The Construction of an Upgraded Fiber Profiler
Involving the Installation of a High–Resolution USB
CCD Camera with a 12X Zoom Lens

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Abstract

Fibers holding test masses within advanced ground-based gravitational wave detectors contribute to thermal noise, limiting the overall sensitivity of the interferometers. Fiber dimensions and surface details impact the amount of noise generated. Current fiber-pulling machines have demonstrated the capability of producing fibers of \( \leq 20 \) microns in diameter\[10\]. Uncovering surface irregularities and measuring fiber diameters at this scale requires a camera with higher magnifications and better resolution than those presently installed in the fiber profiler at the University of Glasgow. This has led to the development of an upgraded fiber profiler.

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1 Introduction

Gravitational waves were first predicted by Einstein when he published his theory of general relativity in 1916\cite{1}. He understood gravity to be a geometric property: the curving of spacetime in the presence of energy and matter. Falling directly out of Einstein’s theory are gravitational waves, which are “ripples” in the fabric of spacetime, carrying gravitational radiation away from accelerating masses that exhibit spherically asymmetric motion.

Gravitational waves stretch and compress spacetime and travel at the speed of light. As a result, to detect a gravitational wave essentially means detecting a minuscule change in length. The gravitational wave detectors currently in operation are Michelson interferometers, the design of which is shown in Figure 1. The detectors must be sensitive to changes in distance on the order of $10^{-19}$ meters if they hope to detect a gravitational wave passing through\cite{2}. It is, therefore, necessary to use a very precise “ruler” to detect such small changes in length. Exploiting the fact that light travels at a constant speed, we use light as our ruler within the arms of the interferometers. The arms of the LIGO detectors are both 4km in length. They are placed at 90 degree angles with respect to one another. In accordance with the diagram above, light first leaves the laser in the form of a coherent beam and travels to the beam splitter. Then,
the beam is split and separate beams travel along each arm. The parts of the interferometer labeled “light storage arm” are cavities in which light bounces back and forth between the two mirrors, increasing the power of the laser beam and effectively lengthening the arms of the detectors, making them more sensitive to weaker gravitational waves. Next, the beams return to the elbow of the interferometer where, theoretically, because they have traveled the same distance at the same speed, they should destructively interfere. In other words, if there is no gravitational wave passing through at a given moment, no light should reach the photodetector.

However, if we were to introduce a gravitational wave propagating perpendicular to the plane of the interferometer, we can no longer expect complete destructive interference when the beams recombine at the elbow.

Above the interferometer in Figure 1, there is an illustration of a gravitational wave propagating from the sky toward the interferometer. As the gravitational wave passes through, one arm of the interferometer will be stretched and the other will be compressed. Then, the reverse will happen (the opposite arms will be stretched and compressed), resulting in an oscillatory sequence of space-time compressions and expansions.

This design led to the birth of a network of ground-based detectors such as GEO 600 in Hanover, Germany, LIGO in Hanford, Washington and Livingston, Louisiana, VIRGO in Pisa, Italy, and KAGRA in Tokyo, Japan. Having a worldwide network of detectors allows us to improve sky localization of the source producing the observed gravitational wave.

The first direct detection of gravitational waves occurred on September 14, 2015, when the Advanced Laser Interferometer and Gravitational Wave Observatory (LIGO) detectors located in Hanford, Washington and Livingston, Louisiana both picked up the signal from two merging stellar-mass black holes. This opens up a new era of astronomy: until very recently, all information gathered by observational astronomers has come in the form of electromagnetic radiation. Now we have a new way of observing the universe: we can investigate properties of
black holes and neutron stars, the sources of the gravitational waves we are observing. Once these detectors reach full sensitivity, the predicted average rate of gravitational wave detections is around 40 per year[3].

2 Sources of Noise

Various sources of noise limit the sensitivity of gravitational wave detectors: quantum noise, seismic noise, gravity gradients, suspension thermal noise, coating brownian noise, coating thermo-optic noise, substrate brownian noise and excess gas[4]. Each of these contributes to the total sensitivity limit, depicted by the black line in Figure 2. It is important that we understand and characterize these noise sources in hopes of reducing them and, thereby, improving our sensitivity to gravitational waves at many different frequencies. The dominant noise source related to the fused silica fibers that suspend the test masses, shown in Figure 3, is suspension thermal noise.

![Figure 2: Advanced LIGO sensitivity curve.](image_url)
3 Thermal Noise in the Suspension Fibers

As shown in Figure 2, in the frequency band of 10-30 Hz, gravitational wave detectors are limited most by thermal noise. In order to minimize thermal noise in the Advanced LIGO suspension systems, a quasi-monolithic design is employed, with fused silica fibers suspending the silica test masses in the interferometer[5].

The Fluctuation Dissipation Theorem[6] relates the thermal fluctuations experienced by a linear system in equilibrium to the dissipation:

$$S_f(\omega) = 4k_bT \Re[Z(\omega)]$$

where $S_f(\omega)$ is the power spectral density of the thermal driving force, $k_b$ is Boltzmann’s constant, $T$ is temperature and $\Re[Z(\omega)]$ is the real part of the mechanical impedance. Mechanical impedance is also known as dissipation, defined as:

$$Z = \frac{F}{v}$$

where $F$ is the force acting on the system and $v$ is velocity of the response.

The power spectral density of the thermal driving force can also be written
in terms of the admittance, \( Y \), the inverse of impedance:

\[
S_x(\omega) = \frac{4k_bT}{\omega^2} \Re[Y(\omega)]
\] (3)

The fused silica fibers undergo both external and internal damping, but internal damping is the primary means of dissipation, as external damping can usually be minimized to a negligible amount\[7\]. The following three subsections (3.1, 3.2, 3.3) discuss mechanisms of internal damping in more detail.

### 3.1 Thermal Displacement Noise

The combined system of a test mass and the fibers attached to it acts as a pendulum. In an idealized system, the pendulum suspensions would be perfectly elastic, thus obeying Hooke’s Law:

\[
F_{spring} = -kx
\] (4)

where \( k \) represents the spring constant and \( x \) represents the displacement of the oscillator from equilibrium. However, no material in actuality is perfectly elastic and able to have an instantaneous reaction to an applied force. Therefore, we call realistic materials *anelastic* materials. In order to accurately mathematically model the imperfect system response, we can rewrite Hooke’s Law in complex form including the addition of a phase lag term\[8\]:

\[
F_{spring}(\omega) = -k(1 + i\phi(\omega))x
\] (5)

The phase lag term is also known as *mechanical loss*, a function of the frequency of the oscillator, \( \omega \), which varies depending on the material being used. In order to minimize thermal noise in the frequency band of GW-detection, mechanical loss must be as low as possible. To show this mathematically, we can consider the equation of motion for a damped harmonic oscillator with internal friction:

\[
m\ddot{x} = -k(1 + i\phi(\omega))x + F_{thermal}
\] (6)

where \( m \) is the mass and \( F_{thermal} \) is the thermal driving force. Taking solutions to be of the form \( x = x_0e^{i\omega t} \), it follows that \( \dot{x} = x_0i\omega e^{i\omega t} \), which can be rewritten as \( \dot{x} = xe^{i\omega t} \).
Expressing the displacement, \( x \), and the acceleration, \( \ddot{x} \), in terms of the velocity, \( \dot{x} \), we have \( \ddot{x} = i\omega \dot{x} \) and \( x = \frac{\dot{x}}{i\omega} \). Solving equation 6 for \( F_{\text{thermal}} \), we find:

\[
F_{\text{thermal}} = i\omega m \dot{x} + \frac{k}{i\omega} (1 + i\phi(\omega)) \dot{x}.
\]  

(7)

Applying equation 2 (given that \( v = \dot{x} \)), we can solve for \( Z \):

\[
Z = \frac{k - \omega^2 m + i k \phi(\omega)}{i\omega}.
\]  

(8)

Because admittance is the inverse of impedance, it can then be shown, with a bit of algebra, that:

\[
Y = \frac{k\phi(\omega)\omega + i\omega k - i\omega^3 m}{(k - \omega^2 m)^2 + k^2 \phi^2(\omega)}.
\]  

(9)

For a harmonic oscillator, the natural frequency, \( \omega_0 \), is equal to \( \sqrt{\frac{k}{m}} \). Taking the real part of 9 and plugging it into 3, along with the substitution of \( \omega_0^2 m \) for the spring constant, we arrive at the following expression for the thermal displacement noise power spectral density:

\[
S_x(\omega) = \frac{4k_B T}{\omega} \frac{\omega_0^2 \phi(\omega)}{m[(\omega_0^2 - \omega^2)^2 + \omega_0^4 \phi^2(\omega)]}.
\]  

(10)

Furthermore, because \( x_{\text{rms}}(\omega) = \sqrt{S_x(\omega)} = \sqrt{x_{\text{thermal}}^2} \), the root mean square displacement can be written as follows:

\[
x_{\text{rms}}(\omega) = 2 \sqrt{\frac{k_B T}{\omega m} \frac{\omega_0^2 \phi(\omega)}{\omega_0^4 \phi^2(\omega) + (\omega_0^2 - \omega^2)^2}}.
\]  

(11)

### 3.2 Dependence of Thermal Displacement Noise on Mechanical Loss

It is not yet entirely obvious that the mechanical loss factor, \( \phi(\omega) \), must be minimized in order to reduce thermal displacement noise, at frequencies of interest, in the detectors.

Let us consider the suspensions to be a single resonance system, whose frequency of motion, \( \omega \), can either be much greater than the resonance frequency,
\(\omega_0\), equal to \(\omega_0\), or much less than \(\omega_0\). Let us also assume that the suspension material has a low mechanical loss \((\phi(\omega) \ll 1)\). This derivation can be generalized to a multi-resonance system, which is a more realistic model of suspensions\[7\].

For the case of \(\omega \gg \omega_0\), with appropriate approximations, the expression for the root mean square displacement can be simplified as follows:

\[
x_{rms}(\omega) = 2 \sqrt{\frac{k_B T \phi(\omega)\omega_0^2}{m \omega^5}}.
\]

(12)

This clearly illustrates that if the mechanical loss of a material is as low as possible, the root mean square displacement and, thus, the thermal displacement noise, will be brought to a minimum.

If \(\omega \ll \omega_0\), the expression becomes:

\[
x_{rms}(\omega) = 2 \sqrt{\frac{k_B T \phi(\omega)}{\omega_0^3 m \omega}}.
\]

(13)

This, too, suggests that materials with the lowest mechanical loss will experience the least thermal displacement noise.

Lastly, in the case of \(\omega = \omega_0\), the expression reduces to:

\[
x_{rms}(\omega) = 2 \sqrt{\frac{k_B T \omega_0}{m \omega_0^3 \phi(\omega)}}.
\]

(14)

At resonant frequencies of the suspension system, having a suspension made out of a material with a lower mechanical loss will cause there to be a greater root mean displacement from equilibrium. This is consistent with the total energy in the system being conserved: as mechanical loss decreases, less energy will be stored at frequencies away from resonance \((\omega \ll \omega_0\) and \(\omega \gg \omega_0\)), and more energy will be stored in the resonant modes \((\omega = \omega_0\).

As it turns out, LIGO’s sensitivity to gravitational waves is, for the most part, unaffected by the modes of resonance. In other words, the majority of the resonant modes lie outside of LIGO’s detection frequency band. As a result, in order to reduce thermal displacement noise as much as possible, LIGO suspension systems are constructed from materials with low mechanical loss: namely, fibers are made from fused silica, which is pulled from stock by a \(\text{CO}_2\) laser.
3.3 Thermoelastic Noise

When a fiber bends, a temperature gradient occurs: the temperature will increase in the compressed regions of the fiber and decrease in regions experiencing expansion. The amount by which the temperature will change along the length of the fiber is determined by the thermal expansion coefficient, $\alpha$, defined as:

$$\alpha = \frac{1}{l} \frac{dl}{dT}$$

(15)

where $l$ is the length of the fiber and $T$ is the temperature of the fiber. The thermoelastic loss can be written as[9]:

$$\Phi_{\text{Thermoelastic}} = \frac{YT}{\rho C} \left( \alpha - \frac{\beta}{Y} \right)^2 \frac{\omega \tau}{1 + \omega^2 \tau^2}$$

(16)

where $Y$ is the Young’s Modulus, $T$ is temperature, $\alpha$ is the linear thermal expansion coefficient, $C$ is specific heat capacity, $\omega$ is frequency, $\beta$ is the thermal elastic coefficient ($\beta = \frac{1}{Y} \frac{dY}{dT}$), $\rho$ is the material’s density, $\sigma_0$ is the static stress on the fiber, and $\tau$ is the characteristic time it takes heat to flow across the object.

If $\sigma = \frac{\alpha Y}{\tau}$, then the thermoelastic loss should, theoretically, be canceled. For a fiber whose cross section is circular, the characteristic time is[7]:

$$\tau = \frac{1}{4.32\pi} \frac{\rho C d}{\kappa}$$

(17)

where $d$ is the diameter of the circular cross section, $C$ is the specific heat capacity, $\rho$ is the density, and $\kappa$ is the thermal conductivity.

4 Dimensional Characterization of Fibers

As we have seen, the amount of dissipation into thermal energy is directly related to the dimensions of the fibers, necessitating careful inspection of their geometries. Not only is profiling the fibers important for quantifying the noise that the fibers produce, but it can also help us ensure that the neck regions are constructed so that they can bond properly to the ears on the sides of the test masses.
Moreover, the dimensional characterization measurements provide data to construct a finite element (FE) model of the fiber using ANSYS software, which numerically solves the boundary value problems and partial differential equations that lead to calculating the total mechanical loss[7].

Fibers are put through strength testing, during which they are pulled until they break. When strength-testing the fibers, it is important to understand why certain irregularities result from a physical perspective. Characterizing these deformities can lend more insight into the relation between surface or cross-sectional deformities and the thermal noise contributions that result. For example, physical deformities on the fiber that had formed during the pulling of the fiber from stock[10] might be able to explain why the fiber broke in a certain location.

One of the primary motivations behind the decision to build a new fiber profiler is to better understand the contributions to thermal loss coming from the fibers’ surfaces. Mechanical loss can be broken down into three main components[7]:

\[ \phi_{\text{fiber material}} = \phi_{\text{surface contribution}} + \phi_{\text{bulk contribution}} + \phi_{\text{thermoelastic contribution}} \]

For very thin fibers, where the surface area to volume ratio is very small, \( \phi_{\text{bulk contribution}} \) is negligible[5]. The majority of the loss in the fiber is due to surface dissipation, but the reason why this lossy layer exists is unknown and begs for further investigation[7]. A camera with better resolution that the one used in the current fiber profiling machine may be able to unveil the underlying cause of this lossy surface layer.

5 Current Profiler and the Upgrade

Fibers of 400 microns in diameter are presently installed in the LIGO interferometers, but fibers of less than 20 microns in diameter are capable of being made. Because the fiber profiler at The University of Glasgow is being used in various projects, the installation of the new high-resolution camera requires the construction of an entirely new profiler (as opposed to making adjustments to
The current profiler uses two cameras, one for high-magnification imaging and one for low-magnification imaging. The reason behind this design is the original use of rectangular ribbon fibers instead of circular-diameter fibers. With rectangular fibers, it became necessary to either turn the fiber 90 degrees to measure both dimensions of length and width or to take simultaneous measurements of ribbon’s length and width using two separate cameras, which was decided upon as the best option. It is now preferred to use circular as opposed to rectangular cross-sectional fibers, but the design of the profiler remains the same.

The profiler is composed of these two cameras, along with an LED light, a DC servo motor and a linear position encoder. The LED light is used to make sure that the image taken by the cameras evenly illuminates all edges of the fiber. The profiler allows the user to measure the cross-sectional width of the fibers using a custom LabVIEW program[7] which makes use of a contrast-based edge detection method developed by National Instruments as part of their Vision Acquisition Software package, NI-IMAQ. The stage upon which the cameras and LED light rest is controlled by the motor, which the user can control via LabVIEW. The user may input how many steps it would like the stage to travel, which corresponds to how many measurements he or she would like to take of the fiber along its length. The linear position encoder is connected to LabVIEW using Labjack U12, a USB Data Acquisition (DAQ) device.

The LabVIEW code[7] that controls the profiler currently in operation employs a state machine structure. A state machine structure allows the program developer to build different states, each with different functionality. The program relies both on user input and in-state calculations to determine which state to execute next.

This code was able to be modified for the new profiler as follows:

- change from two cameras to one camera
- change all camera-related VIs to the new camera’s LabVIEW software (more details in subsection 5.2)
adapt the distance-counting and motor-control states to work with the data acquisition device (LabJack U12)

Once the new profiler becomes fully operational, further minor adjustments to the profiler code may be necessary, but the underlying structure is in place.

5.1 Camera Assembly

The first step of the camera set-up was the installation of the Thorlabs software, which needed to be installed prior to connecting the DCC1240M camera to the USB port of the computer. Next, the MVL12X12Z zoom lens was assembled, along with the MVL12X20L magnifying lens attachment, and attached to the camera as shown in Figure 4.

Figure 4: Left to right: DCC1240M camera, MVL12X12Z zoom lens providing 12 mm of fine focus travel.

5.2 Integrating Camera Software with LabVIEW

The DCC1240M camera comes with a software package including a uc480 LabVIEW interface which contains the necessary drivers as well as example LabVIEW programs (VIs). The camera takes 1280 x 1024 pixel images using complementary metal-oxide-semiconductor (CMOS) technology.

Using a combination of uc480 example VIs, such as LiveStream_32bit_Vision, along with NI-IMAQ and NI Vision Development software, I wrote a LabVIEW program to do the following:
• display a live feed on the Front Panel
• capture and save an image with the click of a button
• measure the intensity across a line of pixels
• count the distance between the edges of an object (edges determined by contrast levels).

Example pictures taken with this camera are shown in section 5.4. Figure 5 displays the portion of the code that accomplishes the tasks listed above.

Figure 5: Customized LabVIEW code used to take pictures, measure intensity and measure width of objects in units of pixels.
5.3 Calibrating the Camera (pixels/µm) with the .05mm Feeler Gauge

Calibrating the camera allows us to accurately measure distances, on the micrometer scale, using images taken. Calibration involves determining the number of image pixels that correspond to a micrometer.

To begin calibration, I needed to first image an object of known width. I displayed a live feed of a .05mm feeler gauge, adjusted the focus, and then counted the distance between the edges of the feeler gauge using IMAQ Clamp Horizontal Max VI. This VI measures the distance between edges of an object in units of pixels.

In order to minimize motion at the tip of the feeler gauge, I had to construct a cartridge to hold it in place on both ends (see Figure 6). Both ends of this cartridge were then clamped down to minimize vibrations caused by motion of the table.

Figure 6: Camera and zoom lens held by clamp, imaging the cartridge holding the .05mm gauge.
Table 1: Table containing values used in the calibration of the .05mm gauge.

<table>
<thead>
<tr>
<th>Variable Magnification Value on Lens</th>
<th>Net Magnification</th>
<th>Distance in Pixels</th>
<th>Size of Image in Microns</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.58</td>
<td>2.32</td>
<td>29.9</td>
<td>116</td>
</tr>
<tr>
<td>1</td>
<td>4</td>
<td>40.9</td>
<td>200</td>
</tr>
<tr>
<td>1.5</td>
<td>6</td>
<td>59.2</td>
<td>300</td>
</tr>
<tr>
<td>2</td>
<td>8</td>
<td>81.3</td>
<td>400</td>
</tr>
<tr>
<td>2.5</td>
<td>10</td>
<td>103.2</td>
<td>500</td>
</tr>
<tr>
<td>3</td>
<td>12</td>
<td>121.9</td>
<td>600</td>
</tr>
<tr>
<td>4</td>
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<td>155.6</td>
<td>800</td>
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<td>20</td>
<td>193.4</td>
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<td>1200</td>
</tr>
<tr>
<td>7</td>
<td>28</td>
<td>266.3</td>
<td>1400</td>
</tr>
</tbody>
</table>

The definition of magnification is as follows:

\[
Magnification = \frac{\text{Size of image}}{\text{Actual size}} \tag{18}
\]

Because the actual size of the feeler gauge (.05 mm or 50 µm) and the magnification were known, the size of the image in units of micrometers could be determined by rearranging equation 18:

\[
\text{Size of Image} = \frac{\text{Magnification}}{\text{Actual size}} \tag{19}
\]

The net magnification column in table one is calculated as follows: multiply the Variable Magnification Value on Lens by 2 (to account for the extension tube), and then multiply again by 2 (to account for the 2X magnifying lens adapter). I plotted the width, in pixels, of the feeler gauge (the Distance in Pixels column in Table 1) against the calculated Size of Image column in Table 1, resulting in the trend line computed by linear regression in Figure 7.

The slope of the line, to two significant digits (0.19), represents the number of pixels per micrometer. This value is confirmed by another calibration experiment in the following section. The importance of knowing the number of pixels per micrometer is that it allows us to measure the width of objects, using the new camera, in micrometers.
5.4 Calibrating the Camera with 75µm Tungsten wire

Following the exact same procedure described in the previous section, I calibrated the camera with 75 micron tungsten wire. I intended to use 25 micron tungsten wire, in order to use an object of roughly the same diameter as the fibers that will be profiled, but there was not any 25 micron wire at my dispense. However, the results using the 75 micron tungsten wire (shown in Figure 8) confirm what I found to be the number of pixels per micrometer in the previous section. An example image taken during calibration is shown in Figure 9.

5.5 DC Servo Motor

The purpose of the DC Servo motor is to move the stage, so that the camera is able to run across the length of the fiber and image all of its parts (the necks and the body). The motor being used for this project is the M589TE 1270 motor.
Figure 8: Pixels per micrometer calibration graph for the tungsten wire.

Figure 9: 75 micron tungsten wire at a magnification of 16. (Lighting makes the wire appear black for the purpose of edge detection.)
manufactured by Mclennan.

After extending and connecting the wires that drive the motor to a DC power supply, I decided to wire up a switch that turns the motor on and off, also allowing the user to change the direction in which the stage moves. The switch is shown in Figure 10.

Figure 10: Toggle switch that turns motor on/off (with directionality) and its corresponding wiring diagram.

5.6 Encoder

One of the most crucial aspects of experimental physics is data acquisition (DAQ): the process of interfacing measurement hardware and computer software to control and monitor input and output of the hardware.

LabJack U12 is a USB DAQ device with one available 32-bit counter on the LabJack U12 (corresponding to the screw terminal labeled, “CNT”). The linear position encoder used in this project is called MSK320 linear magnetic sensor. It is electrically connected to both the DC power supply and the LabJackU12 counter. The encoder is physically attached to the stage and, as it moves, detects incremental differences in position. The differences in position correspond to logic high and low signals (shown in Figure 12) embedded in the magnetic tape underneath the path of the encoder (shown in Figure 11). The encoder communicates the position of the stage to the computer and can be monitored by the user. To increase the encoder’s resolution, multiple counters can be used, however, the LabJackU12 used in this project only has one counter available.
5.7 Controlling the Motor with *LabJackU12*

As previously stated in section 5.5, it is necessary to have the stage be able to move both up and down the body of the profiler machine. In the current setup, the user can control the direction manually, however, the next step is to have the LabVIEW program control the movement and direction of the motor.

L6205 is a DMOS Dual Full Bridge driver that can be used as a motor control chip. The chip is essentially an H bridge, which has four switching elements. When the correct combination of these elements are turned on, the current will flow in the desired direction. I have created one of the recommended circuits
(circuit diagram shown in Figure 13) and placed it in an electronic enclosure for future use.

![Circuit diagram](image1.png)

Figure 13: Circuit with H bridge to control motor.

### 6 Conclusion and Further Work

This project has combined techniques from various disciplines. The final product that will result from the project primarily has implications for the field of gravitational wave astronomy: with a better understanding of the losses in the suspension fibers, we can reduce noise in the detectors. However, the day-to-day work on this project involved interfacing hardware and software (controlling the system with LabVIEW), electronics and circuitry (switches for the motor), and mechanical engineering (the mounting and stabilization of the profiler itself).

There are a few items that still need to be completed before the new profiler can be considered operational. The H bridge motor control needs troubleshooting as well as the counter’s distance measurements that are read from the encoder.
In addition, a fiber cartridge needs to be built and the camera will need to be mounted. Once these items are complete, the only task that remains is to make adjustments to the profiler code as the user sees fit.

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References


