Interstellar Medium Effects and Profile Evolution Worksheet

M. T. Lam
IPTA 2014 Student Workshop

1 Introduction

Pulses that travel through the ISM are subject to a number of effects, all of which can ultimately change the estimated times-of-arrival (TOAs) and affect any other signal we are trying to detect. We will look at the biggest effect, dispersion measure (DM) removal, which induces a frequency-dependent delay on the pulse arrivals that changes with time. The intrinsic emission of the pulsar, assumed to be stationary with time, also has a frequency-dependent effect on TOAs, and separating the two can often be a challenge. Other ISM effects, such as scintillation, scattering, and pulse shape variations, such as in state-changing pulsars, will not be considered here but are all areas of active research.

In this exercise, you will be working towards understanding how we estimate DM and build a model for pulse profile evolution. Throughout, we will make the distinction between the pulse template and a pulse profile. The pulse template is a stationary waveform as a function of observing frequency. Many observed pulse profiles summed together will create the average template shape.

2 Dispersion Measure

The most prominent effect on timing comes from pulses traveling through the cold, ionized plasma of the ISM. The index of refraction of the medium is frequency-dependent, resulting in lower frequencies arriving later at the telescope than higher frequencies. The amount of time that a signal will be shifted by is given by

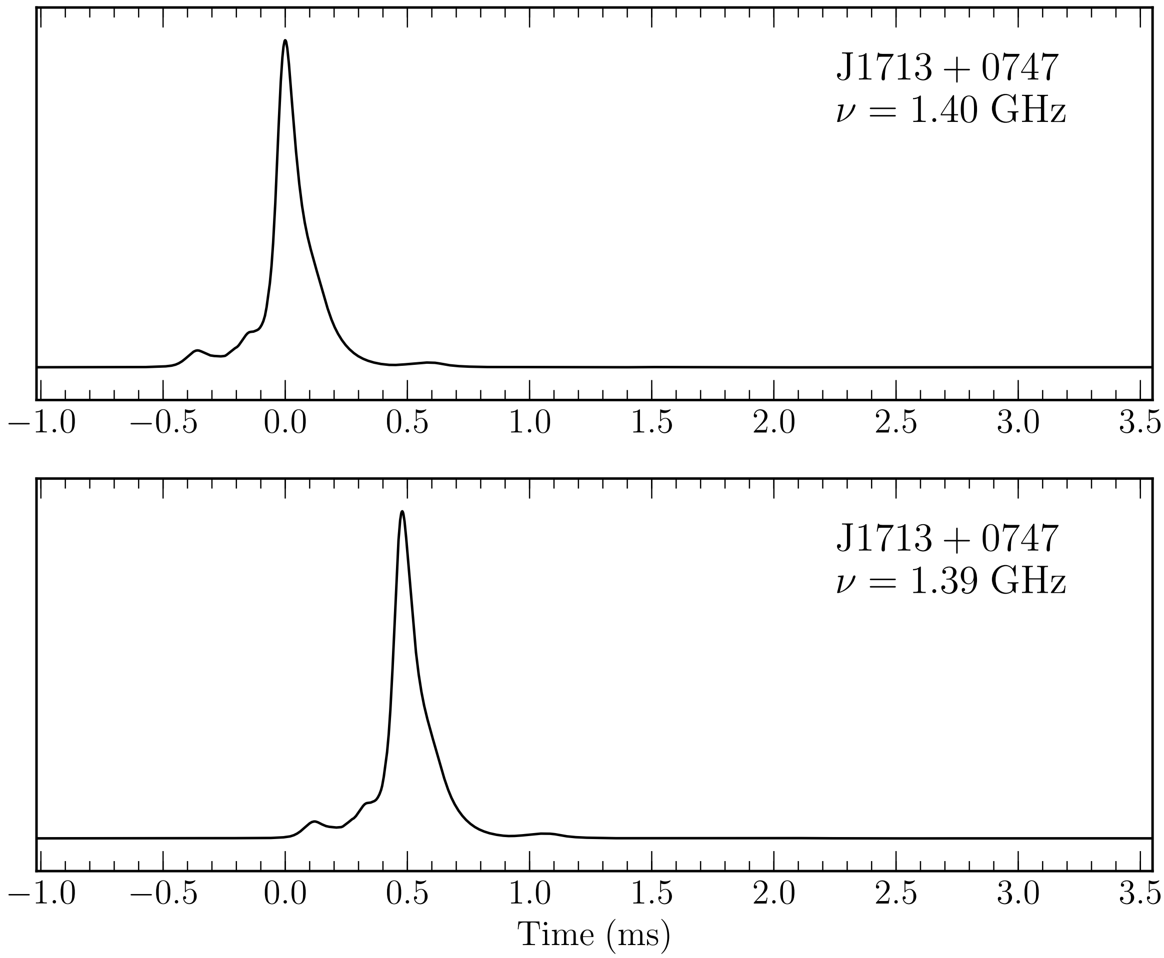
$$t_{\rm DM} = 4.15\ {\rm ms} \left(\frac{\nu}{\rm GHz}\right)^{-2} \left(\frac{\rm DM}{\rm pc\ cm^{-3}}\right) \tag{1}$$

where DM is the dispersion measure, the integral of the electron number density along the line-of-sight, $\mathrm{DM} = \int_0^D n_{\rm e} \mathrm{d}l$, where D is the distance from the Earth to the Pulsar. Because every frequency is shifted by an amount given by equation (1), one can determine the DM by measuring the delay of two different frequencies

$$\Delta t_{\rm DM} = 4.15\ {\rm ms} \left[\left(\frac{\nu_1}{\rm GHz}\right)^{-2} - \left(\frac{\nu_2}{\rm GHz}\right)^{-2}\right] \left(\frac{\rm DM}{\rm pc\ cm^{-3}}\right) \tag{2}$$

in the same units as above. Therefore, by measuring the times-of-arrival (TOAs) of pulses at two different frequencies, we can estimate what the dispersion measure is and remove the effect.

On the next page is a plot of two pulses observed at L band, one at 1.40 GHz and one at a nearby 1.39 GHz. You'll notice that the lower frequency pulse arrives slightly later than the higher frequency pulse. We set $t = 0$ to be the when the maximum of the 1.40 GHz pulse arrives and plot the entire pulse phase.

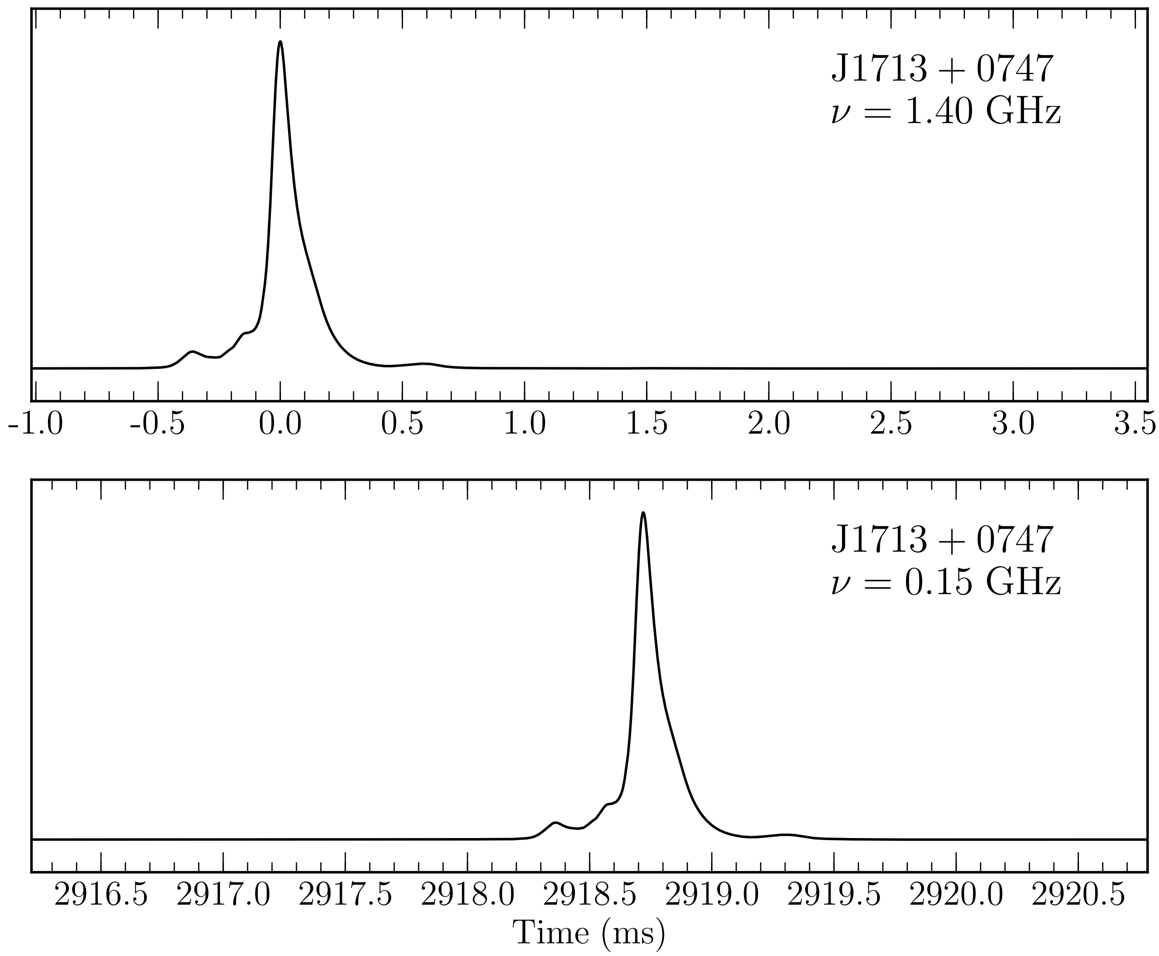


Estimate the DM for this observation.

How precisely can you measure the TOA?

Can you come up with an estimate of the error in your DM measurement?

Let's assume that the pulse profile is the same across all frequencies (not true!). Now we look at a much larger frequency range, one pulse at 1.40 GHz and one at 150 MHz. As before, the maximum of the 1.40 GHz pulse has been set to $t = 0$ and the pulses have been wrapped in phase

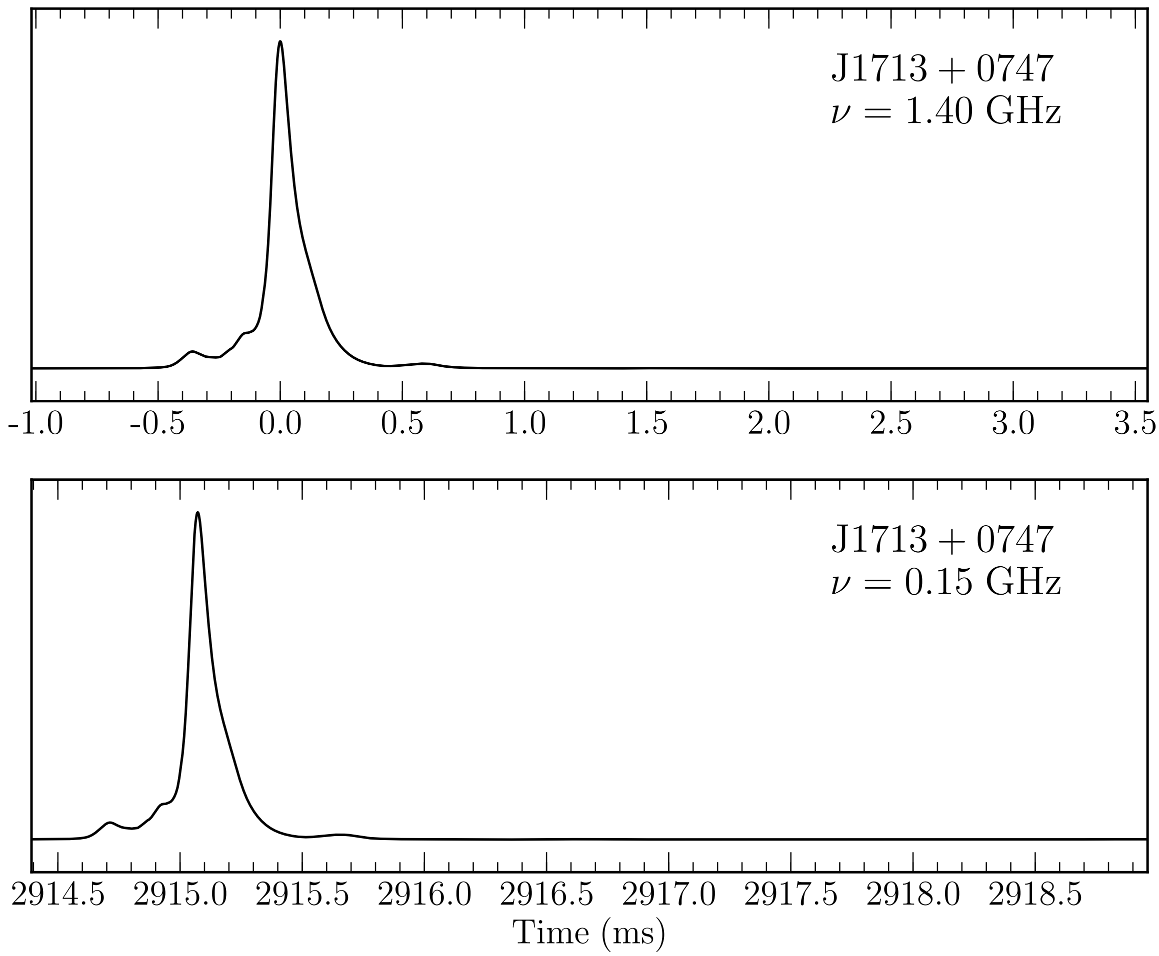


The period of J1713+0747 is $P = 4.57$ ms. How many periods pass before the 150 MHz profile is observed?

What is your estimate for the DM for this observation?

Assuming that your TOA error is the same as previously, what is your estimate of the error in your DM measurement?

On another day, you observe the same pulsar again but notice the following data, shown below.

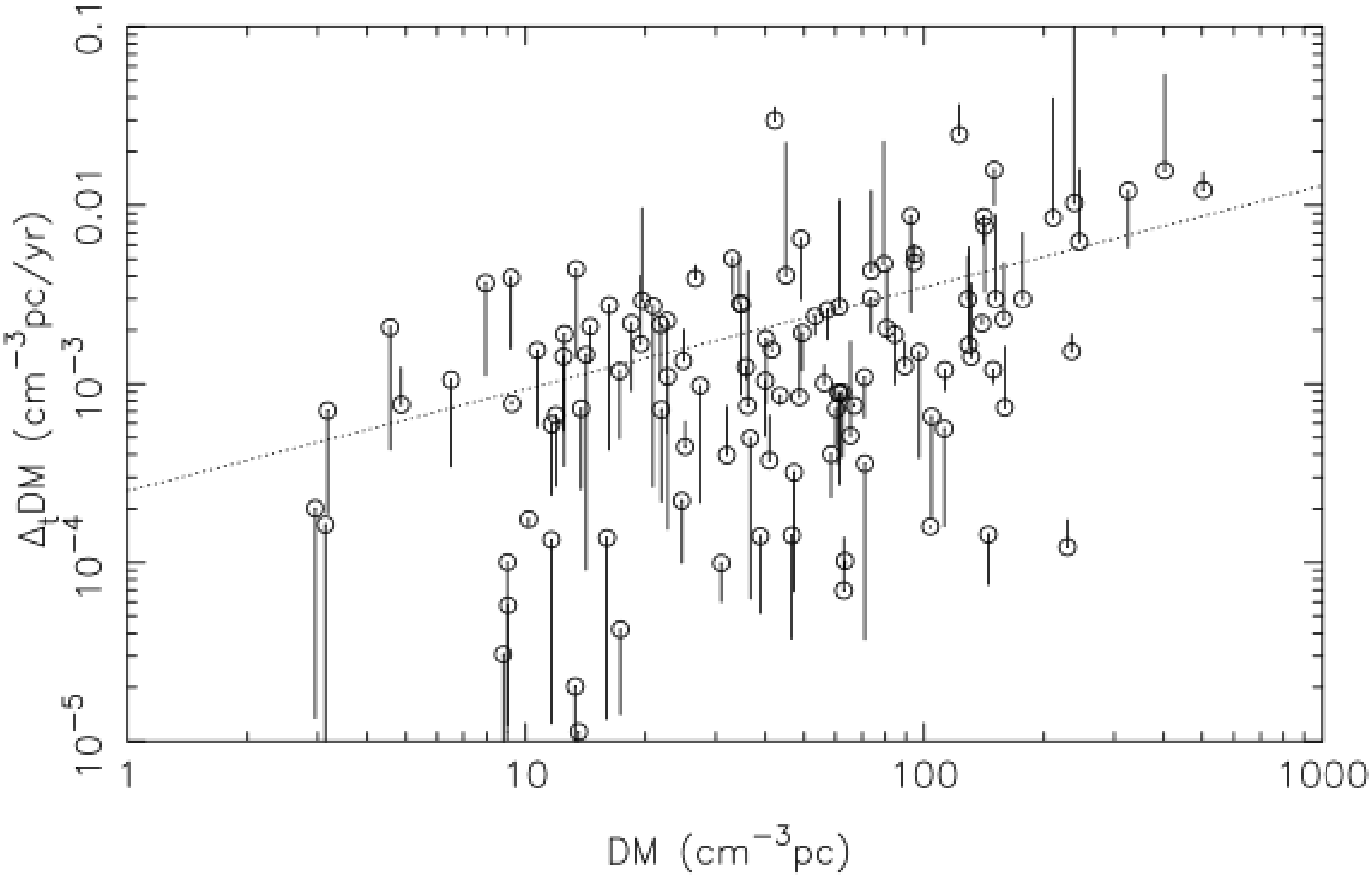


What is your estimate for the DM for this observation?

Again, what is your estimate of the error in your DM measurement?

What happens to your TOA error when you add noise to these pulses? How does this affect your DM uncertainty?

Below is a plot of the derivative of DM with respect to time versus the value of the DM (Hobbs et al. 2004). You can see a possible trend where higher DM pulsars, on average farther away in the galaxy, have absolute changes in DM larger than lower DM pulsars. For high precision timing, we typically choose pulsars towards the left with lower DM values often because they are closer, brighter, and therefore better timers.



3 Dispersion Measure in TEMPO2

Now we are going to apply the skills you have learned to simulated data using TEMPO2. In the DM directory, you will find a number of tim files and a skeleton par file called basic.par that starts with a period close to the period of the pulsar. For simplicity, we've removed all other effects from the pulsar except for the fact that it is spinning and pulses received are dispersed by the interstellar medium. Recall that the TEMPO2 command to run is

```
tempo2 -gr plk -f [par] [tim]
```

where [par] is the name of the par file and [tim] is the name of the tim file. Remember that the values of your post-fit parameters can be found in the terminal.

You first need to determine the spin frequency of the pulsar. One frequency channel of your observation yielded TOAs given in singlechannel.tim. Using TEMPO2, determine the spin frequency of the pulsar and write your answer here.

Open your par file and replace the spin period with the spin frequency parameter F0. Now that you know the spin frequency, open narrowband.tim. You'll notice that there are four channels spaced by 50 MHz each; the 1.40 GHz data is the same as in the previous file. Input a reasonable value for DM (see plot above, or perhaps choose a value close to that of J1713+0747, the pulsar you worked out by hand) and fit over both spin frequency and DM. What are your values and their uncertainties?

During this observation, you were able to observe two frequency bands simultaneously, and so have one frequency channel at a much lower frequency, 150 MHz. Update your value of DM in the par file and repeat the procedure using twoband.tim. What are your new parameter values and their uncertainties?

How do these uncertainties compare with the previous case?

The next night, you install a new, wideband timing system, capable of observing 500 MHz of bandwidth! Unfortunately, you are only able to observe in this mode, which covers 1.30 to 1.80 GHz, with no low frequency measurements. Using wideband.tim, repeat the procedures. What are your values and their uncertainties?

How do these uncertainties compare with the two-band case?

Advanced: As an extra exercise, take a look at DMt.tim. In it, you will see multi-epoch observations of the same pulsar. One possible way of removing the effects of dispersion is by fitting for the DM on a per-epoch basis, known as the DMX model. There are more complicated models one can use, such as the DMMODEL plugin in TEMPO2 or the Keith et al. (2013) method, each with advantages and disadvantages that you will certainly hear about during the science week. For the DMX model, at each epoch, you can measure the deviation from the average DM. For each epoch, you will need three parameters:

- DMX_???? - value of the DM offset
- DMXR1_???? - the bound of the earliest epoch to fit over
- DMXR2_???? - the bound of the latest epoch to fit over

The question marks will be numbers counting each range to fit over, starting with 0001. For example, you might add

```
DMX_0001      0.0    1
DMXR1_0001     40000
DMXR2_0001     41000
DMX_0002      0.0    1
DMXR1_0002     41000
DMXR2_0002     42000
```

to fit two different DMs between MJDs 40000-41000 and 41000-42000.

In your par file, add these DMX parameters as needed. Write down your best fit values for DM(t) and sketch what this curve looks like below.

4 Profile Evolution

Up to now, we have only considered a pulse template that does not change as a function of frequency. As such, we can use the same template to determine the TOA of any subset of data of a particular observing band. However, we know that pulsar emission is not the same across all frequencies but changes in components vary slowly as a function of frequency.

To look at profile evolution, we will use the graphical interface on the PSRCHIVE program *pat*, which produces the TOAs that go into TEMPO2. The command can be written as follows:

```
pat -t -f princeton -s [TEMPLATE] [PROFILE]
```

where [TEMPLATE] is the name of your standard template file and [PROFILE] is the name of your standard profile file. The -t flag selects the diagnostic plot device, -f princeton tells *pat* to output in the format suitable for our reading (for TEMPO2, change to "tempo2"), and -s gives the location of the standard template. In princeton output mode, the first value is the number of the integration (only one in this case), the second is the observed frequency, the third is the TOA, the fourth is the TOA error in μs, and the fifth is a manual DM correction, unused here.

To demonstrate how the program works, we start with our pulsar having a single component. In the PE directory, run *pat* using the standard template single.std with the data profile single.ar. The top panel is the difference profile being calculated after fitting the template (middle panel) to the profile (bottom panel) and subtracting the two. In the terminal, you will see the values of the TOAs.

For a template that ideally matches the data profile, the difference profile will be white noise in a scale that's small in comparison to the total flux of the data profile. How well does single.std fit single.ar?

When we observe our pulsar at lower frequencies, we notice that a smaller, second component appears in our pulse shape. Try to fit single.std to doublesmall.ar, our two-component observation. What do you notice about the TOA and the TOA error as compared to before? What do you notice about the difference profile? Why does it have the shape that it does? Does this make sense with the TOA value you are getting?

After many observations, we try to build a new standard template, given in doublesmall.std. Now try to fit this template to doublesmall.ar. As before, what are the things that you notice? Pay attention to the difference profile shape, the TOA, and the TOA uncertainty.

When we observe our pulsar at even lower frequencies, we notice that the smaller component becomes much larger and actually brighter than our primary component from earlier. Try to fit the doublemedium.std to doublelarge.ar and doublexlarge.ar. What's going on with the shape now? What about the value (all digits!) of the TOA and the TOA uncertainty? Can you explain what's going on? Think about how a computer might handle the calculation and what problems can arise if the pulses had a different shape, such as two components being closer together.

5 Profile Evolution in TEMPO2 (Advanced)

You should complete the previous Advanced section on $\mathrm{DM}(t)$ before you begin this section.

Before we return back to TEMPO2, we should try to quantify the shape of our profile evolution. Using single.std as our reference frequency, calculate the timing offsets for each other template shape (i.e., *std files). Convert the time differences from MJD to milliseconds and record them in the space below. When you are finished, please sketch the time offsets as a function of observing frequency.

Copy your the par file you were working with earlier into the PE directory. The simplest model of dealing with profile evolution is to determine the timing offset at each frequency like you just did and introduce an arbitrary phase into the model that will shift, or "jump", the residuals by this amount. You can do this with JUMP parameters. If you open the file PE.tim, you will notice an additional flag has been added per TOA. Therefore, you can write each JUMP as follows:

- JUMP -i freq* value

where freq* is the actual name of the flag you want to shift and value is the time value in seconds. The observation will be similar to the DMt.tim observation. Please add JUMP parameters as necessary to the par file fit.

When you refit over all parameters, including JUMPs, has anything changed significantly? Why or why not? What are some of the problems that might arise when trying to do this?