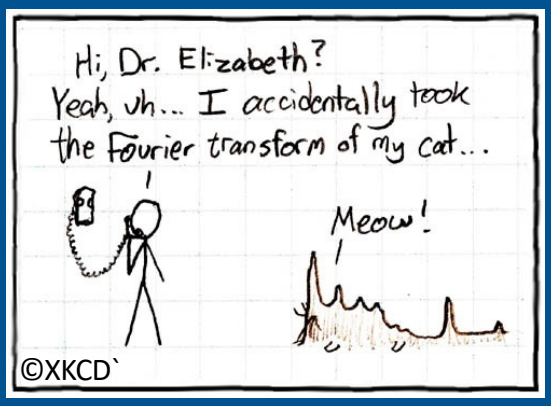
Very Long Baseline Interferometry



Ilse van Bemmel
(JIVE)

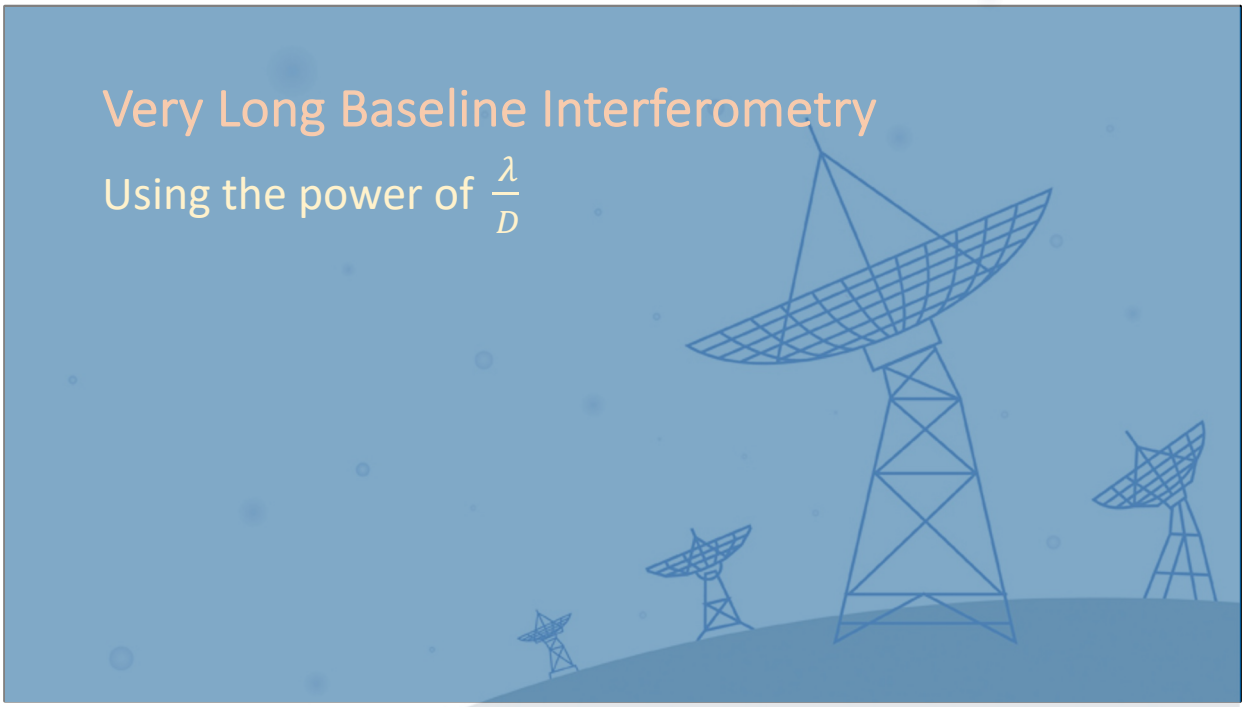
Overview of VLBI lectures

- Three sessions today:
  1. VLBI technology
  2. VLBI science and calibration
  3. Demo/tutorial: living on the fringe

- Advanced sessions tomorrow:
  1. Calibration: from archive to dirty image (Suma & Ilse)
  2. Imaging with Difmap (Gabor & Zsolt)

Very Long Baseline Interferometry

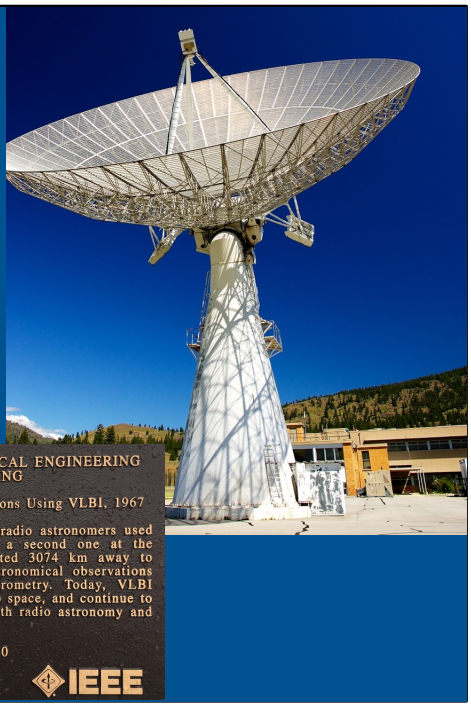
Using the power of $\frac{\lambda}{D}$



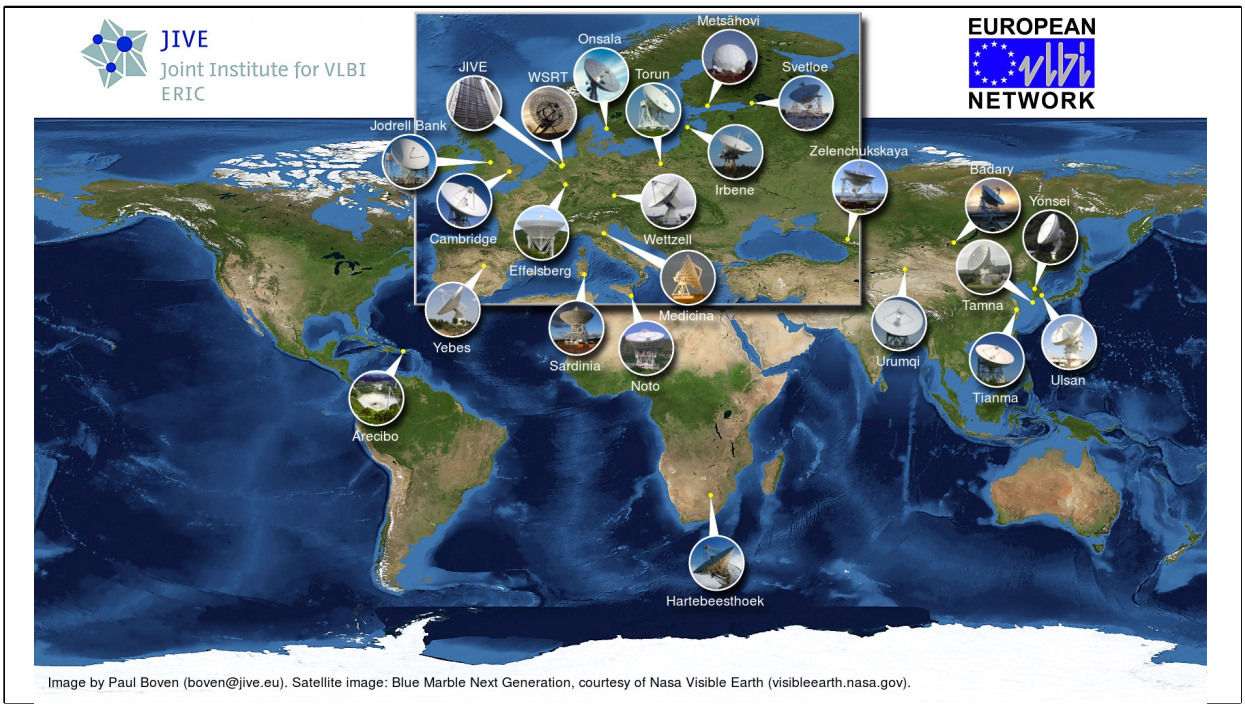
Unique:
Large (>1000km) baselines
Different types of telescopes (mount, size)
Individual clocks and back-end
Sparse uv-coverage
Specific needs for correlation and calibration
Never a true point-source…

History

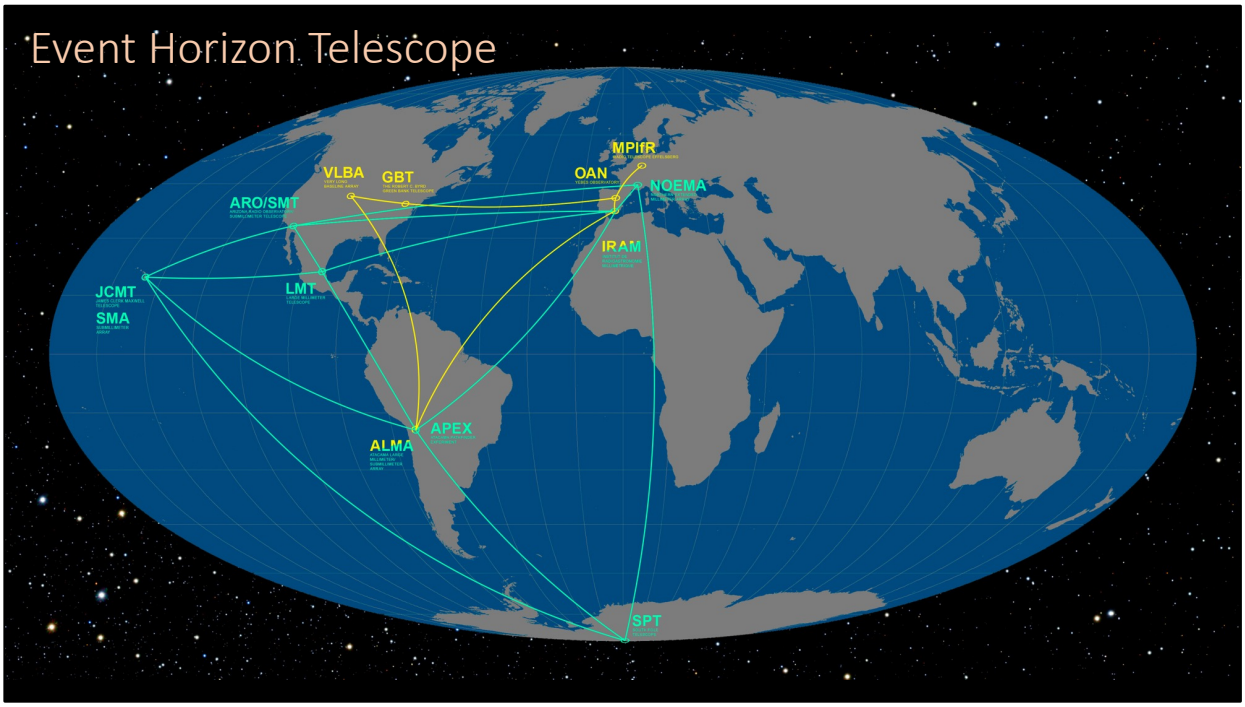
- Almost 55 years old
  - Canada to US
  - Transatlantic: US to Onsala
- First VLBI networks late 1970's
  - European VLBI Network ~1980
- JIVE established ~30 years ago



First experiments just over 50 years ago, makes VLBI a relatively young observational field



In 5 decades, and especially since the early 1980's, several VLBI networks have developed. This is the European VLBI Network, which is no longer limited to Europe only, but extends to Africa, Caribbean and Asia. The EVN is a homogenous array, telescopes are vastly different in size, receiving technology, and mount type.



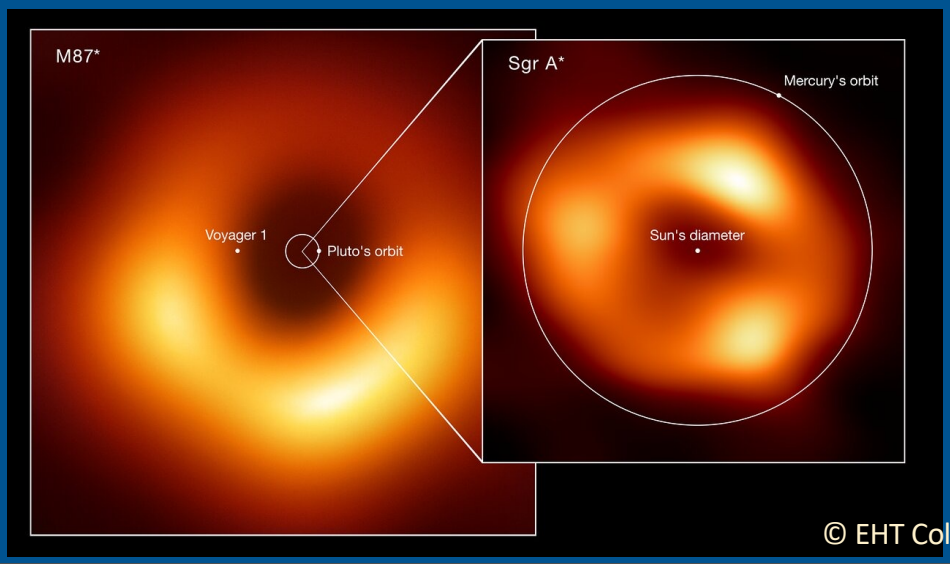
For the highest resolution: Earth sized telescope, highest possible frequency: Event Horizon Telescope goes down to ~10 micro-arcsecond resolution on the longest baselines. The convolved resolution of the M87 image is ~20uas at 230GHz.

Science cases

Compact and bright objects

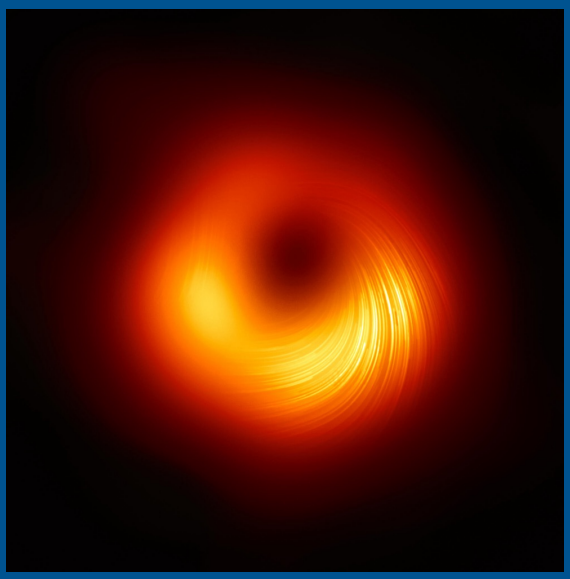
To go over some science for VLBI
Mention the role of VLBI in space missions

Science highlights

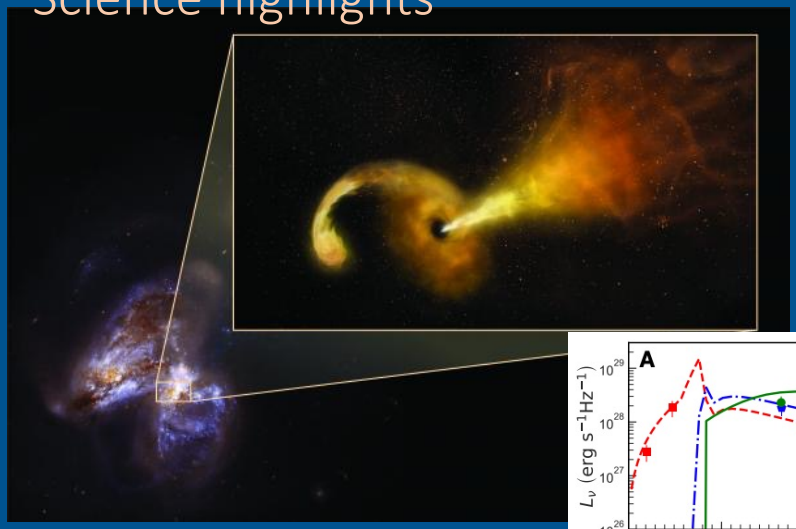


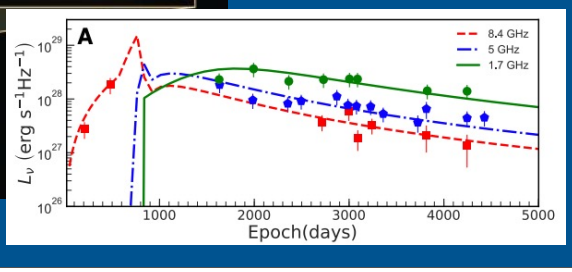
Accretion and jet formation in active galaxies. This is an example of an ad-hoc VLBI array being constructed with the sole purpose of imaging the black hole shadow of SgrA* and M87.

Science highlights



Science highlights

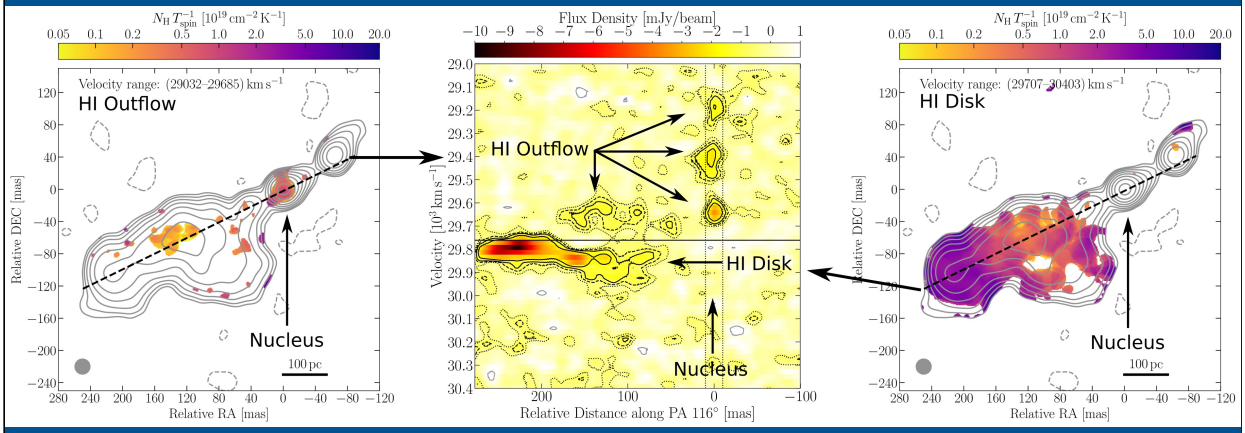




Mattila+ 2018

TDE caught with the EVN: a star wandered to close to a supermassive black hole and is ripped apart, emitting a powerful radio flare while that happens. This TDE was hardly visible in optical, due to being wrapped in dust all the emission is re-radiated in the infrared. Different epochs show that there is a radio jet that evolves and slows over time.

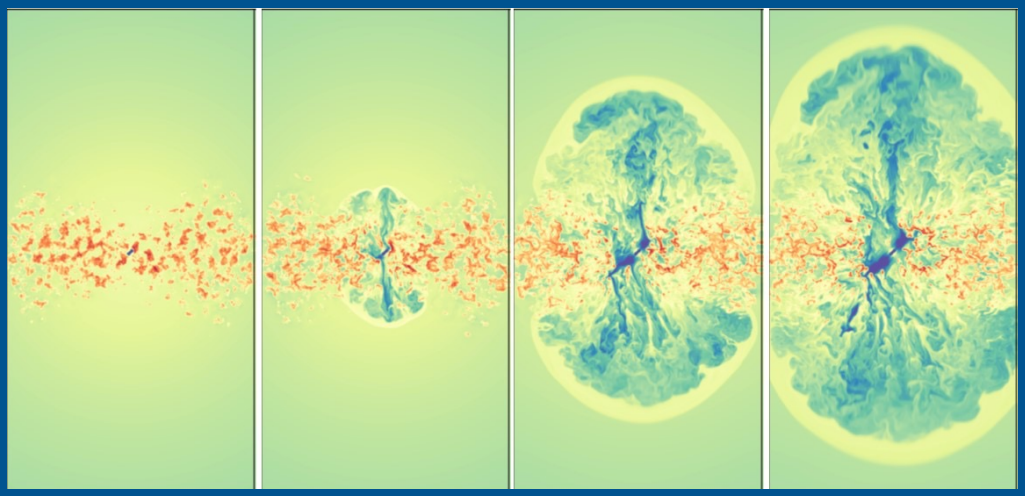
Science highlights



Schulz+ 2018, Morganti+ 2018

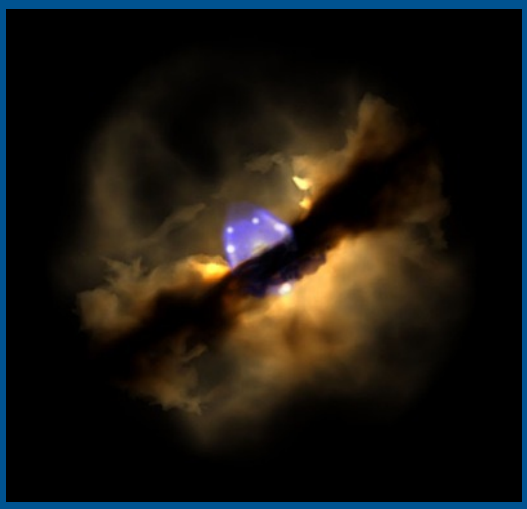
3C236 observed by EVN in HI absorption shows where the jet is pushing neutral gas out of the galaxy

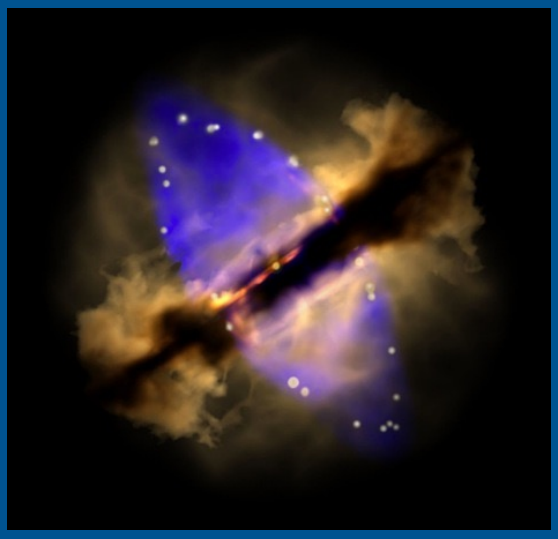
Science highlights



Murthy+ 2022

Science highlights

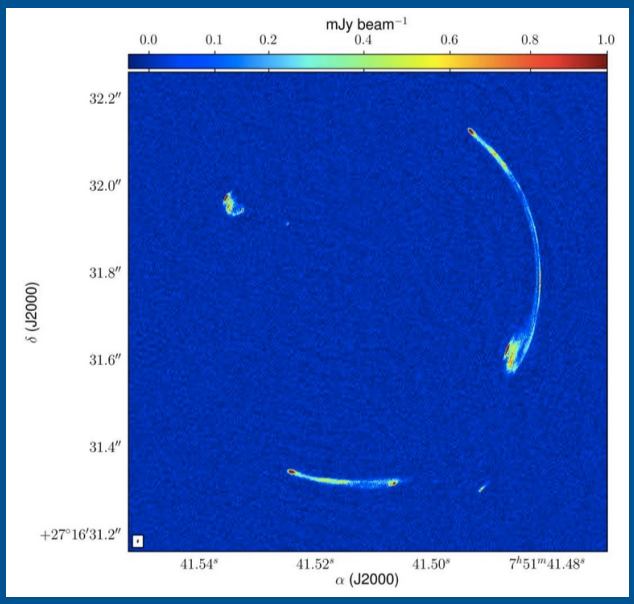




Carrasco-González+ 2015

MASERS are line transitions pumped by the intense emission around young and evolved stars. These show clearly a ring-like structure around a young stellar object. An outburst from the protostar is initially isotropic, but collimated by the dust surrounding it. By observing the MASER spots in time, we can see this process happening in time. Since the star itself is a continuum source, the motion with respect to the star is obvious.

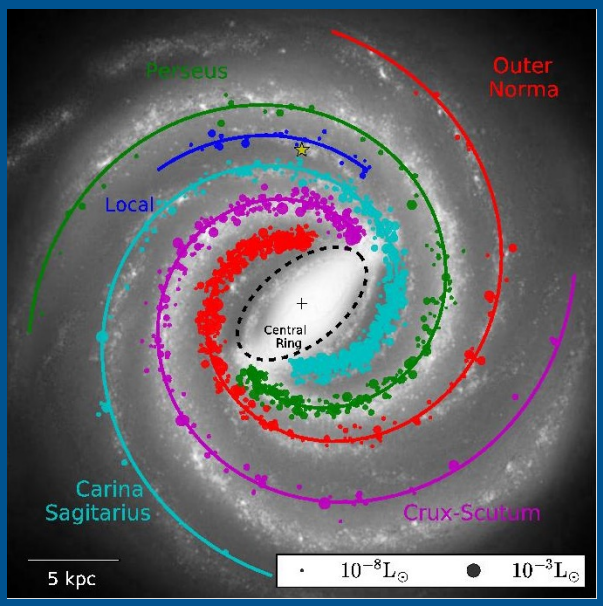
Science highlights



Spingola+ 2018

Large scale structure can be studied with VLBI. This is one of the best examples of high-resolution imaging of a gravitational lense, which enables the reverse engineering of the structure causing the lensing, and thus learn about the density and distribution of dark material in the Universe.

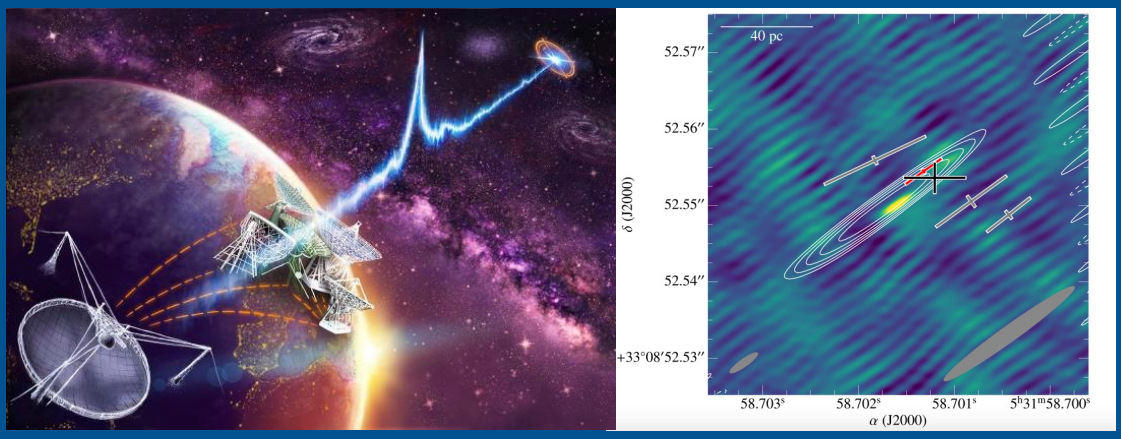
Science highlights



Quiroga+ 2017

Tracing MASERs throughout our Galaxy and combining this information with the exact information that Gaia provides, enables us to determine the Galactic parameters that are at the basis of our Universal distance scale. This image shows what the SKA can do to extend our knowledge of stars in our own Galaxy. Currently we base the information on a relatively small portion of our Solar neighbourhood, SKA will access almost the entire Galaxy.

Science highlights

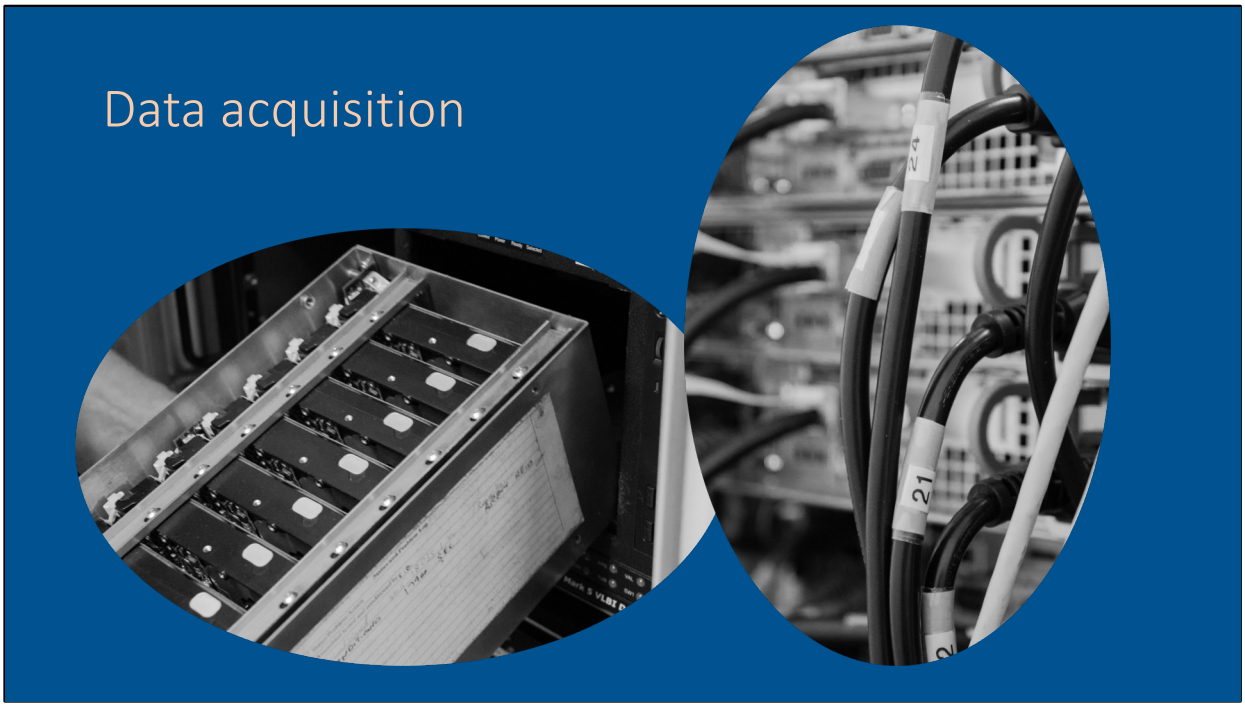


Chatterjee+ 2017, Marcote+ 2017

The repeating FRB is a unique case to allow for localization of the source.

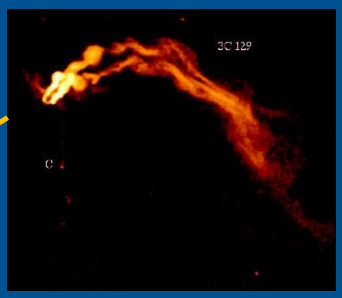
VLBI specifics

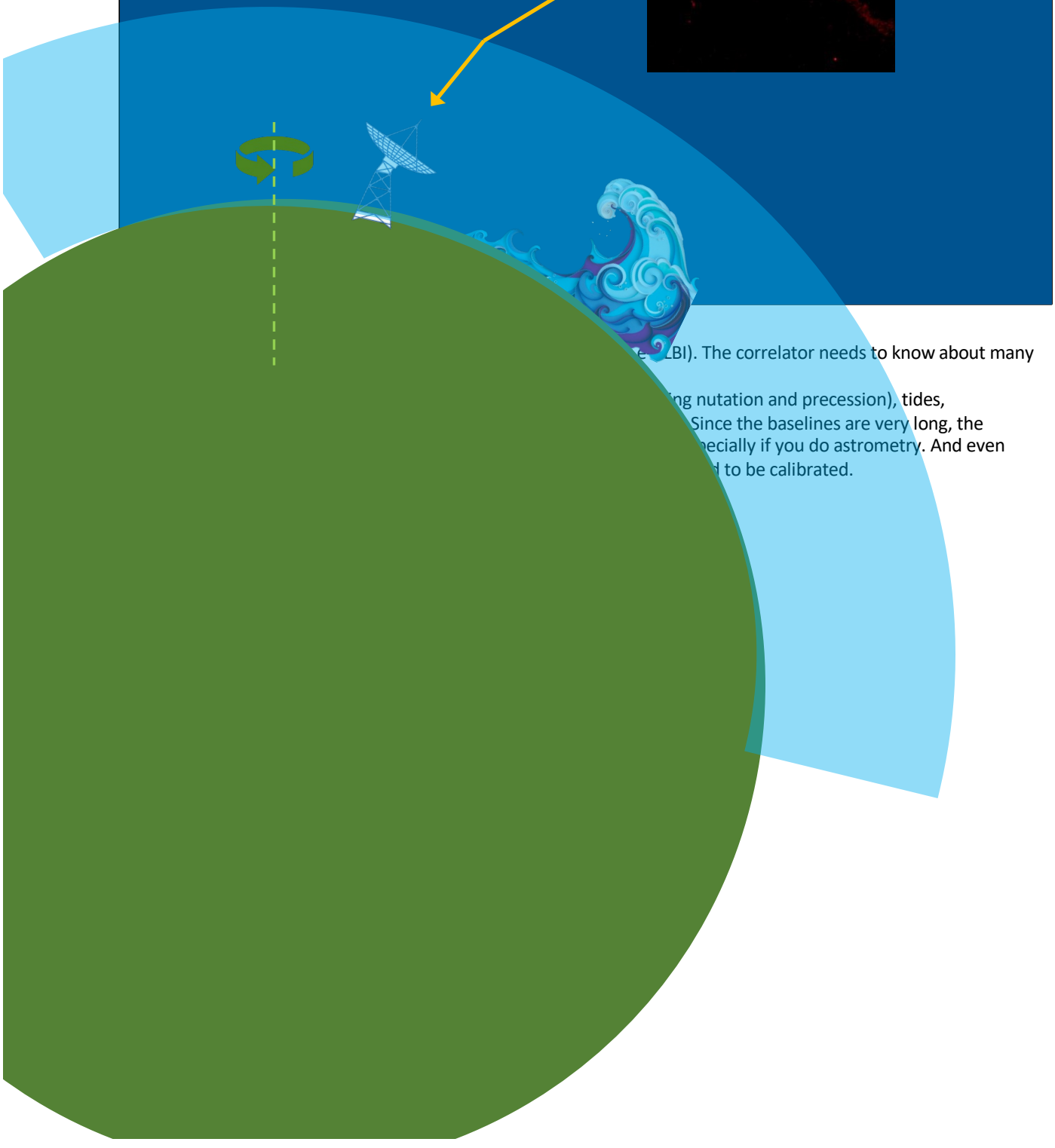
Note that the main difference in VLBI is not just the baseline length, but the fact that the elements are not connected. Each operates with its own clock, recording the data virtually independent from the others. Recording occurs on disk with specific VLBI software to include all information needed to reconstruct the signals from all telescopes at the correlator.



Current day VLBI can be shipped with disk packs (still the standard over very long distances) or the data arrives through broad-band network. We call that e-VLBI, and the e-VLBI network for EVN is slowly expanding. The e-VLBI observations are correlated in real time, providing the PI with the data right after the observations are done

Correlator model





LBI). The correlator needs to know about many

ng nutation and precession), tides,
Since the baselines are very long, the
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to be calibrated.

Inspection

You will note in the upcoming tutorial that ~25% of the time is spent on data inspection and flagging. That is a fair representation of reality. Often the fraction is higher, and in case of EHT (where every visibility counts) there is also a need to recover bad data.

Parallactic angle & mount type

Alt-Az mount (VLA) tracks the source as a human would: we see the crescent moon change rotation with respect to the horizon. For celestial sources the parallactic angle rotates in an alt-az mount, this needs to be corrected. Equatorial mount (WSRT) has the azimuth axis fixed parallel to the NCP direction. This is cheaper for engine use (only one engine needed for tracking). It is like tilting your head back to keep the crescent moon always in the same direction. The field does not rotate, but construction is large and requires counterweights.
Present day technology allows for cheap alt-az mounts which can be digitally corrected for field rotation.

In VLBI the parallactic angle matters: a telescope that sees the source rising sees a different PA than a telescope that sees the source setting. To ensure that the source structure is in the same location when adding the data and to ensure that polarization information is preserved, it is critical that all VLBI data is corrected for parallactic angle rotation during calibration, therefore you need to know the correct mount type.

Good thing is: the software does this for you, but you should make sure to switch on the required parameter!

Polarization

- Circular polarization back-end
- Linear polarization back-end

Originally all VLBI was done in circular basis by inserting a quarter wave plate into the linear optics at the telescope. That causes a loss of sensitivity, and makes it impossible to do real wide-band observations (as the QWP adds it's own limited bandwidth at which it actually is functional). Therefore, newer systems prefer a linear optics system, and thanks to current day computational power, we can actually use software to combine linear and circular instruments in one observation and correct for the differences in polarization after the correlation. To combine linear and circular polarization telescopes in one array, the correlation is done as if all elements have the same basis. After correlation the task polconvert can establish the correct polarization in a single reference frame. See lecture on polarization by Ivan Marti-Vidal

Calibration

Amplitude
- System temperature (Tsys)
- Gain curve

Residual phase errors after correlation
- Clock
- Earth model and telescope positions
- Atmosphere

Amplitude calibration does not use calibrator sources for bootstrapping the flux density. WHY?
- Sources are resolved so not all baselines see the same amount of flux
- This is a problem for polarization calibration, which requires a polarized source to calibrate the polarization angle…

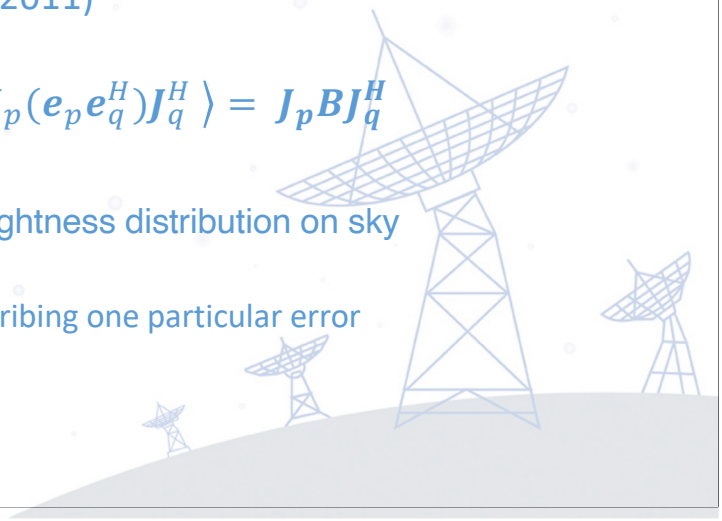
Phase calibration requires additional precision over connected elements to remove small clock errors and other residual correlation issues.
Phases not only encode the information of the source substructure, but minor errors impact your ability to image. Phase errors limit the dynamic range in imaging because you are adding up the snapshots images while the source is moving around a bit → source becomes blurry. In optical words: phase calibration is focusing your telescope.

CASA calibration framework

Based on the Measurement Equation
(Hamaker+ ,1996; Smirnov 2011)

$$V_{pq} = 2\langle \boldsymbol{J}_p(\boldsymbol{e}_p\boldsymbol{e}_q^H)\boldsymbol{J}_q^H \rangle = \boldsymbol{J_pBJ_q^H}$$

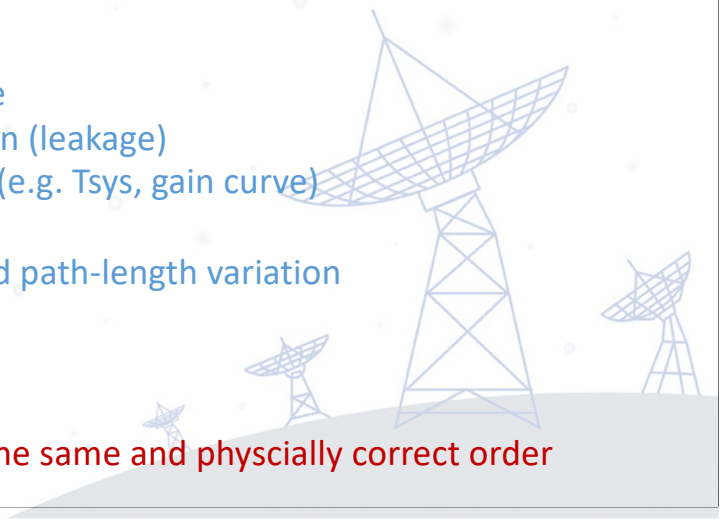
- $\boldsymbol{B} = \begin{pmatrix} \boldsymbol{I+Q} & \boldsymbol{U+iV} \\ \boldsymbol{U-iV} & \boldsymbol{I-Q} \end{pmatrix}$ is the brightness distribution on sky
- $\boldsymbol{J}$ is a 2x2 Jones matrix describing one particular error



The Jones matrices

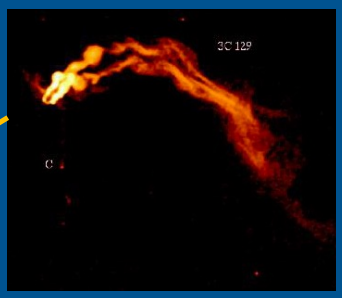
Calibration: determine J_p for all antennas p

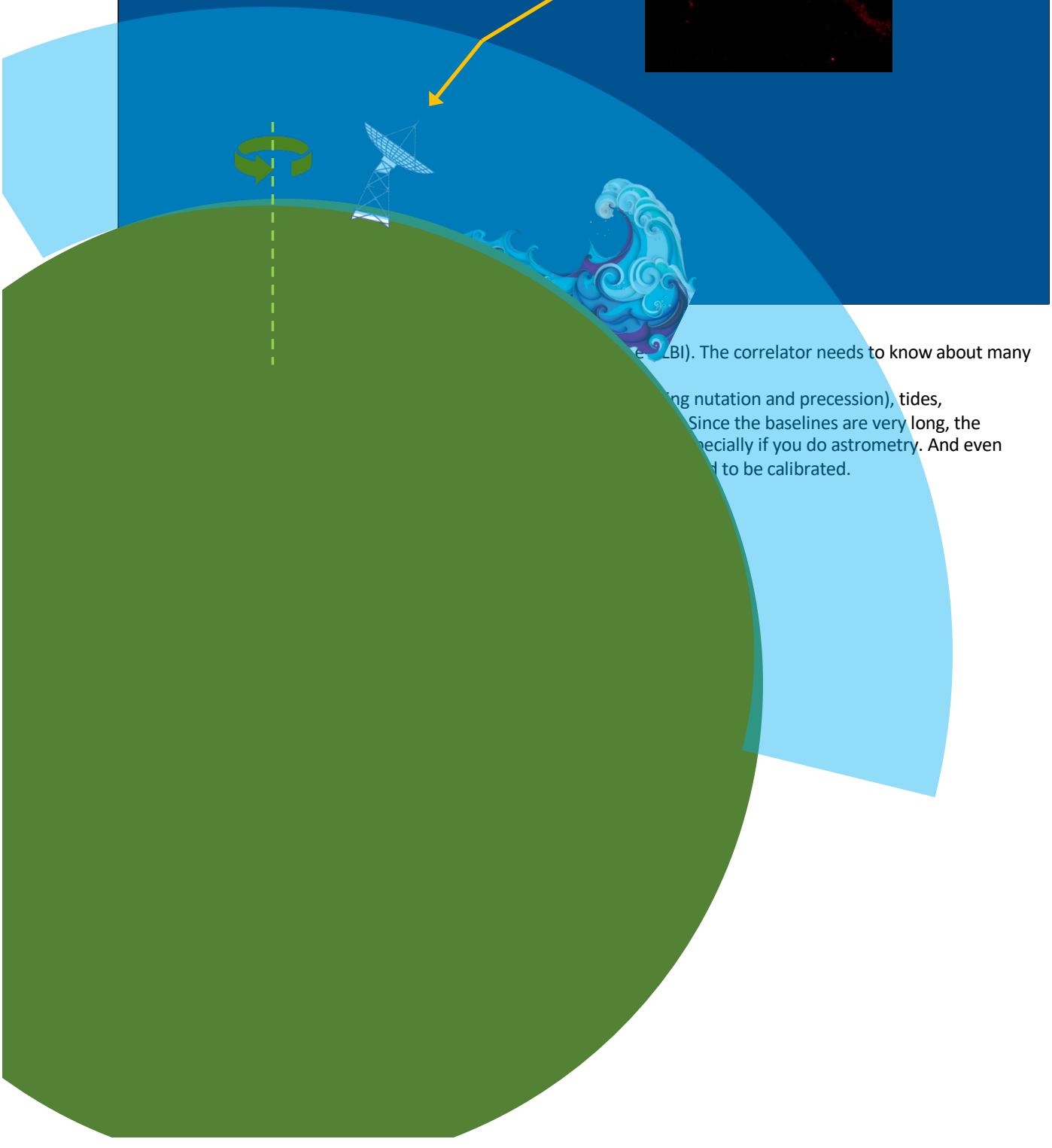
- K_p: delay
- B_p : bandpass
- G_p : electronic gain response
- D_p : instrumental polarization (leakage)
- E_p : telescope based effects (e.g. Tsys, gain curve)
- P_p : parallactic angle
- T_p : tropospheric opacity and path-length variation
- F_p : Faraday rotation
- *(Z_p, beam)*



CASA handles this always in the same and physcially correct order

Correlator model





LBI). The correlator needs to know about many

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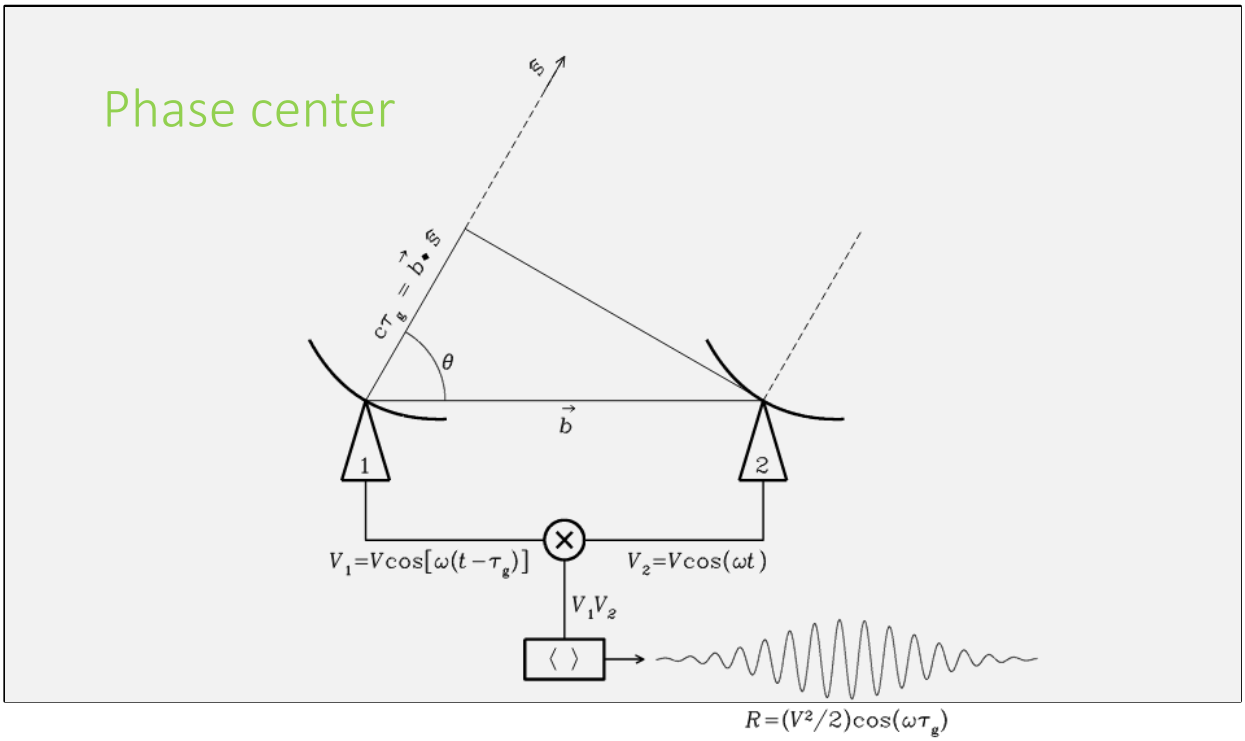
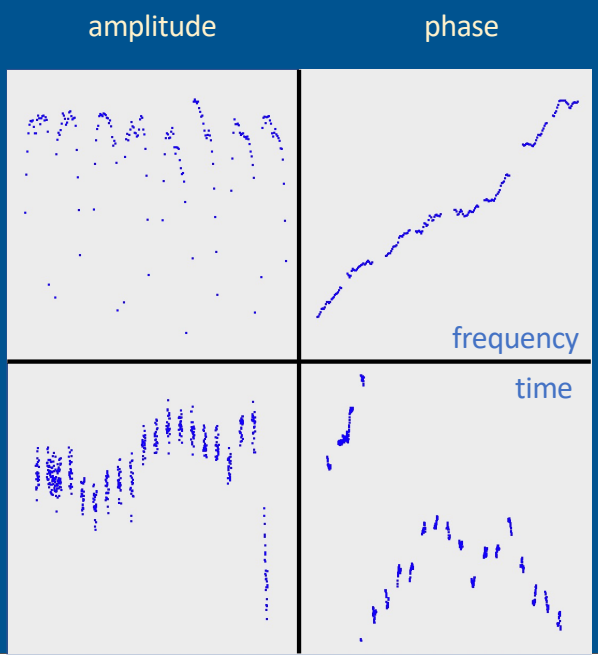
Phase center



An interferometer measures phase differences, i.e. there is no default zero point for your phases, you can select this (you need to!). This is why we use the concept of a reference antenna: zero phase.
This is also why we have the concept of delay or phase tracking center: the point in the sky where your coherence is optimal over the observing band. In principle this means that a point source at that position will have phase = 0 and amplitude = 1 (i.e. all the flux of the source is detected).
That also means you can invert the problem: to make an interferometer look at a different point in the sky you can either change the viewing direction of the telescopes, or change the delay in the back-end or correlator processing.

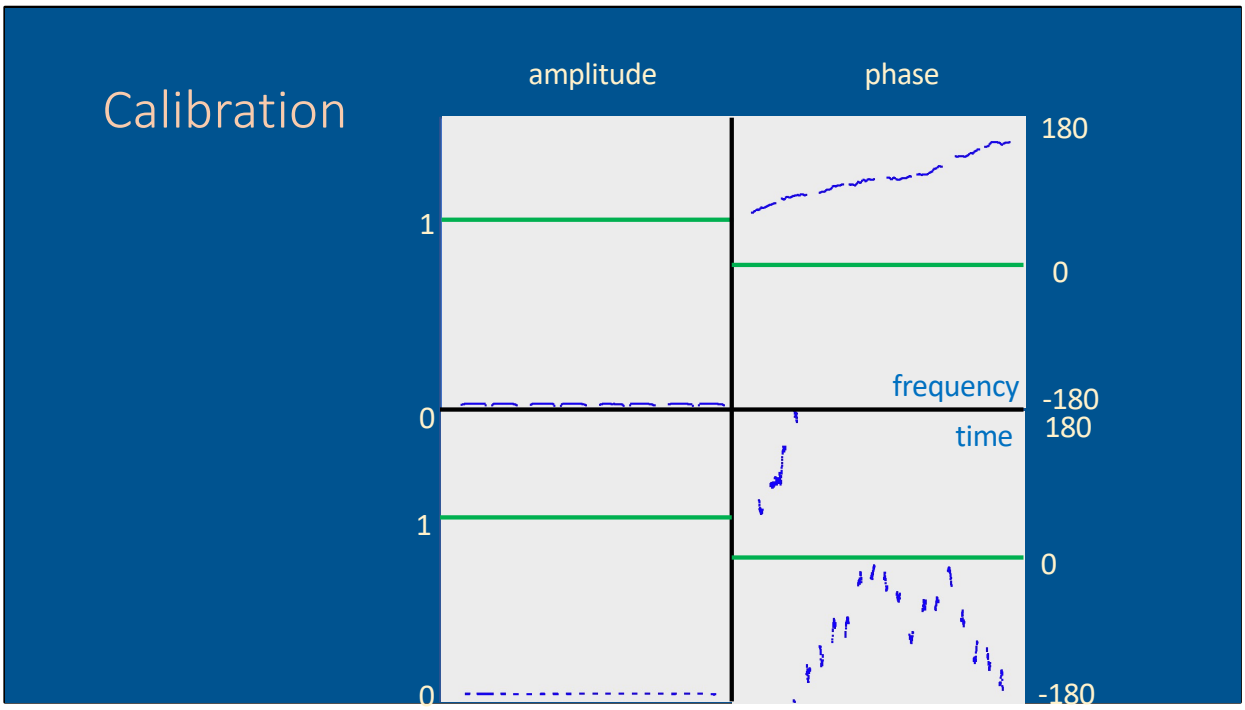
Calibration



One baseline,
one polarization

Let's look at visibilities!

Reminder: a point source observed at the phase center of the array should have amplitudes = 1 and phase = 0 in both time and frequency. That is in a perfect world, but receivers are never perfect.
Do I need to explain the concept of spectral window?
This is an example of an actual bright source from a Network Monitoring Experiment with the EVN. The phases and amplitudes are clearly recognizable, but it is obvious that they do not reflect a point source in the phase center



The green line represents a point source in the phase center, and it is clear that the data is nowhere close to that. To calibrate the system, we need to calculate how to shift the data to the green lines, in essence that is calibration. The complication is that these corrections depend on frequency and time as well, so correcting for one scan does not automatically give the corrections for an entire observation.

System temperature

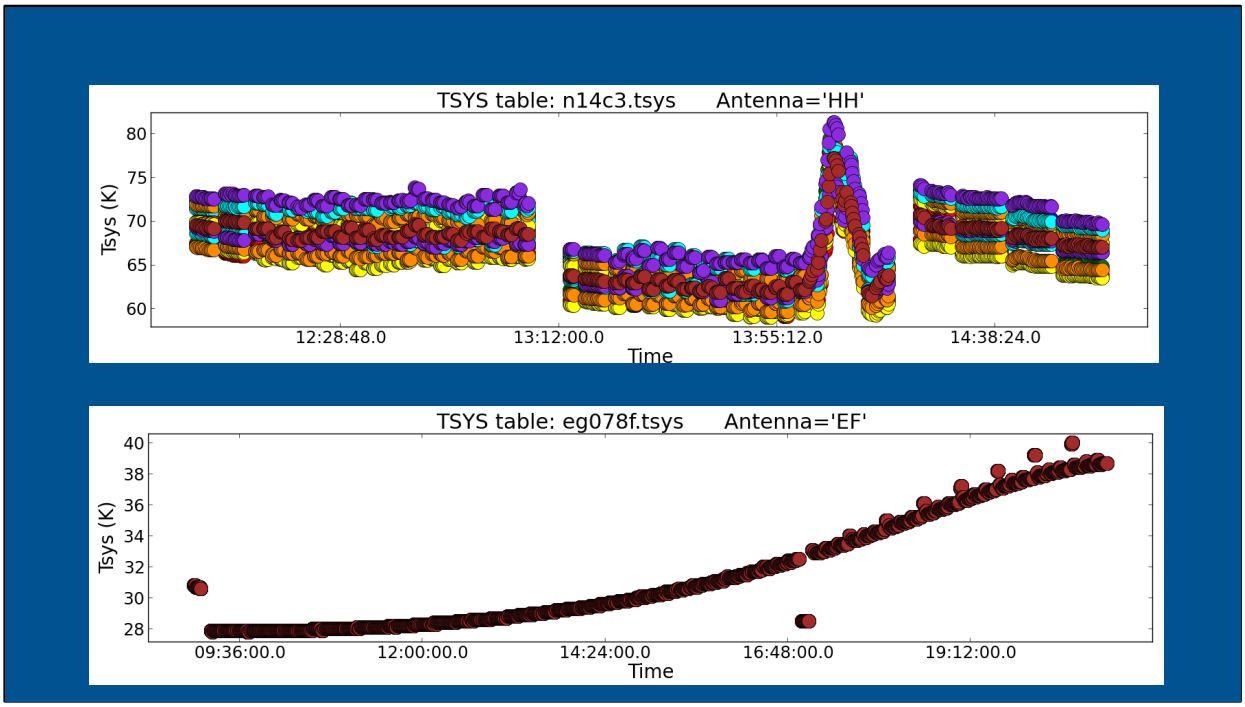
Convert correlator units to flux scale:

System Equivalent Flux Density

$$\text{SEFD [Jy]} = \frac{2k_B T_{\text{sys}}[K]}{\eta_A A_{\text{eff}}}$$

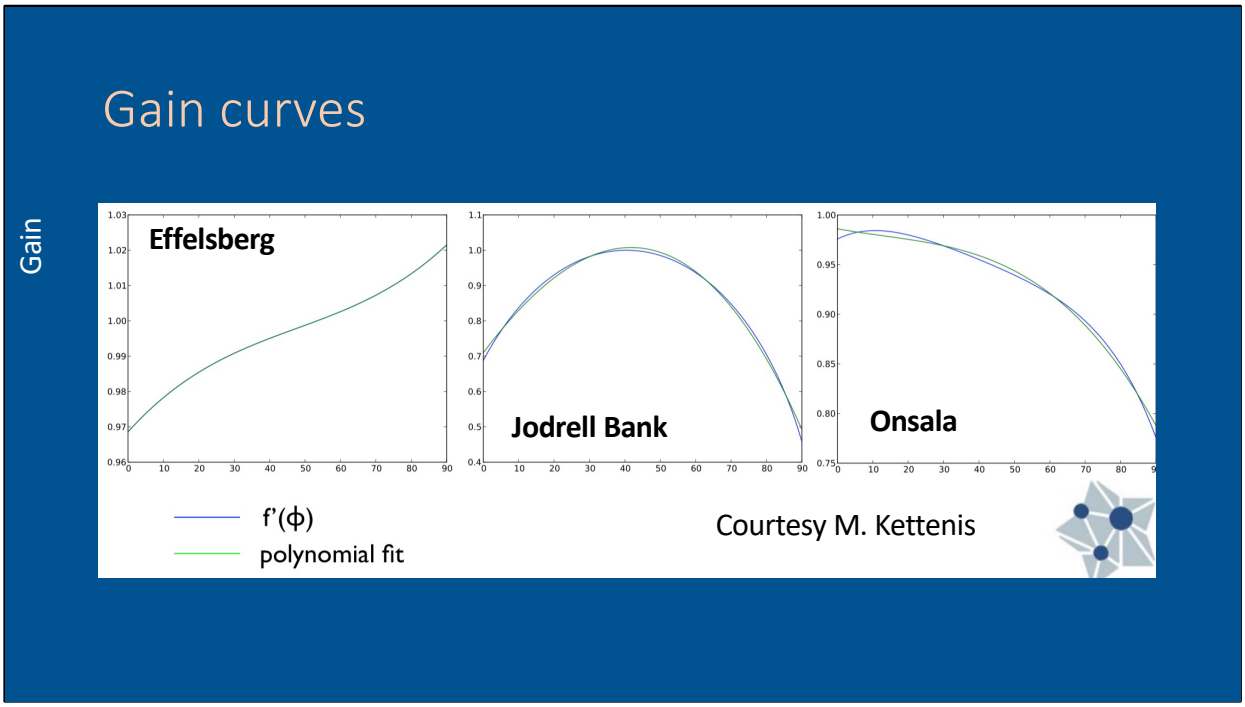
η_A : efficiency
A_{eff}: effective antenna area

To calibrate the amplitude we use the system temperature: tsys. The Tsys relates the noise to the flux density.
Tsys is a sum of many different component: background noise (Galaxy), ground emission, atmosphere, receiver loss
The dominant term is the receiver noise
The SEFD scales inversely with telescope size: bigger telescopes are more sensitive, and thus have lower SEFD.
There are different techniques to measure the Tsys. For VLBI the Tsys needs to be observed as frequently as possible, and over the whole observing frequency band.



The small scale sensitivity variations caused by the instrument and atmosphere can be monitored by measuring the system temperature. This will later be used in the calibration to derive the amplitude calibration as a function of time. The cadence varies widely between telescopes, but it is possible to improve the Tsys tables a-posteriori by interpolating.
The Tsys is measured by using a standard signal, for which the amplitude is known exactly. Bright sources can impact the system temperature, causing jumps in the graph. Same goes for re-pointing.

Gain curves



Antennas are not rigid, as you point away from zenith they slightly change shape and that affects the gain. The construction of the antenna and the size impact how the gain varies as function of zenith angle. Here you see angle on the x-axis and gain on the y-axis going from 96% to 100%. The variations are of order a few percent, with most classical dishes being optimized for maximum gain at ~45 degree elevation.
What is shown in the lines is the difference in the definition of the gain curve in AIPS (f(phi), old package) vs CASA (polynomial fit, new package)

Calibration

- Amplitude: Tsys and gain curve

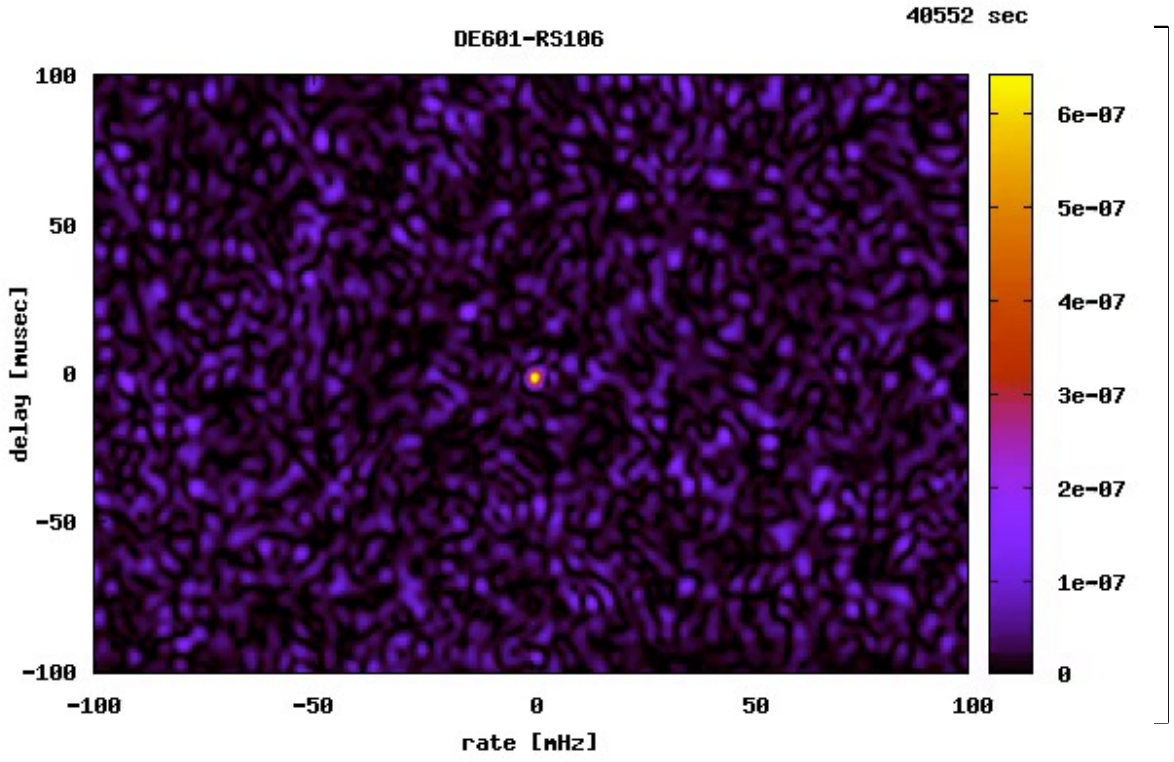
- Phase
- Delay
- Rate

$$\phi_{t,\nu} \approx \phi_0 + \frac{\partial \phi}{\partial \nu}\Delta\nu + \frac{\partial \phi}{\partial t}\Delta t$$

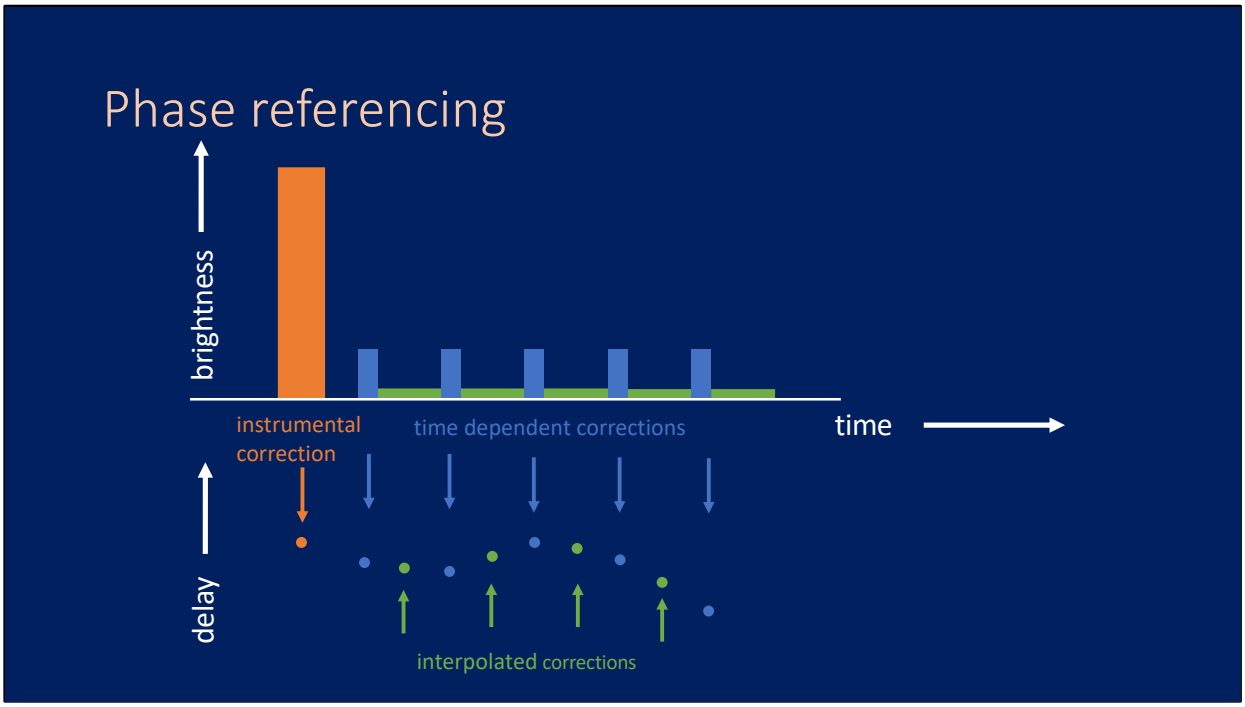
- Higher order terms: dispersive delay, acceleration

Explain delay and rate
Phase encodes your source structure
Get enough SN to go to imaging and self-cal
Mention that without these additional corrections we cannot average VLBI data for imaging: loss of coherence.

This is why: in VLBI we worry not only about the phase calibration, but also about the derivatives of phase with frequency (delay) and time (rate). Small errors in delay and rate will cause phase errors and complicate the imaging, or (in the worst case) wipe out the source completely due to loss of coherence.
For REALLY sensitive cases we also need to include the second-order derivatives for frequency (dispersion at lower frequencies) and time (acceleration, for VLBI with spacecraft)
E.G. ionospheric turbulence is such a higher order phase error. It can be approximated by a linear function such as this, but in fact is has many higher order terms which become especially important at lower frequencies (LOFAR).



(LOFAR fringe movie)

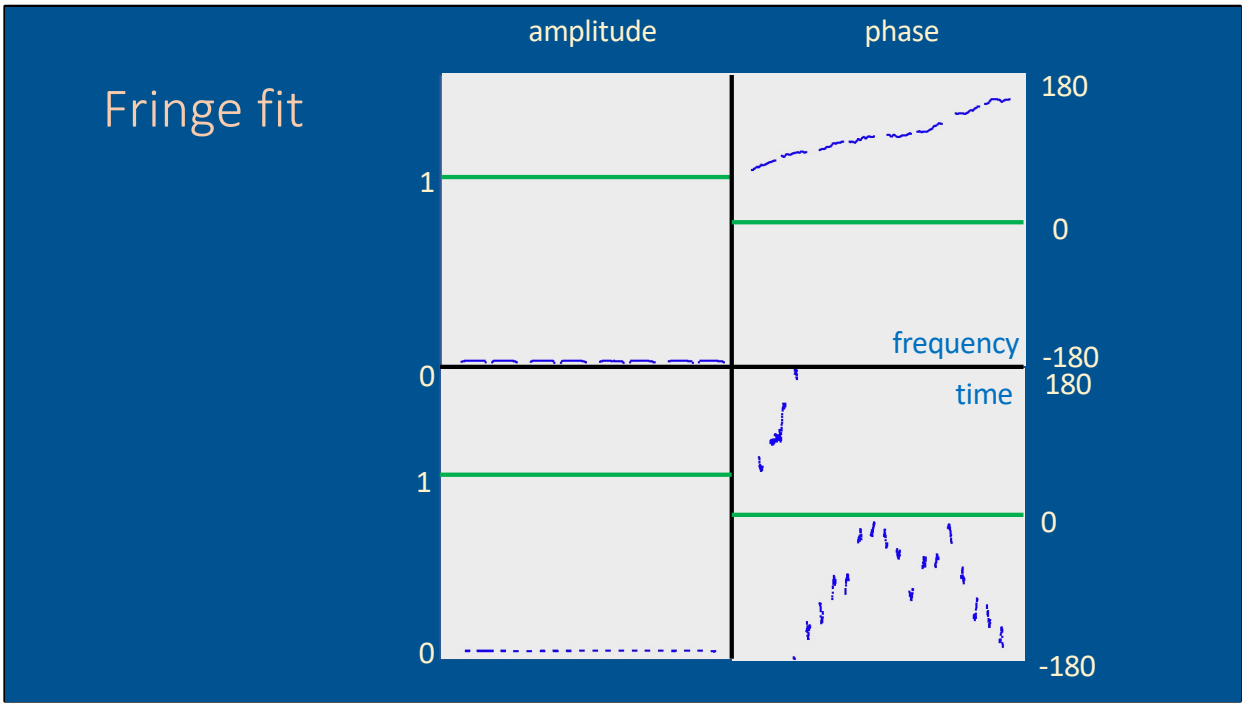


Phase calibration with fringe fitting happens in two steps. First the instrumental delay is corrected, using observations of a very bright source at the start of the observation. This instrumental delay is time and direction independent, so the calibrator can be anywhere in the sky. For long observations a calibrator is observed several times during the experiment. This step is also known as single-band delay calibration.

On top of the instrumental delay, the second step is to correct for time variable delays and rates. Usually your target source is not bright enough to be visible in a single integration, or even a single scan of a few minutes. This is why we employ phase referencing. The target is observed for a length of time (typically ~10 minutes) and then the telescopes look at a compact nearby bright source nearby (the phase calibrator) for a few minutes. This is alternated for the duration of the observation.

The phase calibrator needs to be nearby, as the delay and rate are caused by atmospheric turbulence. It is important that the light from the phase calibrator traces the same path in the atmosphere as the light from the target, both in time and location. Also, we prefer the phase calibrator to be compact, ideally all the phases of the calibrator should be zero (perfect point source in phase center) to calculate the delay and rate offsets that need to be applied to the source. However, if there is some structure, a source model can be used. This second step is called multi-band delay calibration.

Once we have the absolute instrumental correction for the delay, and the time and frequency dependent delay and rates, the corrections for the target source can be obtained by interpolating between the solutions from the other calibrator sources. The corrections are applied to the target source, preserving its spatial information.



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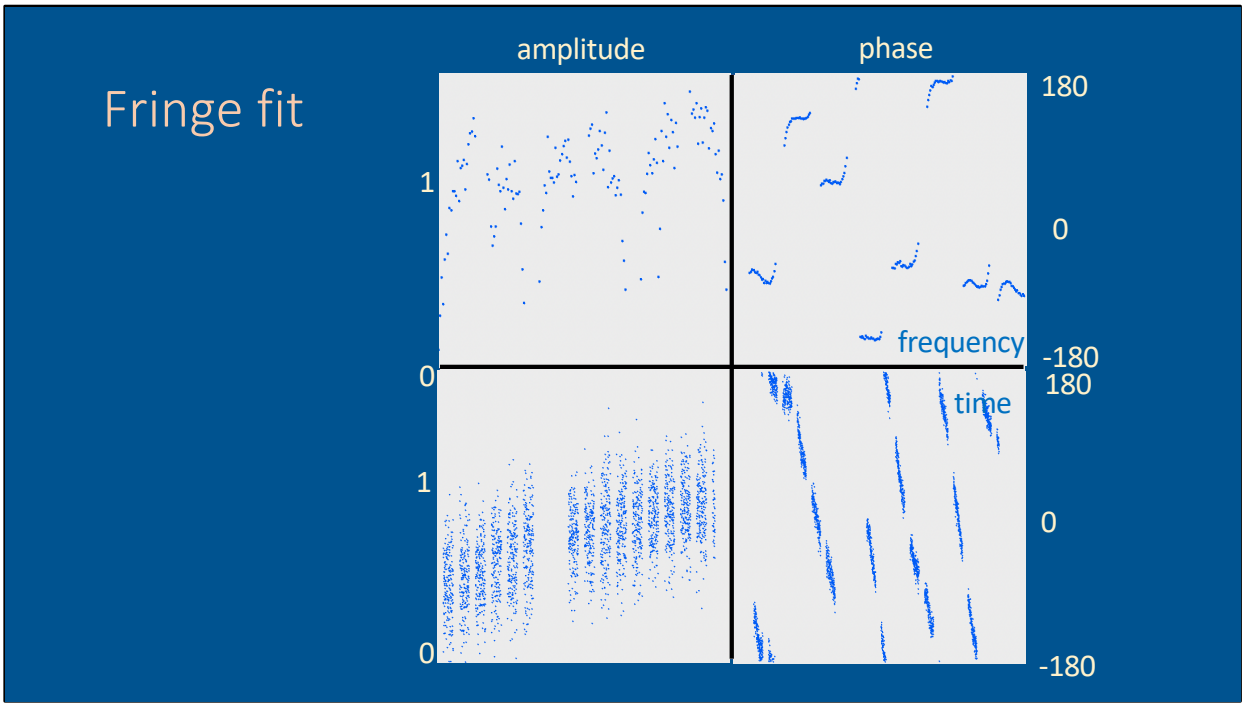
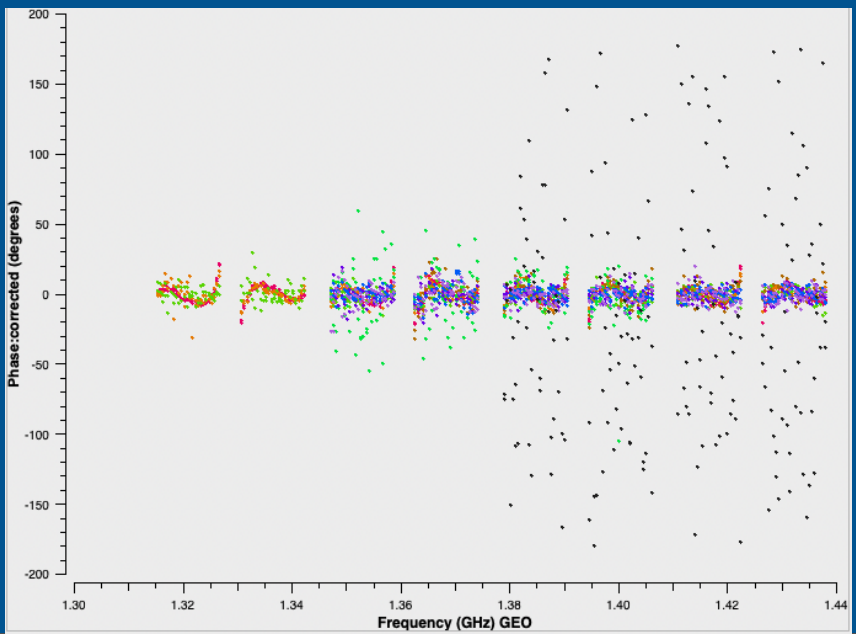


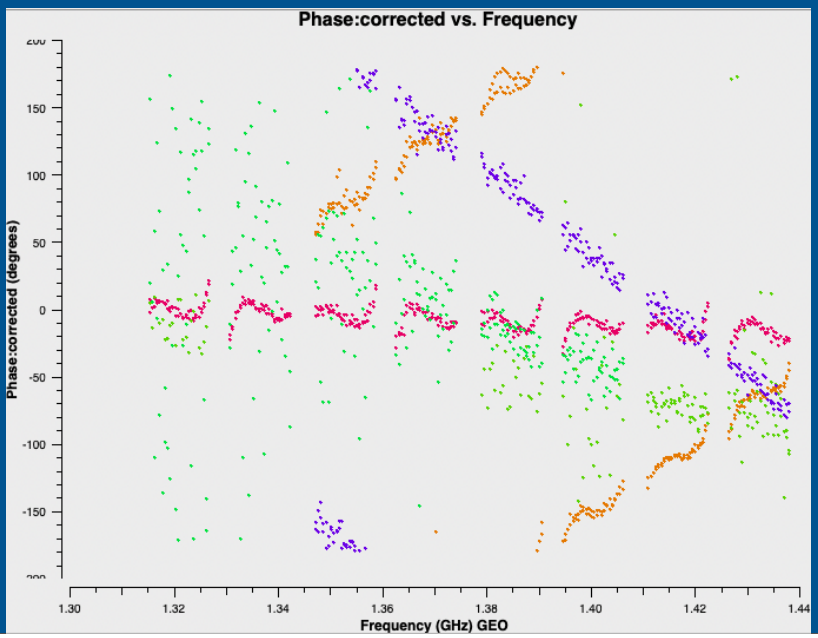
For imaging you want to average this further in time and frequency. What would happen in this case?
This is one of the calibrators that will be part of the advanced tutorial. It is obvious that the data is already a lot messier, but it is still possible to track the phase and amplitude by eye, which is what you need. If you cannot see your phase behavior of the calibrator, you are in trouble…

Fringe fit



Fringe fitting is a two step process. Single band delay (step 1) vs multi band delay (step 2).
Step one is to pick the brightest source in your observations, and correct the visibilities for phase and delay only. Note that correcting for rate on a single scan is pretty useless, since we have not enough temporal information within the scan.
This first step is called ‘single band delay’ or ‘instrumental delay’. The latter name describes its function: this corrects for effects that are constant in time, which are usually instrumental (cable length differences, small clock offsets, other instrumental effects not properly corrected by the correlator).
What you want to see is that after the correction is applied, all phases are flat and around 0 degrees. In this example that has worked OK, except for one station, which is clearly off. What would you do with the station that produces the black points?
And what do you notice about the other datapoints? (Several stations lacking in spectral windows 0 and 1).

Fringe fit



Next: when the instrumental delay corrections are applied to the entire observation, this is what happens to your phase if you select a scan closer to the end of your observation. Any clue why? Changing the time and we did not correct for the rate yet… So the phases are still aligned, but for the longer baselines it becomes apparent that there is a residual slope that needs to be removed. That's why we do a second step in fringe fitting: multi-band delay. Multi-band delay corrects for phase delay and rate on all the scans.

Left to do

- Bandpass calibration
- Imaging
- Self-calibration

Workings of the EVN

JIVE supports the operations of the EVN:

- Archive
- Proposal handling
- Observation planning
- Correlation and data quality
- Assistance with advanced calibration

A little information on what we do at JIVE

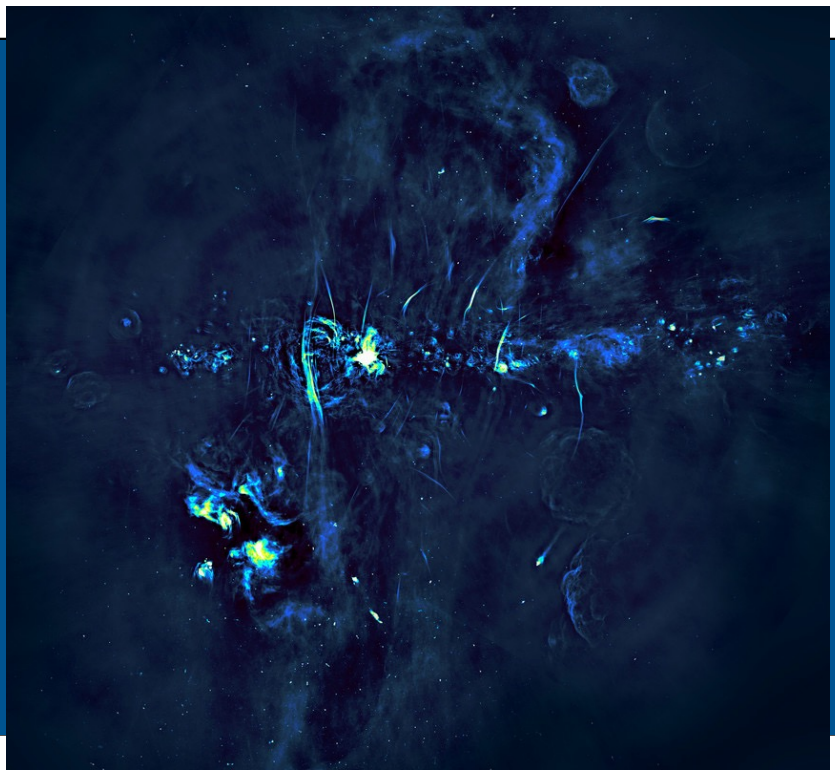
Software development

- CASA now ready for VLBI
- Pipeline development:
  - ALMA
  - VLA
  - EHT
  - rPicard (and others)
  - EVN
  - VLBA

CASA-VLBI workshop

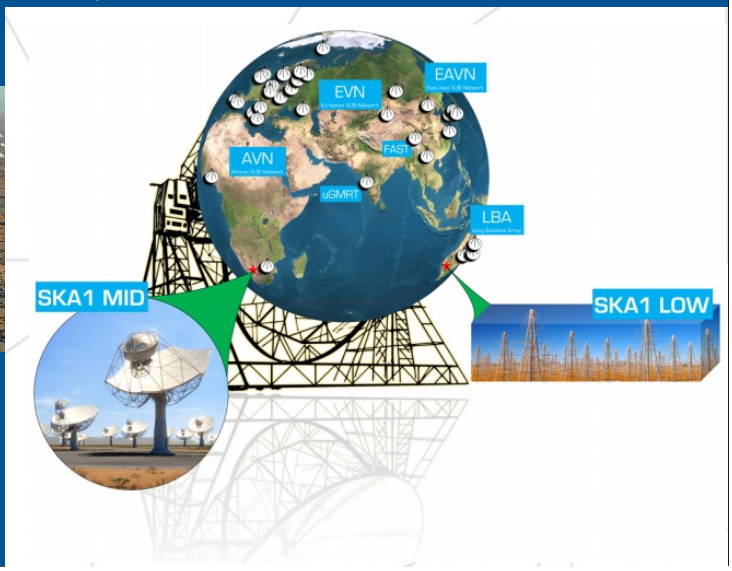
- Tentative dates for first full week of June 2023
- All the nitty-gritty details of CASA
- Even more VLBI
- Jupyter notebooks!

Advertised through: JIVE website, EVN Newsletter, VLBI mailinglists



Heywood+ 2019
MeerKAT telescope

Square Kilometre Array



Next: try for yourself

code.jive.eu/bemmel/ERIS_VLBI

Open a terminal and type:

```
git clone https://code.jive.eu/bemmel/ERIS_VLBI.git
```

You now have a directory **ERIS_VLBI** with all the materials

OR: click the download button on the right side of the page