JIVE
Joint Institute for VLBI
ERIC

VLBI (Amplitude) Calibration

(and other a-priori calibration)

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CASA VLBI workshop

Measurement Equation
(RIME)

- Formulated by: Hamaker, Bregman & Sault, 1996, A&AS, **117**, 137
- Reformulated in: Smirnov, 2011, A&AS, **527**, A106
- Mathematical basis for calibration of a radio interferometer
- Fully incorporates polarization

Electric field at the source: $\mathbf{e} = \begin{pmatrix} e_r \\ e_l \end{pmatrix}$

Recorded voltages of feeds at telescope: $\mathbf{v} = \mathbf{J}\mathbf{e}$ with (2x2) Jones matrix $\mathbf{J}$

Visibility matrix produced by the correlator: $\mathrm{V}_{pq} = 2\langle \mathbf{v}_p \mathbf{v}_q^H \rangle$

Measurement equation: $\mathrm{V}_{pq} = 2\langle \mathbf{J}_p (\mathbf{e}_p \mathbf{e}_q^H) \mathbf{J}_q^H \rangle = \mathbf{J}_p \mathbf{B} \mathrm{J}_q^H$ with brightness matrix $\mathrm{B} = \begin{pmatrix} I+Q & U+iV \\ U-iV & I-Q \end{pmatrix}$

Goal is to determine $\mathbf{J}_p$ for all antennas p.

Measurement Equation
continued

$\mathbf{J}_p = \mathbf{B}_p\mathbf{G}_p\mathbf{D}_p\mathbf{E}_p\mathbf{P}_p\mathbf{K}_p\mathbf{T}_p$

- $\mathbf{T}_p$ Polarization-independent multiplicative effects introduced by the troposphere, such as opacity and path-length variation.
- $\mathbf{K}_p$ Delay (this is VLBI!)
- $\mathbf{P}_p$ Parallactic angle, which describes the orientation of the polarization coordinates on the plane of the sky. This term varies according to the type of the antenna mount.
- $\mathbf{E}_p$ Effects introduced by properties of the optical components of the telescopes, such as the collecting area's dependence on elevation.
- $\mathbf{D}_p$ Instrumental polarization response. "D-terms" describe the polarization leakage between feeds.
- $\mathbf{G}_p$ Electronic gain response due to components in the signal path between the feed and the correlator.
- $\mathbf{B}_p$ Bandpass (frequency-dependent) response, such as that introduced by spectral filters in the electronic transmission system.

CASA always applies these in the same (physically correct) order!

CASA calibration

SN table

- CASA calibration tables represent Jones matrices
  - Have an identity
  - Contain real or complex parameters that are used to calculate elements
    Complex gain: $\mathbf{G} = \begin{pmatrix} g_r & 0 \\ 0 & g_l \end{pmatrix}$ is described by tow complex paramaters.
  - Can be given arbitrary (meaningful) names
- **Always explicitly specify calibration tables to be applied!**
  - There is no equivalent of an AIPS CL table

CASA calibration

continued

- Calibration tables are specified with task parameters:
  - `gaintable = [`*`caltable1`*`, `*`caltable2`*`]`
  - `gainfield = [`*`field1`*`, `*`field2`*`]` e.g. `'3C84', 'J1023+43'`
    (*`field1`* applies to *`caltable1`*, *`field2`* to *`caltable2`*)
  - `interp = [interp1, interp2]` e.g. `'linear', 'nearest'`
    (*`interp1`* applies to *`caltable1`*, *`interp2`* to *`caltable2`*)
  - `parangle = True` or `False` (default)
- Per-scan interpolation modes:
  - `'linearperscan', 'nearestperscan'`

new in CASA 6.5.5

- Data without calibration solutions is automatically flagged!
  - Can be bypassed when applying the final calibration
- Data is aggressively flagged if it is partly flagged:
  - `corrdepflags = True` or `False` (default); `True` prevents flagging both pols if one is flagged

Data Formats

- MeasurementSet (v2)
  Native data format of CASA; MS for short
- UV-FITS
  What AIPS writes
- FITS-IDI
  Produced by the SFXC (EVN) and DiFX (VLBA, LBA, …) correlators

All thee formats can contain metadata such as gain curves and T_{sys}

VLBI amplitude calibration

- VLBI observations typically use 2-bit sampling
- For maximum efficiency the 4 states should be sampled ~17% in the “high” state and 33% in the “low” state.
- This is done by automatically adjusting the gain on a (relatively) short timescale
- As a consequence all amplitude information is lost in the correlated visibilities
- Standard CASA amplitude calibration using the setjy/fluxscale tasks does not work:
  - Calibrater sources are either variable (in time) or resolved at VLBI scales!

VLBI amplitude calibration
continued

- System equivalent flux density

  $$\text{SEFD} = \frac{T_{sys}}{G}$$

  where *G* is the antenna gain

  $$G = \text{DPFU} \times g(el)$$

- DPFU: “degrees per flux unit”, conversion factor from temperature scale (K) to flux density scale (Jansky)

- g(el): gain curve; correcting for deformation under gravity of the dish (normalized)

- Flux density on a particular baseline

  $$S_{i,j} = \sqrt{\text{SEFD}_i \cdot \text{SEFD}_j} \cdot r_{c,i,j}$$

  where $r_{c,i,j}$ is the **normalised** correlation coefficient

VLBI amplitude calibration

T_{sys} measurement methods

- Classic noise diode:
  - Noise diode get fired in gap just before start of scan
  - Backend tracks total power; this is then used to extrapolate T_{sys}
  - Must flag data when noise diode is on
- “Continuous Cal”
  - Noise diode is turned on and off at a rate of (typically) 80 Hz
  - Can track T_{sys} directly
  - Lower power of noise diode means data does not have to be flagged
- Chopper or Hot/Cold load
  - Places an object twith properties similar to a blackbody of known temperature in front of the receiver
  - Typically used for mm-VLBI

$$T_{sys} = \frac{P_{off}}{P_{on} - P_{off}} T_{inject}$$

Preparing your data

ANTAB

scripts at https://github.com/jive-vlbi/casa-vlbi

- Attach gain curves and DPFU from ANTAB files
    - Using append_gc.py script:

      ```
      casa —-no-gui -c append_gc.py antabfile idifile
      ```

    - Using casavlbitools python module:

      ```
      import casavlbitools.fitsidi
      casavlbitools.fitsidi.append_tsys(antabfile, idifiles)
      ```

- Attach T_{sys} measurements from ANTAB files
    - Using append_tsys.py script:

      ```
      casa —-no-gui —c append_tsys.py antabfile idifiles…
      ```

    - Using casavlbitools python module:

      ```
      import casavlbitools.fitsidi
      casavlbitools.fitsidi.append_tsys(antabfile, idifiles)
      ```

    - Provide the names of **all** FITS-IDI files here)!

VLBA data already includes this metadata

new EVN data also (from mid 2022)

Preparing your data
Some installation notes

- On a Mac, create symlinks for CASA:
  - run `!create-symlinks` command from the CASA prompt
- Set the PYTHONPATH environment variable:
  - `export PYTHONPATH=$PYTHONPATH:/path/to/casa-vlbi`
- Scripts will emit a (harmless) waring message:
  - `PyFITS is deprecated, please use astropy.io.fits`
- Scripts may appear in a future CASA release
  - Including tools to add ANTAB information directly to MS!

Importing your data

FITLD

- FITS-IDI data can be imported using the importfitsidi
    - A single FITS-IDI file:

```
importfitsidi(vis=ms, fitsidifiles=[fitsfile],
                  scanreindexgap_s=seconds)
```

15 seconds is good (matches FITLD)

- Multiple FITS-IDI files for a single observation:

```
importfitsidi(vis=ms, fitsidifiles=[fitsfile1, fitsfile2],
                  constobsid=True, scanreindexgap_s=seconds)
```

Use Python glob module for EVN data

```
import glob
fitsfiles =  sorted(glob.glob("N20C2_1_1.IDI*"))
```

- Applies digital corrections for DiFX correlator (VLBA & Co)
- Data is marked to be in a geocentric frame
  (**incorrect for EVN data correlated before 2012!**) (EVN & Co)
- Warnings about telescope diameter and scan numbers can be ignored

- UVFITS data can be imported using importuvfits

```
importuvfits(vis=ms, fitsfile=[fitsfile])
```

This does not import most of the VLBI metadata correctly!

Normalizing your data

AIPS ACCOR

- Fix correlation amplitudes based on autocorrelations (VLBA & Co)

```
accor(vis=ms, caltable=caltable)
```

- Generates G-type calibration table

- CASA data selection provides AIPS `ACSCL` functionality

Flagging your data

UVFLG

scripts at https://github.com/jive-vlbi/casa-vlbi

- Apply a-priori flagging (EVN & Co)

```
$ flag.py uvflgfile fitsfile > flagfile
```

```
flagcmd(vis=ms, inpmode='list',inpfile=flagfile)
```

- Apply a-priori flagging (VLBA)

```
flagcmd(vis=ms, inpmode='table')
```

- Additional (interactive) flagging can be done using `plotms`

A Diverse bunch

Amplitude calibration

Dr. Schorsch, https://creativecommons.org/licenses/by-sa/3.0/deed.en

ESO, https://creativecommons.org/licenses/by-sa/3.0/deed.en

Alessandro Cattani

JJ Harrison, https://creativecommons.org/licenses/by-sa/3.0/deed.en

Amplitude calibration

ANTAB

- Generate caltables for gain curves:

  `gencal(vis=ms, type='gc', caltable=gctable)`

- Generate caltables for T_{sys}:

  `gencal(vis=ms, type='tsys', caltable=tsystable, uniform=False)`

  Using uniform=False is important; without it your data will be (mostly) flagged!

- Generates G-type calibration tables
- To apply use:

  `gaintable=[gctable, tsystable]`

  In subsequent calibration tables.

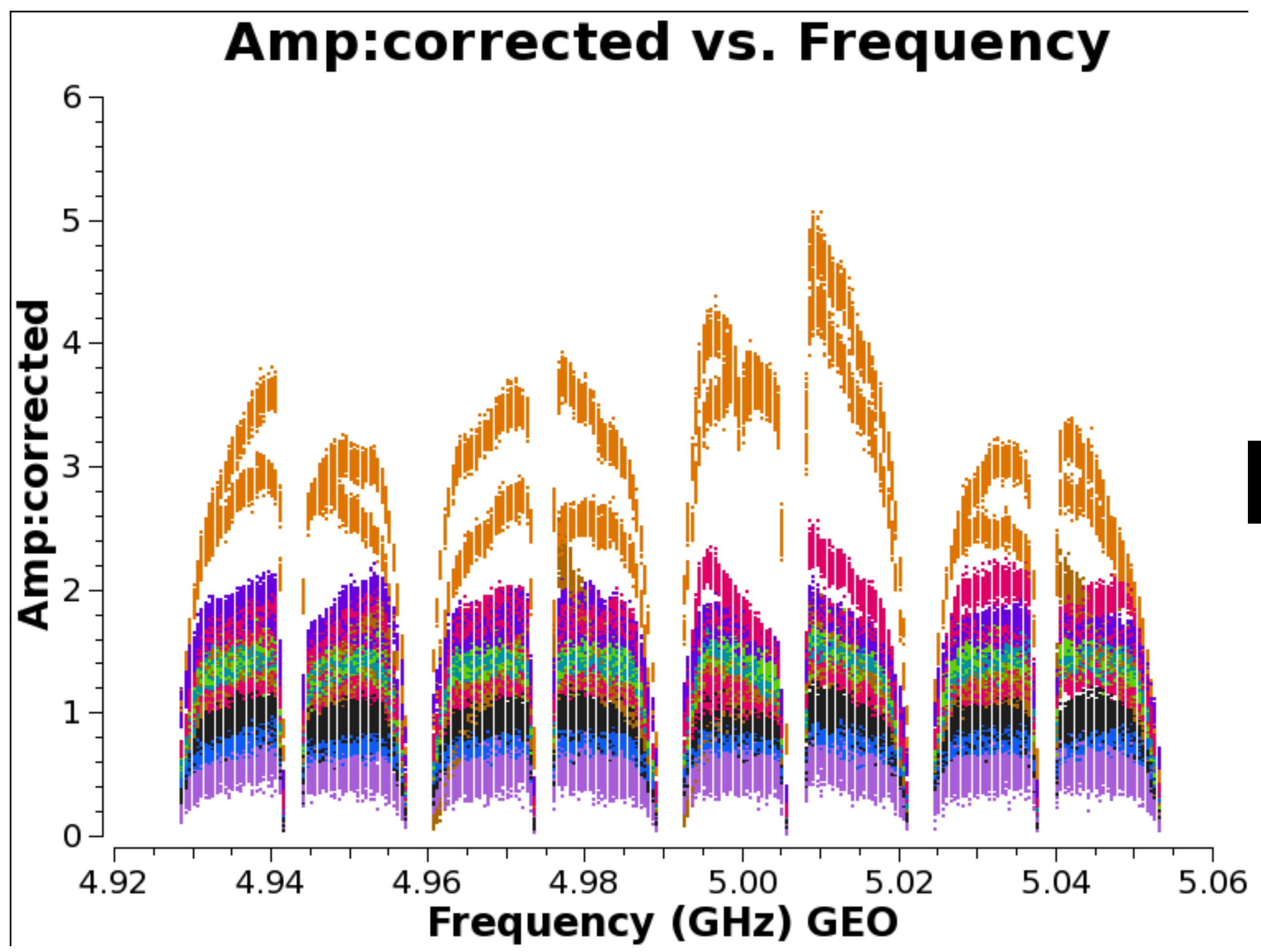
Bandpass calibration

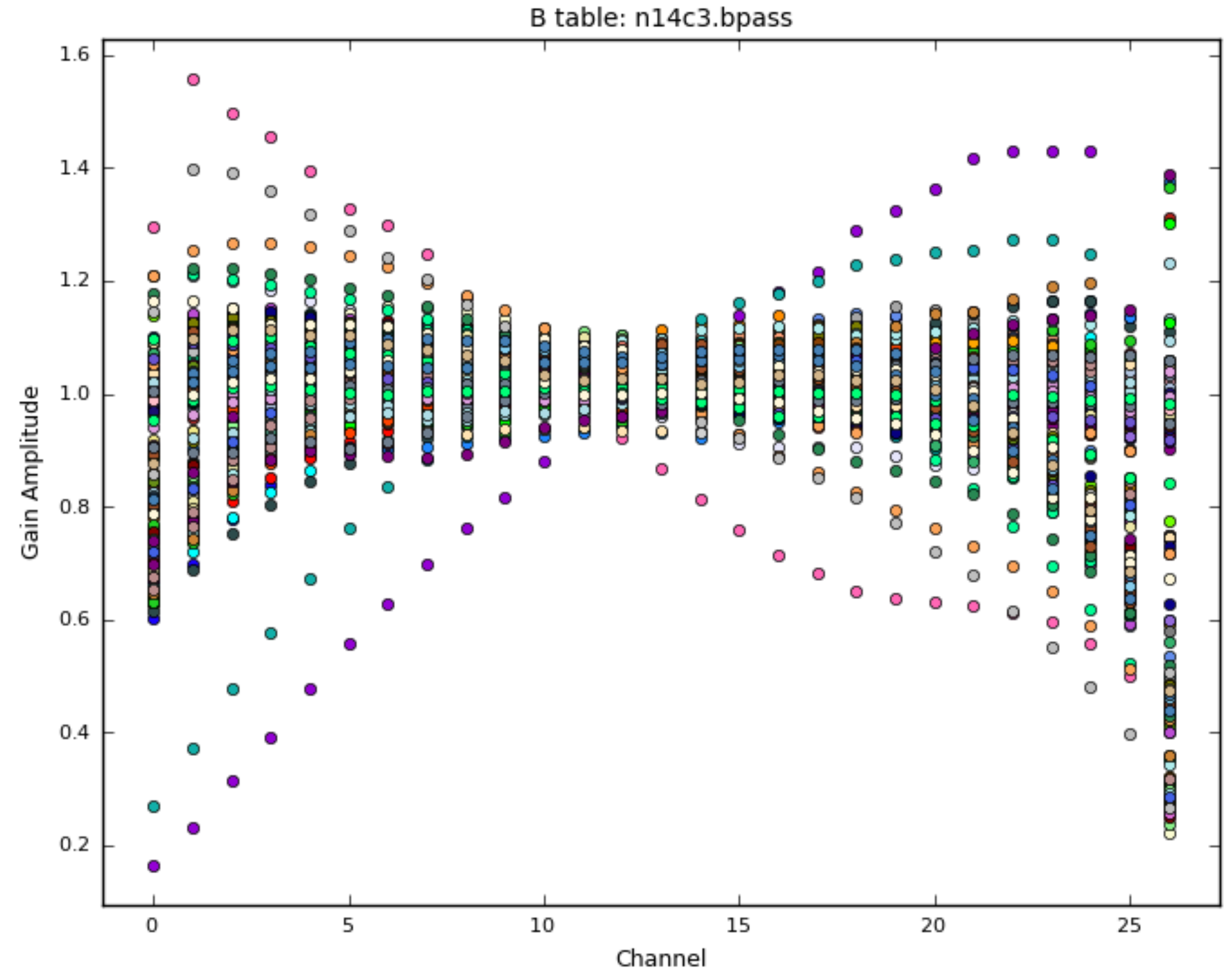
BPASS

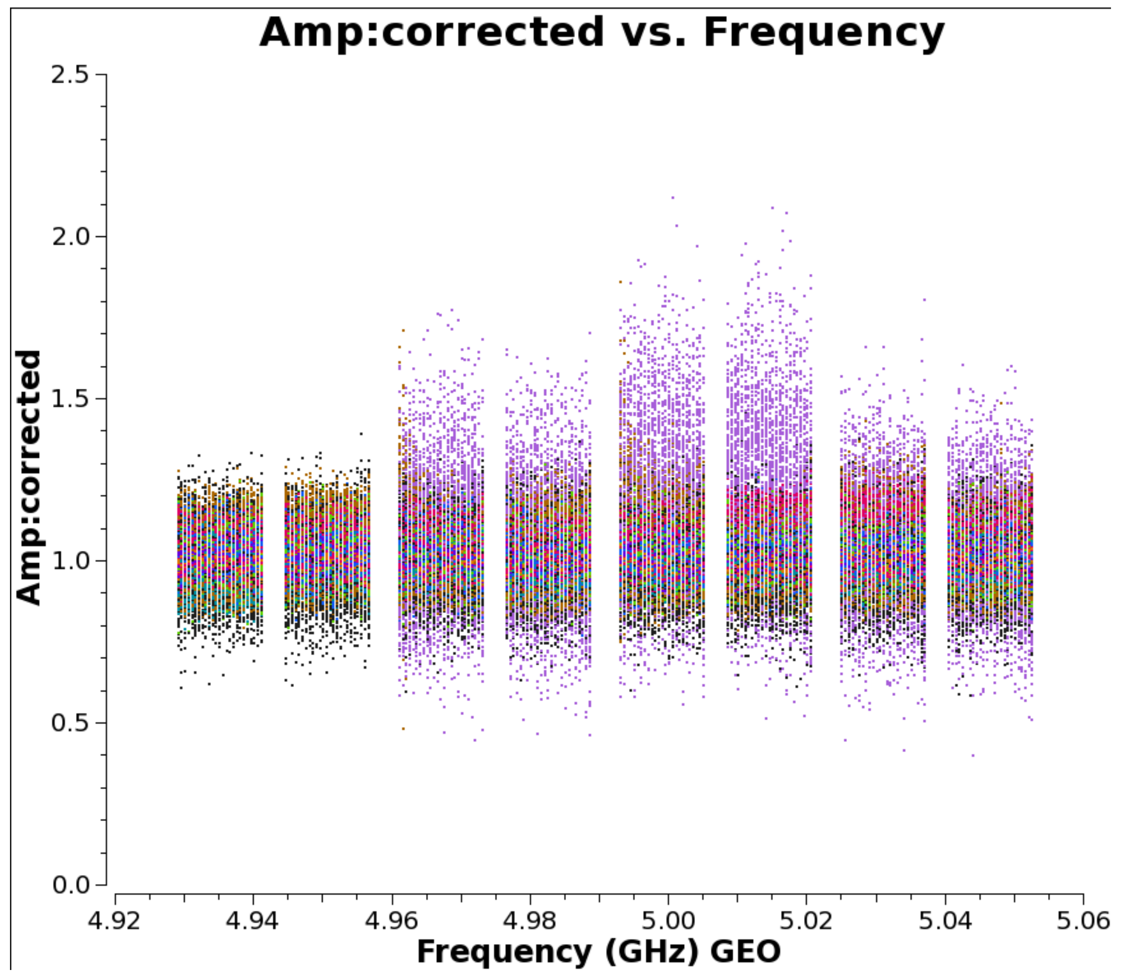
- Generate caltables for gain curves:

```
bandpass(vis=ms, field=field, refant=refant,
    gaintable=[…], solnorm=True, caltable=bptable)
```

- Generates B-type calibration tables



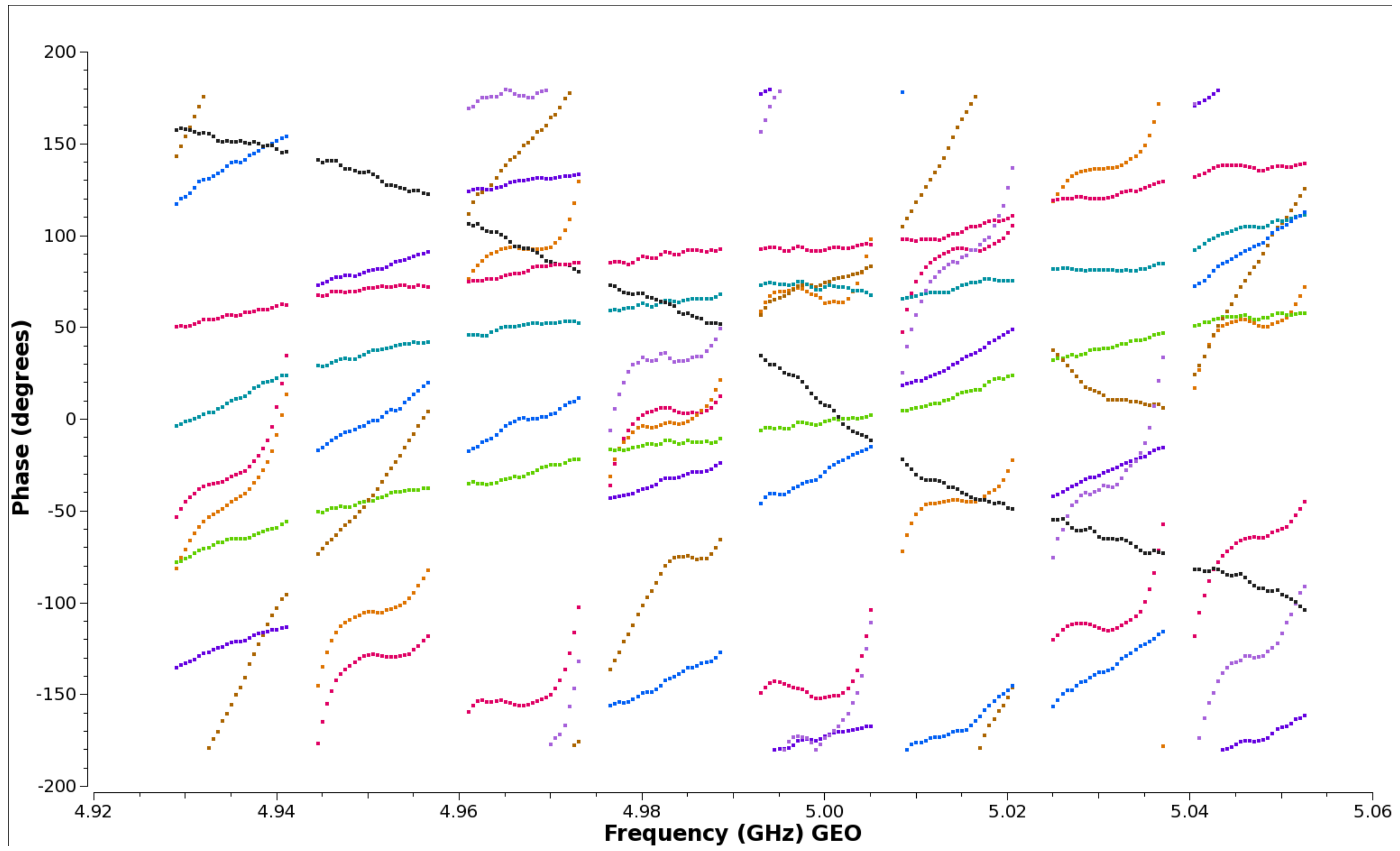


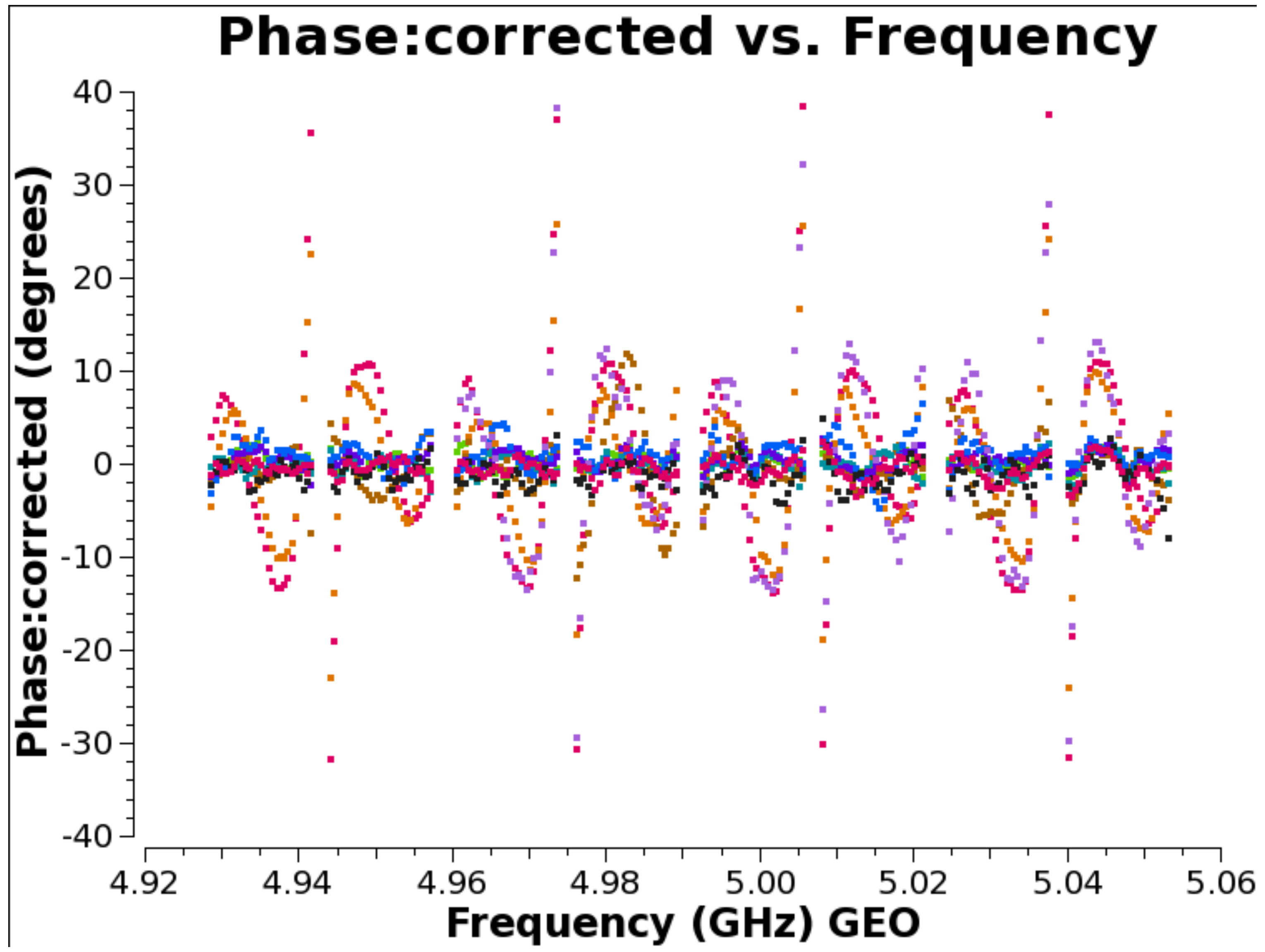


Fringe Fitting

FRING

- See lecture by Des Small on tuesday





Apply calibration

SPLIT

- Applying calibration to the whole MeasurementSet:

```
applycal(vis=ms, gaintable=[…], interp=[…], …)
```

  - Adds a CORRECTED_DATA colum; full copy of the data
- Split the MeasurementSet:

```
split(vis=ms, outputvis=splitms, field=field, …)
```

  - Supports averaging (time & frequency)
  - Needs to be run for each field you want to image
  - The `mstransform` task can also be used.
    - Ends up running the same code.

Tasks under development

EOP correction

CLCOR

- EOP (Earth Orientation Parameters) correction task
  - EOPs are used by correlator to calculate delays
  - EOPs have to measeured/modelled; final values available after a few weeks
  - predicted or non-final values may have been used during correlation
  - New task will make appropriate phase corrections
  - **Important for astrometry!**

Tasks under development

Ionospheric correction

TECOR

- Apply (dispersive) delay corrections based on TEC (Total Electron Content)
  - Uses TEC maps in IONEX format based on GPS measurements
  - IONEX files are automatically downloaded
  - **Important for low frequencies and wide bandwidths!**
  - **Mechanics are implemented but generate wrong corrections for VLBI**
  - Under investigation
- Generate caltables for ionospheric corrections:

```
from casatasks.private import tec_maps
tec_maps.create(vis=ms, doplot=False, imname=tecmap)

gencal(vis=ms, type='tecim', infile=tecmap, caltable=tectable)
```

- Generates G-type calibration table

Tutorial

- Amplitude calibration tutorial uses N14C3 dataset
- Deliberately explores some of the things that can go wrong!
- Will show you how applying the amplitude calibration will change the visibility weights of baselines.

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