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November 8, 2013

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To: UVLBI Group

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Subject: Merging low- and high-bands of EHT observations.

It is desirable for EHT observations of weak sources to join properly low- and high- band in order to improve the SNR of the detections.

One of the tools that is available to perform this task is the HOPS task *fourmer*. *Fourmer* joins two scans into one, then the resulting scan data can be used by *fourfit*.

Suppose that, for example, we want to join scans 086-1634\_LOW and 086-1634\_HIGH of experiment 3429. The root files of each scan are BLLAC.wtuitm and BLLAC.wvorim, respectively. To join the scans we could type:

```
fourmer 3429/086-1634_LOW/BLLAC.wtuitm 3429/086 1634_HIGH/BLLAC.wvorim
```

which would produce a new root file and new type-1 files in the current directory. The new scan will be named 086-1634\_JOIN and the files should be placed in a new directory called 086-1634\_JOIN under the 3429 directory. We had better do a loop in the case that we have a large number of scans. For this particular experiment I have written a python script (*fourmer-loop.py*), so we can type

```
echo "086-1634" >> 3429.scans
```

```
python fourmer-loop.py
```

which produces the same result as the former sentence. The scans we want to join must be listed in the file 3429.scans. This script can be easily edited for another experiment as it is indicated in the script code.

Once the scans are joined, we use *fearfit* (a hacked version of *fourfit*) to create *fourfit* control files for every baseline of a particular scan. Control files are constructed with the script *fearfit-make-cf.sh*. For our particular example we could type:

```
DATADIR=working directory
```

```
fearfit-make-cf.sh expn=3429 target=BLLAC prefix=SF ref=S rem=F \  
cfdir=cfs words=\"'interpolator iterate'\" 086-1634_JOIN
```

which would produce a *fourfit* control file named `SF-086-1634_JOIN.cf` in the directory `cfs`.

The control file includes manual pc phases and delay offsets in order to flatline the multiband delay. A control file created in this way for a particular scan can be used to do the fringe-searching in all scans on same day and baseline.

To evaluate the control file created above we use the script `fearfit-scan-cf.sh` as follows:

```
fearfit-scan-cf.sh odir=Test-SF cfdir=cfs prefix=SF ref=S rem=F \  
3429/*JOIN/BLLAC*
```

that would *fourfit* all joined scans on BL Lac of experiment 3429 and generate fringe plots in the directory `Test-SF`.

Looking at the resulted fringe plots we can notice that a single control file does not work well for all scans, and a gap between low- and high band is sometimes obtained (see Figure 1). Do all baselines show a gap? How the gap depends on time? In order to answer these questions I have created *fourfit* control files for scan 086-1634 on BL Lac and baselines SF, SP, TJ and PF. A total of 16 scans on BL Lac of about 300 seconds of integration time were recorded on day 086. The resulted cross-power spectra taken from the fringe plots that were obtained with the script `fearfit-scan-cf.sh` are shown in figures 2 to 5. The scan ID is indicated in the top of each subplot in the figures. We see that there is not a gap in baselines SP and TJ, but it is clearly visible in baselines SF and PF.

In figure 6 the magnitude of the gap (phase difference between high- and low-bands) is plotted as a function of time. Most of the scans for baseline SF have big gaps, of about 50 degrees or even more (the same occurs for baseline PF). Baselines SP and TJ have phase gaps very close to zero, as is seen in the plots and in the corresponding cross-power spectra (polarization was flipped at station J during scan 086-153400 resulting in noisy phases on baseline TJ).

The above analysis suggests us that station F (phased-CARMA) is introducing errors that prevent the coherently integration through the joined bands on baselines including that station. In order to remove the phase gap we could set the `lsb_offset` keyword of *fourfit*. This parameter represents an additive phase in degrees, for the LSB relative to the USB. Following the example described above, we could *fearfit* the set of joined scans and store the channel-by-channel phases in order to compute the lsb offsets:

```
export HOPS_FEARFIT_PCPHASE_VERB=0  
  
fearfit -t -p -b SF -c cfs/SF-086-1634_JOIN.cf 3429/*JOIN \  
set interpolator iterate >> fearfit.out
```

which would do the fringe-searching on every scan and send the channel-by-channel phases and some additional output to the file `fearfit.out`. For every scan the lsb offset can be obtained as the phase of the channel q minus the phase of channel o. The python script

`lsb_offset_3429.py` will read the file `fearfit.out` and print this phase difference, as well as the scan ID to the terminal. Next we add in our control file the lsb offsets as follows:

```
if station F and scan 086-151400 lsb_offset 236.88
if station F and scan 086-152400 lsb_offset 22.27
if station F and scan 086-153400 lsb_offset 255.7
if station F and scan 086-154400 lsb_offset 60.85
if station F and scan 086-155400 lsb_offset 300.93
if station F and scan 086-161400 lsb_offset 326.3
if station F and scan 086-162400 lsb_offset 134.66
if station F and scan 086-163400 lsb_offset 359.94
if station F and scan 086-165000 lsb_offset 333.74
if station F and scan 086-170000 lsb_offset 129.49
if station F and scan 086-172000 lsb_offset 230.59
if station F and scan 086-173000 lsb_offset 33.2
if station F and scan 086-174000 lsb_offset 264.44
if station F and scan 086-175000 lsb_offset 58.54
if station F and scan 086-180000 lsb_offset 282.43
if station F and scan 086-181000 lsb_offset 98.91
```

Notice that, because we are using manual pc phases and delays offsets from scan 086-163400 and applying to all data, the lsb offset is zero for this scan.

To see the results we can type:

```
fearfit -t -p -b SF -c cfs/SF-086-1634_JOIN.cf 3429/*JOIN \
set interpolator iterate
```

The resulted cross-power spectra phases are shown in Figure 7. Because the phase offsets between low- and high-band are being introduced by station F, the same lsb offsets could be added to control file `PF-086-1634_JOIN.cf`, so we could type:

```
fearfit -t -p -b PF -c cfs/PF-086-1634_JOIN.cf 3429/*JOIN \
set interpolator iterate
```

The lsb offsets work equally well as seen in Figure 8.

It was noticed that, for this particular experiment, the lsb offsets are increasing with time at a constant rate of around  $0.332 \text{ deg s}^{-1} = 0.922 \text{ mHz}$ . It was also found that this systematic effect originates in an offset of 30.51758 Hz in the USB at CARMA, which was present during all sessions of the run. Because of the VLBI processing, the phase repeats every 60 seconds, then an offset of 30.51758 Hz corresponds to 1831.0548 rotations in 60 seconds or a phase change of 0.0548 rotations in 60 seconds = 0.91333 mHz.

The lsb offsets can then be obtained by assuming a linear divergence of the phase difference between low- and high-band. This can be seen in Table 1. For all scans on BL Lac, baseline SF and day 086, I compare the SNR and amplitude that I get by using lsb offsets estimated in the way described above (columns 2 y 3), with the SNR and amplitude that result using lsb offsets obtained assuming a linear divergence of the phase difference between bands (columns 4 y 5). The relative discrepancy between SNRs and amplitudes is given in columns 6 and 7. We see that for most of the scans this relative discrepancy is less than 1% and ~2% in the worst case.

Finally, I have calibrated separately low- and high-bands. I have used `fringex`, `average`, and `search` to estimate amplitudes and closure phases segmented at 5 seconds with incoherently determined rates and delays.

If  $\text{SNR}_{\text{low}}$  and  $\text{SNR}_{\text{high}}$  are the SNR of the detections at low-band and high-band, respectively, it is expected that if we join both bands then the SNR increases by a factor of  $2^{1/2}$ , assuming  $\text{SNR}_{\text{low}} = \text{SNR}_{\text{high}}$ . As I have obtained these two quantities separately I can estimate the expected SNR as

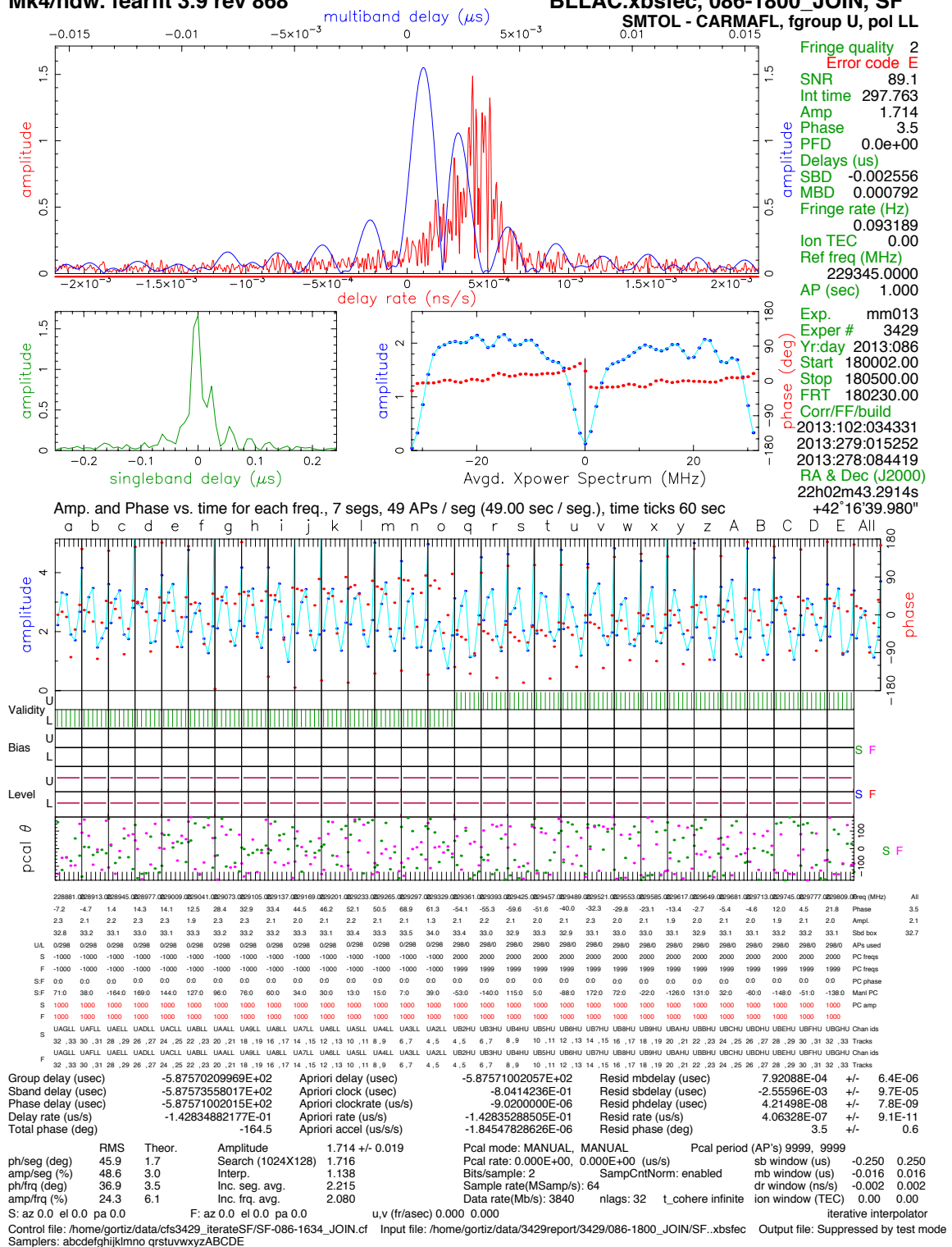
$$[\text{SNR}_{\text{low}}^2 + \text{SNR}_{\text{high}}^2]^{1/2}$$

and compare with the measured SNR of joined bands.

In Figure 9 black data points correspond to the expected SNR and blue data points to the measured SNR. We see that both quantities are very similar.

The closure phases are compared in Figure 10 for triangles FSP (CARMAF(L)-SMT(L)-SMA(L)) and TJQ (SMT(R)-JCMT(R)-SMA(R)). We see consistent closure phases between low-band (green), high-band (red) and joined bands (blue). Figure 10 also shows closure phases for triangles GTQ (CARMAF(R)-SMT(R)-SMA(R)) and JGT (JCMT(R)-CARMAF(R)-JCMT(R)), where we see good agreement between polarizations.

**BLLAC.xbsfec, 086-1800\_JOIN, SF**  
**SMTOL - CARMAFL, fgroup U, pol LL**



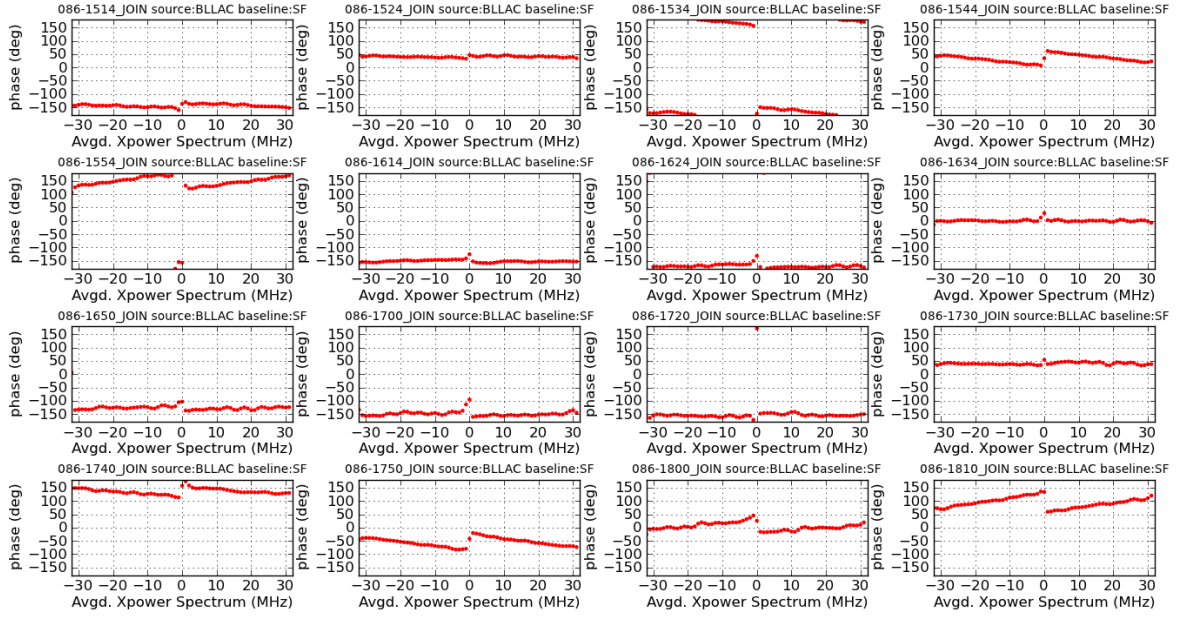


Figure 2: Cross-power spectra phase for baseline SF. The scan at which the control file is being evaluated is indicated at the top of each spectrum.

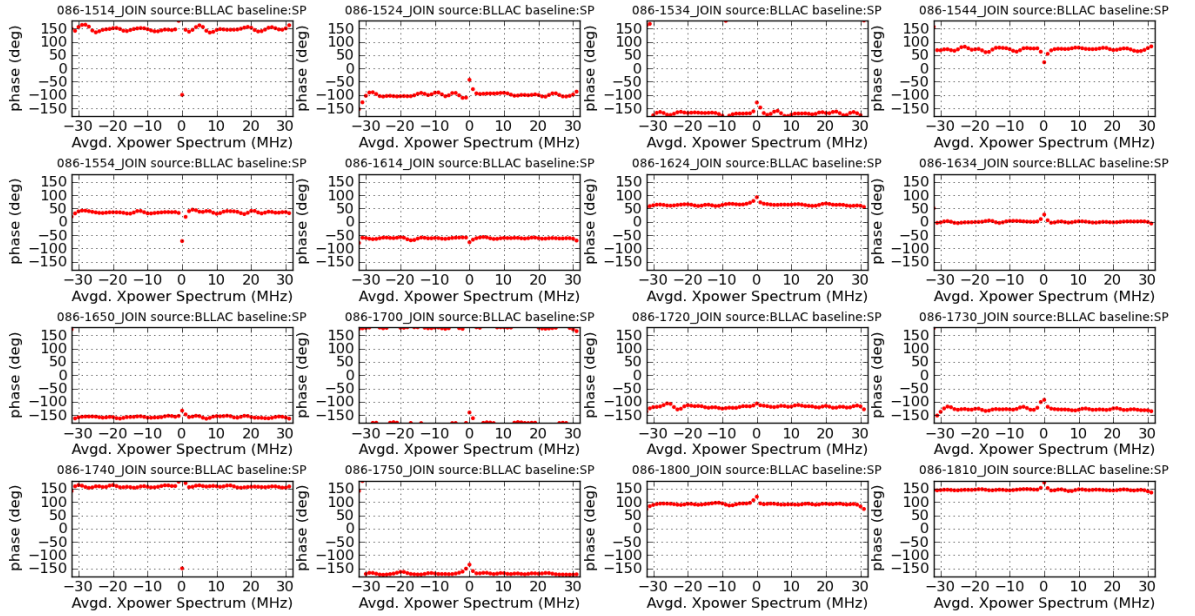


Figure 3: Cross-power spectra phase for baseline SP. The scan at which the control file is being evaluated is indicated at the top of each spectrum.

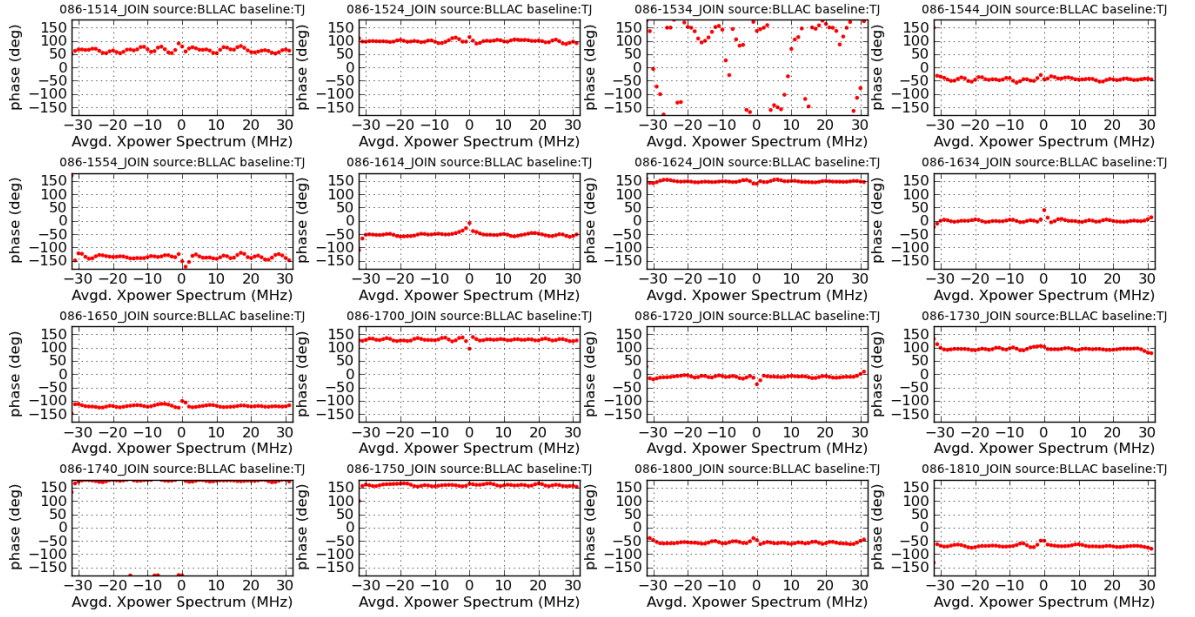


Figure 4: Cross-power spectra phase for baseline TJ. The scan at which the control file is being evaluated is indicated at the top of each spectrum.

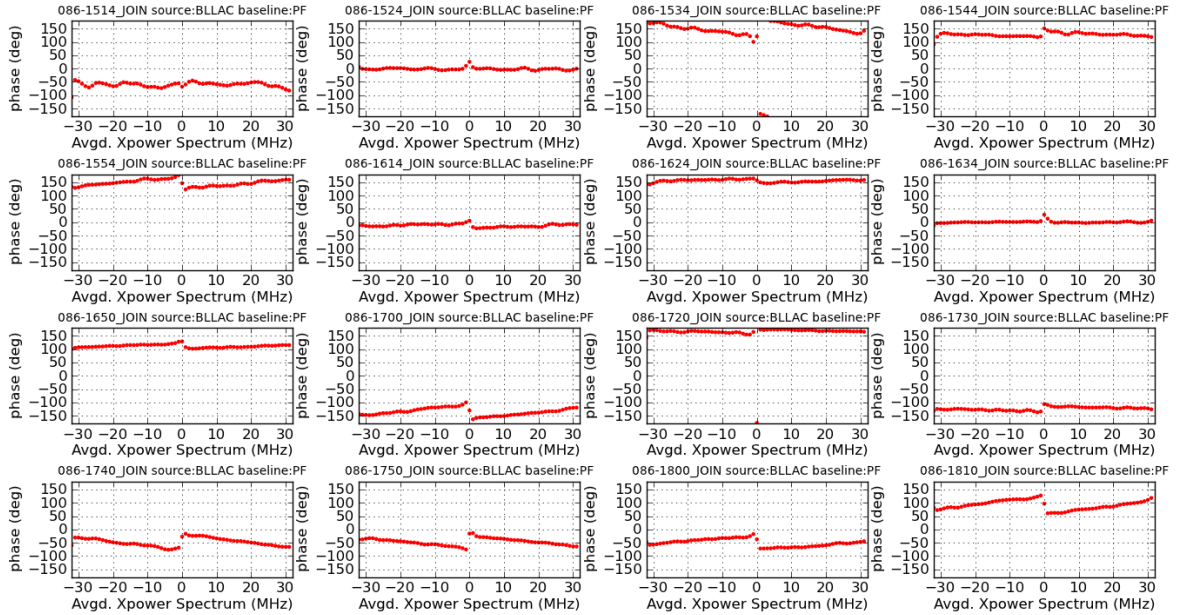


Figure 5: Cross-power spectra phase for baseline PF. The scan at which the control file is being evaluated is indicated at the top of each spectrum.

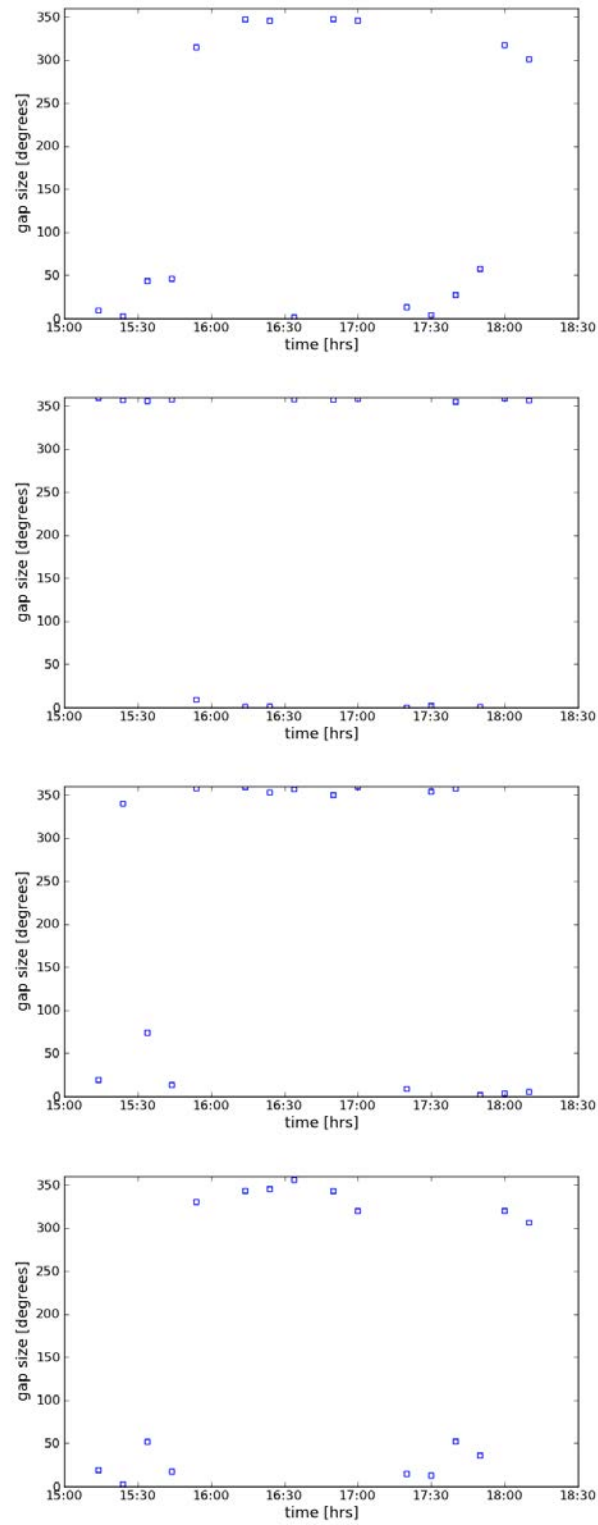


Figure 6: Phase gap size as a function of time for BL Lac on day 086. Baselines are (from top to bottom) SF, SP, TJ and PF. The phase gap size was obtained from the cross-power spectrum of the fringe plot output.



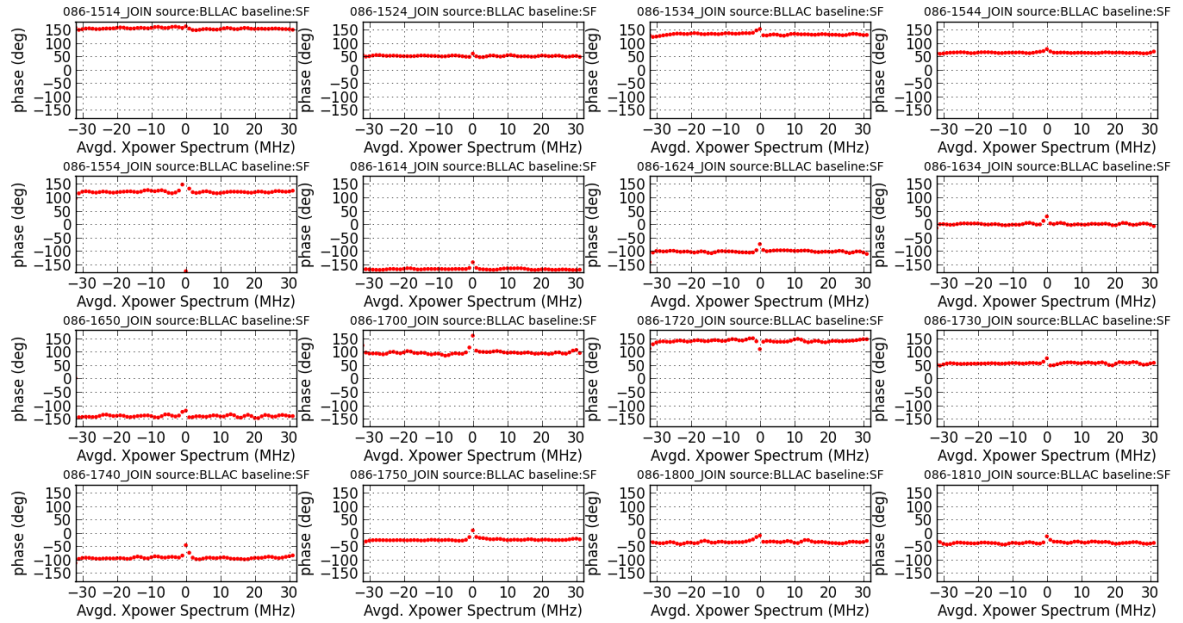


Figure 7: Cross-power spectra phase for baseline SF after the lsb offset keyword has been set.

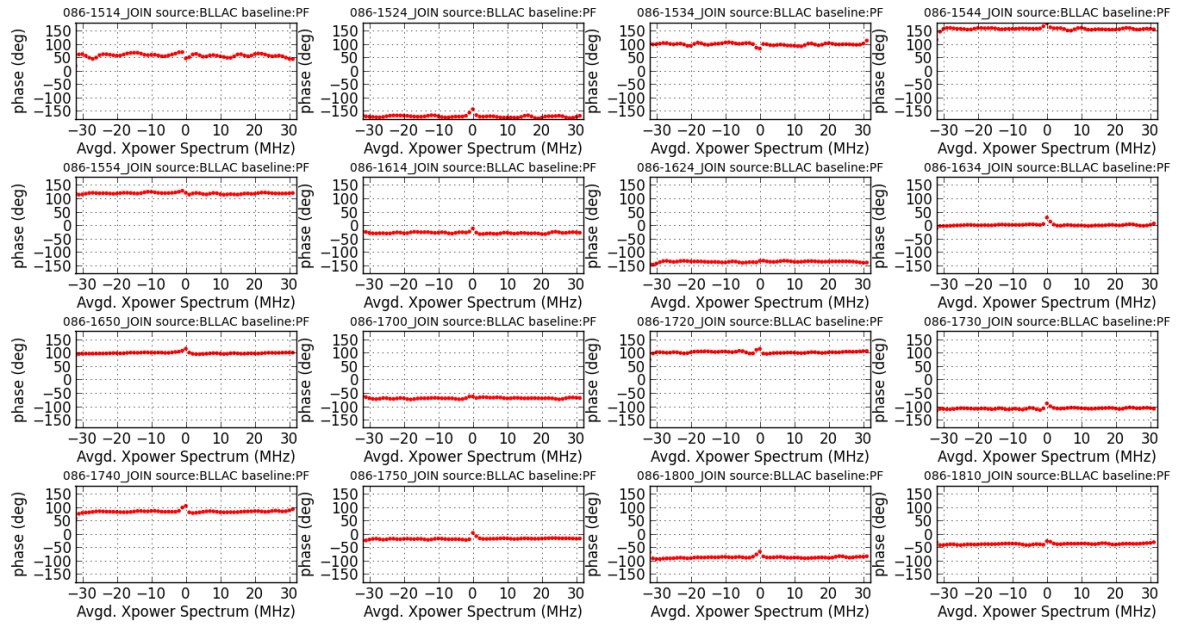


Figure 8: Cross-power spectra phase for baseline PF after the lsb offset keyword has been set.

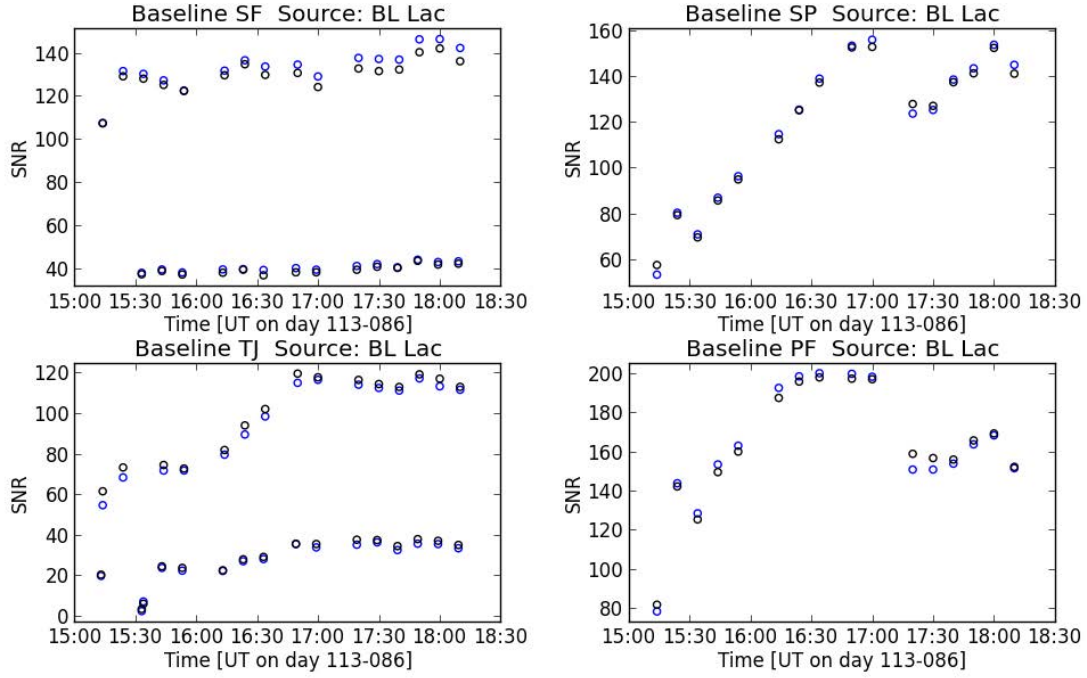


Figure 9. SNR as a function of time on day 086. Short scans have, as expected, lower SNR. Key to the colors: measured SNR of joined bands (blue);  $[\text{SNR}_{\text{low}}^2 + \text{SNR}_{\text{high}}^2]^{1/2}$  (black).

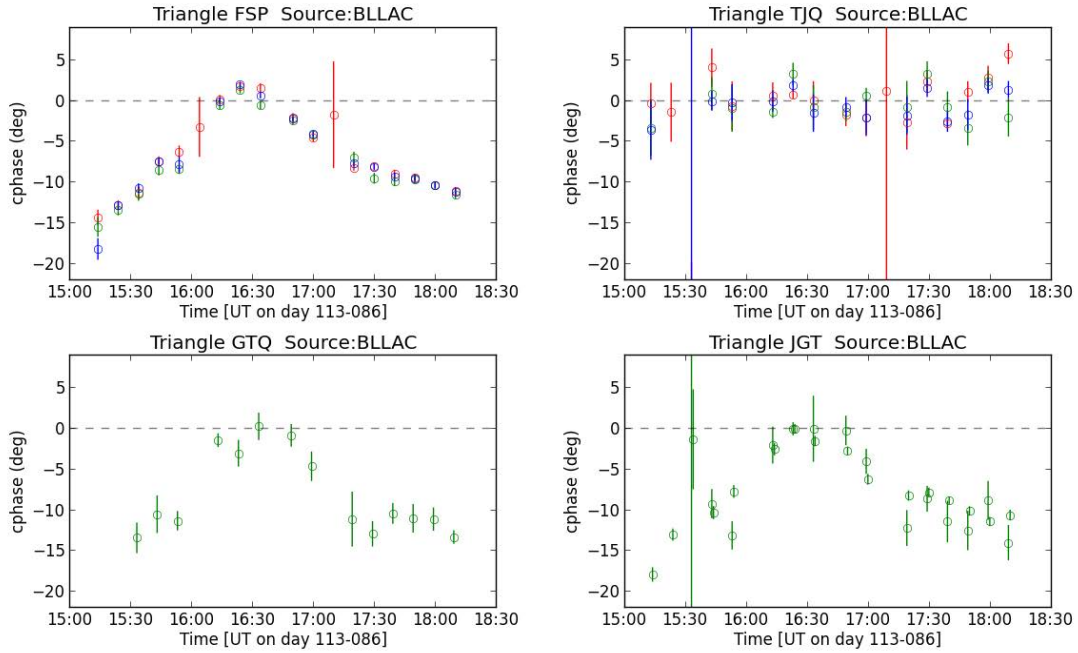


Figure 10. Closure phases of BL Lac as a function of time on day 086. Key to the colors: low-band (green); high-band (red); joined bands (blue).

Table 1. Amplitudes and SNRs reported by fourfit for scans on BL Lac, baseline SF. Columns 2 and 3 were obtained using lsb offsets estimated as a phase difference between low -and high-band channels. Columns 4 y 5 were obtained using lsb offsets obtained assuming a linear divergence of the phase difference between bands.

Scan time	Amp <sub>1</sub> x 10 <sup>-4</sup>	SNR <sub>1</sub>	Amp <sub>2</sub> x 10 <sup>-4</sup>	SNR <sub>2</sub>	Amp <sub>1</sub> -Amp <sub>2</sub>  /Amp <sub>1</sub> %	SNR <sub>1</sub> -SNR <sub>2</sub>  /SNR <sub>1</sub> %
086-151400	2.75	161.7	2.75	162.8	0.0	0.68
086-152400	2.91	171.8	2.90	170.9	0.34	0.52
086-153310	4.19	74.87	4.19	75.13	0.0	0.35
086-153400	3.34	196.4	3.35	197.3	0.3	0.46
086-154310	4.48	80.99	4.48	80.65	0.0	0.42
086-154400	3.15	186.2	3.14	185.5	0.32	0.38
086-155310	3.94	71.06	3.95	71.44	0.25	0.53
086-155400	2.35	139.4	2.35	139.3	0.0	0.07
086-161310	3.72	67.19	3.73	67.32	0.27	0.19
086-161400	2.78	164.4	2.78	164.4	0.0	0.0
086-162310	4.49	81.29	4.52	81.90	0.67	0.75
086-162400	2.67	157.6	2.69	159.0	0.75	0.89
086-163310	3.43	61.97	3.43	61.97	0.0	0.0
086-163400	1.84	108.9	1.84	108.9	0.0	0.0
086-164910	4.19	75.61	4.19	75.59	0.0	0.03
086-165000	2.08	123.0	2.09	123.2	0.48	0.16
086-165910	4.30	77.27	4.31	77.67	0.23	0.52
086-170000	1.74	102.6	1.75	103.4	0.57	0.78
086-171910	4.25	76.81	4.33	78.19	1.88	1.8
086-172000	1.98	117.7	2.00	118.5	1.01	0.68
086-172910	4.68	83.77	4.68	83.76	0.0	0.01
086-173000	1.77	103.8	1.77	103.8	0.0	0.0
086-173910	4.48	80.28	4.50	80.50	0.45	0.27
086-174000	2.07	121.8	2.09	122.6	0.97	0.66
086-174910	4.91	88.06	4.91	88.25	0.0	0.22
086-175000	2.95	171.9	2.94	172.5	0.34	0.35
086-175910	4.78	85.64	4.81	85.80	0.63	0.19
086-180000	2.03	119.1	2.03	119.2	0.0	0.08
086-180910	4.53	80.66	4.52	80.86	0.22	0.25
086-181000	2.31	133.2	2.30	133.7	0.43	0.38