LISA Autocollimator

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Introduction:

My project for the last ten weeks has been to test and develop a design for an autocollimator intended for use in the Laser Interferometer Space Antenna (LISA). It will be used for a ground test of the device designed to keep the light beams at 60° angles. Among the requirements set by NASA for this autocollimator are that it must (1) work at a distance of 1 meter, (2) have a dynamic range of 1°, and (3) achieve a noise level of 1 nrad/√Hz.

The device we have developed uses a green (530nm) LED to illuminate an array of slits of width 135µm which are imaged onto a linear CCD camera by reflection off a mirror placed behind a 450mm planar-convex lens. A 40R/60T beam splitter, placed between the lens and mirror at a slight angle to the lens, images the pattern again on another part of the camera. This pattern, called the reference pattern, is stationary, while the other moves through the dynamic range. While the device is not fully developed, we have demonstrated that it will be able to meet the criteria.

Design:

Initial design

Inspiration for the design was taken from an autocollimator developed by Cowsik et. al. [1] which implemented a grating to achieve sub-nanoradian resolution. The idea is that while autocollimators generally use a point source of light, passing light through slits will produce multiple peaks that can be measured while still using a single light source. Rather than using the image of only one grating pattern as Cowsik did, however, the initial design called for three: two stationary patterns flanking a dynamic pattern in the center. To achieve this, two beam splitters would be placed just beyond the main lens, tilted at the angles necessary to produce two images of the pattern on the outer edges of the camera. See Figure 1 for a diagram of the initial design idea.

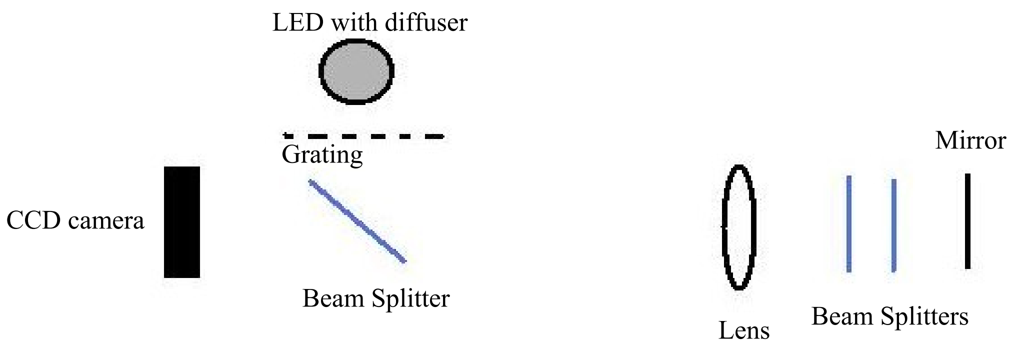

Figure 1: Initial design concept

Each part of the autocollimator needed to be developed and tested to determine what would be needed to achieve the specifications set by NASA. The following is a brief summary of the development of each component that led to the current configuration.

Main Lens

Lenses introduce challenges to an optical setup because they have some amount of aberrations simply by their nature. However, it is possible to minimize their effects. First of all, we used a monochromatic light source to eliminate any chromatic aberrations. Secondly, generally speaking, the longer the focal length the better, so our lens has a 450mm focal length. Additionally, aberrations get worse as the area of the lens used increases, i.e. the quality of the lens decreases the further you move from its center. There are a few ways to fix or at least optimize this—one is to use an aperture to allow light to pass only through a small area in the center of the lens, and another is to use a large lens. We used both methods; our lens is 145mm in diameter, and up until a development in the light source which will be discussed later made it unnecessary, we placed an aperture between the light source and the main lens. It is a common practice to use correcting lenses such as achromats or apochromats to reduce aberrations in an optical system as well, but so far our lens is of sufficient size and quality that this has not been necessary.

Grating

After testing several different widths of slits, 135μm has produced the lowest noise so far, though more sizes will be tested in the future. The material the grating is made from has undergone several changes as well. Transparencies, photographic negatives, and 35mm slides have been tested so far, with 35mm slides being currently used because they had much better contrast than the other two materials. However, there is evidence that some of the noise in the system is coming from fluctuations in the magnification of the image, and a likely culprit is expansion and contraction of the slide due to temperature fluctuations, so we have ordered a grating made from a glass photomask which should prove more stable and will be tested as soon as it arrives.

Beam splitters

When we installed the two beam splitters and attempted to adjust them to the necessary angles and positions to produce two stationary reference patterns on the edges of the camera, we discovered that the light reflecting amongst the two beam splitters and the mirror produced a barrage of ghost patterns that we were not able to place outside the range of the camera while still leaving the desired patterns within its range. This is a very recent development, so it's possible that a solution may still be found; however, for now, we discovered that by removing one of the beam splitters, the remaining ghost images can be kept in check and a useable reference pattern can be produced. Having only one reference pattern rather than two limits our ability to measure the linearity of the system, but it has the advantage that the pattern can be made wider and still have the necessary dynamic range, resulting in more peaks to measure and thus lower noise.

Light Source

Most autocollimators use a laser as a light source; however, laser light passing through slits would produce undesirable diffraction effects. At the same time though, monochromatic light is ideal to eliminate chromatic aberrations as I mentioned earlier, so a light emitting diode (LED) was chosen for this application. Initially the color of choice was red (637 nm), but changed to green (530nm) because the camera is more sensitive to this wavelength.

Several other factors went into the development of the light source as well. First, there was the issue of a diffuser. A diffuser would ideally produce a uniform source of light so that the pattern imaged on the camera had uniform intensity. However, a diffuser also has the effect of decreasing the overall intensity, and, the lower the intensity, the higher the noise.

We experimented with several different materials for the diffuser, including tape, plastic, paper, and sanded glass, and found that plastic worked best. We polished an aluminum tube and placed it between the LED and the diffuser to produce internal reflections and thus make the light a more uniform intensity, but the dampening of the intensity was still hurting the noise level in our system.

We got around this problem by placing a small planar-convex lens between the LED and the grating. As long as the lens was placed close enough to the grating, it produced a very uniform circle of light, which eliminated the need for a diffuser or an aperture. The lens also greatly increased the light intensity because previously a lot of light was lost when it was absorbed or scattered by the diffuser.

Detailed Overview of Current Design

The result of all these changes is shown in the diagram (Figure 2) of the current setup.

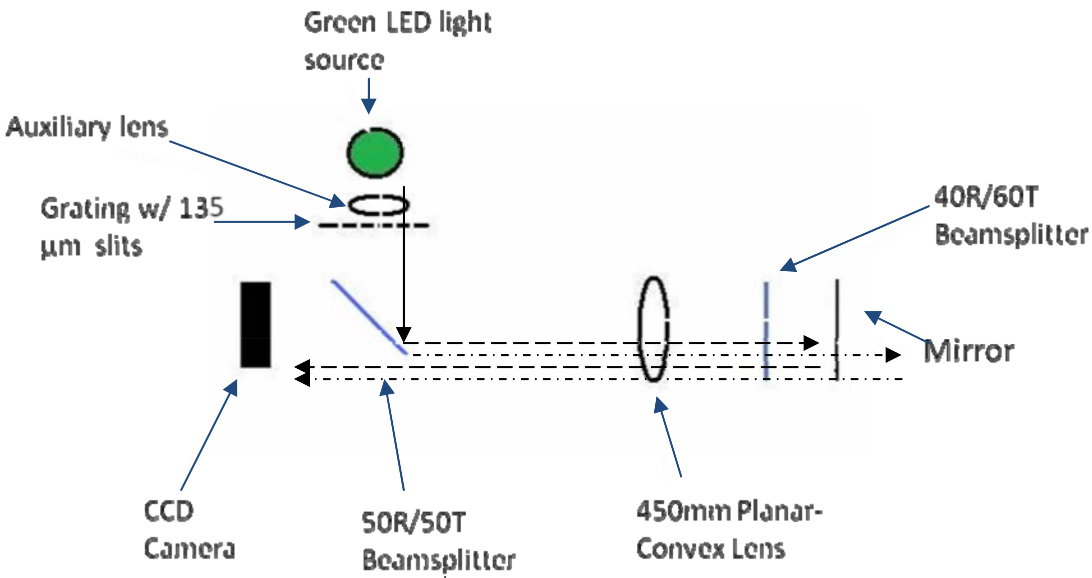

Figure 2: Current setup

Light from a green 530nm LED is converged onto a grating with 135µm slits by a 50mm PCX lens (auxiliary lens) and then hits a 50R/50T beam splitter set at a 45° angle. Half the light is reflected and then passes through a 450mm PCX lens (main lens). Here the light hits a 40R/60T beam splitter tilted at a slight angle with respect to the lens. The part of the light that gets transmitted hits a mirror and is reflected back through the 60/40 beam splitter, the main lens, the 50/50 beam splitter, and finally the grating is imaged on the CCD camera. The part of the light that gets reflected by the 60/40 beam splitter will pass through the main lens and the 50/50 beam splitter and will also image the grating on the camera. The image produced from the light that hits the mirror is the main or dynamic pattern, while the one imaged from the 60/40 beam splitter is the reference pattern.

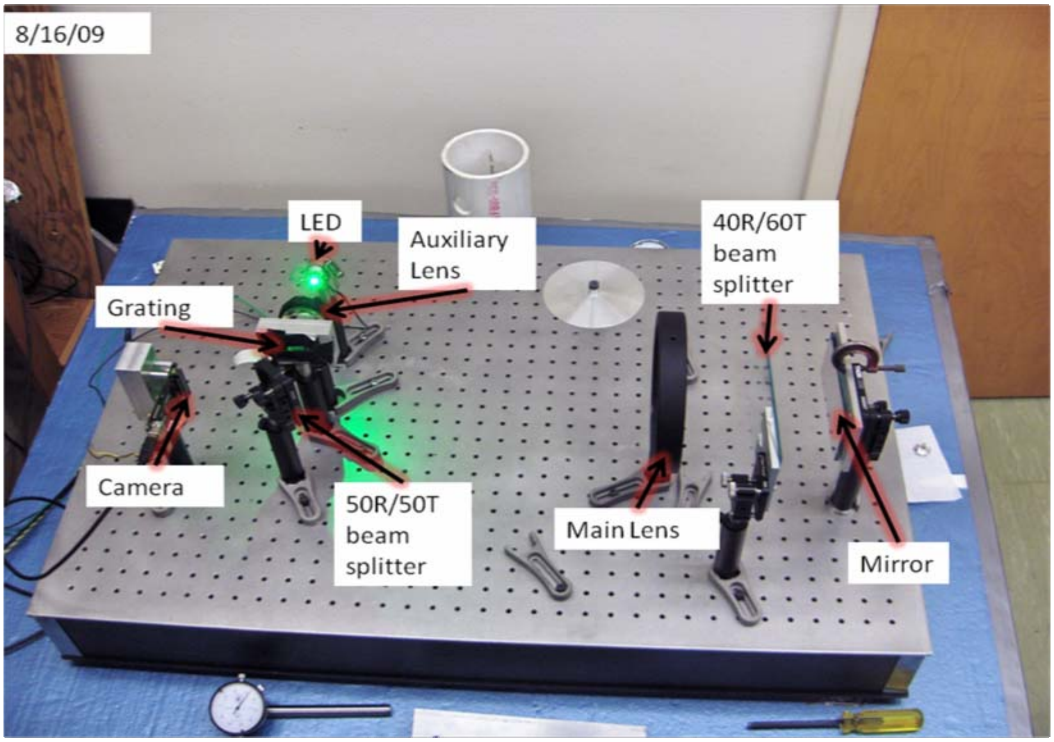

Figure 3: Photograph of current setup

Data Analysis:

The data analysis methods are not the focus of this paper, but I will explain a few key points briefly that are important to understanding the results.

First, the data analysis program finds the peaks by looking for data points above a certain threshold, which is the blue line in Figure 4. It collects all the data points above the threshold and saves them as a collection of peaks, and then the position of each peak is calculated. As you can see in Figure 4, there is a gap in the center of the pattern. This is from a double black line in the center of our grating pattern, and it's used as a marker in the data analysis.

We calculate the noise level within a pattern using the sum or difference of the positions of all the peaks to the left and all the peaks to the right of the gap, which is then averaged. Our current method for calculating the noise of both patterns together is to take the difference between the average sums of each pattern. FFTs are then taken of these values, and these plots can be seen in Figure 7 in the ***Noise*** section.

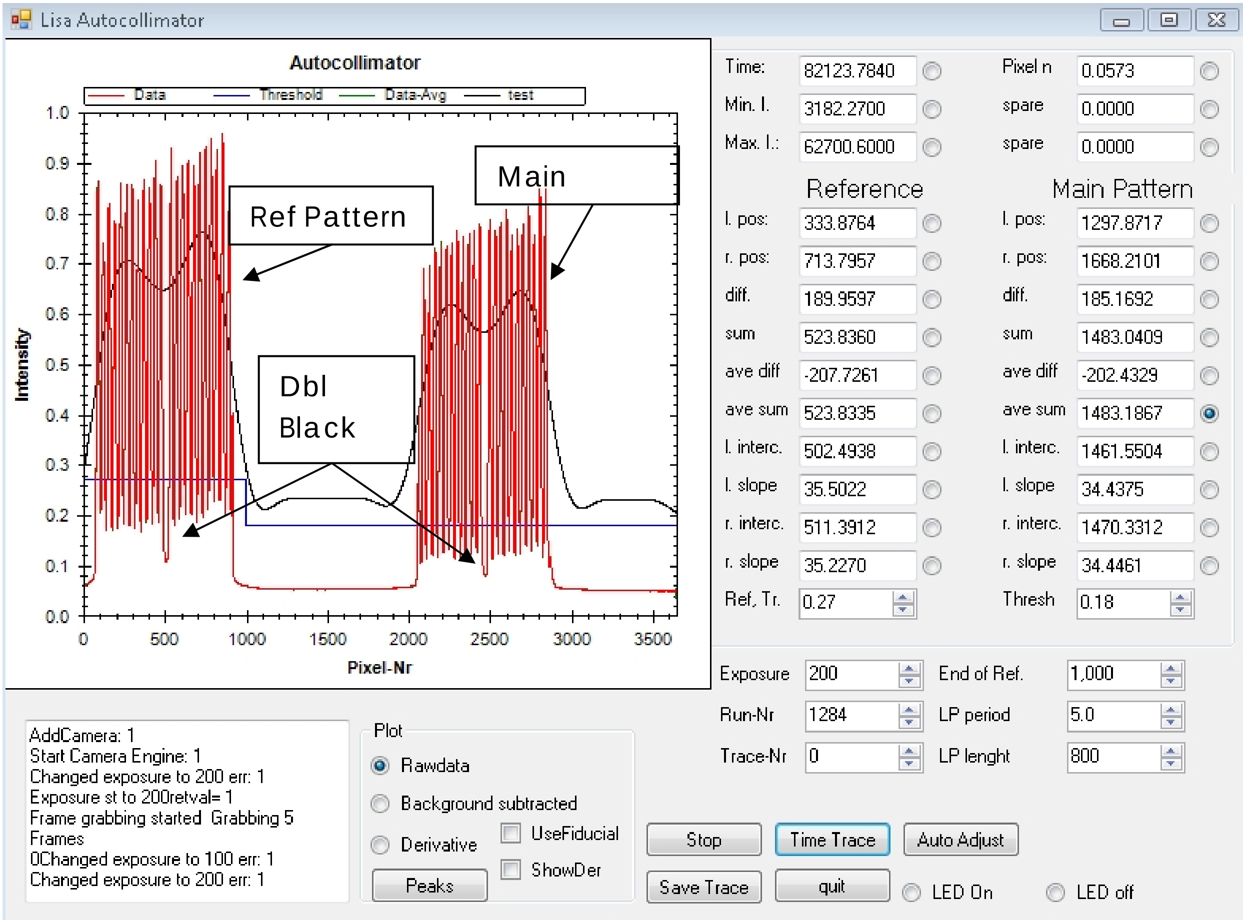

Figure 4: Computer interface; Left- reference pattern; Right- main pattern

Results:

Operating distance

We have tested the system by moving the mirror to a distance of 1m from the main lens; while the beam spreads out greatly, our 145mm diameter lens is large enough to compensate, and we have shown that a clear pattern can still be produced at this range. The mirror was not mounted very firmly (see picture in Figure 5), so reasonable noise calculations could not be done, but as an initial test we proved that it works in principle.

Figure 5: Mirror mounted at a distance of 1m

Dynamic Range

We're able to translate the pattern all the way across the CCD camera (3648 pixels of 8μm width) with it remaining stable. The dynamic range is only limited by the width of the pattern. A ghost pattern does appear when the pattern is moved across a large range, but its intensity is below the threshold, so it does not interfere with the data.

Noise

We have data that shows some of our noise is coming from a slight change in the magnification of the image, which can be seen in Figure 6. Lines were fitted to the peaks left and right of the gap, and the slopes were used as an indication of magnification. Figure 6 is plotted vs. time. The difference in the slopes (red line) was compared to the average difference in peak location (magenta line), and they are clearly related. This fluctuation, as I mentioned earlier, is likely due to expansions and contractions of the grating, but it's also possible that they are caused by the motion of one or more of the optical components.

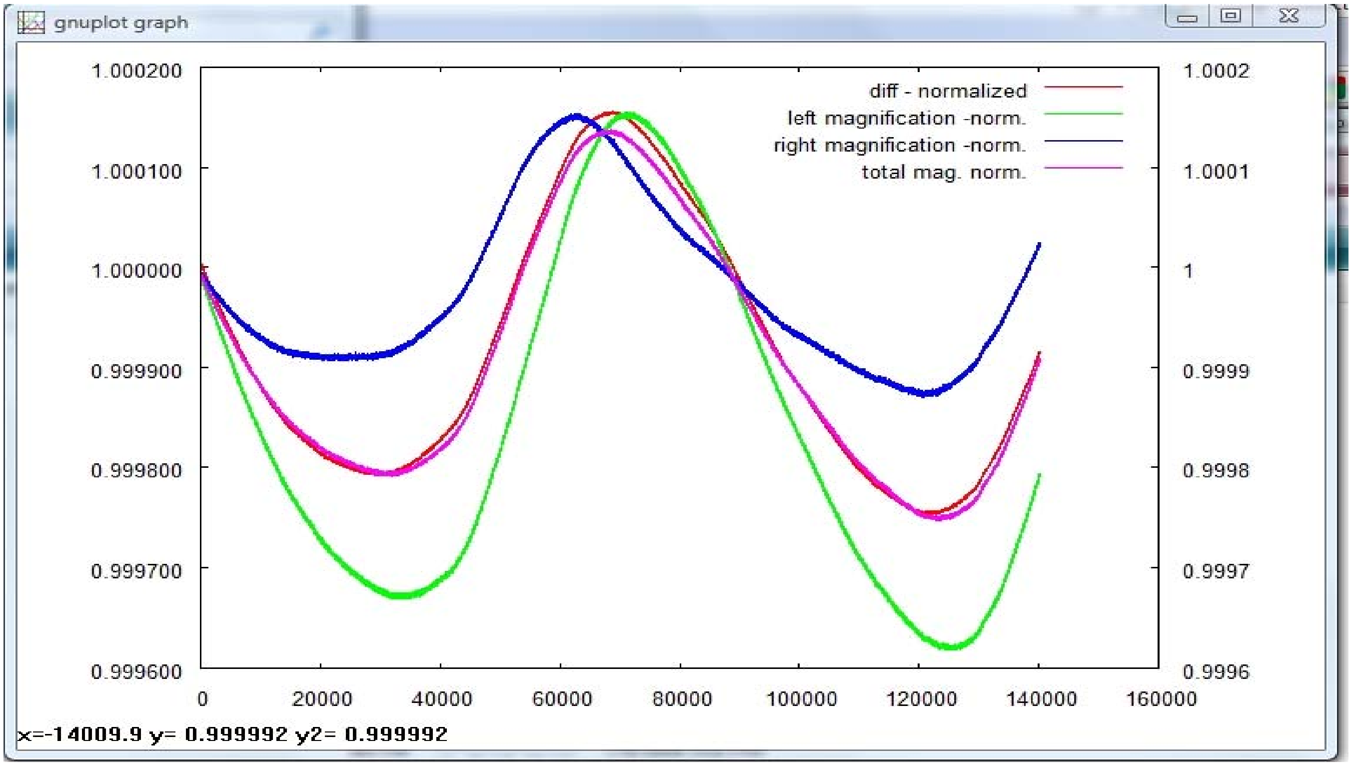

Figure 6: Magnification effect

Figure 7 below shows FFTs of some of our most recent data. The top plot is from the average sums, while the bottom is from average differences. You can see in the sums plot there are resonance peaks indicating some common mode noise. We believe this is being caused by some movement in one or more of our components as well, possibly one of the lenses or the grating mount. We're currently doing tests to determine if this is true and exactly what the source is.

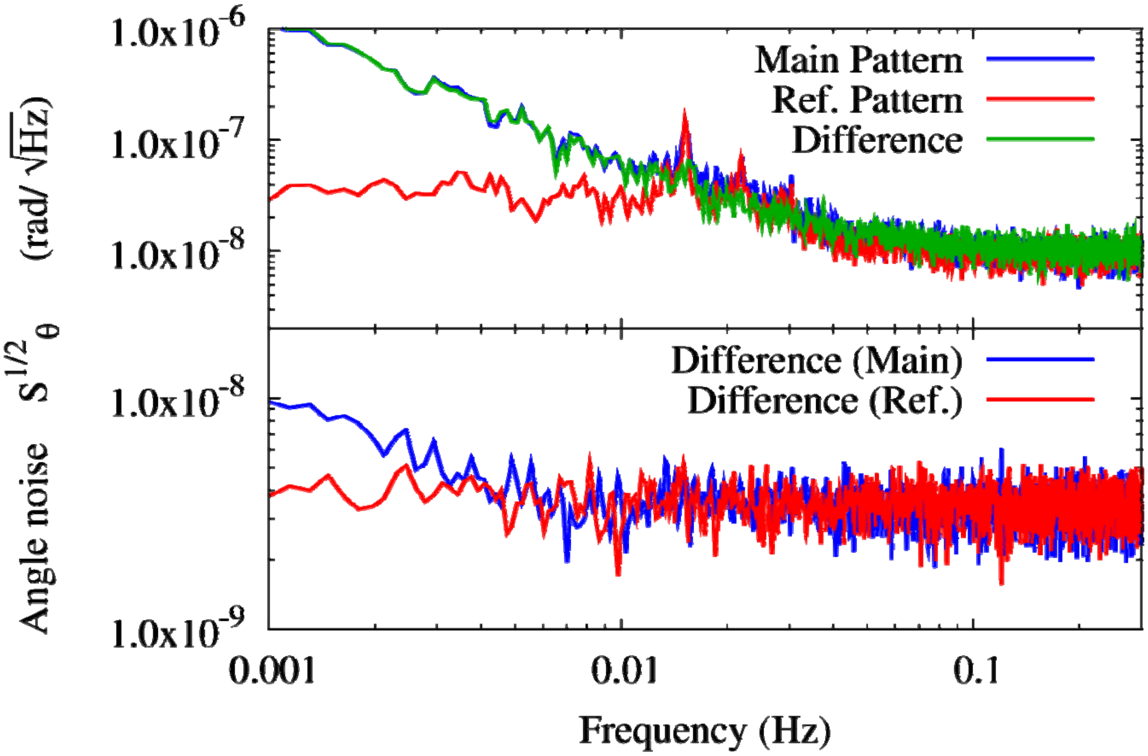

Figure 7: Top- noise trace of the average sums; Bottom- noise trace of the average differences

Temperature fluctuations are another concern; the apparatus is enclosed inside a Styrofoam box to insulate it from air currents and to keep it somewhat more temperature-controlled, but of course it still heats up and cools down over time. We recently installed hardware and software to measure the temperature over time, so we will be studying the effect of temperature on the noise of the system in hopes of eliminating it.

Overall, however, the noise level looks very promising, and with further improvements I have no doubt that the goal of 1 nrad/√Hz is well within the reach of this autocollimator.

Future:

While we have demonstrated that the device will be able to meet the specifications, there is still quite a lot of progress that needs to be made. I have discussed some upcoming improvements in some of the features such as the photomask grating, but looking further ahead with a final design idea in mind, the arrangement will probably need to be made more compact, possibly by folding the beam path.

Additionally, more stable mounting mechanisms will need to be developed, as well as a stable housing device for the finished autocollimator. While this autocollimator is being developed for LISA, its wide dynamic range and low noise level will make it useful for a variety of applications.

(1) R. Cowsik, R. Srinivasan, S. Kasturirengan, A. Senthil Kumar, and K. Wagoner, *Rev. Sci. Instrum.* **78**, 035105 (2007)