}. For data error corrections, a FPGA-based Reed-Solomon (RS) encoding technique is applied to demonstrate the viability of reliable optical communications. To this end, a RS(n=15,k=9) scheme with m = 4-bit symbols has been implemented, where n corresponds to the code length and k refers to the data symbols per code. This includes (n-k) parity symbols, resulting in an effective data rate of 14.6 kbps, and subsequently an equivalent receiver sensitivity of $\approx 366\,\mathrm{photons/bit}$ with coding for the standard 10^{-9} BER in coherent communication systems.

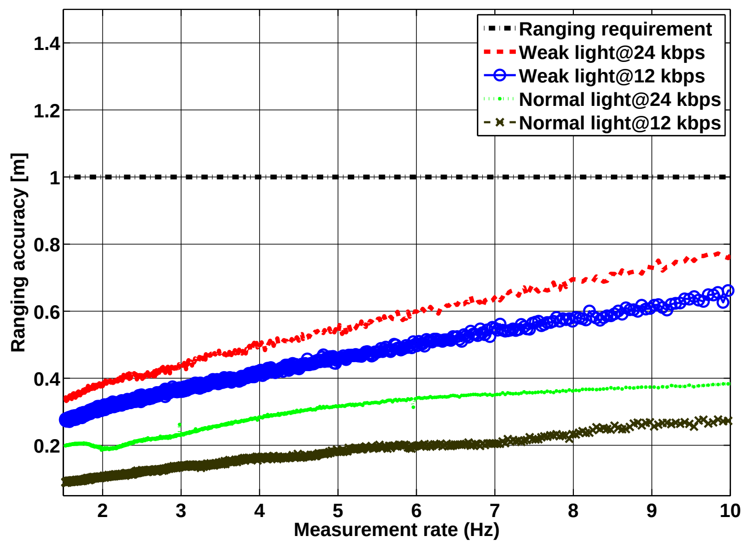

Fig. 7. Ranging rms noise of the optical ranging measurements for different data rates and in the presence of LISA-like noise sources, including interference with a second PRN and simulated inter-spacecraft velocity.

Table 1. Ranging Accuracies for Different Data Rates and Different Optical Power Conditions

Code parameters		Ranging rms noise		Bit Error Rate (BER)	
Optical Power	Data rate	10 Hz	3 Hz	Raw data	Reed-Solomon
10 nW	12 kbps	25 cm	15 cm	No error detected	No required
10 nW	24 kbps	38 cm	22 cm	No error detected	No required
1 pW	12 kbps	62 cm	38 cm	$< 6 \times 10^{-4}$	No error detected
1 pW	24 kbps	76 cm	42 cm	$< 26 \times 10^{-3}$	No error detected

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As shown in Table 1, this technique provides the necessary data correction to achieve an error-free optical transmission. The fundamental limit of the measurement under weak-light conditions is shot noise. An estimate of the rms ranging error in meters due to shot noise can be computed as $\sigma \approx c \cdot T_c/\sqrt{SNR_L}$ [15], where c is the speed of light, SNR_L is the signal-to-noise ratio in the loop bandwidth B_w (3-10 Hz), and T_c is the chip period (1/1.5 MHz). For a received carrier-power-to-noise density ratio (C/N_0) of ≈ 64 dB-Hz ($SNR_L = C/N_0\, B_w$) at the input of the ranging system, i.e., by applying a modulation depth of 0.1 rad, and a total incoming phase noise contribution due to the shot noise of $\approx 58\,\mu\text{rad}/\sqrt{(\text{Hz})}$, we obtain a theoretical accuracy limit of ≈ 20 cm at 3 Hz. Our measured results are a factor of two above this level. A more detailed noise investigation, requiring additional testing is necessary to identify the origin of the excess ranging noise and to quantify the noise contribution of effects like data transfer and interference of the second PRN signal.

5. Conclusion

We have demonstrated operation of a ranging scheme at sub-meter accuracy with data communication capabilities based on a laser transponder configuration with heterodyne detection at picowatt power levels. Such a system can be integrated with precise laser interferometry at picometer accuracy and offers a promising technology for future optical satellites given the advanced laser link functionalities. In particular, it enables clock comparison of remote stations, Doppler estimations through optical phase tracking, and wavefront tilt measurements for precise laser pointing techniques or satellite drag-free control.

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