

Range-Gated Metrology: an ultra-compact sensor for dimensional stabilization

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ABSTRACT

Point-to-point laser metrology systems can be used to stabilize large structures at the nanometer levels required for precision optical systems. Existing sensors are large and intrusive, however, with optical heads that consist of several optical elements and require multiple optical fiber connections. The use of point-to-point laser metrology has therefore been limited to applications where only a few gauges are needed and there is sufficient space to accommodate them.

Range-Gated Metrology is a signal processing technique that preserves nanometer-level or better performance while enabling: (1) a greatly simplified optical head – a single fiber optic collimator – that can be made very compact, and (2) a single optical fiber connection that is readily multiplexed. This combination of features means that it will be straightforward and cost-effective to embed tens or hundreds of compact metrology gauges to stabilize a large structure.

In this paper we describe the concept behind Range-Gated Metrology, demonstrate the performance in a laboratory environment, and give examples of how such a sensor system might be deployed.

Keywords: Laser metrology,

1. INTRODUCTION

Point-to-point laser metrology is the technique of choice for the precision measurement of displacement. Applications have ranged from semiconductor lithography machines to the stabilization of large space-based optical systems, with a typical precision of a nanometer or less.

Most systems monitor the distance to a target by reflecting laser light (the ‘measurement’ beam) from the target and beating the return signal against a ‘local oscillator’ beam of slightly different frequency. A phase can be measured from this target detector output. To avoid sensitivity to path lengths internal to the measuring system, the phase of a second ‘reference’ return is measured, which includes the internal path but not the path under test. High precision requires that there be minimal cross-talk or leakage between the measurement and reference beams. Figure 1(a) shows an example of how this high degree of isolation is implemented using the components in the optical head of a state-of-the-art metrology system. The multiple fiber optic and free-space components places significant demands on initial alignment accuracy and alignment stability, and the large overall size can make integration a challenge.

Range-Gated Metrology moves the complexity out of the optical head and into the signal processing. The resulting head is shown in Fig. 1(b). It is extremely compact, requires minimal internal alignment, has only a single fiber connection, and yet preserves the high performance of much larger heads.

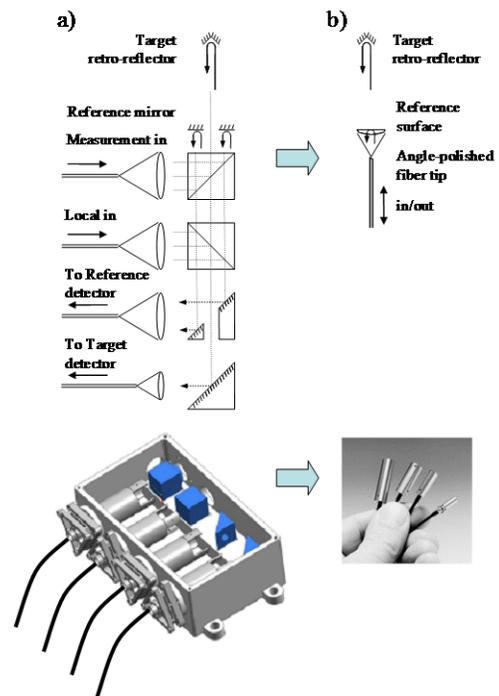


Figure 1: (a) Optical head for traditional laser metrology system with 4 optical fibers and multiple internal optics. (b) Compact optical head for Range-Gated Metrology with single optical fiber.

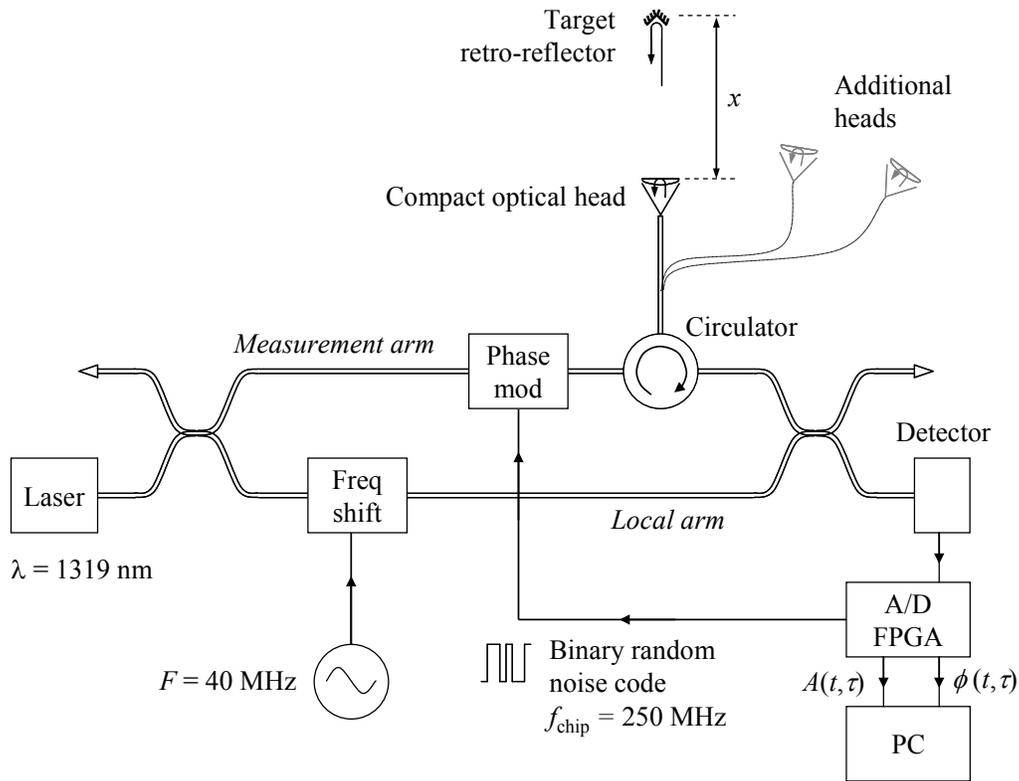


Figure 2: Schematic Range-Gated Metrology system, for measuring changes in the length x .

In the next section we describe the basic principle of operation, followed by more detail of the signal processing in Section 3, a summary of the measured performance in the lab in Section 4, a description of multiplexing options in Section 5, and a discussion of possible applications in Section 6.

2. PRINCIPLE OF OPERATION

Two key innovations behind Range-Gated Metrology is the use of a Pseudo-Random Noise (PRN) codes on the outgoing laser signal. This was recently proposed by Daniel Shaddock to improve the rejection of stray light for LISA mission [1]. Figure 2 shows a typical configuration.

Light from a stabilized laser (in this case a Lightwave Nd:YAG NPRO system with $\lambda = 1319$ nm) is coupled into single-mode, polarization-maintaining optical fiber and split into two arms. A phase modulator imposes a random binary noise code (0 or π phase shift) on the outgoing measurement beam, with a 50% probability of inverting the amplitude at each clock cycle or ‘chip’. A circulator sends the measurement beam to the optical head, and then directs the superimposed returns from target and reference to the single detector, where the light mixes with frequency-shifted light from the lower ‘local’ arm. In the absence of the code modulation, the target and reference returns would each produce a beat signal at frequency F with a phase difference given by $\Delta\phi = 4\pi x / \lambda$. But since only the sum of the two sinusoids is measured, it would not be possible to measure this phase. The presence of the code enables us to separate the returns, based on their differing propagation delays. To extract the desired return signal, the detector output is multiplied by an appropriately delayed version of the random code. The desired signal is correctly demodulated and recovered as a sinusoid of frequency F , while the returns with the incorrect delay remain modulated and contribute only as a source of near-white noise. This process is conducted in parallel to extract simultaneously both the signal and reference returns (and any other return of interest). Once the sinusoids have been demodulated, their phase difference $\Delta\phi$ can be measured and the displacement obtained as before.

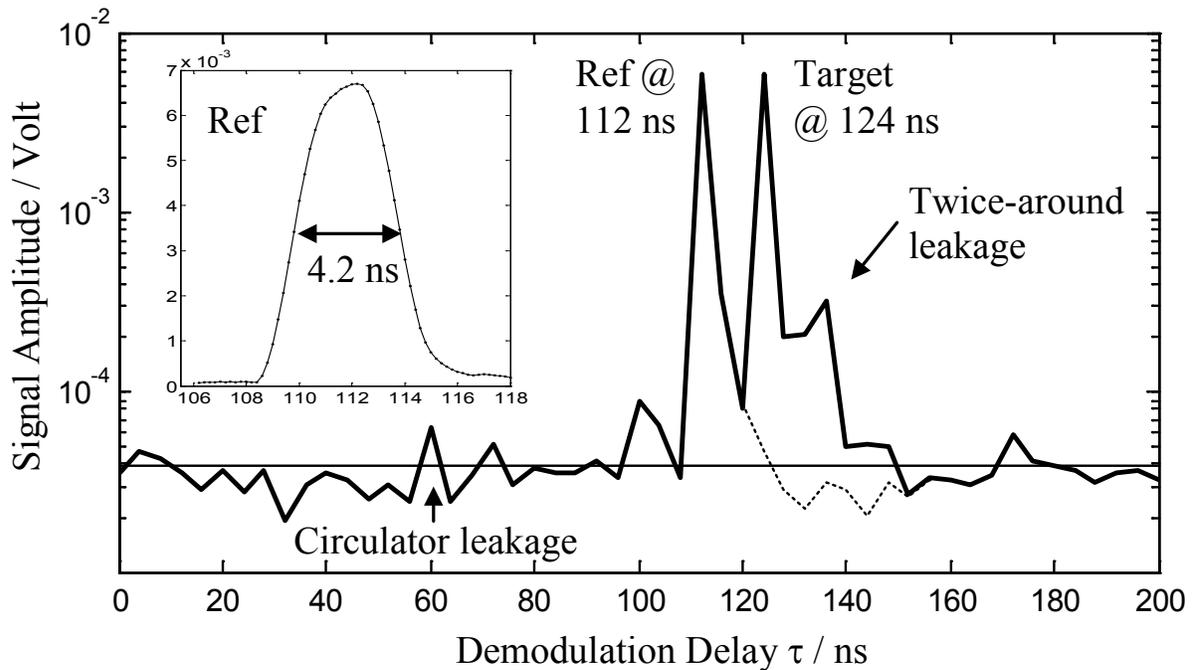


Figure 3: Signal correlation vs demodulation delay. Dashed line indicates the correlation obtained when the target is blocked. Inset shows reference peak on a linear scale, sampled with finer delay steps.

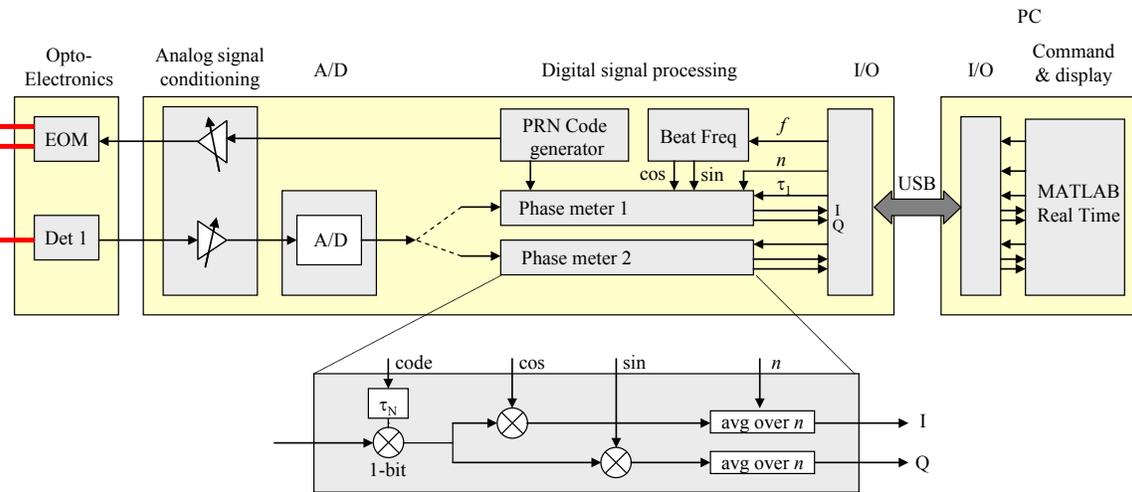
The signal processing effectively establishes a set of ‘range gates’ to discriminate between the optical returns and reject unwanted sources of leakage, whether they are optical or electrical in nature. The width of the range gate is given by $c / 2f_{\text{chip}}$, where c is the speed of light and f_{chip} is the chip frequency of the code. For $f_{\text{chip}} = 250$ MHz, the range gate is ~ 0.6 m wide. The use of noise codes to create multiple signal channels is the basis for Code Division Multiplexing, a widespread and mature spread spectrum technology in the communications arena

Figure 3 shows the correlation of the photodetector output as a function of delay offset for the code demodulation. The first large peak at 112 ns corresponds to the return from the reference surface, followed by the target return 12 ns (3 clock chips) later. Also evident is the twice-around leakage (i.e. ref – target – ref – target) and a small peak at 60 ns from leakage through the circulator that bypasses the optical head. By correlating with the noise code in the signal processing, we can isolate each of these features from the others. In practice, we measure only the reference and target returns. The width of the range gate sets a lower limit to the separation of the optical head and the target. If they are any closer then the two returns become blended together. For the example shown in Fig. 3, the separation is 1.7 m, compared to the range gate width of ~ 0.6 m.

While random noise codes have long been applied to Continuous-Wave LIDAR measurements to extract target range, it is important to realize that in this application the purpose of the code is not to determine the range (the resolution would only be tens of centimeters); rather it is to isolate the two principal optical returns so that their coherent phase can be measured (displacement resolution of nanometers).

3. FPGA SIGNAL PROCESSING

An initial proof-of-concept experiment was conducted using a digital oscilloscope to record the code and the photodetector output, and then apply the signal processing steps off-line using Matlab [2]. Since then, a real-time signal processing system has been implemented on an Analog Devices ADC evaluation board clocked at 250 MHz, as shown in Fig. 4. The random noise code is a so-called M-code, generated using a simple set of shift registers. A little amplification is needed to boost the logic levels of the FPGA to the 4 volt swing needed to drive the electro-optic phase modulator (EOM) for a π phase shift. The outgoing code is also passed into a buffer which can be tapped at the delay offset needed for the code demodulation. The photodetector output is amplified to give a peak-to-peak swing of order 1 V, and is then digitized by the Analog-to-Digital converter (250 MHz, 10 bits). The digitized output is split into two streams, one for the reference channel and one for the target channel. For each channel, the code is demodulated with a simple 1-bit multiplication by the appropriately delayed version of the code to give a sinusoid at frequency F . The in-phase (I) and quadrature (Q) components of this sinusoid are measured by multiplying by cosine and sine, respectively, and then accumulating the sum over n clock cycles. These accumulated values of I and Q for each of the 2 channels are then output to a PC over a USB interface at up to 5 kHz. Matlab routines then convert the I and Q values into amplitude and phase. The displacement is given by $\delta x = (\lambda/4\pi)(\phi_{\text{target}} - \phi_{\text{ref}})$. The appropriate code delays for the target and reference channels are readily determined from a scan through delay space (Fig. 3), and are loaded as parameters into the FPGA.



(a)



Figure 4: (a) Schematic of signal processing system developed for Range-Gated Metrology. Inset shows detail for one phasemeter channel. (b) Implementation on an Analog Devices ADC evaluation board.

4. PERFORMANCE

The real-time system is now operating successfully in the lab, operating at up to 5 kHz output rate with a scrolling real-time display of the displacement. The predicted displacement precision is given by

$$\sigma_x = \frac{\lambda}{4\pi} \sqrt{\frac{f_{\text{update}}}{f_{\text{chip}}}} \sqrt{\frac{1}{\chi} + \chi}, \quad (1)$$

where χ is the intensity ratio of the target and reference returns [2]. For wavelength $\lambda = 1319$ nm, update rate of $f_{\text{update}} = 2.5$ kHz, chip frequency $f_{\text{chip}} = 250$ MHz, and $\chi = 1$, the precision is 0.47 nm. The performance measured in the lab is consistent with this. Fig. 5 shows a Power Spectral Density plot of the noise in the system when measuring a stabilized path length of 2 m. The dominant source of noise is the residual of the unwanted return in each channel, i.e. for the phasemeter channel that measures the reference return, the noise is from the incorrectly demodulated target return signal, and vice versa. This noise is manifested as the discrete frequency peaks and is deterministic – it can in principle be removed with a simple calibration procedure.

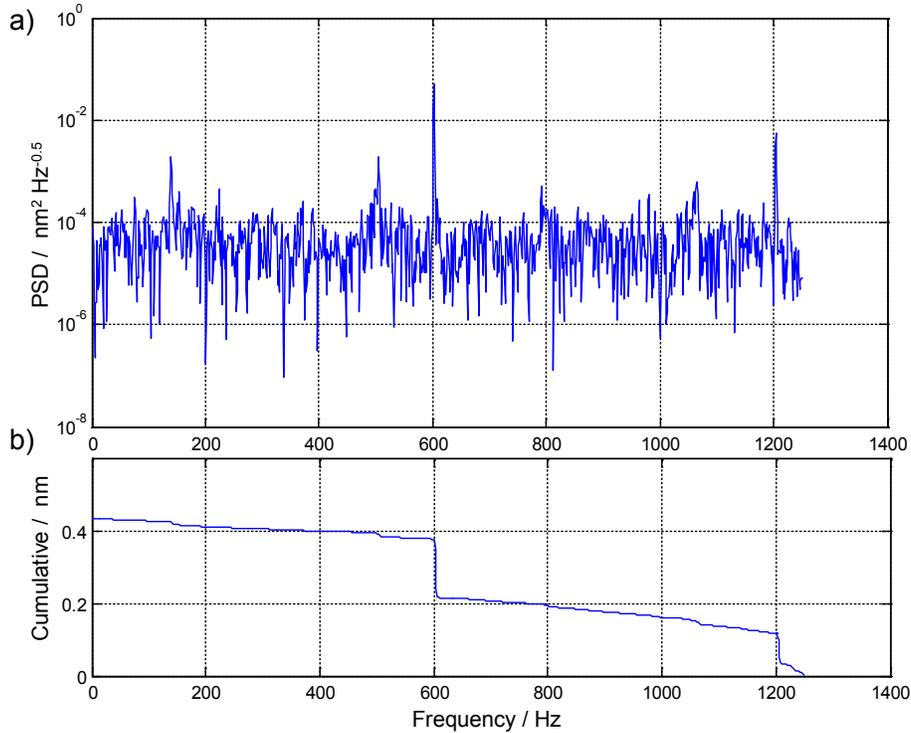


Figure 5: Example of performance in the lab for measurement for a stabilized path. (a) Power spectral density. (b) Cumulative noise, showing that most of the error is introduced by peaks at 600 Hz and 1200 Hz. Overall rms is 0.43 nm, with update rate = 2.5 kHz.

5. MULTIPLEXING OPTIONS

The single fiber connection to the optical head makes multiplexing much easier than for previous designs. Figure 6 shows 3 examples.

The time-multiplexed case depicted in Fig. 6(a) uses a computer-controlled fiber optic switch to select the head of interest. A single signal processing chain can be used to sequentially examine a large number of optical heads, ideal for monitoring slow drifts in a large structure. Commercial fiber switches have become a key component of communications networks, and several different technologies are available. Electro-optical designs are fast (10 ns switching time) but have significant cross-talk (~ -20 dB) that may be an issue for some applications. Magneto-optical designs have switching modest speed (~ 50 us) but much lower crosstalk (~ -50 dB). Opto-mechanical designs are slower (~ 10 ms), while MEMs (Micro-Electro-Mechanical) devices offer great flexibility with 10s or 100s of outputs.

A delay-multiplexed case is shown in Fig. 6(b). The varying lengths of fiber mean that the returns from the multiple heads can be separated by the signal processing in the delay domain and tracked independently. This is a cost-effective way to obtain simultaneous measurements from multiple gauges, but care must be taken to avoid cross-talk from all possible optical paths (e.g. the twice-around peak in Fig. 3).

The third example in Fig. 6 shows a fully parallel scheme in which all heads are monitored simultaneously with separate signal processing chains. This approach would be appropriate when it is necessary to measure vibrations in a structure simultaneously over many gauges.

Hybrid schemes are also possible. For example, a 4 x 16 switch could be used to select any 4 out of 16 optical heads for continuous monitoring with 4 signal processing chains in parallel.

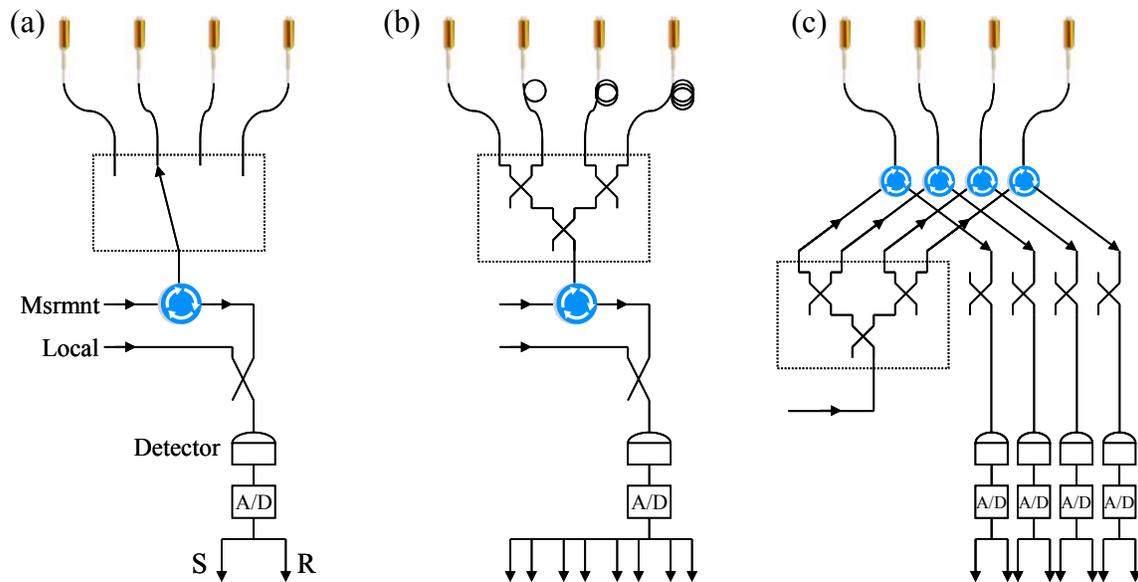


Figure 6: Multiplexing options. (a) Time multiplexing between multiple heads with a fiber optic switch; (b) Delay multiplexing: multiple heads are connected in parallel with different lengths of fiber and the multiple returns are separated by the signal processing; (c) Full parallel operation with one detector and A/D unit per optical head.

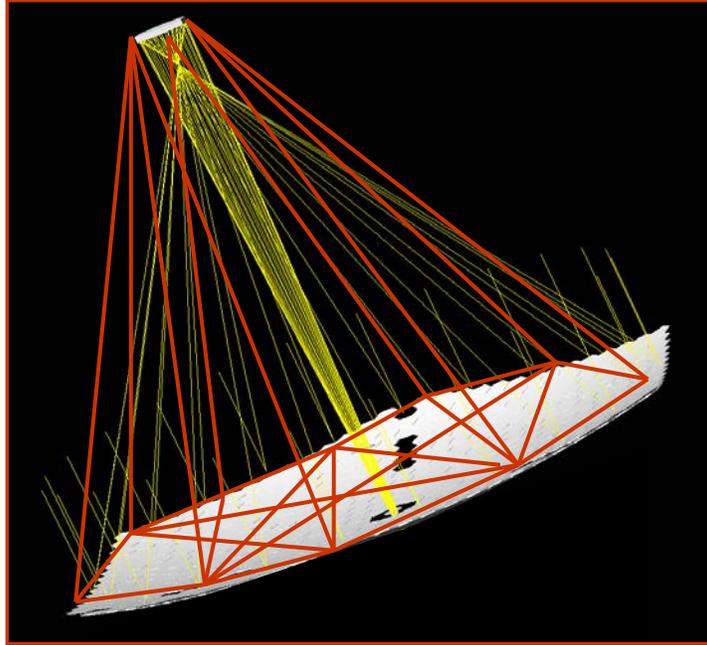


Figure 7: Notional segmented telescope stabilized with multiple laser metrology gauges.

6. APPLICATIONS

Range-Gated Metrology offers two key advantages over existing point-to-point metrology systems: the very compact optical head makes it much easier to integrate gauges into a structure, and the single optical fiber makes it much easier to multiplex tens or hundreds of gauges.

Large optical systems in which sub-wavelength dimensional stability is required over a large structure could benefit from this technology. Examples are monolithic and segmented telescopes and interferometers, operating at wavelengths from X-ray to far-infrared, both ground- and space-based. The heads are small enough to be integrated with primary mirror segments, a secondary mirror or back-end optics, where they can be used to monitor vibration and distortions introduced by the thermal environment and gravity (Fig. 7). They can be built into hollow tubes in combination with a PZT actuator to form an ‘active strut’ with infinite stiffness and zero thermal expansion, from which entire structures could be constructed. An RGM system could also be deployed in a lab or testbed environment to monitor vibration and drift in optical systems.

In addition to providing displacement measurements (relative metrology), Range-Gated Metrology can also be combined with multiple wavelength techniques to measure absolute distance. In particular, the addition of a second phase modulator in the ‘Local’ arm of Fig. 2 allows us to implement the MSTAR absolute metrology scheme [3], enabling ranging with micron-level accuracy.

7. SUMMARY

Range-Gated Metrology is a new point-to-point laser ranging system with nanometer precision using an optical head that is drastically smaller than previous designs. This size reduction is enabled by a signal processing technique based on a random noise code modulation, and is readily implemented in an FPGA. We have demonstrated an end-to-end system operating in real time, and showed that the sub-nanometer precision obtained is consistent with model predictions. The single optical fiber to the head makes a number of different multiplexing options possible, in which a large number of optical heads can be used to monitor a structure at low cost. The small head size and ease of multiplexing are ideally suited to the new generation of large, actively controlled, space- and ground-based telescopes.

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