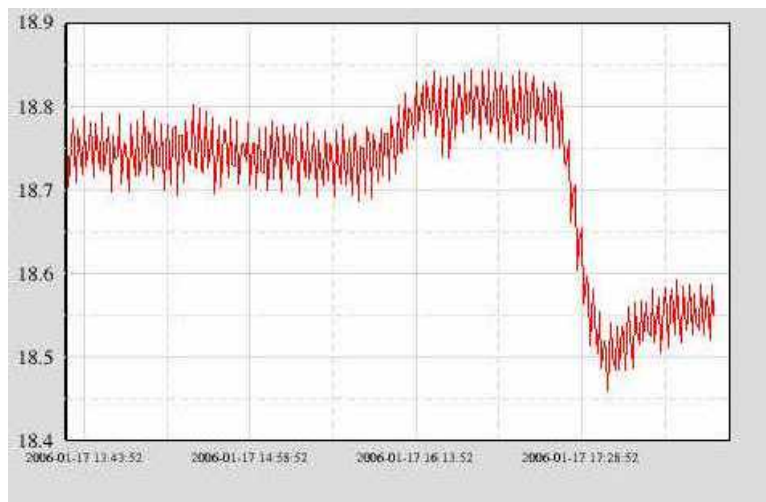


# Searching for Gravitational Waves in Noisy Data

## Teachers Key for the Student Activity Worksheet

### Introduction

You have probably done science experiments in which you measured a small handful of variables a small number of times. Using computers for help, gravitational wave detectors like LIGO measure and record thousands of different variables at the same time, all of the time. Some of these measurements occur once a second; others occur over 16,000 times per second. Scientists then search for patterns in these data by making plots such as the one shown here. Notice that the trace is not smooth but that it constantly jiggles up and down by about 20% of the span of the vertical axis. Scientists call this jiggle *noise*, and it shows up at some level in almost all real data that is measured through time. To a scientist, the term *noise* means more than sound. Noise represents all the vibrations in the data, often coming from a variety of sources that make it harder to



see the pattern of interest or *signal*. On this plot the main features of the pattern (the signal) are easy to distinguish from the noise, especially the sharp drop on the right. In this activity you will search for the evidence of gravitational waves in noisy data. Although the data you will use are simulated and not actual detector data, the exercise will give you a good look at the strategies that scientists of all types use to hunt for real signals.

### Instructions

In the activity your teacher will provide four plots of simulated data, labeled Signal 1 through Signal 4. These are printed on transparency sheets. You will notice that each plot shows the presence of a signal plus a lot of noise. Your job is to characterize the signal in each data plot by finding the best match between the data and a signal *template*. There are four sets of templates; M, C, P and X. Each set contains six individual templates; M1, M2 ... M6 and so on. The templates are graphs of mathematical equations. These equations and their graphs are *models*. They represent scientists' expectations of what gravitational waves will look like in the data.

Compare the noisy data plots to the signal templates (models) by laying the data transparencies over the templates. Find what you feel is the best match for each data plot. Record your results in the table below

### Characterization of Gravitational Wave Signals

Data set	Signal 1	Signal 2	Signal 3	Signal 4
Label of template that gives the best match	M1	C4	P6	X3

**\*\* Teachers: See the Activity Key on p 3 for additional discussion of the templates and signals.**

### Questions

To the teacher: These questions are somewhat open-ended and students may generate a variety of interesting responses. The comments below are not intended to serve as the “correct” responses but may provide ideas for additional discussion.

1. Did you always agree with your classmates as you chose what you thought were the best matches? Can you see how scientists could disagree with each other as they try to match models to signals in their data? Explain. Students often initially disagree about the matches because of the subtle frequency differences that exist between templates of the same set. The realization that a data plot matches template set P might occur smoothly, but just which particular P template gives the best match is often tougher to discern. Scientists face the same challenge in analyzing gravitational wave data. Identifying the waveform of the signal will be challenging, and pinning down its frequency with precision will be even tougher and will give rise to much animated discussion among the data analysts.
2. Scientists use models to help them understand the behavior of real systems. One purpose of models is to simplify the system under study. In this activity how do the models (the templates) simplify the real systems (the data sets)? Do the templates help you understand the data sets better? Explain. The templates are formed from plots of mathematical functions. The M templates are cosines of different frequencies. The other template sets represent more complicated waveforms. These ‘pure’ plots represent what we think is the behavior of the gravitational wave sources – neutron stars, black holes, etc. Instrument noise in the data tends to obscure the pure patterns that the sources will create. The noise-less templates, simplifications of the real data, make it easier to find and characterize gravitational wave patterns in the data. Imagine looking at the data without the templates to help. In addition, matching a template to the data connects the source’s behavior to a set of mathematics that can be used to reveal other properties of the source.
3. You may have made a model of the solar system in school. Astronomers now use computers to make models of the solar system, stars, galaxies and clusters of galaxies. Why are these models necessary, or in what ways are they helpful? Why don’t the astronomers just study the galaxies themselves? (Think about how the models (templates) helped you in this activity.) In the activity the templates help us understand the data more clearly by highlighting and clarifying the signal patterns that exist within the noise. In the same way, computer models of stars and star systems help us focus on important behaviors of these systems by allowing us to manipulate variables with the model (its easy for astrophysicists to change the mass distribution of a galaxy in a computer model, not so easy on the galaxy itself (!)).

4. Write a short paragraph summarizing what you have learned in this activity. Use the following terms in your paragraph (not necessarily in this order): *data, signal, noise, template, model*. An example: One way that scientists take data is to measure the same variable at repeated intervals over time. Plots of these measurements that place time on the x-axis will show how the variable changes over time. Often the data will bounce around in a somewhat chaotic way from point to point, and the graph will show this wiggle. Scientists call this “noise.” In addition to the noise, the graph may show a more organized pattern of change, often called the signal. Characterizing the signal in the presence of noise can be difficult. To improve the characterization, scientists will make several mathematical models of what they think the signal pattern should look like. The models are also called templates, and they don’t contain noise [An aside: scientists often add fake noise to their models on purpose to improve their analyses. This is easy to do on a computer]. Then the scientists compare their actual data to these models to find the model that matches the data most closely.

## Gravitational Wave Activity Key

<http://cgwp.gravity.psu.edu/outreach/activities>

**Signal 1 = M1**

**Signal 2 = C4**

**Signal 3 = P6**

**Signal 4 = X3**

### **Signal 1/Template M: "Monochromatic"**

Monochromatic gravitational waves are perfect, single frequency waves (a single frequency is like a single tone or note). They are created in many astrophysical systems which move in stable circular motions, like the orbit of two white dwarf stars, or like a small bump on the surface of a rapidly spinning neutron star.

### **Signal 2/Template C: "Coalescing"**

Gravitational waves suck energy out of astrophysical binary systems and cause them to slowly spiral together. The information about the slow death spiral can be seen in the gravitational waves, which become stronger (“bigger amplitude”) and higher frequency as the stars or black holes spiral together. The waveform associated with this coalescence is often called a “chirping” waveform.

### **Signal 3/Template P & Signal 4/Template X: "Extreme Mass Ratio Inspiral, + & x waveforms"**

Occasionally supermassive black holes in galactic nuclei will capture smaller stellar mass objects, like white dwarfs, neutron stars or smaller black holes. The gravitational waves we will see from these captures carry detailed information about the supermassive black hole. All gravitational waves are emitted in two types (called “polarizations”) which together encode a complete map of the gravitational structure in the system that generated the waves; these polarizations are called “plus” and “cross.”