MIT
HAYSTACK
OBSERVATORY

Post-correlation Processing

VGOS Correlation Workshop

MIT Haystack Observatory

May 9, 2019

Outline

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- Overview
- Nominal data
- Pre-pass and first look at correlator output
- Channel-by-channel phase corrections
- Y-X polarization phase/delay offsets
- Pseudo Stokes-I fringe-fitting and output

Data processing overview

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- Objective is an accurate broadband delay.
- To get this we need to correlate and perform fringe-fitting of both polarizations and all four bands together.
- The broadband delay solution is determined through pseudo Stokes-I fringe-fitting.
- Pseudo Stokes-I polarization product is the coherent sum [1]:

$$I = (\overline{X_a \star X_b} + \overline{Y_a \star Y_b}) \cos(\Delta) + (\overline{X_a \star Y_b} - \overline{Y_a \star X_b}) \sin(\Delta) \quad (1)$$

- This produces an observable which is *independent* of the parallactic angle difference, Δ, and (to 1st order) polarization leakage terms.
- However, to do this we need to know relative phase and delay between the X and Y signal path at each station.
- We also need to simultaneously fit for differential ionosphere, ΔTEC.

[1] https://ivscc.gsfc.nasa.gov/publications/memos/ivs-2007-011v01.pdf

Nominal input

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Some assumptions about the data in the following discussion:

- No large chunks of missing time from any of the stations.
- No missing bands or polarizations from any of the stations.
- All stations have phase-cal.
- No clock jumps.
- No additional hardware issues (warm-receiver, pointing-problems, failed disk on data module, etc.)
- Network wide phase/delay reference-station OK.

The list above is not comprehensive and most problems are not insurmountable, but they do complicate the processing, so we will leave further discussion for later.

Pre-pass

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- Good idea to do an initial fringe-fitting pass over experiment data with initial (a-priori) control file
- Helps catch issues in the data, and provide information to improve correlation.
- Inspect data with fourfit, alist, aedit.

Minimal VGOS fourfit control file

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- Some basic information has to be specified in the control file which is not normally present in SX experiment control files.
- Basic information does not typically change between sessions.

```
dr_win -5.e-6 5.e-6       *specify delay rate window
pc_mode multitone         *specify that phase-cal will be given as multi-tone data
pc_period 1               *integration period for phase-cal tones
ion_smooth true           *smooth the dTEC fit function to avoid spurious peaks
mbd_anchor sbd            *use single-band delay to guide multi-band delay fit
samplers 4 abcdefgh ijklmnop qrstuvwx yzABCDEF    *group channels of each sampler
ref_freq 6000.0           *specify the reference frequency
weak_channel 0.1          *lower the weak channel G code threshold
pc_amp_hcode .001         *lower the phase-cal amplitude for H codes
ion_npts 45               *set number of coarse dTEC evaulation points
ion_win -88.0 88.0        *set wide search window for dTEC
```

- Also necessary: `sampler_delay_x/y`
- Highly desirable: `pc_tonemask`
- Must be augmented further before pseudo Stokes-I fringe fitting can be done.

VGOS fringe plot

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Features of interest:

- Fringe plots of individual polarization-products (XX,YY,XY,YX) or pseudo Stokes-I (Ixy).
- Basic information, SNR, Q-code, etc.
- Single-band and multi-band delay function plots
- dTEC plot
- Channel-by-channel phase/amplitude behavior
- Phase-cal information
- Parallactic angle

VGOS fringe plot

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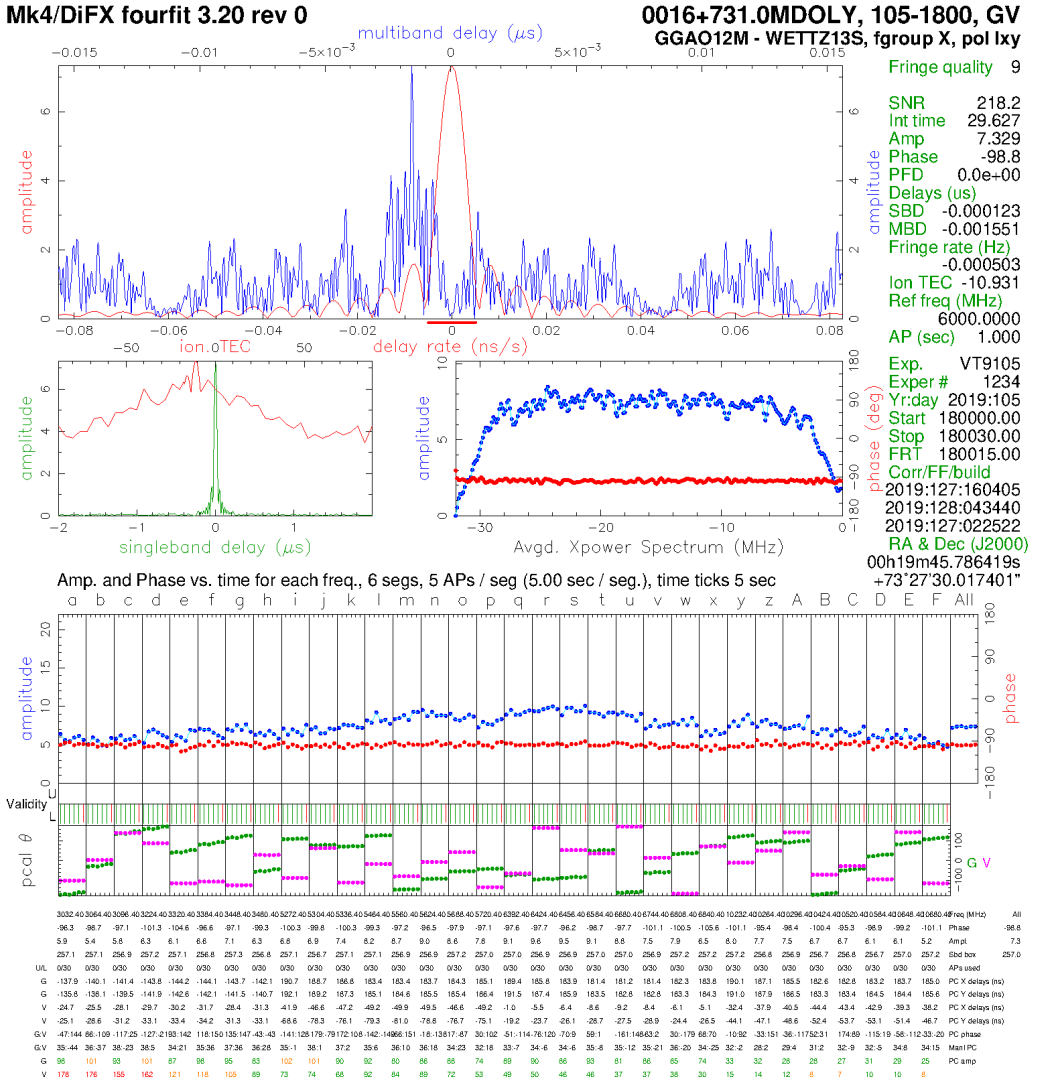

Group delay (usec)(sbd)	3.54046686604E+03	Apriori delay (usec)	3.54046841676E+03	Resid mbdelay (usec)	-1.55072E-03	+/-	7.6E-07
Sband delay (usec)	3.54046829426E+03	Apriori clock (usec)	8.2615646E+01	Resid sbdelay (usec)	-1.22500E-04	+/-	7.9E-05
Phase delay (usec)	3.54046837104E+03	Apriori clockrate (us/s)	9.4300002E-07	Resid phdelay (usec)	-4.57187E-05	+/-	2.4E-07
Delay rate (us/s)	6.66396359390E-02	Apriori rate (us/s)	6.66397197723E-02	Resid rate (us/s)	-8.38333E-08	+/-	1.4E-08
Total phase (deg)	81.4	Apriori accel (us/s/s)	-3.212066529 82E-05	Resid phase (deg)	-98.8	+/-	1.8

	RMS	Theor.	Amplitude	7.329 +/- 0.034
ph/seg (deg)	0.9	0.6	Search (64X1024)	7.297
amp/seg (%)	1.0	1.1	Interp.	0.000
ph/frq (deg)	2.4	1.5	Inc. seg. avg.	7.329
amp/frq (%)	16.9	2.6	Inc. frq. avg.	7.332

Pcal mode: MULTITONE, MULTITONE PC period (AP's) 1, 1 dTEC +/- 0.019
Pcal rate: 0.000E+00, 0.000E+00 (us/s) sb window (us) -1.000 1.000
Bits/sample: 2x2 SampCntNorm: disabled mb window (us) -0.016 0.016
Sample rate(MSamp/s): 64 dr window (ns/s) -0.005 0.005
Data rate(Mb/s): 8192 nlags: 256 t_cohere infinite ion window (TEC) -88.00 88.00

G: az 346.0 el 52.3 pa 138.6 V: az 341.9 el 39.0 pa 46.4 u,v (fr/asec) -94.299 -617.642 simultaneous interpolate

Control file: ./cf_1234_GEHSVY_pstokes Input file: /media/barrettj/data/geodesy/tow2019/1234/105-1800//GV..0MDOLY Output file: Suppressed by test mode
Samplers: abcdefgh ijklmnop qrstuvwx yzABCDEF

Channel-by-channel phase corrections

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- Why do we need them?
- How to we estimate them?
- Running the script ffres2pcp.py
- Data quality check

Channel-by-channel phase corrections

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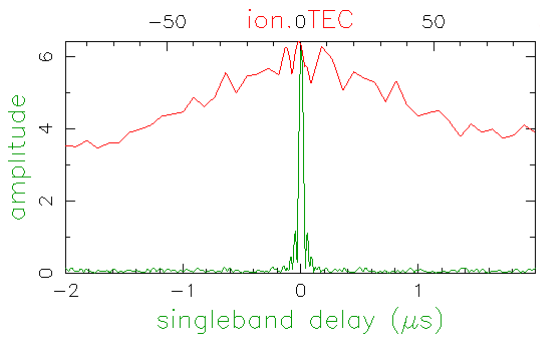
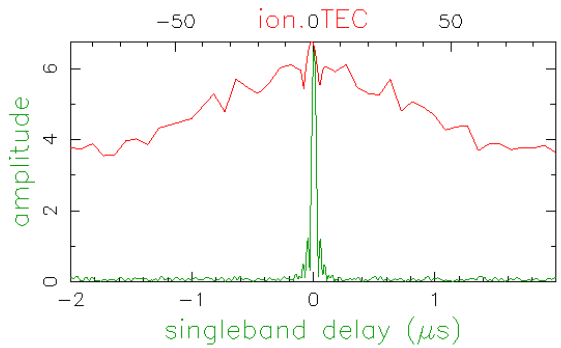
- Multi-tone p-cal only removes phase/delay changes in signal chain after point of introduction.
- Stations still require manual phase corrections to eliminate uncalibrated phase structure.
- Correction of phase residuals helps eliminate degenerate ΔTEC solutions.



Ionosphere ΔTEC search space on GY baseline without manual phase corrections.



Ionosphere ΔTEC search space on GY baseline with manual phase corrections.

- Multi-peak ΔTEC solutions are especially problematic for pseudo Stokes-I fringe fitting if different polarization product (e.g. XX vs. YY) fits happen to fall at different values since ΔTEC is highly correlated with the delay solution.

Channel-by-channel phase corrections

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- Construct initial control file (usually informed from last session).
- Pick a network reference station, (for consistency nearly always use GGAO X-polarization).
- Fringe fit all baselines to reference station with initial control file for all four pol-products (XX,YY,XY,YX).
- Select candidate scans for each baseline.
  - Apply cuts based on SNR, typically require > 30.
  - Apply cuts based on the difference in ΔTEC between the four pol-products (XX,YY,XY,YX), typically require < 1.0 TECU.
- Use circular mean of channel phase residuals to determine the channel-by-channel phase corrections `pc_phases_x/y`.
- Assume phase closure over pol-products to calculate phase corrections for network reference station Y-pol w.r.t X-pol.
- Output new control file with appropriate `pc_phases_x/y`.

Using ffres2pcp.py

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- Script to generate channel-by-channel phase corrections, options documented with –help.
- Requires initial control file.
- Specify the network reference station, and additional stations for which to generate corrections.
- Experiment directory only needs to contain Mk4, (ovex) root files, type-1, and type-3 data.

```
ffres2pcp.py ./cf_3659_firstpass G HEVI ./3659/
```

- Will generate a report .json file which can be use to generate some diagnostic plots.
- Run `summarize_report.py <ffres2pcp-report-file>` to produce summary plots and text info.

Example station phase corrections

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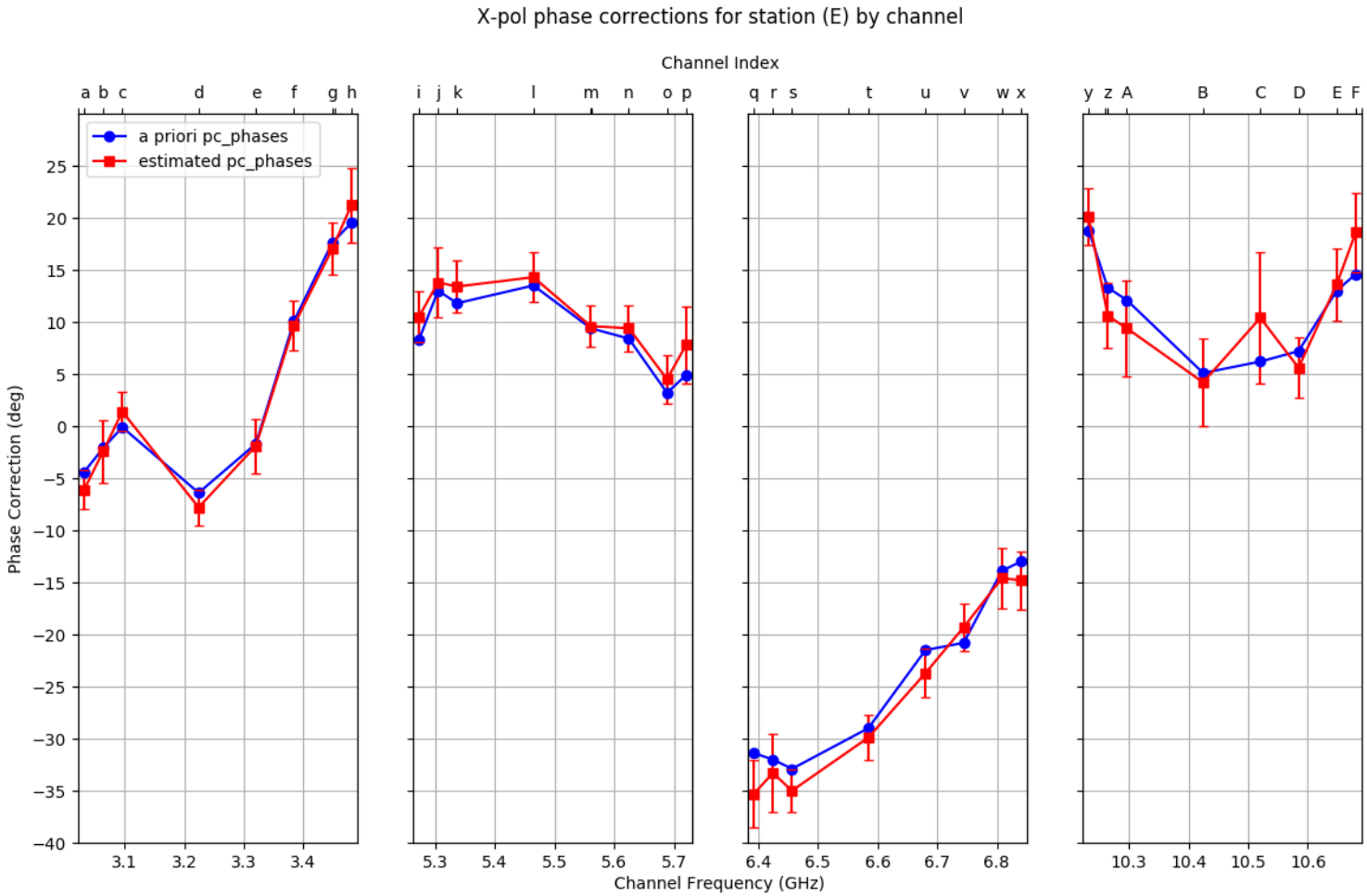

Station E (Wf) phase corrections for X polarization vs. frequency for the four bands. Blue is a priori estimate, red is value derived from session vt8218.

Example station phase corrections

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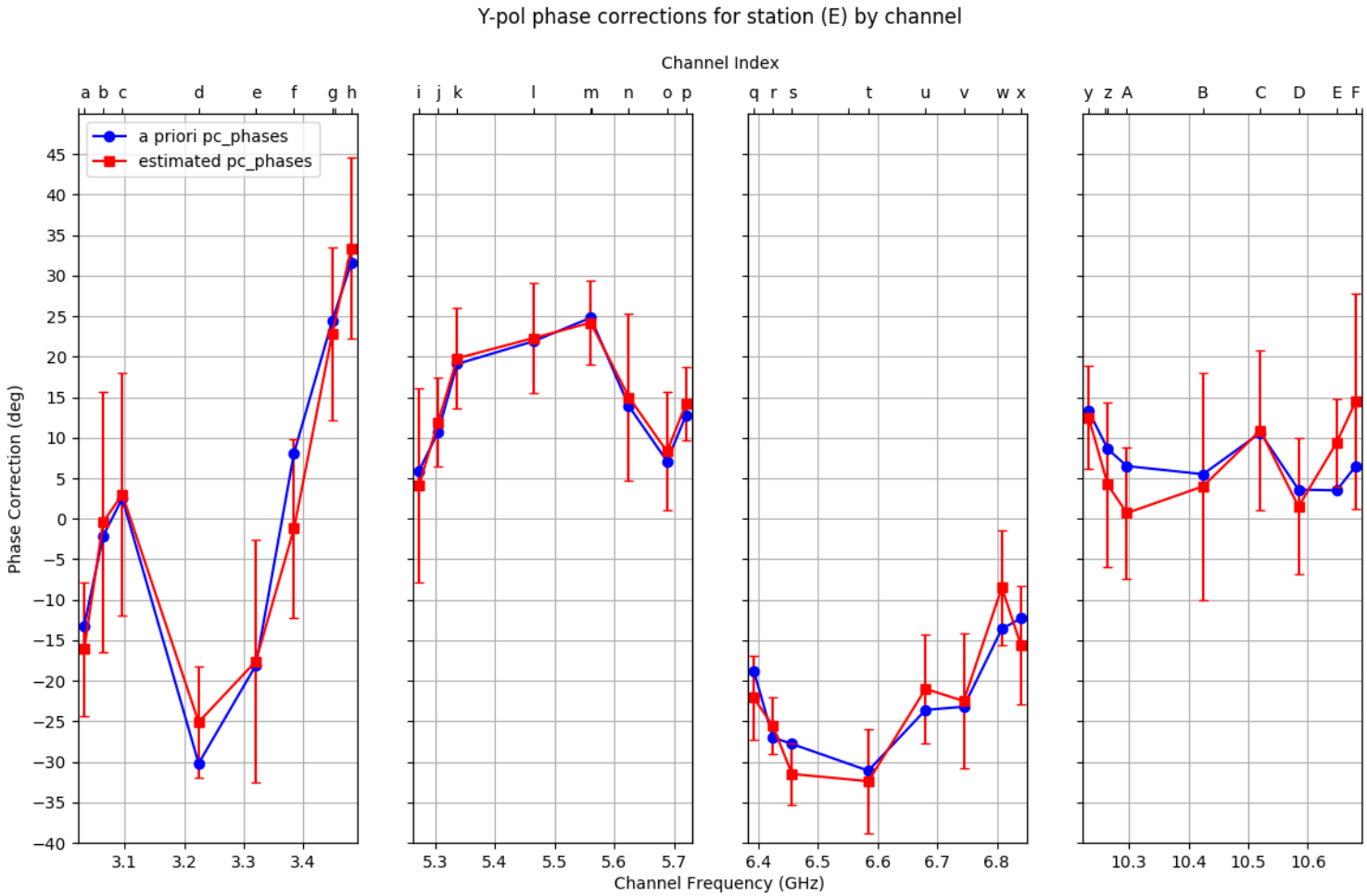

Station E (Wf) phase corrections for Y polarization vs frequency for the four bands. Blue is a priori estimate, red is value derived from session vt8218.

Estimation of Y-X polarization phase/delay offsets

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- Why do we need them?
- How do we estimate them?
- Running the script fourphase.py
- Data quality check

Y-X polarization phase/delay offsets

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- Re-fringe fit entire session for all baselines/bands/pol-products with new control file containing phase corrections.
- Select candidate scans for each baseline, apply SNR and ΔTEC base cuts.
- For candidate scans, force ΔTEC to mean value for (XX,YY,XY,YX), and re-fringe fit.
- Assume phase/delay closure over pol-products to calculate phase and delay offsets between Y, X polarizations at each station.
- Find mean value for Y-X phase/delay offsets.

Using fourphase.py

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- Script to generate Y-X phase/delay offset corrections
- Requires the control file generated by `ffres2pcp.py`.
- Specify the network reference station, and additional stations for which to generate corrections
- Experiment directory only needs to contain Mk4, (ovex) root files, type-1, and type-3 data.

```
fourphase.py ./cf_3659_pcphases G HEVI ./3659/
```

- Will also generate a report .json file which can be use to generate some diagnostic plots.
- Run `summarize_report.py <fourphase-report-file>` to produce plots and text summary.

Example station Y-X delay offset

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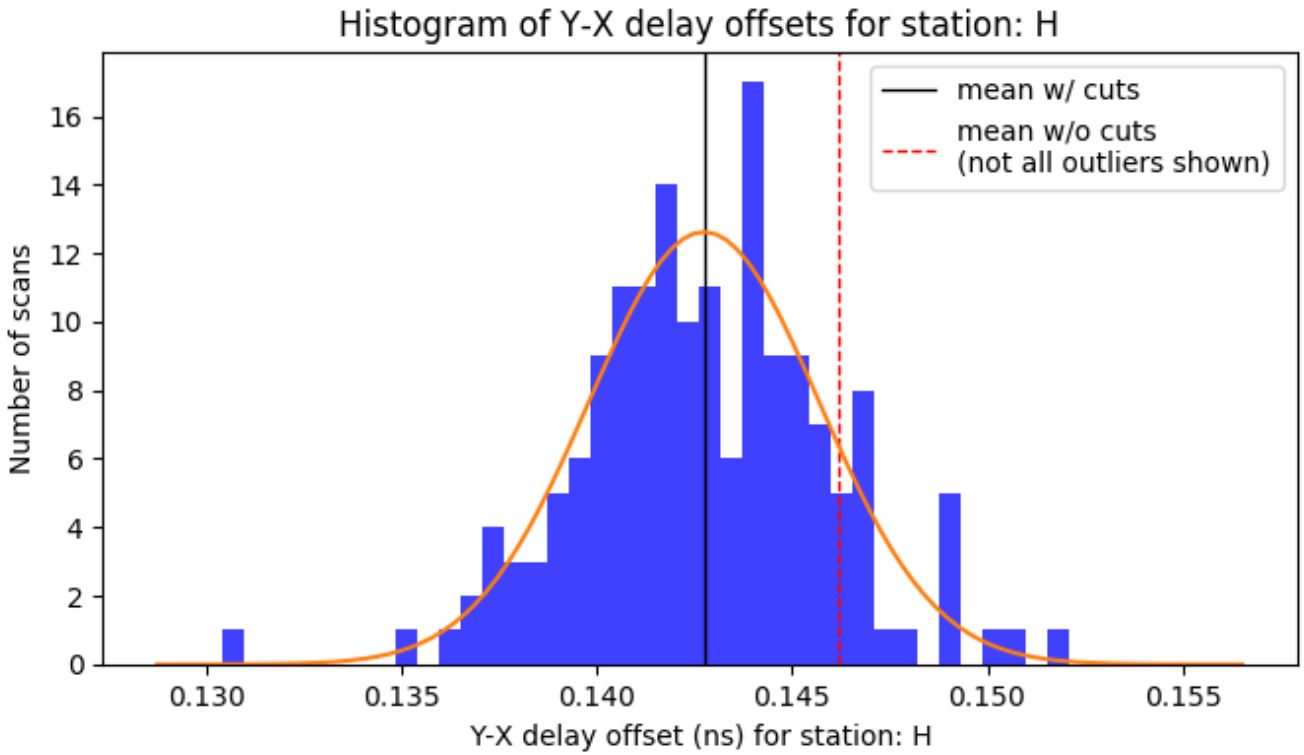

Histogram of Y-X delay offsets for scans passing cuts for station H, session vt8218

Example station Y-X phase offset

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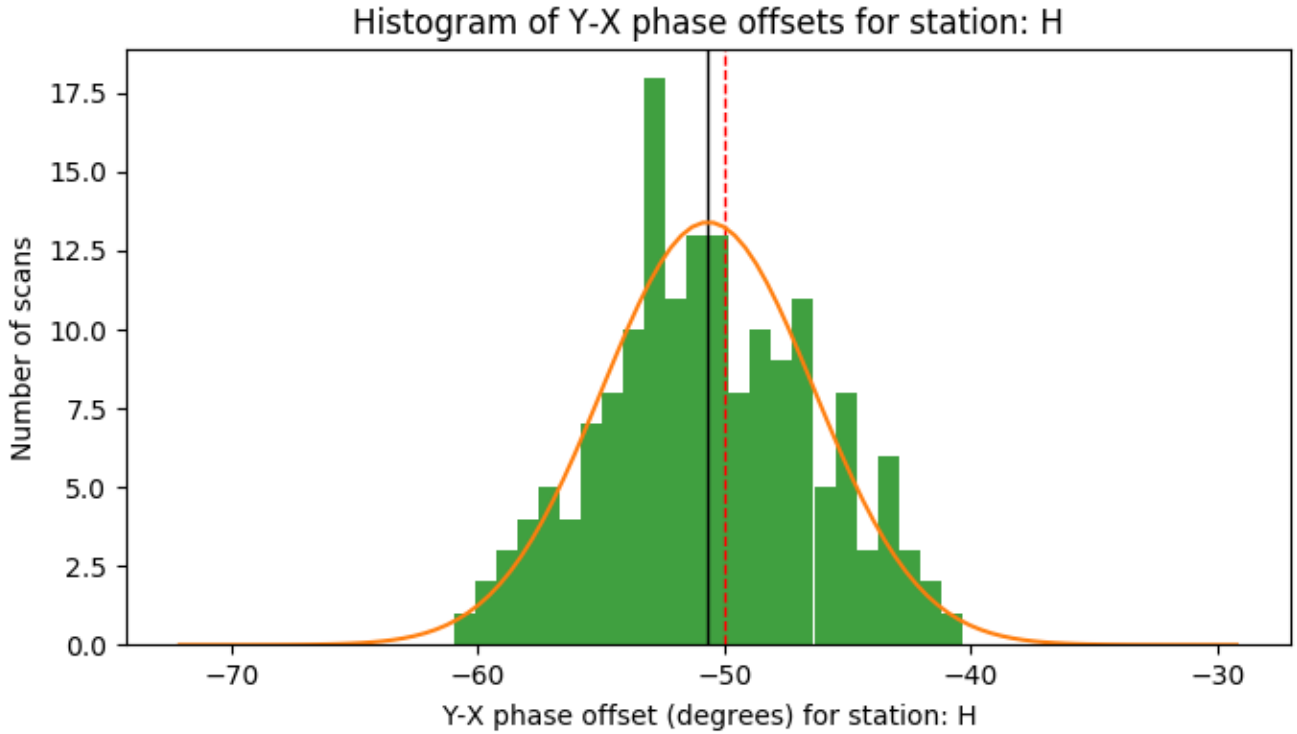

Histogram of Y-X phase offsets for scans passing cuts for station H, session vt8218

Pseudo Stokes-I for fringe fitting

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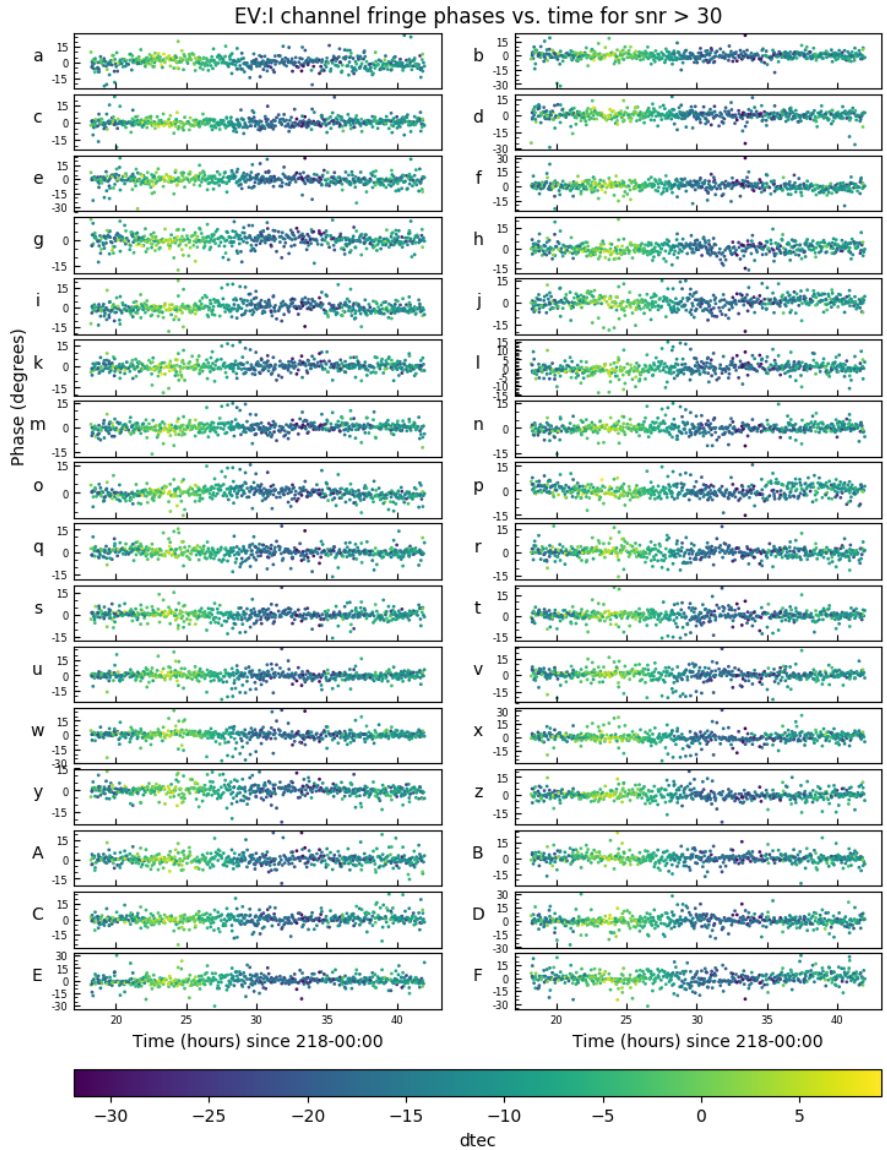
- Need control file with both channel-phase and Y-X phase/delay corrections.
- Can generate this final control file in one step through the convenience script `vgsocf_generate.py` which runs the previous two steps in sequence.
- Then final pseudo Stokes-I fringe fit is performed for all baselines.
- One quick data quality check prior to generating database is to examine phase residuals for all baselines/channels.
- Shown is a nominal/good channel-by-channel phase residual plot for vt8218, Westford-Wettzell baseline, (pseudo Stokes-I), colored by ΔTEC.



Channel phase residuals

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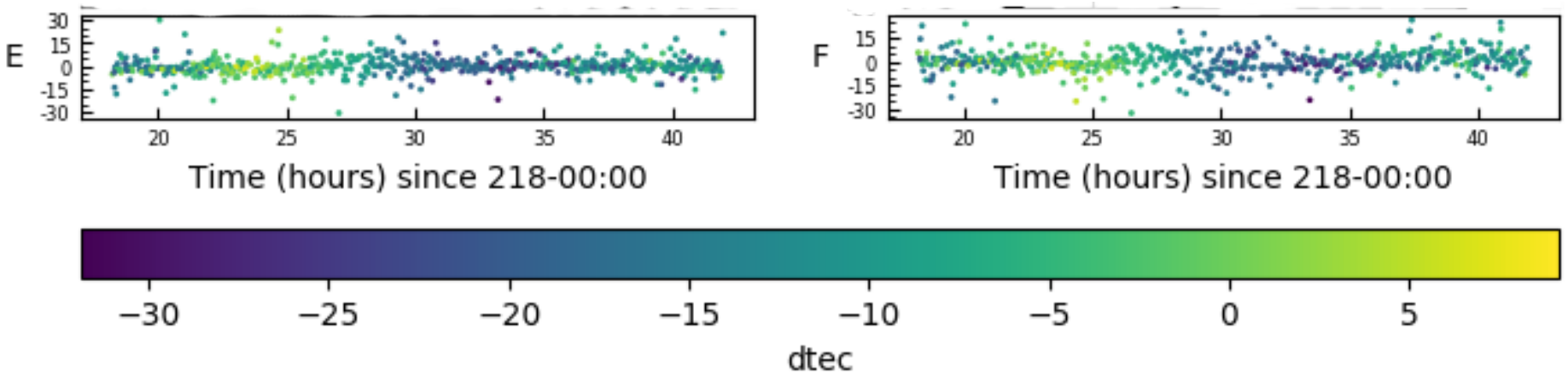

Further data quality checks include:

- Q-code/SNR distribution
- MBD delay trends