Physcs 281 – Computational Physics

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<u>Projet 2 – the Large Millimeter Telescope</u>

Background

The Large Millimeter Telescope (LMT) is the world's largest mm-wavelength telescope. Perched on a 15,000 foot mountaintop in Mexico, the LMT enjoys beautifully clear skies and excellent access to some of the most deeply studied patches of our Universe.

The LMT has a 50m diameter, fully steerable main dish and is able to point to any location on the sky above 10 degrees elevation. Building such a large piece of machinery is an enormously challenging enterprise – the project is now in its 20th year and all the construction is complete. Now it is our job to make this machinery into a real telescope.

Your three main tasks in this project center on three challenging characterizations of the telescope: focusing the antenna, building a pointing model, and characterizing the gain vs elevation. You will be using real LMT data in this work and so my hope is that you will get a real sense of what a working astronomer/physicist does.

Preliminaries

All three sub-projects in this project rely on your ability to fit linear models using the techniques we developed in Class 15. If you were not present at Class 15 or you feel you need additional review, contact me or one of the TAs immediately so that you can get the help you need.

Subproject 2.1 – Focusing the LMT

All cameras and telescopes need to be focused and the LMT is no exception. We do this by moving the "secondary" reflector (also known as M2) in relation to the "primary" reflector (also known as M1) in the z-coordinate (see the Class 16 notes for the geometry). In this part of the project you will build a program that reads in data from five different maps of a point source and then determines the best-fit focal position of the secondary reflector.

Data:

The data for the five maps is available on the course Moodle page under Project 2. You will be using the five files listed as focus<1-5>.nc. I have also put a piece of code called "read_focus_map.py" that illustrates how to extract the data from a single .nc file. You will need to extend this script to read in all the focus data.

Focus Model:

For small motions of the secondary mirror away from the nominal focus position, the amplitude of a detected source will change in the form of a quadratic. The point on the quadratic function where the amplitude peaks is the optimal focus point. Your model for the point-source amplitude of each of the five maps is then:

$$amplitude = p_0 + p_1 M2_z + p_2 M2_z^2$$

where $M2_z$ is the offset of the M2 mirror in the z-direction and p_0, p_1, p_2 are free parameters in the fit.

Subproject Tasks and Goals:

Use the five files provided to determine a new z-position of the M2 mirror that will maximize the amplitude of the detected signal – that is, you want to find the value of M2z that maximizes the fitting function above after you've found the best-fit parameters. [Hint: the new z-position will not be one of the z-positions from the files – you need to use your determination of the parameters in the model to find the best new z-position.] In your write-up you should

1. clearly state what this new z-position is as well as its associated error (this will require some error propagation),
2. plot the different amplitudes from the file along with your best fit model.
3. show the residuals to the fit (data-model) with error bars
4. examine the other extracted parameters from the map file and discuss their values in light of what you intuit about an out of focus system.

Make sure that each step is discussed in your written report and that you submitted code reflects the work you did to accomplish each step.

Subproject 2.2 – Pointing the LMT

In order to use the Large Millimeter Telescope properly, we must be able to point the antenna to a random spot on the sky and have the antenna beam centered on that position. For a large antenna, with a small beam, this is a big technical challenge.

Our approach is to make observations of known objects at known positions and measure the difference between the place the antenna points and the actual location of the source with respect to the antenna's axis. There are many misalignments in the antenna structure that can cause the antenna's pointing to be off. What we do is to observe the behavior over the whole sky and then fit a model, which includes these effects, to the observed positions. The model fit results in estimates of the alignment parameters, which can then be used to predict the pointing of the antenna for future sources.

In this project we will conduct a fit of the LMT pointing model to some actual pointing data. The data were measured on radio sources using the Redshift Search Receiver, which is aligned with the axis of the antenna. We believe that the position of a star is measured with an accuracy of 2 arcseconds by this procedure.

The antenna has two axes of motion:

Azimuth - an axis perpendicular to the Earth's surface, pointing up. Azimuth is defined to be 0 when the antenna is pointed to the North and increases as the antenna turns towards the East.

Elevation - an axis perpendicular to azimuth which measures the angle between the antenna reflector's axis and the ground. Elevation is defined to be 0 when the antenna is pointed to the horizon and it increases as the antenna points up above the horizon. The antenna pointed at zenith has an elevation angle of 90 degrees.

Data:

Our measurements are in the comma-separated-value (CSV) data file pointing_data.csv. There are 44 data points in the file. Each data point has the pointing offset found for a source located at a particular azimuth and elevation. The pointing offset is measured in the azimuth direction and the elevation direction.

The file consists of 44 lines with 9 columns. We don't need all of the columns for the fit. The first column is the azimuth of the observation (in radians). The second column is the elevation of the observation (in radians). The third and fourth columns are not needed. The fifth column is the pointing offset measured in azimuth (in radians). The sixth column is the pointing offset measured in the elevation direction (in radians). The seventh is an ID number for the observation. The remaining 2 contain some information about the receiver which we don't need for the fit.

Pointing Model:

There are two models that we use to assess the pointing of the telescope – one for the azimuth offsets and one for the elevation offsets. The models are:

$$\delta Az = A_1 + A_2 \sin(El) + A_3 \cos(El) + A_4 \sin(El)\sin(Az) + A_5 \sin(El)\cos(Az)$$

$$\delta El = E_1 + E_2 \cot(El) + E_3 \cos(El) + E_4 \cos(Az) + E_5 \sin(Az)$$

The parameters are related to the following physical misalignment errors:

- **A1** - Antenna Collimation Error - Alignment of optical camera and the structural axis of the antenna
- **A2** - Axis Collimation Error - Deviation from perpendicular of Azimuth and Elevation axis intersection.
- **A3** - Encoder Zero Error - Offset in the azimuth axis encoder reading from 0 when the antenna is actually pointed to 0 azimuth.
- **A4,A5** - Describe the effect of the Tilt of the Azimuth Axis from Vertical

and for elevation:

- **E1** - Encoder Zero Error - Offset in the elevation axis encoder reading from 0 when the antenna is actually pointed to 0 elevation.
- **E2** - Refraction Error - Offset caused by refraction in the Earth's atmosphere.
- **E3** - Gravity Sag Error - Offset caused by gravitational distortion of antenna structure with changing elevation.
- **E4,E5** - Describe the effect of the Tilt of the Azimuth Axis from Vertical.

Notice that there is some degeneracy in the parameters (that is, they reflect the same physical process). In this model, E4=A4 and E5=-A5.

Subproject Tasks and Goals:

Here are some steps to go through for this sub-project. Make sure that each step is discussed in your written report and that you submitted code reflects the work you did to accomplish each step.

1. Look at the data. For this step you will want to convert the angular measurements given to sensible units. For example, I like to look at azimuth and elevation values in degrees but I look at differences in angles in arcseconds. Calculate the standard deviation in the pointing offsets for both azimuth and elevation offsets. How big is the error? Make histograms of the raw offsets for later comparison with the residuals of your model fits. Discuss what you see. Are offsets bigger in some areas of azimuth or elevation?
2. Fit the data to the two models provided above. You will want to do two separate fits: one for the azimuth offsets and one for the elevation offsets. Be sure to give the best-fit values of each of the 10 parameters and their errors.
3. Now assess the fits. Make a plot of the residuals and compare the standard deviation of the residuals to the standard deviation of the raw pointing offsets. Has your pointing model improved the pointing? Discuss your conclusion. Now answer the following questions:
    a. Are the residuals in Azimuth the same size as those in Elevation? Discuss.
    b. Do the residuals look like they are drawn from a normal distribution? Discuss.

c. Quantitatively, how likely is it that the residuals from the model arise from normally distributed errors in the measurements assuming that the measurement errors have sigma=2 arcseconds? Discuss.
d. Are there any structures in the plot of the residuals that suggests that there may be unmodeled effects? Discuss.

Subproject 2.3 – The LMT's Gain Curve with Elevation

The LMT is so large that as it tilts to different elevations the structure flexes and the main dish changes shape. The active surface of the LMT can account for some of this flexing by pushing the primary mirror back into shape, but there are some modes of change that we cannot measure easily and so we cannot correct for them. This results in an elevation-dependent gain of the dish. In this sub-project, you will use a fit to characterize this change in gain so that observers can properly prepare for it.

Data:

The data for this sub-project consists of measurements of a single detector from the AzTEC camera of a set of bright point sources. Of the sources available, only the asteroids Ceres and Pallas have well-known fluxes. The radio galaxies are all variable and so the flux-error on that set of sources is large. The data is contained in the file LMT_gain.csv. The columns are described in header information at the top of the file.

Gain vs. Elevation Model:

The gain vs. elevation model is an M^{th} order polynomial in elevation. That is

$$gain = p_0 + p_1 El + p_2 El^2 + p_3 El^3 + \cdots + p_{M-1} El^{M-1}$$

Subproject Tasks and Goals:

Use the data provided to determine a proper parameterization of the LMT's gain for this detector. You will need to inspect the data and then choose a model that best-describes the data. More than either of the other sub-projects, this sub-project asks you to be creative and judicious in your choice of model. Discuss what you do to choose the best value of M. Discuss what happens if your choice of M is big and what happens if M is too small. Conclude with your best-fit parameters and their associated errors. Make a plot of the data and your best-fit gain as well as the residuals of the fit.