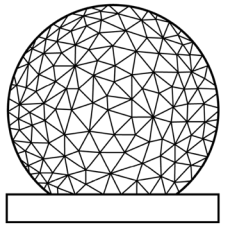
IONEX Predictions for differential TEC

Dan Hoak (for the Haystack correlation team)

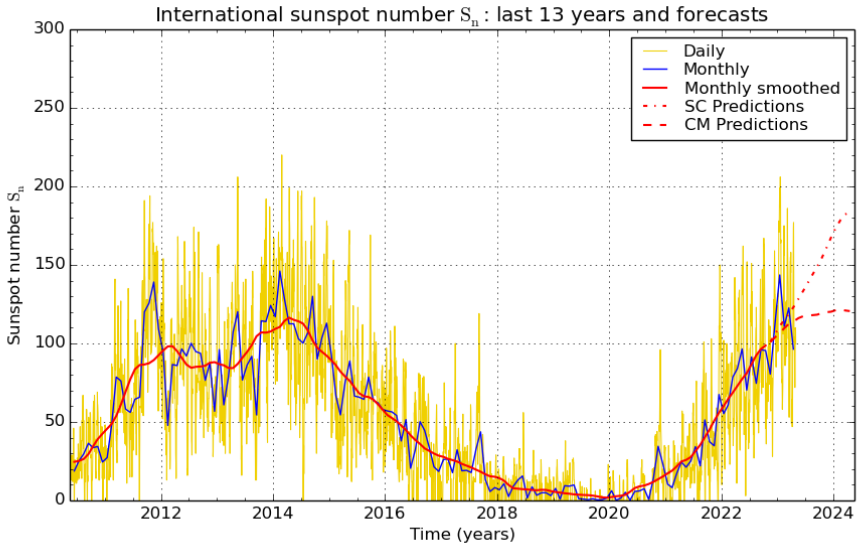
TOW Correlator Workshop May 4-5 2023



MIT
HAYSTACK
OBSERVATORY

Solar Activity

The Sun is becoming more active!



Space Weather Prediction Center

fourfit's ion_search

fourfit performs:

1. A coarse grid search for maximum amplitude, using parameters in the control file (at most 75 search points; hard coded in HOPS, also a significant computational burden)

2. A fine grid search, 25 points, +/-10 TECU around coarse search max

3. An interpolation of the fine search results for the solution

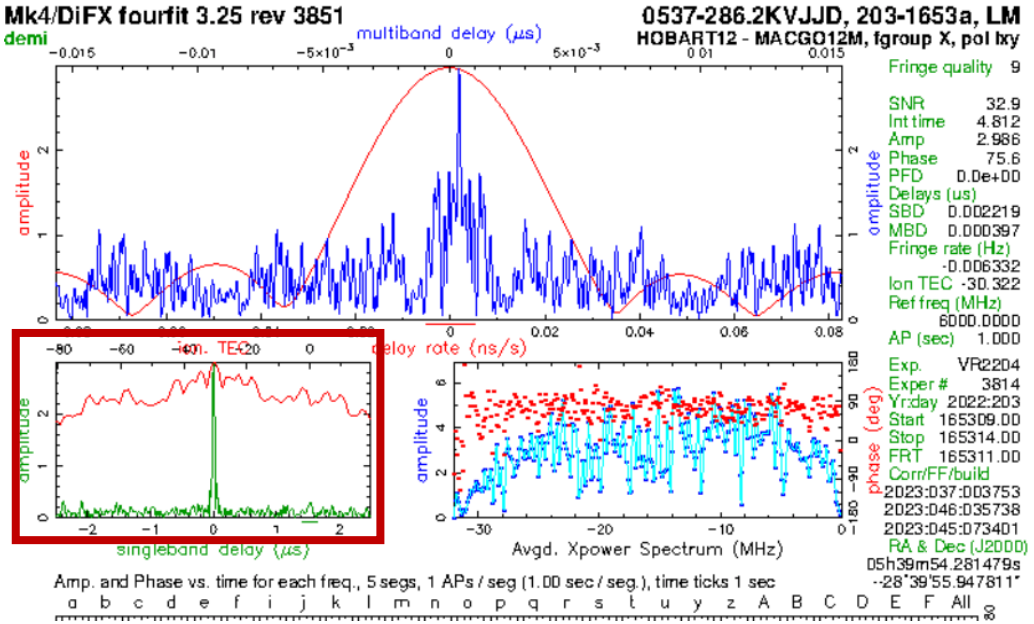
The goal is to find the dTEC value that maximizes fringe amplitude.

Problems:

- dTEC can have many local maxima! Need to keep the coarse grid search spacing small (<3 TECU)
- The best-fit value may be outside of search window! Need to make the search window wide.

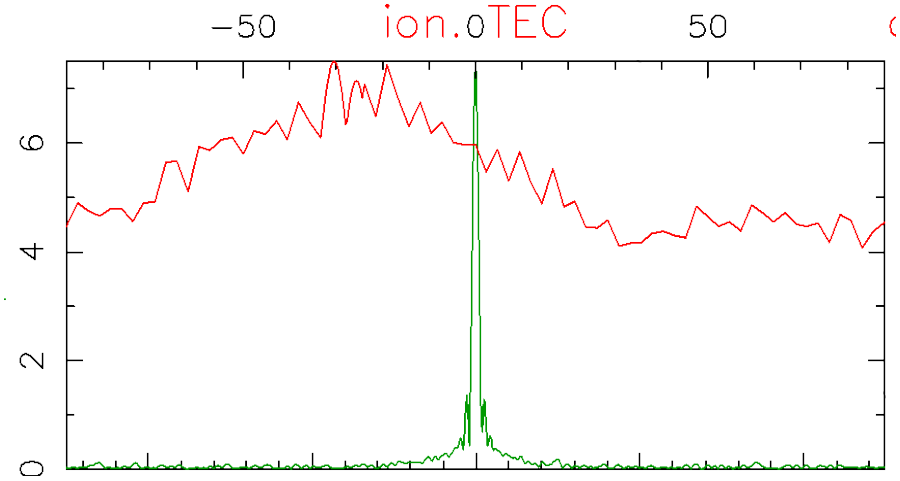
Relevant settings in the control file:

```
ion_smooth true
ion_npts 75
ion_win  -100.0 100.0
```



ion_search challenges

1. Choosing the wrong dTEC peak can lead to differences in the multiband delay of ~100s of nanosec. Scan 112-1137 from VO2111, LS baseline, two peaks separated by 12 TECU. Search grid must be dense enough to find the highest peak! (This was due to incorrect pcphases for Hobart).



2. Long baselines can have several dozens of scans with dTEC that exceeds the nominal search window.

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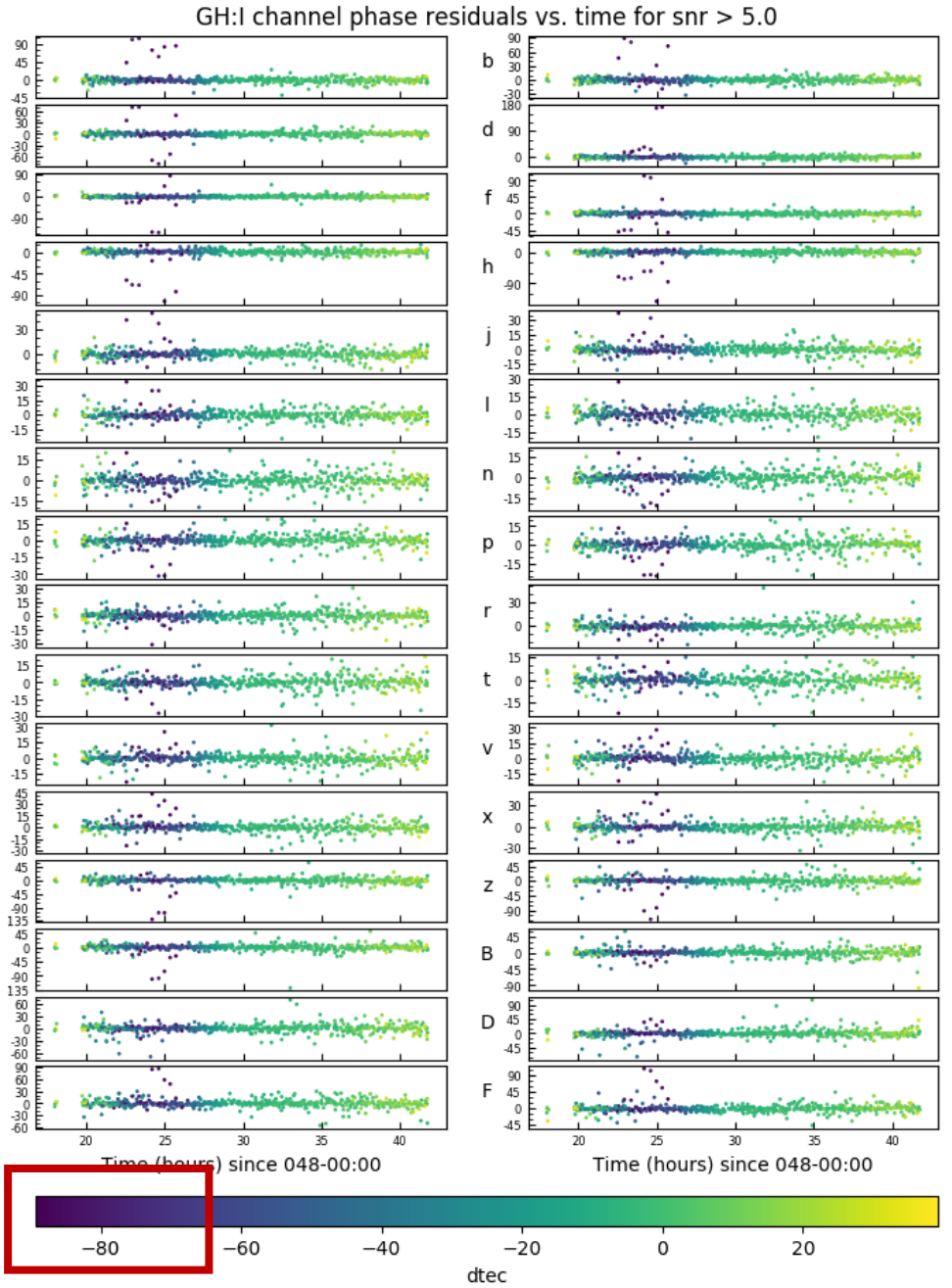
2. Long baselines can have several dozens of scans with dTEC that exceeds the nominal search window.

Use the phase_resid.py script with "-z dtec" option to set the colorbar; check for scans that are limited by the search window range.

Recent VO, VR experiments have had dozens of scans with the best-fit dTEC outside of the usual ion_win range. First noticed in VR2201 (1-Jan-2022).



IONEX predictions for station line-of-sight TEC

Solution: use space weather predictions from GNSS data to set the ion_win parameter scan-by-scan using fourfit command-line options.

Step 1: Get the IONEX predictions from CDDIS:

```
$ get_ionex_dtec_bounds.py /data-sc03/difxoper/vo2348/ .
vo2348_ionex_tec.json
```

This script uses methods from Ivan Marti-Vidal's PolConvert code to calculate the line-of-sight TEC for each station and each scan. It reads the *.calc files from DiFX, downloads the IONEX files, calculates TEC.

Step 2: Use the predictions in the final pseudo-Stokes I fringe fitting:

```
$ batch_fourfit.py cf_3826_GEHLNPSTY_final GEHLNPSTY I .
    -n 16 -p -t vo2348_ionex_tec.json
```

The batch_fourfit script will take the predictions and modify the ion_win parameter for each scan/baseline. Sets the window with the larger of +/-50 TECU or 30% of dTEC prediction. The scripts of vgoscf_generate (ffres2pcp and fourphase) have not been modified.

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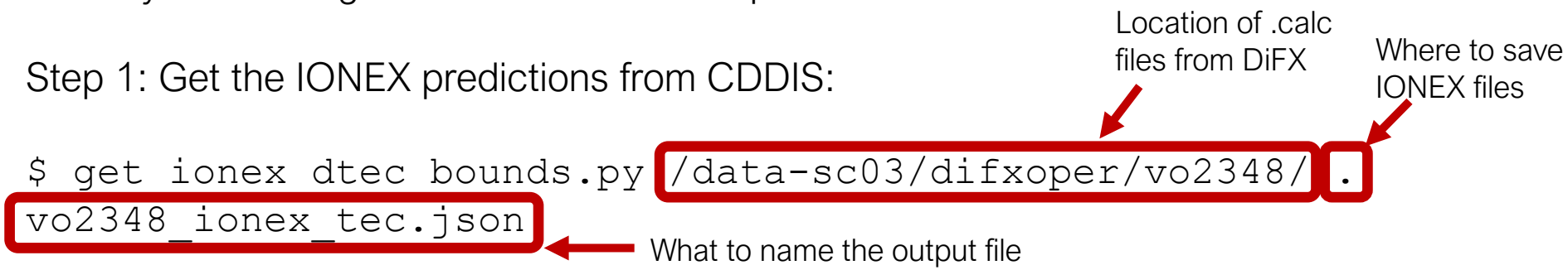

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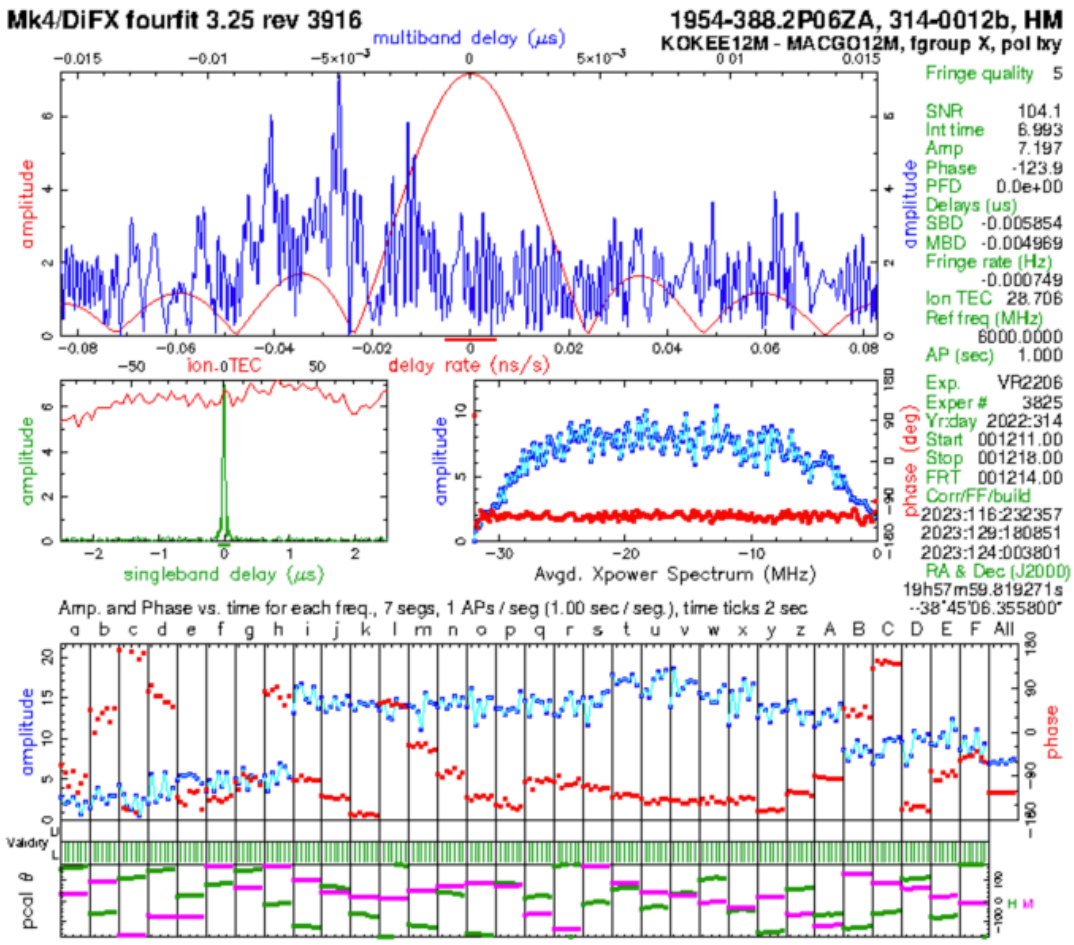
dTEC search window too small: example

An example of what happens when the best-fit dTEC is far outside of the search window in the control file:

Here, we're running the Stokes Ixy **`fourfit`** job for VR2206, scan 314-0012b, Kokee-MGO baseline.

If we run **`fourfit`** with the usual ionospheric search window:
`ion_win  -88.0  88.0`

…we get this fringe plot. The dTEC curve has no clear maximum (best fit is 28 TECU), the fringe quality is low (indicating the SNR is much lower than expected), and the phase residuals are quite scattered (even though this is the final pseudo-Stokes **`fourfit`**'ing, and we have already calculated good pcphases with ffres2pcp!) What's going on?



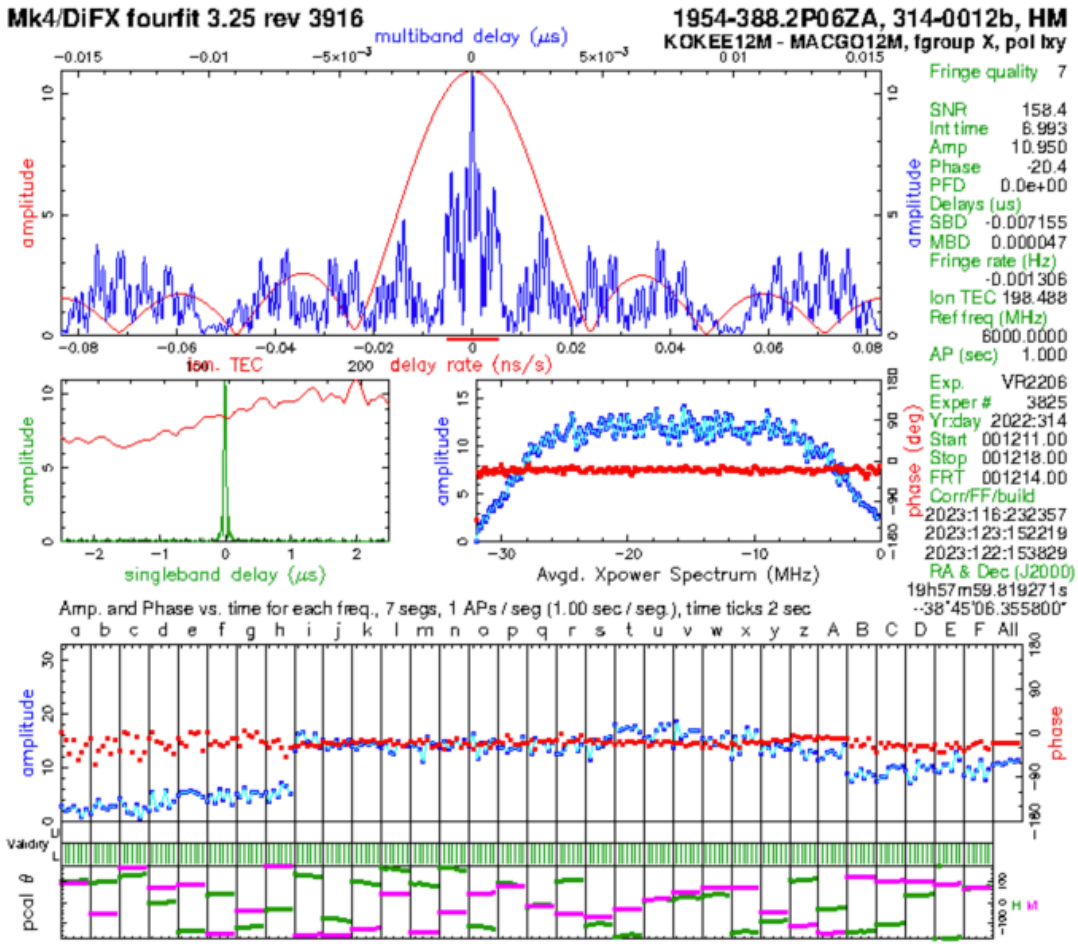
dTEC search window too small: example

The IONEX prediction for this scan & baseline is 158 TECU, way outside the default search range!

The ionospheric search was not looking in the right place!

Here's the result when we set the ion_win parameter using the IONEX prior (here, we used [108,208] as the ion_win, so +/- 50 TECU from the prediction).

The SNR has increased from 104 to 158, the fringe quality improved, the residual phases are flat, and the best-fit dTEC is 198 TECU – actually quite far from the IONEX prediction, but still inside our search window.

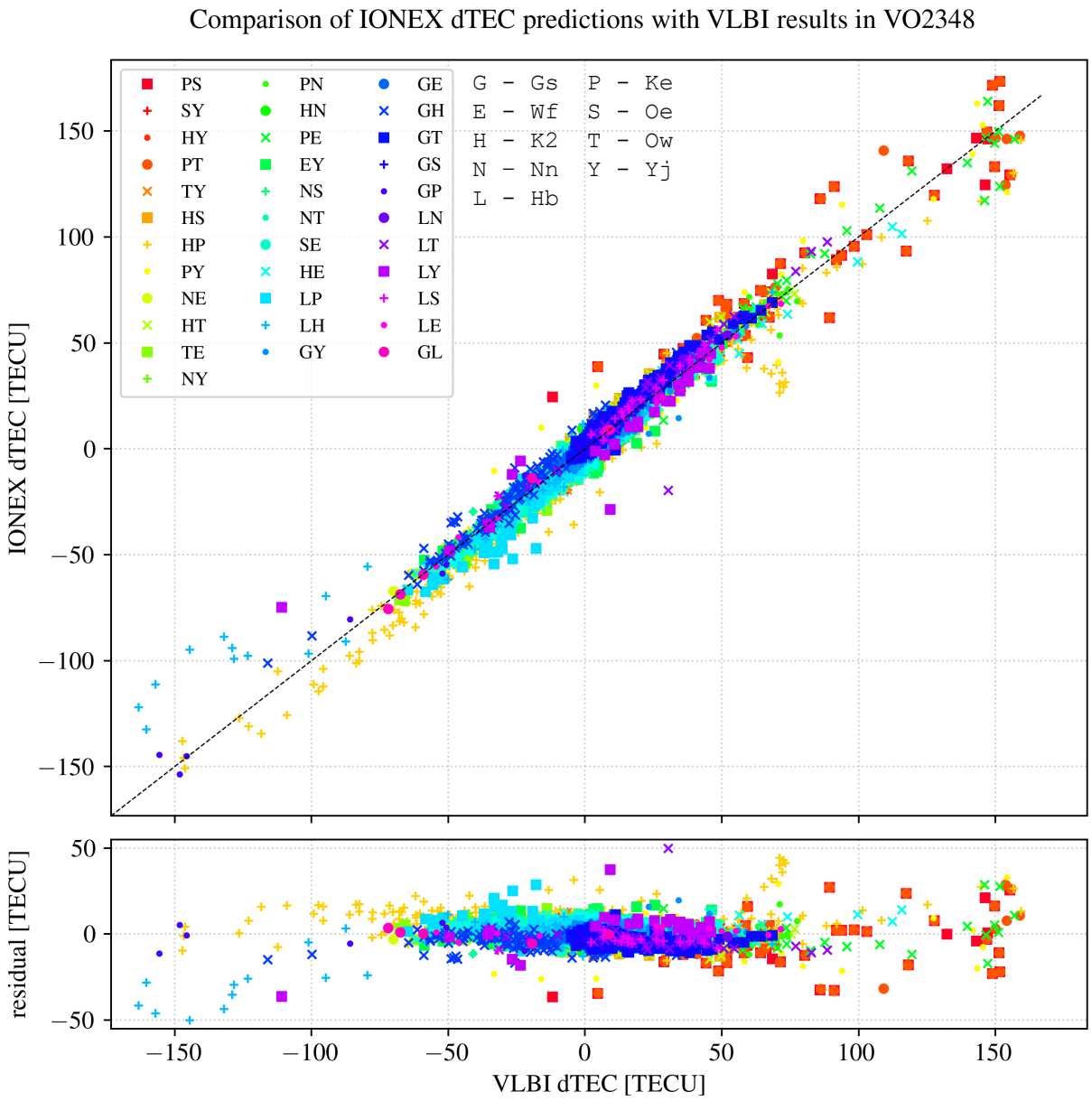


Comparisons of VLBI and IONEX dTECs

IONEX predictions for VLBI dTEC perform “well enough”: by setting the search window scan-by-scan, can maintain a dense search spacing but cover >2x default range.

Long baselines are harder to predict. The ion_win parameter still needs to be fairly wide (+/- 50 TECU instead of +/-100).

Typically the largest dTEC values are baselines from Europe to Kokee, Hobart, Katherine, due to the diurnal variation in line-of-sight TEC.



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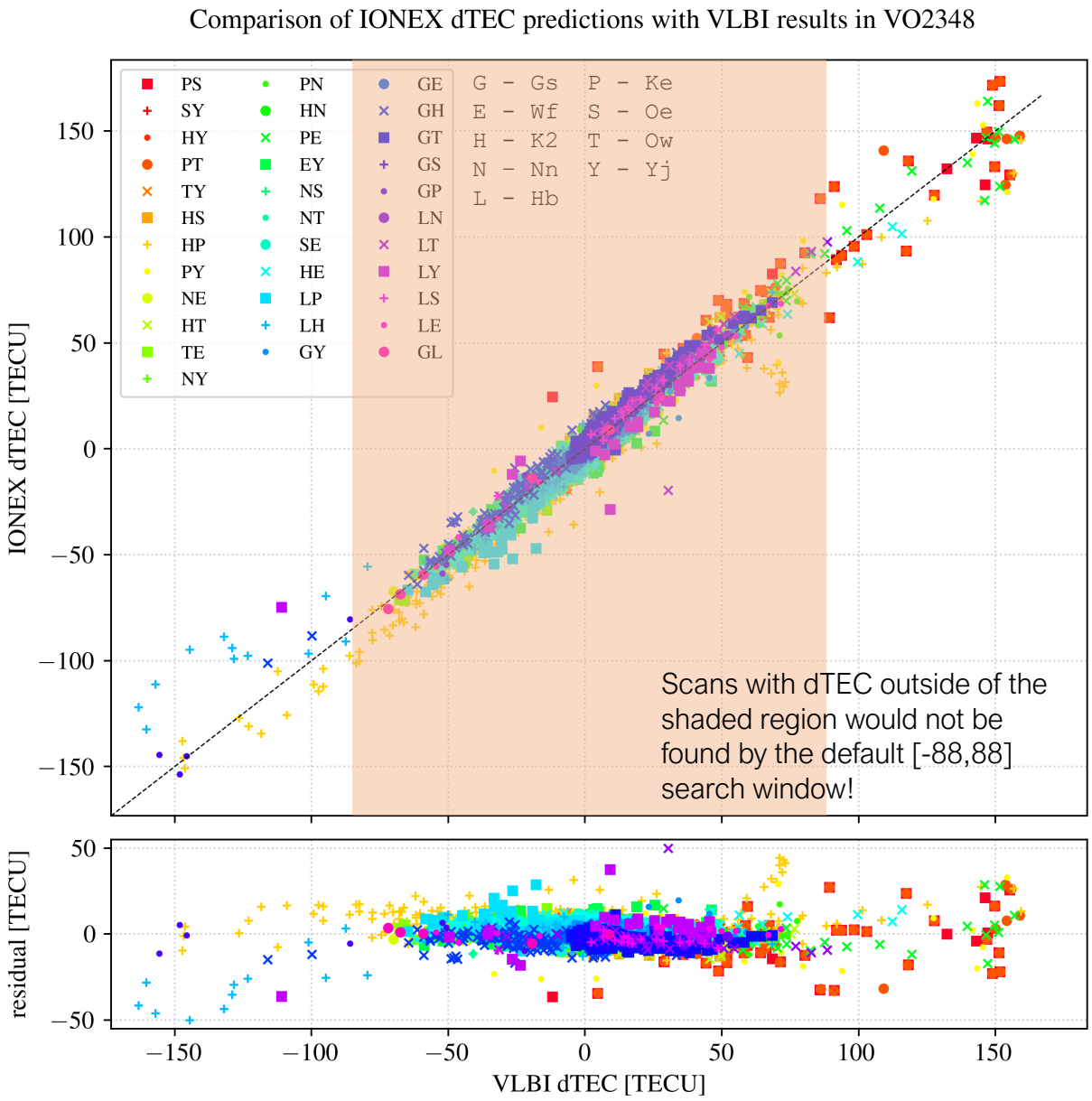
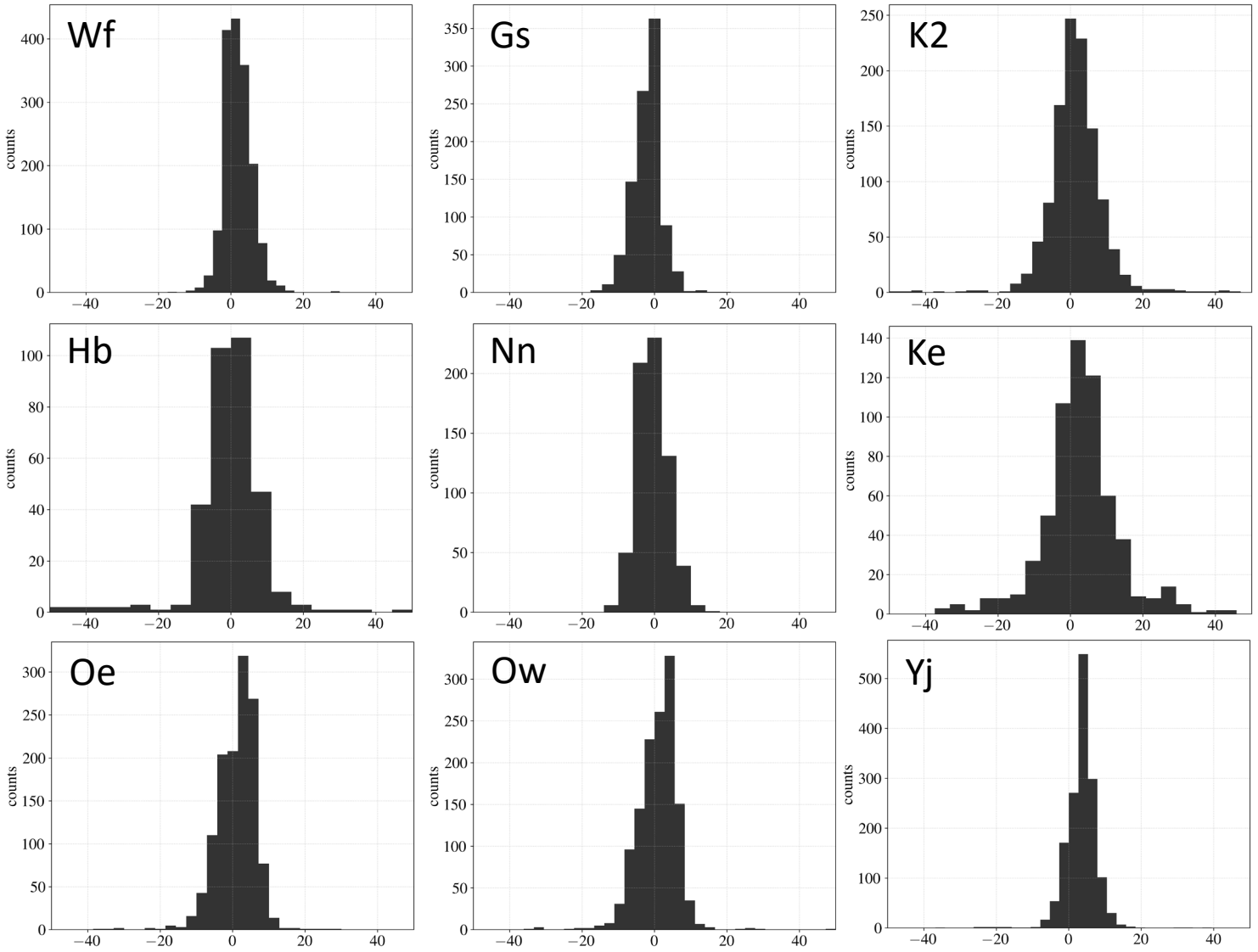


Comparisons of VLBI and IONEX dTECs

But, the VLBI result can disagree with the IONEX prediction by 10s of TECU.

Histograms of VLBI-IONEX difference for VO2348 (x-axis is +/-50 TECU).



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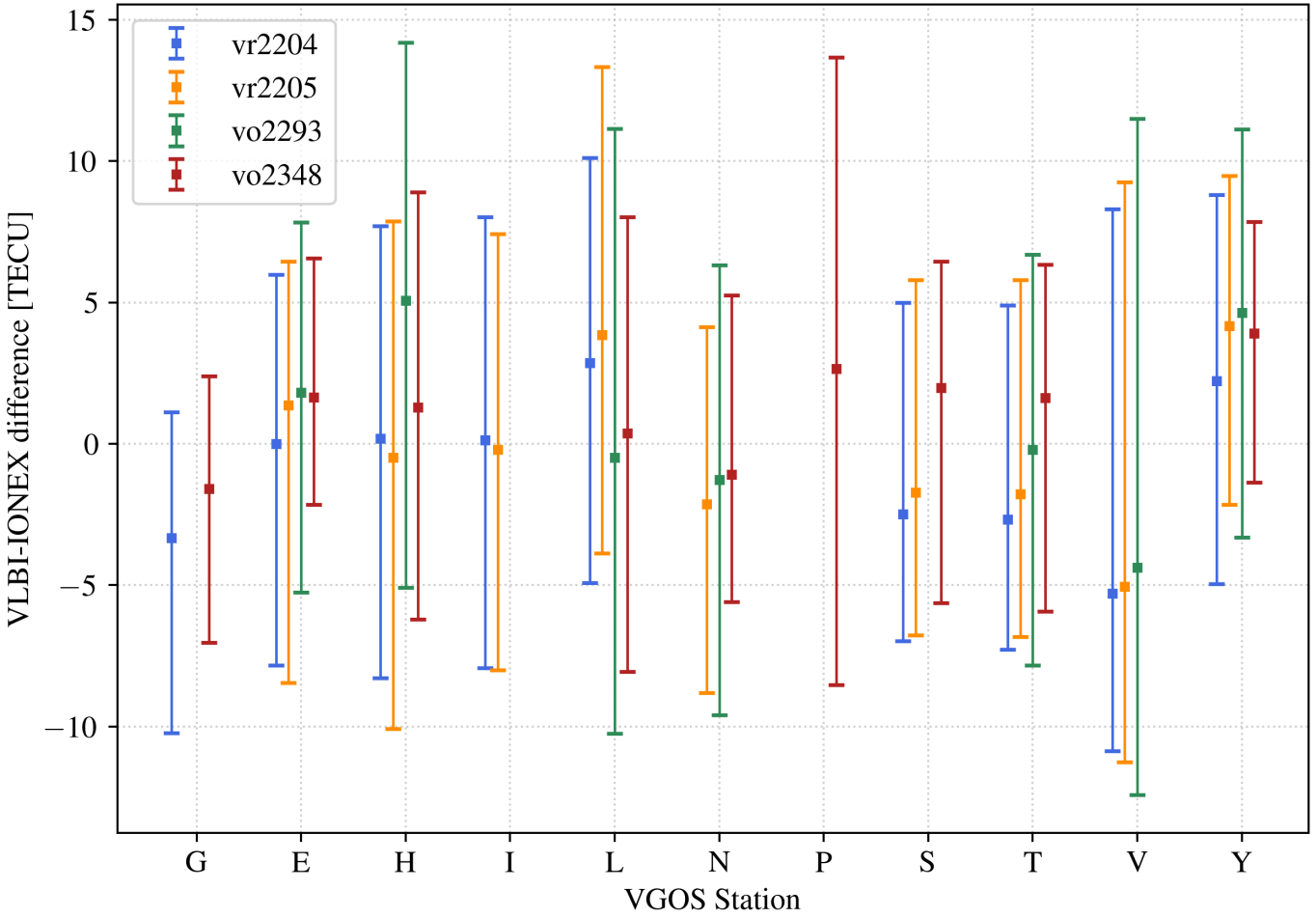


Error bars are 90% intervals.

VLBI result can disagree with the IONEX prediction by 10s of TECU. Long baselines & stations with poor GNSS coverage have larger scatter, some stations have systematic offsets. We can't set the dTEC value with IONEX priors; it's not accurate for VLBI.

Optimizing the ionosphere thin shell model (altitude/thickness) might improve things.

What about VGOS Intensives?

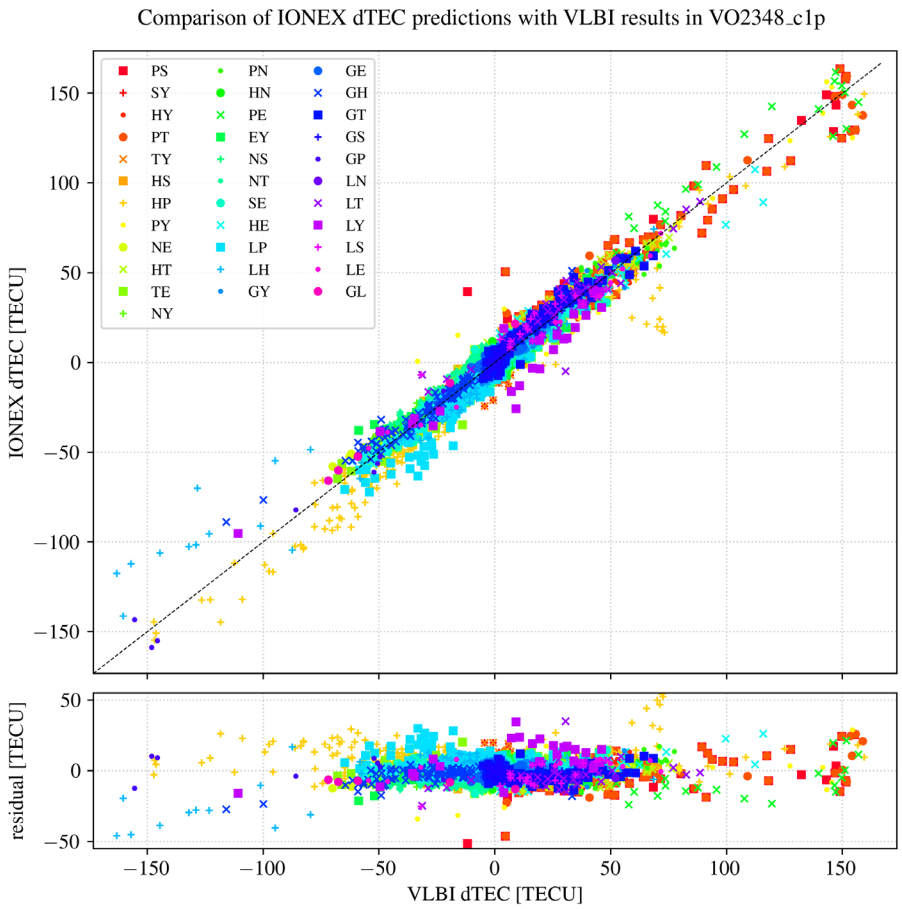
Typically, dTEC for a particular baseline doesn't vary much over one hour, so tuning the ion_win parameter in the control file may work for all scans.

For 24-hr sessions with several stations, we can't set one ion_win large enough and avoid missing the true maxima.

IONEX file types and availability:

```
c2p: CODE 2-day prediction (D-1)
c1p: CODE 1-day prediction (D+0)
cor: CODE rapid prediction (D+1)
jpr: JPL rapid prediction (D+1)
jpl: JPL full solution (D+3)
```

All of these work well! Use the '-a' flag with get_ionex_dtec_bounds.py (eg "-a c1p").



CORE 1-day prediction (c1p). 1-sigma uncertainties are about 20% worse.

https://cddis.nasa.gov/Data_and_Derived_Products/GNSS/atmospheric_products.html

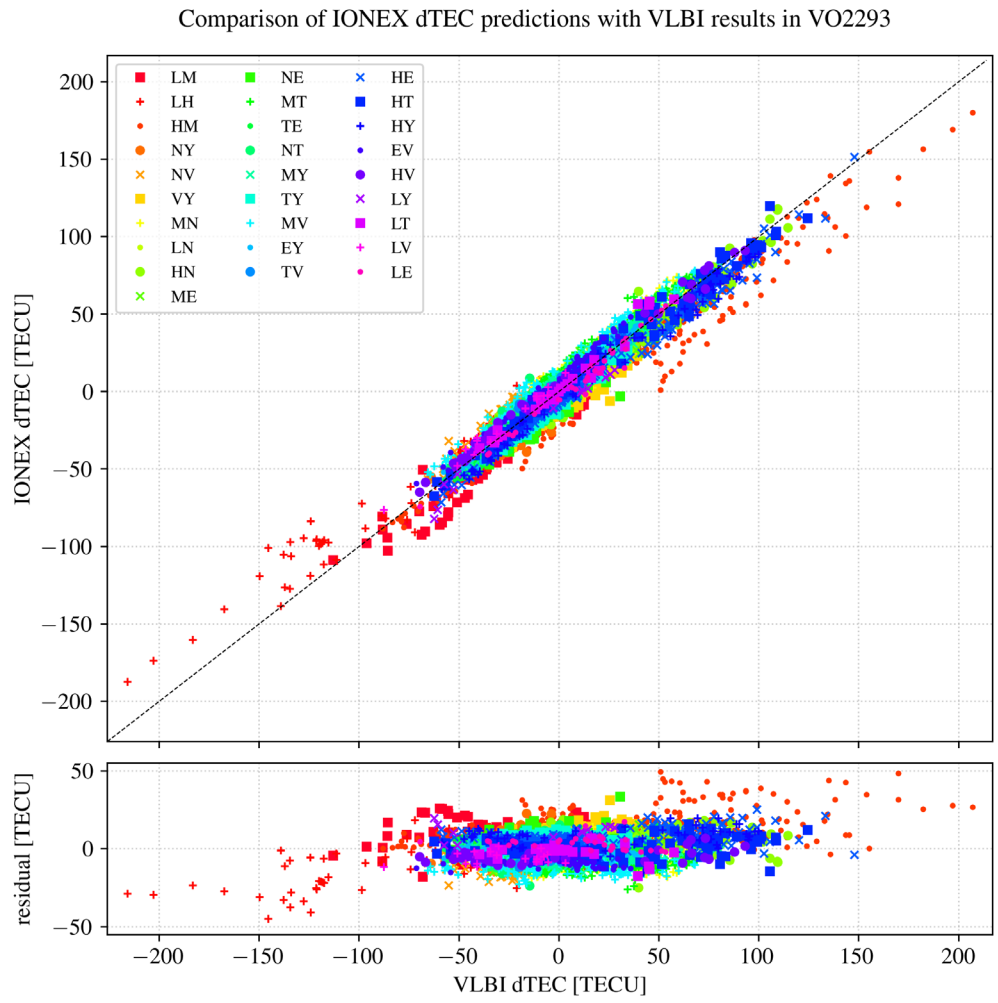
Conclusions

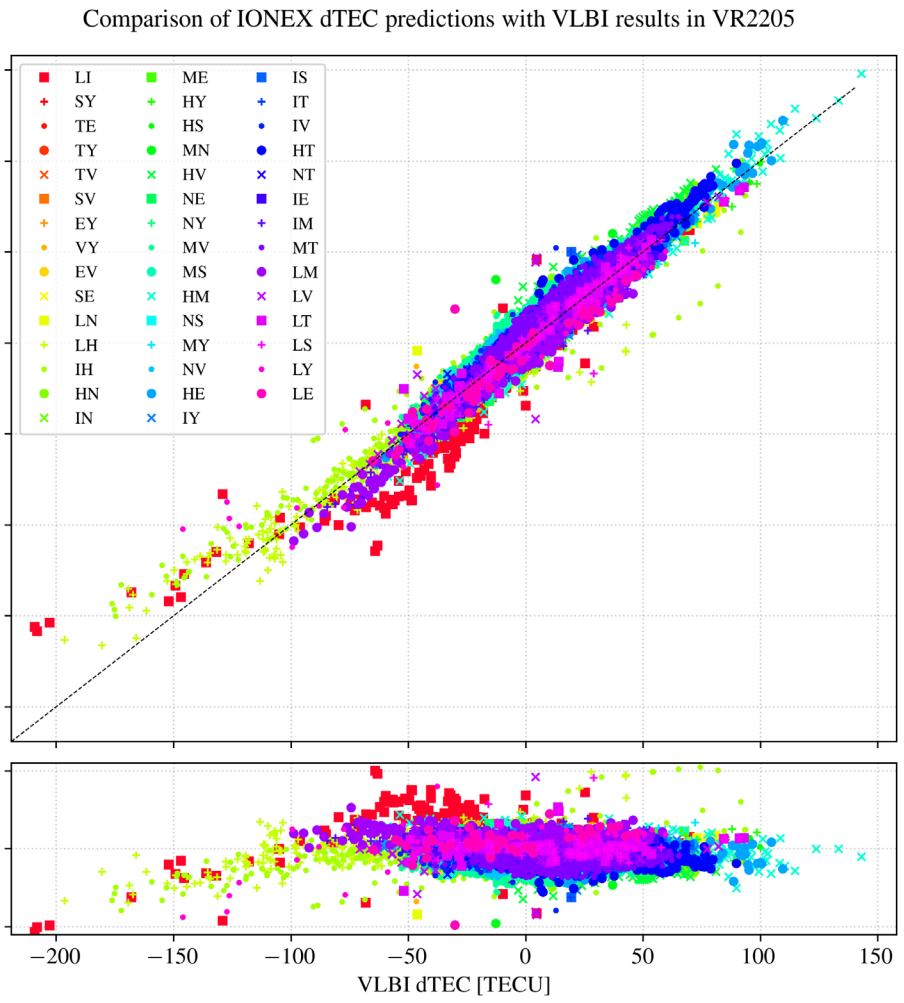
The Sun has woken up from a historic solar minimum – this is affecting VLBI!

Predictions from space weather models provide a good a priori guess at the differential TEC for each scan and baseline in a VGOS experiment.

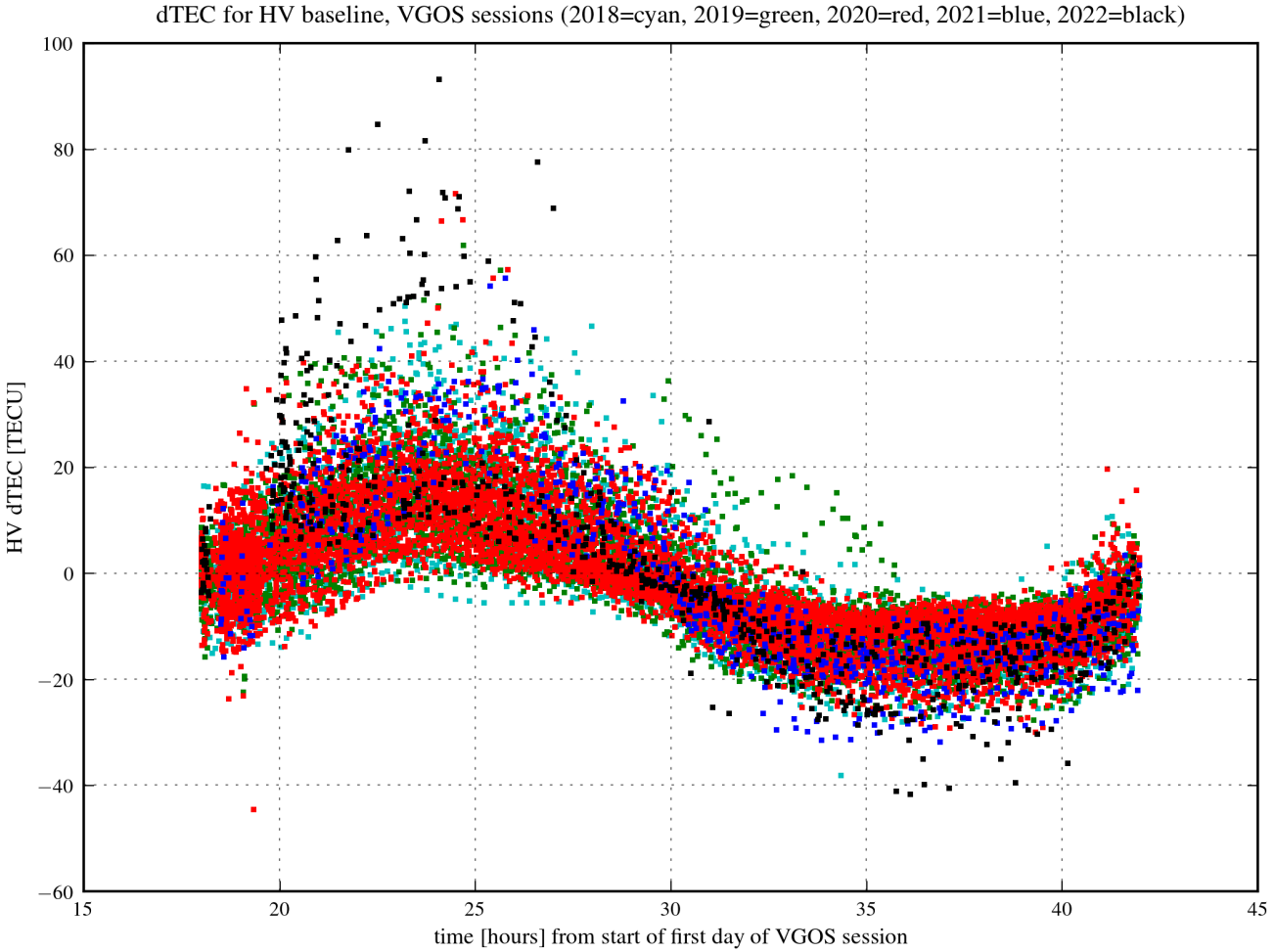
So far, 24-hr experiments can have ~dozens of scans that exceed the default ionospheric search window. We don't know how active this solar maximum will be!

Comparisons of VLBI and IONEX dTECs





VGOS Data Since 2018



On short baselines, both stations see approximately the same ionosphere; differential TEC is small.

On long baselines, the ionosphere can be very different (especially with diurnal variation). Midnight in Europe is noon in Hawai'i.