rPicard and mm-VLBI

CASA VLBI workshop, June 2023 @JIVE

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OPTICON RadioNet Pilot

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M2FINDERS

MAX-PLANCK-GESELLSCHAFT

Max-Planck-Institut für Radioastronomie

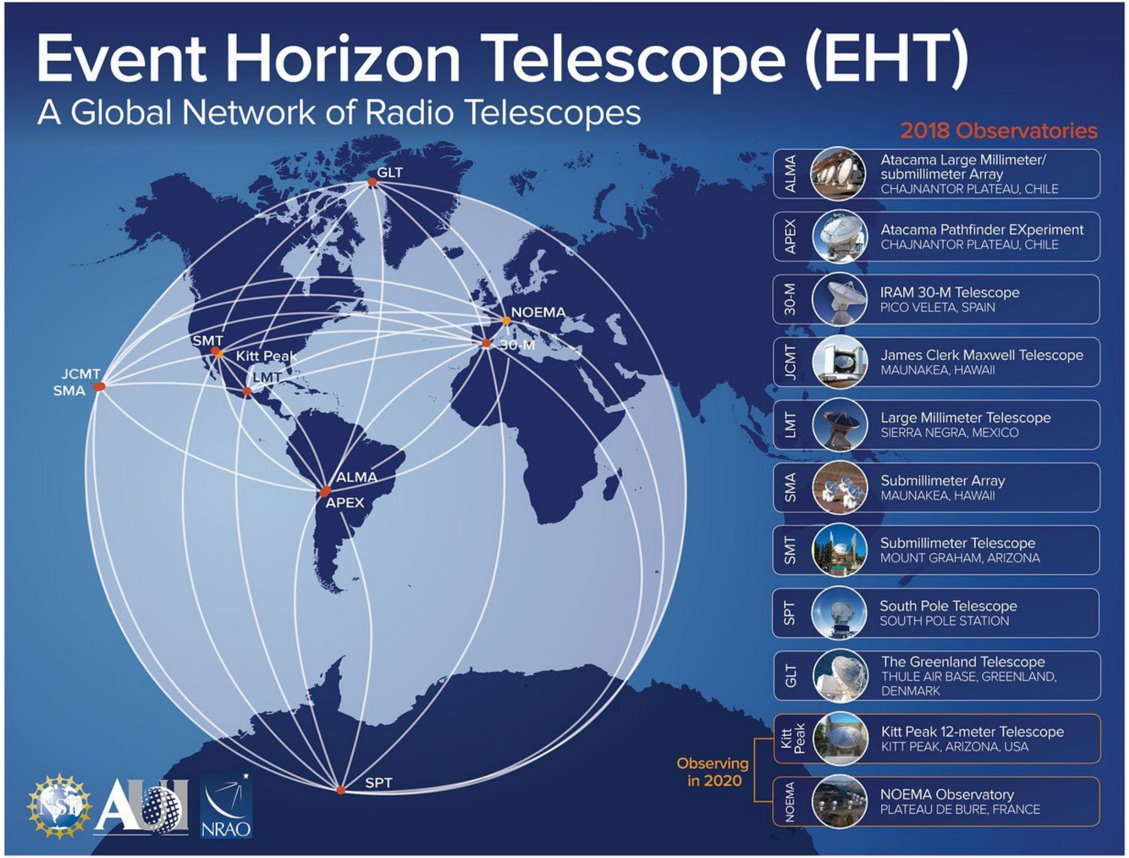
mm VLBI

- Q-band to highest EHT frequency.
- 43 – 345 GHz.
- 7 – 0.87mm.

EHT

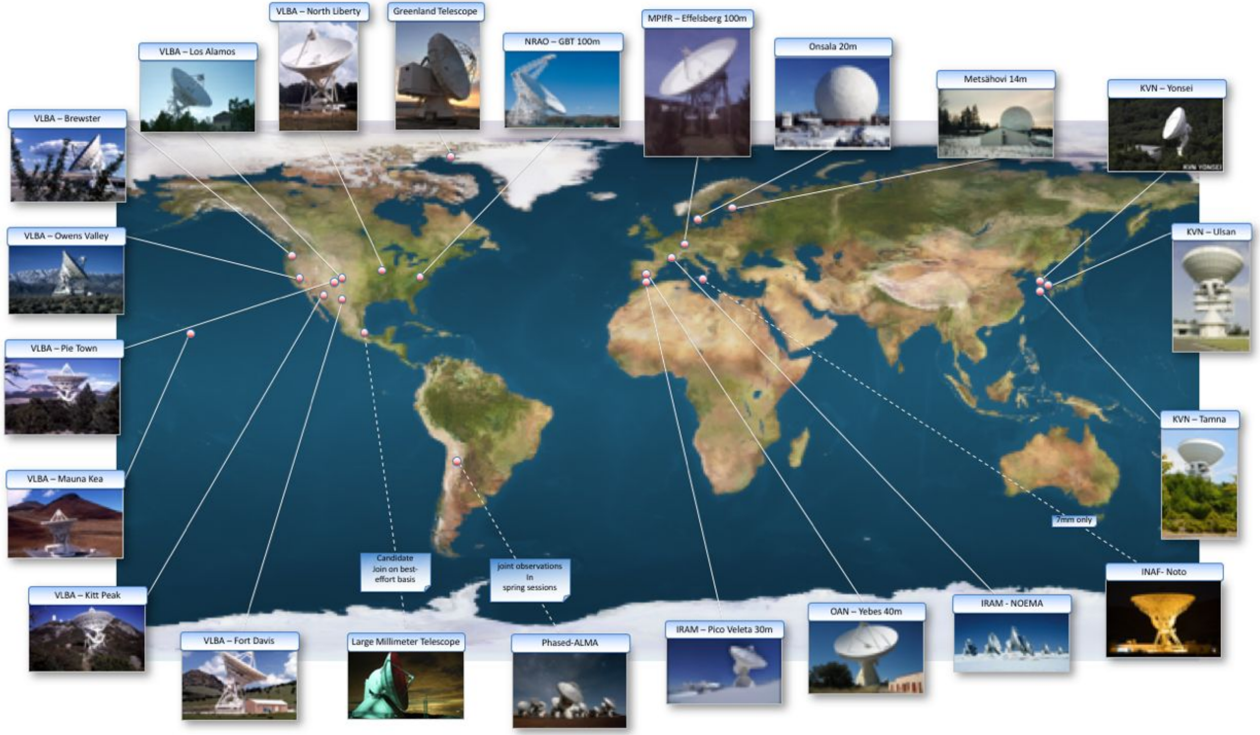
- 214, 228, 253, 267, 336, 348 GHz (not simultaneous).

- 15 μas.



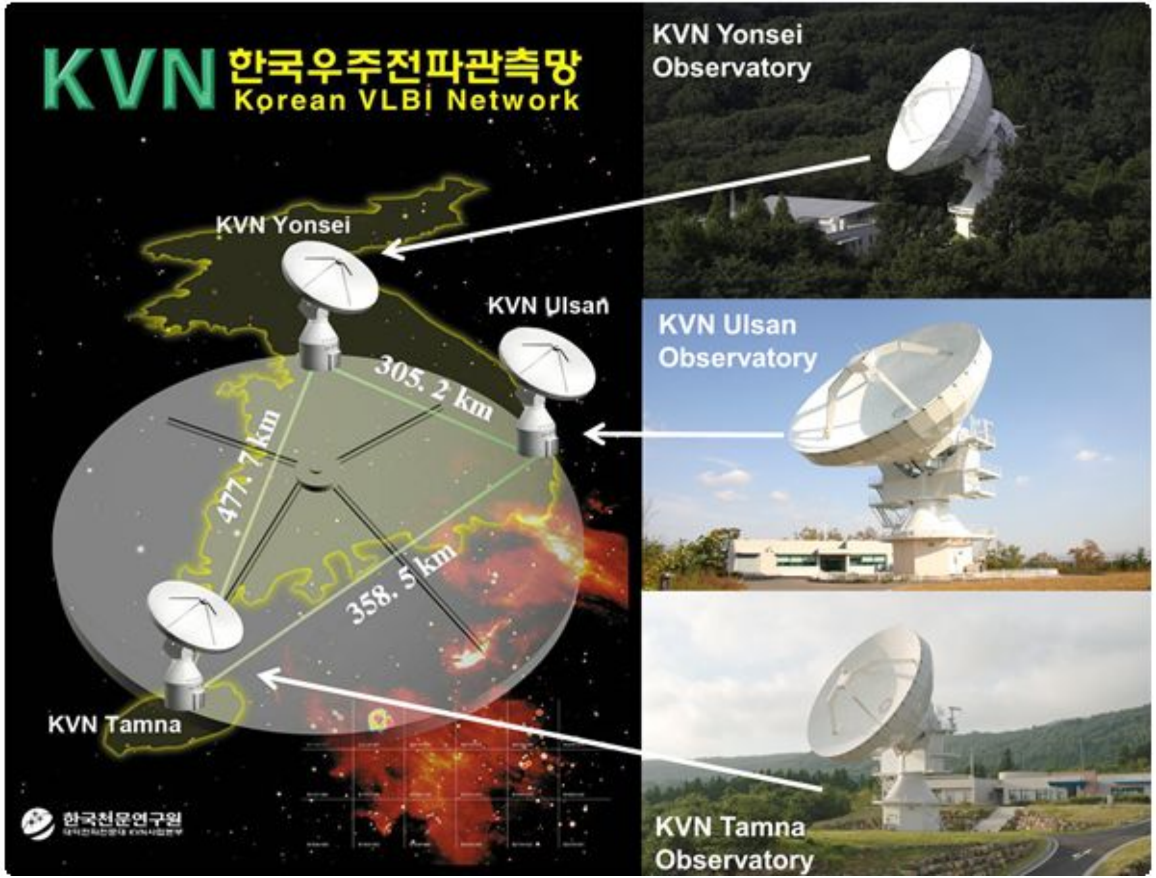
GMVA

- 86 GHz.
- 56 µas.

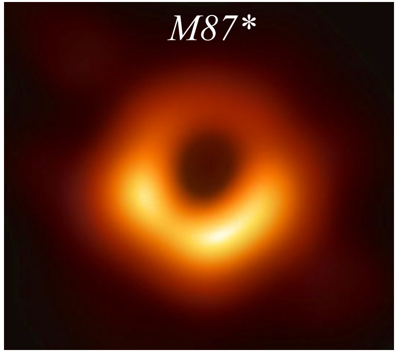


KVN

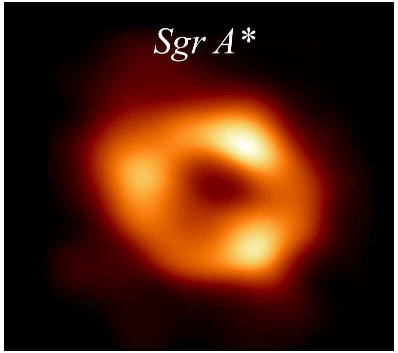
- 22 + 43 + 86 + 129 GHz.
- 1 mas.
- Drives multi-band receiver development.



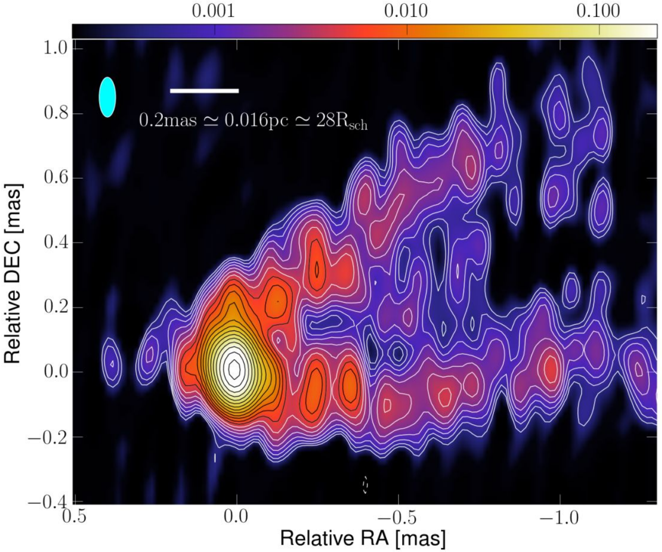
mm VLBI science



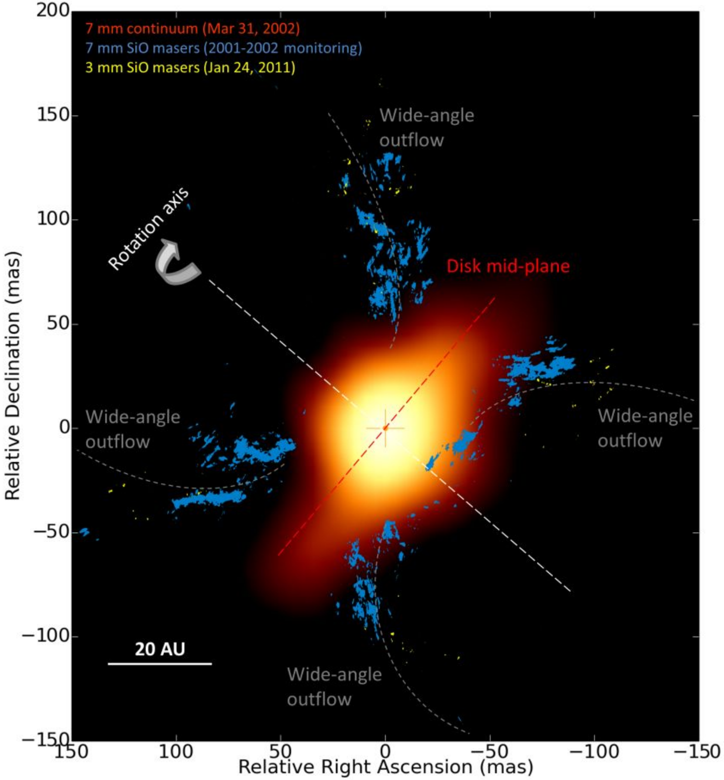
EHT Collaboration et al. 2019, ApJL, 875, L1-6



EHT Collaboration et al. 2022, ApJL, 930, L12-L17



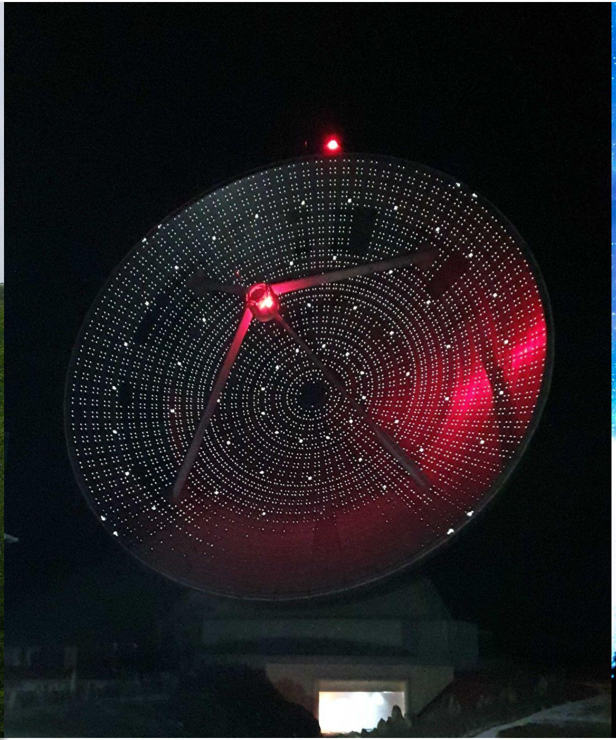
Kim et al. 2018, A&A, 616, A188. M87 jet



Issaoun et al. 2017, A&A, 606, A126. YSO

mm VLBI challenges

- Reflective telescope dishes with excellent surface accuracies needed
  → Collecting areas are typically small!



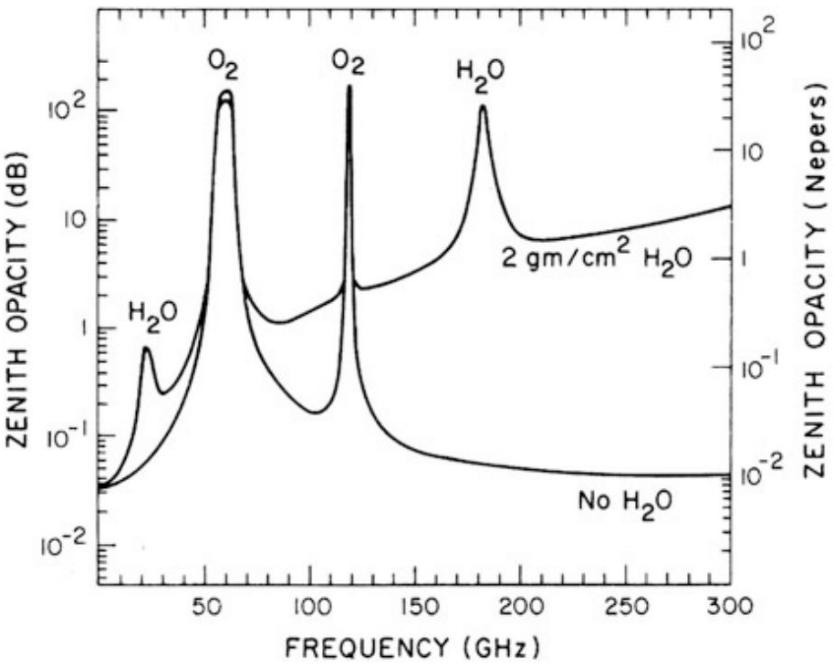
mm VLBI challenges

1. Reflective telescope dishes with excellent surface accuracies needed → Small collecting areas

2. Troposphere: The water vapor problem
   a. Short (~seconds) coherence times due to atmospheric turbulence
   b. Emission → larger SEFDs (+ large receiver noise)
   c. Absorption → source signal attenuated

3. To (partially) counter atmosphere: Must be on high and dry site & have good weather → sparse arrays!

Taken from TMS III



mm VLBI challenges

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What it means in practice

- **Typically, you have sparser and noisier data → Watch out for imaging artefacts, maybe use new ~MEM algorithms**

- **No phase-referencing**
  → Must fringe-fit the target:
  ≥ 10 – 100 mJy compact flux density
  ⇒ Except: In-beam phase-referencing & multi-freq receivers

  (Also note limits of phased arrays like ALMA: ≥ 750 mJy or passive phasing at 345 GHz)

How you can do it: rPICARD

- Janssen et al., A&A, 626 (2019) A75, https://bitbucket.org/M_Janssen/picard
- No lengthy process of setting parameters and running tasks manually.
- Open source & scientific reproducibility.
- Built-in MPI acceleration for all tasks.
- Low barrier to entry.
- 57 pages of documentation.
- Works for any VLBI array.
  Note also VPIPE from previous talk:
  https://github.com/jradcliffe5/VLBI_pipeline
- Many diagnostics to inspect.
  Easy to adjust strategy and re-run steps.

```
#Bright calibrators for instrumental phase and delay calibration.
calibrators_instrphase = 3C279, NRAO530

#Bright calibrators for complex bandpass calibration.
#If bandtype_cmplx_bandpass = 'BPOLY' is set in array.inp, only a single source can be set here,
#since POLY bandpasses cannot be averaged.
calibrators_bandpass = 3C279

#Bright calibrators for rl delay and phase offsets.
#Should always be set, also for non-polarization experiments to do the fringe-fitting correctly.
#If set to None, the rl delay calibration will be skipped.
calibrators_rldly = 3C279

#Calibrators for D-term calibration.
#Must be polarized and observed over a wide range of parallactic angles for every antenna.
#D-terms should be solved in a post-processing step after calibrators have been imaged.
#If set to None, the D-term calibration will be skipped.
calibrators_dterms = None

#Phase-referencing sources.
#If set, the phase-referencing mode is activated.
#For a list of comma separated science_targets, use a corresponding csv list here.
#Example: science_target = s1, s2, s3 and calibrators_phaseref = p1, p2 means that
#p1 is used as phaseref source for s1, p2 is used for s2, and no phase-referencing is
#done for s3.
calibrators_phaseref = None

### End of calibrator lists.                                                   ###


#Whether or not to also fringe-fit the science targets themselves in phase-referencing mode.
#Set to False for very weak science targets, then only the fringe solutions from
#calibrators_phaseref are applied to the science targets.
#Set to True if the science targets are strong enough for a residual fringe-fit. In that case,
#after a transfer of fringe solutions from calibrators_phaseref, the science targets themselves
#are fringe-fitted as well, to take out residual phase/delays/rates.
#Generally, this should be False for astrometry. It should be True when the calibrator is far away
#from the science target and/or at higher frequency observations.
phaseref_ff_science = False

#Parameters that enable and control the spectral line calibration mode.
#Set to False for continuum observations.
#Otherwise, the channel or frequency range of the line can be given for one or multiple sources.
#Channels are given as spw:chan numbers, frequencies as ...GHz. For example:
#spectral_line=0:6                              for one science_target, fringe-fit only channel number
#                                               6 in spectral window number 0.
#spectral_line=1:2~8                            channel range 2-8 in spw 1.
#spectral_line=5.123GHz                         select the single channel closest to 5.123GHz.
#spectral_line=22.3GHz~22.4GHz                  channel range between 22.3 and 22.4 GHz.
#spectral_line=1:6; 2:5~8; 1GHz~2GHz; 3GHz      for four science_targets (separated by ;),use channel
#                                               6 in spw 1, channels 5 to 8 in spw 2, channels between
#                                               1GHz-2GHz, the closest channel to 3GHz, respectively.
#The selected line channels must be within a single spectral window! Hence, process the data
#separately with different pipeline runs when there are multiple line spectral windows.
#If the spectral_line mode is set, the science_target(s) will not be used for the scalar bandpass
#calibration and no delays are fitted for the science_target(s).
#If needed, normal phase+delay+rate phase-referencing can be set via calibrators_phaseref.
#You will then probably want to set phaseref_ff_science=True to correct the rates.
#For spectral line observations, setting long_solint_no_mpi=False in constants.inp should also
#be safe.
#If set to 'search', the code will pick the channel with the highest amplitude in the auto-
#correlation spectra. The determined channel will also be written into a
#'spectral_line_peak_channel.txt' file in the working directory.
#The search is done before the first science target fringefit step.
spectral_line = False
```

Installing rPICARD

- `git clone https://bitbucket.org/M_Janssen/picard`
- `./picard/setup.py -p <path/to/your/CASA/installation>`
- `printf '\nexport PATH=$PATH:'"$(pwd)"'/picard/picard\n' >> ~/.bashrc`
- `printf '\nexport PYTHONPATH=$PYTHONPATH:'"$(pwd)"'/picard/picard\n' >> ~/.bashrc`

- (optional) Install https://github.com/haavee/jiveplot and/or https://sylabs.io/singularity and add it to your path

- Or run containerized within Singularity/Docker: https://bitbucket.org/M_Janssen/picard/src/master/README.md

Setting up rPICARD

- Create a clean working directory and link input data there
  - Link (`ln -s`) to FITS-IDI, ANTAB, and (for mm VLBI) weather/wx files
  - Add optionally: flag txt file, t_rec/t_rx txt file, source models
- `cp -r /path/to/installation/picard/input_template/ input`

```
michael@mjpc:~/Software/Bitbucket_repos/Picard/testing$ ls
3C84.smodel  example.antab  example_EVN.IDI1  example.flag  example.trx  input
```

- Minimally set parameters in input/observation.inp and input/array.inp:
  - Names of science target(s) and calibrators.
  - Name of the array (EVN, VLBA, GMVA, …) and list of reference antennas.

Running rPICARD

- `cd /path/to/working/dir && ls`

```
michael@mjpc:~/Software/Bitbucket_repos/Picard/testing$ ls
3C84.smodel  example.antab  example_EVN.IDI1  example.flag  example.trx  input
```

⇒ **`picard -p`**

- Some further examples

`picard -l e`	Load data, write listobs, exit
`picard -pq h,i,k`	Plot the uncalibrated data
`picard -n 4 -pq 4`	Run only step 4 using 4 cores

Check data before setting input and running full pipeline

Step-by-step reduction of mm VLBI data following rPICARD

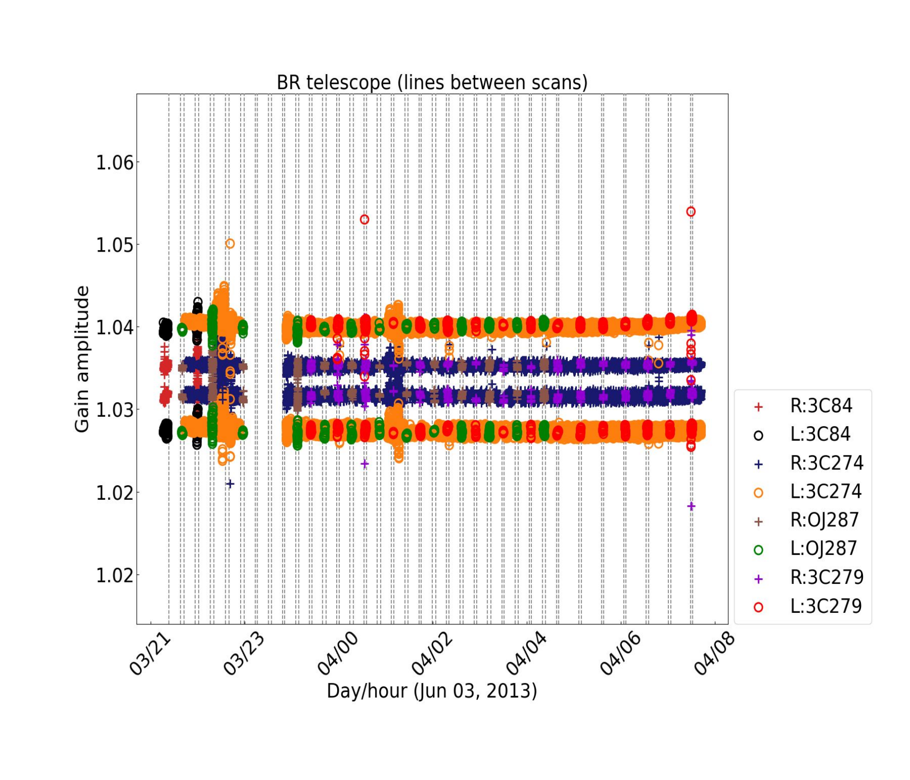
1. Pre-calibration:
   a. Gather and process metadata (see Mark's lecture on Tuesday)
   b. Load the data into a MeasurementSet
   c. Load source models
   d. Flag bad data

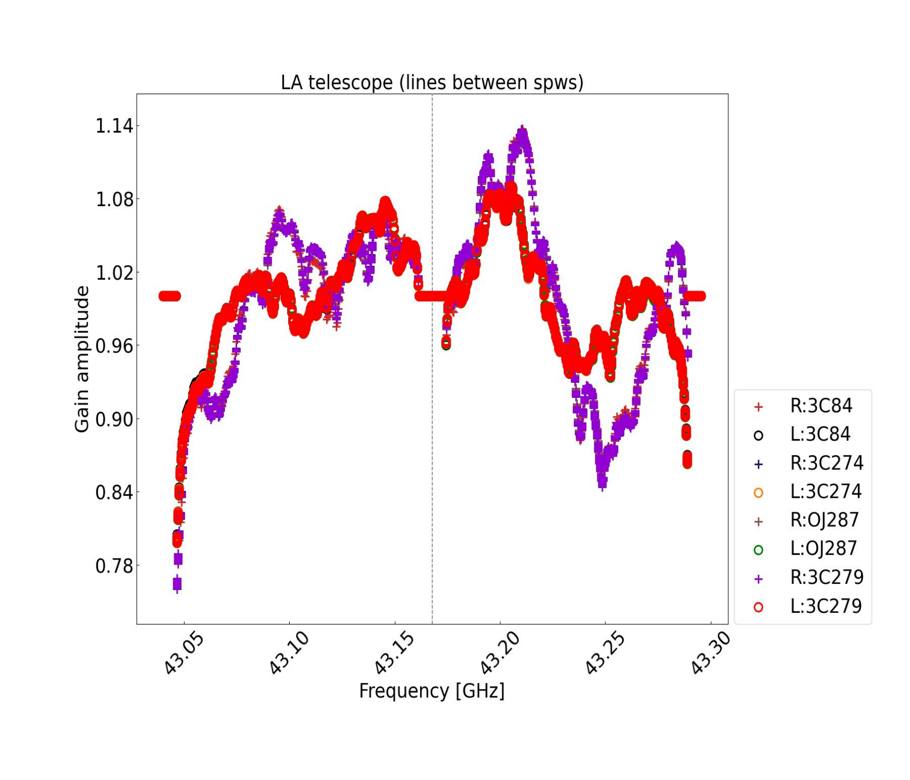
2. **Calibration steps:**
   a. **Flux density**
   b. **Fringe-fit & phase calibration of calibrator sources**
   c. **Solve instrumental effects**
      i. **Align spws, bandpass, align correlation products (RL phase+delay)**
   d. **Fringe-fit science targets over VLBI scans, combine correlation products for max S/N**
   e. **Residual fringe-fit science targets with narrow windows and tuned solution intervals**

3. Post-calibration:
   a. Apply calibration solutions
   b. Plot the calibrated data
   c. Export averaged data as MS and UVFITS

Amplitude calibration

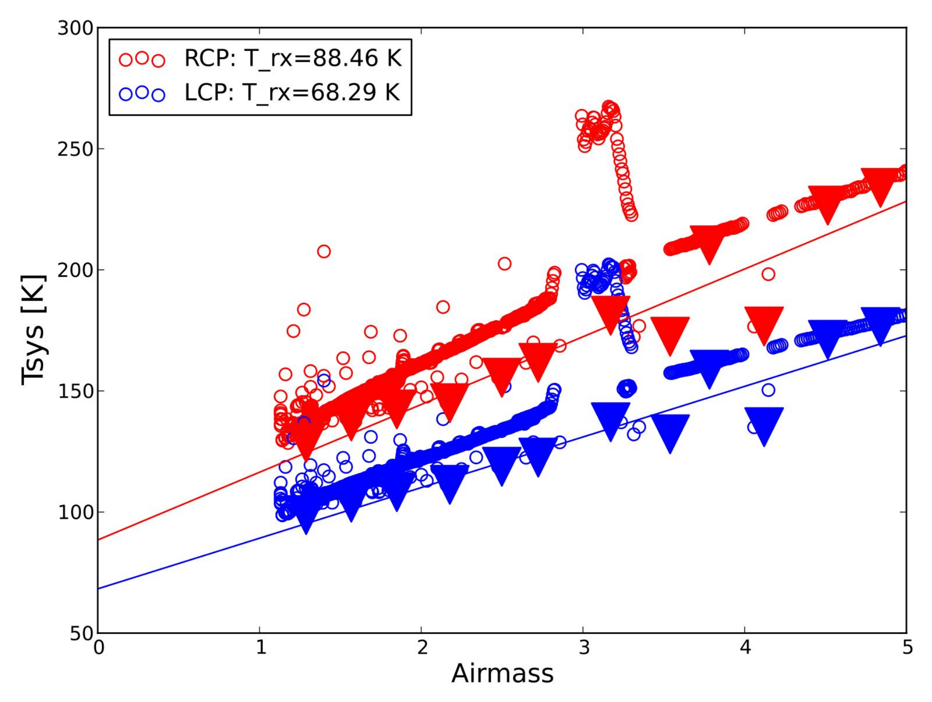
Accor & scalar bandpass (step 0, 1)

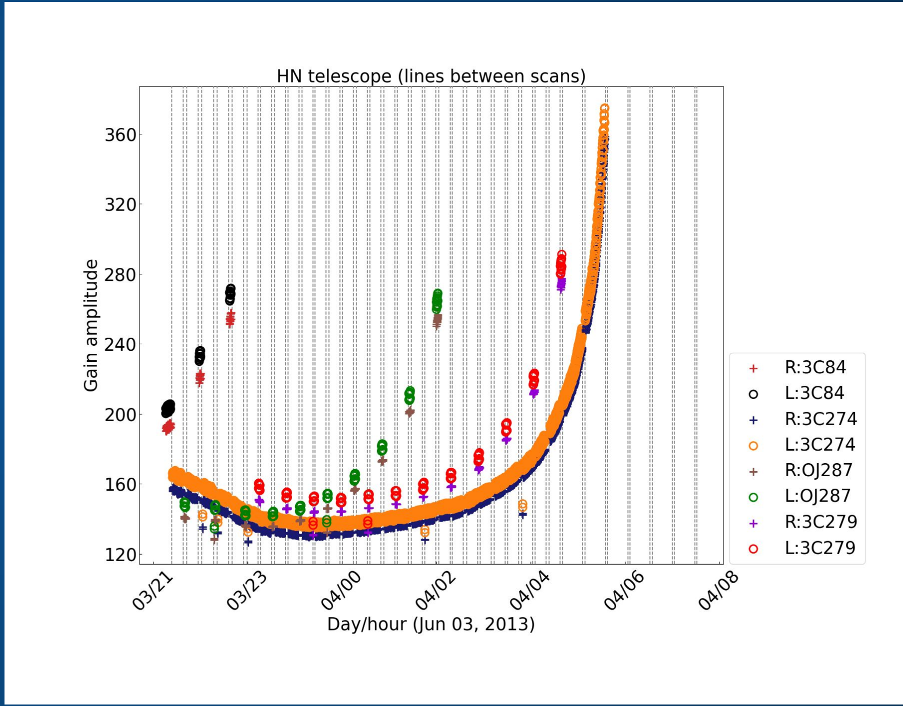




7mm VLBA data of M87. Project code: BW0106.

Tsys calibration (step 2, 3)



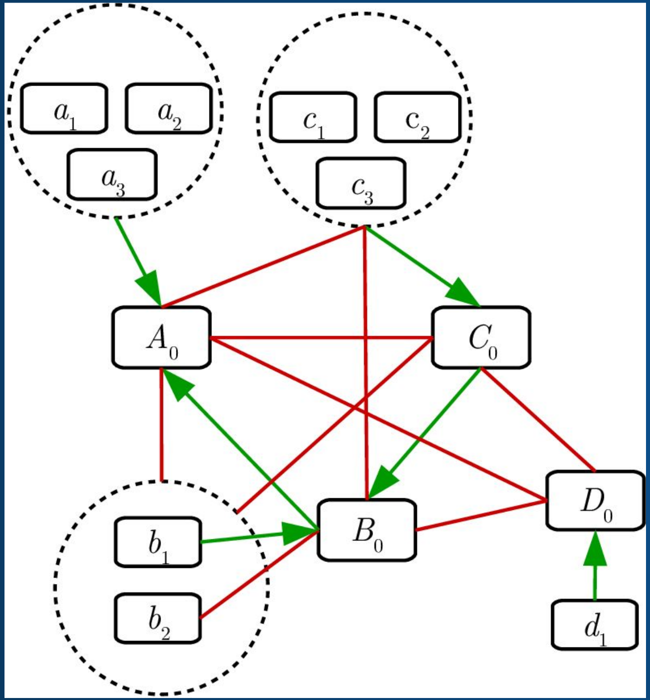


7mm VLBA data of M87. Project code: BW0106.

$T_{sys} \sim T_{rx} + (1 - e^{-\tau})T_{atm} \rightarrow T_{sys} * e^{\tau}$

Phase calibration

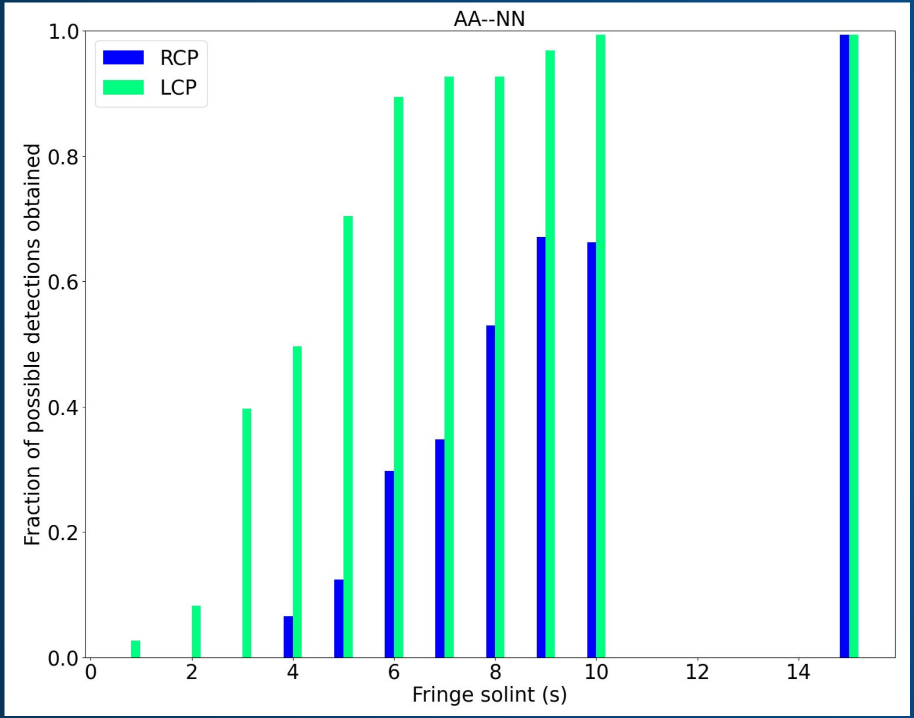
Intra-scan exhaustive fringe search

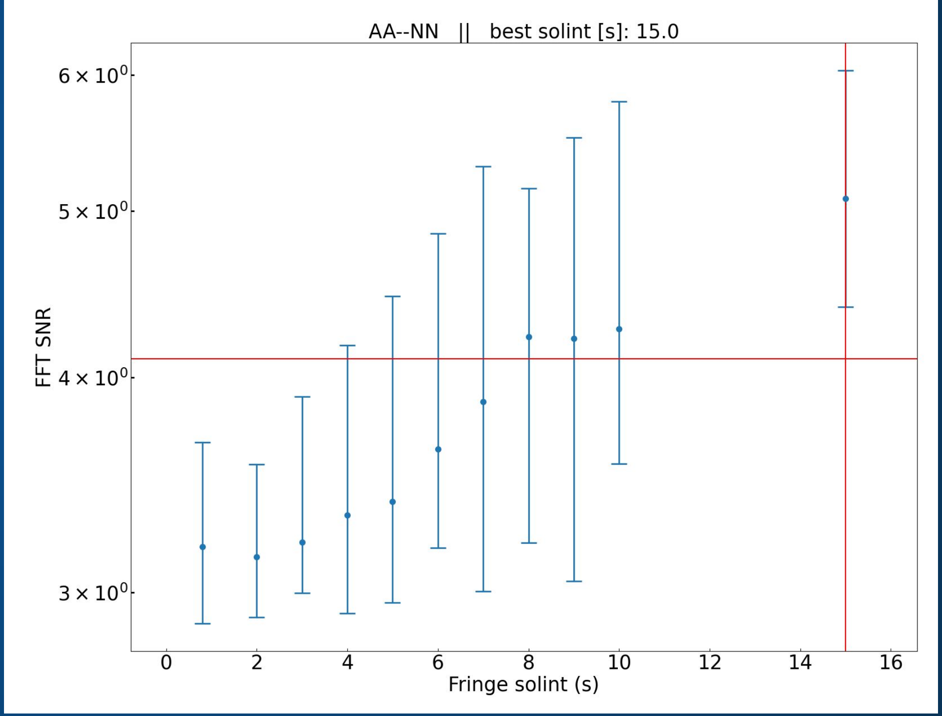


- A_0, B_0, C_0, D_0 list of prioritized reference stations.
- Green : detection.
- Red: Non-detection.
- D_0 and d_1 still un-calibratable.
- b_1, C_0, c_i calibratable via re-referencing.

Solution interval estimation per ant/scan (step 4)

- Can calibrate stations with sensitive baselines on short timescales and still get detections on longer timescales for baselines with weak signals.



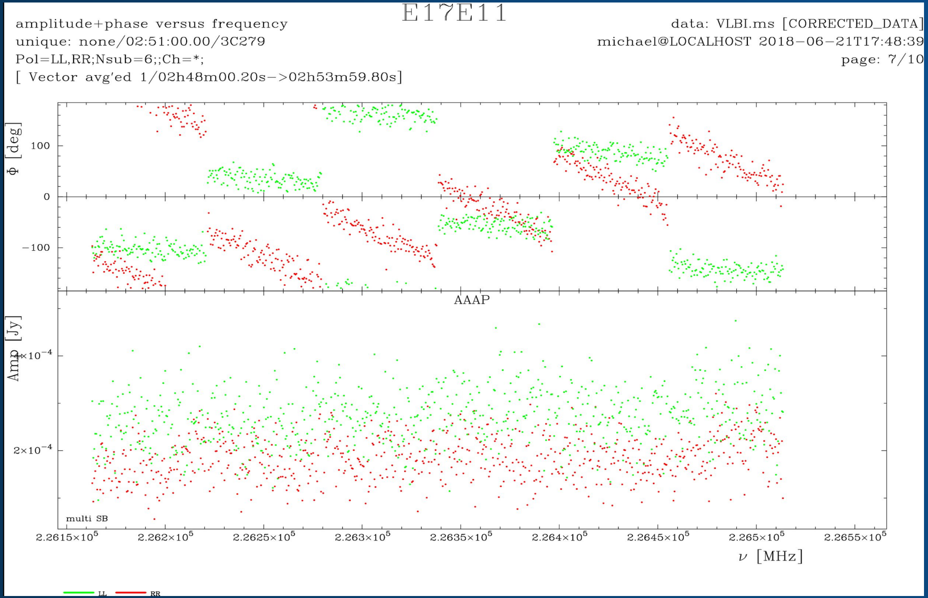


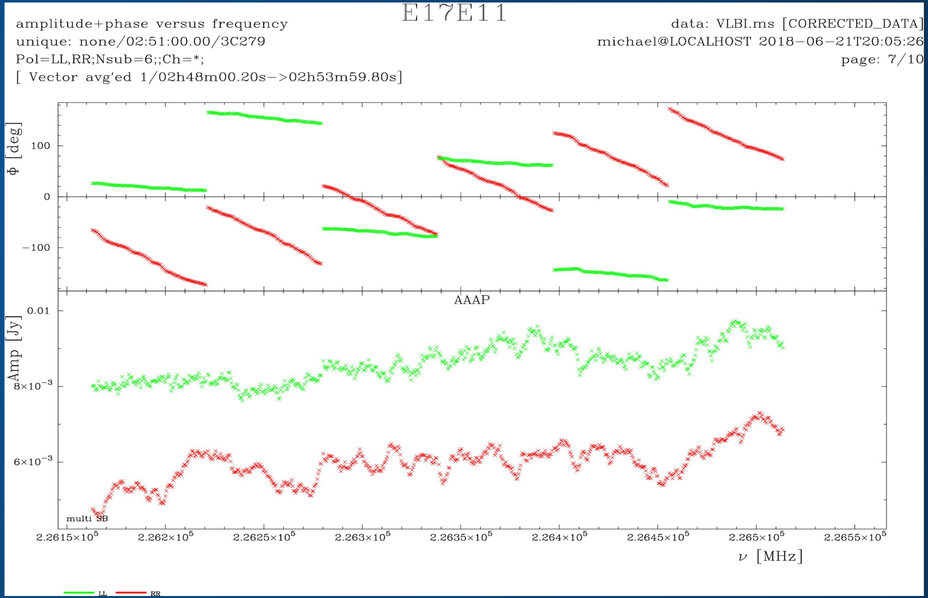
Some 1mm EHT data

Coherence calibration (step 5)

Atmospheric phase stabilization

==========================>



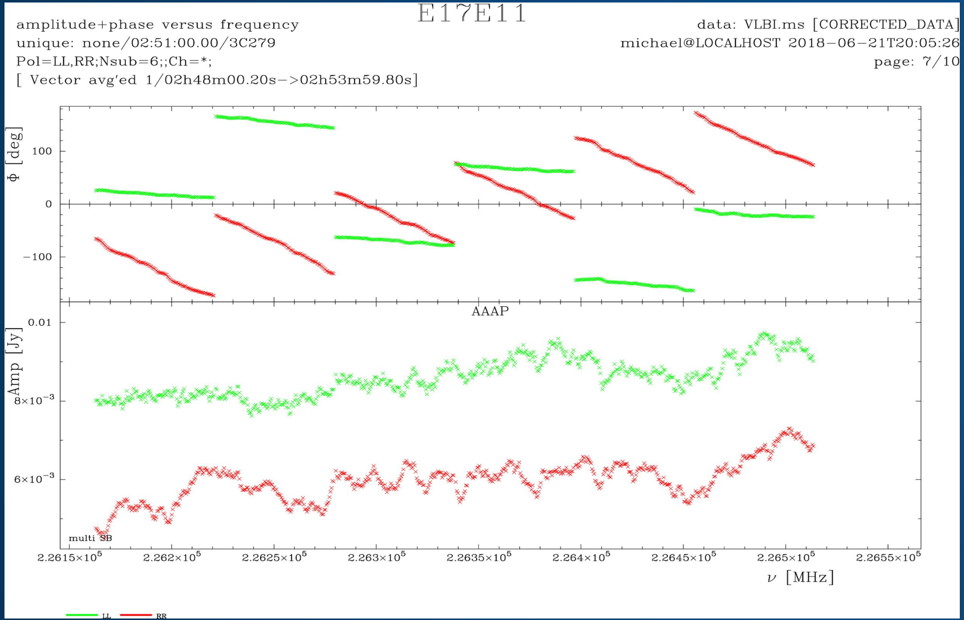


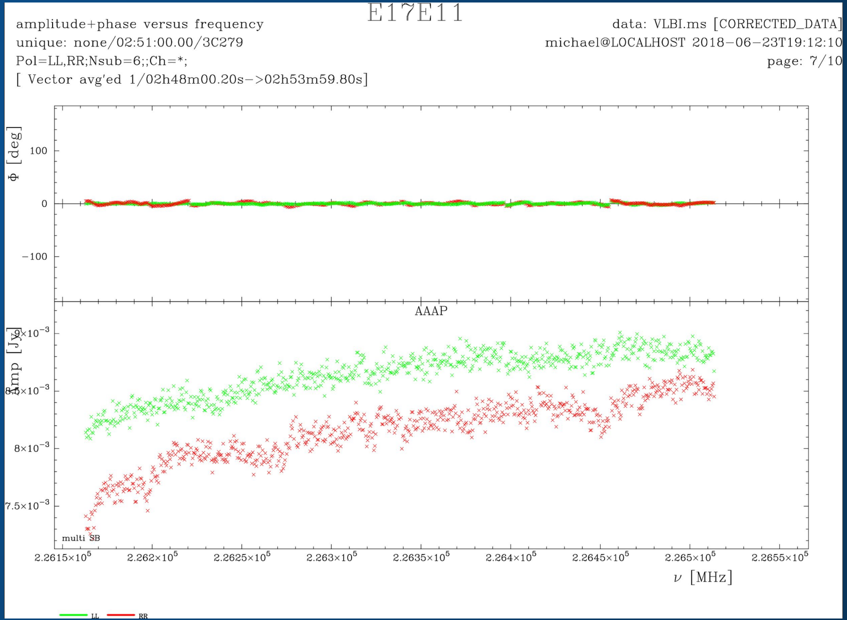
Some EHT data (1mm). Plots made with jiveplot!

Instrumental phases and delays (step 6)

Per-spw fringefit

==========================>

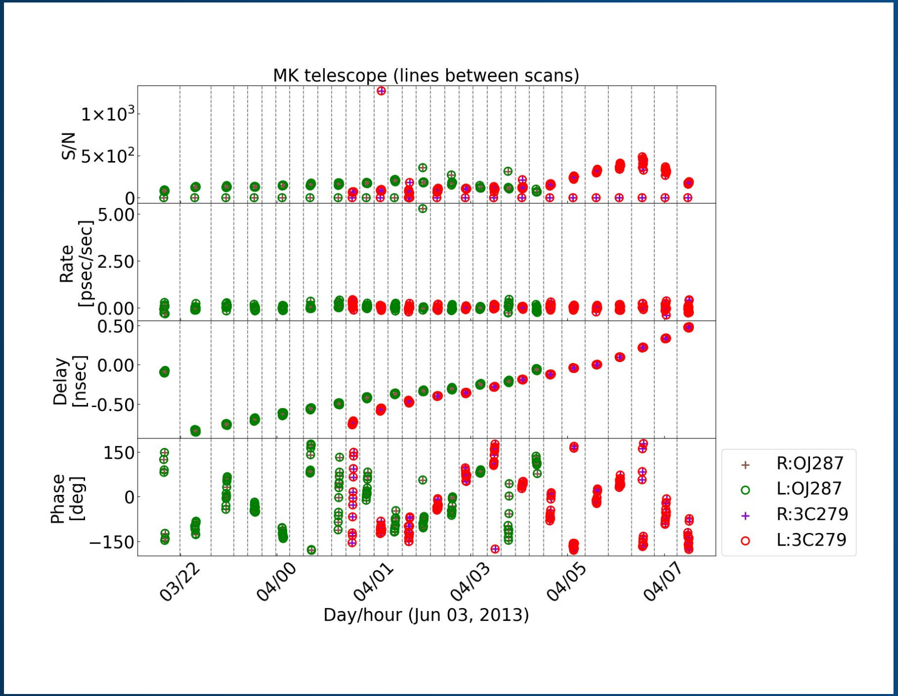


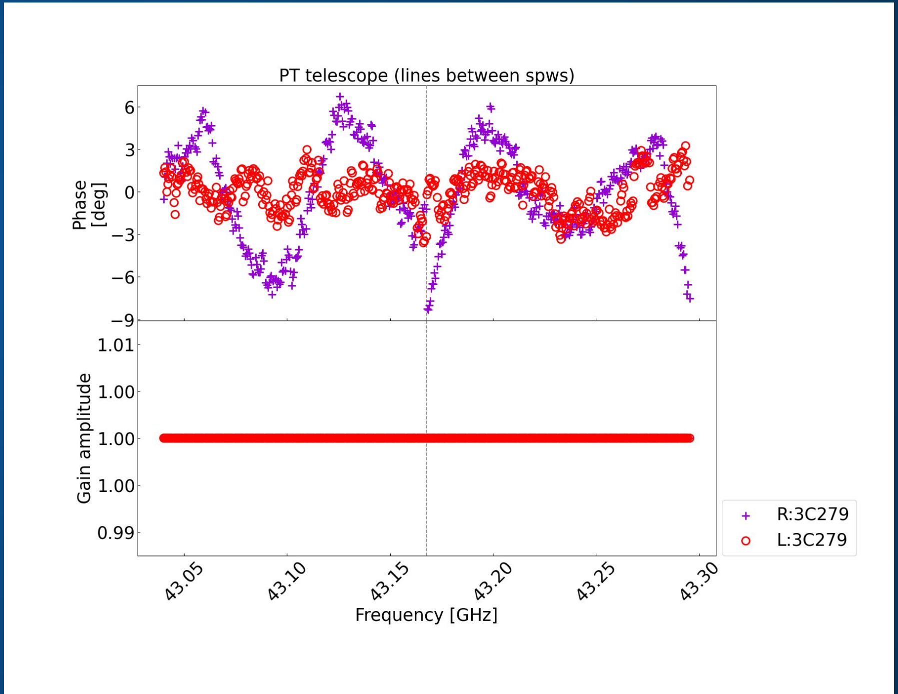


Some EHT data (1mm). Plots made with jiveplot!

Multi-band fringe & complex bandpass (steps 7,8)

- **Redo coher cal with aligned spws to solve for multi-band delays. Phase-only bandpass.**





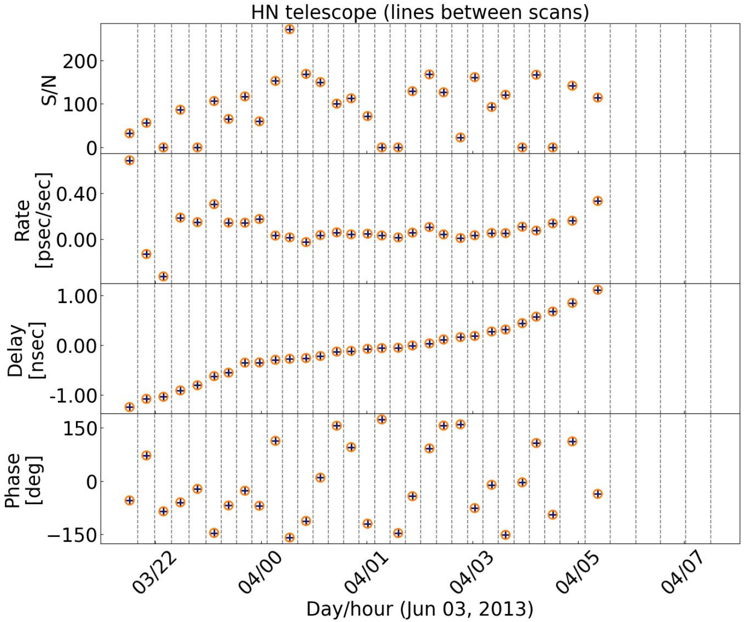
7mm VLBA data of M87. Project code: BW0106.

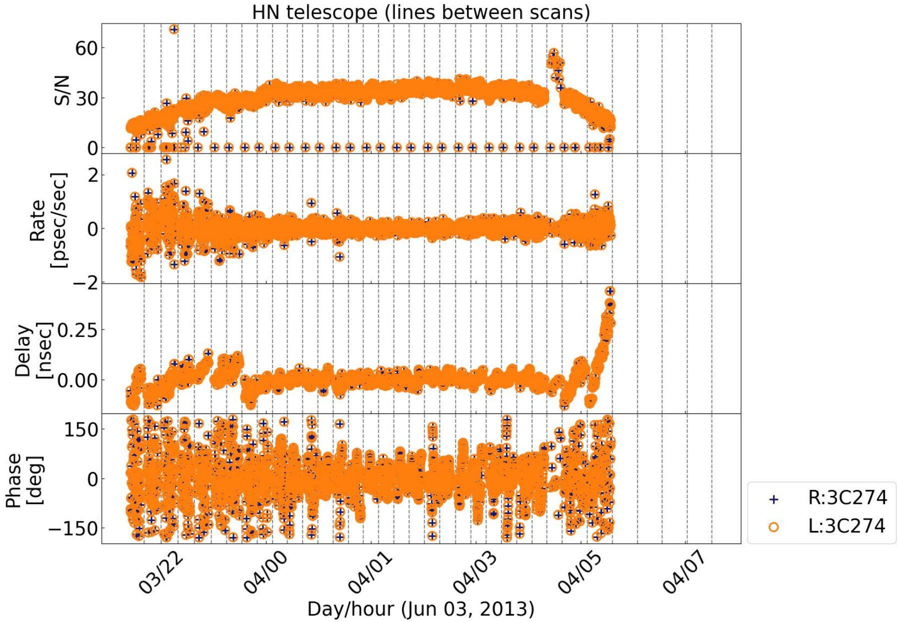
Last calibration steps: fringe-fit science targets (steps 12, 13, 14)

- First: long integration (entire scan) to take out bulk delay or rate with maximized SNR.
  → Source detected or not?
  Typically with open FFT search windows. Over aligned spws and correlation products (pols after RL phase+delay).

- Then: Use narrow windows (small false detection probability) to solve for residual intra-scan atmospheric effects on short timescales.
  → Using optimized solution intervals.

Last calibration steps: fringe-fit science targets





7mm VLBA data of M87. Project code: BW0106.

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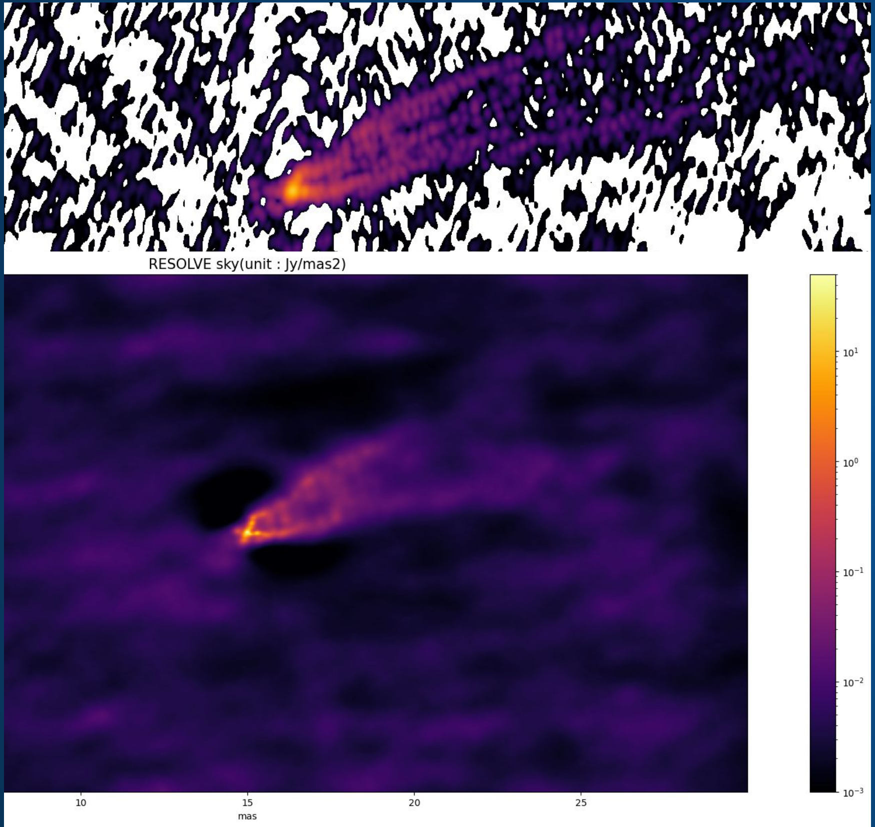
  → Using optimized solution intervals.

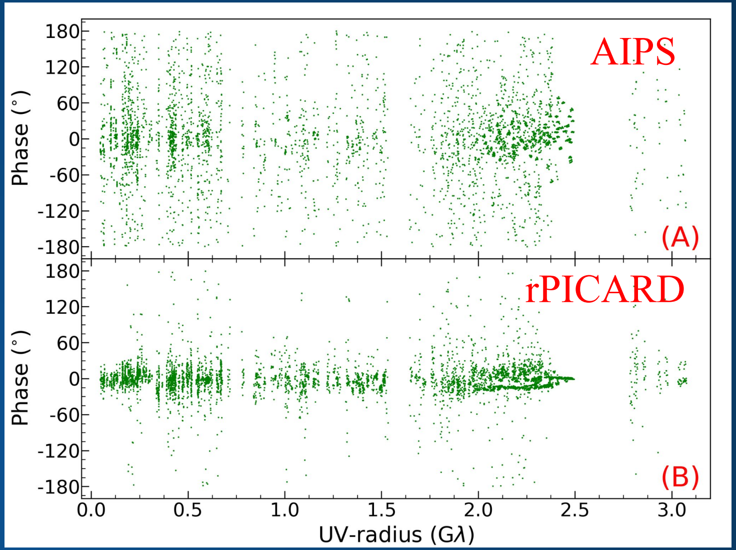
- Note difference with other rPICARD modes.
  - No fringe-fit on science target or only search for residuals in phase-referencing mode.
  - No fit for delay in spectral line mode on science target.
  - Longer adaptive solution intervals for longer observing wavelengths.

New vs old

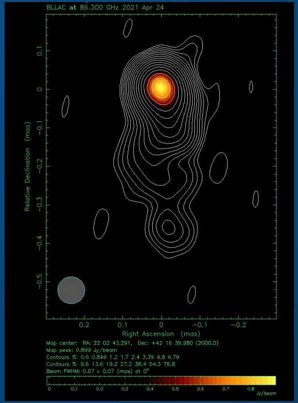


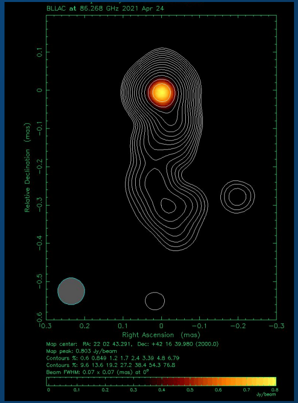
Kim et al., in prep.

Kim et al., in prep.



AIPS

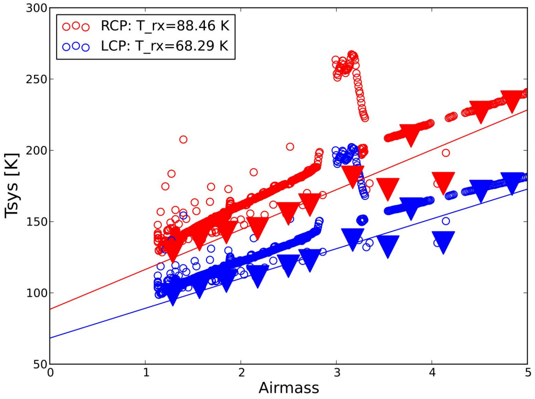


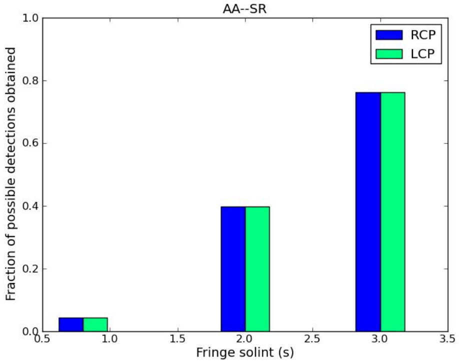


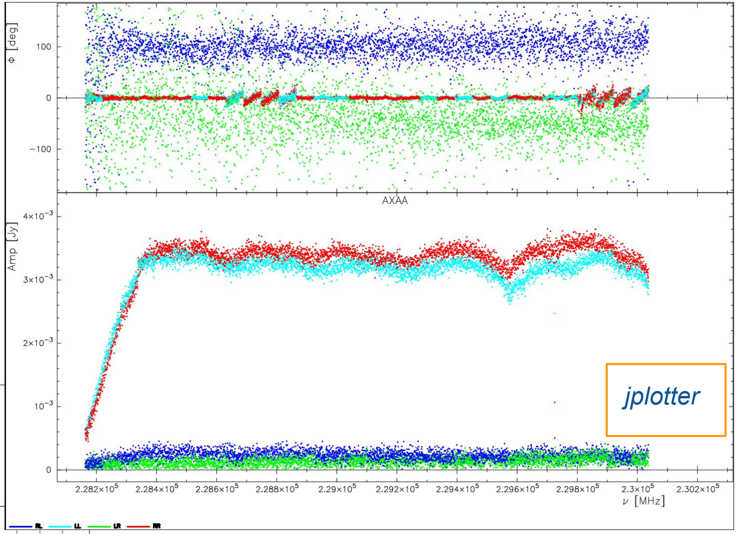
rPICARD

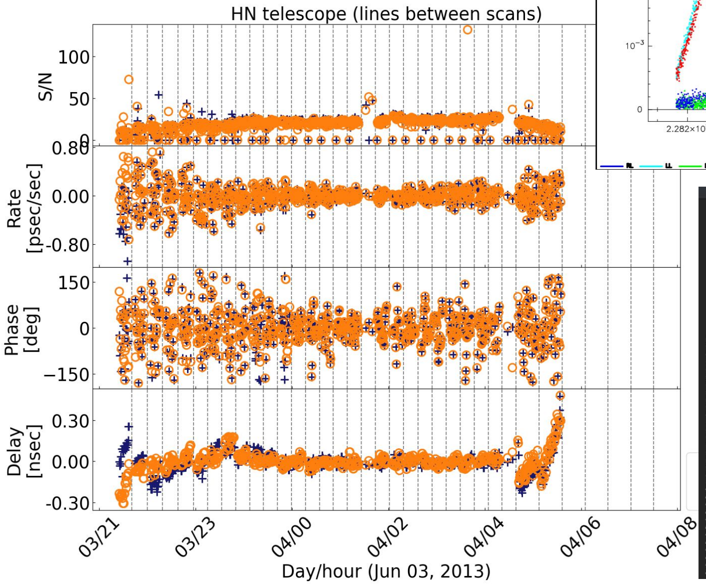
Backup slides

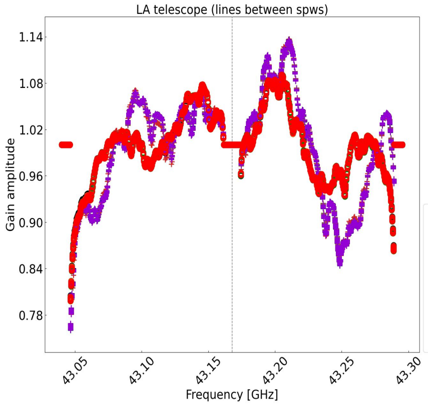
rPicard diagnostics

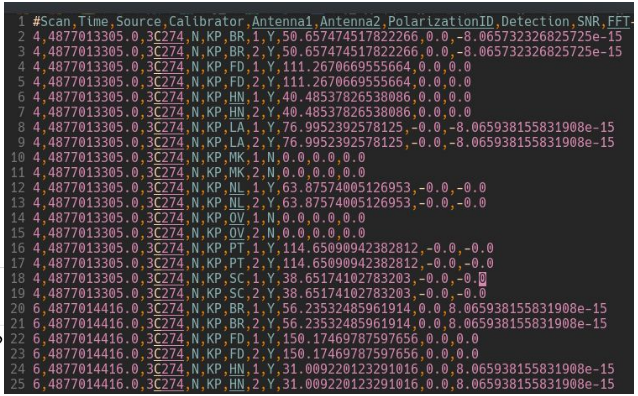












```
#Scan,Time,Source,Calibrator,Antenna1,Antenna2,PolarizationID,Detection,SNR,FFT-
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4,4877013305.0,3C274,N,KP,BR,2,Y,50.657474517822266,0.0,-8.065732326825725e-15
4,4877013305.0,3C274,N,KP,FD,1,Y,111.2670669555664,0.0,0.0
4,4877013305.0,3C274,N,KP,FD,2,Y,111.2670669555664,0.0,0.0
4,4877013305.0,3C274,N,KP,HN,1,Y,40.48537826538086,0.0,0.0
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6,4877014416.0,3C274,N,KP,HN,2,Y,31.009220123291016,0.0,8.065938155831908e-15
```

rPICARD calibration: determine reference stations for global fringe-fit

- Two input parameters
  - List of prioritized reference stations, e.g. EF, YS, MC, NT.
  - Minimum fraction of valid (unflagged) data that must be present in a scan χ.

- For each scan, the first antenna in the refant list with valid data > χ is picked as refant for that scan.

- If all valid data fractions < χ, the antenna with the most valid data is picked.

- X should be small for polarization experiments and/or when a single very sensitive station is present in the array (e.g., ALMA).

- In the end all fringe solutions are re-referenced to one common antenna over the entire experiment for phase stability.

rPICARD calibration: fringe-fit calibrators -- solution interval estimation

- Fringe-fitting can be used to calibrate for intra-scan atmospheric effects on short timescales.
- A source is detected when the SNR of the initial FFT is high enough.
  The more detections per scan, the better the atmospheric calibration.
- Input parameter: Search range depending on array sensitivity and observing frequency.
- For each scan, the solution interval which yields the most detections on all baselines is used.
- Can calibrate sensitive baselines on short timescales and still get detections on longer timescales for baselines with weak signals.