European VLBI Network - EVN data processing steps

Zsolt Paragi
JIVE

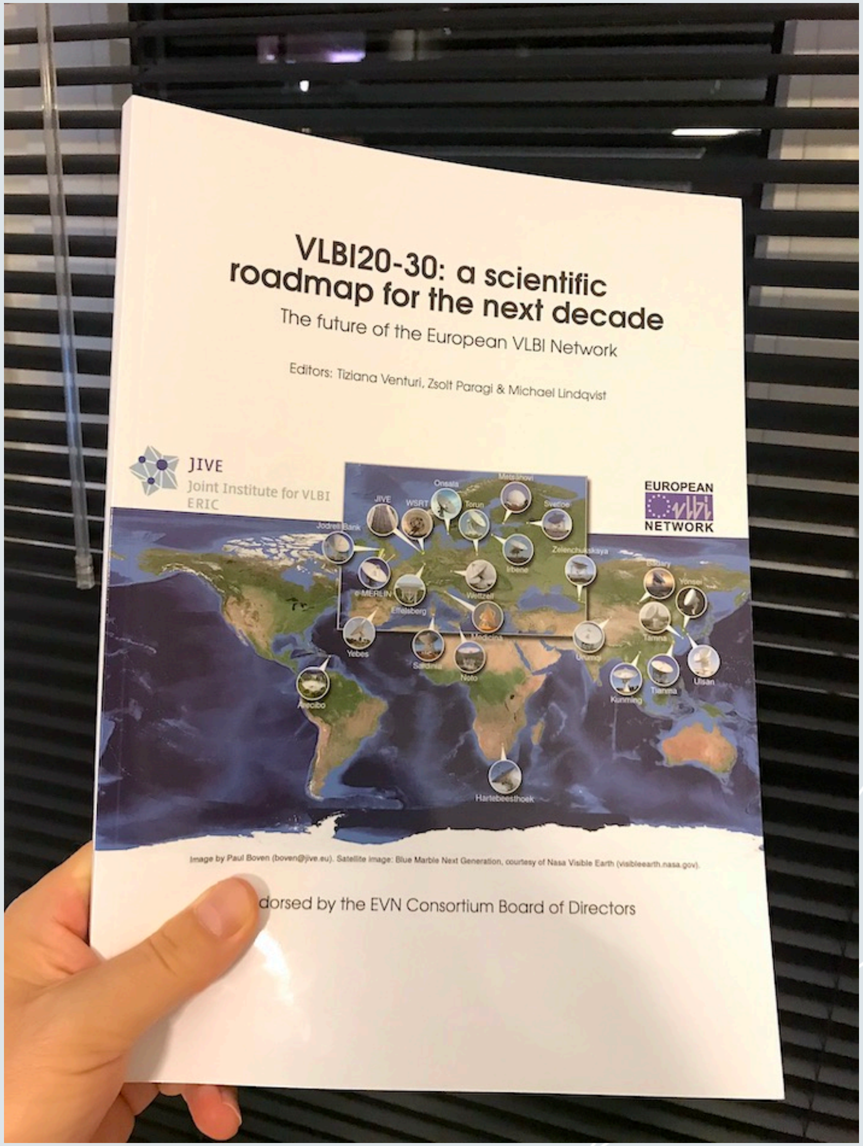
The European VLBI Network

- ➢ **Combining some of the most powerful telescopes in the world:**
- ➢ **To detect extremely weak signals, and image them at the highest detail**

Photo: Zsolt Paragi

- Central data processor and data archives at JIVE
- The EVN Software Correlator (SFXC) flexible operations: real-time e-VLBI, continuum, spectral line, pulsar binning, fast transients, multiple phase-centres

EVN Vision Document

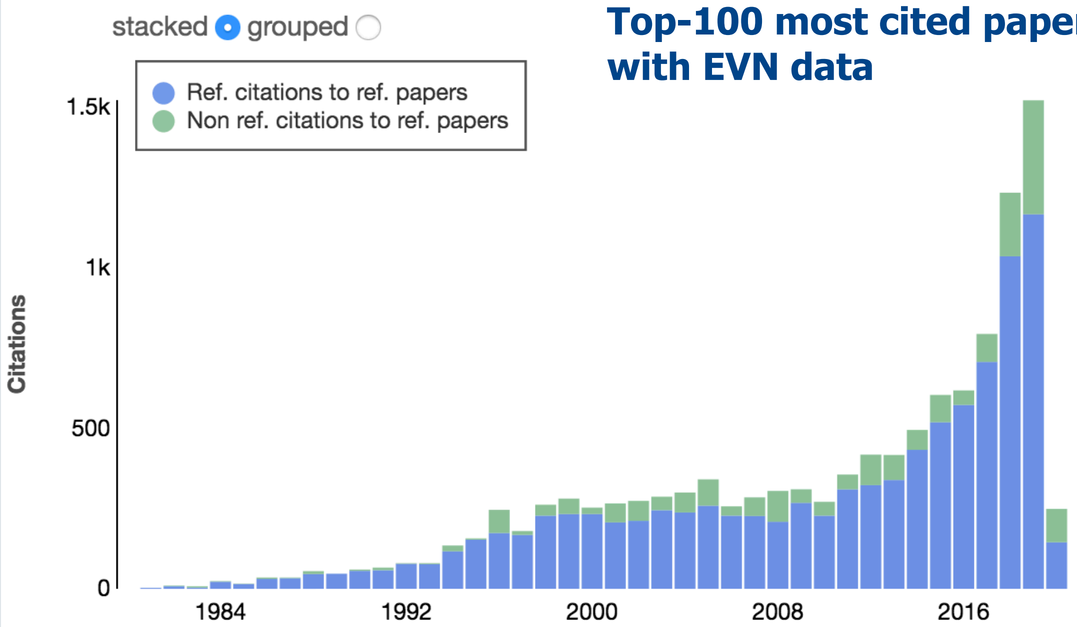


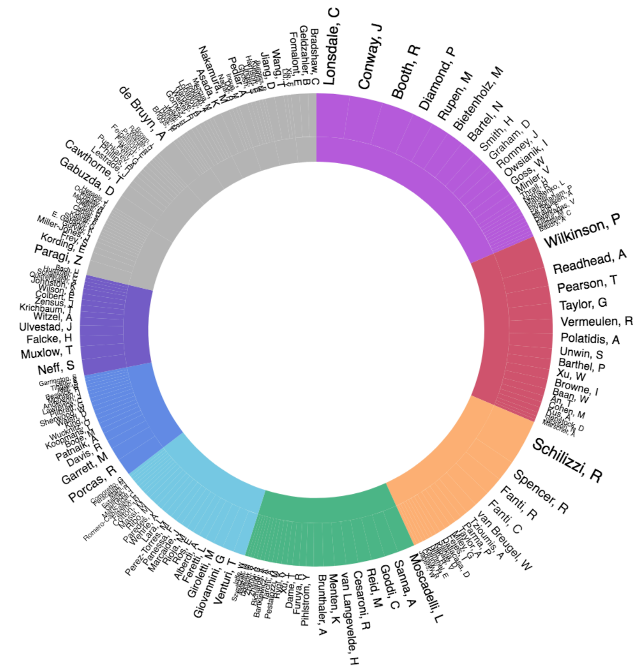
- The VLBI20-30 scientific roadmap has been published and printed
- JUMPING JIVE WP7 final deliverable
- A technological roadmap was derived from the science requirements

arXiv:2007.02347
https://arxiv.org/abs/2007.02347

The EVN Transformation

Top-100 most cited papers with EVN data



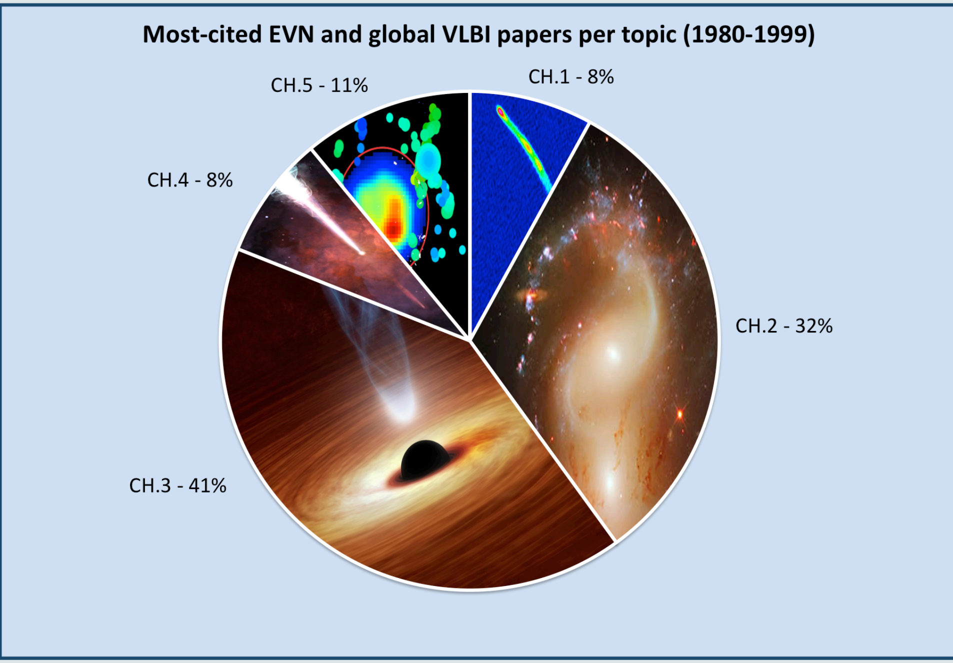


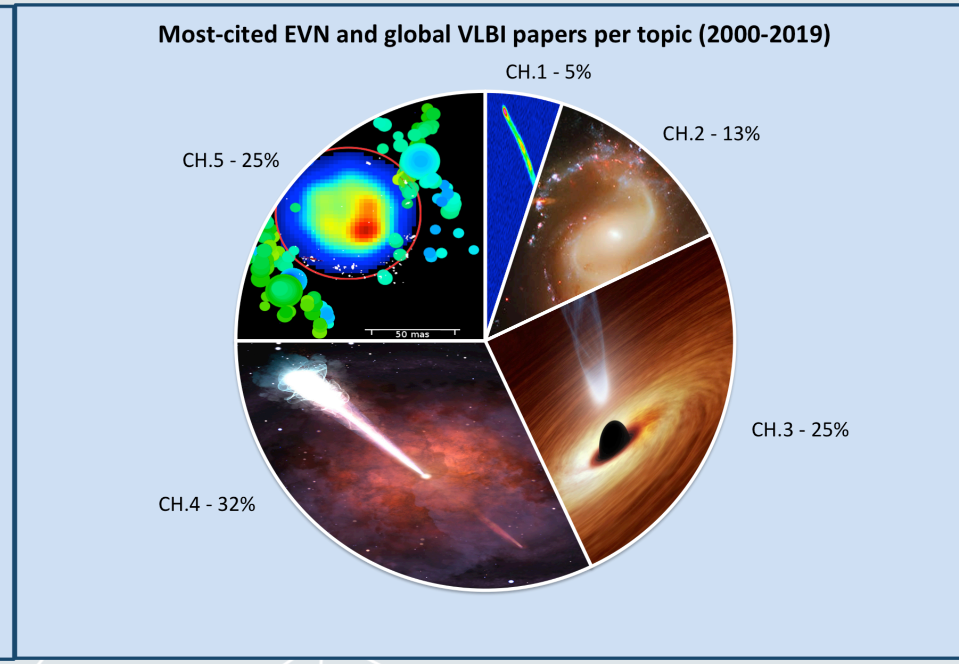
- **Technical developments (sensitivity; e-VLBI; SFXC) transformed our science**
- **There is a globalization in astronomy, preferring large collaborations around cutting edge instrumentation**

  (simple citation counts thus may also be misleading, but still…)

The EVN Transformation

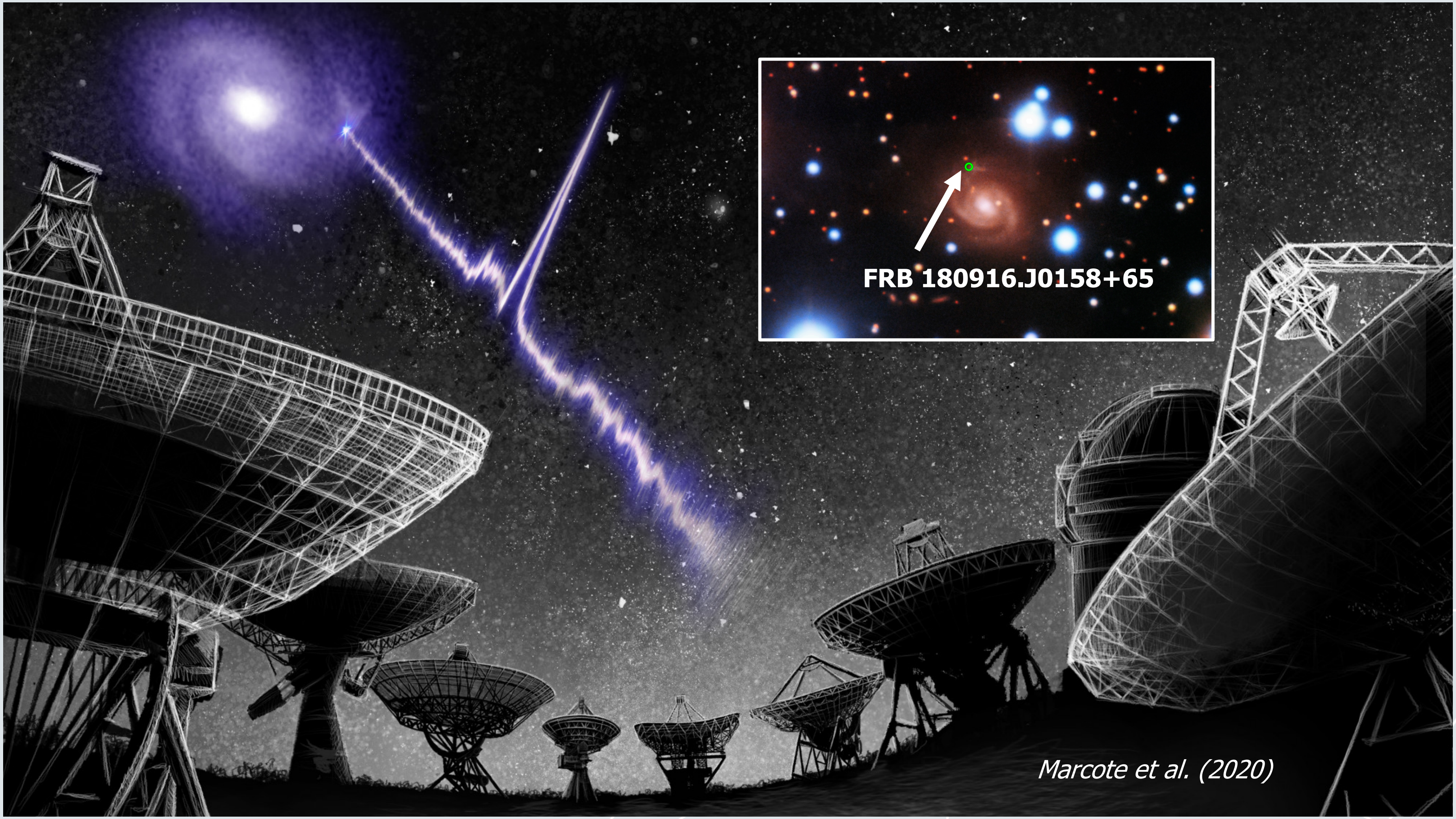
Top-100 most cited papers with EVN data





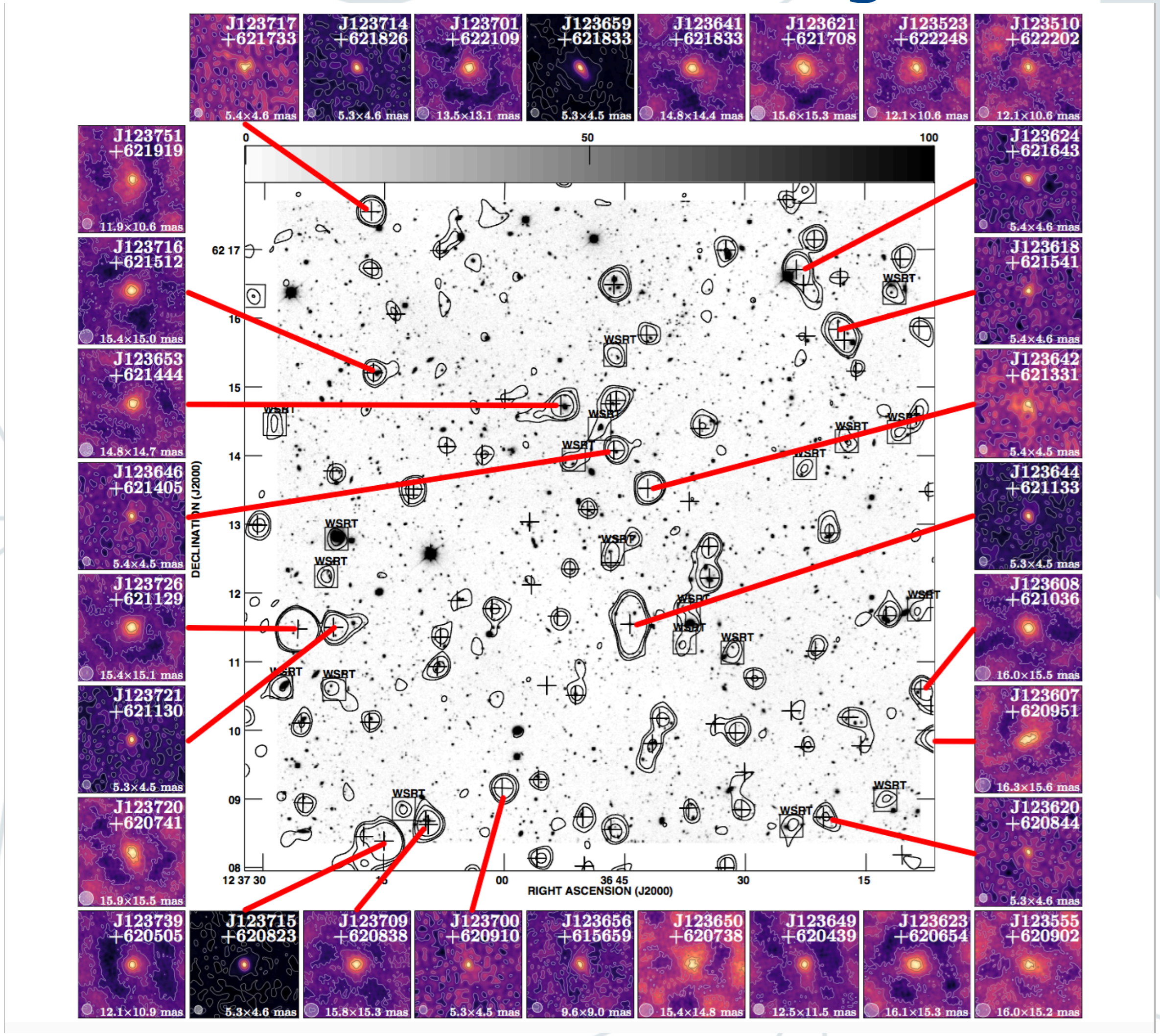
- **Following global trends also meant broadening science scope**
  (Galactic and extragalactic astronomy as well as transients science)
- **Further steps require exploiting synergies with multi-messenger astronomy, SKA, EHT etc. as well as exceling data mining and processing techniques and developing the EVN Archive**

EVN Science Example



- **Fast Radio Burst (FRB): mysterious flashes of millisecond duration**
- **EVN is the only instrument capable of FRB localization on milliarcsecond scales**
  (doing "SKA science" today)

Wide-field VLBI: our former “big data” challenge



Radcliffe et al. (2018)

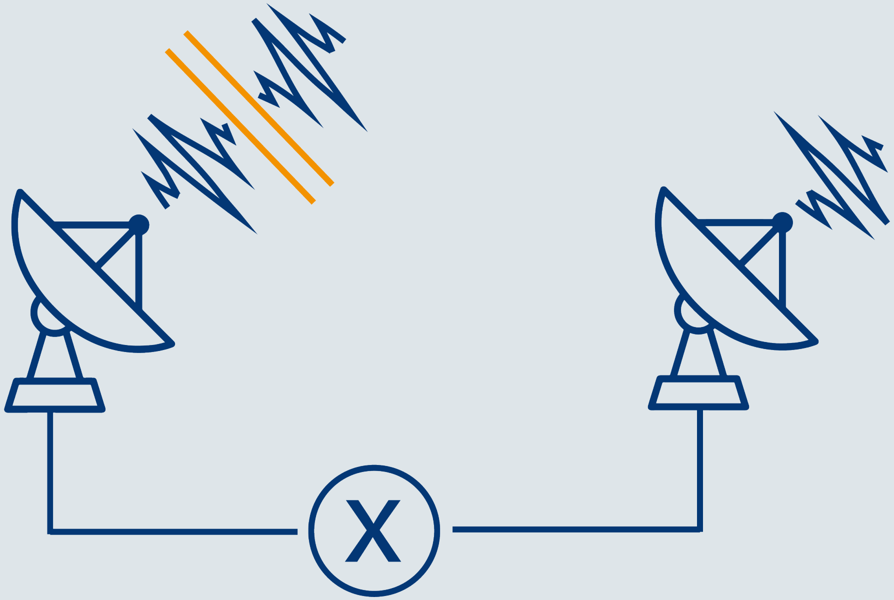
- **Terabytes of data per experiment ➔ needs averaging ➔ drastic decrease of FoV**
- **Wide-field correlation ➔ shift *uv* - data to a large number of phase-centres for averaging**

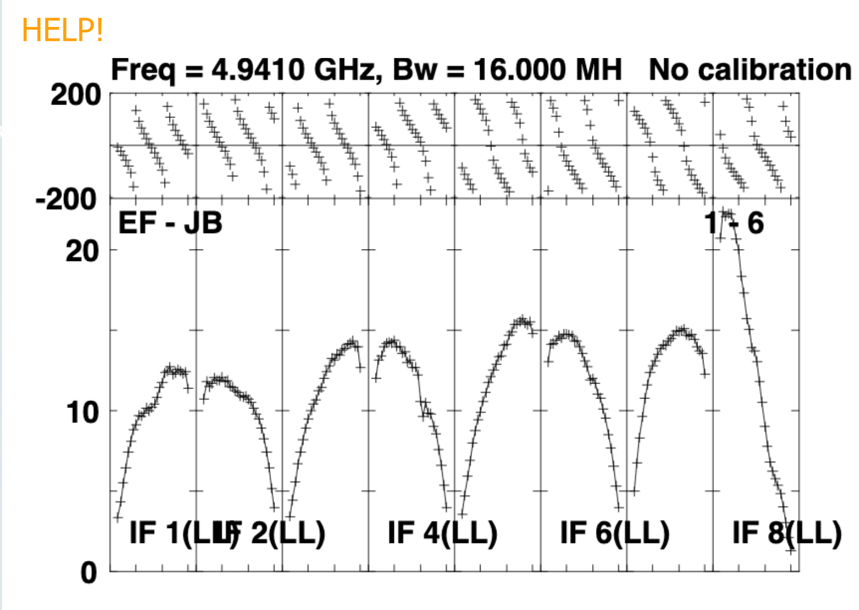
Workflow of EVN Science

1. Science idea
2. Proposal writing
3. Evaluation by the EVN PC (Programme Committee)
4. Schedule the observations
5. Observations (typically either in regular disc session or using real-time e-VLBI)
6. Correlation (unless real-time e-VLBI)
7. Calibrate and reduce the data
8. Science (publish or perish; and acknowledge EVN and JIVE!)

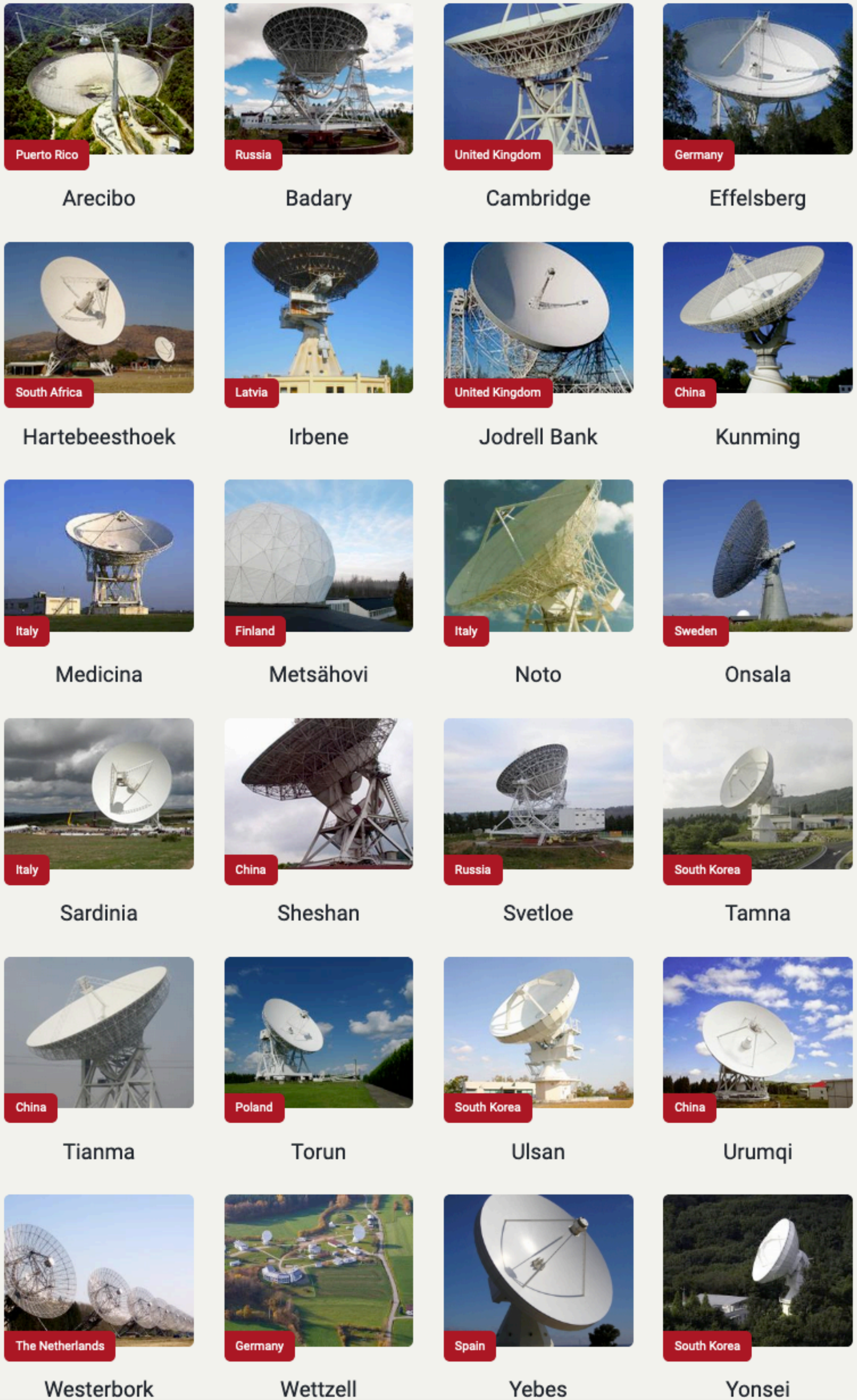
- **Usually from science idea to publication is year(s) timescale**
- **From idea to data can be accelerated if justified**
  - ✓ **Student projects are favorably judged, and brought forward in the correlation queue as well**
  - ✓ **Target of Opportunity projects are much shorter timescale (especially with real-time e-VLBI)**

Why VLBI is special?

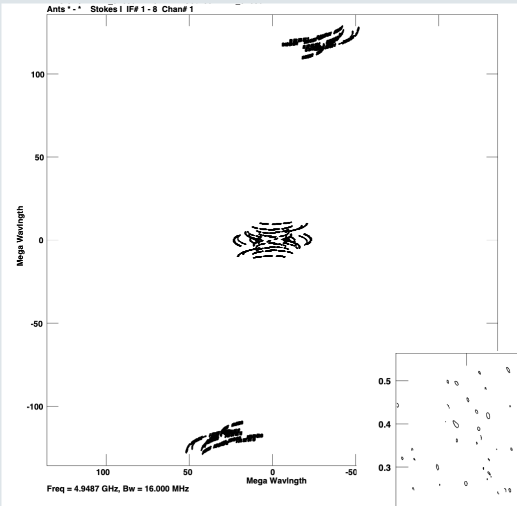




- **Compared to connected elements interferometry:**
  - Independent clock/frequency standards + troposphere & ionosphere mean special ways of processing required: FRINGE-FITTING (and more…)
  - Data recording & transport (disc/electronic-VLBI) may introduce special issues
  - Off-site data processing: access from correlator archives

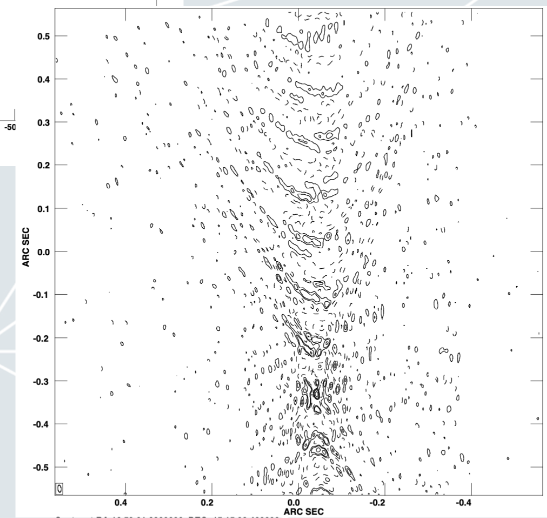


Why VLBI is special?



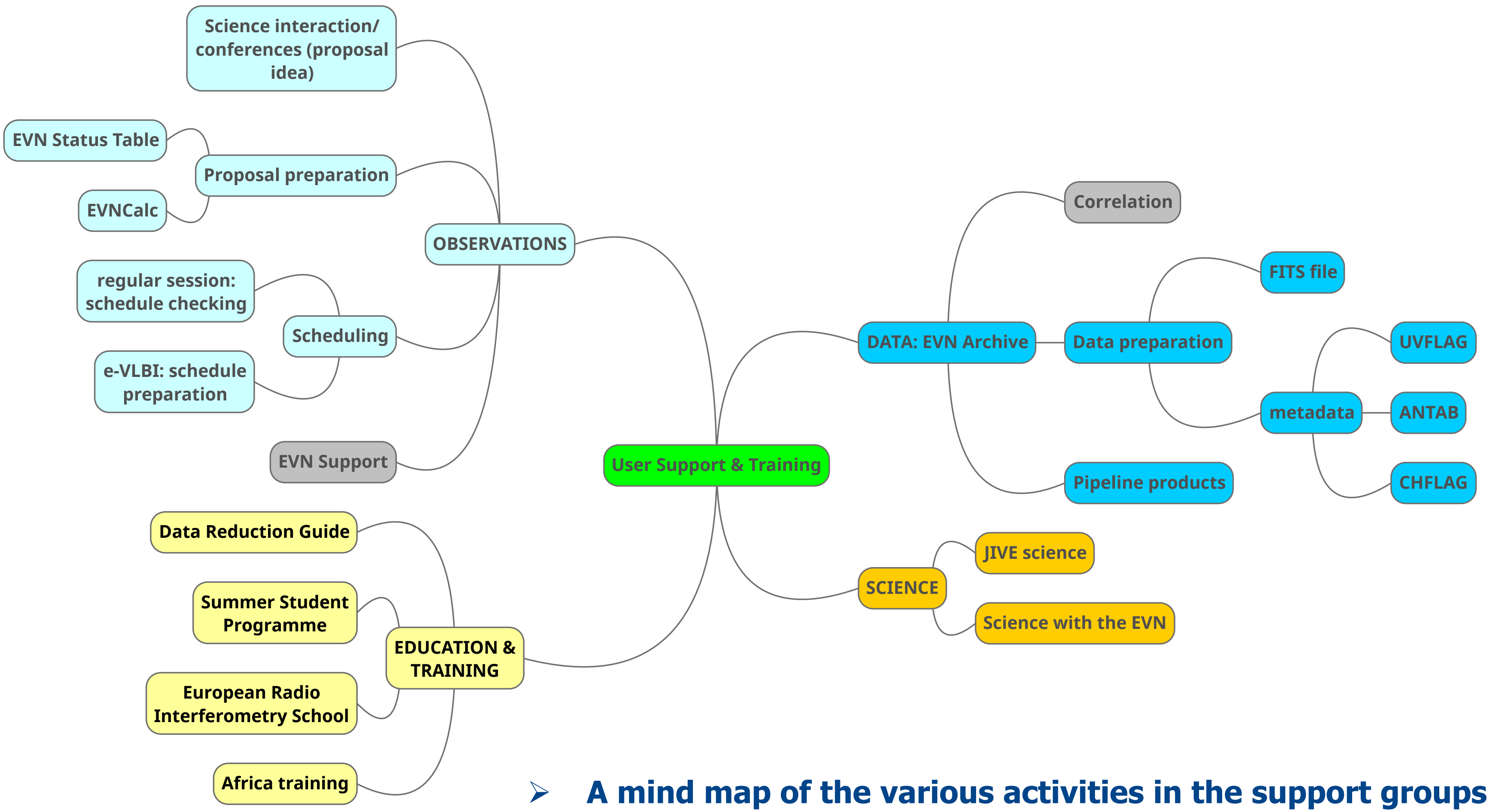
SPARSE UV-COVERAGE

"DIRTY" MAPS



- **Moreover:**
  - Sparse, typically heterogeneous arrays
  - Individual stations with special issues
  - Non-trivial scheduling, observing and processing
    - ➔ Users require extensive help

EVN & User Support at JIVE



- **A mind map of the various activities in the support groups**
- **2-3 postdocs (50-50%) + 3 permanent staff**

Workflow of EVN Science – User Support

1. Science idea	2. Proposal writing	3. Evaluation by the EVN PC (Programme Committee)	4. Schedule the observations
5. Observations (typically either in regular disc session or using real-time e-VLBI)	6. Correlation (unless real-time e-VLBI)	7. Calibrate and reduce the data	8. Science (publish or perish; and acknowledge EVN and JIVE!)

- **User support at JIVE is available for all (most) of the above steps**
  - ✓ **Science idea: check feasibility with JIVE provided tools and with support scientists!**
  - ✓ **Proposal writing: check requested array, observing strategy and correlation mode with us**
  - ✓ **Schedule observation: we will double check it for you (e-VLBI: extensive schedule support!)**
  - ✓ **Observations: EVN support, fringe tests etc. - the observations are done for you!**
  - ✓ **Correlation: we prepare FITS files, calibration metadata, we run a pipeline => EVN Archive**
  - ✓ **Data reduction: you do this, but help is available online or at JIVE – visit us!**

Proposal idea

- **Checklist before submitting a proposal**

  - ✓ **Science idea: Do you have well-defined science questions the observations will answer?**
  - ✓ **Would the target be visible for arrays in the Northern hemisphere?**
  - ✓ **Do you know its coordinates accurately enough (typically within an arcsecond)?**
  - ✓ **Is milliarcsecond (mas) – scale resolution necessary to achieve the science goals?**
  - ✓ **Does the target source have structure in the mas-100 mas(-arcsec) range detectable by the EVN(+e-MERLIN)?**
  - ✓ **Was the source observed before? Is it justified to obtain new data?**
  - ✓ **Do you have an observing strategy (required array, frequency, uv-coverage, sensitivity)?**
  - ✓ **Do you have a calibration strategy (phase-referencing y/n, amplitude & polarization calibrators)**
  - ✓ **Do you have a correlation strategy (e.g. for field of view, multi-phase centres y/n)?**
  - ✓ **Would the project benefit from real-time e-VLBI correlation / rapid response?**
  - ✓ **…**

⇒ **Submit your proposal**

Seek for advice:

usersupport@jive.eu

zparagi@jive.eu
(Zsolt Paragi, Head User Support)

Proposal submission

Sign up for the VLBI exploders

http://mailman.astron.nl/listinfo/evntech

https://listmgr.nrao.edu/mailman/listinfo/vlbi

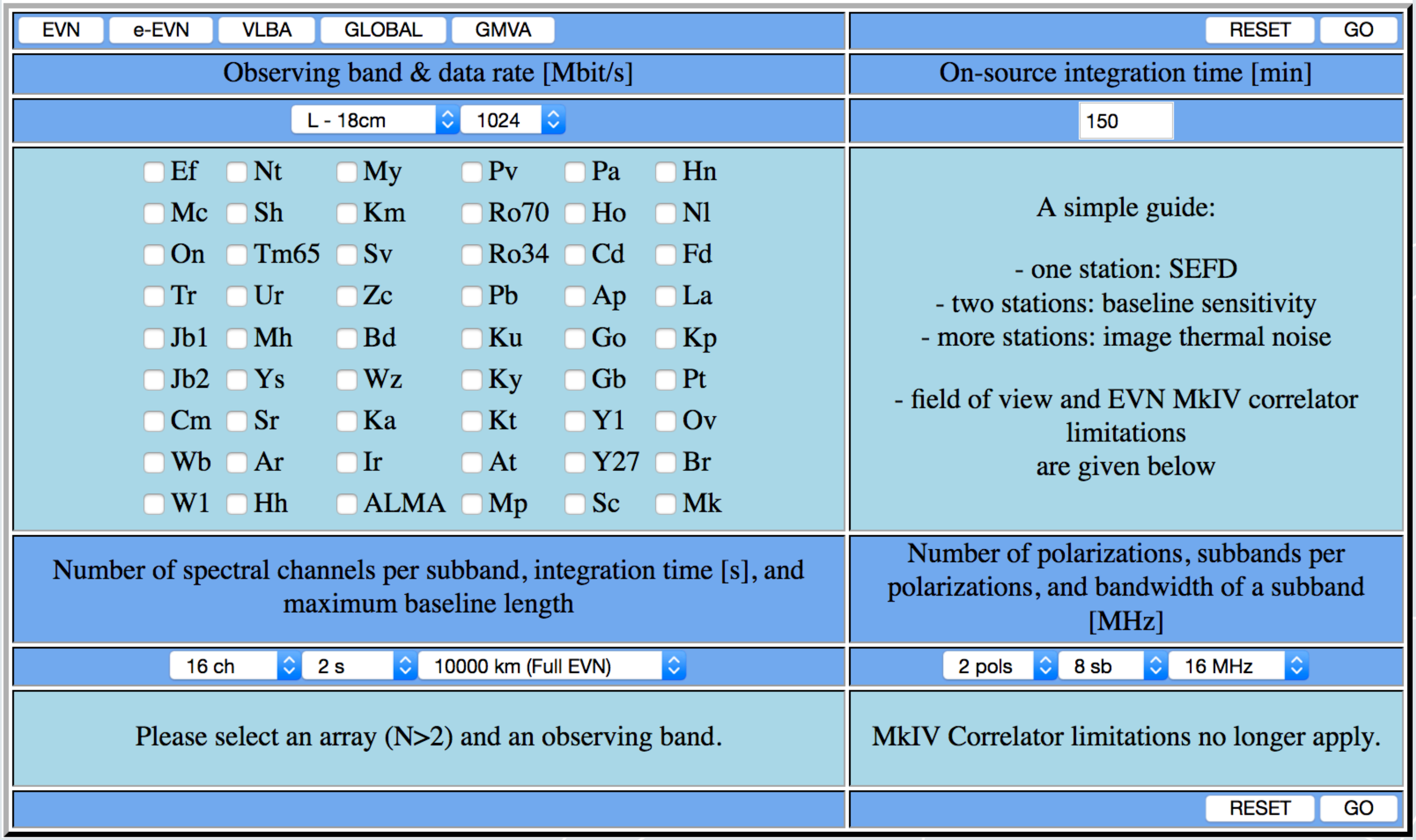
Check the EVN web pages:

https://www.evlbi.org/using-evn

⇒ Submit your proposal through NorthStar – you will need an account!

https://proposal.jive.eu

EVN Calculator



http://www.evlbi.org/cgi-bin/EVNcalc

EVN Observation Planner

EUROPEAN vlbi NETWORK

EVN Observation Planner

JIVE
Joint Institute for VLBI
ERIC

The EVN Observation Planner allows you to plan observations with the European VLBI Network (EVN) and other Very Long Baseline Interferometry (VLBI) networks. The EVN Observation Planner helps you to determine when your source can be observed by the different antennas, and provides the expected outcome of these observations, like the expected sensitivity or resolution.

beginners

GUIDED MODE

GUIDED SETUP OF YOUR OBSERVATION

MANUAL MODE

MANUAL SETUP OF YOUR OBSERVATION

experts

- More extensive help to plan an observation or to prepare for proposal submission, including array selection, target visibility at telescopes, uv-coverage, resolution and more…

https://planobs.jive.eu/

Data and pipeline products

EVN Data Archive at JIVE

Availability of standard plots, pipeline and fitsfiles.

Select Sort order: Experiment Observation period: 2016 - 2017 Submit Query

Experiment	Stnd	Pipe	Fits	P.Investigator	Stations	Obs. Date	Distr. Date	Publ. Date	Support Scientist
EA057B	x		x	Anderson	JbWbEfO8McTrSvZcSr	160305	160905	170905	Campbell
EA058A	x	x	x	Argo	JbWbMcO8UrTrSvZcBdCmDaKnTaEfRo	161028	170407	180407	Burns
EB059	x	x	x	Blanchard	JbWbEfMcNtO8TrYsT6HhAr	160921	161208	171208	Blanchard
EB060A				Bach	JbEfMcNtO6TrYsSvZcBdHhMhKtKyKu	170309			
EB061	x	x	x	Burns	JbWbMcNtO8TrArT6Hh	170510	170515	180515	Burns
EC052F	x	x	x	Cseh	EfHhJbMcO8TrWbT6	160112	160113	170113	Paragi
EC054C	x	x	x	Cao	EfHhJbMcO8TrWbT6	160113	160114	170211	Paragi/Marcote
EC054D	x	x	x	Cao	EfJbMcNtO8TrYsWbHhT6Ox	160203	160211	170211	Marcote
EC057A	x	x	x	Cutini	EfJbMcNtO6TrYsUrSvZcBdSrMhKtKyKu	160614	161202	171202	Blanchard
EC057B				Cutini	EfJbMcNtO6UrTrYsSvZcBdMhKtKyKuRo	170308			
ED040A	x	x	x	Deane	JbEfO8HhNtMcT6TrYsWbUrSvZcBdIr	161026	170331	180331	Marcote
ED040B				Deane	JbEfO8HhMcT6TrWbUrSvZcBdIr	161101			Marcote
EG078D	x	x	x	Garrett	T6WbO8McNtTrSvBdZcUrEfJbRo	160306	161026	171028	Campbell
EG078E	x	x	x	Garrett	T6WbO8McNtTrSvBdZcUrEfJb	160308	161028	171028	Campbell
EG082G	x	x	x	Gawronski	EfJbMcNtO8TrYsWbHhT6Ox	160202	160210	170704	Marcote
EG082H	x	x	x	Gawronski	EfJbMcNtO8TrYsWbHhT6	160316	160323	170704	Marcote
EG082I	x	x	x	Gawronski	EfJbMcNtO8TrYsWbHhSh	160510	160512	170704	Paragi/Marcote
EG082J	x	x	x	Gawronski	EfJbMcNtO8TrYsShWbHhSvZcBd	160621	160704	170704	Marcote
EG088	x	x	x	Giroletti	MpHoAtKyKuKtUrBdZcSvJbMcNtSrO6TrMhEfYsHh	160614	170322	180322	Blanchard
EG089C				Gurvits	JbEfMcNtO8T6UrTrYsSvZcBdIrPu	160224			
EG089D				Gurvits	JbEfMcO8UrTrSvZcBdIrGtShT6RoPu	160304			
EG091A	x	x	x	Ghirlanda	EfJbMcNtO8TrYsWbHhT6	160315	160321	180221	Marcote
EG091B	x	x	x	Ghirlanda	EfJbMcNtO8TrYsWbHhT6	170214	170221	180221	Marcote
EG092A	x	x	x	Guirado	JbWbEfMcNtO8T6UrTrZcHhSrRo	160304	160802	180315	Marcote
EG092B	x	x	x	Guirado	JbWbEfMcO8T6UrTrZcHhSrIrRo	160527	161213	180315	Marcote
EG092C	x	x	x	Guirado	JbWbEfMcO8T6UrTrZcHhRoIr	161102	170315	180315	Marcote
EG094A				Gurvits	AtPaMpHoCdTiKsWwT6UrShBdSvZcJbEfWbMcO8TrHhIrRa	160920			

http://archive.jive.nl/scripts/listarch.php
http://www.jive.eu/select-experiment

Data and pipeline products

WARNING: This is a transitional period

- Currently the pipeline products are only available for the AIPS ParselTongue pipeline (standard package / processing in the past decades)
- We are moving over to a CASA-based solution (Notebooks, see later)
- The tutorials later will therefore be for CASA

http://archive.jive.nl/scripts/listarch.php
http://www.jive.eu/select-experiment

EVN Data Reduction Guide

EUROPEAN vlbi NETWORK

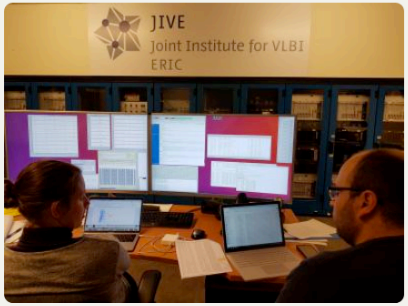
Home · About the EVN · Using the EVN · Block Schedule · Data Access · More info · old evlbi.org · EN

Home

EVN Data Reduction Guide

Become familiar with EVN data reduction in AIPS or CASA. Here you can find the basic commands to calibrate your EVN data using any of the two packages (AIPS instructions on the left column, CASA instructions on the right column). **Hover your mouse over the different parameters to know their meaning and the explanation about the chosen values.** Note that VLBI data reduction under CASA is still under heavy development, and thus several options available in AIPS may still be missing in CASA.
You can also access the EVN Data Reduction Tutorials to follow a hands on calibration.

- First steps.
- Inspecting the data.
- Calibration:
  - Atmospheric corrections.
  - Bandpass calibration.
  - Instrumental delay correction.
  - Delay and rate calibration (fringe).
- Split the data.
- Imaging.
- Post-imaging steps:
  - Image fitting and statistics.
  - Self-calibration.
- Specific observing modes:
  - Multi phase-center observations.
  - Primary beam corrections.
- Frequently Asked Questions (FAQ).



Obtaining the data

The very first step is to obtain your EVN data, that can be retrieved from the EVN Data Archive. See the detailed instructions from the EVN Data Access page.

At this point you should have several FITS IDI files containing the visibility data from your observation and a `tasav.FITS` file containing the calibration tables generated by the EVN Pipeline.

http://www.evlbi.org/user_guide/evn_datareduc.html

EVN Data Reduction Guide

AIPS

Start AIPS and load the data

AIPS can be started by typing (you may need to initialize the environment before hand): `aips tv=local:0`. Introduce the AIPS user number that you wish to use for the session.

The EVN data need to be loaded as:

```
default fitld
datain 'PWD:experiment_1_1.IDI
digicor -1
doconcat 1
ncount n
outname 'exp'
go fitld
recat
```

And the same for the `tasav` FITS file:

```
tget fitld
datain 'PWD:experiment_tasav.FITS
digicor -1
doconcat -1
ncount 1
outname 'exp'
go fitld
```

The useful calibration tables from the EVN Pipeline must be transfered from the tasav file to the data. In the case of EVN data, this means the CL table no. 2 (calibration table containing the parallactic angle and a-priori gain corrections), the a-priori flagging (FG) table, and, optionally, the bandpass (BP) calibration.

```
default tacop
getn 2
geton 1
inext 'CL'
invers 2
ncount 1
go tacop
```

```
tget tacop
inext 'FG'
invers 1
ncount 1
go tacop
```

CASA

Start CASA and load the data

Before starting CASA it is required to download some external Python scripts located under this link (`append_tsys.py, flag.py, key.py, gc.py`). A new environmental variable `$PYCAPATH` needs to be set, pointing to the directory where these scripts are located, and `$PYTHONPATH` also needs to be set/updated to include the same directory.
Additionally to the previous downloaded files, another two files from the EVN Data Archive are required. Under the "Pipeline" tab, download both the *Associated EVN calibration* (`antab file`) and the *UVFLG flagged data* (`uvflg file`).

First, the a-priori flag commands will be converted into a CASA-compatible format:

```
python $PYCAPATH/flag.py experiment.uvflg experiment_1_1.IDI1 > exper
iment.flag
```

Second, the a-priori gain calibration (system temperature measurements) will be incorporated into the IDI FITS files:

```
casa --nogui -c $PYCAPATH/append_tsys.py experiment.antab experiment_
1_1.IDI*
```

Note that this step can only be run once. Multiple runs will cause problems later and it cannot be undone.
Finally, the gain curve calibration table (how the system temperature values are converted to Jansky units) must be generated with:

```
casa --nogui -c $PYCAPATH/gc.py experiment.antab EVN.gc
```

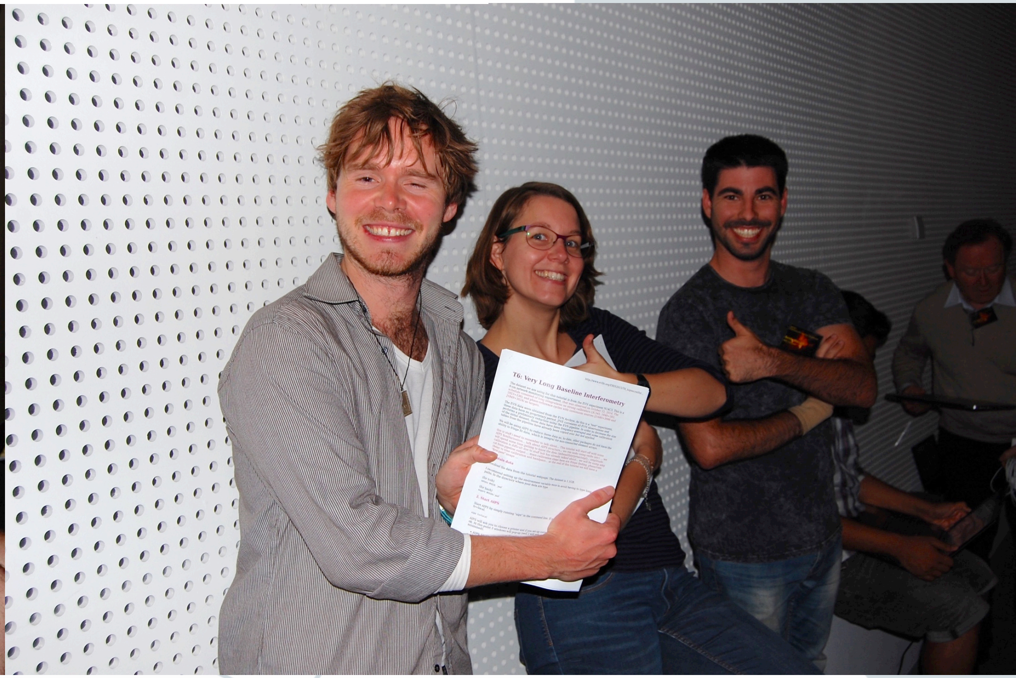
In some cases a restricted range for the acceptable elevation values must be set with the options , as some extreme values may cause the gain curves to fail.

CASA can be started by typing `casa`. The IDI FITS files may be converted to a Measurement Set (MS) file, the native format for CASA:

```
import glob
myidifiles = sorted(glob.glob('experiment*IDI*'))
importfitsidi(vis='experiment.ms',
    fitsidifile=myidifiles,
    constobsid=True,
    scanreindexgap_s=15.0)
```

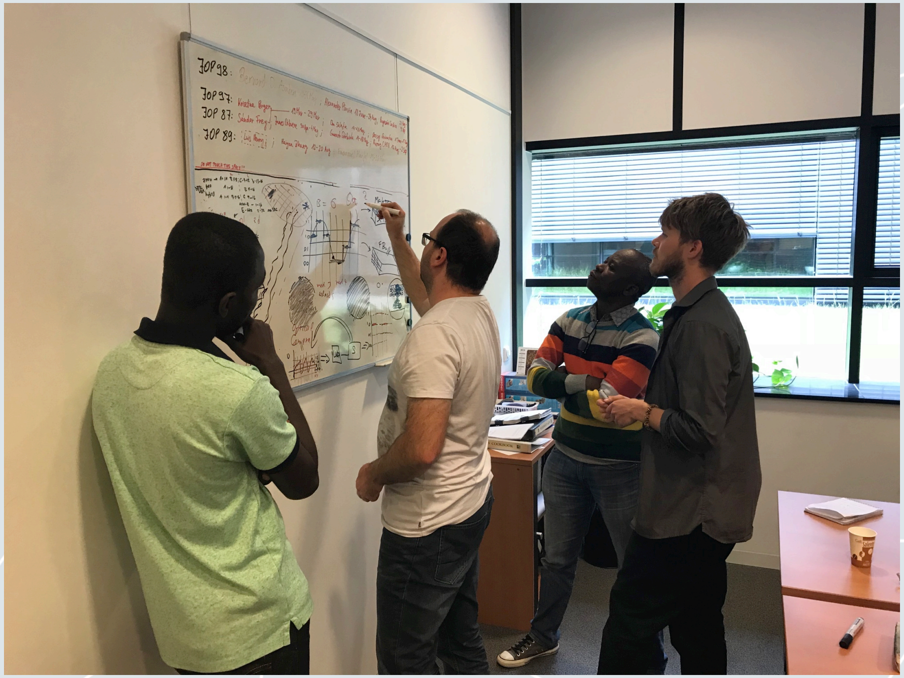
Education and Training

Helpers during the ERIS 2018 VLBI tutorial in Dwingeloo



- **No archives can fully replace human interaction in knowledge transfer**
- **Improving user experience, forming a healthy community are also important**
  (VLBI is about collaboration on global scales, after all!)

Education and Training: Africa



- Jumping JIVE work package “VLBI in Africa”
- Training the SKA generation

User Support: visit JIVE!

- Users visiting for real-time e-VLBI observations (left)
- Data reduction visits (right)

Access to the EVN*

- **RadioNet, funded by the EC Horizon 2020 Research and Innovation programme**

- **Trans-national access back since January 2017. Eligibility rules:**
  - The PI is from an institute in a country of the EU or Associated States
  - The same criterion, but applied collectively to 50% or more of the individual members of the research team
  - The research team is defined by the co-authors listed on the observing proposal, and the association of researcher with institute remains fixed at that shown on the proposal

- **Acknowledge please!**
  - EVN (with project code)
  - e-VLBI
  - TNA support

*** Will be updated soon. More information:**

TNA support – see Bob Campbell
JIVE visits arrangements – see Zsolt Paragi

http://www.evlbi.org/access/access.html

N14C3: Data reduction*

- **VLBI experiments have a code, starting with**
  E – for EVN, G – for globals (EVN+VLBA), R – rapid response science
  N – network monitoring experiment, F – fringe-test

  Usually followed by PI's surname initial, and a number: e.g. EP100

- **N14C3 has no PI, it is a Network Monitoring Experiment, observed in 2014, in band C (5 GHz), in session 3 during the fall**

- **These experiments are not going through the EVN PC, they are organized by JIVE staff, to frequently monitor telescope performance**

- **For these purposes, few hours observations on bright calibrators are required**

Ideal for tutorial purposes as data has a size of ~3 GB, small compared to typical experiments with size often exceeding 10 TB.

*By "Data reduction" we mean the process of calibrating our data and then – for most purposes – do some averaging in time and frequency, reducing the data size.

**The following is based on Jack Radcliff's DARA presentation in 2019.

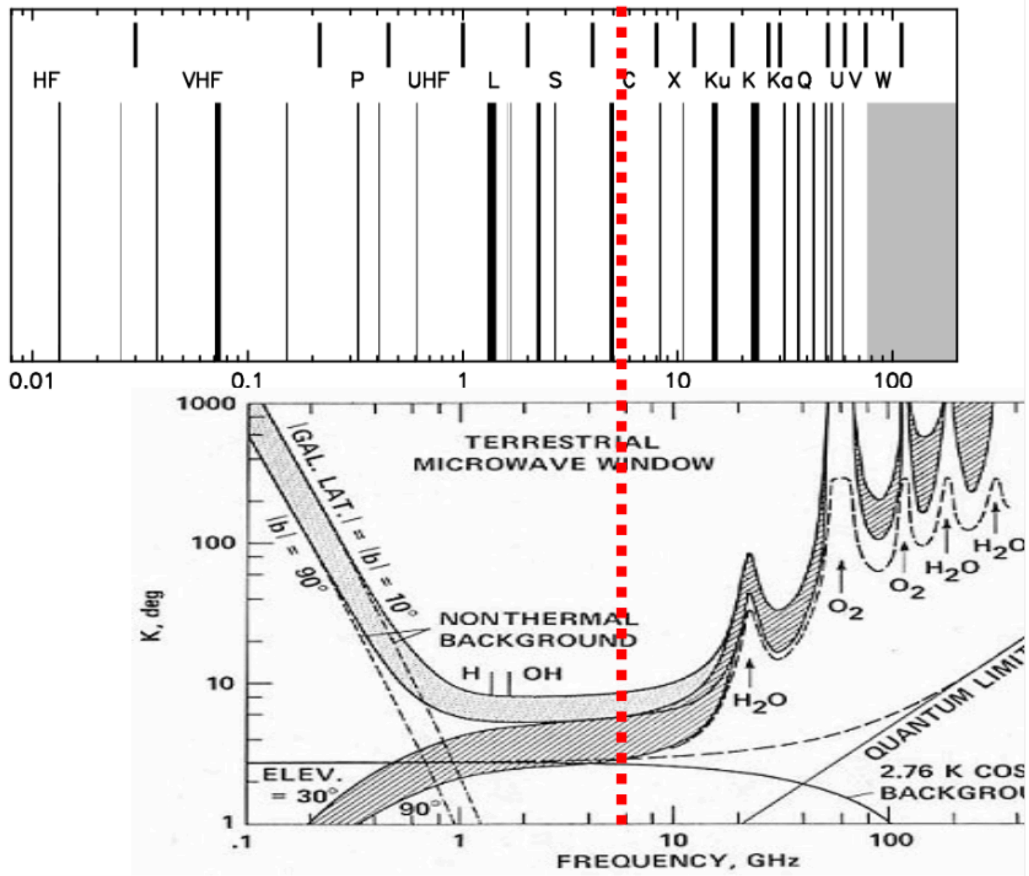
N14C3: the observations

- **22 October 2014**
  for 3 hours

- **Targeted 5 sources**
  (including fringe-finders,
  phase calibrators) and
  target sources

- **Observed at C-band**
  (5 GHz)

- **Sweet spot for VLBI as:**
  - ✓ Receivers are sensitive
  - ✓ Sky noise is low
  - ✓ Has limited impact from the atmosphere



N14C3: the observations

- **12 antennas used (highlighted in yellow)**
- **Data recorded on disc**
- **DPFU & Tsys measurements**
  - Used to set the flux scale of the observations
- **Gain curves are also available**
  - Elevation-dependence of sensitivity,
  - Taking into account the atmosphere as well
- **Data correlated at JIVE**
- **IDI-FITS file and calibration data available from the EVN Archive**

EVN OBSERVATORIES	TELESCOPE Code	Diameter(m)
Jodrell Bank (UK)	Jb-1 Lovell	76
	Jb-2 Mk2	25
Cambridge (UK)	Cm	32
Westerbork (NL)	Wb	25
Effelsberg (DE)	Ef/Eb	100
Medicina (IT)	Mc	32
Noto (IT)	Nt	32
Sardinia (IT)	Sr	65
Onsala (SE)	On-85	25
	On-60	20
Sheshan(Shanghai,CN)	Sh	25
Tianma(Shanghai,CN)	Tm65 (T6)	65
Nanshan(Urumqi,CN)	Ur	25
Torun (PL)	Tr	32
Metsaehovi (FI)	Mh	14
Yebes (ES)	Ys	40
Arecibo (USA)	Ar	305
Hartebeesthoek (SA)	Hh	26
	Ht	15
Wettzell (DE)	Wz	20
Svetloe (RU)	Sv	32
Zelenchukskaya (RU)	Zc	32
Badary (RU)	Bd	32

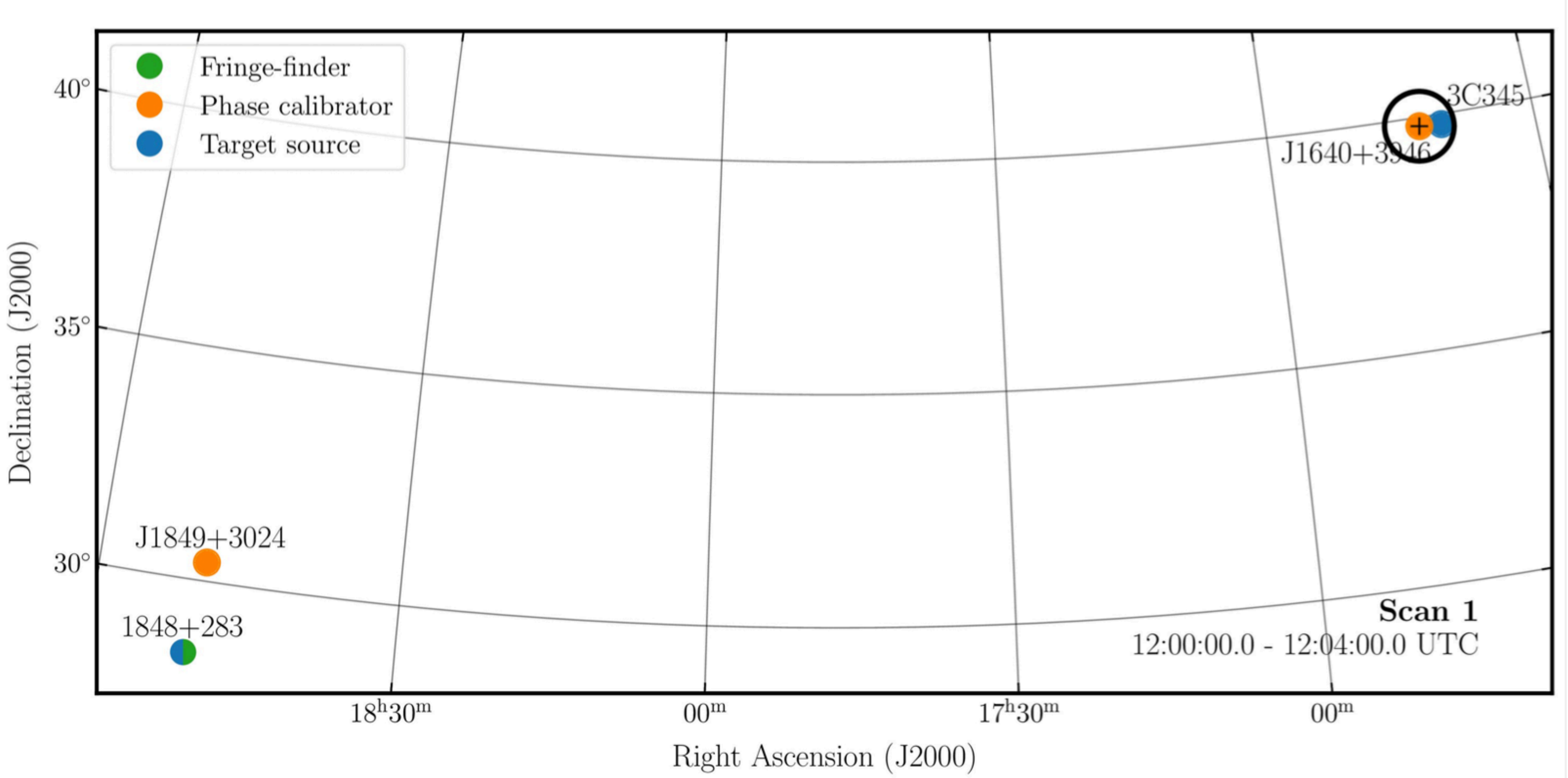
N14C3: observing strategy

The experiment is scheduled with bright and compact sources
- these may serve various purposes such as

- **Fringe-finder:** usually the brightest sources to easily solve residual delays on a subband per subband basis
- **Phase-calibrator:** a compact and still relatively bright source within a few degrees of the target, to provide regular solutions to the residual fringe delay, rate and phase; must be observed frequent enough, to provide solutions within the coherence time, to avoid decorrelation losses
- **Amplitude calibrator**: usually the most compact and relatively bright sources, with correlated flux densities not dropping significantly at long u-v distances; note there are no absolute flux density calibrators for VLBI, all compact sources are variable!

N14C3: observing strategy

Starts at 12:00 UT – end at 15:00 UT



N14C3: correlation

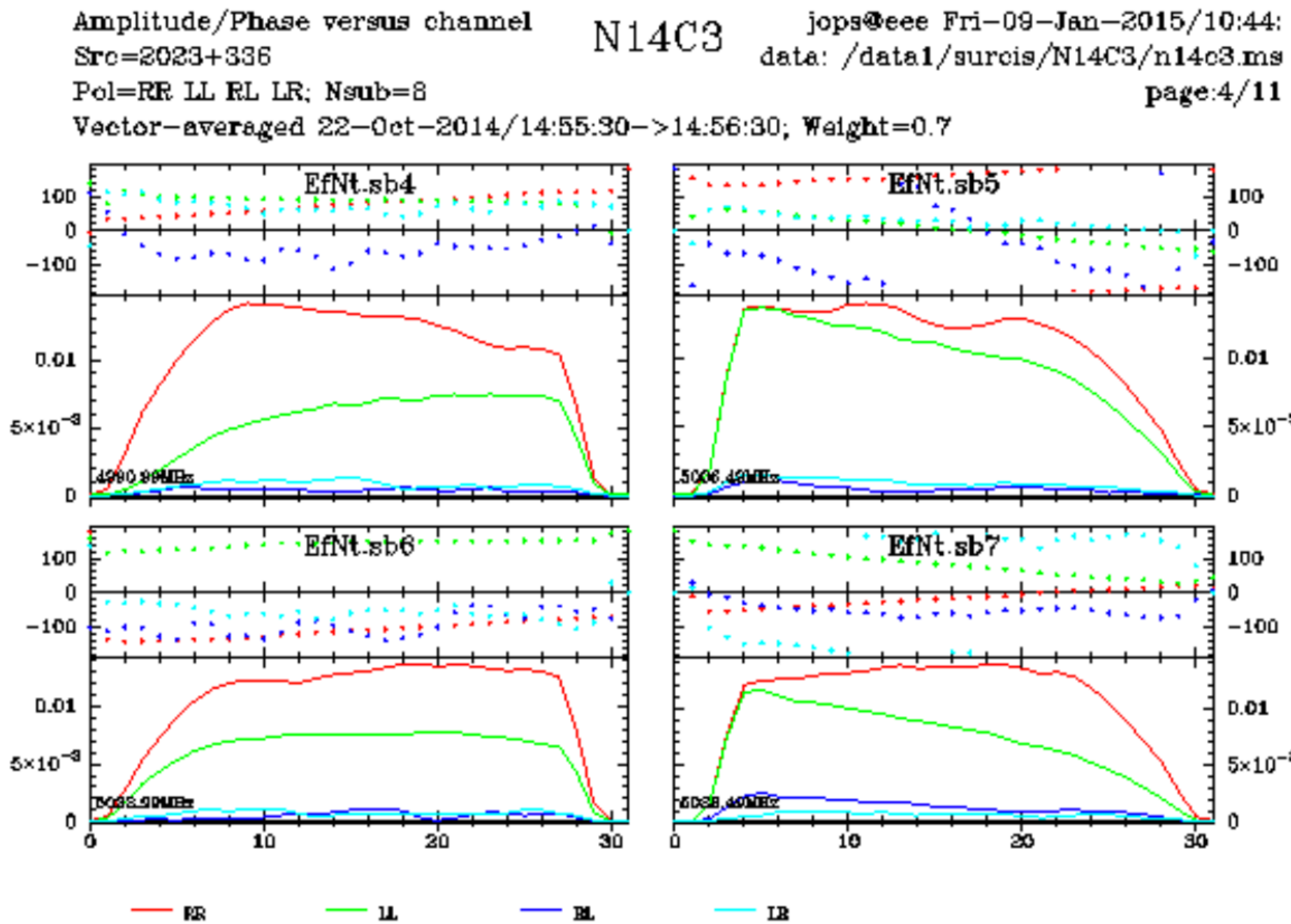
- **Correlator used:** done at JIVE using the SFXC correlator
- **Clock-searching:** the initial step before the correlation. A short segment of fringe-finder data is used to measure (and correct for) a the bulk of the residual delay between correlator model and the data. At this stage it is usually dominated by clock errors.
- **Correlation:** a process of coherently combining the data on each baseline; this usually results in time and frequency resolution of 1-2 seconds and 0.5-1 MHz per spectral channel (for standard continuum experiments). A time-dependent calibration of further residual delays, rates and phases is necessary in post-processing the data.
- **Sources of additional delay errors can be:**

$$\tau_{\mathrm{obs}} = \tau_{\mathrm{geo}} + \tau_{\mathrm{rot}} + \tau_{\mathrm{str}} + \tau_{\mathrm{trop}} + \tau_{\mathrm{ion}} + \tau_{\mathrm{ins}} + e_{\mathrm{noise}}$$

  - ✓ **Source coordinates, telescope positions, Earth Orientation Parameters (EOP)…**
  - ✓ **Source structure**
  - ✓ **Atmosphere**
  - ✓ **Instrumental delays, electronic path effects**

N14C3: the data

- **Phase (up) and amplitude (down) vs. frequency plots** (shown for the upper four subbands)
- **Signal-to-noise ratios are excellent** (for now, consider only the parallel hands, **RR** and **LL**)
- **Amplitudes:** the values show raw correlation coefficients; notice filter shapes - bandpasses
- **Phases**: frequency slope (delay) must be corrected for



N14C3: calibration strategy

- **Preparations:** apply parallactic angle correction (corrects for feed rotation of Alt-Az antennas), apply a-priori flag tables (if available), look at your data! Identify bad subbands or antennas that may need flagging (do a few A&P vs frequency plots). Find a suitable scan with all telescopes providing good data.

- **A-priori amplitude calibration:** apply T_{sys} measurements and gaincurves. This provides an approximate flux scale (accurate to 10-15%). To refine this, one would need to measure the flux density of one or more VLBI calibrators by comparing them to a primary flux calibrator source, using arrays with shorter (~>100 km) spacings.

- **"Manual phasecal":** take a good calibrator scan of say ~2 minutes and derive inter-channel delay and phase offsets – apply this to all sources for the whole timerange. (Note do not solve for rate!!!) This will remove instrumental delays, and will allow you to fringe-fit the data coherently across the whole band. Instrumental delays are (should be!) stable during the observations. Check this by looking at scans far apart in time!

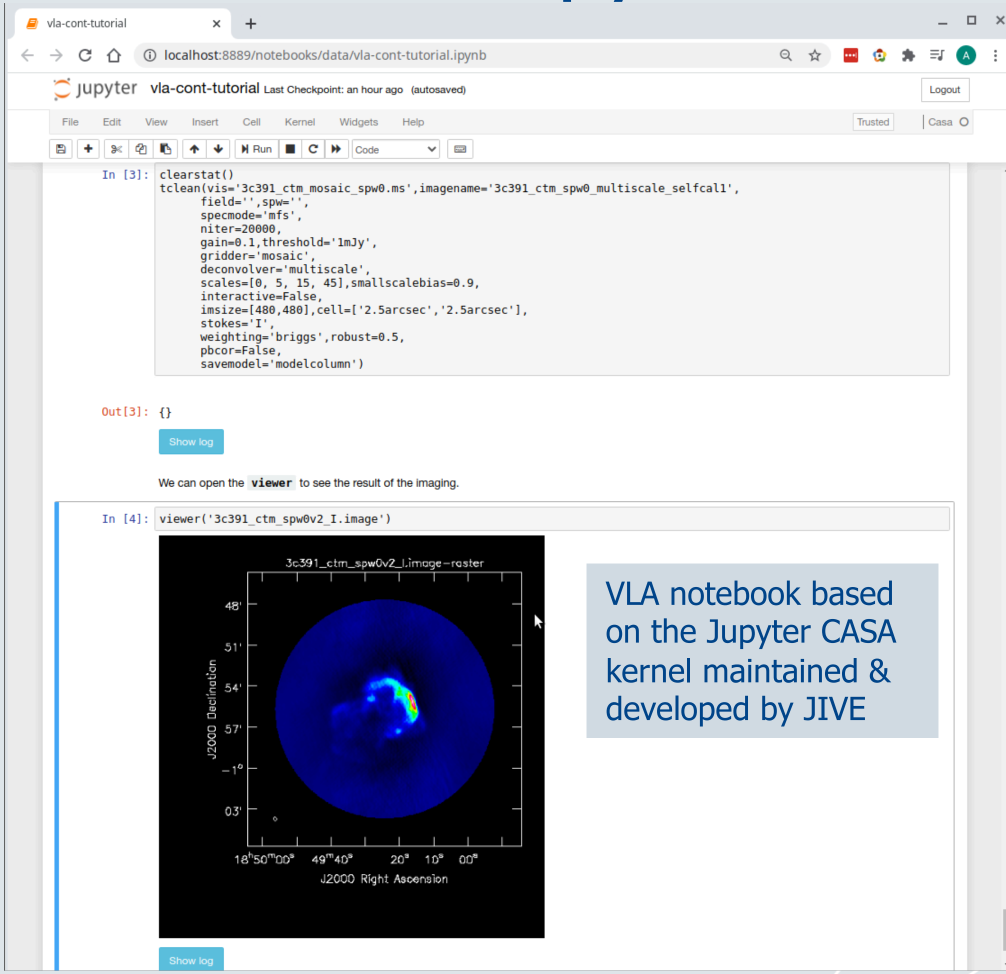
- **Fringe-fitting:** derive residual delays, rates and phases for the whole experiment using short (typically 1-2 minutes) solution intervals. Use the whole band (i.e. combine the channels) for this. You only use data for the dedicated phase calibrators, but the solutions will be applied to both calibrators and target sources (a.k.a phase-referencing).

- **Bandpass calibration**: you always do bandpass calibration after fringe-fitting (to separate delay and bandpass effects).

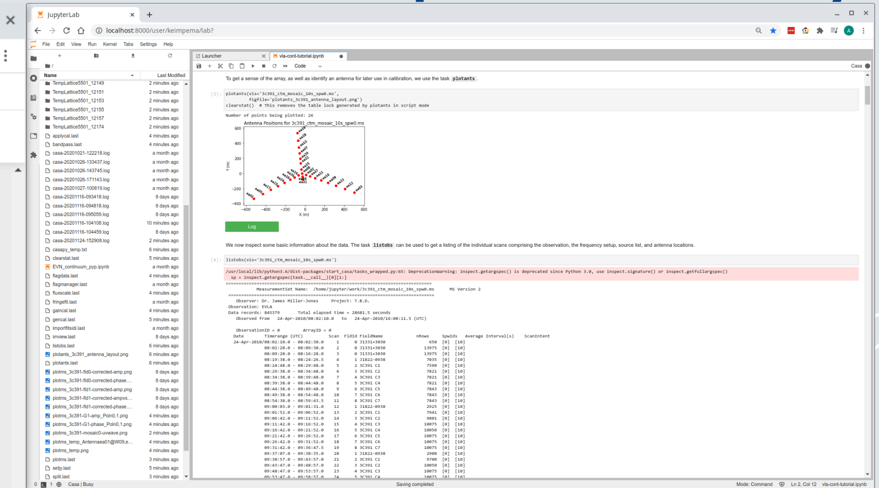
N14C3: imaging & self-calibration

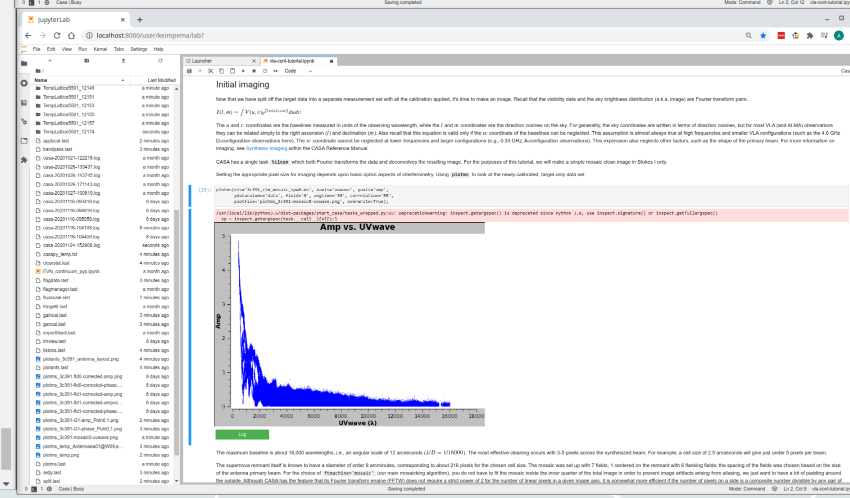
- **Preparations:** you already applied all calibrations to both calibrator(s) and target(s).
- **First round of imaging:** make in image by iteratively cleaning the "dirty map". Watch how he source model builds up – compare model visibilities to data. Very relevant is the "radplot", the amplitude (and phase) vs. uv-distance plots.
- **Self-calibration:** use the image to self-calibrate the data. Initially, only phases are calibrated. Image the data again. Watch how the model flux builds up. Never self-calibrate on amplitudes if you miss significant flux! If you cannot reach a satisfactory initial model, repeating too many cycles of phase selfcal will not help. Identify the problem instead (e.g. a station or stations with very poor amplitude calibration present). If you have a good model, proceed with amp&phase self-calibration and imaging.
- **Image the target:** once the calibrator image is satisfactory, apply the calibration to the target as well. Image the target. If bright enough, you may attempt self-calibrating on the target itself! (Do not do this if the goal of the project is relative astrometry!)
- **Science**: you are ready to do detailed analysis (model-fitting for example) of your results, interpret them, and publish your data. Congratulations!

The future: Jupyter notebooks for reproducibility



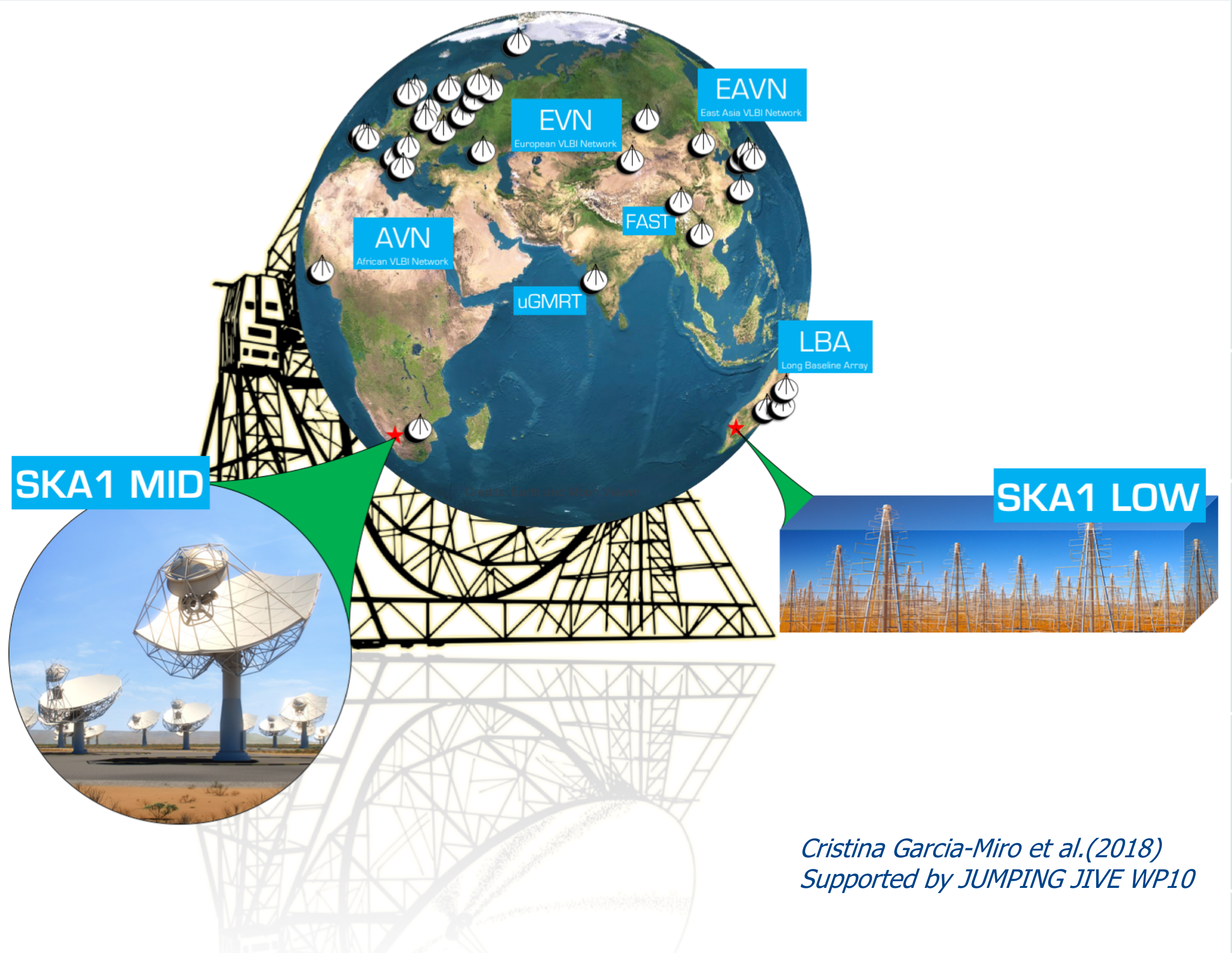
VLA notebook based on the Jupyter CASA kernel maintained & developed by JIVE





- ➢ **ESCAPE (2020-2022): implement EVN Notebook**
- ➢ **Goal to be able to archive Notebooks with data in the EVN Archive**

The future: VLBI with the AVN & SKA as well?



- **Strong science driver is** *ultra-precise astrometry (~1 µas; e.g. Paragi et al. 2015)*
- **Requires n>4 SKA1-MID beams** *(L1 requirements now aligned with design capabilities)*

At your service!

JIVE

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