On fringe rate mapping for phase referencing experiments

Huib Jan van Langevelde, 24 September 2009

In VLBI maser experience I have come across this situation more than once: you can clearly detect the maser in the cross-power spectra, but it seems impossible to image the source and make a map. Is it calibration, or resolving out the emission, or maybe a position offset preventing proper imaging? I have frustrated myself (and a few students) by trying to find the right position for such cases by imaging larger areas and concentrating on the short baselines. In principle fringe rate mapping should be able to solve this situation readily; it should detect the right position over many arcseconds and it should be less susceptible to short-time phase fluctuations in theory. But getting the AIPS task FRMAP to work for these cases seems almost impossible. Below are some notes on my attempt to understand FRMAP and code something more sensible in ParselTongue.

AIPS task FRMAP

Fringe rate mapping in AIPS is implemented in FRMAP. Its implementation follows the early paper by Walker 1981 (the year I entered University) and focuses on the problem to find maser spots in a large star forming region, after phase referencing on the brightest spectral feature. It is an elaborate piece of work in which a lot of effort focuses on finding multiple spots in a single channel by decomposing the fringe rate spectra.

As such, its goals are quite different from what I usually want to do. I typically have data phase referenced on a nearby calibrator, and would like to find the position of the brightest maser spot, which could be arcseconds offset from the nominal phase center. For this objective, FRMAP has various shortcomings. First the parameter settings for such use are not straightforward (it took me days to find that you must set CHANNEL=-1 in order to avoid referencing to an internal spectral channel, yes RTFM). Secondly the data selection works particularly bad for many short time intervals, like you typically encounter in phase referencing. Next, as internal reference channels are assumed, the algorithm is not optimal for working in presence of atmospheric phase fluctuations. In particular it is not possible to collect a lot of data over a large range of time and baselines, as the task runs easily out of memory. Finally the accuracy the task presents seems overly optimistic too me; this may be related to the fact that it assumes perfect phase calibration.

Alternative approach

The principle of fringe rate mapping is that on a baseline/time interval one can measure the residual fringe rate. It can easily be shown that this fringe rate is related to the rate of change in u and v. In a projection of the sky one can draw lines for each such interval, which should cross in a single position, which determines the offset position of the source. Obviously the algorithm is not very sensitive, as a high SNR detection of fringe rate needs to be made for every single baseline interval. It is not adding the data linearly as happens in Fourier imaging.

$$\frac{du}{dt}\Delta\alpha' + \frac{dv}{dt}\Delta\delta = \frac{d\Delta\varphi}{dt}$$

Now this holds for perfect calibration, and you would only need a few sensitive baselines to determine this position. But this is not the case we are interested in, instead we are doing the phase reference case, where the phase is not perfectly calibrated. It is obvious that an error in fringe rate from atmospheric contributions, will shift any line and they will typically no longer cross at a single point. Looking for closure properties I realized that all baselines from a triangle must cross at a single point even in the presence of phase noise, as long as it is antenna based. Admittedly, I have not been able to prove this formally, because it is a lot of writing out, but intuitively it fairly obvious from the fringe rate mapping formula. See Figure 1 for an example. So each triangle results in a single estimate of the position (even when one baseline is missing) and the phase errors (atmospheric conditions and phase reference transfer) shift this position around.

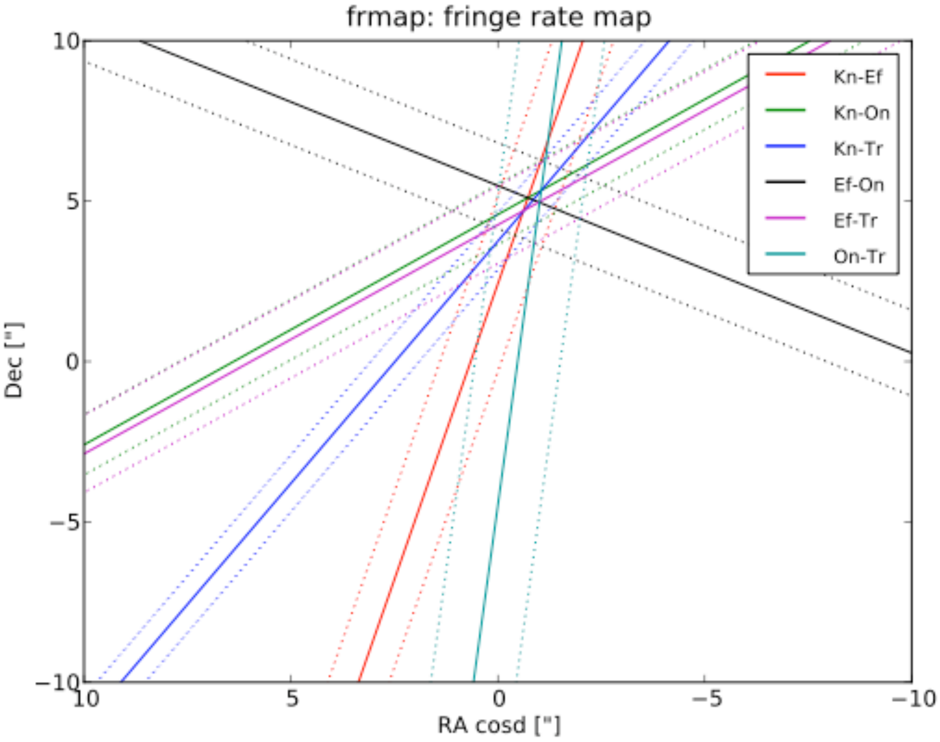

Figure 1. Very short data interval (3 min) on calibrator data, 3C345, arbitrarily shifted to (-1,+<5). This data is from EA038, which was an L band EVN experiment with 4 MERLIN stations participating. Note that with 4 antennas, there are 6 baselines, and 4 triangles. For each triangle all 3 lines go through a single point, giving 4 position measurements, but not quite 4 independent ones.

So for every time interval one can get a single source position estimate from each triangle. In this way it becomes much easier to collect a distribution of source position estimates, rather than attempting to do a least squares fit to all the lines separately. Now we can take hundreds or thousand baseline intervals together to measure the position.

Implementation

I have implemented this in ParselTongue. It is fairly easy to improve the timerange selection, even for phase reference data. It is also easy to determine du/dt and dv/dt directly with ParselTongue from the data. I have not (yet) attempted to code a fringe rate detection method; instead for measuring individual fringe rates I rely either on FRMAP (single baseline at the time) or BLING. In both cases the output can be channelled directly to the ParselTongue script and they give comparable results. It is however quite noticeable that these two methods give totally different estimates of the fringe rate error (much smaller for FRMAP). A comparison with FRMAP confirms that these give identical fringe rate maps, but the first advantage is that the code can generate images with a much larger number of fringe rate lines (Figure 2).

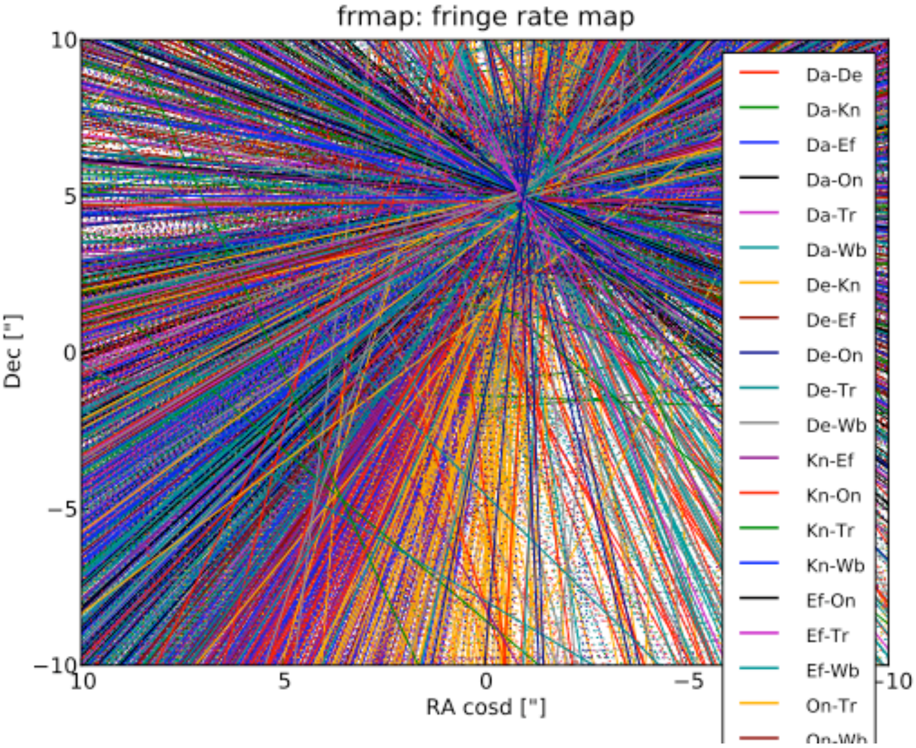

Figure 2 Taken all baselines on the 3C345 test data with 3 minutes intervals over 1.5 hour observations. Obviously not a plot you want to present in your papers, unless you aim to impress your audience with large file sizes…

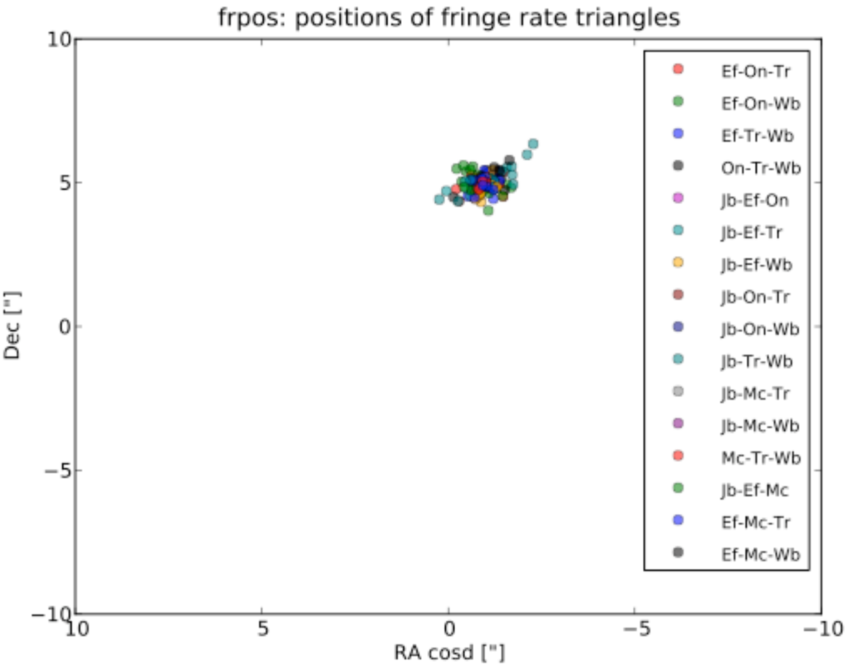

Figure 3. Same artificial data, but now limited to VLBI stations only, clearly all the triangles aim at the same position.

So instead of all these confusing lines, a direct estimate can be obtained from each triangle as demonstrated in Figure 3

Now, a scientific result without an error estimate does not really help anybody, so we must try to do something about errors. Obviously from Figure 3, one can average the points and find a position with a standard deviation. But the real story on the errors is quite complex. In principle we have a formal error on the fringe rate determinations that we can propagate. At first I thought this was not going to be useful at all because the distribution width of the dots above comes from phase disturbances, which are not necessarily entering in the estimates of the fringe rate errors. Moreover, the errors in the individual dots are not independent whatsoever; a single antenna based phase error enters into each triangle and the correlations between the dots must be huge. However, it is still very crucial to propagate the fringe rate errors, as the short baselines should have much less weight in the final averaging. As the du/dt and dv/dt terms are small for these, they indeed blow up the errors in the determination, and should be down-weighted. This demonstrated in Figure 4.

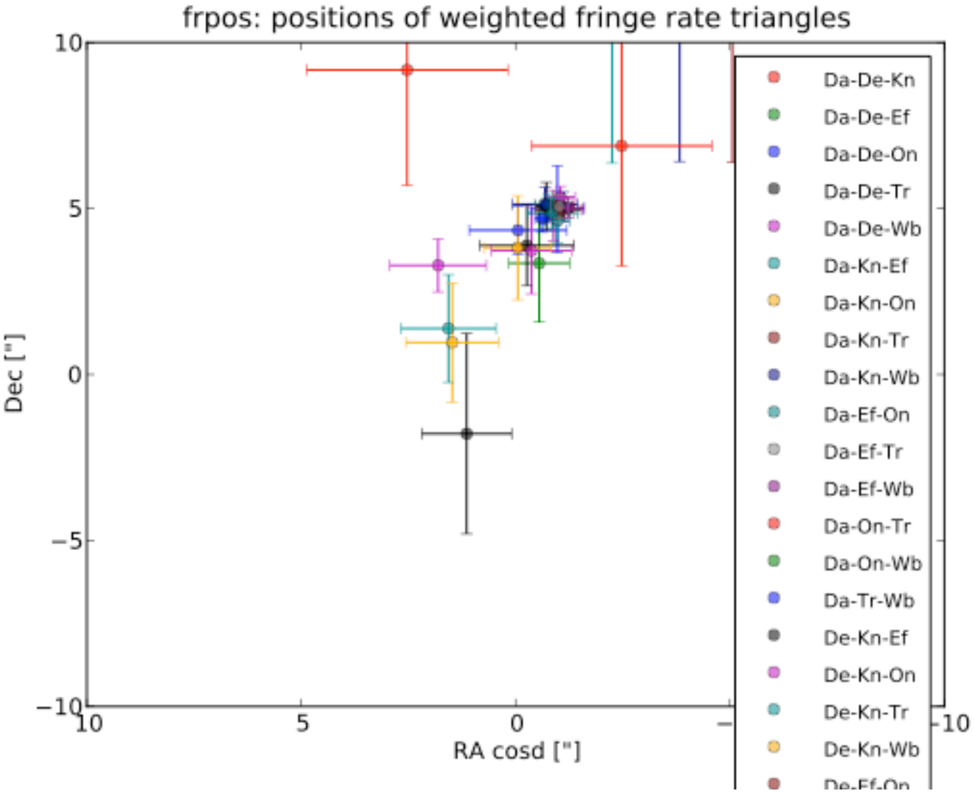

Figure 4. Distribution of fringe rate triangle determinations. The error bars are proportional to the errors in fringe rate, propagated with the u,v rates. It can be seen that the short baselines have larger errors. The absolute sizes are scaled to match a χ^2 distribution.

However, from a χ^2 test it is fairly obvious that the errors are pessimistic (not shown in the figure) when they come from BLING and overly optimistic when they come from FRMAP (and not normally distributed most likely). I have adopted a error scaling to normalize the χ^2 in the end to estimate the error in the final result.

In the end the algorithm was doing fairly well on the test data. By interactively optimizing the integration time for fringe rate detection and selection of the best (longest with a detection) baselines I could get to a result in Figure 5, which has convincing accuracy.

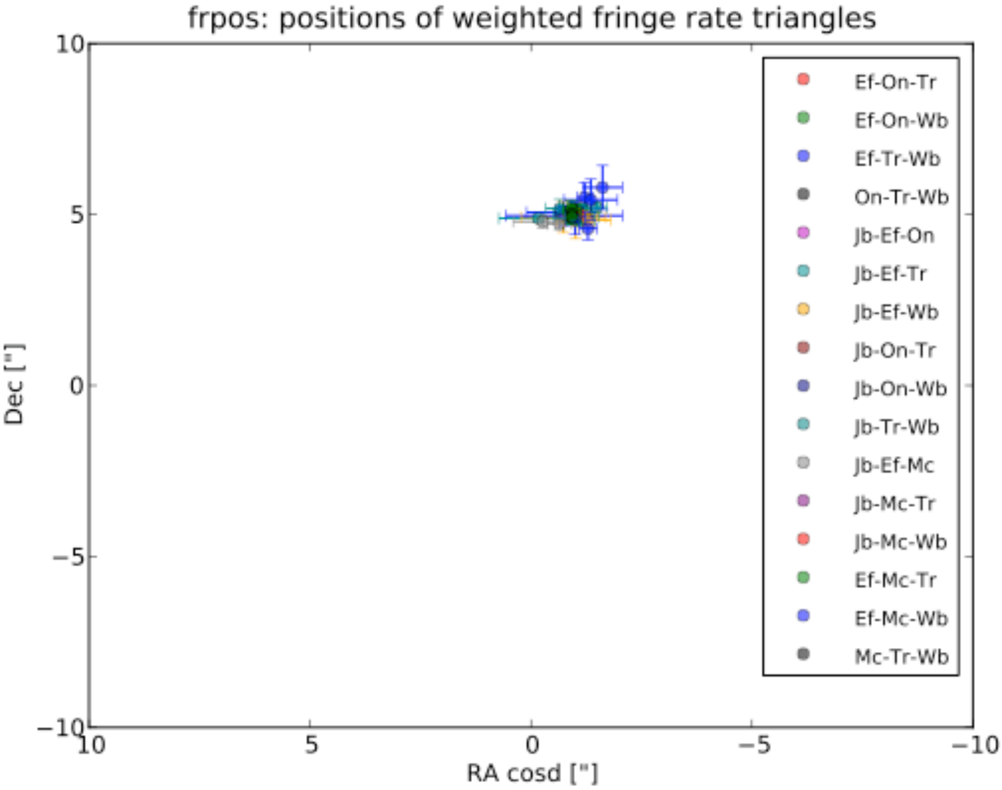

Figure 5. Best estimate of the offset position for this shifted source is obtained by having 10min integrations for every fringe rate and restricting the array to the VLBI stations. The resulting accuracy was: -1.001 +/- 0.039, 5.007 +/- 0.039, reaching an accuracy of tens of mas.

So far so good. Now will this help me in finding our masers? I ran various batches on the OH masers in EA038. The best result is shown in Figure 6. Although a result with this accuracy could in principle be useful, it was not, because this was also the only detection we had made convincingly using conventional approaches.

It turns out that in the cases of the OH masers the method usefulness is limited because many masers are really resolved on the longer baselines. I added a feature that allows a display of the uv track sections during which a fringe rate was detected to help me in this analysis. Another problem is surely that the observations were done with limited uv coverage and short observations. Finally, the method presumably only works when the phase referencing is holding together satisfactory, which was probably not the case for all targets.

A shortcoming of this implementation is surely that it requires triangles, which prohibits one to focus on the most sensitive few baselines. I am sure approaches for that could be implemented too.

Conclusions and future work

I think I have started to satisfy my long-standing curiosity whether fringe rate mapping could be useful for phase reference experiments. Although a different approach was found, I have yet to find a use case where it is actually contributing to the science.

Coding this in ParselTongue was again a greatly satisfactory experience. An improvement in speed could be realized if there were fast access methods to indexed visibilities in large data-sets. I am happy to share the implementation of FrrMap.py with others and intend to upload it to the ParselTongue repository (http://www.jive.nl/dokuwiki/doku.php/parseltongue:grimoire). Although it is reasonably well structured it cannot be run on other experiments directly without coding experiment specific details. I am happy to assist anybody who has (a more) interesting case to work on. Finally I thank Bob Campbell for being able to resonate instantaneously on the details.

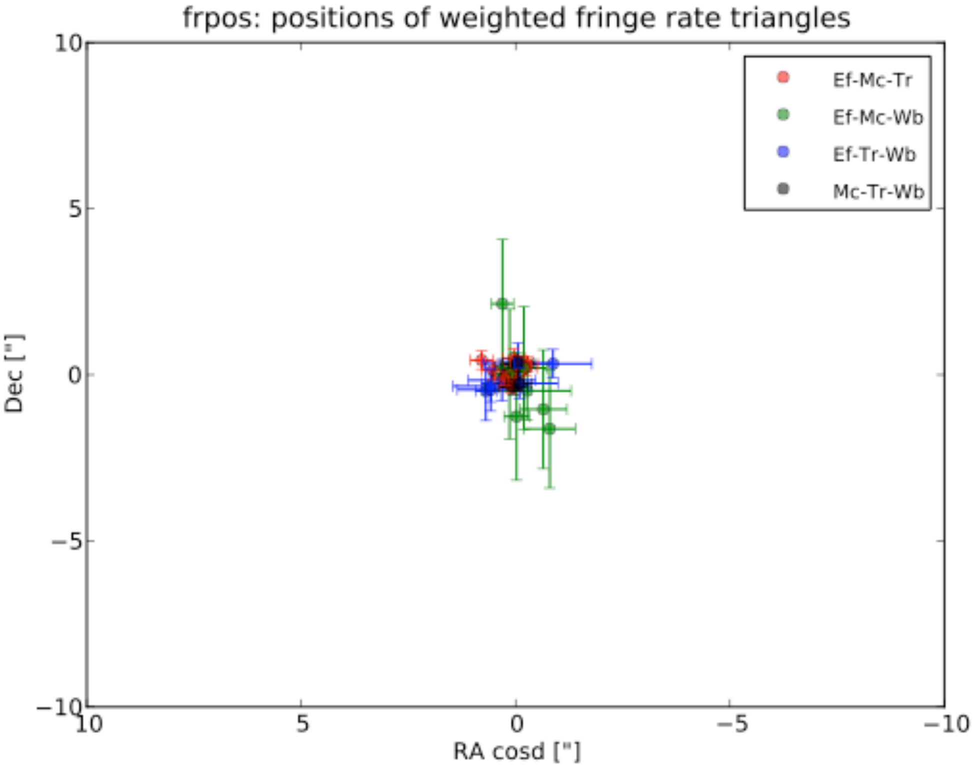

Figure 6. Fringe rate triangle map for the OH maser OH129-0.0. The result of the measurement was: 0.165 +/- 0.281, 0.093 +/- 0.347.