EHT/HOPS Tutorial

Vincent L. Fish

Scope of this talk

You have observed and recorded data

The correlator operator has handed you correlated data (in Mark 4 format)

Now: It's time to process the data

Later (beyond the scope of this talk): Someone will take your results, incorporate metadata from the observatories, and produce a fully calibrated dataset

Correlated data products

Data are averaged in time at a cadence called the "accumulation period" ("AP")
- a.k.a. "[correlator] dump time"
- sometimes a.k.a. "integration time" (though this is ambiguous with "scan length")

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In the examples that follow, the AP is 1 second and the total bandwidth is 480 MHz
- 15 x 32-MHz channels, each subdivided into 1-MHz pieces

Every data point is a complex number (amplitude and phase, or equivalently real and imaginary)

For instance, if the scan is 300 seconds long, there are 300 x 15 x 32 complex numbers

Fringe fitting

The correlator has a delay (and rate) model based on the observations
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Incorrect delays and rates cause phase slopes
- Rate: derivative of phase w.r.t. time
- Singleband delay: derivative of phase w.r.t. frequency within each channel
- Multiband delay: derivative of phase w.r.t. frequency across all channels

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We want to find and remove phase slopes in each dimension to get the complex visibilities
to line up in phase (i.e., so we can vector-average the visibilities)

We also want to remove phase offsets between channels (i.e., manual pcals)
- In fact, we have to do this first

Fourfit

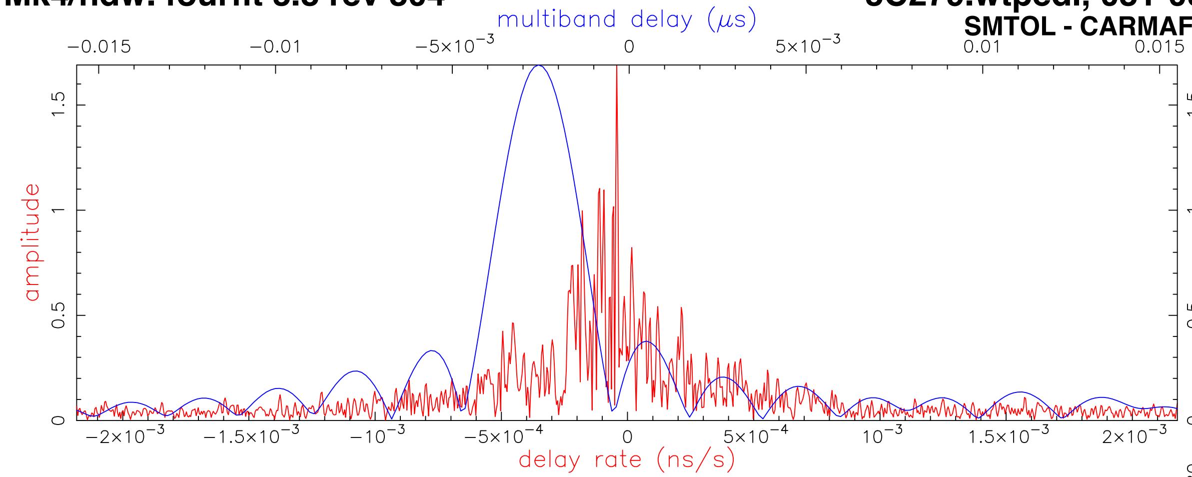
The main tool in HOPS for fringe fitting is fourfit

Lots of information on one page

Very helpful for diagnosing problems, identifying weak potential fringes and false positives

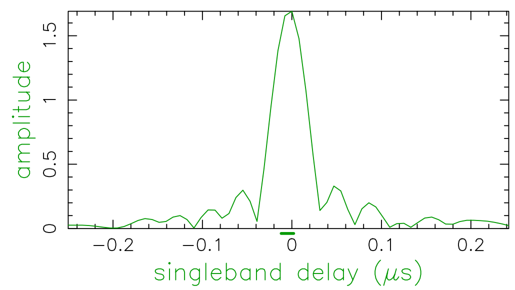
Mk4/hdw. fourfit 3.8 rev 804

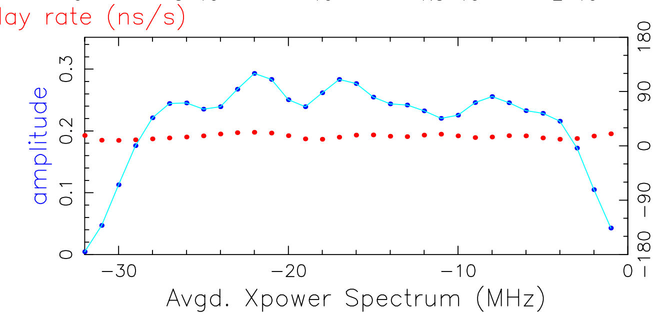
3C279.wtpedl, 081-0920_LOW, SF
SMTOL - CARMAFL, fgroup U, pol LL



Fringe quality 5

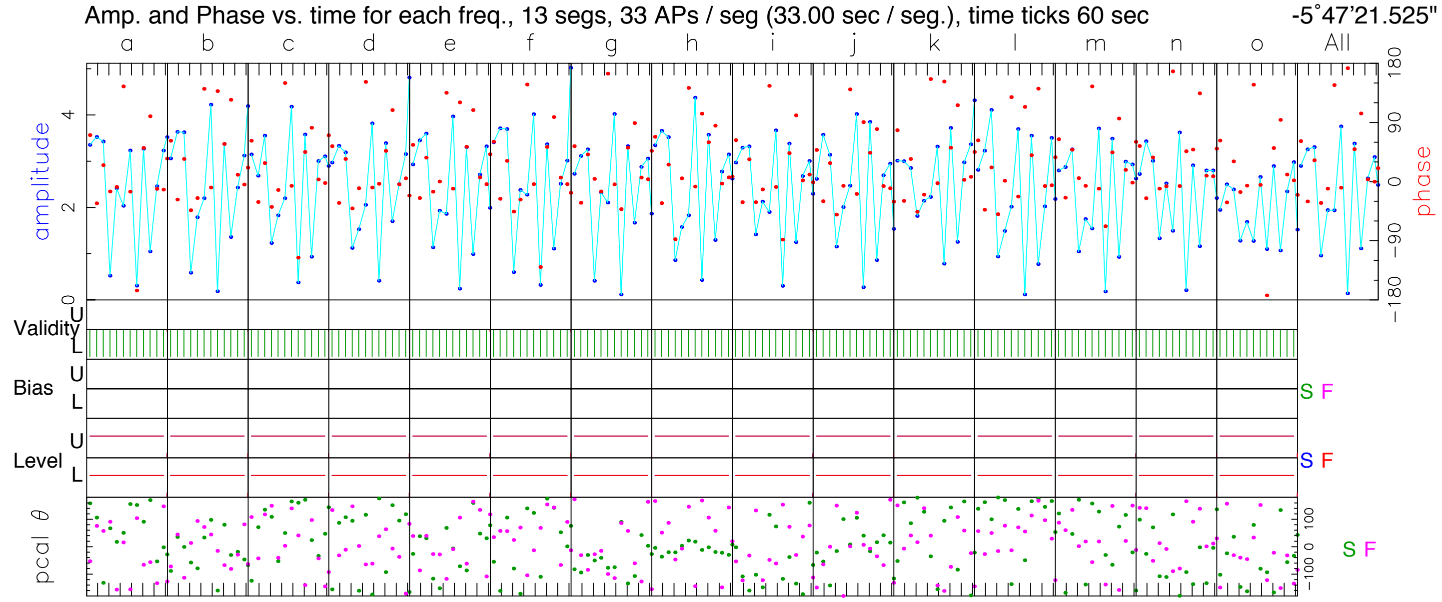
SNR 82.8
Int time 397.731
Amp 1.707
Phase 17.5
PFD 0.0e+00
Delays (us)
SBD -0.002812
MBD -0.002558
Fringe rate (Hz)
-0.009446
Ion TEC 0.00
Ref freq (MHz)
229089.0000
AP (sec) 1.000





Exp. mm013
Exper # 3425
Yr:day 2013:081
Start 092002.00
Stop 092640.00
FRT 092320.00
Corr/FF/build
2013:097:205647
2013:133:164120
2013:133:083810
RA & Dec (J2000)
12h56m11.1666s
-5°47'21.525"

Amp. and Phase vs. time for each freq., 13 segs, 33 APs / seg (33.00 sec / seg.), time ticks 60 sec



	228881.00	228913.00	228945.00	228977.00	229009.00	229041.00	229073.00	229105.00	229137.00	229169.00	229201.00	229233.00	229265.00	229297.00	229329.00	Freq (MHz)	All
	14.9	20.5	15.9	16.5	19.3	17.0	20.2	20.7	16.6	10.2	21.6	10.8	22.4	16.7	18.6	Phase	17.5
	1.6	1.7	1.8	1.7	1.9	1.8	1.7	1.8	1.8	1.8	1.6	1.7	1.8	1.7	1.4	Ampl.	1.7
	32.4	32.6	32.5	32.5	32.6	32.7	32.5	32.6	32.4	32.6	32.9	32.6	32.9	32.7	33.1	Sbd box	32.6
U/L	0/398	0/398	0/398	0/398	0/398	0/398	0/398	0/398	0/398	0/398	0/398	0/398	0/398	0/398	0/398	APs used	
S	-1000	-1000	-1000	-1000	-1000	-1000	-1000	-1000	-1000	-1000	-1000	-1000	-1000	-1000	-1000	PC freqs	
F	-1000	-1000	-1000	-1000	-1000	-1000	-1000	-1000	-1000	-1000	-1000	-1000	-1000	-1000	-1000	PC freqs	
S:F	0:0	0:0	0:0	0:0	0:0	0:0	0:0	0:0	0:0	0:0	0:0	0:0	0:0	0:0	0:0	PC phase	
S:F	117:180	96:180	89:0	86:0	74:0	74:0	66:0	65:0	61:0	69:0	68:0	82:0	88:0	107:0	157:0	Manl PC	
S	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	PC amp	
F	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000		
S	UGLL	UFLL	UELL	UDLL	UCLL	UBLL	UALL	U9LL	U8LL	U7LL	U6LL	U5LL	U4LL	U3LL	U2LL	Chan ids	
	32,33	30,31	28,29	26,27	24,25	22,23	20,21	18,19	16,17	14,15	12,13	10,11	8,9	6,7	4,5	Tracks	
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Group delay (usec)	5.42259975970E+02	Apriori delay (usec)	5.42262534222E+02	Resid mbdelay (usec)	-2.55825E-03	+/-	1.4E-05
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Phase delay (usec)	5.42262534433E+02	Apriori clockrate (us/s)	-8.9850002E-06	Resid phdelay (usec)	2.11658E-07	+/-	1.7E-08
Delay rate (us/s)	-1.93058988129E-01	Apriori rate (us/s)	-1.93058946894E-01	Resid rate (us/s)	-4.12342E-08	+/-	7.3E-11
Total phase (deg)	270.3	Apriori accel (us/s/s)	-2.11252455948E-06	Resid phase (deg)	17.5	+/-	1.4

	RMS	Theor.		
			Amplitude	1.707 +/- 0.021
ph/seg (deg)	34.3	2.4	Search (1024X64)	1.625
amp/seg (%)	76.0	4.2	Interp.	1.627
ph/frq (deg)	3.5	2.6	Inc. seg. avg.	2.391
amp/frq (%)	6.5	4.5	Inc. frq. avg.	1.708

Pcal mode: MANUAL, MANUAL Pcal period (AP's) 9999, 9999
Pcal rate: 0.000E+00, 0.000E+00 (us/s) sb window (us) -0.012 0.002
Bits/sample: 2 SampCntNorm: enabled mb window (us) -0.016 0.016
Sample rate(MSamp/s): 64 dr window (ns/s) -0.002 0.002
Data rate(Mb/s): 1920 nlags: 32 t_cohere infinite ion window (TEC) 0.00 0.00

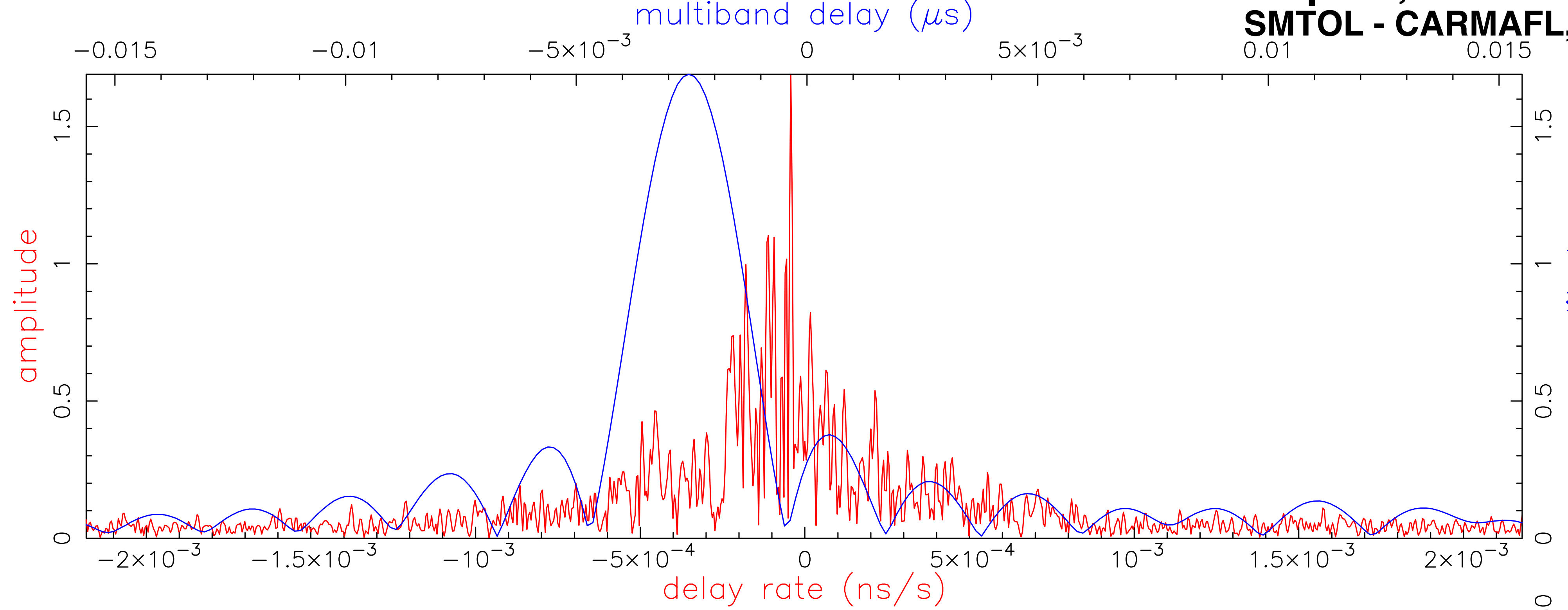
S: az 0.0 el 0.0 pa 0.0 F: az 0.0 el 0.0 pa 0.0 u,v (fr/asec) 0.000 0.000 iterative interpolator

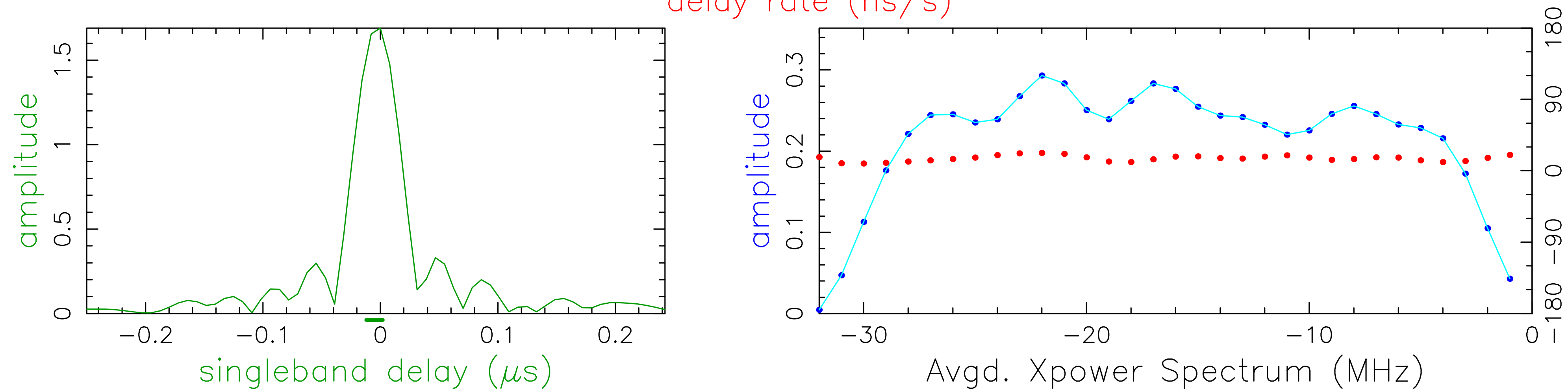
Control file: cf_3425_229089 Input file: /data2/3425/081-0920_LOW/SF..wtpedl Output file: /data2/3425/081-0920_LOW/SF.U.63.wtpedl

Mk4/hdw. fourfit 3.8 rev 804

3C279.wtpedl, 081-0920_LOW, SF

SMTOL - CARMAFL, fgroup U, pol LL





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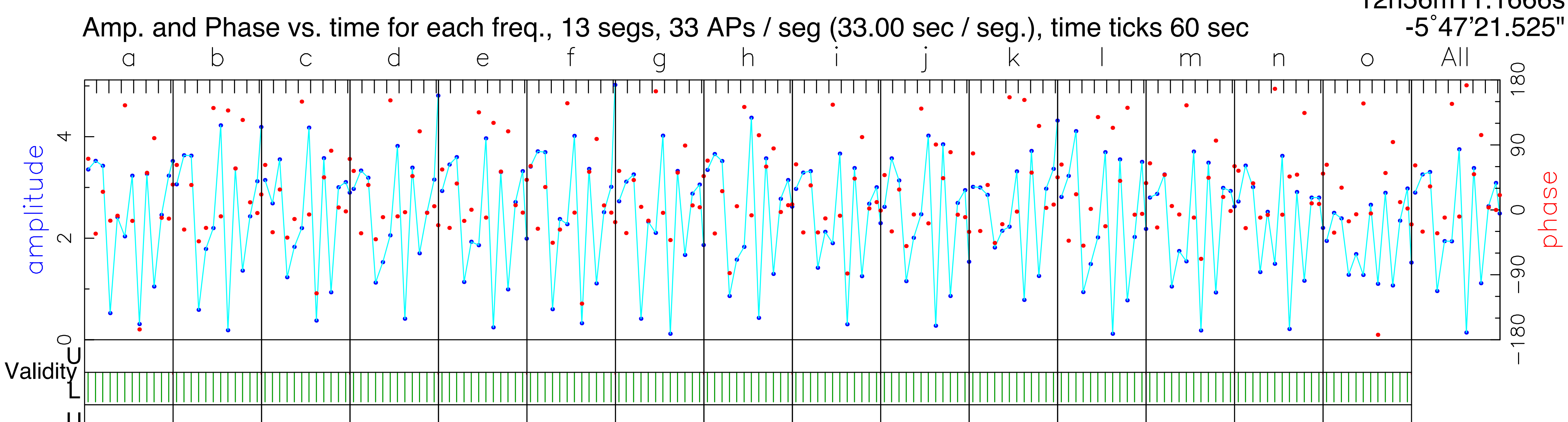

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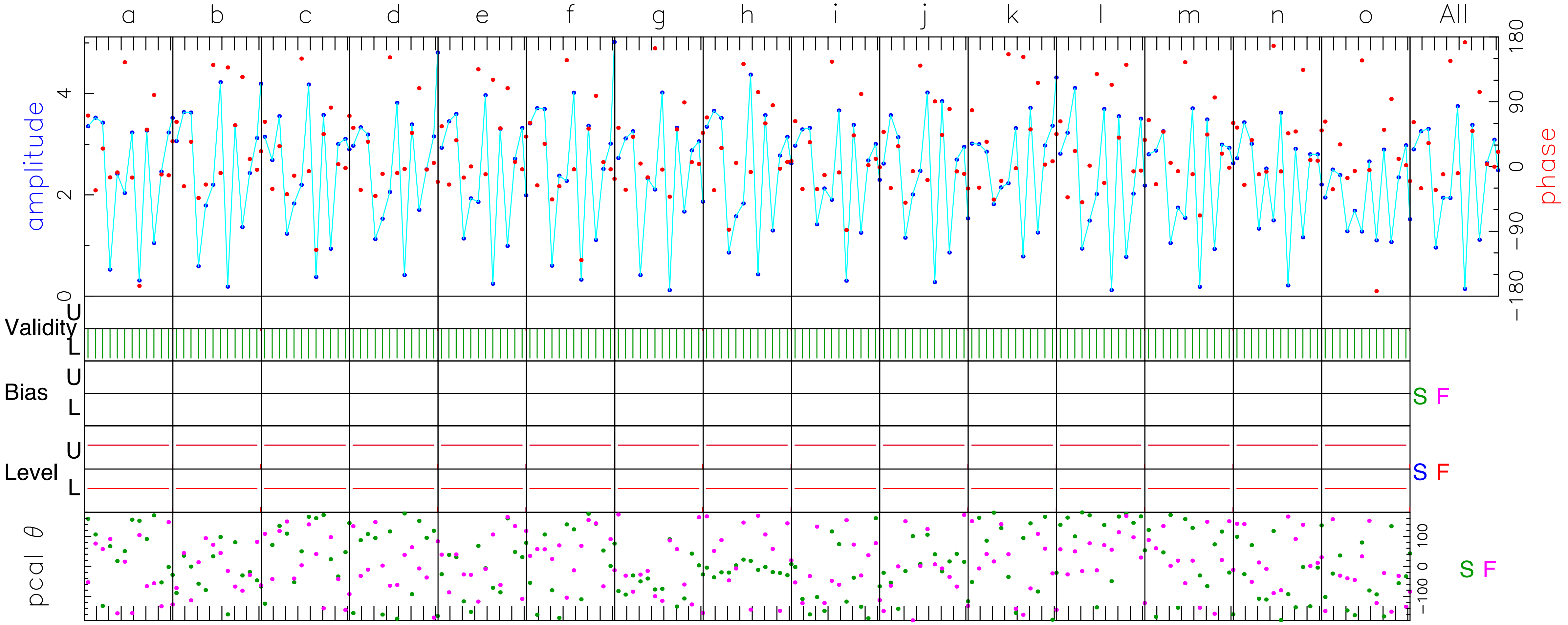

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S	UGLL	UFLL	UELL	UDLL	UCLL	UBLL	UALL	U9LL	U8LL	U7LL	U6LL	U5LL	U4LL	U3LL	U2LL	Chan ids	
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Pcal rate: 0.000E+00, 0.000E+00 (us/s)
Bits/sample: 2   SampCntNorm: enabled
Sample rate(MSamp/s): 64
Data rate(Mb/s): 1920   nlags: 32   t_cohere infinite

sb window (us)	-0.012	0.002
mb window (us)	-0.016	0.016
dr window (ns/s)	-0.002	0.002
ion window (TEC)	0.00	0.00

S: az 0.0 el 0.0 pa 0.0   F: az 0.0 el 0.0 pa 0.0   u,v (fr/asec) 0.000 0.000   iterative interpolator

Control file: cf_3425_229089   Input file: /data2/3425/081-0920_LOW/SF..wtpedl   Output file: /data2/3425/081-0920_LOW/SF.U.63.wtpedl

Mark 4 directory structure

$DATADIR (/data2/tutorial)
- Experiment number
  - Scan directories
    - Files associated with each scan

```
vfish@reu6: /data2/tutorial/3425/081-0600_LOW
File  Edit  View  Terminal  Help
vfish@reu6:/data2/tutorial$ ls
3425
vfish@reu6:/data2/tutorial$ cd 3425
vfish@reu6:/data2/tutorial/3425$ ls
081-0600_LOW  081-0720_LOW  081-0840_LOW  081-1004_LOW  081-1044_LOW
081-0620_LOW  081-0740_LOW  081-0900_LOW  081-1014_LOW  081-1054_LOW
081-0640_LOW  081-0800_LOW  081-0920_LOW  081-1024_LOW  081-1104_LOW
081-0700_LOW  081-0820_LOW  081-0954_LOW  081-1034_LOW
vfish@reu6:/data2/tutorial/3425$ cd 081-0600_LOW
vfish@reu6:/data2/tutorial/3425/081-0600_LOW$ ls
3C273.wtmnat  F..wtoxfr    P..wtoxfr    S..wtmnat    T..wtoxfr
3C273.wtoxfr  G..wtoxfr    SF..wtmnat   S..wtoxfr
F..wtmnat     PF..wtoxfr   SP..wtoxfr   TG..wtoxfr
vfish@reu6:/data2/tutorial/3425/081-0600_LOW$
```

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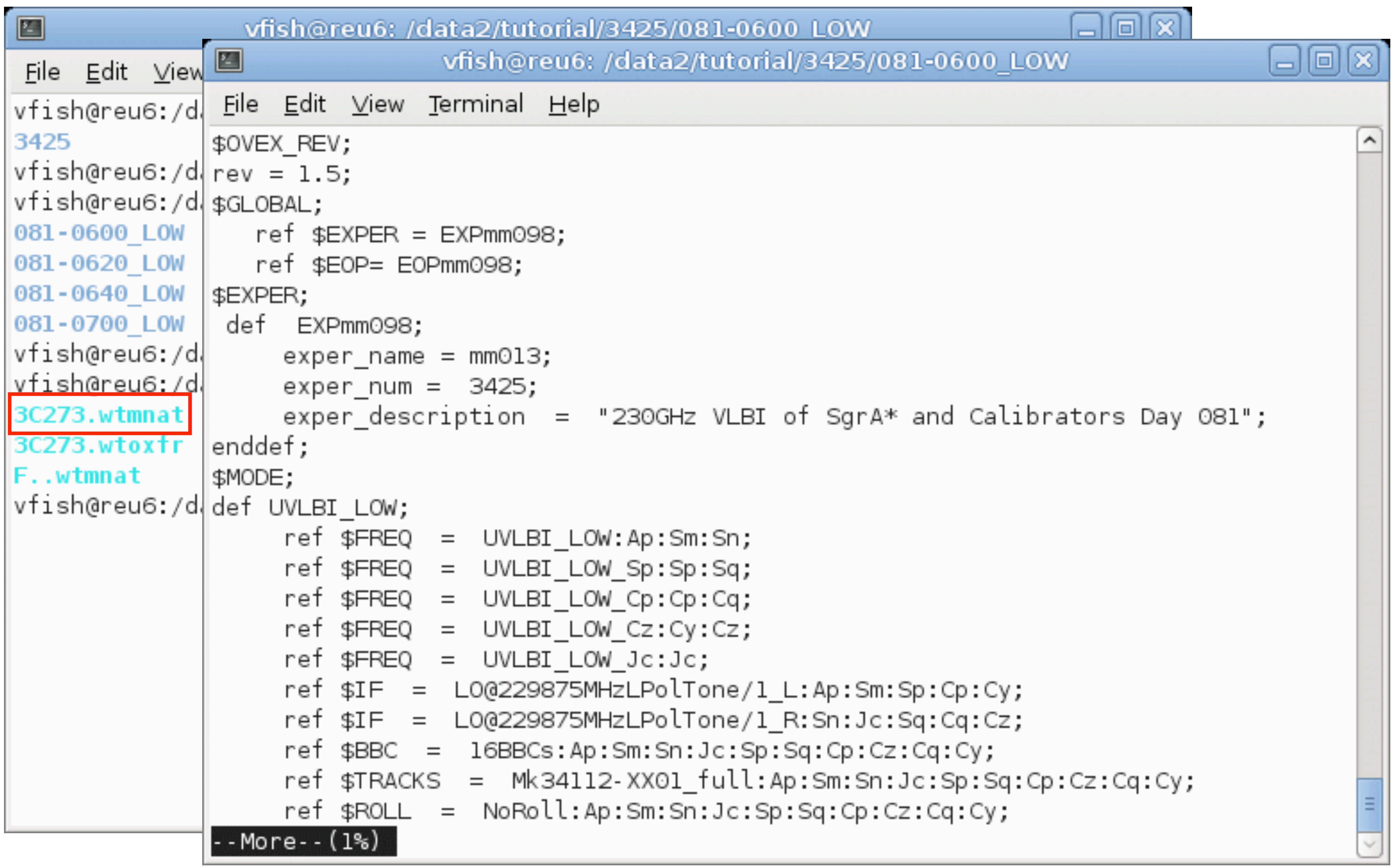
Root



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```
vfish@reu6: /data2/tutorial/3425/081-0600_LOW
File  Edit  View  Terminal  Help
vfish@reu6:/data2/tutorial$ ls
3425
vfish@reu6:/data2/tutorial$ cd 3425
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081-0600_LOW  081-0720_LOW  081-0840_LOW  081-1004_LOW  081-1044_LOW
081-0620_LOW  081-0740_LOW  081-0900_LOW  081-1014_LOW  081-1054_LOW
081-0640_LOW  081-0800_LOW  081-0920_LOW  081-1024_LOW  081-1104_LOW
081-0700_LOW  081-0820_LOW  081-0954_LOW  081-1034_LOW
vfish@reu6:/data2/tutorial/3425$ cd 081-0600_LOW
vfish@reu6:/data2/tutorial/3425/081-0600_LOW$ ls
3C273.wtmnat  F..wtoxfr    P..wtoxfr   S..wtmnat   T..wtoxfr
3C273.wtoxfr  G..wtoxfr    SF..wtmnat  S..wtoxfr
F..wtmnat     PF..wtoxfr   SP..wtoxfr  TG..wtoxfr
vfish@reu6:/data2/tutorial/3425/081-0600_LOW$
```
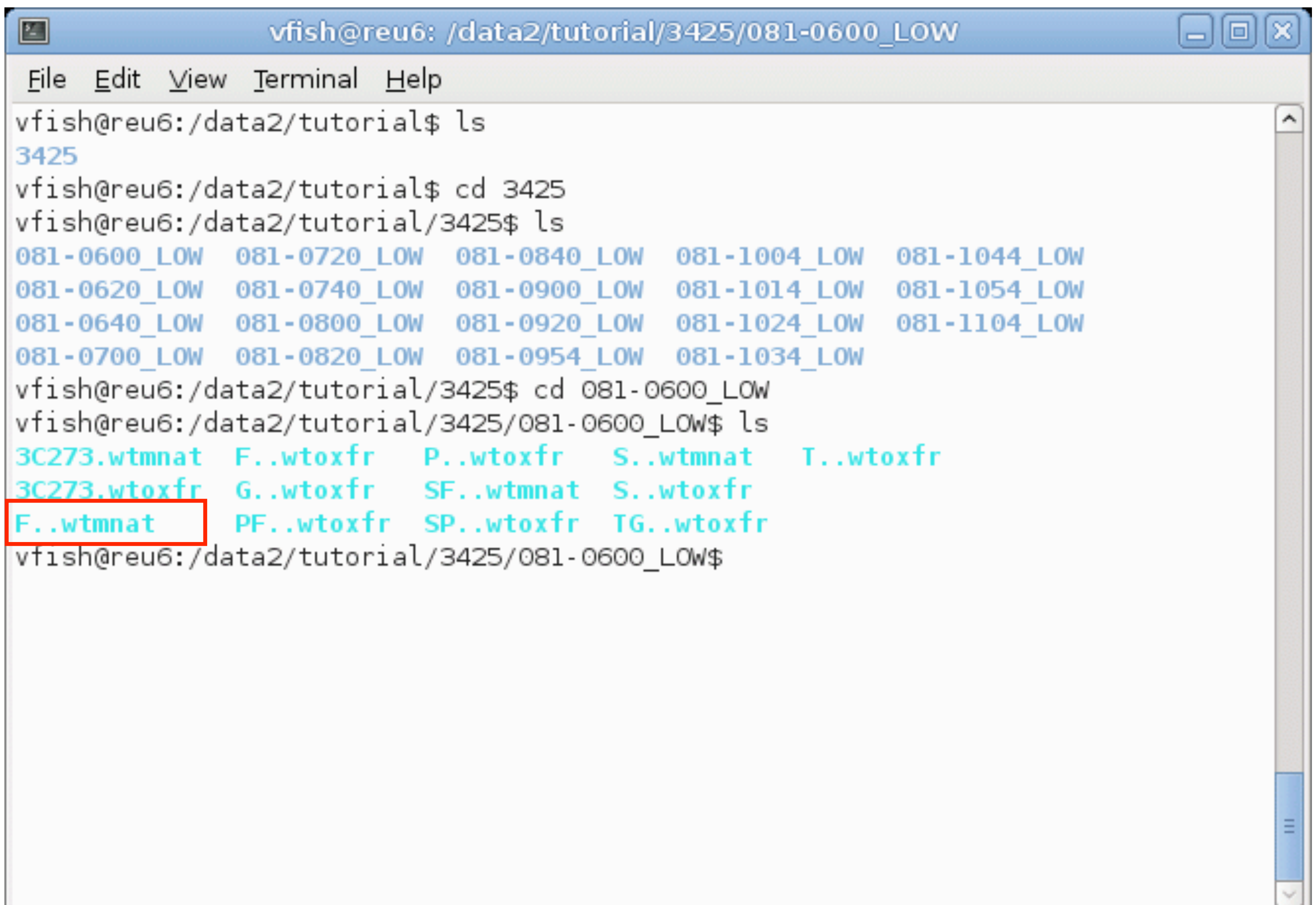

Type 1

Mark 4 directory structure

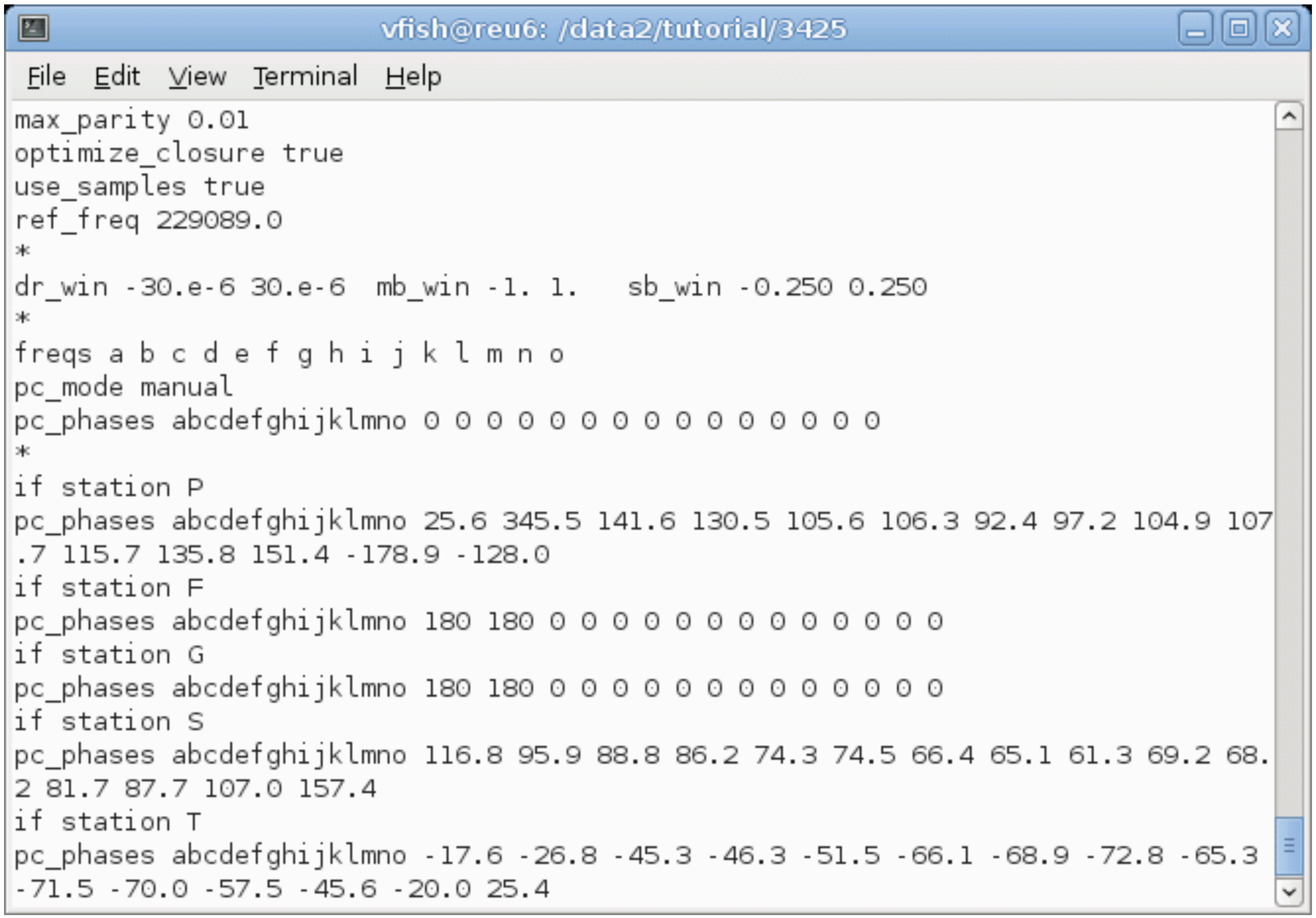
$DATADIR (/data2/tutorial)
- Experiment number
  - Scan directories
    - Files associated with each scan

Type 3



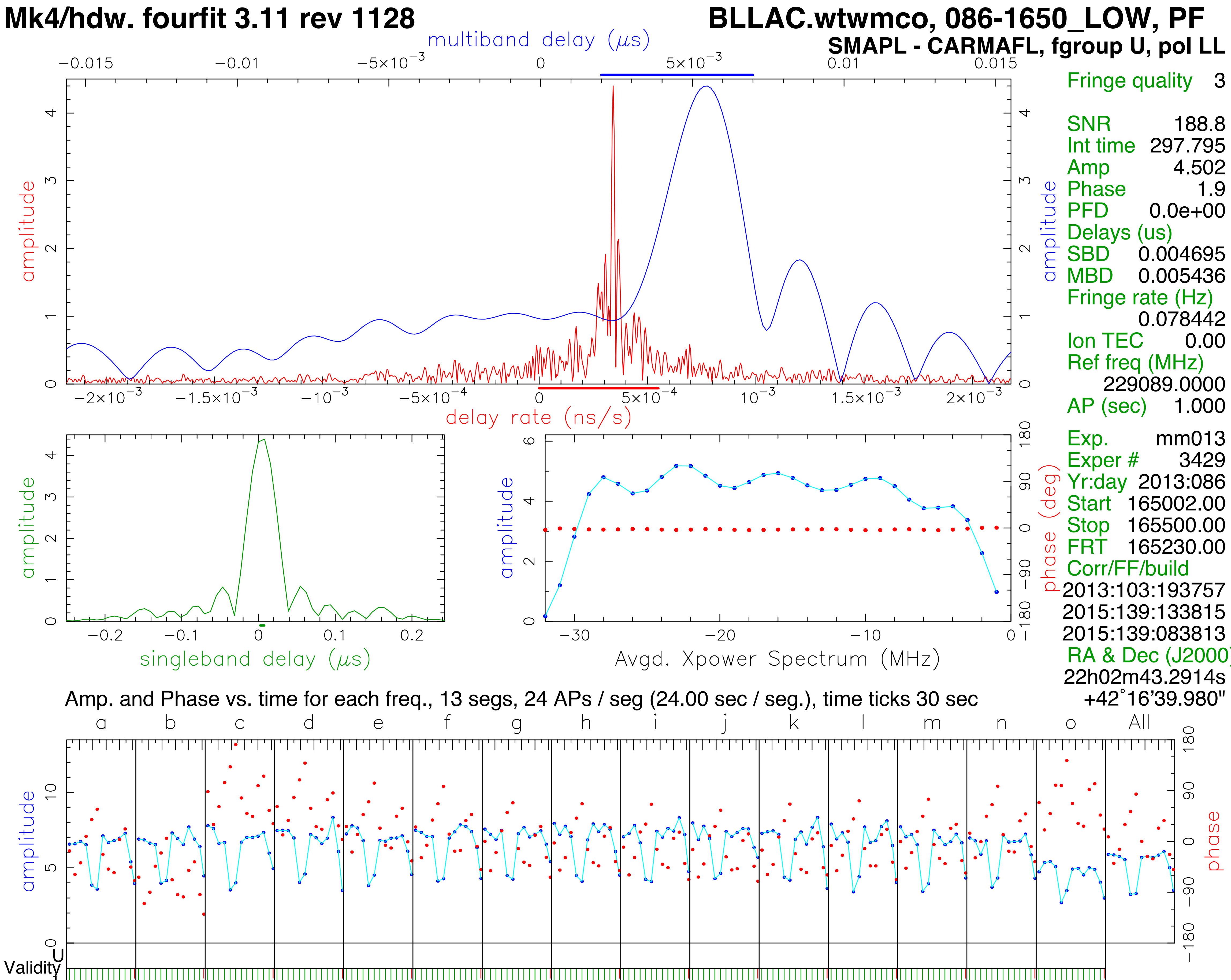
Running fourfit

Fourfit takes a control file as input




```
max_parity 0.01
optimize_closure true
use_samples true
ref_freq 229089.0
*
dr_win -30.e-6 30.e-6  mb_win -1. 1.   sb_win -0.250 0.250
*
freqs a b c d e f g h i j k l m n o
pc_mode manual
pc_phases abcdefghijklmno 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
*
if station P
pc_phases abcdefghijklmno 25.6 345.5 141.6 130.5 105.6 106.3 92.4 97.2 104.9 107
.7 115.7 135.8 151.4 -178.9 -128.0
if station F
pc_phases abcdefghijklmno 180 180 0 0 0 0 0 0 0 0 0 0 0 0 0
if station G
pc_phases abcdefghijklmno 180 180 0 0 0 0 0 0 0 0 0 0 0 0 0
if station S
pc_phases abcdefghijklmno 116.8 95.9 88.8 86.2 74.3 74.5 66.4 65.1 61.3 69.2 68.
2 81.7 87.7 107.0 157.4
if station T
pc_phases abcdefghijklmno -17.6 -26.8 -45.3 -46.3 -51.5 -66.1 -68.9 -72.8 -65.3
-71.5 -70.0 -57.5 -45.6 -20.0 25.4
```

Manual pcals



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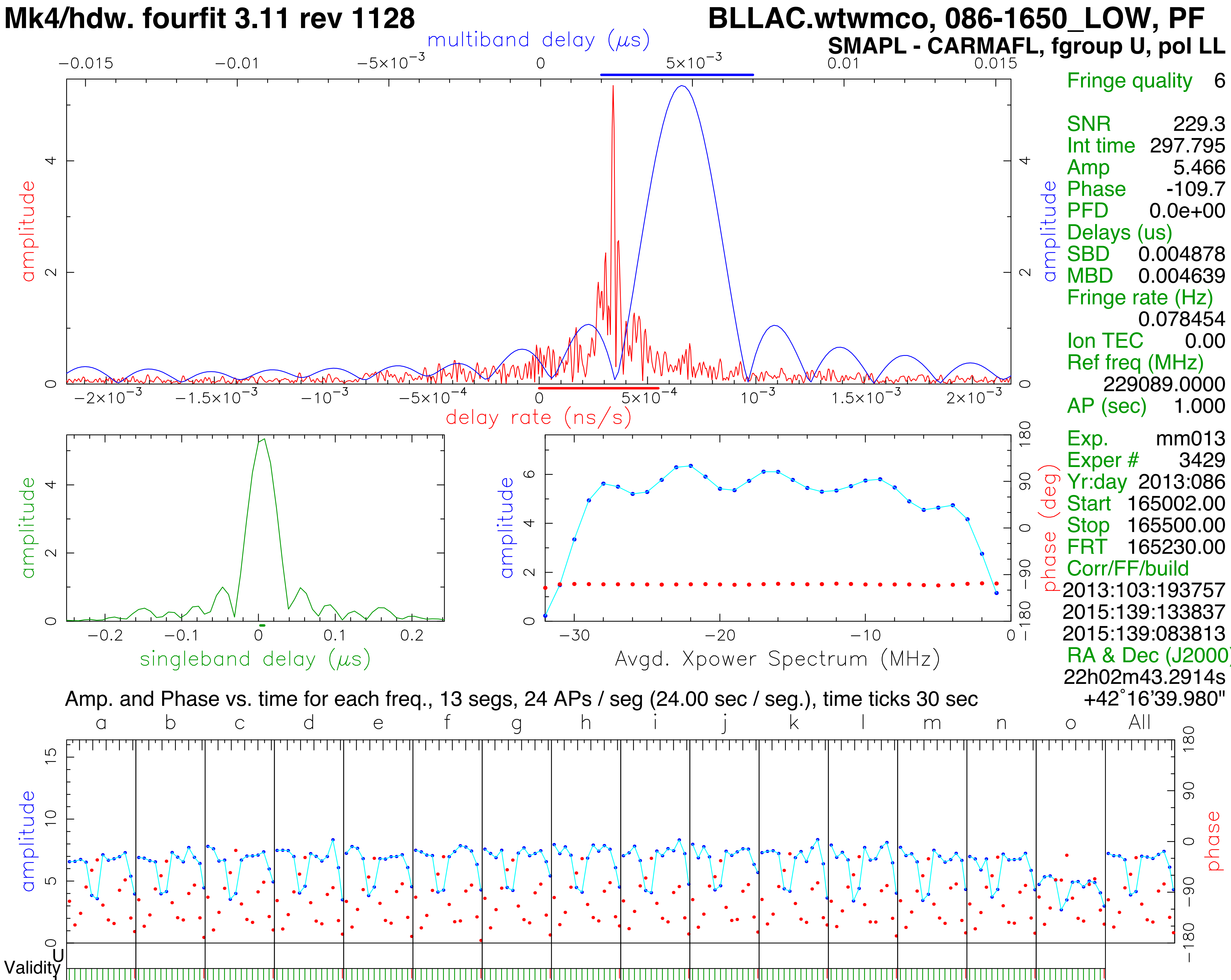


Manual pcals

Multiband delays are meaningless until pcals are defined

Slope in pcal values will shift multiband delay peak

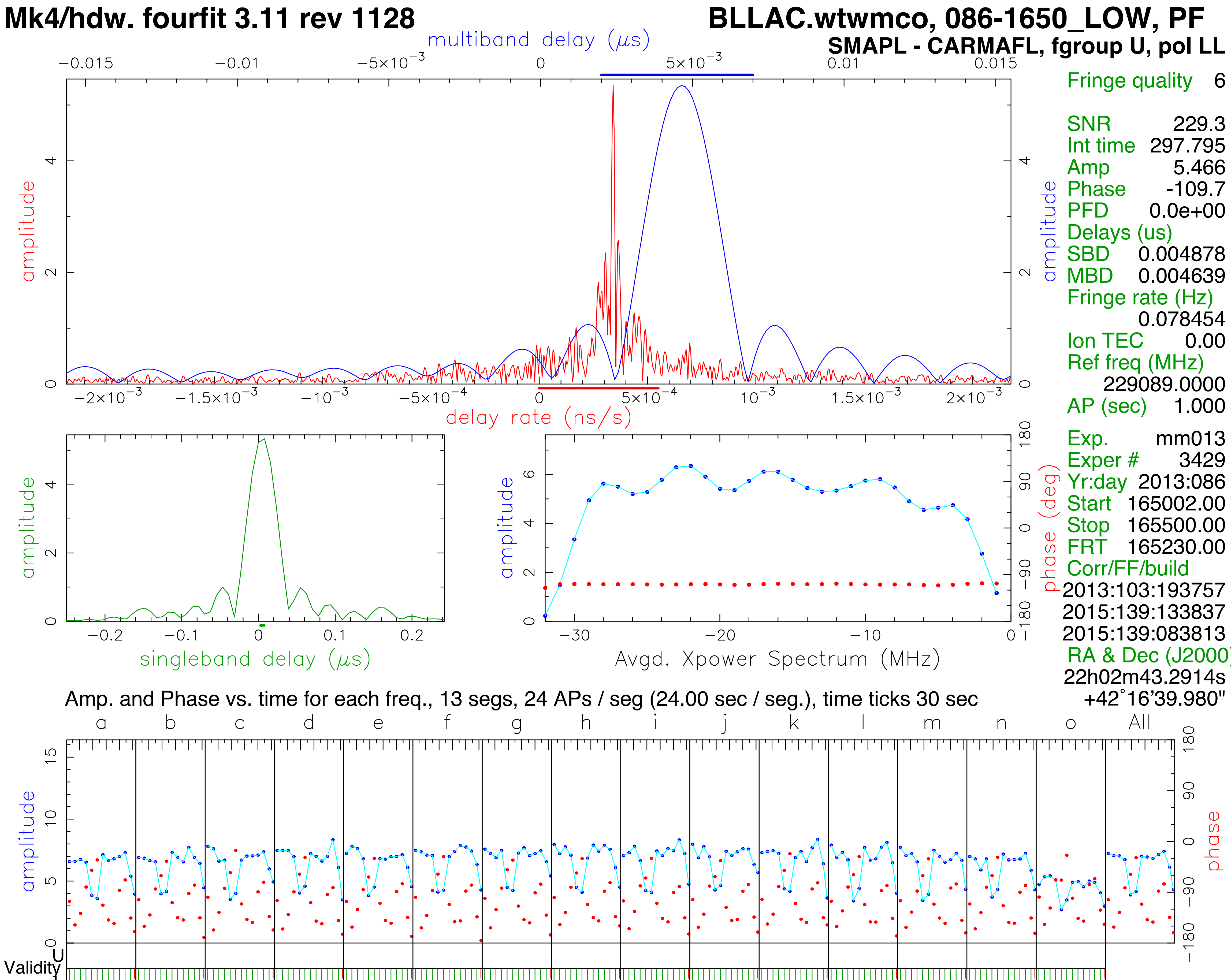
vfish@reu6: /data2/3429

File Edit View Terminal Help

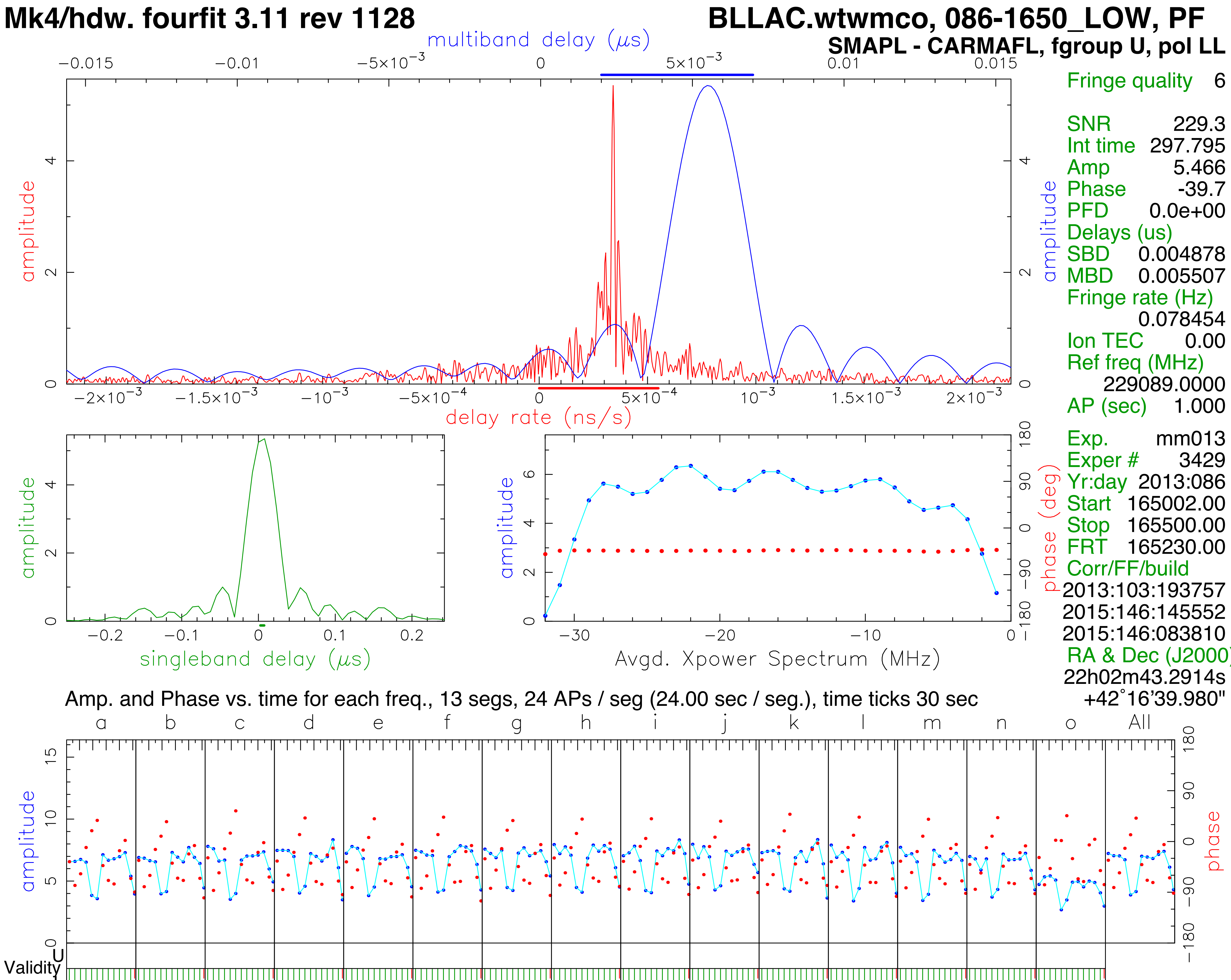
```
freqs a b c d e f g h i j k l m n o
pc_mode manual
pc_phases abcdefghijklmno 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
*
if station P
pc_phases abcdefghijklmno 25.6 345.5 141.6 130.5 105.6 106.3 92.4 97.2 104.9 107
.7 115.7 135.8 151.4 -178.9 -128.0
if station F
*pc_phases abcdefghijklmno 180 180 0 0 0 0 0 0 0 0 0 0 0 0 0
pc_phases abcdefghijklmno 180 190 20 30 40 50 60 70 80 90 100 110 120 130 140

vfish@reu6:/data2/3429$
```

Manual pcals



Manual pcals



Manual pcals

Multiband delays are meaningless until pcals are defined

Slope in pcal values will shift multiband delay peak

In this example:

- Difference is a slope of 10 deg/channel
  - i.e., 1 turn of phase in 36 x 32 MHz = 1152 MHz
- Inverse bandwidth is 0.868 ns

- Old mbd solution: 4.639 ns
- New mbd solution: 5.507 ns
- Difference: 0.868 ns

Manual pcals

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In this example:

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- Inverse bandwidth is 0.868 ns

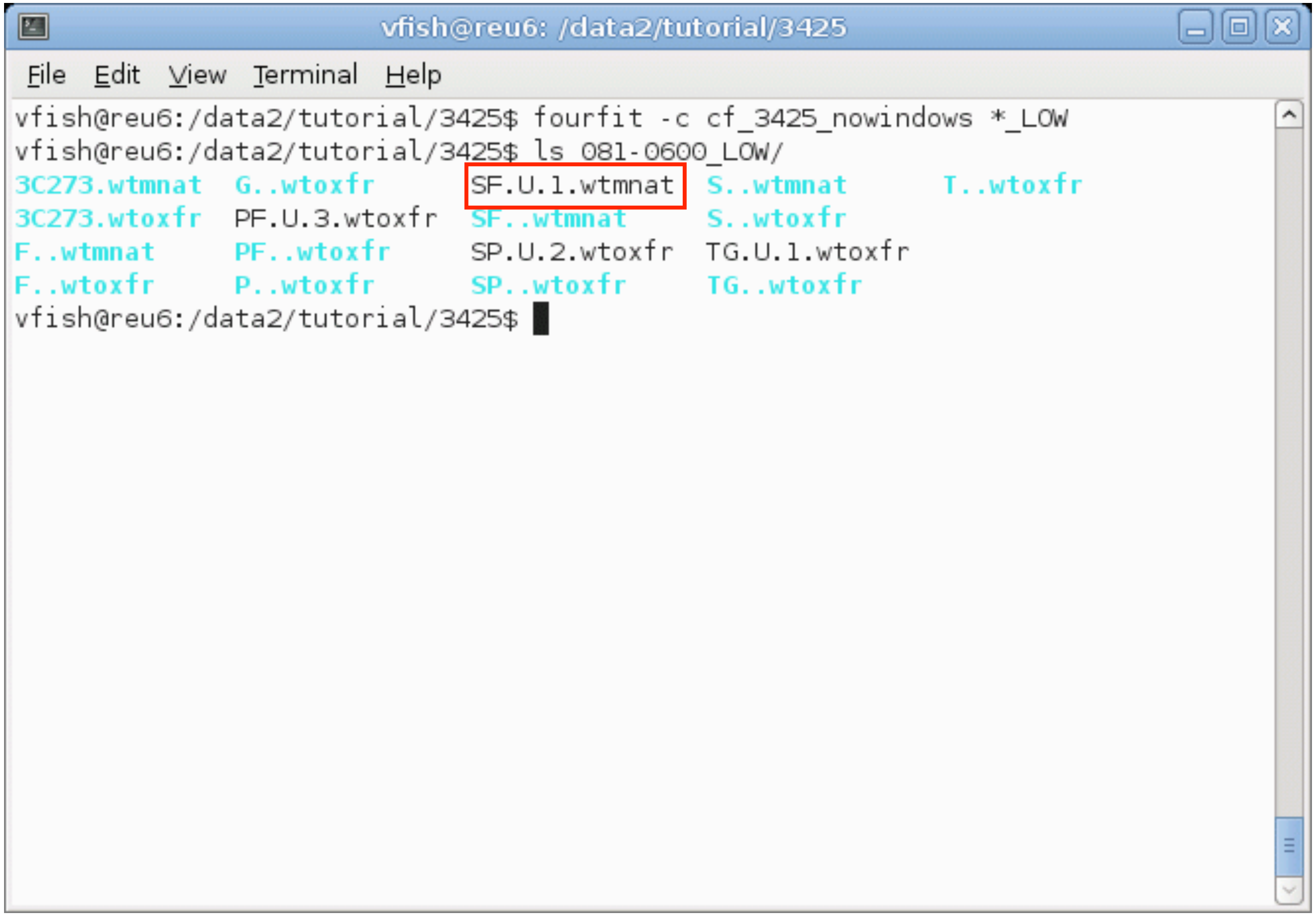
- Old mbd solution: 4.639 ns
- New mbd solution: 5.507 ns
- Difference: 0.868 ns

Manual pcal values should usually be determined on an ensemble of strong scans and then applied to the entire experiment

Running fourfit

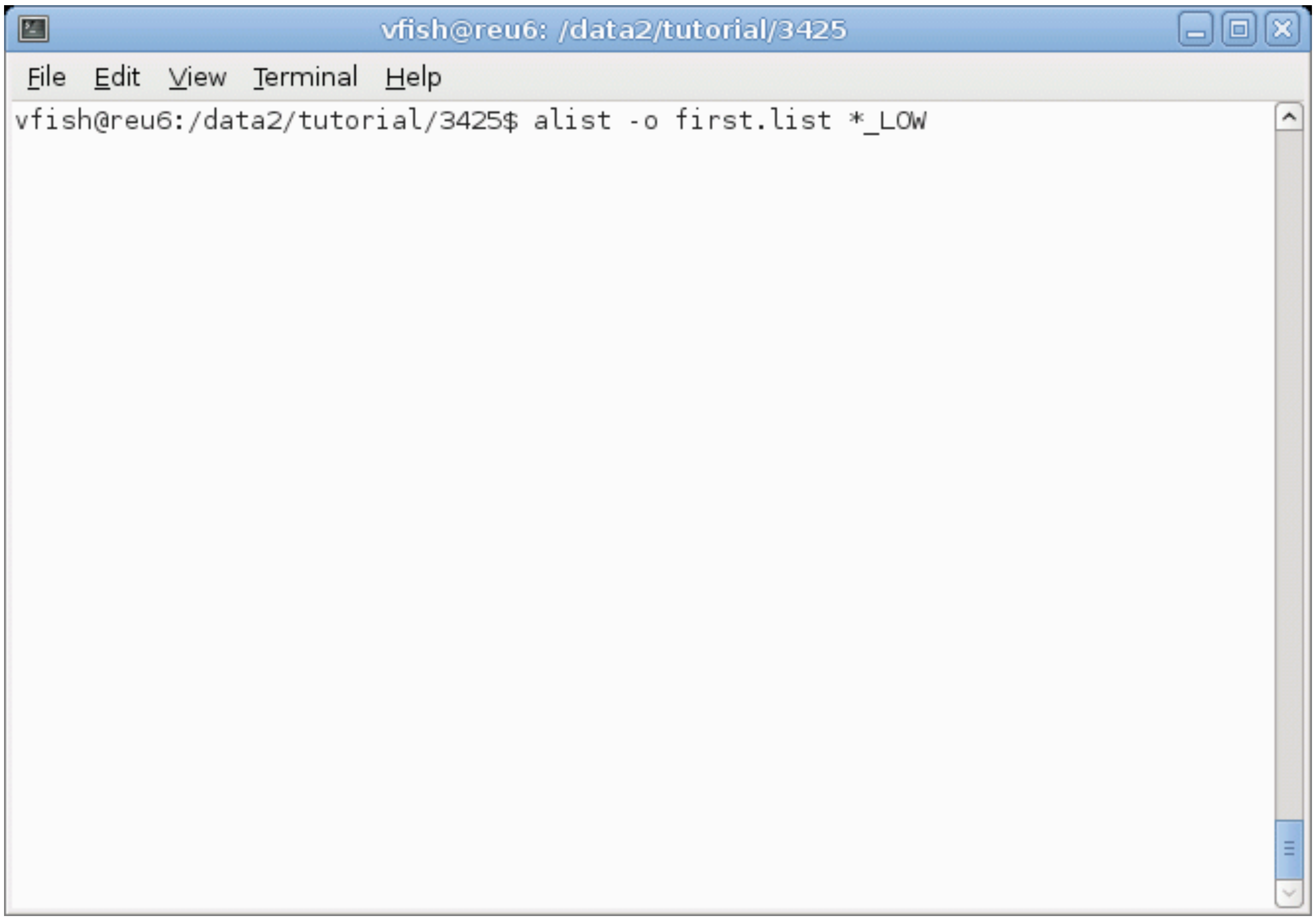
Fourfit takes a control file as input

...and produces type-2 files as output



A-lists

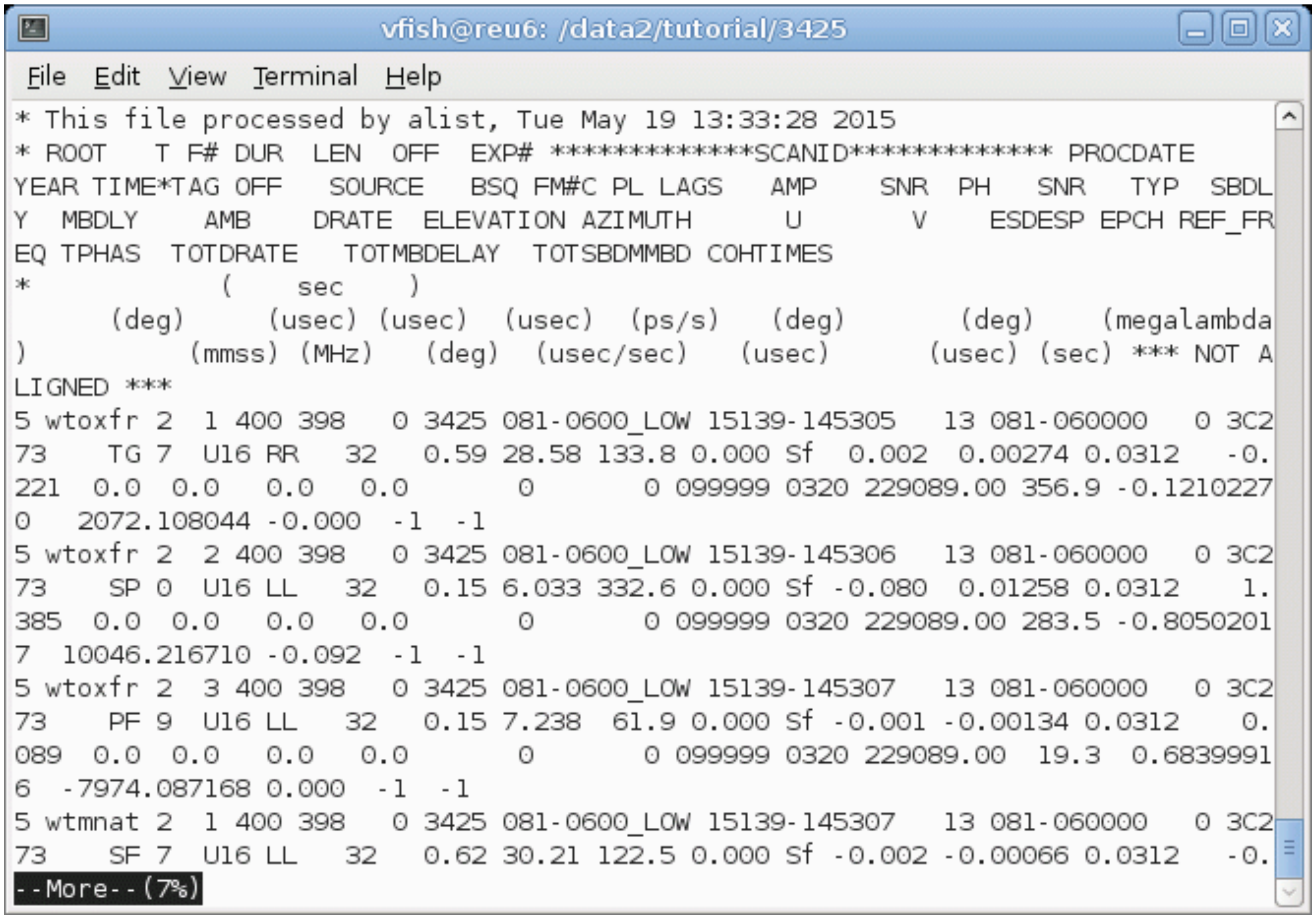
Formatted text files to keep track of type-2 (fourfit) files



A-lists

Formatted text files to keep track of type-2 (fourfit) files

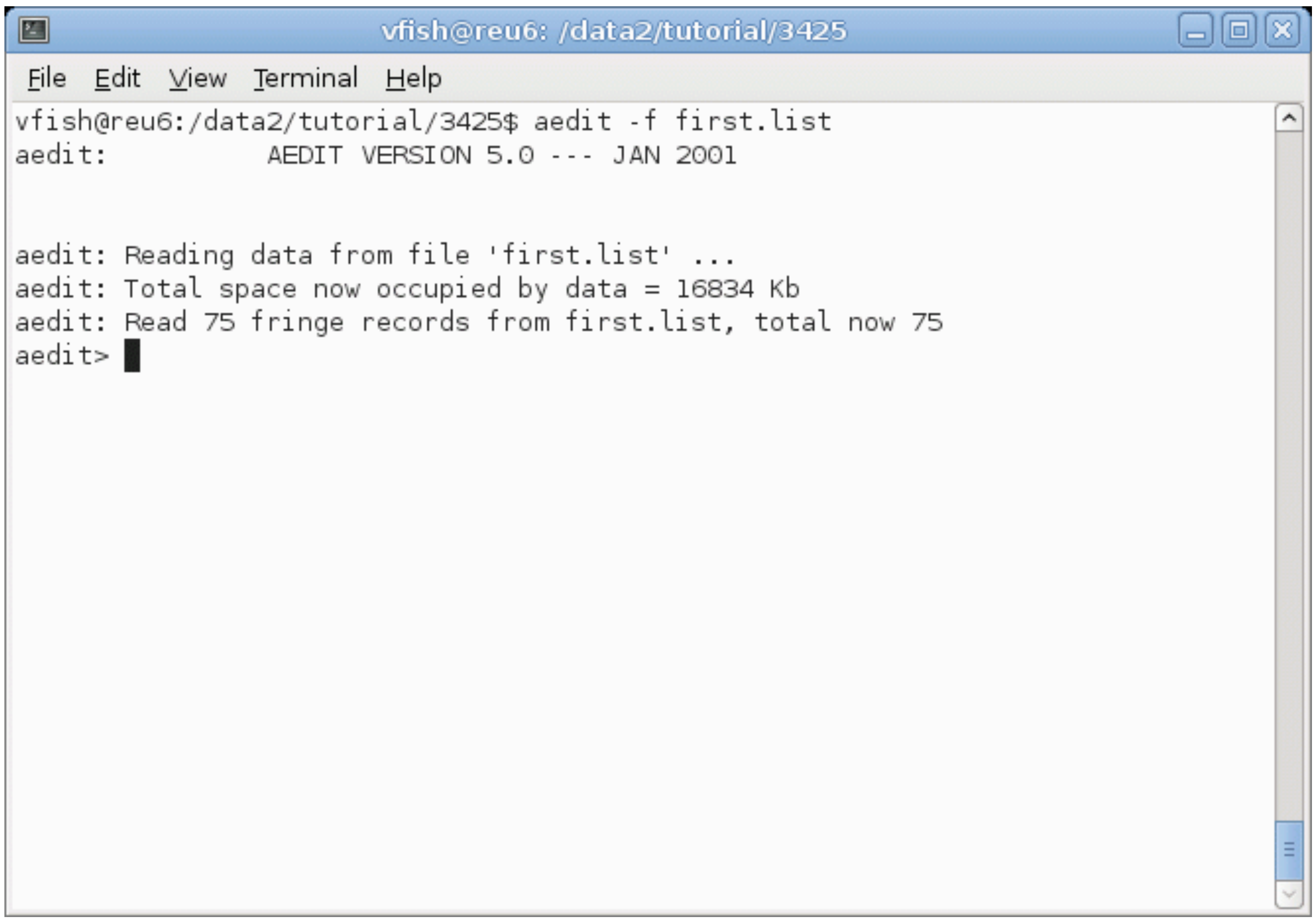
One line per scan/baseline/processing/...



```
vfish@reu6: /data2/tutorial/3425
File Edit View Terminal Help
* This file processed by alist, Tue May 19 13:33:28 2015
* ROOT   T F# DUR  LEN  OFF  EXP# *************SCANID************** PROCDATE
YEAR TIME*TAG OFF   SOURCE   BSQ FM#C PL LAGS   AMP    SNR  PH   SNR   TYP  SBDL
Y  MBDLY    AMB    DRATE  ELEVATION AZIMUTH     U       V     ESDESP EPCH REF_FR
EQ TPHAS  TOTDRATE   TOTMBDELAY  TOTSBDMMBD COHTIMES
*           (     sec     )
      (deg)     (usec) (usec)  (usec)  (ps/s)   (deg)       (deg)    (megalambda
)          (mmss) (MHz)   (deg)  (usec/sec)   (usec)      (usec) (sec) *** NOT A
LIGNED ***
5 wtoxfr 2  1 400 398   0 3425 081-0600_LOW 15139-145305   13 081-060000   0 3C2
73    TG 7  U16 RR   32   0.59 28.58 133.8 0.000 Sf  0.002  0.00274 0.0312   -0.
221  0.0  0.0   0.0   0.0       0       0 099999 0320 229089.00 356.9 -0.1210227
0   2072.108044 -0.000  -1  -1
5 wtoxfr 2  2 400 398   0 3425 081-0600_LOW 15139-145306   13 081-060000   0 3C2
73    SP 0  U16 LL   32   0.15 6.033 332.6 0.000 Sf -0.080  0.01258 0.0312    1.
385  0.0  0.0   0.0   0.0       0       0 099999 0320 229089.00 283.5 -0.8050201
7  10046.216710 -0.092  -1  -1
5 wtoxfr 2  3 400 398   0 3425 081-0600_LOW 15139-145307   13 081-060000   0 3C2
73    PF 9  U16 LL   32   0.15 7.238  61.9 0.000 Sf -0.001 -0.00134 0.0312    0.
089  0.0  0.0   0.0   0.0       0       0 099999 0320 229089.00  19.3  0.6839991
6  -7974.087168 0.000  -1  -1
5 wtmnat 2  1 400 398   0 3425 081-0600_LOW 15139-145307   13 081-060000   0 3C2
73    SF 7  U16 LL   32   0.62 30.21 122.5 0.000 Sf -0.002 -0.00066 0.0312   -0.
--More--(7%)
```

Aedit

Program to view and edit contents of A-lists



Aedit

Summary of baseline data

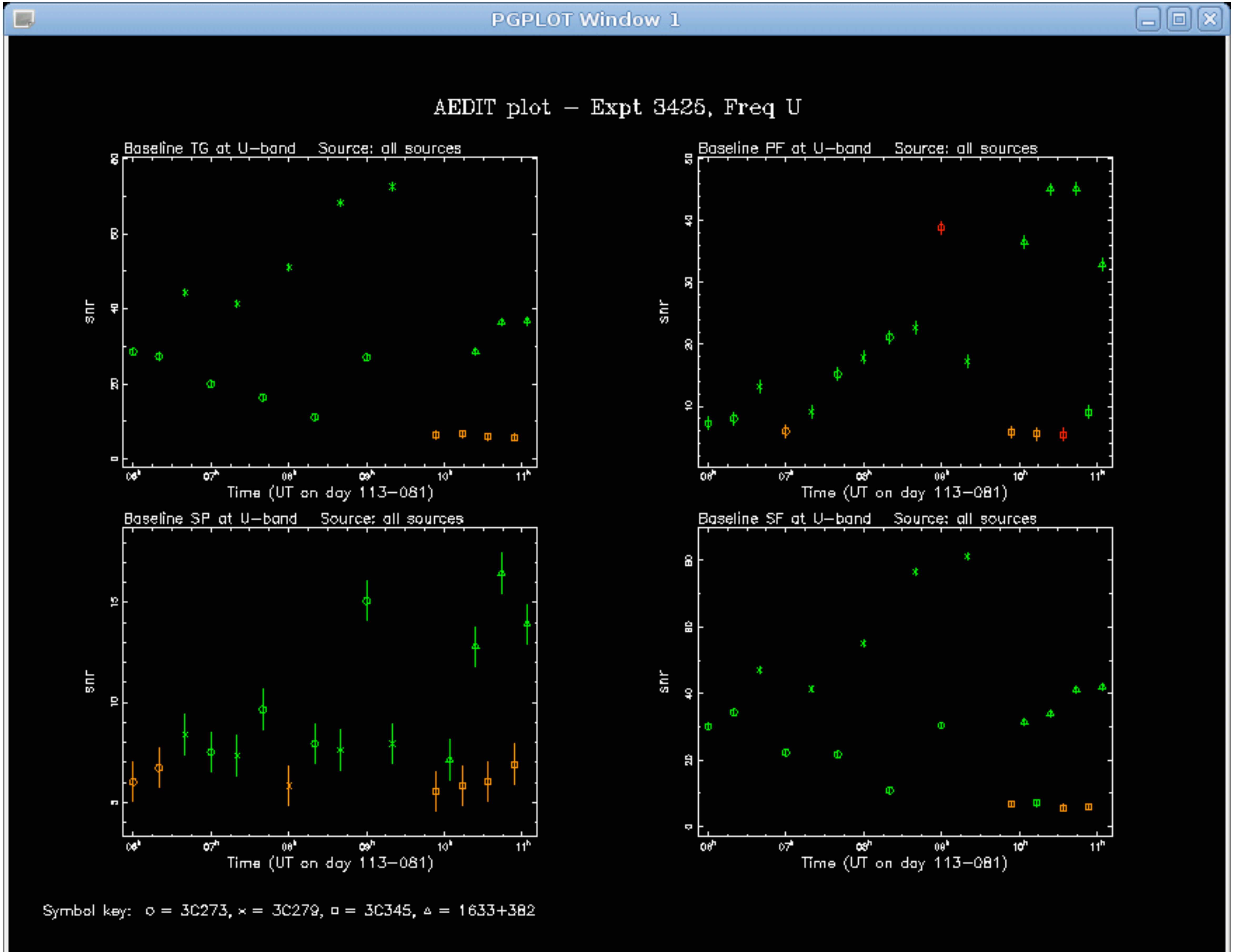
```
aedit> summ 2


               SUMMARY OF UNFLAGGED DATA IN MEMORY
               -----------------------------------

Total number of unflagged fringe records = 75

Earliest scan:       113-081-060000
Latest scan:         113-081-110400
Earliest procdate:   115-139-1453
Latest procdate:     115-139-1454
Stations present:    FGPST
Baselines present:   TG SP PF SF
Frequencies present: U
Polarizations present:   RR LL
SNR extrema:         5.407  81.15
Experiments present: 3425
Sources present:     1633+382 3C273 3C279 3C345
Quality code summary:
        A B C D E F G H 0  1 2 3 4 5  6 7  8 9  ?
        0 0 0 0 0 0 1 0 18 0 0 0 0 17 0 15 0 24 0

There are 0 flagged records present
```

Aedit

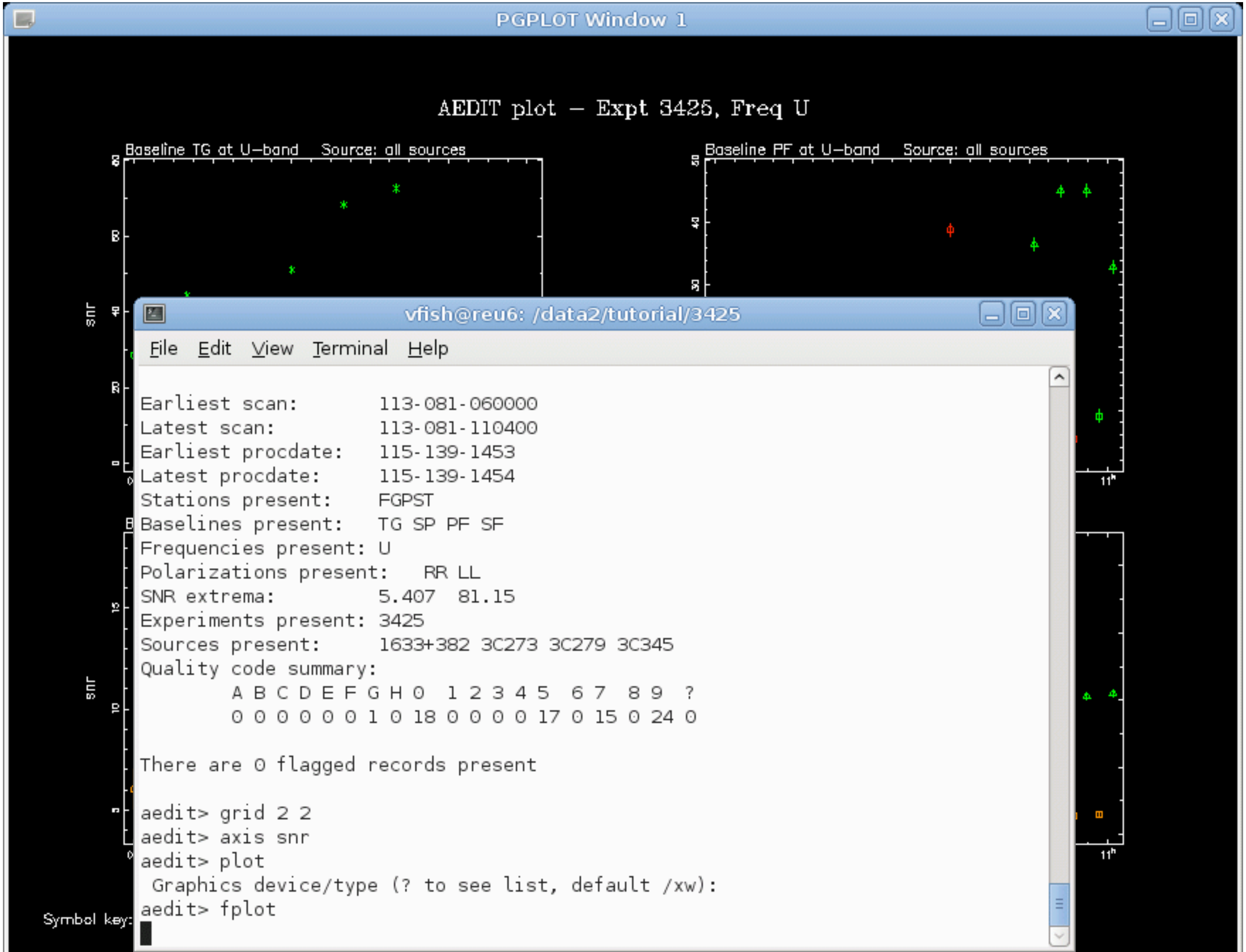
Plot data by signal-to-noise ratio

```
vfish@reu6: /data2/tutorial/3425
File  Edit  View  Terminal  Help

Earliest scan:        113-081-060000
Latest scan:          113-081-110400
Earliest procdate:    115-139-1453
Latest procdate:      115-139-1454
Stations present:     FGPST
Baselines present:    TG SP PF SF
Frequencies present: U
Polarizations present:   RR LL
SNR extrema:          5.407  81.15
Experiments present: 3425
Sources present:      1633+382 3C273 3C279 3C345
Quality code summary:
        A B C D E F G H 0  1 2 3 4 5  6 7  8 9  ?
        0 0 0 0 0 0 1 0 18 0 0 0 0 17 0 15 0 24 0

There are 0 flagged records present

aedit>
aedit> grid 2 2
aedit> axis snr
aedit> plot
 Graphics device/type (? to see list, default /xw):
aedit> 
```

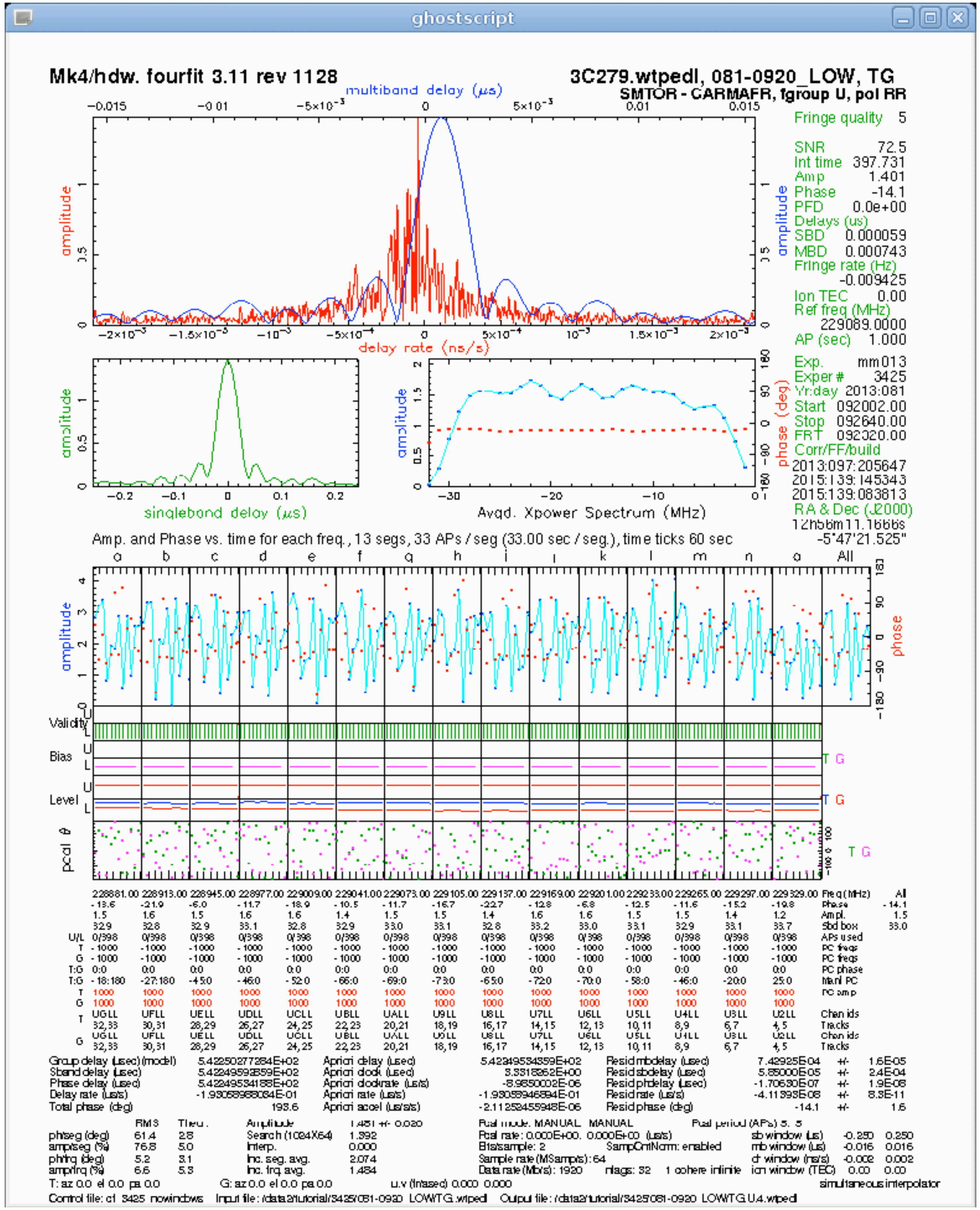
Aedit


PGPLOT Window 1
AEDIT plot — Expt 3425, Freq U
Baseline TG at U-band Source: all sources
Baseline PF at U-band Source: all sources
Baseline SP at U-band Source: all sources
Baseline SF at U-band Source: all sources
snr
Time (UT on day 113-081)
Symbol key: o = 3C273, × = 3C279, □ = 3C345, △ = 1633+382

Aedit


PGPLOT Window 1
AEDIT plot — Expt 3425, Freq U
Baseline TG at U-band Source: all sources
Baseline PF at U-band Source: all sources
snr
Symbol key:
vfish@reu6: /data2/tutorial/3425
File Edit View Terminal Help
Earliest scan: 113-081-060000
Latest scan: 113-081-110400
Earliest procdate: 115-139-1453
Latest procdate: 115-139-1454
Stations present: FGPST
Baselines present: TG SP PF SF
Frequencies present: U
Polarizations present: RR LL
SNR extrema: 5.407 81.15
Experiments present: 3425
Sources present: 1633+382 3C273 3C279 3C345
Quality code summary:
A B C D E F G H 0 1 2 3 4 5 6 7 8 9 ?
0 0 0 0 0 0 1 0 18 0 0 0 0 17 0 15 0 24 0
There are 0 flagged records present
aedit> grid 2 2
aedit> axis snr
aedit> plot
Graphics device/type (? to see list, default /xw):
aedit> fplot

Aedit


ghostscript
Mk4/hdw. fourfit 3.11 rev 1128
3C279.wtpedl, 081-0920_LOW, TG
SMTOR - CARMAFR, fgroup U, pol RR
multiband delay (μs)
amplitude
delay rate (ns/s)
Fringe quality 5
SNR 72.5
Int time 397.731
Amp 1.401
Phase -14.1
PFD 0.0e+00
Delays (us)
SBD 0.000059
MBD 0.000743
Fringe rate (Hz)
-0.009425
Ion TEC 0.00
Ref freq (MHz)
229089.0000
AP (sec) 1.000
Exp. mm013
Exper # 3425
Yr:day 2013:081
Start 092002.00
Stop 092640.00
FRT 092320.00
Corr/FF/build
2013:097:205647
2015:139:145343
2015:139:083813
RA & Dec (J2000)
12h56m11.1666s
-5°47'21.525"
singleband delay (μs)
Avgd. Xpower Spectrum (MHz)
phase (deg)
Amp. and Phase vs. time for each freq., 13 segs, 33 APs / seg (33.00 sec / seg.), time ticks 60 sec
phase
Validity
Bias
Level
pcal θ
T G

Aedit

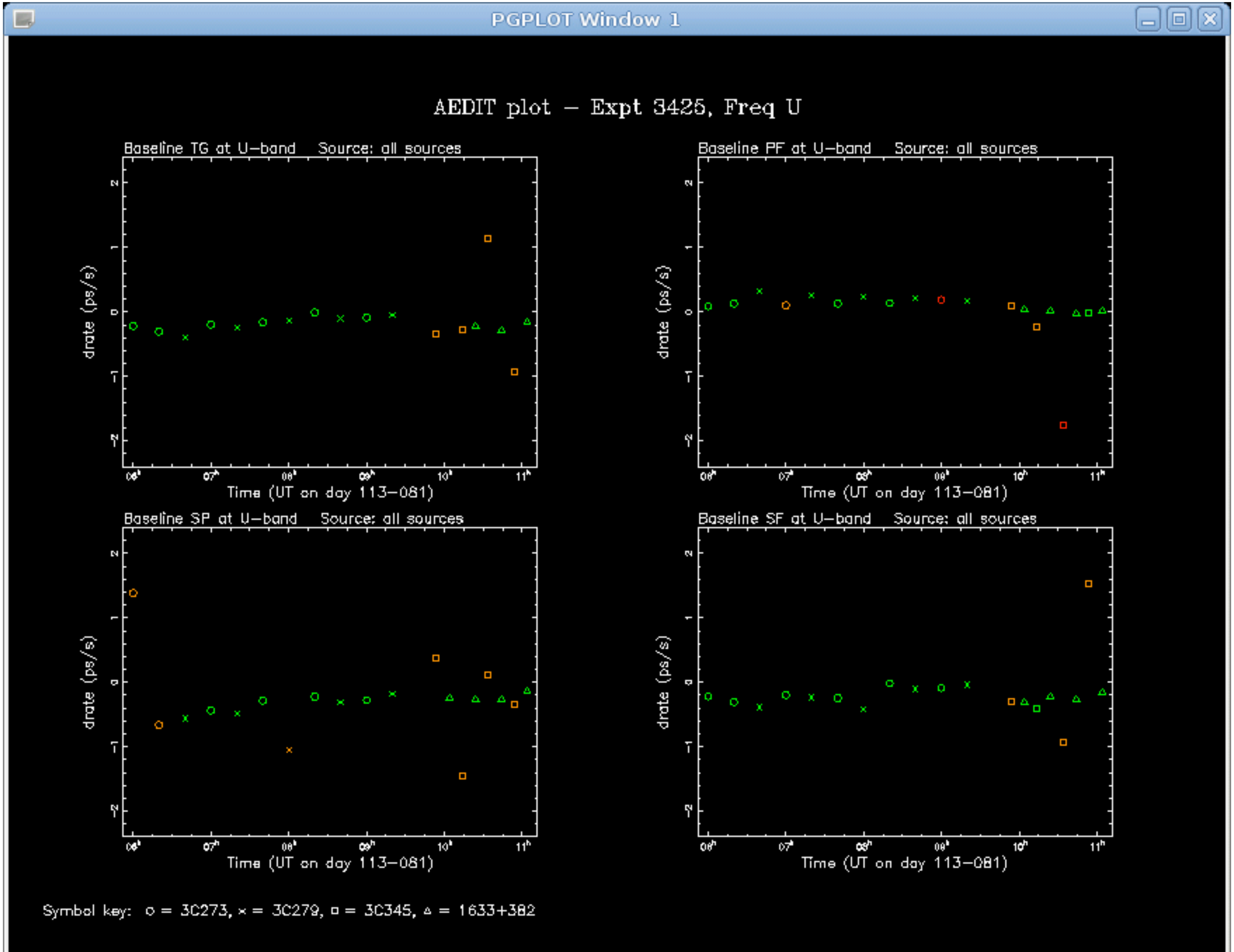
Plot data by delay rate

vfish@reu6: /data2/tutorial/3425

File Edit View Terminal Help

```
Latest procdate:     115-139-1454
Stations present:    FGPST
Baselines present:   TG SP PF SF
Frequencies present: U
Polarizations present:   RR LL
SNR extrema:         5.407  81.15
Experiments present: 3425
Sources present:     1633+382 3C273 3C279 3C345
Quality code summary:
        A B C D E F G H 0  1 2 3 4 5  6 7  8 9  ?
        0 0 0 0 0 0 1 0 18 0 0 0 0 17 0 15 0 24 0

There are 0 flagged records present

aedit> grid 2 2
aedit> axis snr
aedit> plot
 Graphics device/type (? to see list, default /xw):
aedit> fplot
aedit> axis drate
aedit> yscale -2.4 2.4
aedit> plot
Continue with next page (y/n) or edit points (e)? y
aedit>
```

Aedit


PGPLOT Window 1
AEDIT plot – Expt 3425, Freq U
Baseline TG at U-band Source: all sources
Baseline PF at U-band Source: all sources
Baseline SP at U-band Source: all sources
Baseline SF at U-band Source: all sources
drate (ps/s)
Time (UT on day 113-081)
Symbol key: o = 3C273, × = 3C279, □ = 3C345, △ = 1633+382

Aedit

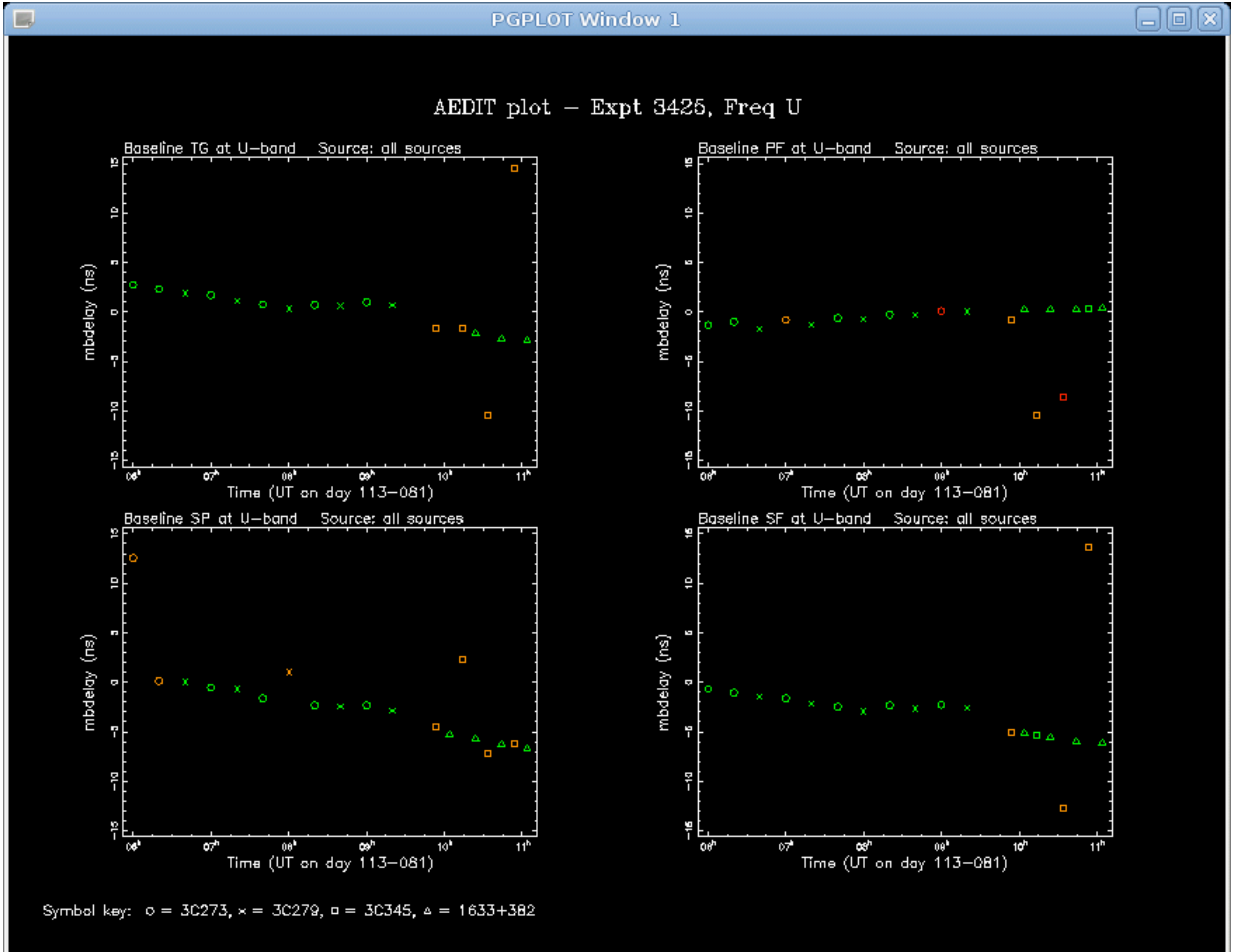
Plot data by multiband delay

vfish@reu6: /data2/tutorial/3425

File Edit View Terminal Help

```
SNR extrema:         5.407  81.15
Experiments present: 3425
Sources present:     1633+382 3C273 3C279 3C345
Quality code summary:
        A B C D E F G H 0  1 2 3 4 5  6 7  8 9  ?
        0 0 0 0 0 0 1 0 18 0 0 0 0 17 0 15 0 24 0

There are 0 flagged records present

aedit> grid 2 2
aedit> axis snr
aedit> plot
 Graphics device/type (? to see list, default /xw):
aedit> fplot
aedit> axis drate
aedit> yscale -2.4 2.4
aedit> plot
Continue with next page (y/n) or edit points (e)? y
aedit> axis mbd
aedit: Warning, Y-axis scale reset to default
aedit> yscale -15.625 15.625
aedit> plot
Continue with next page (y/n) or edit points (e)? y
aedit>
```

Aedit



PGPLOT Window 1
AEDIT plot – Expt 3425, Freq U
Baseline TG at U-band Source: all sources
Baseline PF at U-band Source: all sources
Baseline SP at U-band Source: all sources
Baseline SF at U-band Source: all sources
mbdelay (ns)
Time (UT on day 113-081)
Symbol key: o = 3C273, × = 3C279, □ = 3C345, △ = 1633+382

Aedit

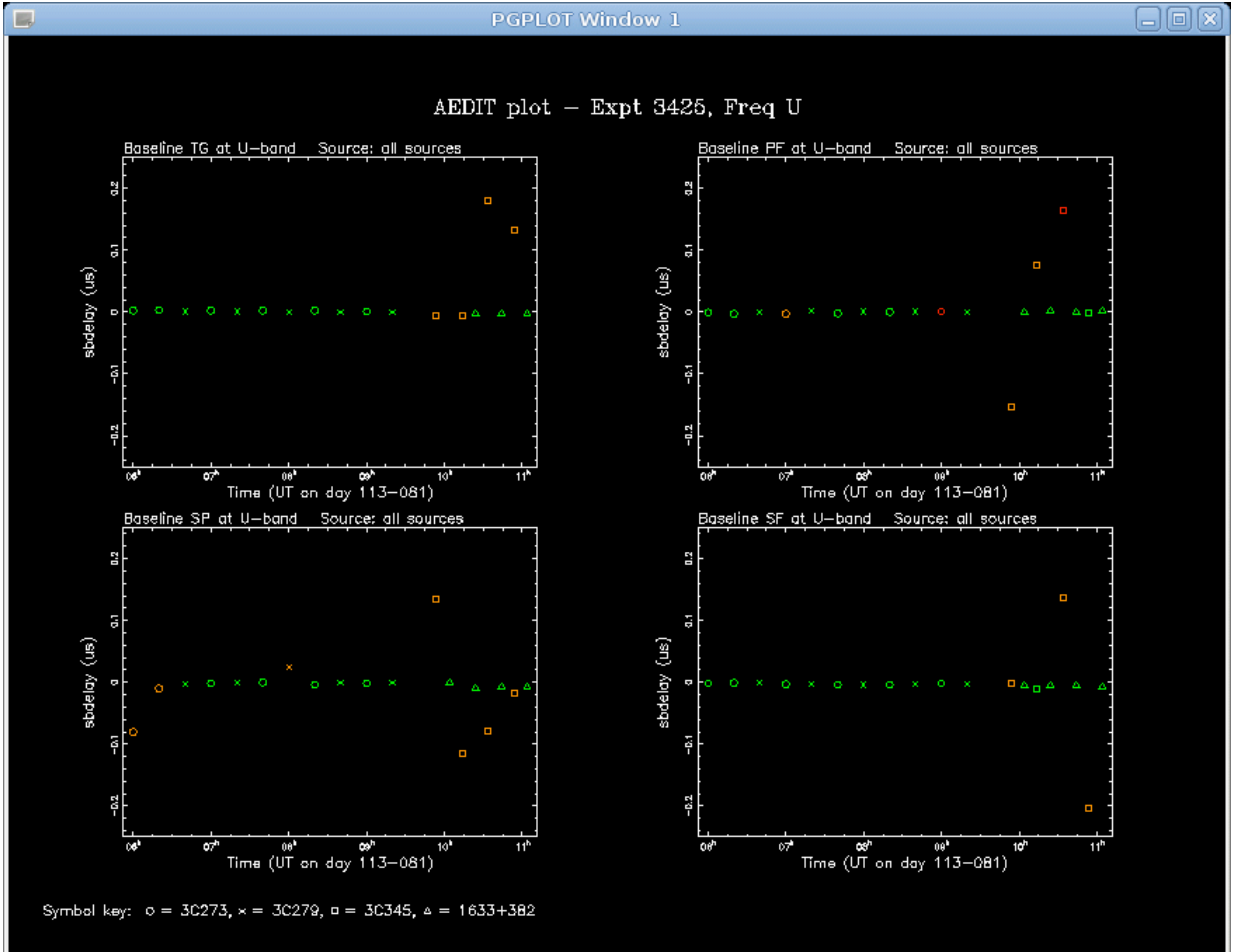
Plot data by singleband delay

vfish@reu6: /data2/tutorial/3425

File Edit View Terminal Help

```
        0 0 0 0 0 0 1 0 18 0 0 0 0 17 0 15 0 24 0

There are 0 flagged records present

aedit> grid 2 2
aedit> axis snr
aedit> plot
 Graphics device/type (? to see list, default /xw):
aedit> fplot
aedit> axis drate
aedit> yscale -2.4 2.4
aedit> plot
Continue with next page (y/n) or edit points (e)? y
aedit> axis mbd
aedit: Warning, Y-axis scale reset to default
aedit> yscale -15.625 15.625
aedit> plot
Continue with next page (y/n) or edit points (e)? y
aedit> axis sbd
aedit: Warning, Y-axis scale reset to default
aedit> yscale -0.25 0.25
aedit> plot
Continue with next page (y/n) or edit points (e)? y
aedit>
```

Aedit


PGPLOT Window 1
AEDIT plot — Expt 3425, Freq U
Baseline TG at U-band Source: all sources
Baseline PF at U-band Source: all sources
Baseline SP at U-band Source: all sources
Baseline SF at U-band Source: all sources
sbdelay (us)
Time (UT on day 113-081)
Symbol key: o = 3C273, × = 3C279, □ = 3C345, △ = 1633+382

Aedit

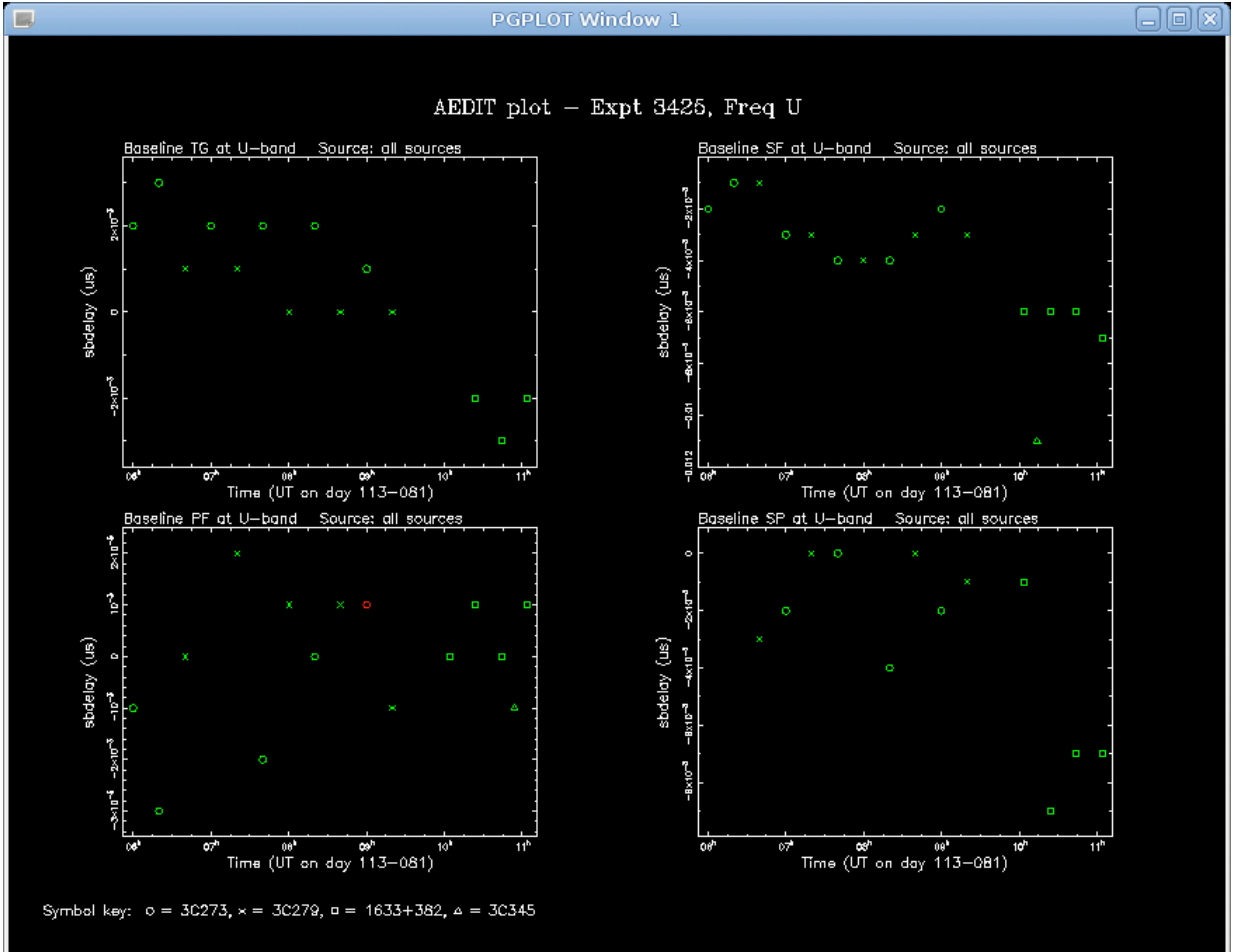
Plot data by singleband delay after imposing S/N >= 7

vfish@reu6: /data2/tutorial/3425

File Edit View Terminal Help

```
aedit> axis drate
aedit> yscale -2.4 2.4
aedit> plot
Continue with next page (y/n) or edit points (e)? y
aedit> axis mbd
aedit: Warning, Y-axis scale reset to default
aedit> yscale -15.625 15.625
aedit> plot
Continue with next page (y/n) or edit points (e)? y
aedit> axis sbd
aedit: Warning, Y-axis scale reset to default
aedit> yscale -0.25 0.25
aedit> plot
Continue with next page (y/n) or edit points (e)? y
aedit> snrmin 7
aedit> ed inp
aedit:  Summary of editing on type-2 (fringe) data:
aedit:  New edits       Flag    Total   Remaining
aedit:  18              18      75      57
aedit:
aedit> yscale
aedit> plot
Continue with next page (y/n) or edit points (e)? y
aedit>
```

Aedit


PGPLOT Window 1
AEDIT plot — Expt 3425, Freq U
Baseline TG at U-band Source: all sources
Baseline SF at U-band Source: all sources
Baseline PF at U-band Source: all sources
Baseline SP at U-band Source: all sources
sbdelay (us)
Time (UT on day 113-081)
Symbol key: o = 3C273, × = 3C279, □ = 1633+382, △ = 3C345

Singleband delays

Fourfit is the only HOPS task to find/set singleband delays

We must constrain the singleband delays on nondetections

Good news: We don't have to be that accurate at first

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32 MHz channels: Inverse bandwidth is 31.25 ns

Each ns we're off gives slope from -6 to +6 deg across channel

A few ns error produces little signal loss
but tens of ns will kill fringes

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32 MHz channels: Inverse bandwidth is 31.25 ns

Each ns we're off gives slope from -6 to +6 deg across channel

A few ns error produces little signal loss
but tens of ns will kill fringes

Strategy: Set wide-ish singleband delay windows for searching,
then narrow them later if necessary for amplitude estimation

Fourfit again

Add sb_win statements to control file

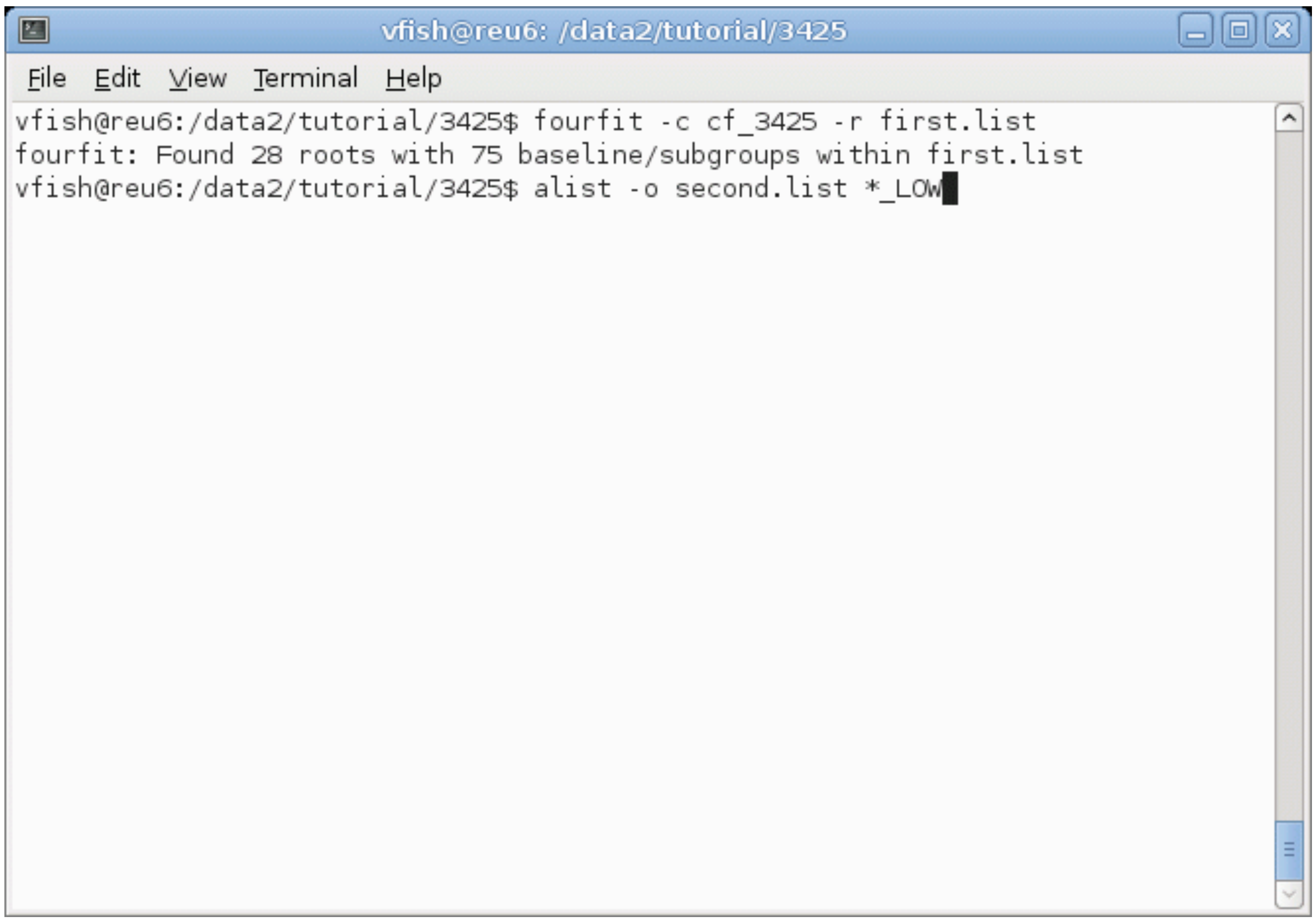
vfish@reu6: /data2/tutorial/3425

File Edit View Terminal Help

```
.7 115.7 135.8 151.4 -178.9 -128.0
if station F
pc_phases abcdefghijklmno 180 180 0 0 0 0 0 0 0 0 0 0 0 0 0
if station G
pc_phases abcdefghijklmno 180 180 0 0 0 0 0 0 0 0 0 0 0 0 0
if station S
pc_phases abcdefghijklmno 116.8 95.9 88.8 86.2 74.3 74.5 66.4 65.1 61.3 69.2 68.
2 81.7 87.7 107.0 157.4
if station T
pc_phases abcdefghijklmno -17.6 -26.8 -45.3 -46.3 -51.5 -66.1 -68.9 -72.8 -65.3
-71.5 -70.0 -57.5 -45.6 -20.0 25.4

if baseline PF
  sb_win -0.004  0.005

if baseline SF
  sb_win -0.012  0.002

if baseline TG
  sb_win -0.011  0.004

if baseline SP
  sb_win -0.012  0.002
vfish@reu6:/data2/tutorial/3425$
```

Fourfit again

Add sb_win statements to control file and run fourfit again

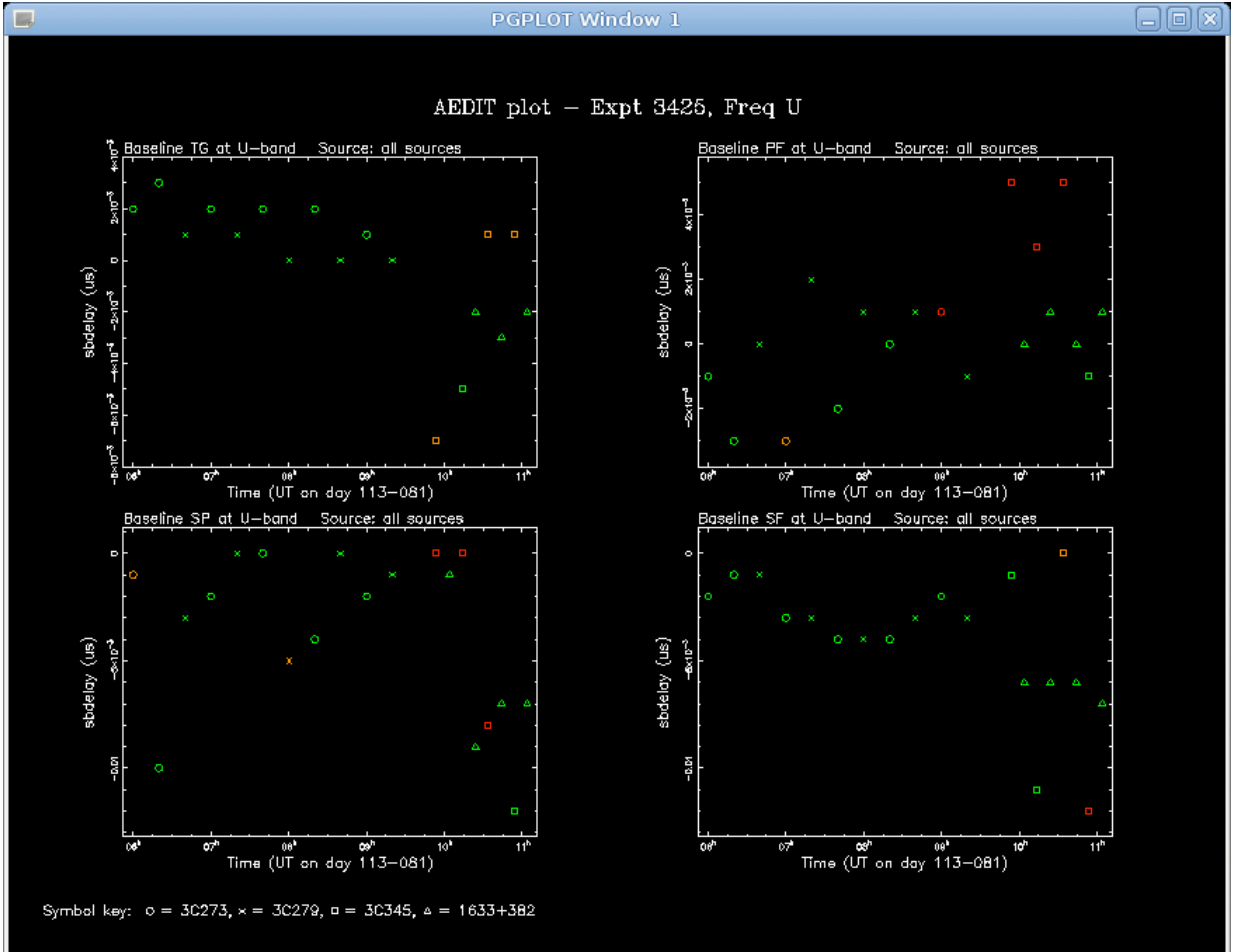


Fourfit again

Add sb_win statements to control file and run fourfit again using aedit to filter out old (unwindowed) scans

```
vfish@reu6: /data2/tutorial/3425
File  Edit  View  Terminal  Help
vfish@reu6:/data2/tutorial/3425$ aedit -f second.list
aedit:          AEDIT VERSION 5.0 --- JAN 2001


aedit: Reading data from file 'second.list' ...
aedit: Total space now occupied by data = 16834 Kb
aedit: Read 150 fringe records from second.list, total now 150
aedit> ed dup procdate
aedit:  Summary of editing on type-2 (fringe) data:
aedit:  New edits       Flag    Total   Remaining
aedit:  75              75      150     75
aedit:
aedit> write second.list
aedit: File exists and contains data.  Proceed? (y/n) : y
aedit: Wrote 75 fringe records successfully
aedit>
```

Fourfit again



Fourfit again

Separating out clear detections from questionable/nondetections

vfish@reu6: /data2/tutorial/3425

File Edit View Terminal Help

```
aedit> plot
 Graphics device/type (? to see list, default /xw):
aedit> snrmin 7.2
aedit> ed inp
aedit:  Summary of editing on type-2 (fringe) data:
aedit:  New edits        Flag    Total   Remaining
aedit:  20               20      75      55
aedit:
aedit> write second.dets
aedit: Wrote 55 fringe records successfully
aedit> snrmin
aedit> unflag snr
aedit: Type 2 (fringe) data:
aedit:  Restored         Flag    Total   Remaining
aedit:  20               0       75      75
aedit> snrmax 7.1999
aedit> ed inp
aedit:  Summary of editing on type-2 (fringe) data:
aedit:  New edits        Flag    Total   Remaining
aedit:  55               55      75      20
aedit:
aedit> write second.nondets
aedit: Wrote 20 fringe records successfully
aedit>
```

Coherence times

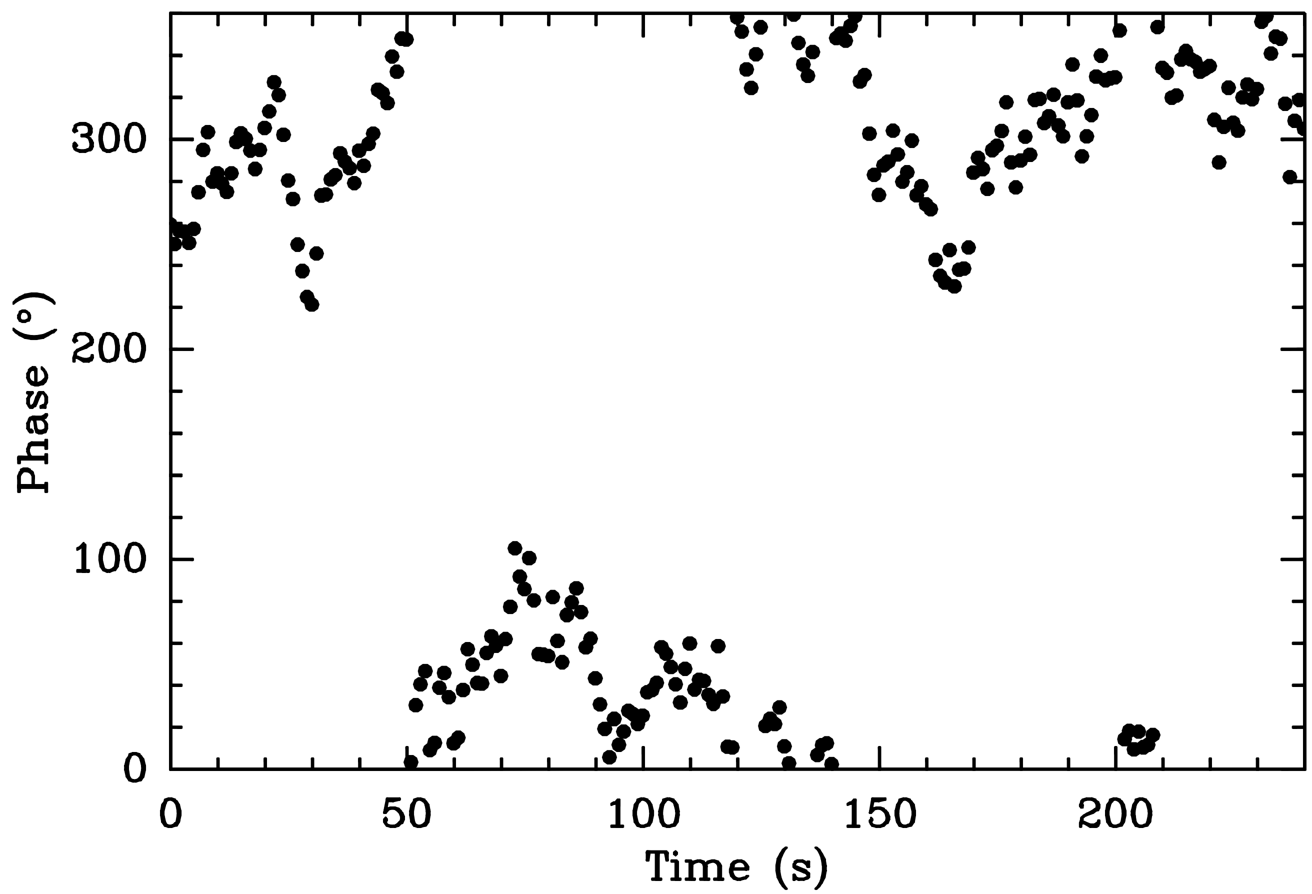
Atmosphere introduces time-variable phase noise, the amount of which varies with time and location

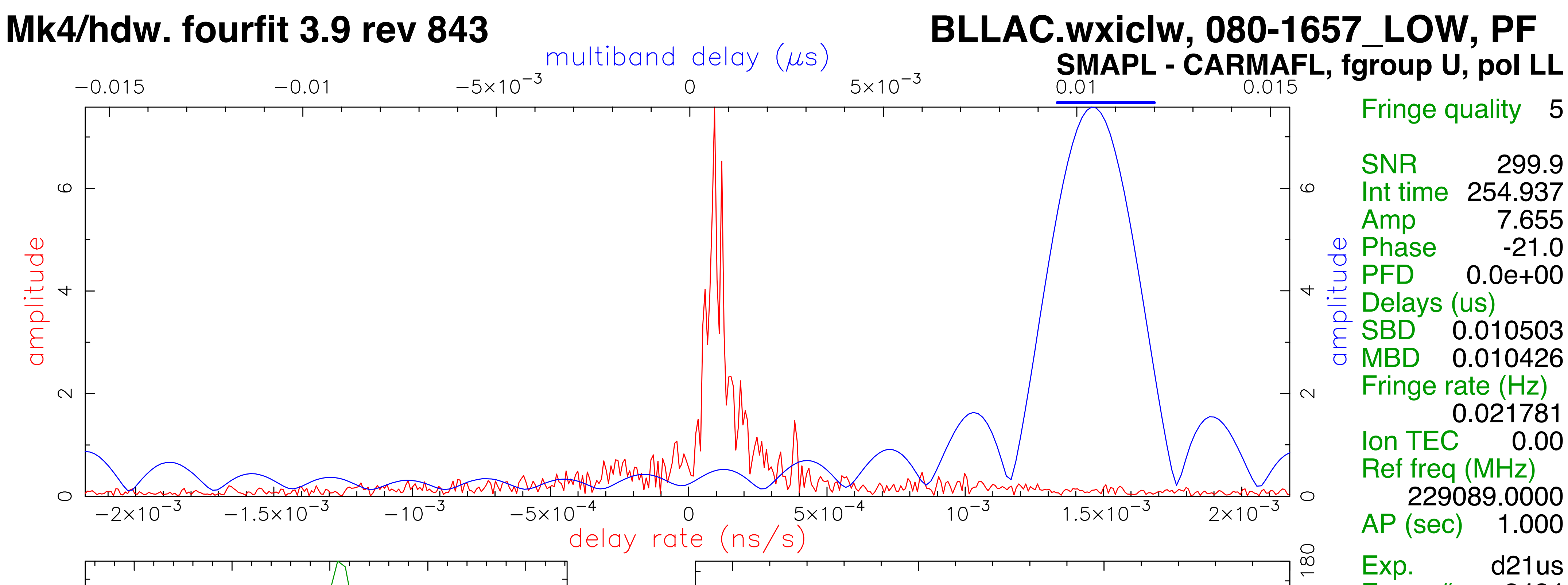
Vector averaging: S/N goes as $t^{1/2}$
Scalar averaging: S/N asymptotes to $t^{1/4}$

As the segment length increases, vector averaging is superior right up to the point that it isn't

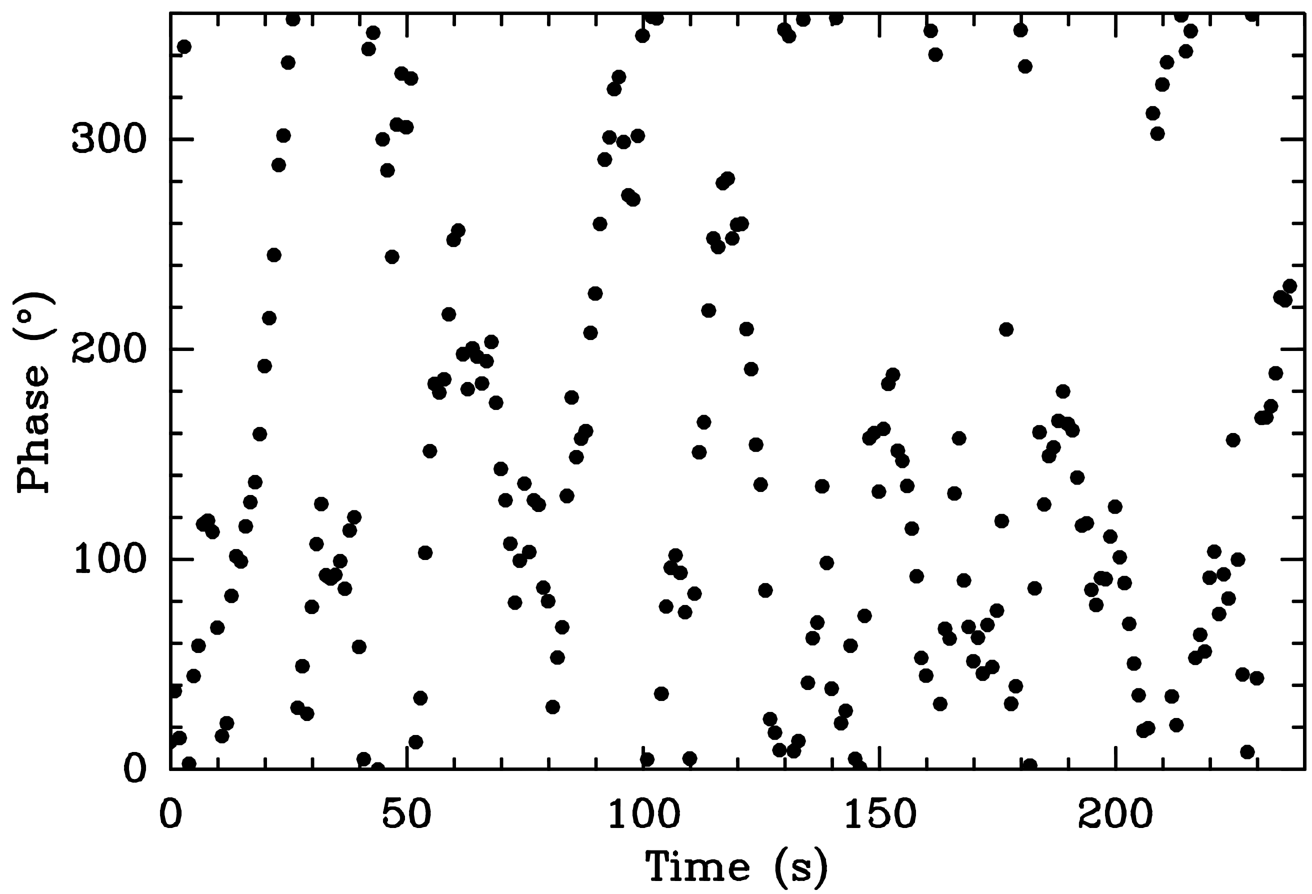
But what segment length is right?

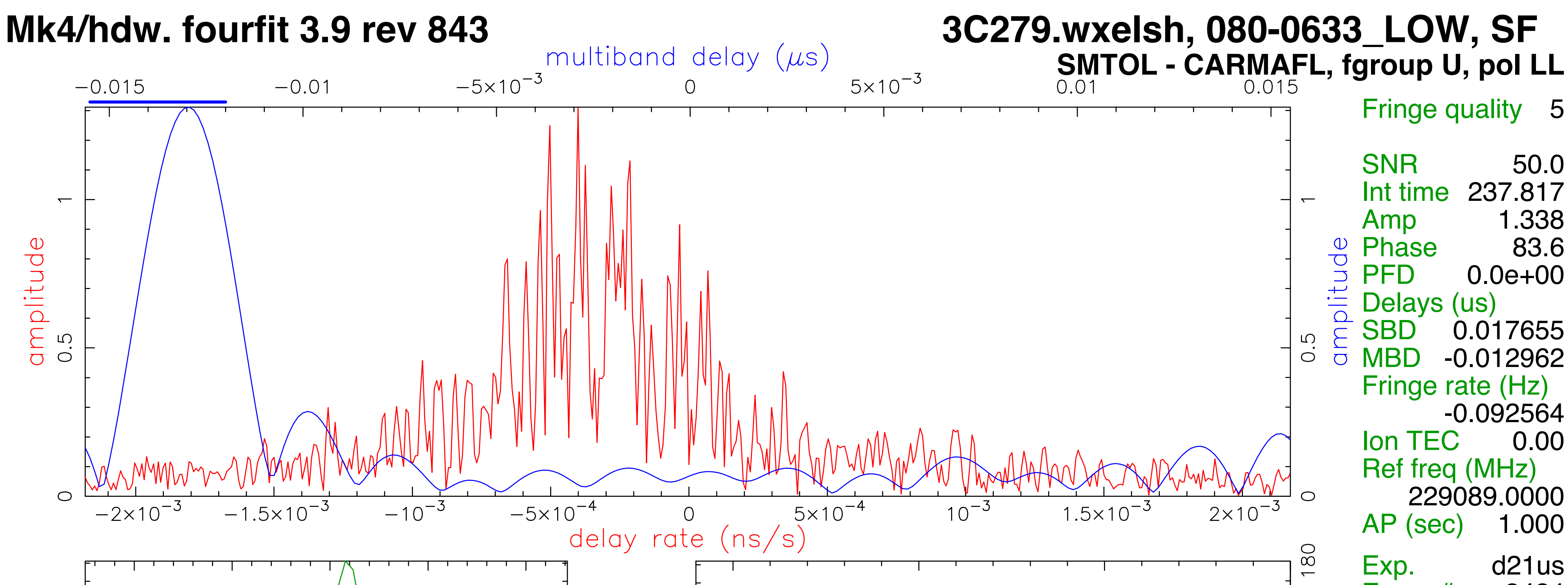
Coherence times





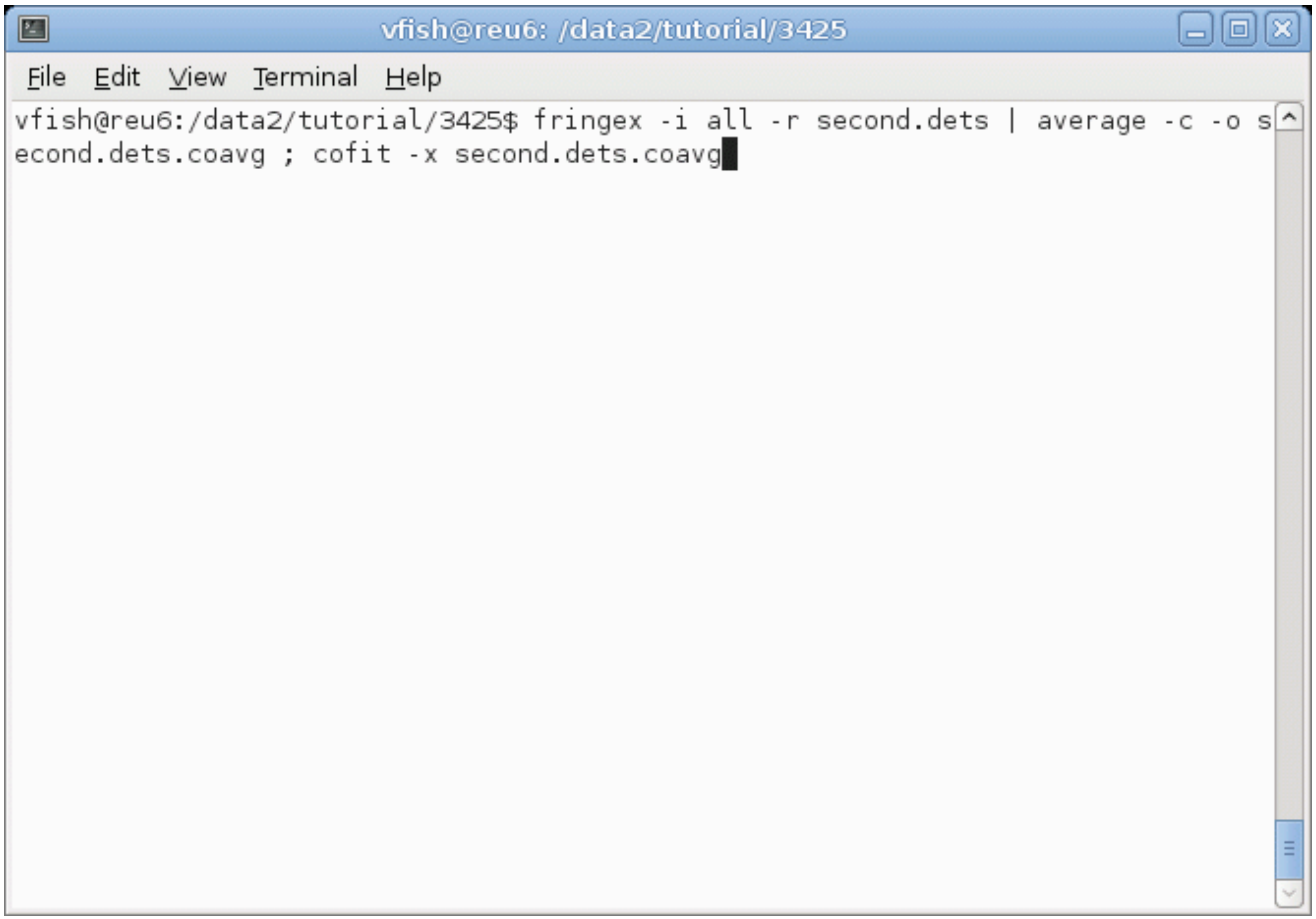
Coherence times



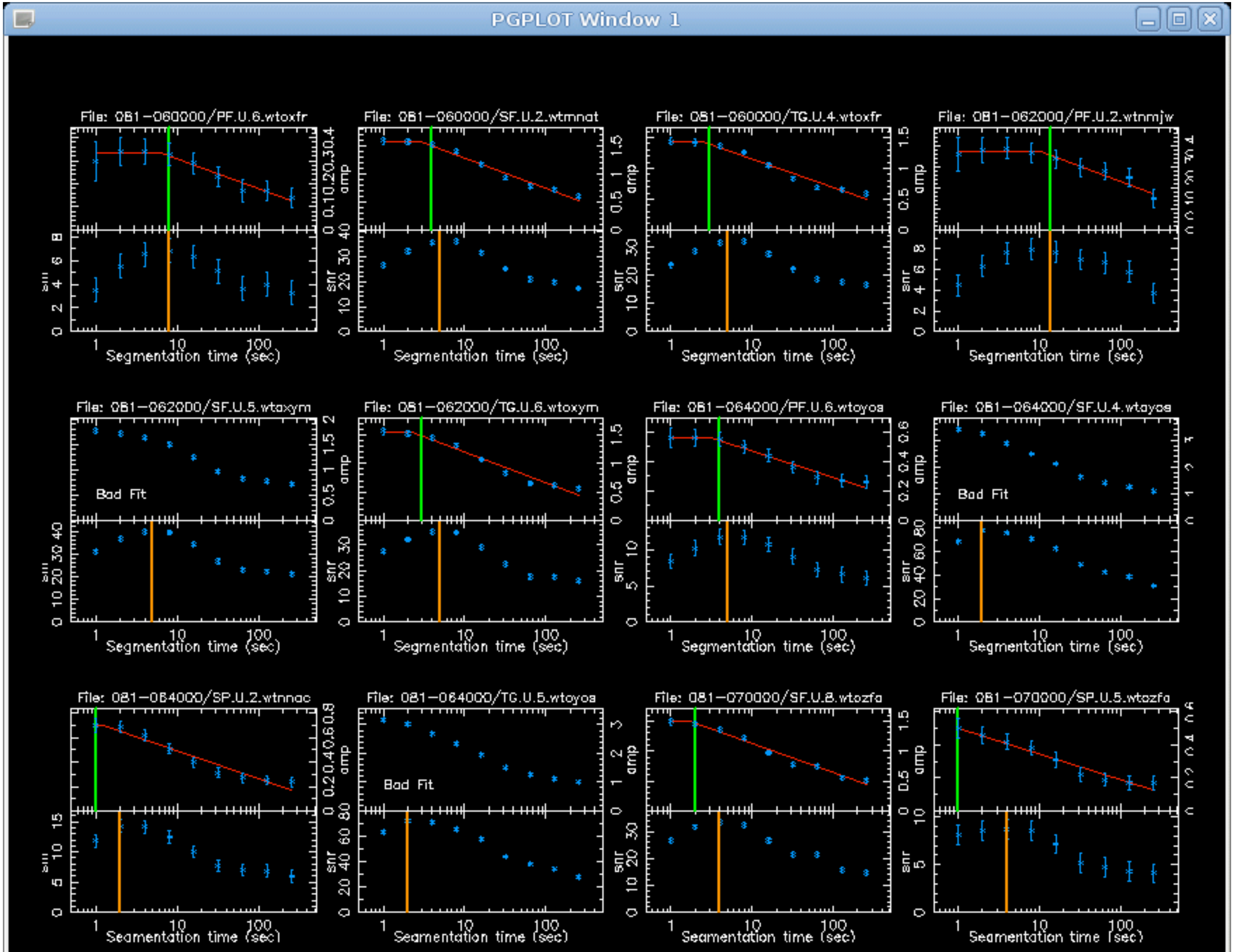


Coherence times

Segment data at a variety of times
Fit curves to amplitude and S/N



Coherence times



Incoherent fringe search

Coherent (vector-averaged) fringe fitting (i.e., fourfit) may fail to find fringes because atmospheric phase variations wash out the signal

Alternate strategy is to break data into segments and incoherently (amplitude-only) average the segments

Incoherent fringe search

Coherent (vector-averaged) fringe fitting (i.e., fourfit) may fail to find fringes because atmospheric phase variations wash out the signal

Alternate strategy is to break data into segments and incoherently (amplitude-only) average the segments

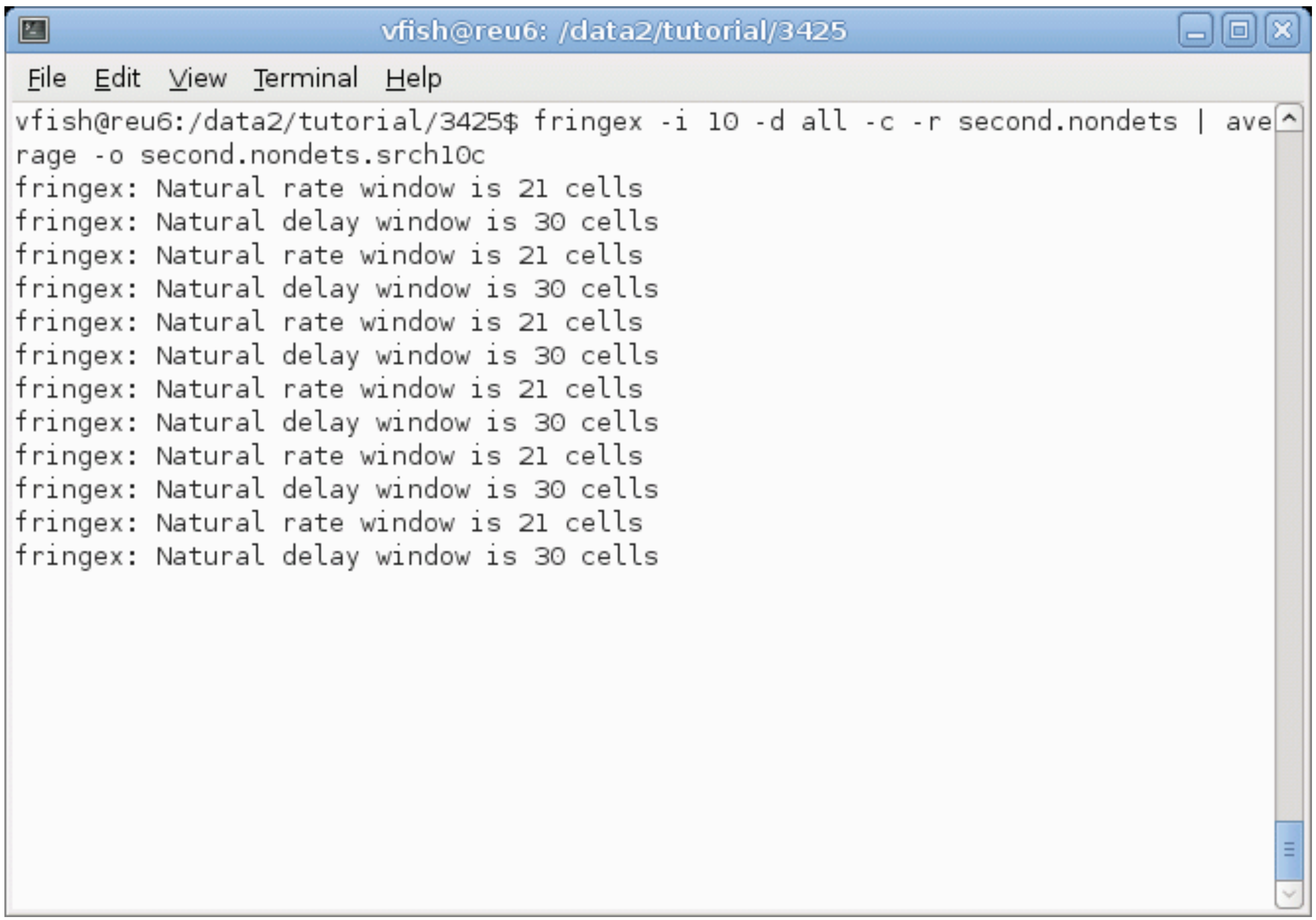
We can create a cube in multiband delay, rate, and time

If a fringe is there, it may show up weakly at the same location in multiband delay and rate

If we collapse the cube along the time axis, we may find fringes that fourfit has missed

Incoherent fringe search

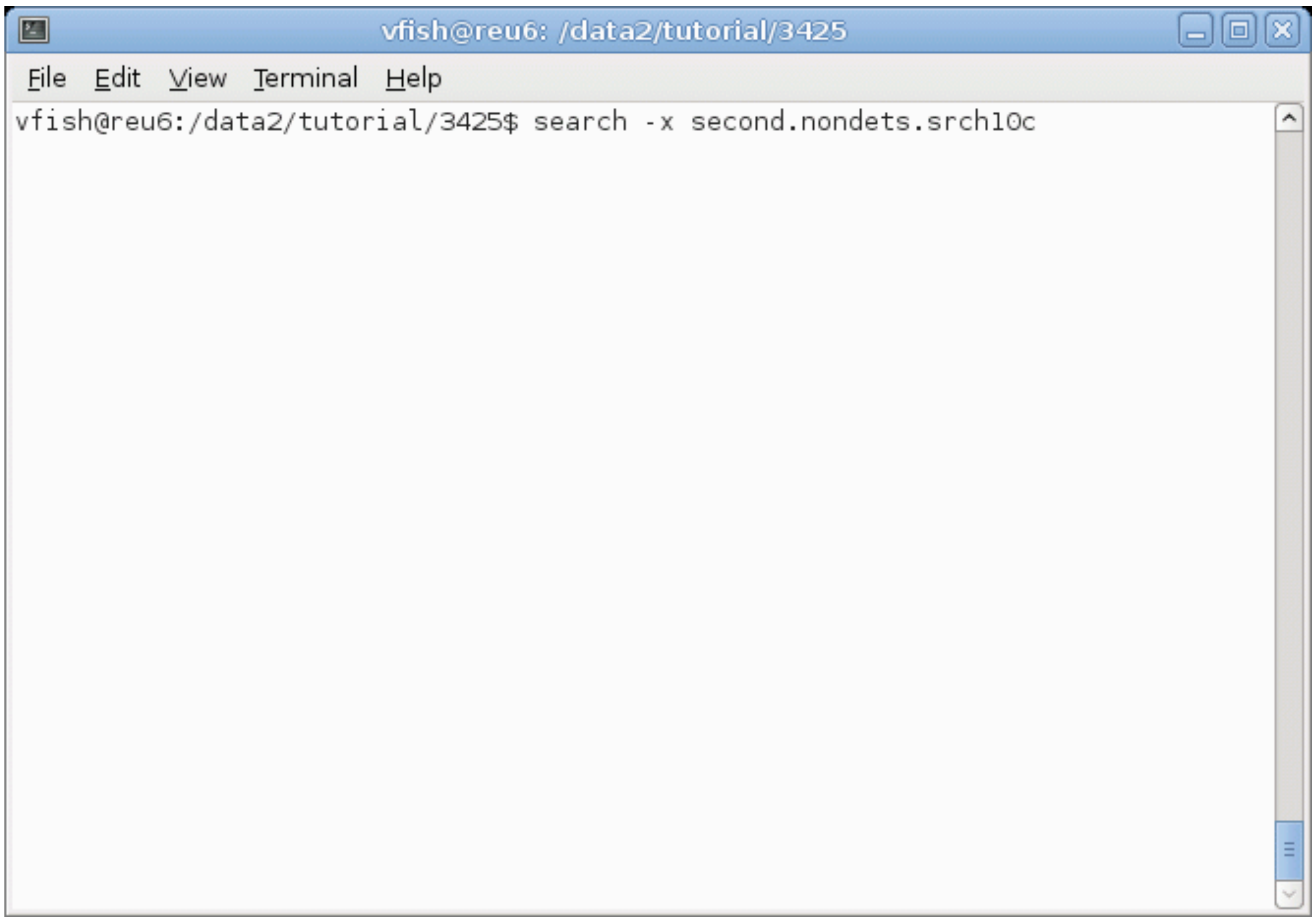
Create cubes (mbd,rate,time) and average along the time axis



Incoherent fringe search

Create cubes (mbd,rate,time) and average along the time axis

Look for peak in the mbd/rate plane



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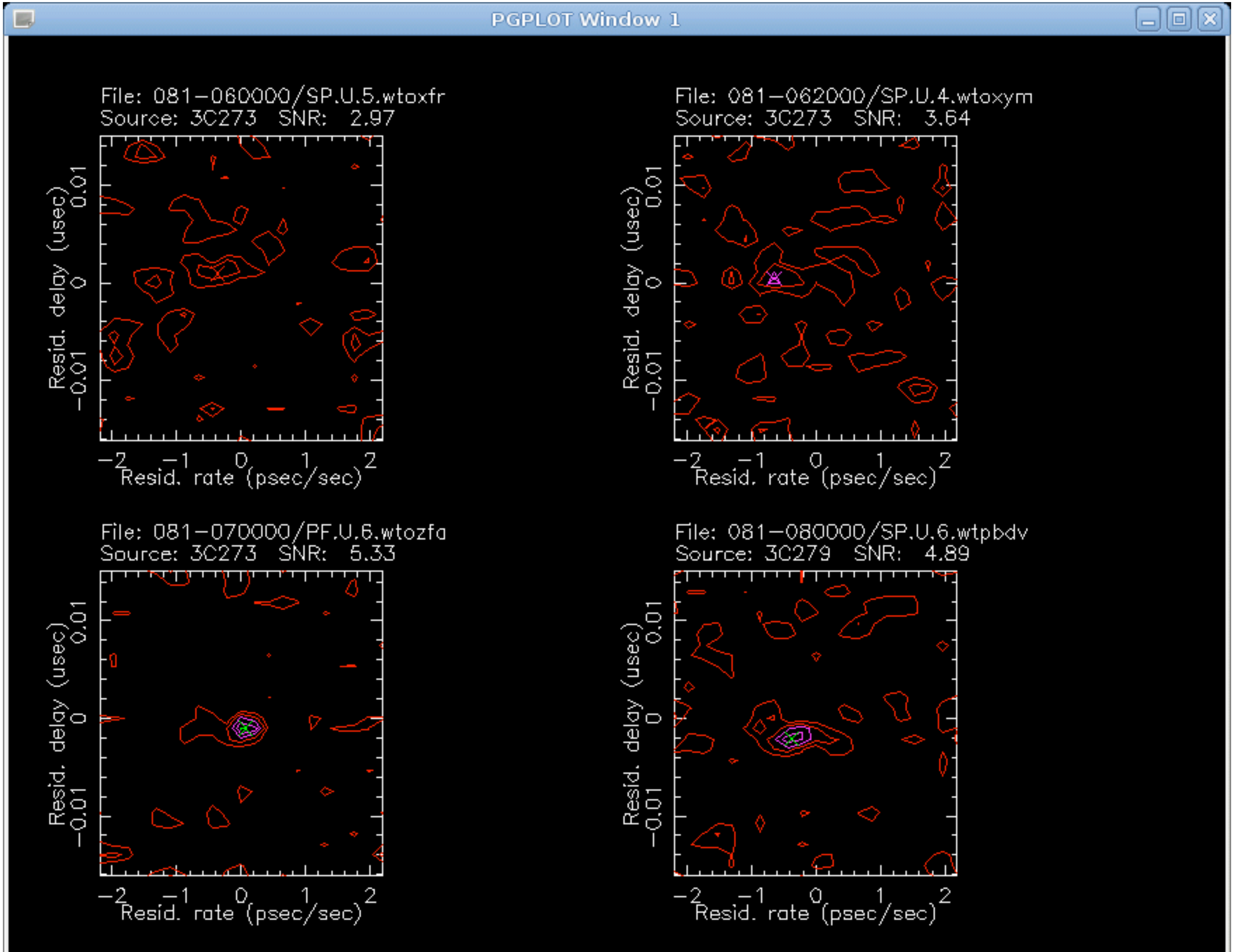

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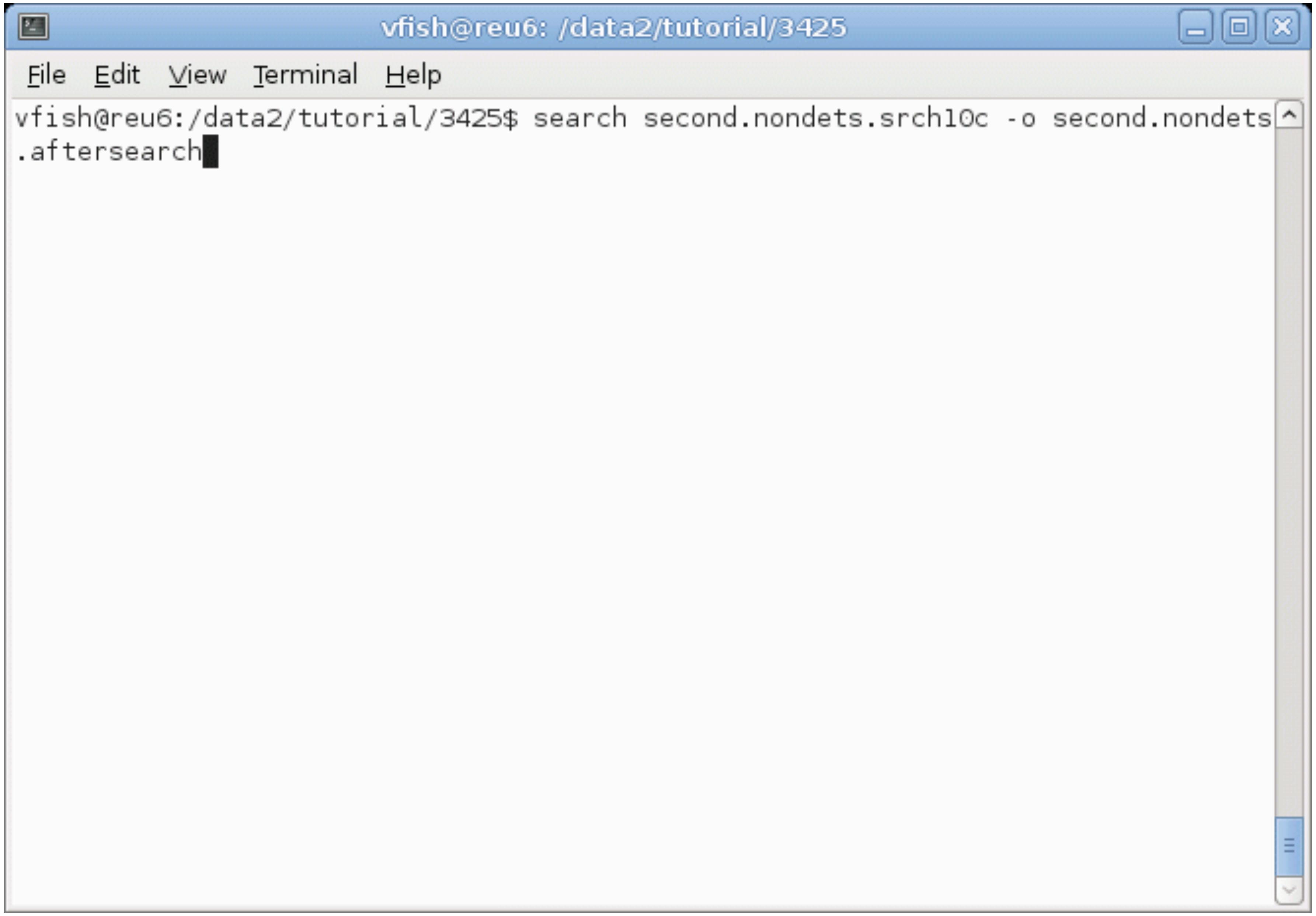
Search can create an A-list of these peak locations



Incoherent fringe search

Before

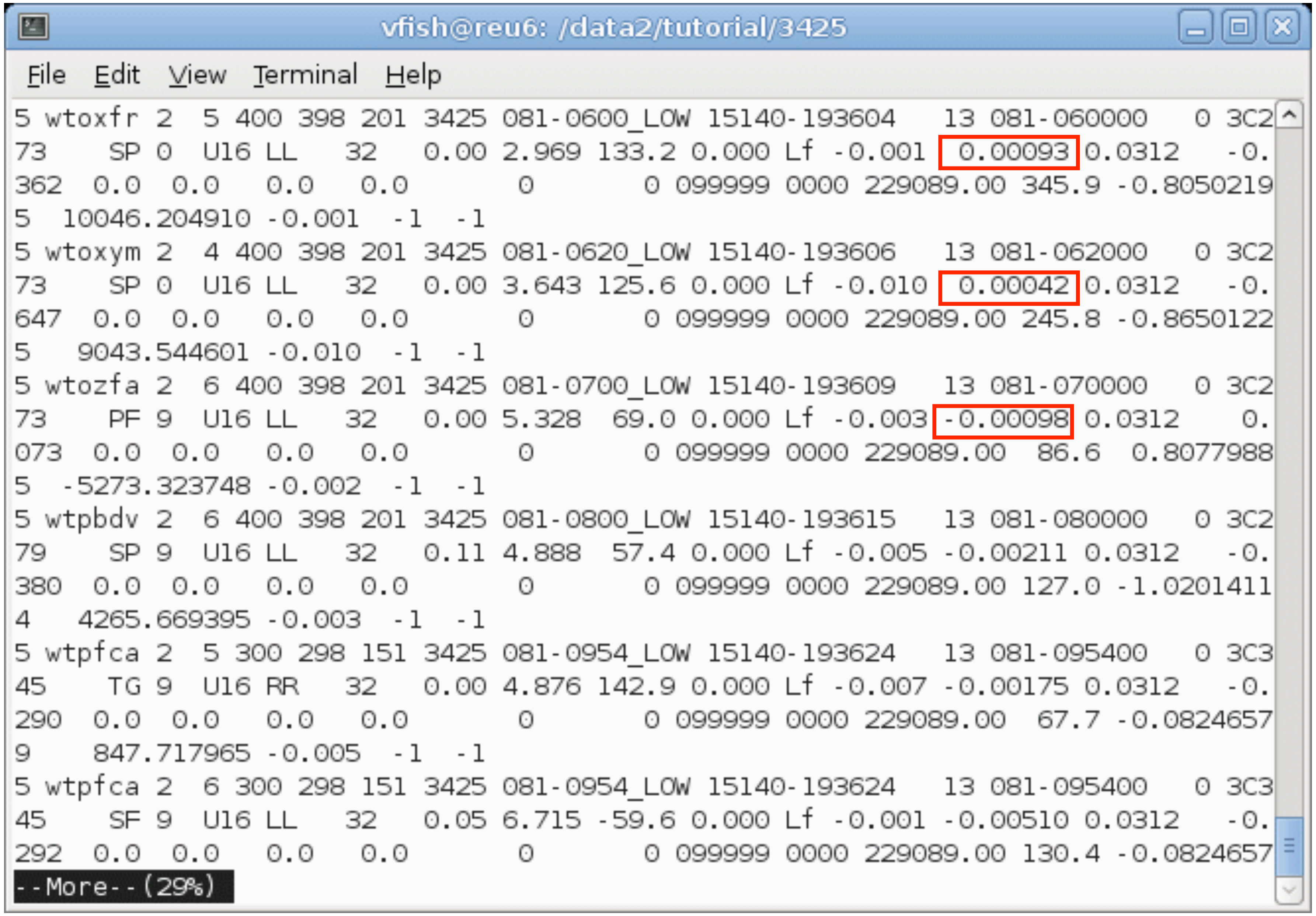
vfish@reu6: /data2/tutorial/3425

File Edit View Terminal Help

```
5 wtoxfr 2  5 400 398   0 3425 081-0600_LOW 15140-193604   13 081-060000   0 3C2
73     SP 0  U16 LL   32   0.11 5.549 271.8 0.000 Sf -0.001  0.00078 0.0312   -0.
396  0.0  0.0   0.0   0.0        0       0 099999 0320 229089.00 222.7 -0.8050219
5  10046.204910 -0.001  -1  -1
5 wtoxym 2  4 400 398   0 3425 081-0620_LOW 15140-193606   13 081-062000   0 3C2
73     SP 9  U16 LL   32   0.14 6.734 107.0 0.000 Sf -0.010  0.00013 0.0312   -0.
661  0.0  0.0   0.0   0.0        0       0 099999 2320 229089.00 246.2 -0.8650122
5   9043.544601 -0.010  -1  -1
5 wtozfa 2  6 400 398   0 3425 081-0700_LOW 15140-193609   13 081-070000   0 3C2
73     PF 0  U16 LL   32   0.12 5.978 266.9 0.000 Sf -0.003 -0.00081 0.0312    0.
100  0.0  0.0   0.0   0.0        0       0 099999 0320 229089.00 266.3  0.8077988
5  -5273.323748 -0.002  -1  -1
5 wtpbdv 2  6 400 398   0 3425 081-0800_LOW 15140-193615   13 081-080000   0 3C2
79     SP 0  U16 LL   32   0.12 5.723 256.3 0.000 Sf -0.005 -0.00175 0.0312   -0.
368  0.0  0.0   0.0   0.0        0       0 099999 0320 229089.00  62.6 -1.0201411
4   4265.669395 -0.003  -1  -1
5 wtpfca 2  5 300 298   0 3425 081-0954_LOW 15140-193624   13 081-095400   0 3C3
45     TG 0  U16 RR   32   0.15 6.351 344.1 0.000 Sf -0.007 -0.00172 0.0312   -0.
344  0.0  0.0   0.0   0.0        0       0 099999 5630 229089.00 105.3 -0.0824657
9    847.717965 -0.005  -1  -1
5 wtpfca 2  6 300 298   0 3425 081-0954_LOW 15140-193624   13 081-095400   0 3C3
45     SF 9  U16 LL   32   0.16 6.795  89.6 0.000 Sf -0.001 -0.00510 0.0312   -0.
308  0.0  0.0   0.0   0.0        0       0 099999 5630 229089.00 256.0 -0.0824657
--More--
```

Incoherent fringe search

After



vfish@reu6: /data2/tutorial/3425

File Edit View Terminal Help

```
5 wtoxfr 2  5 400 398 201 3425 081-0600_LOW 15140-193604   13 081-060000   0 3C2
73    SP 0  U16 LL    32    0.00 2.969 133.2 0.000 Lf -0.001  0.00093 0.0312   -0.
362  0.0  0.0   0.0   0.0        0        0 099999 0000 229089.00 345.9 -0.8050219
5  10046.204910 -0.001  -1  -1
5 wtoxym 2  4 400 398 201 3425 081-0620_LOW 15140-193606   13 081-062000   0 3C2
73    SP 0  U16 LL    32    0.00 3.643 125.6 0.000 Lf -0.010  0.00042 0.0312   -0.
647  0.0  0.0   0.0   0.0        0        0 099999 0000 229089.00 245.8 -0.8650122
5   9043.544601 -0.010  -1  -1
5 wtozfa 2  6 400 398 201 3425 081-0700_LOW 15140-193609   13 081-070000   0 3C2
73    PF 9  U16 LL    32    0.00 5.328  69.0 0.000 Lf -0.003 -0.00098 0.0312    0.
073  0.0  0.0   0.0   0.0        0        0 099999 0000 229089.00  86.6  0.8077988
5  -5273.323748 -0.002  -1  -1
5 wtpbdv 2  6 400 398 201 3425 081-0800_LOW 15140-193615   13 081-080000   0 3C2
79    SP 9  U16 LL    32    0.11 4.888  57.4 0.000 Lf -0.005 -0.00211 0.0312   -0.
380  0.0  0.0   0.0   0.0        0        0 099999 0000 229089.00 127.0 -1.0201411
4   4265.669395 -0.003  -1  -1
5 wtpfca 2  5 300 298 151 3425 081-0954_LOW 15140-193624   13 081-095400   0 3C3
45    TG 9  U16 RR    32    0.00 4.876 142.9 0.000 Lf -0.007 -0.00175 0.0312   -0.
290  0.0  0.0   0.0   0.0        0        0 099999 0000 229089.00  67.7 -0.0824657
9    847.717965 -0.005  -1  -1
5 wtpfca 2  6 300 298 151 3425 081-0954_LOW 15140-193624   13 081-095400   0 3C3
45    SF 9  U16 LL    32    0.05 6.715 -59.6 0.000 Lf -0.001 -0.00510 0.0312   -0.
292  0.0  0.0   0.0   0.0        0        0 099999 0000 229089.00 130.4 -0.0824657
--More--(29%)
```

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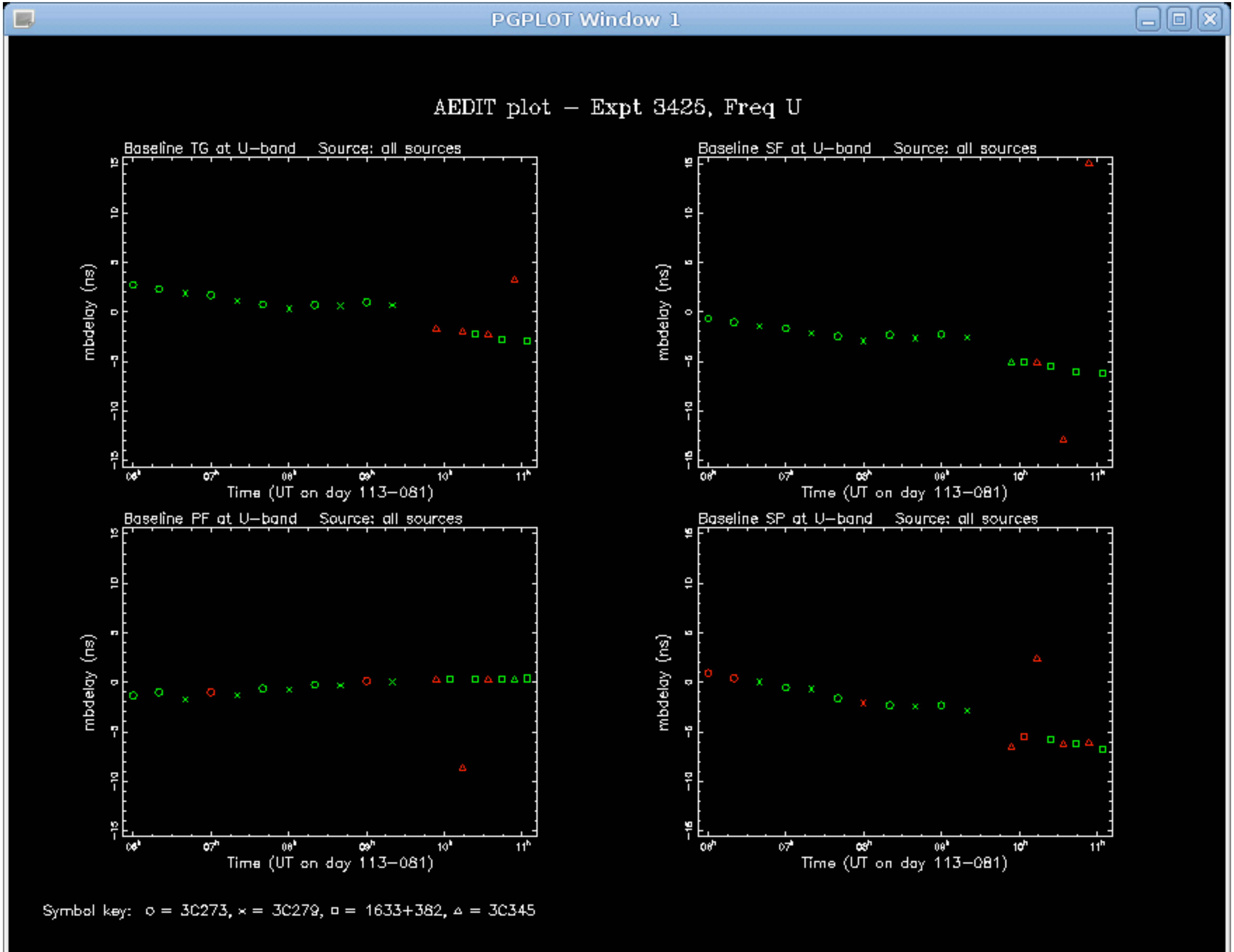

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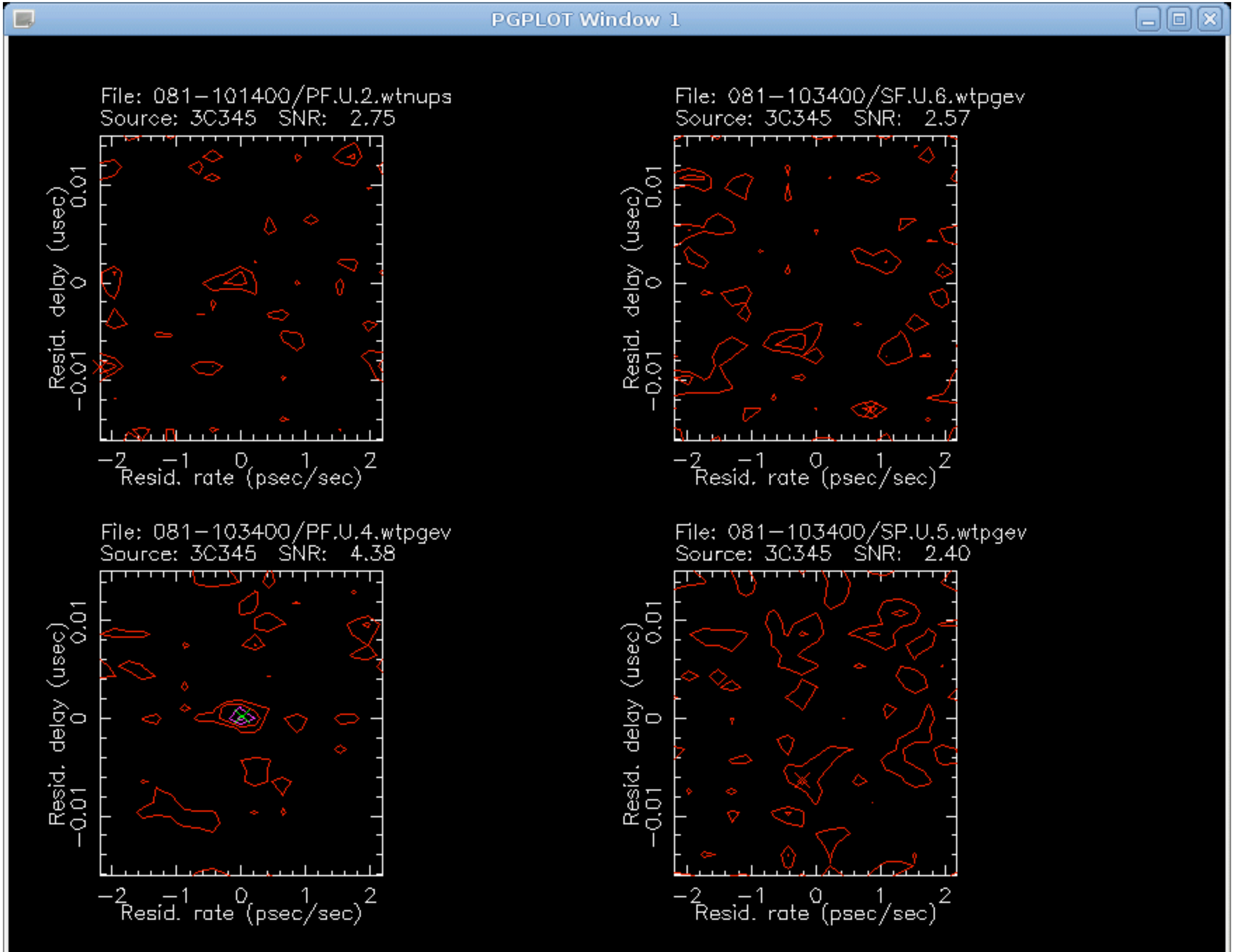

Phase calibration

If we have prior phase information, we would like to apply it to improve coherence and S/N

Some stations in the future may have partial phase information from WVRs

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Self-calibration is another common technique to improve S/N in interferometry

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Limitation: Absolute phase information is lost
(but atmospheric phase contribution is so large we never had it to begin with!)

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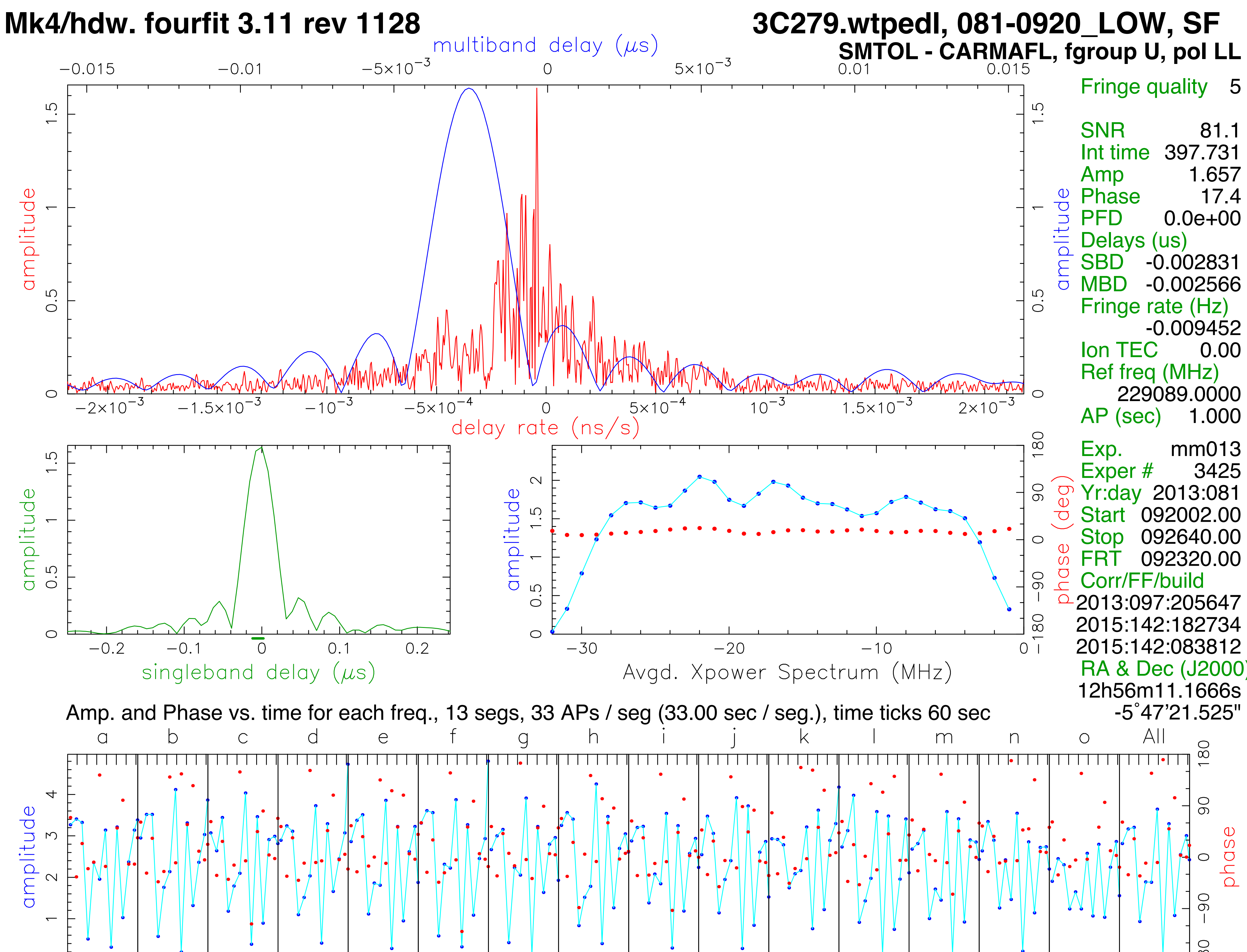
Unlike most other interferometry packages, HOPS is built around baselines instead of stations

Still, we can determine phase information from the data and apply this “ad hoc” phase information in fourfit to extend coherence

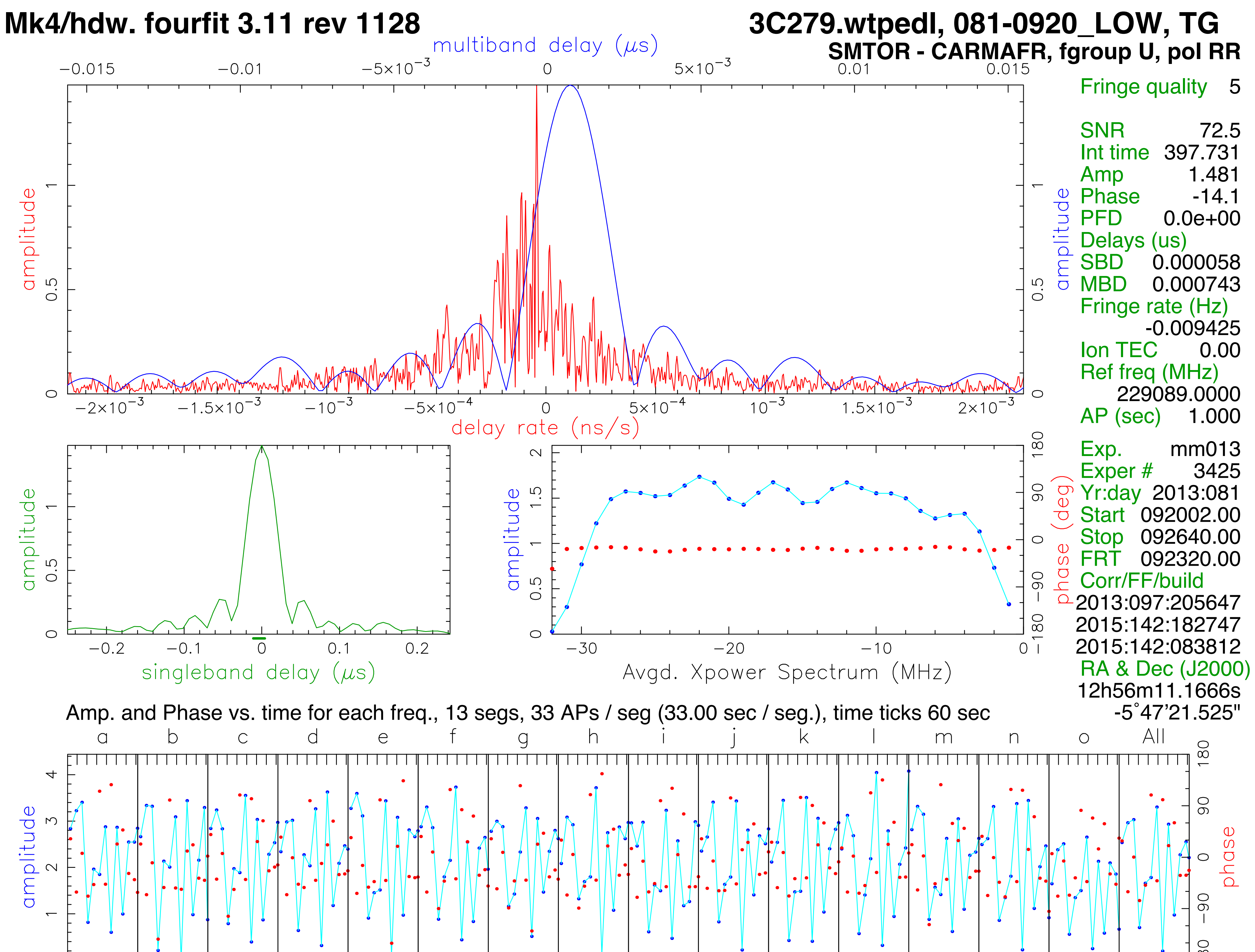
Example: Polarization

LL



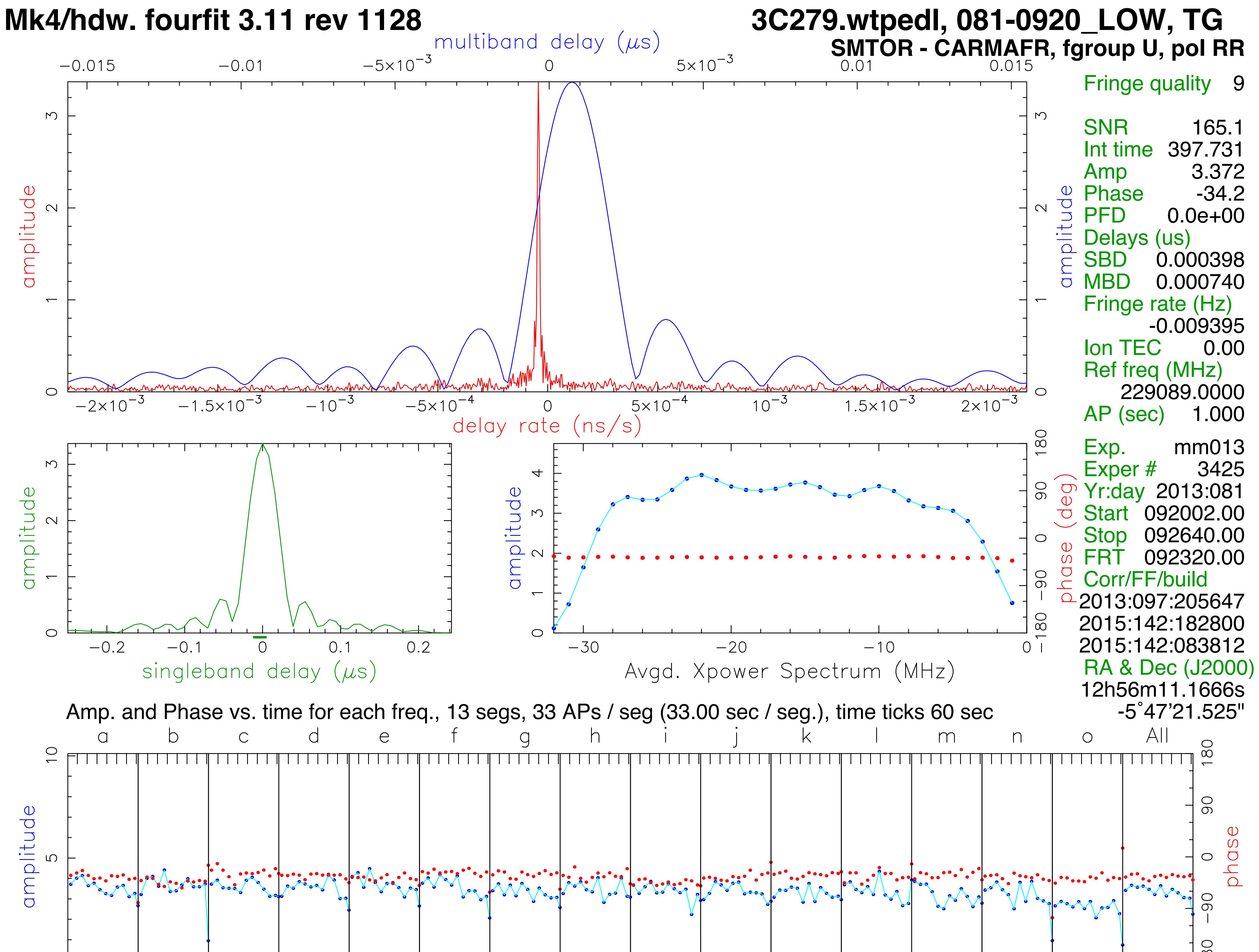
Example: Polarization

RR without ad hoc phases



Example: Polarization

RR with ad hoc phases



Ad hoc phases

Common uses:

- Applying phases from one polarization to the other
- Applying phases from one frequency band to an adjacent band
- Applying phases from two legs of a triangle to the third leg

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Cadence of ad hoc phases must be chosen carefully

- Long enough to build enough S/N to be useful
- Short enough to capture most of the atmospheric phase variation
- If derived from weak scans, there may be no good cadence
  - (i.e., ad hoc phases can make things worse!)

Look at the data

Aside from nondetections, are there any obvious problems?

- Late-to-source or missed scans (should be in scan logs, but...)
- Corrupted data
- Unexplained oddities in the data

Refining fringe solutions

We have found lots of fringes, but it can be worth going back and starting over

Lots of options:

- Use tighter windows based on ensemble of solutions and/or delay closure (AB+BC+CA = 0)
- Fix singleband delay to multiband delay if offset is zero (usually true, but not always)
- Search incoherently with different segment lengths
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These items are analogous to AIPS processing:

- Delay closure is automatic (since solutions are station-based)
- Can fit one delay or one per channel in FRING/KRING
- Can adjust SOLINT (though averaging is coherent)
- Can copy SN table from one polarization/IF/station to another
- Can set BIF/EIF, BCHAN/ECHAN

So you've found your fringes. Now what?

Correlation coefficients

- Steer to fringe location, segment data, and average the baseline data
- Short segment lengths are preferable to minimize coherence losses
- The task "average" does noise debiasing (but not perfect in low-S/N regime)

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  - Use ad hoc phases carefully so as not to bias amplitudes

And now the fun begins

Correlation coefficients must be converted to Jy

Polarimetric calibration required to utilize polarimetric ratios

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Models, imaging, etc.

Science!

Papers