

Overview

The Atacama Cosmology Telescope (ACT) is a telescope designed to study the cosmic microwave background (CMB) in millimetre (mm) wavelengths. Its main science goal is to study the nature of our universe, how it began, and its subsequent evolution through the CMB. A novel field in mm astronomy is conducting time domain science on data from cosmological telescopes, where instead of using the data for mapmaking, we look directly at the time streams themselves. We seek to use ACT data to search for pulsars, specifically the Crab pulsar, which resides within the bright Crab nebula. At the frequencies used by ACT, the Crab has a flux density of around 10^2 Jy [1], and the upper bound of the pulsar flux is estimated to be of order 10^{-1} Jy or less at these frequencies. The nebula is orders of magnitude brighter than the pulsar, which is well studied at radio, visible light, and gamma frequencies, but not so much at ACT frequencies. In order to study the pulsar, we first have to search for, or detect it in our data. To do so, we simulated the Crab pulsar and the Crab nebula and developed a working method for recovering a peak flux. The method involves performing linear regression using a boxcar template, and solving for a peak flux. Through a number of simulations and test cases, we confirmed the veracity of our fitting method. We then apply a slight variation on the real Crab pulsar, with the goal of a detection.

1. Developing an extraction method

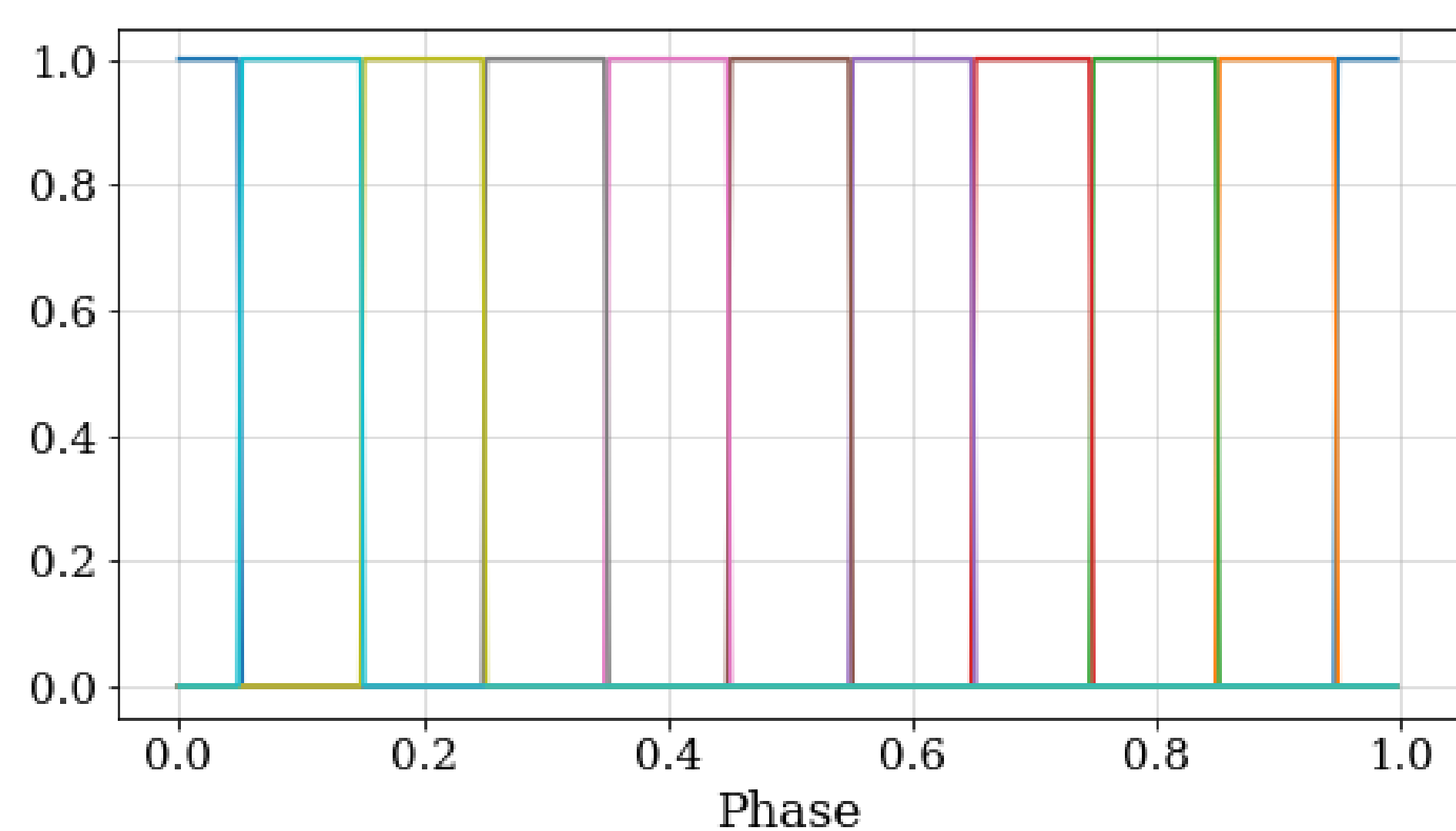


Fig. 1: The boxcar template.

We develop a method for recovering a pulsar's peak flux and test it on simulations of the Crab pulsar, which lies within the bright Crab nebula. The simulation consists of a periodic signal (the Crab pulsar) embedded on top of a bright, constant signal (the Crab Nebula). This simulation uses a source flux of 90,000 mJy, and a source-to-pulsar flux ratio of $r = 0.0001$, giving the pulsar a flux of 9 mJy.

To recover a pulsar's peak flux, we perform linear regressions using a boxcar template. The boxcar template splits the phase space into ten bins (see Figure 1) and performs the linear regression in each bin. In theory, each phase bin should only "pick up" a signal if the phase of the pulsar resides in that phase bin. We expect the rest of the bins to have a value of 0 since the template fit would be out of phase.

Linear regression

We assume that the pulsar signal $d_i(t)$ is of the following form,

$$d_{i,t} = I_{\text{peak}} T_{i,t} + n_{i,t} \quad (1)$$

where $n_{i,t}$ is a noise model. We want to solve for the peak flux I_{peak} given a template $T_{i,t}$. The solution is given by,

$$I_{\text{peak}} = \frac{\sum_{i,t} T^t N^{-1} d}{\sum_{i,t} T^t N^{-1} T} \quad (2)$$

where N^{-1} is the inverse of the variance of the TOD per detector. The standard error, assuming additive noise, is given by,

$$s = \left(\sum_{i,t} T^t N^{-1} T \right)^{-\frac{1}{2}} \quad (3)$$

The solution sums over every detector in every TOD, and is then summed over all the TODs.

2. Fitting the simulated Crab

We apply the aforementioned linear regression technique using a boxcar profile on the Crab simulations. Since the constant source is much brighter than the pulsar signal, all the values returned in each phase bin will be around the flux of the source. By taking the mean of these values and subtracting it from the values, which is essentially subtracting off the source, we recover the peak pulsar flux in the residue (see Figure 2).

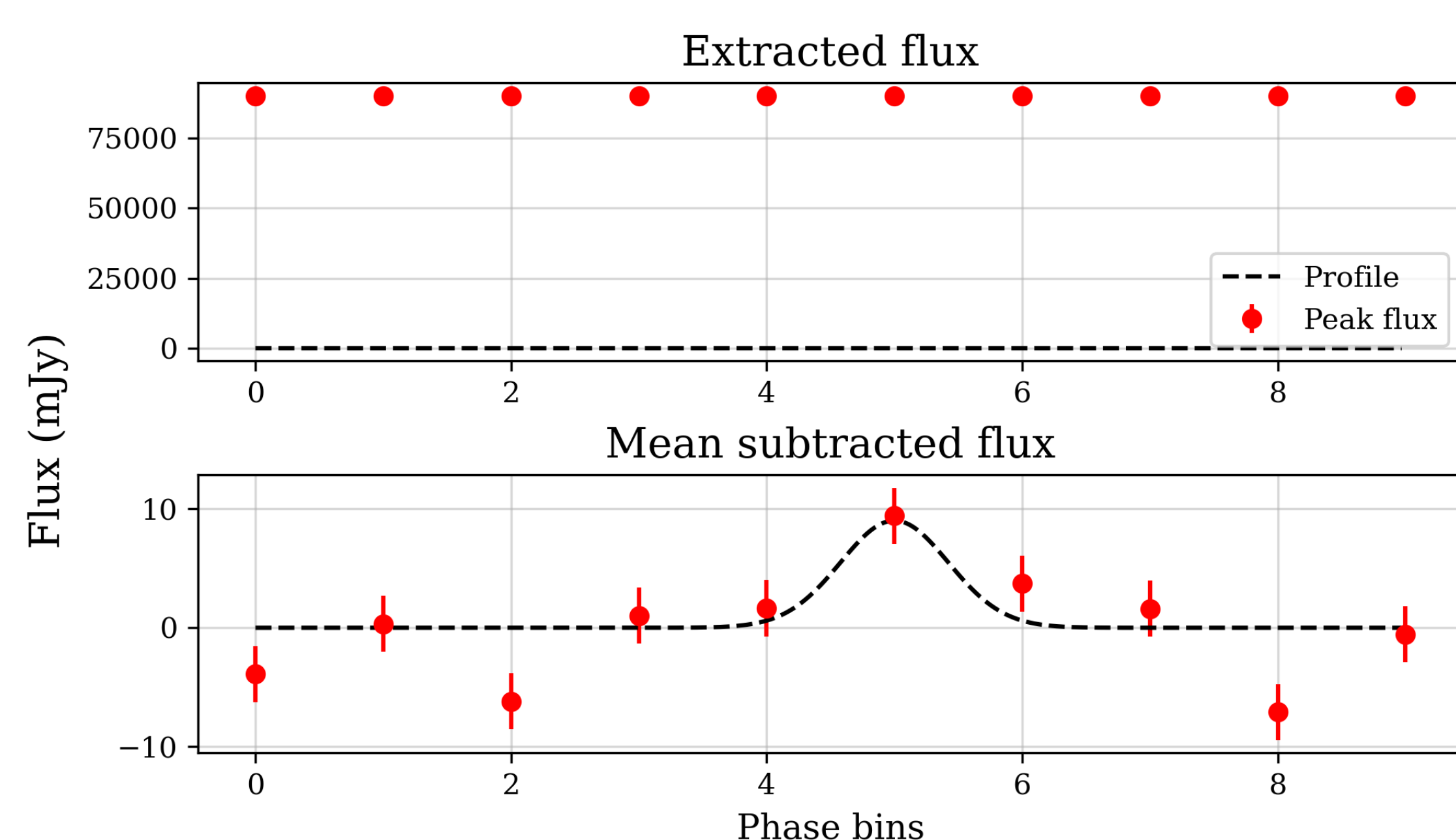


Fig. 2: Constant source fitting with the boxcar profile. Note that the values at phase bins 2 and 8 are comparable to the actual pulsar flux measurement. This behaviour is still being investigated.

3. Fitting the real Crab

A big challenge in this project was obtaining the proper error bars for the Crab pulsar fit. Our initial analysis using the simulations only assumed additive noise, since we were injecting a pulsar signal on a relatively dark area on the sky. This resulted in our error bars being severely underestimated. Since the Crab nebula is bright, the noise is now also multiplicative, and the previous error estimation is no longer valid (see Equation 3). To deal with the multiplicative noise and obtain proper error bars, we alter our approach slightly.

Additionally, we use a monitoring program for pulsar timings to account for the fact that the pulsar is no longer a simple periodic function as in the simulations [2].

4-split fitting

The same fitting with the boxcar profiles is performed, but instead of doing so on one data set, we separate the data into 4 splits. Running the fitting on each of these 4 splits gives us a set of 4 results. The respective mean of each set is subtracted from each set, so that only the (potential) pulsar signal remains, much like the approach before.

Now, we subtract the 4 sets of data from each other. There are 6 ways to subtract the 4 from each other, resulting in 6 sets of what should only be noise, since the pulsar signal is essentially cancelled out. Then, the standard error is taken across 6 sets of noise, to get an error for each of the 10 bins. With this approach, the mean error across the 10 bins is roughly 17 mJy. The preliminary results are shown in Figure 3.

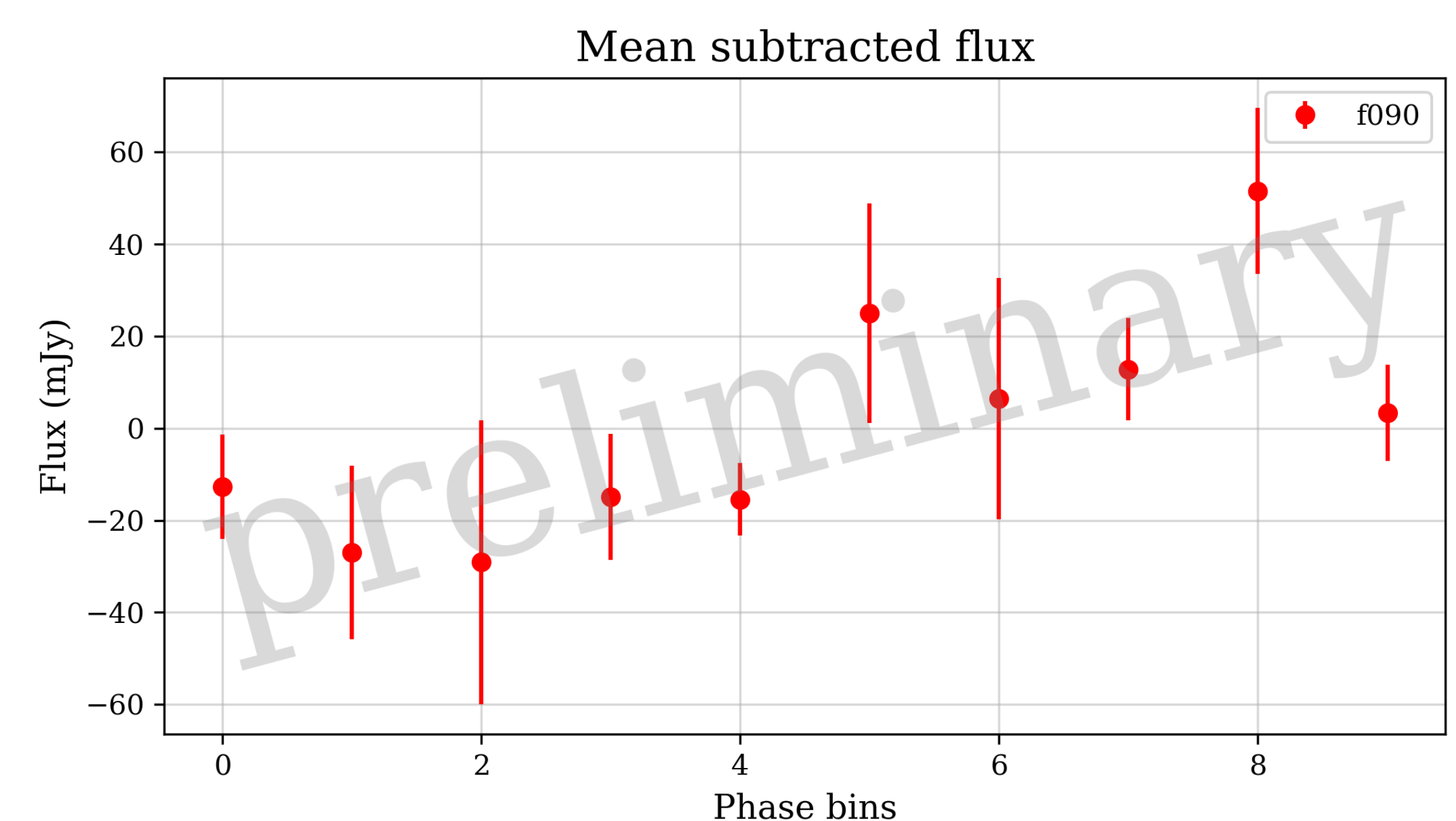


Fig. 3: 4-split fitting of the Crab. The mean across the 4 splits is plotted for each bin. The errors were obtained as described above. Results are preliminary.

4. Conclusions & future work

The motivation behind this project was to detect the Crab pulsar's flux in the mm wavelengths. Liu et al. (2019) have successfully detected pulses from the Vela pulsar in the mm with the Atacama Large Millimetre/submillimetre Array (ALMA), but there are few, if any, measurements of the Crab pulsar flux at these wavelengths [3]. While the statistics indicate a non-detection, we were able to at least constrain the Crab pulsar's flux to < 17 mJy. Future work can involve refining, or adapting the methods further in order to produce a detection result. There is room for improved precision, by accounting for small beam, gain, and pointing errors, in order to possibly obtain precise flux measurements, which can be further explored in the future. The analysis conducted in this project used 90 GHz frequency band data, but ACT also has data in the 150 GHz and 220 GHz band which this analysis can be extended to easily. As well, a similar analysis can be extended and applied to study magnetars, which typically have longer periods compared to pulsars, using CMB data.

- [1] R. G. Arendt et al. "THE RADIO-2 mm SPECTRAL INDEX OF THE CRAB NEBULA MEASURED WITH GISMO". In: *The Astrophysical Journal* 734.1 (May 2011), p. 54. DOI: 10.1088/0004-637x/734/1/54. URL: <https://doi.org/10.1088/0004-637x/734/1/54>.
- [2] A. G. Lyne, R. S. Pritchard, and F. Graham-Smith. "23 years of Crab pulsar rotational history." In: *MNRAS* 265 (Dec. 1993), pp. 1003-1012. DOI: 10.1093/mnras/265.4.1003.
- [3] Kuo Liu et al. "Detection of Pulses from the Vela Pulsar at Millimeter Wavelengths with Phased ALMA". In: *ApJL* 885.1, L10 (Nov. 2019), p. L10. DOI: 10.3847/2041-8213/ab4da8. arXiv: 1910.07974 [astro-ph.GA].