VLBI observations: From scheduling to data reduction

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EUROPEAN vlbi NETWORK

JIVE Joint Institute for VLBI ERIC

ACME Astrophysics Centre for Multimessenger studies in Europe

Funded by the European Union

The path towards a good image

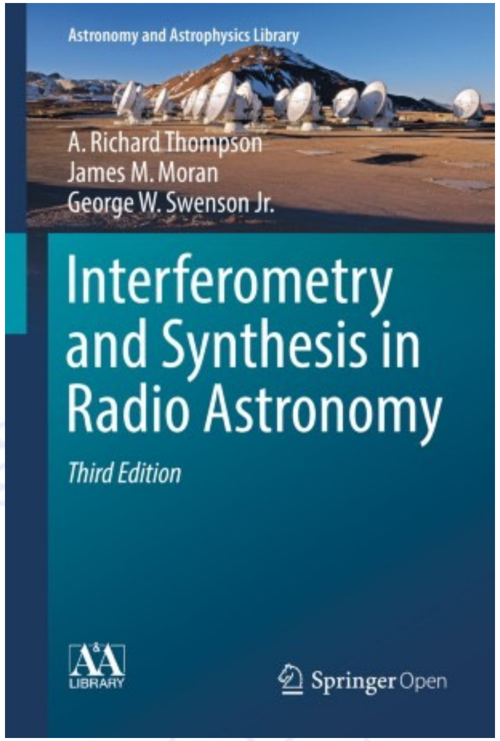
VLBI data as provided by the current observatories need to be calibrated.
Still a semi-manual process in many cases...

- *A-priori gain calibration*
- *Flagging*
- *Phase calibration*
- Imaging/cleaning
- Self-calibration & more imaging

In this lecture…

This is not a deep lecture on fundamentals of radio interferometers but…

A few slides to get the main concepts you need to be aware of (and how to apply them)!



[Interferometry and Synthesis in Radio Astronomy]

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Image by Paul Boven (boven@jive.eu). Satellite image: Blue Marble Next Generation, courtesy of Nasa Visible Earth (visibleearth.nasa.gov).


Target
$\hat{s}$
Ionosphere
Troposphere
$c\tau_{geo} = \vec{b} \cdot \hat{s}$
θ
$\vec{b}$
1
2
X
$\langle V_1 V_2^* \rangle$

Interferometers

Visibilities

- ☑ Complex numbers: $V_{i,j}\,(u,v)$
- ☑ Baseline vector: $\mathbf{b}_{i,j} = \lambda(u,v,w) = \mathbf{r}_i - \mathbf{r}_j$
- ☑ Sky intensity: $I_\nu(l,m)$

$$V_{i,j}(u,v) = \int I_\nu(l,m)\, \mathrm{e}^{-2\pi i\,(ul+vm)}\mathrm{d}l\;\mathrm{d}m$$

The interferometer measurement equation

Gain amplitude and phase

Baseline-based errors

Errors due to elevation

Opacity and path length variation

$$V_{i,j}^{\text{obs}} = M_{i,j} B_{i,j} G_{i,j} D_{i,j} E_{i,j} P_{i,j} T_{i,j} V_{i,j}^{\text{true}}$$

Bandpass response

Change in parallactic angle

Instrumental polarization

The interferometer measurement equation

It’s all about phases

$$\tau_{\mathrm{obs}} = \tau_{\mathrm{geom}} + \tau_{\mathrm{src}} + \tau_{\mathrm{trop}} + \tau_{\mathrm{iono}} + \tau_{\mathrm{instr}} + \epsilon_{\mathrm{noise}}$$

Source/Station/Earth orientation

(correlator)

Source structure

Propagation

Instrumental effects

(calibration)

Phase evolution

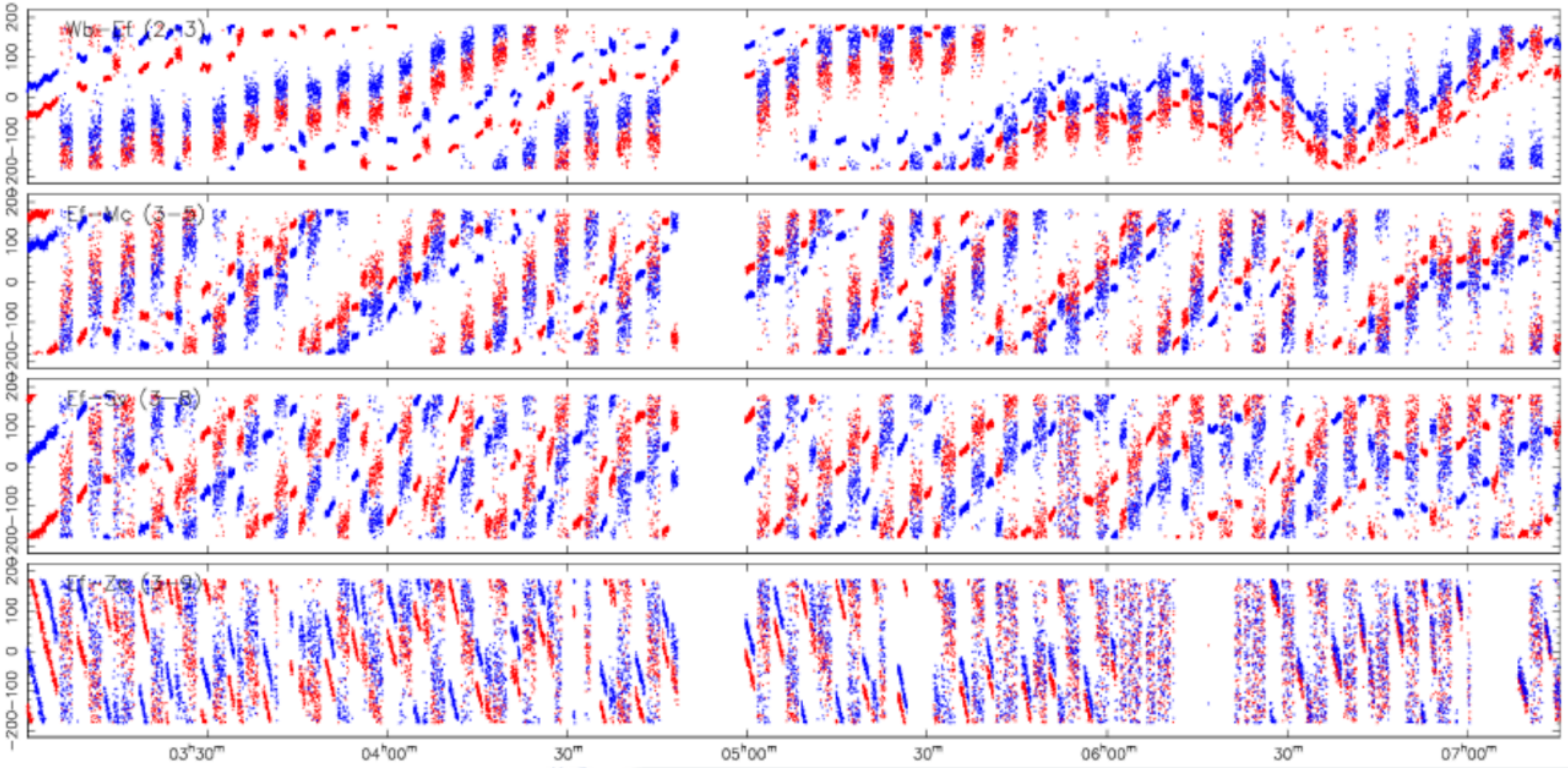
Phases may evolve faster with time for longer baselines.

Phases: φ

Delays: $\dfrac{\partial\varphi}{\partial\omega}$

Rates: $\dfrac{\partial\varphi}{\partial t}$

(fringe-fitting)



Point-like source at the phase center (phases should be zero!)

The need for additional sources

Bright (high S/N) and compact sources are mandatory for calibration purposes.

Target: faint or resolved? —> requires a nearby phase-calibrator source.

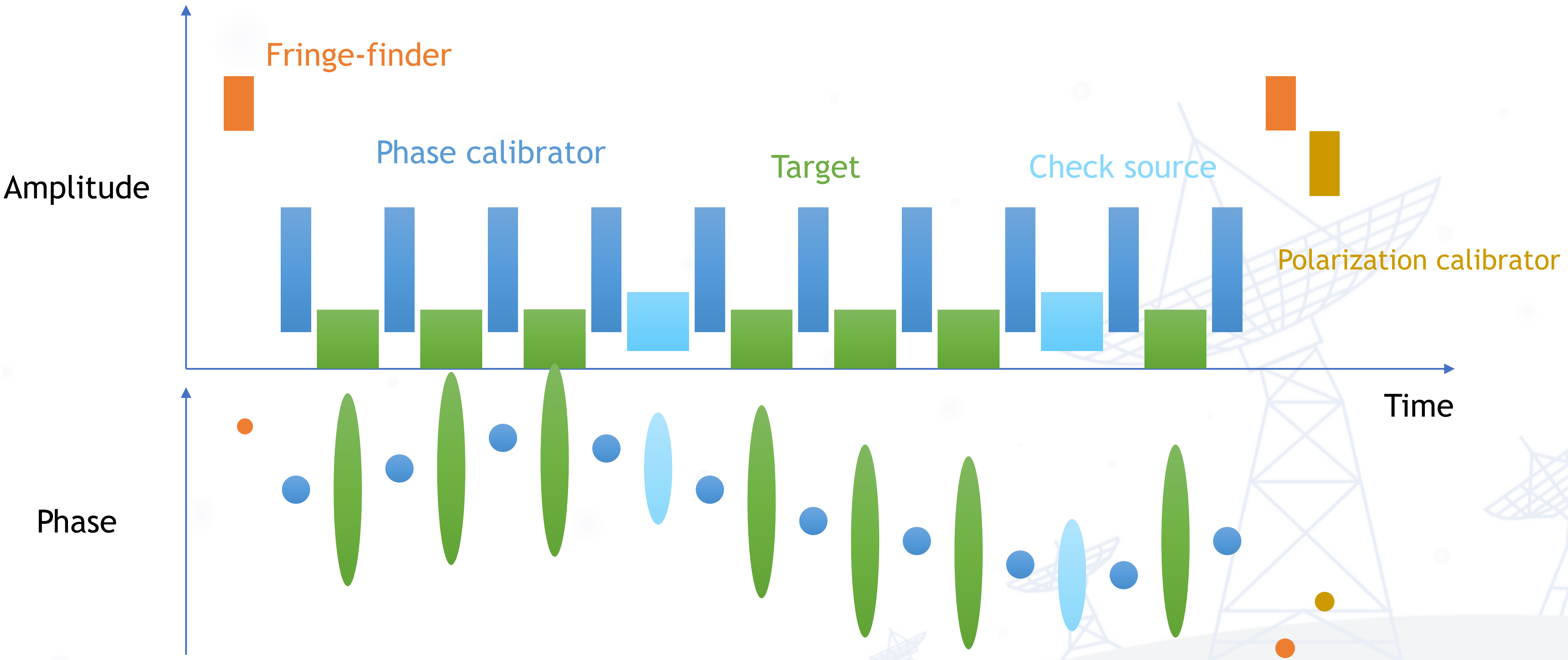
Absolute astrometry? —> requires a nearby calibrator source.

Phase calibrator: strong and compact source within a few degrees.

Fringe-finders (bandpass calibrators): strong sources, can be farther away.

Polarization calibration? —> unpolarized calibrator or with known polarization degree

A typical VLBI observation



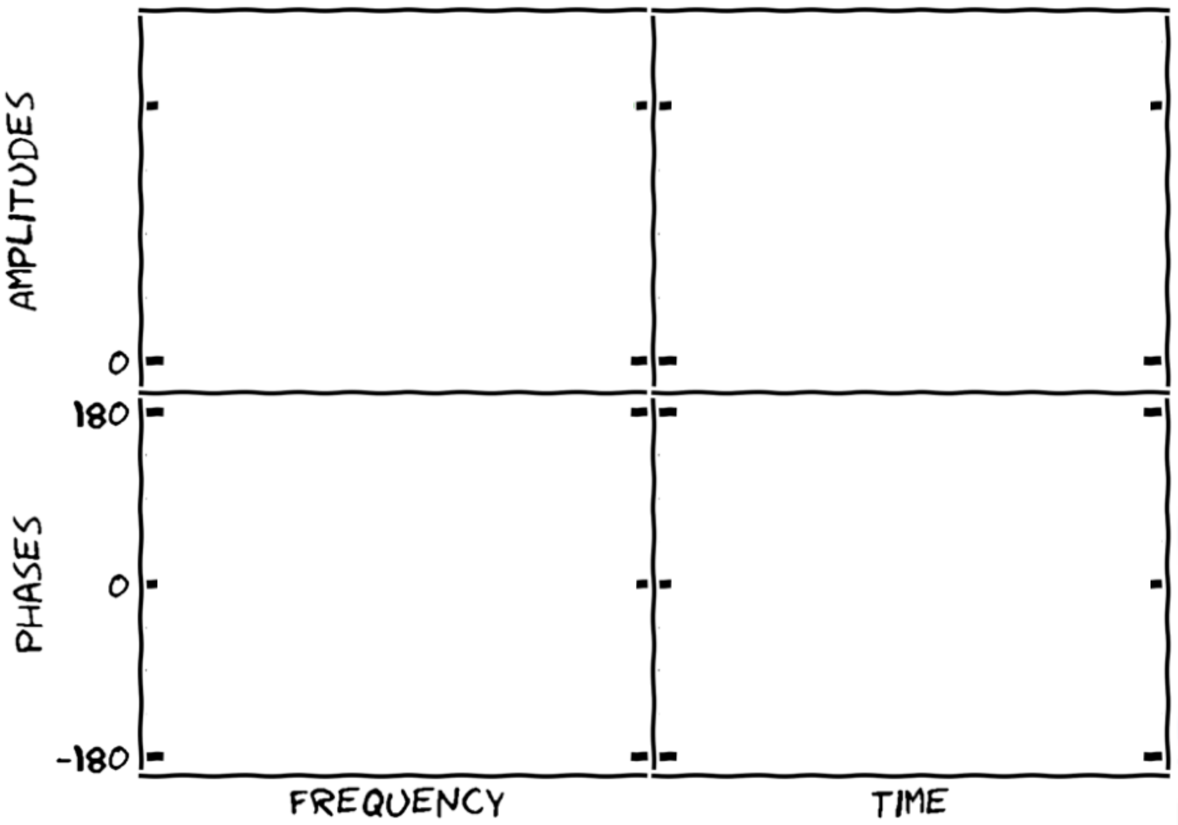
Calibrating your data

It all comes down to have a good calibration strategy

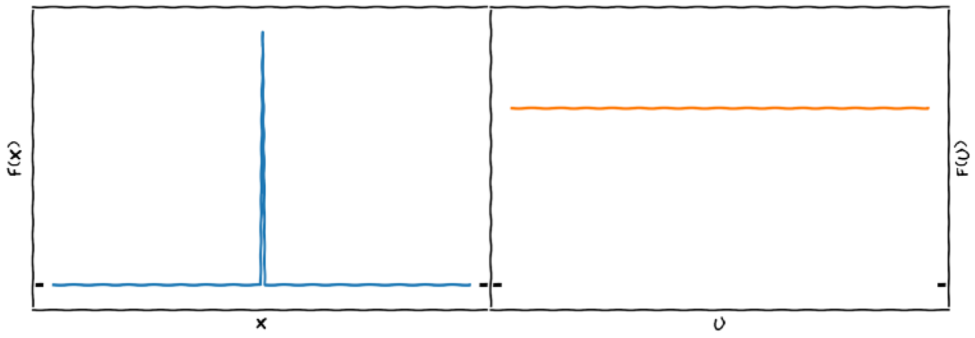
Calibrating your data

Let's remember Fourier transforms and amplitudes and phases…

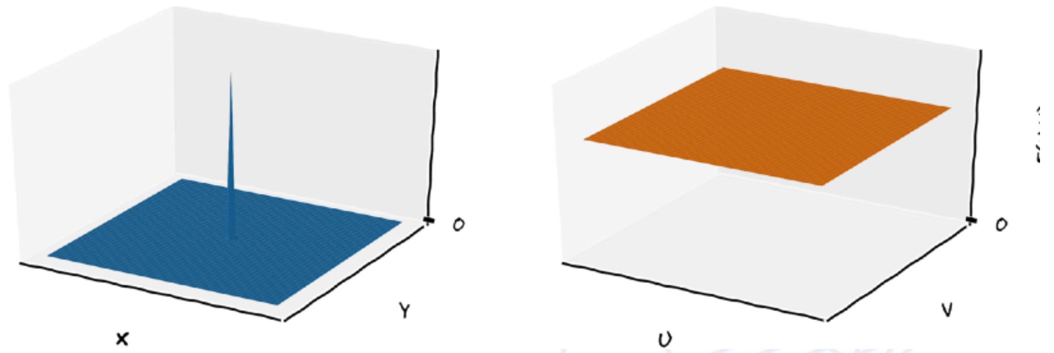
If we have a point-like source right at the phase center, it will look like… (for a given baseline)?



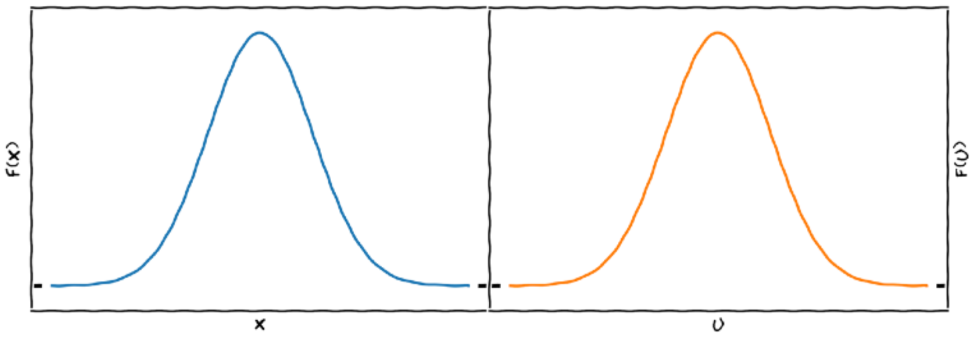
[Reminder] Fourier transforms



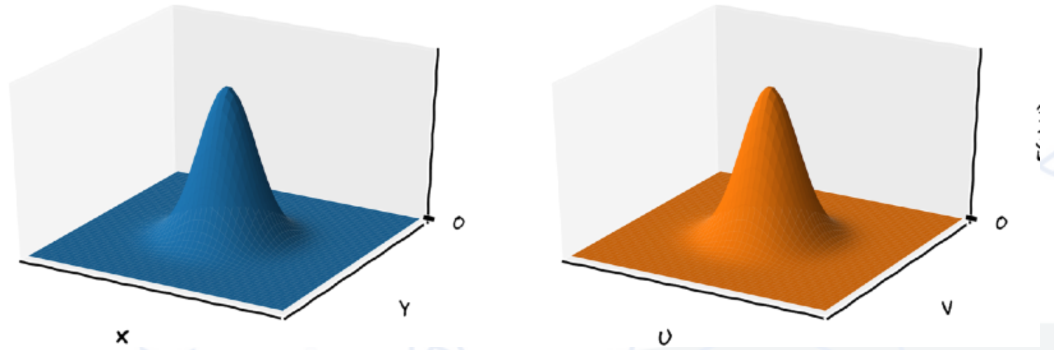
A Delta function is transformed into a constant.
* If offset from x = 0, then into a sinusoidal function.



A 2D Delta function is transformed into a plane (any U, V point sees the same value).



A Gaussian function is transformed into another Gaussian function.

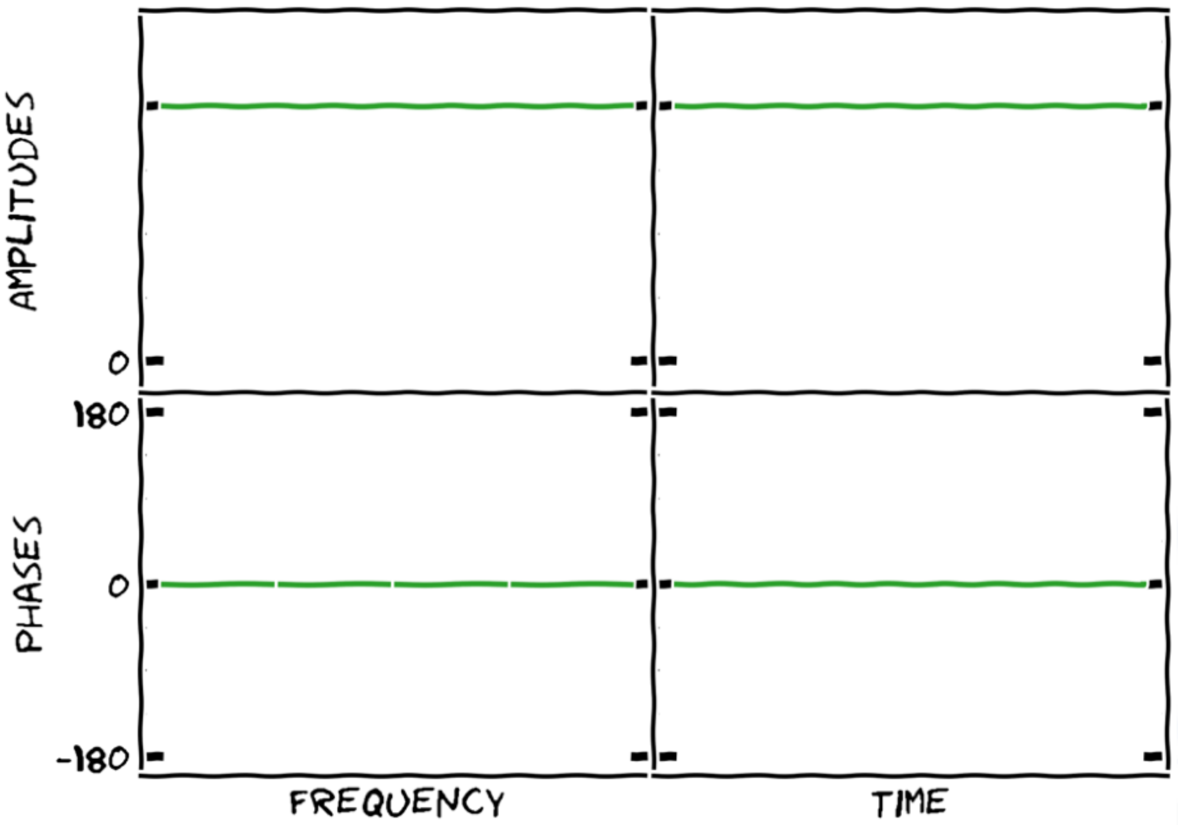


A 2D Gaussian function is transformed into a 2D Gaussian.

Calibrating your data

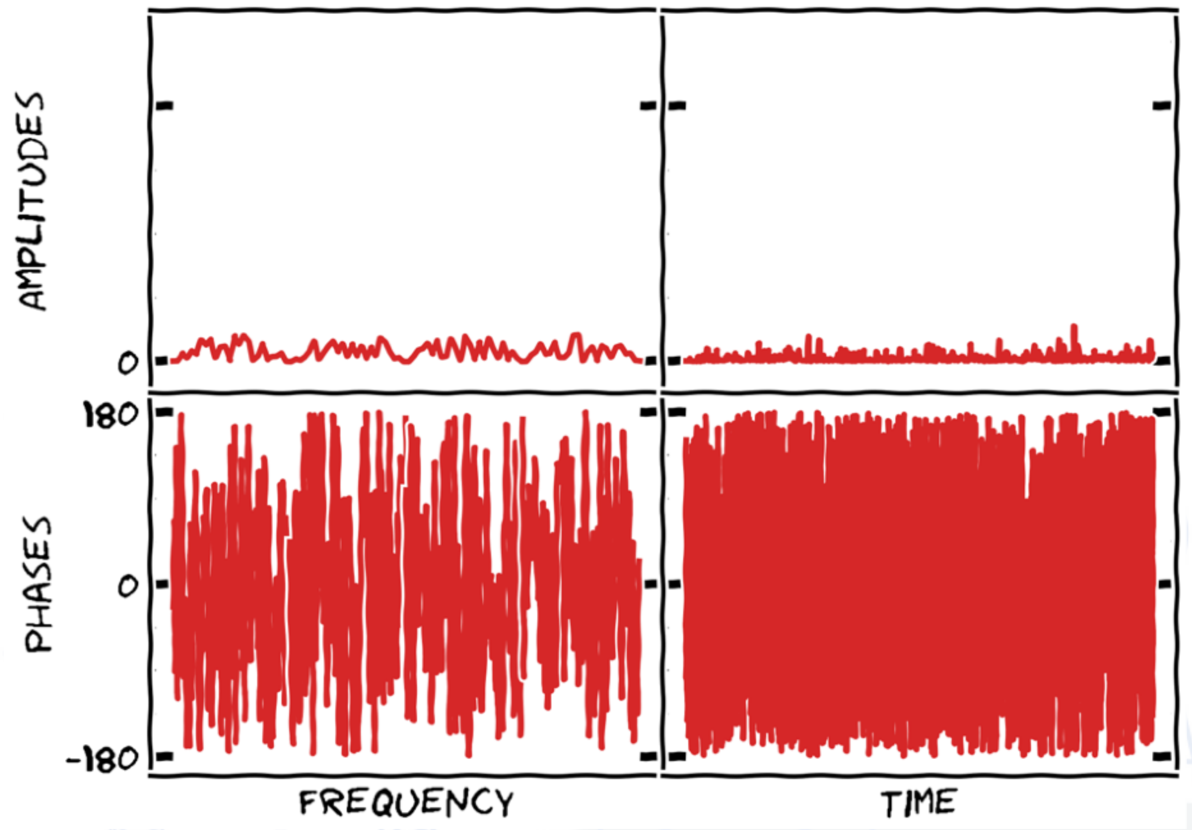
Let's remember Fourier transforms and amplitudes and phases…

If we have a point-like source right at the phase center, it will look like… (for a given baseline)?

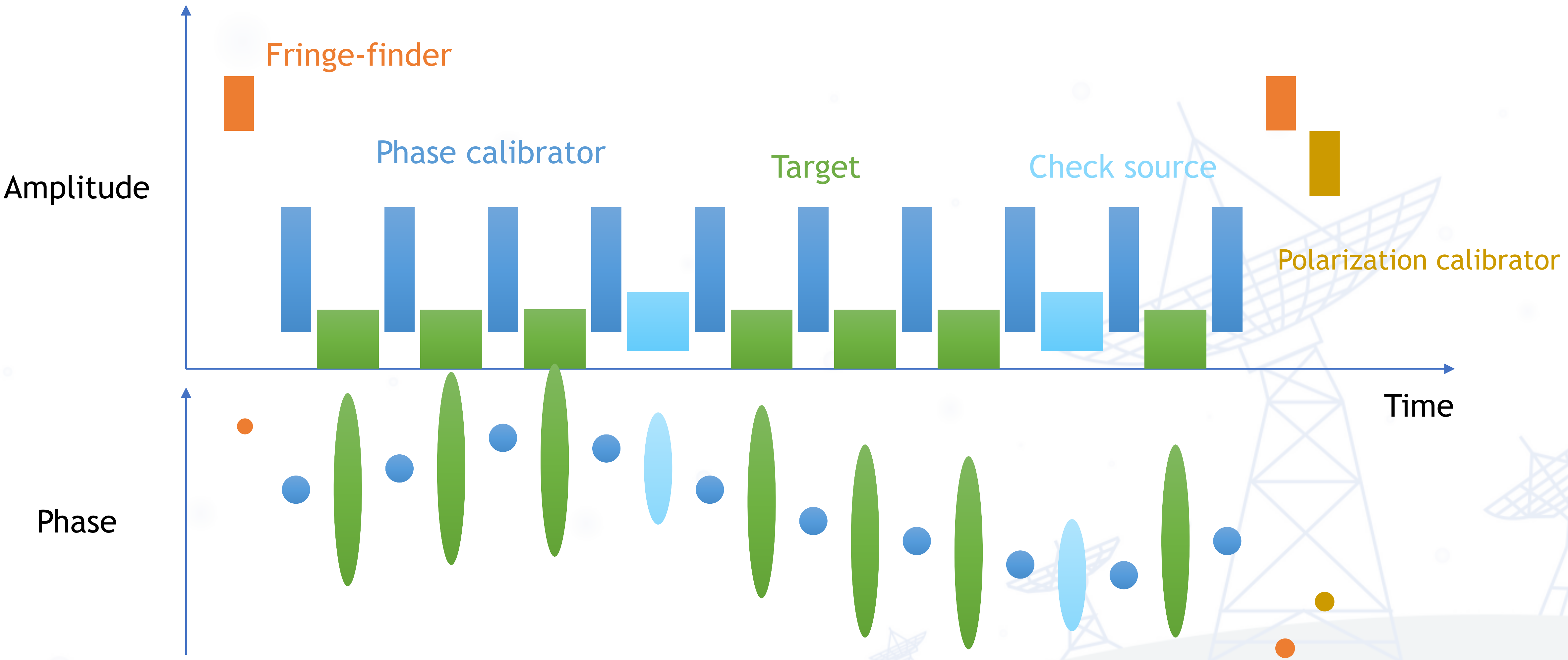


Calibrating your data

But in general this will be your target!

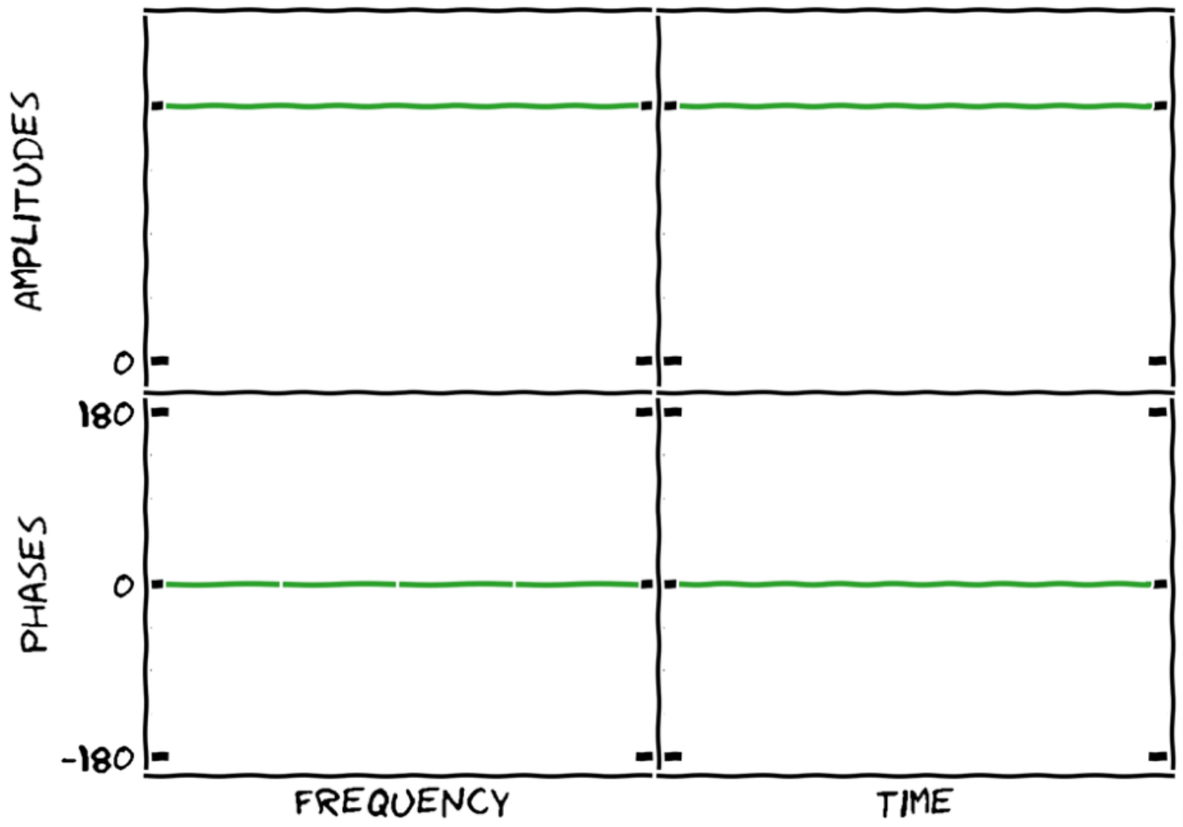


A typical VLBI observation



Calibrating your data

Our perfect point-like source in "real" data



Calibrating your data

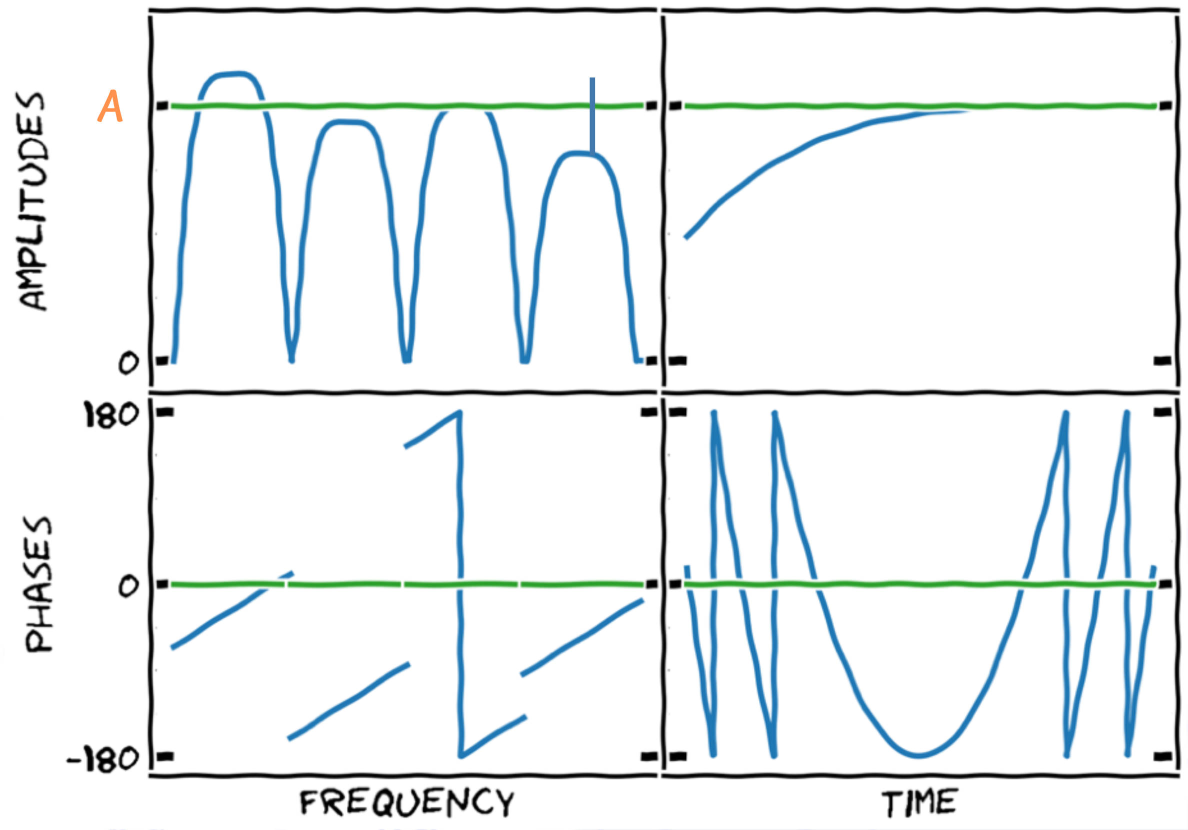
A-priori gain calibration

Telescopes record *temperatures* or *voltages*, but not **Jansky units.**

Necessity to apply a conversion to the amplitudes in our visibilities.

Connected interferometers rely on **amplitude calibration sources.**

VLBI relies on **system temperatures.**



Calibrating your data

A-priori gain calibration

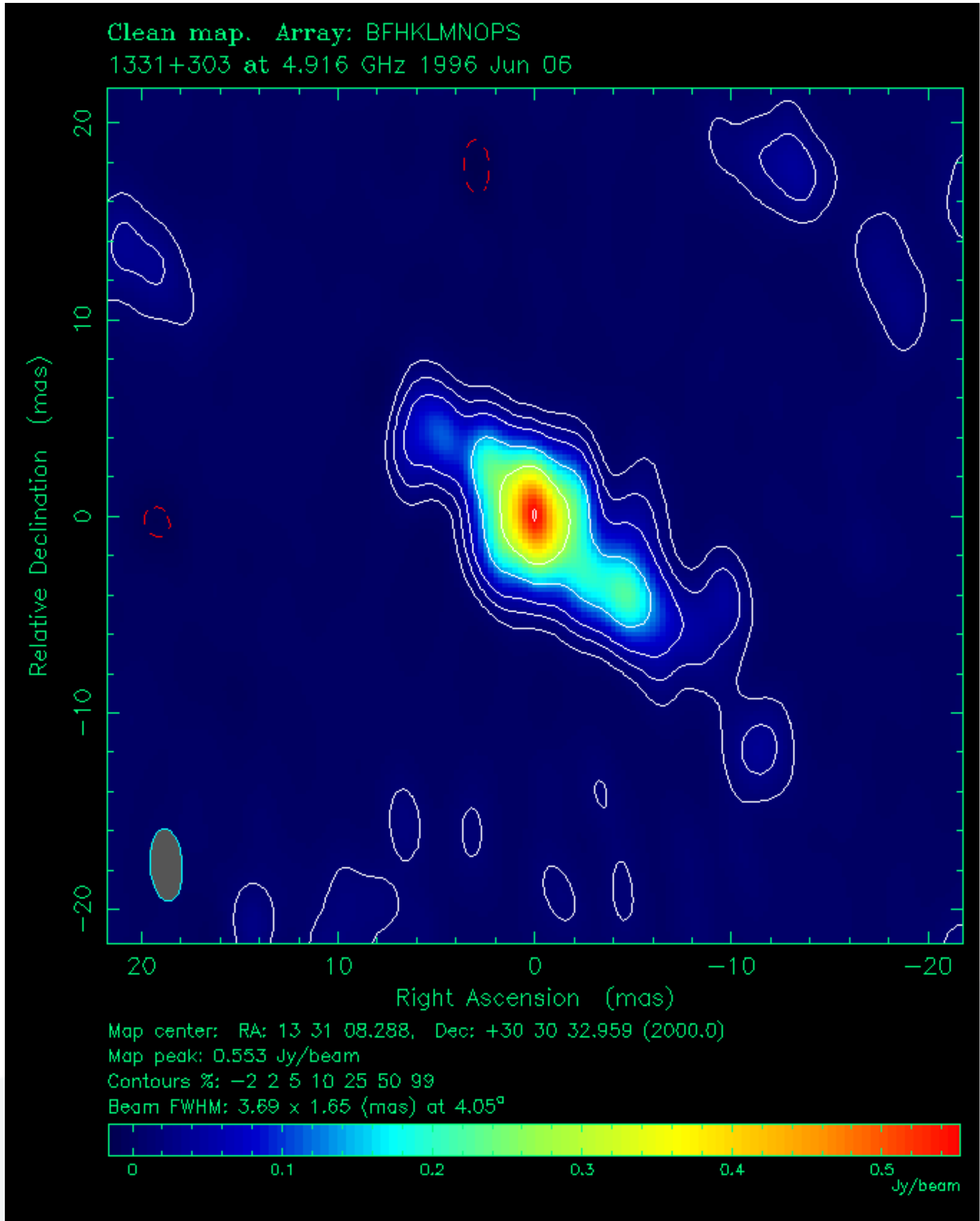
Amplitude calibration sources:

A source that has a known ***flux*** and does not vary in time.

In VLBI:

– Most of the sources are resolved to some extend.

– The compact ones are typically highly variable.



Calibrating your data

A-priori gain calibration

System temperature:
“Power” measured by the station only from the system noise.

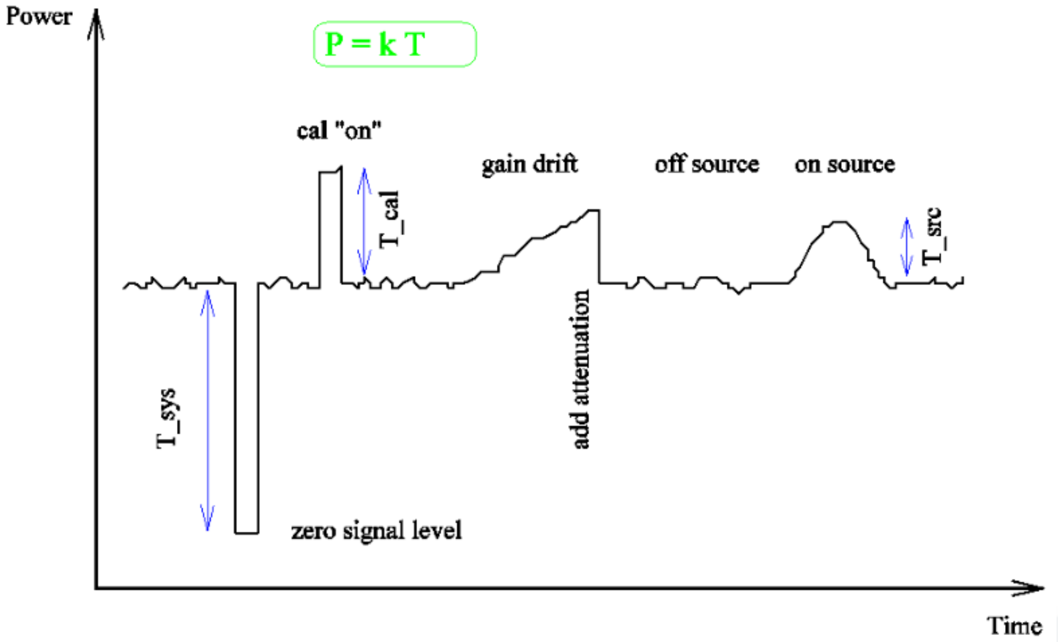
System Equivalent Flux Density (SEFD).
Flux density of a fictitious source delivering the same power as the system noise.

Gain (or sensitivity):
Increase in *Temperature* for a source of 1 Jy.

Absolute gain: DPFU (degrees per flux unit)

Gain curve: dependency with zenith angle (elevation, etc...).

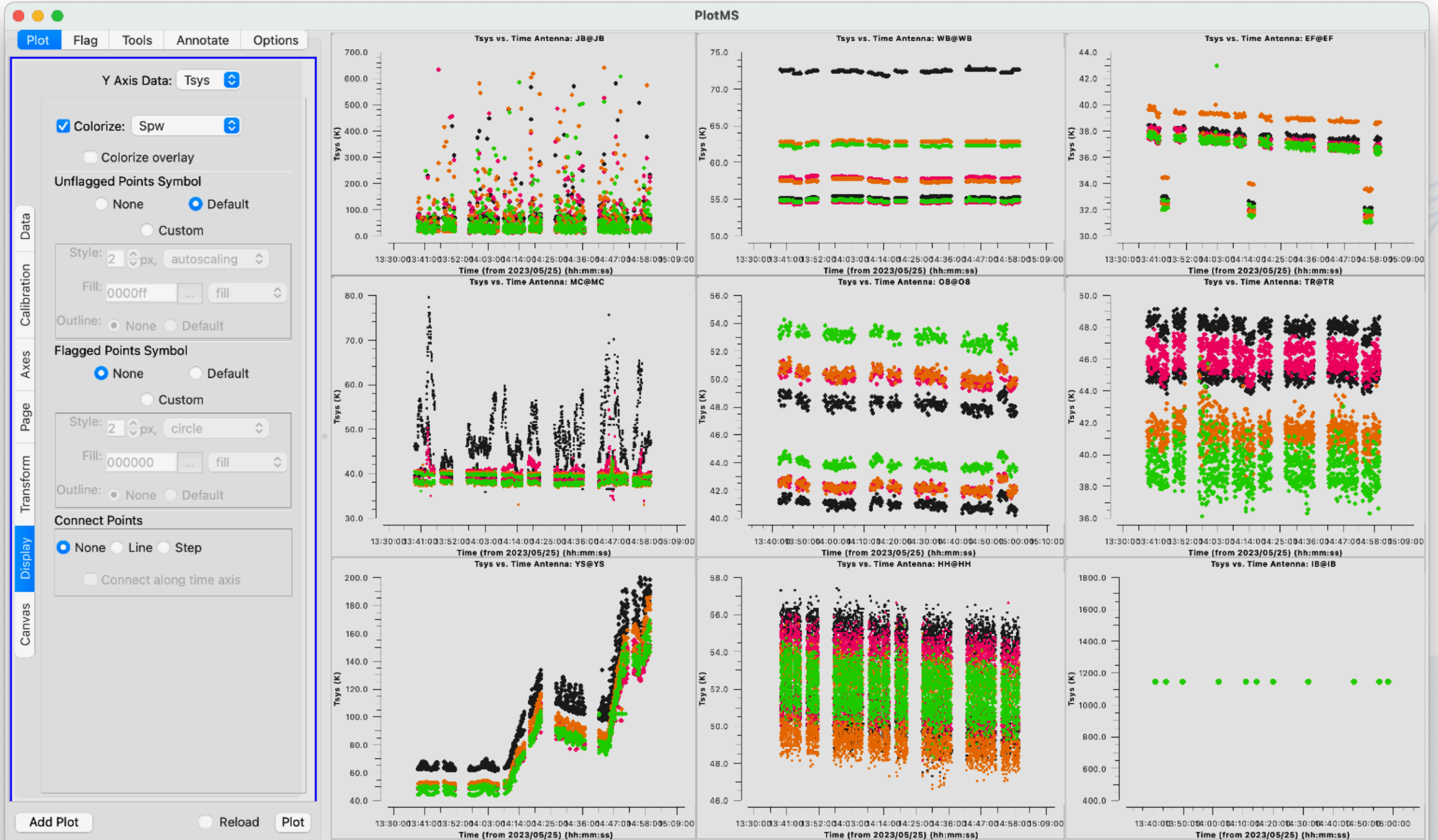
$$\mathrm{SEFD} = \frac{T_{\mathrm{sys}}}{\mathrm{DPFU} \cdot g(z)}$$



Always ~10-15% uncertainty in the absolute scale!

Calibrating your data

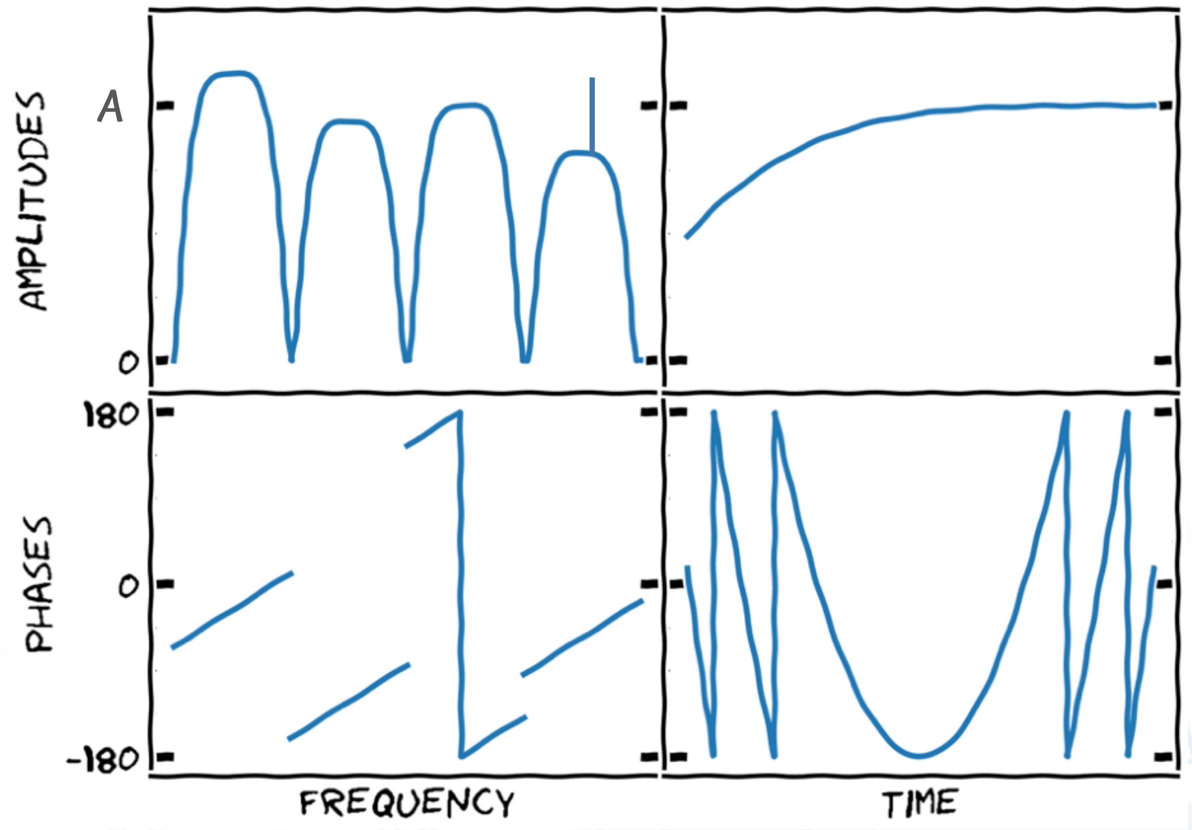
A-priori gain calibration



Calibrating your data

A-priori gain calibration

Our perfect point-like source in “real” data



Calibrating your data

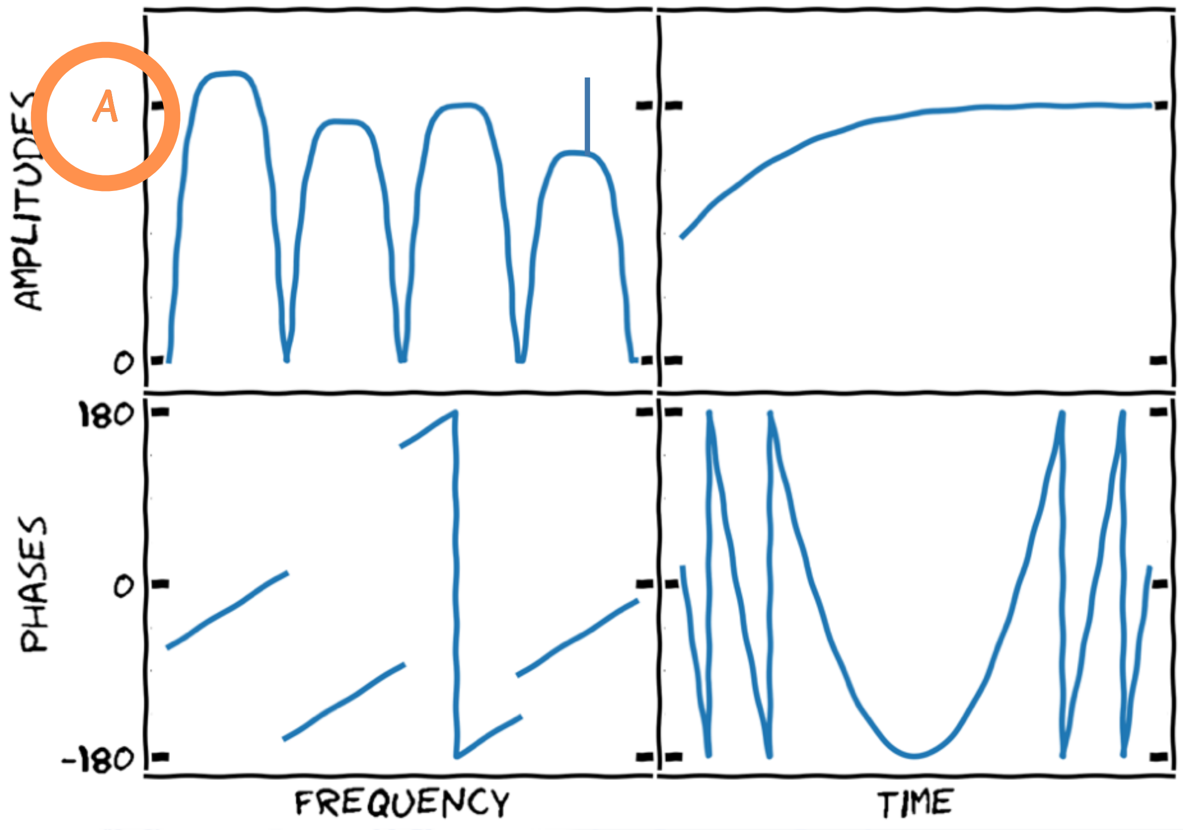
A-priori gain calibration

In EVN data, the T_{sys} and gain curve (GC) **information is included in the MS data** *(unless observations are before January 2022)*.

You can directly create a calibration table:

```
gencal(vis='n23c2.ms',
       caltable='n23c2.tsys',
       caltype='tsys',
        uniform=False)

gencal(vis='n23c2.ms',
        caltable='n23c2.gcal',
        caltype='gc')
```



Calibrating your data

Ionospheric calibration (only if you observe at < 5 GHz)

The ionosphere contributes to the light path.

And it's a $\propto \nu^2$ relation.

–> There are maps of the ionospheric total electron content (TEC) across the world, that can minimize this contribution.

–> Or via dispersive fringe fit.

```
from casatasks.private import tec_maps

tec_maps.create(vis='n23c2.ms',
                doplot=True,
                imname='n23c2.iono')

gencal(vis='n23c2.ms',
       caltable='n23c2.tecim',
       infile='n23c2.iono.IGS_TEC.im',
       caltype='tecim')
```

```
> calibration table 'n23c2.tecim'.
```

Or in **fringefit** (see later) with the option:

```
paramactive=[True, True, True]
```

Calibrating your data

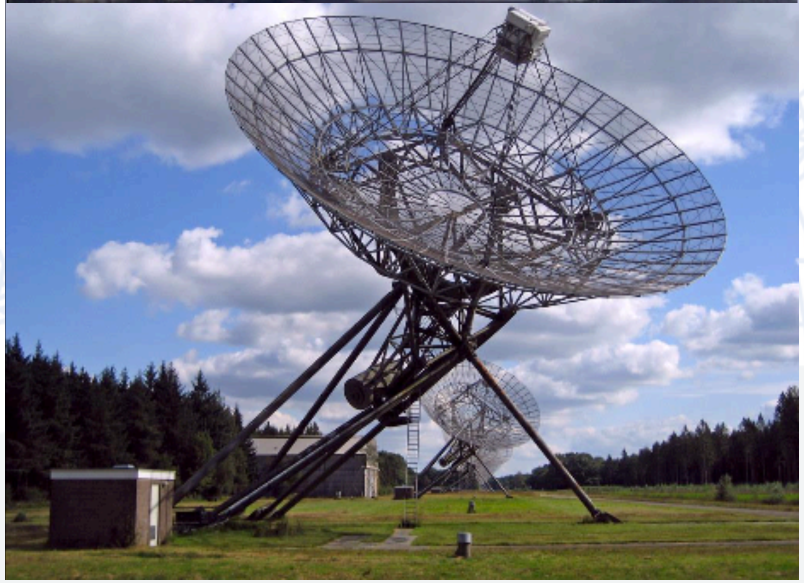
Parallactic angle correction

For alt-azimutal telescope mounts, the sky rotates along the observation.

This needs to be taken into account.

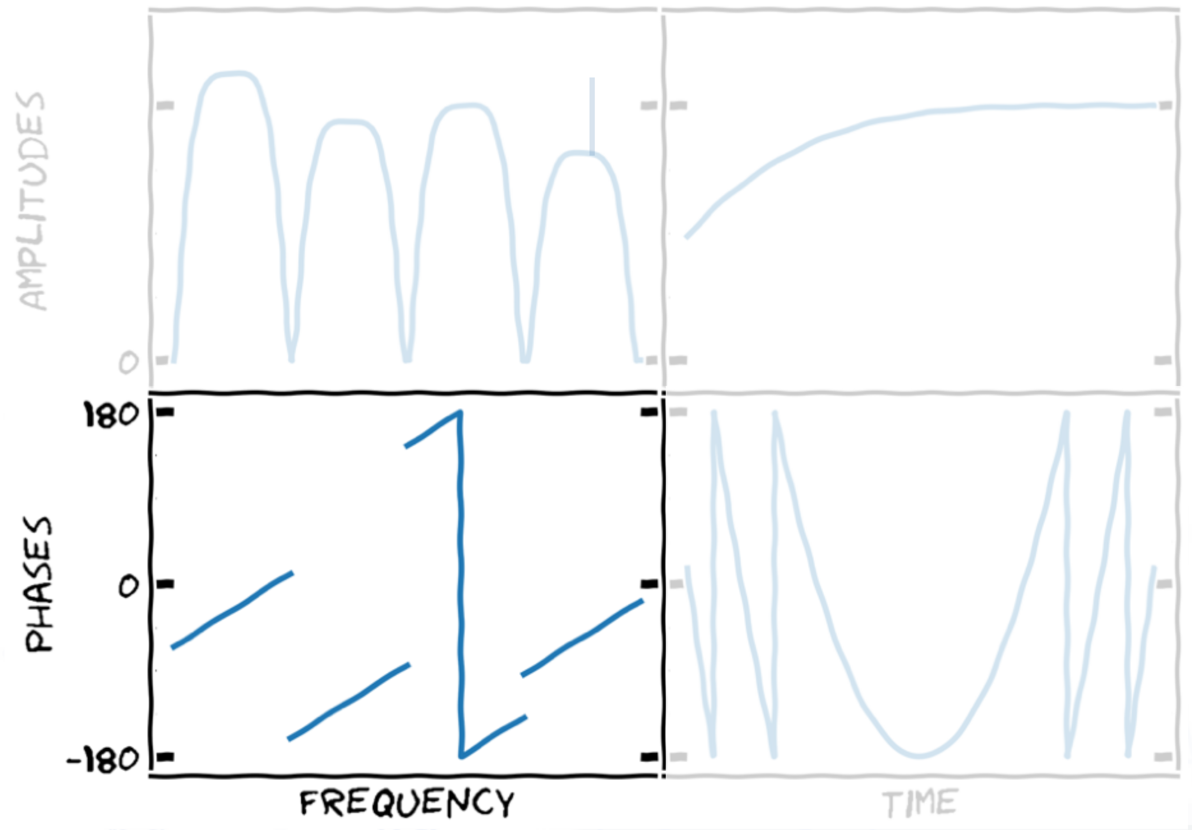
No single step in CASA, but **keep the following parameter during all main calibration steps:**

```
parang=True
```



Calibrating your data

Let's start with these phases at a particular time…



Calibrating your data

Instrumental delay calibration

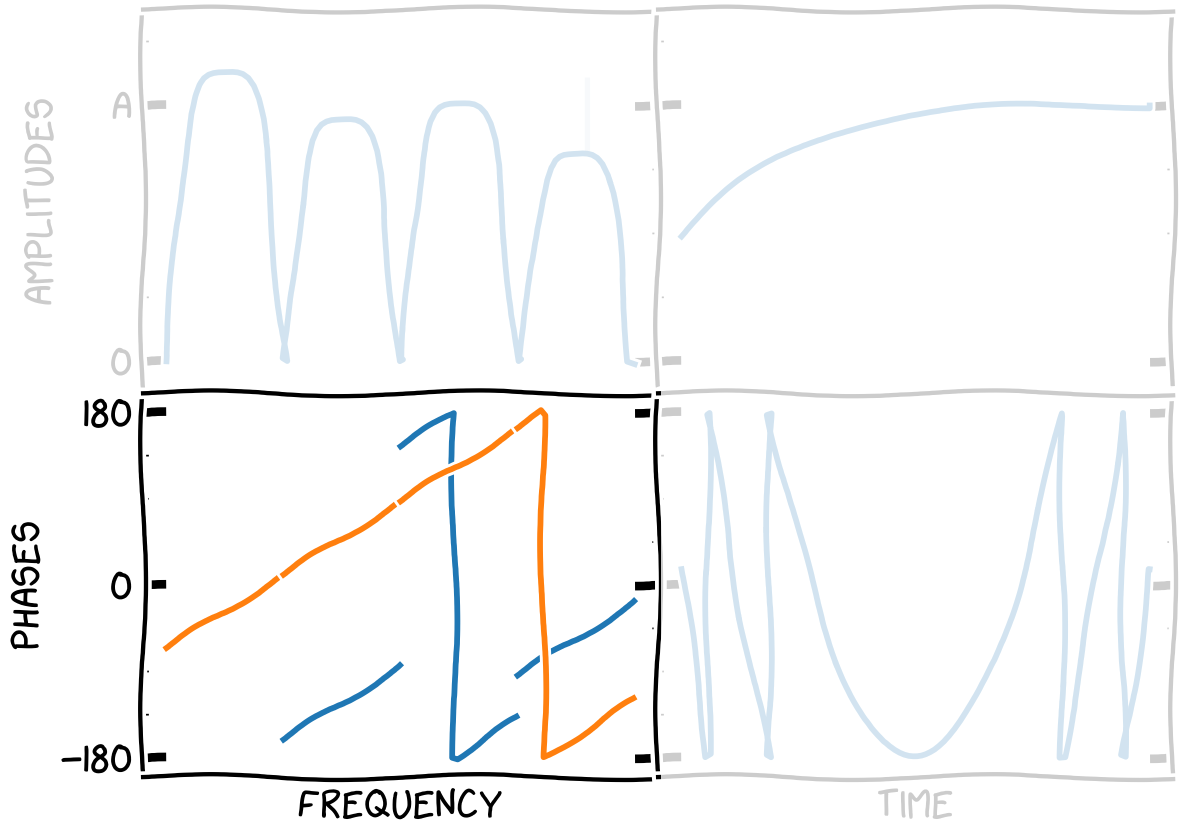
Phase jumps between (some) subbands.

Signal paths go through different hardware.

These jumps should be consistent along the observation.

–> Pick up just a single scan on the brightest source (e.g. fringe finder). *All antennas must be present.*

```
fringefit(vis='n23c2.ms',
    caltable='n23c2.sbd',
    field='J0854+2006',
    timerange='14:00:00~14:01:00',
    solint='inf',
    zerorates=True,
    refant='EF',
    minsnr=10,
    gaintable=['n23c2.gcal', 'n23c2.tsys'],
    interp=['nearest', 'nearest,nearest'],
    parang=True)
```



Calibrating your data

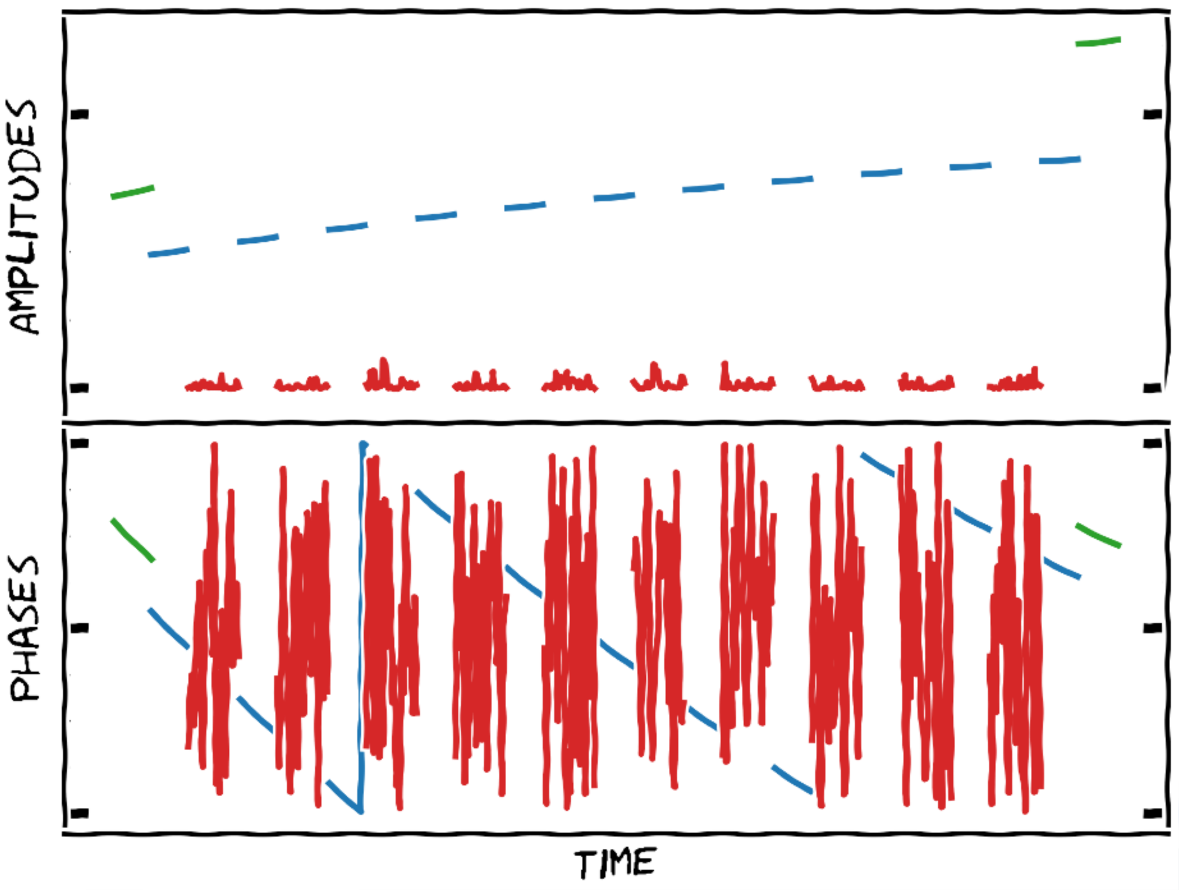
Multi-band delay (global fringe-fit) calibration

Frequency- and time-dependent phase calibration.

Fit the evolution of delays and rates for each calibrator source along the observation.

Corrections depend on the propagation effects (atmosphere).

```
fringefit(vis='n23c2.ms',
    caltable='n23c2.mbd',
    field='J0854+2006',
    timerange='',
    solint='60s',
    zerorates=False,
    refant='EF',
    combine='spw',
    minsnr=5,
    gaintable=['n23c2.gcal', 'n23c2.tsys', 'n23c2.sbd'],
    interp=['nearest', 'nearest,nearest', 'nearest'],
    parang=True)
```



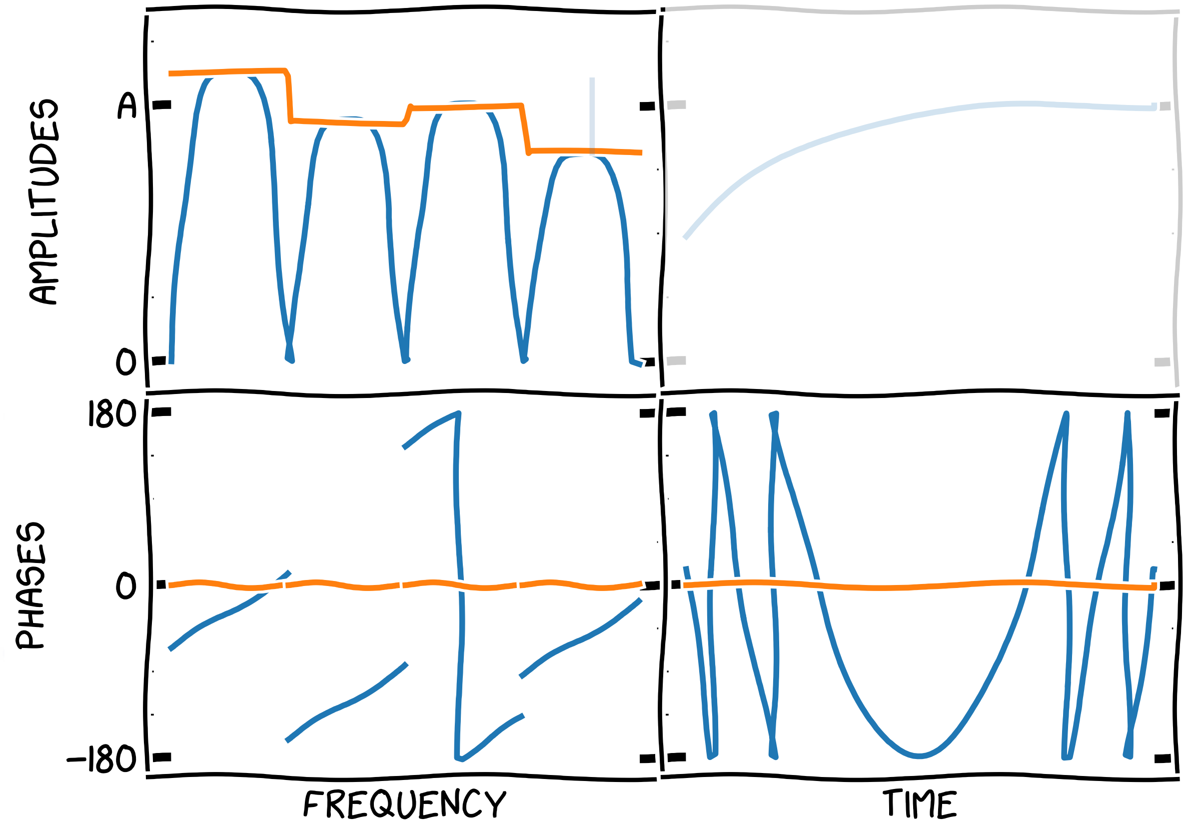
Calibrating your data

Bandpass calibration

Correct for the effect of the bandpass in the different subbands.

Instrumental effect. Constant in time/source (but different for each observation).

Use the brightest source for that (highest S/N)
—> fringe finder(s).




```
bandpass(vis='n23c2.ms',
    caltable='n23c2.bpass'
    field='J0854+2006',
    solnorm=True,
    solint='inf',
    refant='EF',
    bandtype='B',
    gaintable=['n23c2.gcal', 'n23c2.tsys', 'n23c2.sbd', 'n23c2.mbd'],
    interp=['nearest', 'nearest,nearest', 'nearest', 'linear'],
    spwmap=[[],[],[],[0,0,0,0]],
    parang=True)
```

Calibrating your data

Apply calibration and split

Once you apply the calibration, it is recommended to **split** (**mstransform**) the data to generate a MS with a single source and all calibration applied (thus *CORRECTED_DATA -> DATA*).

But **keep in mind:** if you average in frequency/time, then your field of view (FoV) is more limited.

For compatibility with **Difmap** (if you are going to use it), then:

```
mstransform(vis='n23c2.ms',
    outputvis='n23c2.J0905+2052.ms',
    field='J0905+2052',
    datacolumn='corrected',
    keepflags=False,
    chanaverage=True,
    chanbin=64)
```

```
exportuvfits(vis='n23c2.J0905+2052.ms',
    fitsfile='n23c2.J0905+2052.uvfits',
    datacolumn='data',
    combinespw=True,
    padwithflags=True,
    multisource=False)
```

Calibrating your data

Self-calibration

A *second-order* calibration for the phases.

Solve the amplitude-related issues.

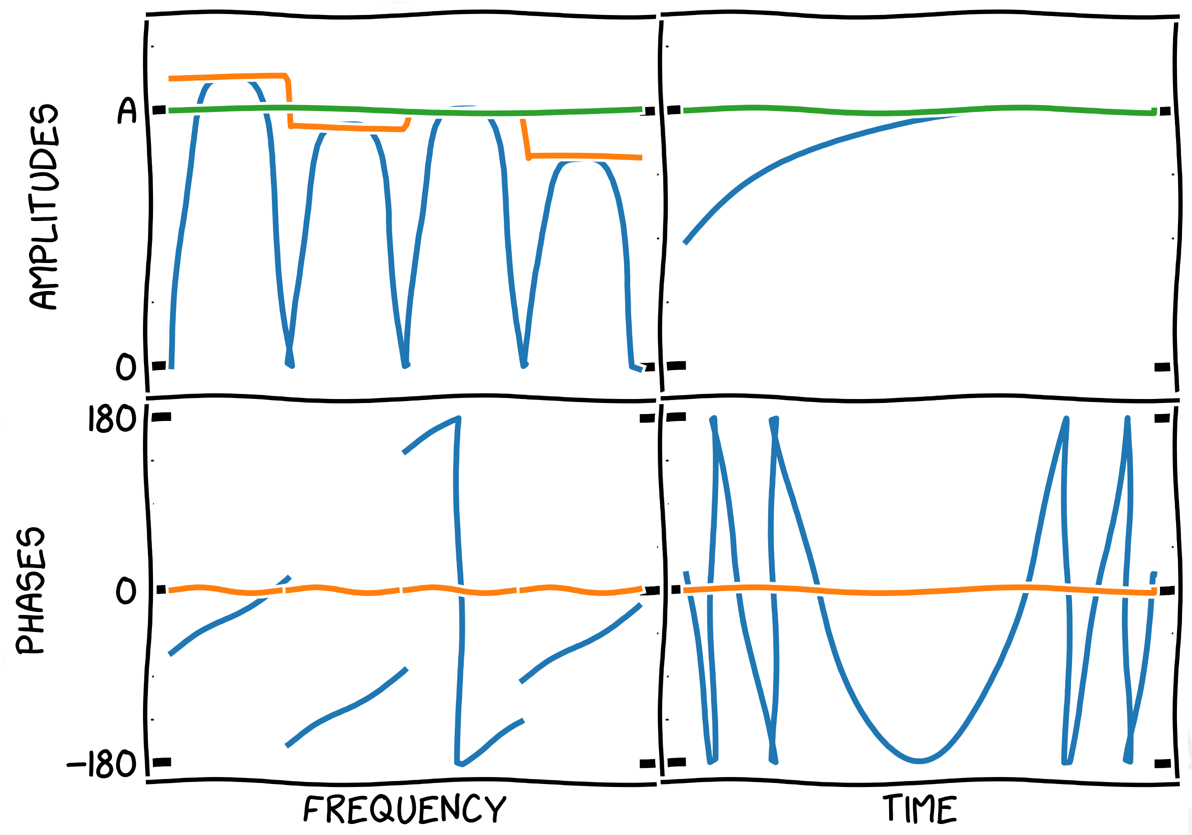
–> It will significantly increase the S/N of your images.

–> But it breaks the astrometry!

Same way as you saw in previous tutorials.

(with some remarks…)

But you need to image first!



Calibrating your data

Imaging

VLBI particularities:

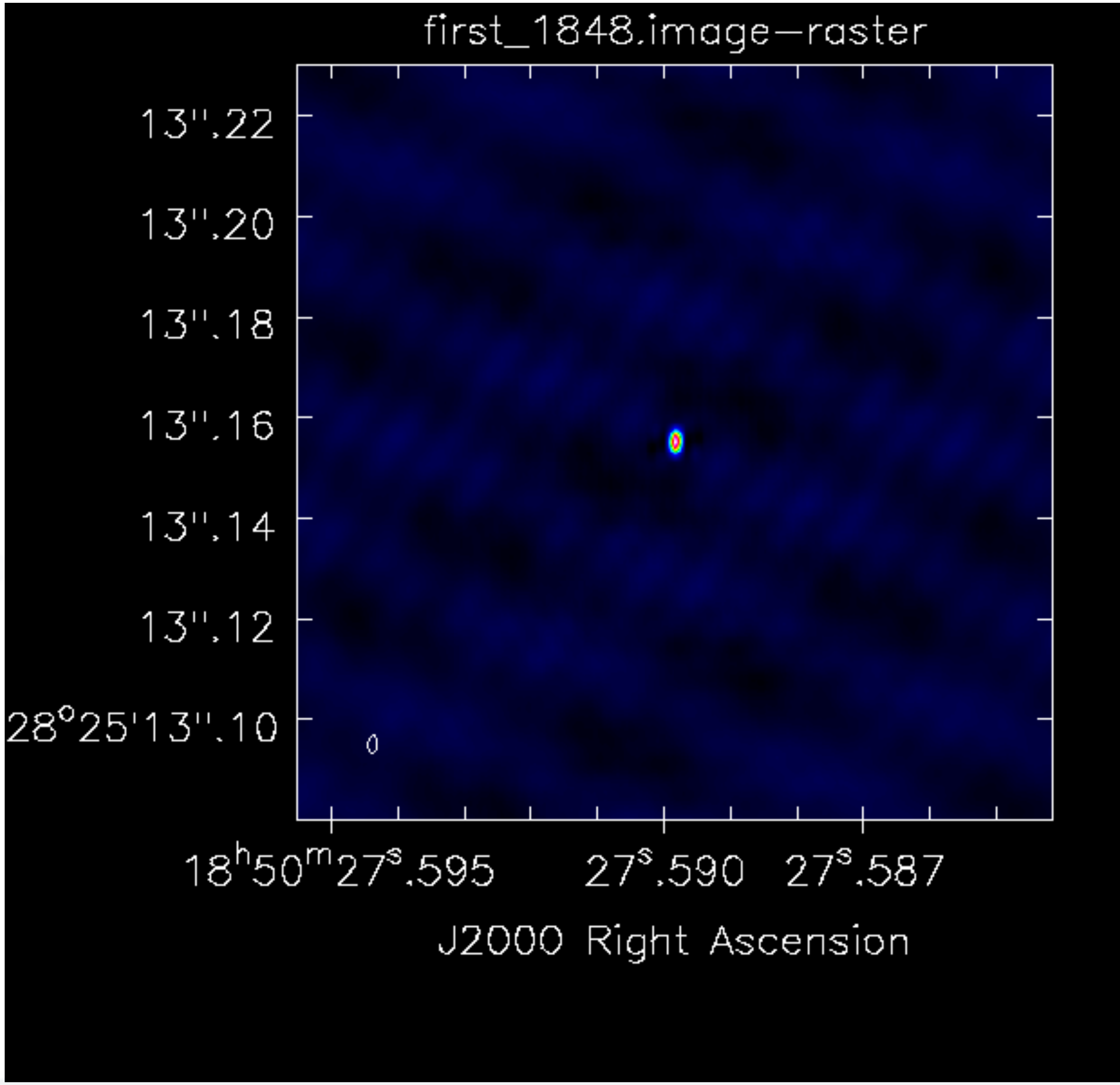
–> *uv* coverage is much poorer.

–> Single source in your entire field.

–> Non-gaussian noise.
Stronger spikes in the imaged field:
6-σ level required for detections.

–> Measured flux densities may (slightly) differ when doing in the **image plane** or ***uv* plane**.

–> Different **weighing** schemes may provide quite different images.



Calibrating your data

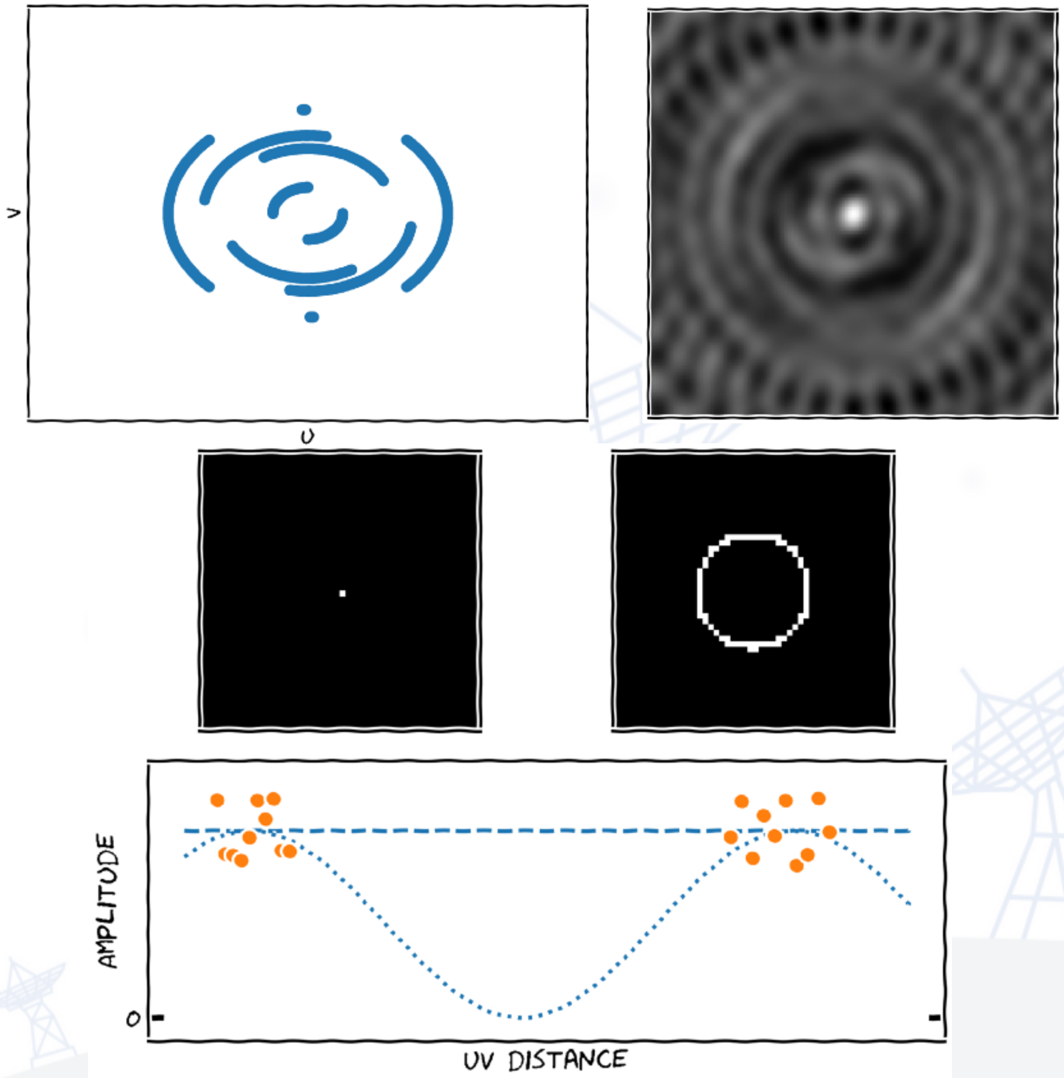
Imaging and self-calibration

Getting an accurate model of your source is critical!

Self-calibration "modifies" your data to fit your model.

Can easily scale up/down your station amplitudes (artificially).

It needs high signal-to-noise…



NOTE: *parang=False* from now on!

Summary

EVN Data Reduction Guide (AIPS & CASA, *to be updated soon*):
evlbi.org/evn-data-reduction-guide

Tutorial for the advance sessions:

jive.eu/jvs2025 -> data reduction guide

General information for EVN astronomers (and links to different tutorials):
evlbi.org/evn-for-astronomers

Pipelines are coming online!

VPIPE (Jack Radcliffe), *rPicard* (Michael Janssen), *PSRVLBIReduce* (Hao Ding & Adam Deller), ...