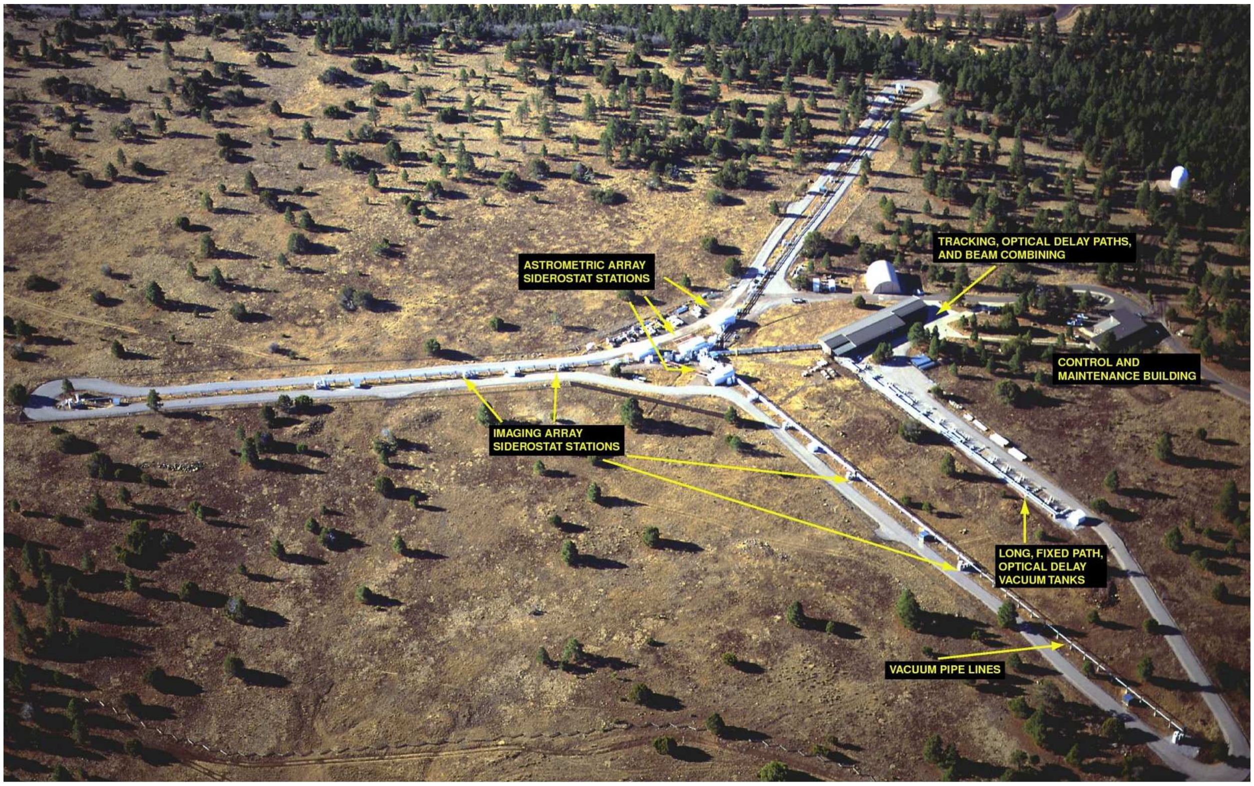
EE 521 Measurement and Instrumentation

Fall 2006 - Dr. Anders M. Jorgensen

Heterodyne Laser Metrology System



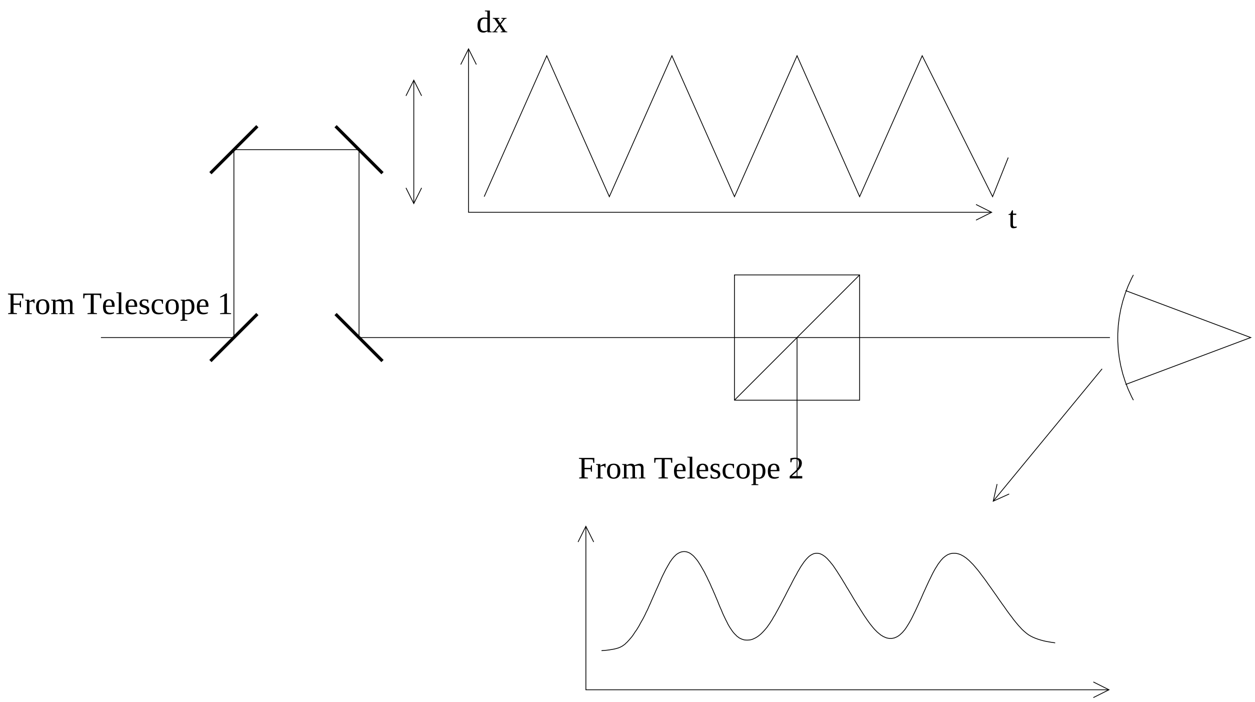
In this project you will analyze data from a laser metrology system used to measure the position of a piezo-electric positionining device. The piezo is nominally tracing a triangular waveform at a frequency of 500 Hz and an amplitude of a few micrometer.

Background: The Navy Prototype Optical Interferometer (NPOI) is located in Flagstaff, AZ. It measures approximately 400 m in diameter, which allows it to obtain a angular resolution in the sky at visible wavelengths ($\sim 500\,\mathrm{nm}$) of approximately

$$\frac{\lambda}{D} = \frac{500\,\mathrm{nm}}{400\,\mathrm{m}} = 10^{-9}\,\mathrm{radians} = 0.3\,\mathrm{mas}$$

One milliarcsecond (mas) is approximately $3 \times 10^{-7\circ}$. By comparison, the resolution of the human eye is approximately 3 arcminutes, or 0.05°. The extremely high resolution of optical interferometers is necessary because stars have very small angular diameters. An interferometer works by collecting light at telescope pairs, transmitting it to a central location and interfering the two beams. The intensity measured by a detector depends on the relative phase of the two beams, and varies sinusoidally as the relative path is changed.

The amplitude and phase of this intensity pattern is related to the Fourier transform of the image of the object being observed. In order to measure this we delay the two beams relative to each other in a triangular pattern with a high frequency (500 Hz) and an amplitude of a few wavelengths (See Figure), using a piezo-electric device.



In this lab we are not interested in the scientific data but rather in measuring the actual motion of the piezo. The piezo is driven open-loop by a triangular waveform of several hundred volts. To measure the actual position of the piezo, we implement a heterodyne interferometer metrology system like the one depicted in Northrop Figure 7.52, where RR1 is attached to the piezo. The light source is a Helium-Neon laser and the heterodyne frequency generated by an Acousto Optical Modulator (AOM) is $\Delta f = 2\,\text{MHz}$. Note also that the change in the distance x_1 in Figure 7.52 is twice the movement of RR1.

Assignment

1. Derive expressions for the voltages produced by PD1, $R(t)$, and PD2, $M(t)$ (Assume the voltages are proportional to the incident light intensity).

2. Plot the waveforms $R(t)$ and $M(t)$ for an appropriate triangular motion of RR1. Pick parameters such that the change in frequency of $M(t)$ is easily visible.

3. Write a program which can read one of the data files into an array. The data files contain signed 2-byte (16-bit) integers in Intel processor byte-order.

4. Plot a short segment of both the reference and measuring signal. They should look like periodic signals, not quite sinusoidal. The departure from a sinusoidal shape is due to non-linearities in the detection system. Note that the signals have been high-pass filtered such that they are centered around zero, not around some mean brightness level. Note that the two files are synchronized, such that the i'th measurement in the reference file is recorded at the same time as the i'th measurement in the measuring file.

5. Derive a position determination algorithm. Assume that $R(t)$ and $M(t)$ are passed through logic discriminators such that a 1 is produced when the inputs are greater than

some values (for example halfway between minimum and maximum), and 0 otherwise. Next derive an algorithm which can be used to compute the position. You should end up with something like $\Delta x_1 = (n + \delta)\,\lambda$.

The following description may be helpful, "We maintain a counter `n`. We scan forward in time. Each time we encounter a upward zero-crossing in the reference signal we increment `n`. Each time we encounter a upward zero-crossing in the measuring signal we decrement `n`. $\mathtt{n} \times \lambda/2$ gives us a rough measure of the position of RR1, to within a wavelength. But we can do better. In addition, we compute at each upward zero-crossing in the measuring signal the quantity δ, which is the time since the last upward zero-crossing in the reference, divided by the period of the reference. We can now get a more accurate measure of the position, which is $(\mathtt{n} + \delta) \times \lambda/2$."

You can of course make use of both the upward and downward zero-crossings, but using just one of them is better. If you use both of them you have to carefully select the zero level that defines the crossings. If you use only the crossings in one direction the choice of zero level is not important. **Bonus:** get 50% extra credit on this question if you adequately explain why this is so.

6. Write a program which calculates the times of upward zero-crossings in seconds. A possible definition of such a zero-crossing is that it occurs when point i is less-than-or-equal-to zero, and point $i + 1$ is greater than zero. You will need to interpolate the time of the zero-crossing or you will not get good precision.

7. Plot histograms of times between upward zero-crossings in the reference and measuring signals. Explain why they look the way they do (The triangular variation of x_1 is superimposed on a linear variation of x_1 with time).

8. What is the mean and uncertainty of the measured period of the reference signal?

9. What is the mean period of the measuring signal? Use that to compute the mean velocity of RR1, and its uncertainty.

10. Write a program which uses information about zero-crossings to compute the position of RR1 as a function of time (position computed at each zero-crossing in the measuring signal). **Note:** Since the reference signal has constant period you can simplify the algorithm a little. At each zero-crossing in the measuring signal you can calculate both the number of zero-crossings in the reference signal and the time since the last reference zero-crossing without having to search through you table of reference zero-crossings. This makes the program much simpler.

11. Estimate the uncertainty in the position of RR1.

12. Plot a short segment of the position of RR1. Then subtract the constant velocity term, and plot again.

13. Plot the power spectrum of the position data (after subtracting the constant velocity term). Discuss features in the power spectrum.

Finding positive zero-crossings. We have a signal $\{S_i\}$. A positive zero-crossing occurs when the $S_i < 0$ and $S_{i+1} \geq 0$. If measurements i and $i+1$ are obtained at times t_i and t_{i+1} then the precise time of the zero-crossing, t_z, can be interpolated using the following relationship

$$\frac{S_i}{t_z - t_i} = \frac{S_{i+1} - S_i}{t_{i+1} - t_i}$$

Be sure to have a the $\geq$ in your algorithm, and not just $<$ and $>$, otherwise the program will skip zero-crossings where a measurement is exactly zero, and give the wrong result.

Data: You are given two data files. The first file `reference` samples the output of the reference signal photo diode (PD1 in Northrop Figure 7.52), and the second file `measuring` contains the output of the measuring signal photo diode (PD2). Each signal is sampled at 50 MHz, and they are synchronized such that the i'th measurement in the reference file is measured at the same time as the i'th measurement in the measuring signal. The data values in the file are signed 16-bit (2-byte) integers, and trace out periodic curves. Note that the signals have been high-pass filtered to remove a DC component, and are thus centered around zero instead of around a mean brightness level.

Reference:

A. M. Jorgensen, D. Mozurkewich, J. Murphy, M. Sapantaie, J. T. Armstrong, G. C. Gilbreath, R. Hindsley, T. A. Pauls, H. Schmitt, D. J. Hutter, "Characterization of the NPOI fringe scanning stroke," Proc. SPIE Astronomical Telescopes and Instrumentation, Orlando, FL, SPIE 6268 Advances in Stellar Interferometry, 2006.