

Improved Grating Angular Sensor for LISA and MGRS

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Abstract. LISA requires high precision angular beam pointing and telescope steering. In this paper, we report recent results for an improved grating angular sensor. We have achieved better than $0.2 \text{ nrad/Hz}^{1/2}$ at 1 kHz with 14 mW of incident power, a factor of 5 improvement over our previously reported results. At 1 Hz we achieved 1-2 nrad/Hz $^{1/2}$. We realized these improvements by enclosing the grating angular sensor assembly in a vacuum chamber and mounting the optics components on a zerodur glass plate, thereby lowering the noise floor at low frequencies. Furthermore, by upgrading the electronics and thus the detector power handing capability, we also investigated sensitivity scaling versus incident laser power. The results will benefit the design of grating angular sensors.

1. Introduction

Spacecraft constellation missions, such as LISA, DECIGO, and BBO, require high precision angular pointing and steering, primarily for measuring relative position between spacecraft. LISA also needs to measure proof mass angular orientation. The precision required for the proof mass angular orientation measurement is $\sim 100 \text{ nrad/Hz}^{1/2}$, and for telescope steering $\sim 1 \text{ nrad/Hz}^{1/2}$. As a future technology for LISA type missions, the modular gravitational reference sensor (MGRS) will have similar angular sensing needs.

Grating angular sensors outperform traditional angular sensors based on simple specular reflection thanks to grating angular magnification and beam cross-section compression [1]. We have conducted a series of experiments and demonstrated the performance of grating angular sensors. In the first proof of principle experiment [1], we used an off-the-shelf, 1200 line/mm grating, and demonstrated $10 \text{ nrad/Hz}^{1/2}$ angular sensitivity over a mere 5 cm of working distance with 1 mW of incident power at 1 kHz.

In a second experiment [2], we improved angular sensitivity and demonstrated the robustness of the symmetric grating angular sensor against laser frequency noises. We custom-designed a 935 line/mm grating, and used it in conjunction with a 1064 nm Nd:YAG NPRO laser to form a symmetric grating angular sensor. With an input laser power of 4 mW, the angular sensitivity of the symmetric grating angular sensor at 1 kHz was observed to be $\sim 1 \text{ nrad/Hz}^{1/2}$ [2]. In the presence of large frequency excursions of the laser, the angular sensor output remained constant [2].

Also, we developed three different methods of fabricating localized gratings on the surface of a proof mass [3]: electron-beam lithography, transfer-imprinting, and focused ion beam milling. We fabricated grating patterns with submicron features and line densities of 935 lines/mm using each of

the methods. These fabrication techniques will enable patterning of the proof mass for precision angular sensing.

In addition, we demonstrated a dual range grating sensor, in which the first order diffraction is used to achieve high angular sensitivity, and the zeroth order is used to increase the dynamic range of the angular sensor [4].

In this paper, we report on recent progress in grating angular sensor performance. We improved the environmental shielding of the grating angular sensor. By mounting the optics components on a zerodur glass plate and enclosing the grating angular sensor assembly with a vacuum chamber, we lowered the noise floor at low frequencies. At 1 Hz, the noise floor was lowered to $1\text{-}2 \text{ nrad/Hz}^{1/2}$, which meets LISA requirement at this frequency. Furthermore, by upgrading the electronics and thus the detector power handing capability, we were able to investigate sensitivity scaling versus incident laser power. We have achieved better than $0.2 \text{ nrad/Hz}^{1/2}$ sensitivity at 1 kHz with 14 mW of incident laser power.

2. Angular measurements at lower frequencies

The LISA sensitivity band ranges from $30 \mu\text{Hz}$ to 1 Hz, and the BBO sensitivity band from 0.1 Hz to 10 Hz. Therefore we have attempted to measure the grating sensor performance at low frequencies.

Figure 1 shows the improved experimental setup. For better isolation, we acquired a vacuum enclosure and associated turbo pumping system. The vacuum pressure in the chamber was first pumped down to 1×10^{-5} torr and then the pump was stopped to reduce vibration during data taking. Fine realignment was needed since the change of air pressure induced minute chamber deformations. The laser beam was directly coupled into the chamber via a window, and the beam path was enclosed in tubing to reduce air flow-induced beam walking. A zerodur glass plate was placed inside the vacuum chamber. The angular sensor was then mounted on an aluminum breadboard via the zerodur plate as the first rigid contact. The movement of the optical mounts thus largely followed the zerodur plate. Our intention was to take advantage of the low coefficient of thermal expansion ($\sim 5 \times 10^{-8} \text{ 1/C}^0$) of zerodur, thereby improving low frequency performance in the presence of normal environmental

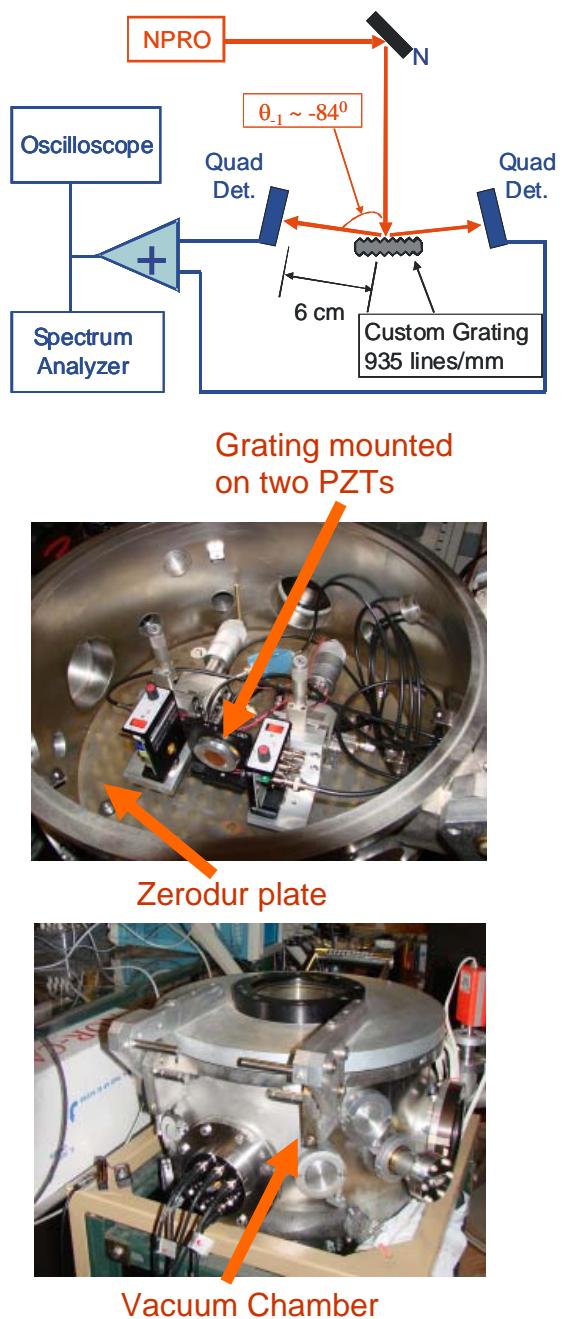


Figure 1. Improved experimental setup for the grating angular sensor.

temperature change.

Figure 2 (a) and (b) show the measurement results. Figure 2 (a) shows results from 0.1 to 10 Hz. For calibration, a 1 Hz, 0.5 μ rad grating rotation was applied by differentially driving a pair of PZTs. We observed \sim 1-2 nrad/Hz $^{1/2}$ of angular sensitivity in the frequency range from 1 Hz to 10 Hz. Above 10 Hz the increased noise level was due to seismic noise in the lab. The noise floor at 0.1 Hz was measured to be \sim 5-10 nrad/Hz $^{1/2}$. From 0.4 to 0.1 Hz, the increase of noise approximately scaled as 1/f. However, a 3-6 dB correction could be needed due to electronics coupling.

Figure 2 (b) shows the measurement result from 0.1 to 1000 Hz. A 10 Hz, 0.5 μ rad rotation of the grating was applied as a calibration signal. From 0.1 to 10 Hz, similar behavior as that in Figure 2 (a) was shown. From 10 to 50 Hz, the noise floor was dominated by ground vibrations.

There is still much room for improvement in the measurement apparatus, depending on available resources. However, the current performance level has exceeded our expectations for the initial measurements at low frequencies.

3. Angular sensitivity scaling versus incident laser power level

We have employed quad-photodiodes and direct detection for the grating angular sensors. Therefore the output signal is proportional to the incident laser power, limited by the saturation of photodiode and electronics circuitry. In the recent experiment, we improved the photodetector electronics of the grating angular sensor by optimizing gain and other parameters of the circuits. The photodetector could thus receive higher laser powers without saturation.

We investigated sensitivity scaling versus incident laser power. These measurements were taken around 1 kHz where environmental noises were lower, and the measured sensitivity represents the intrinsic optics and electronics performance of the grating angular sensor. The angular sensitivity was measured \sim 2 nrad/Hz $^{1/2}$ for 1 mW of incident laser power, \sim 0.8 nrad/Hz $^{1/2}$ for 2.4 mW, 0.6 nrad/Hz $^{1/2}$ for 4 mW, and 0.2 nrad/Hz $^{1/2}$ for 14 mW. The 0.2 nrad/Hz $^{1/2}$ sensitivity represents a factor of 5 improvement over our previously reported results. Figure 3 shows the spectrum from this measurement, including the 0.5 μ rad rotation calibration signal at 1 kHz. The dependence of the noise floor, or the angular sensitivity, on input laser power is plotted in Figure 4. The linear fit indicates the dependence follows a power law with a

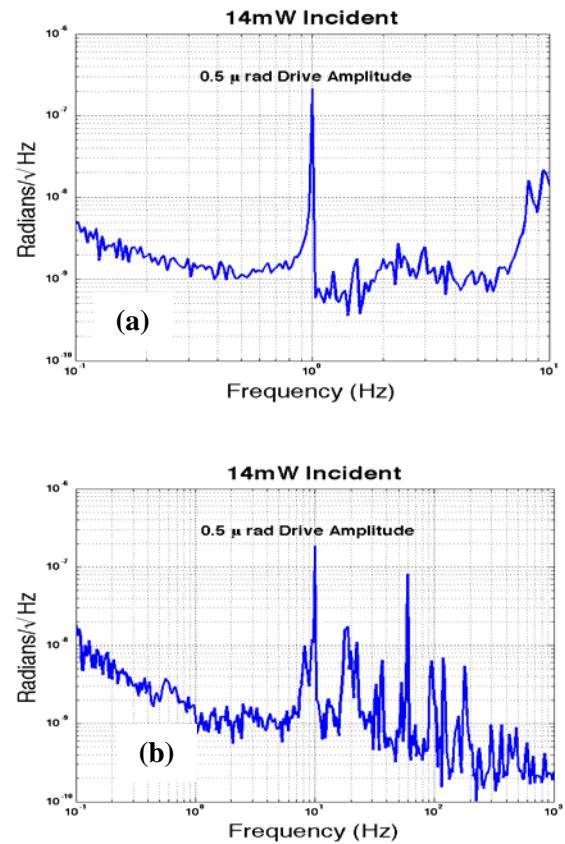


Figure 2. (a) Grating Sensitivity measurement for the grating angular sensor from 0.1 to 10 Hz. A 0.5 μ rad, 1 Hz calibration angular motion was applied to the grating. (b) Sensitivity measurement for the grating angular sensor from 0.1 to 1000 Hz. A 0.5 μ rad, 10 Hz calibration angular motion was applied to the grating. In both (a) and (b), the noise floor at 1 Hz is approximately 1-2 nrad/Hz $^{1/2}$. Also in both graphs, 10 Hz seismic vibrations show as strong noise sources. In (b) the 60 Hz line interference was also large. At low frequencies, the thermal and ground motion are dominant noise source for this particular experimental setup. A \sim 6dB correction to the 0.1 Hz measurement might be needed to account for electronics circuit responses in the near dc region.

exponent ~ -0.77 , which could result from a combination of residual laser intensity noise and electronics noise.

Above 14 mW incident laser power, we observed the onset of detector saturation. However, the current photodetector can be further improved to handle higher incident laser power.

The laser power scaling of angular sensitivity is useful for selecting correct laser power level when designing systems for the grating angular sensor realistically. To illustrate this point, we plot power scaling of the signal-to-noise ratio (SNR) in Figure 5 for several signal strengths.

The top curve shows the SNR measured from our experiments using 0.5 μ rad calibration signal. Under it are four extrapolated curves where the signal strengths are taken to be the proof mass angular sensing requirement of the LISA GRS (0.1 μ rad/Hz $^{1/2}$), the further reduction of coupling noise (10 nrad/Hz $^{1/2}$), the telescope pointing requirement (1 nrad/Hz $^{1/2}$), and the noise floor we measured using 14 mW of incident power (0.2 nrad/Hz $^{1/2}$). As an example, to achieve 10 nrad/Hz $^{1/2}$ resolution sensing with an SNR \sim 10, the input laser power should be \sim 1.2 mW.

4. Conclusion

A novel grating angular sensor that meets LISA requirements has been experimentally demonstrated. The sensitivity of 0.2 nrad/Hz $^{1/2}$ is better than the LISA gravitational reference sensor requirement by a factor of 500. This sensitivity level is measured at 1 kHz. However, it represents the intrinsic performance for the grating angular sensor. The first low frequency measurements reported here show that environmental noises dominate the noise floor. The highly sensitive performance of the grating angular sensor should be extended to lower frequency bands with proper environmental control.

The design of gratings and their fabrication on proof masses have many applications in precision spaceflight and industry. The grating angular sensor is expected to have better mechanical and thermal stability than a conventional angular

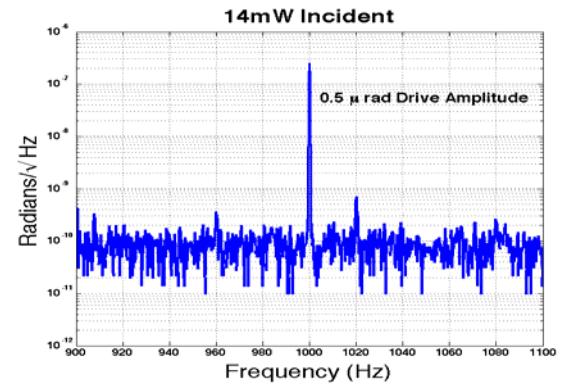


Figure 3: Input laser power was 14 mW. The noise floor was below 2×10^{-10} rad/Hz $^{1/2}$

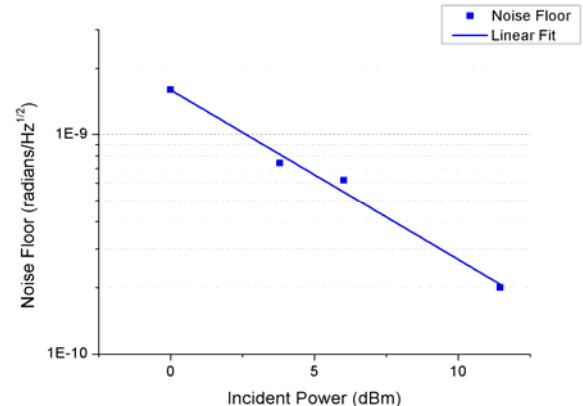


Figure 4. Sensor noise floor vs. incident laser power.

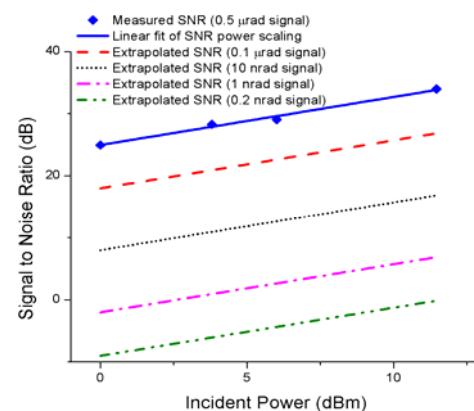


Figure 5: Plot of grating angular sensor SNR as a function of incident power for various assumed signals. The slope of the fit is 0.77.

sensor, and has broad implications for gravitational reference sensing, telescope pointing, and spacecraft flight control [5].

Acknowledgements

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