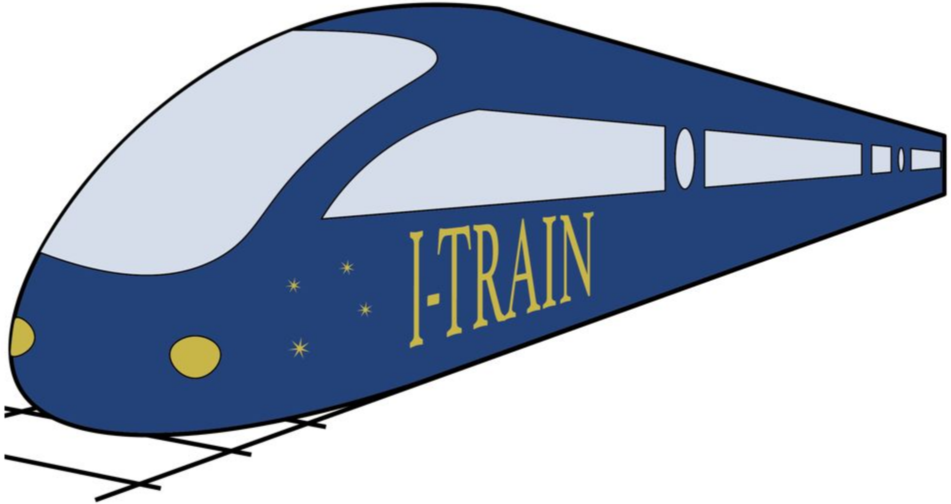
Calibrating mm VLBI data that includes phased ALMA

VLBI I-ITRAIN II
16 May 2025

Michael Janssen



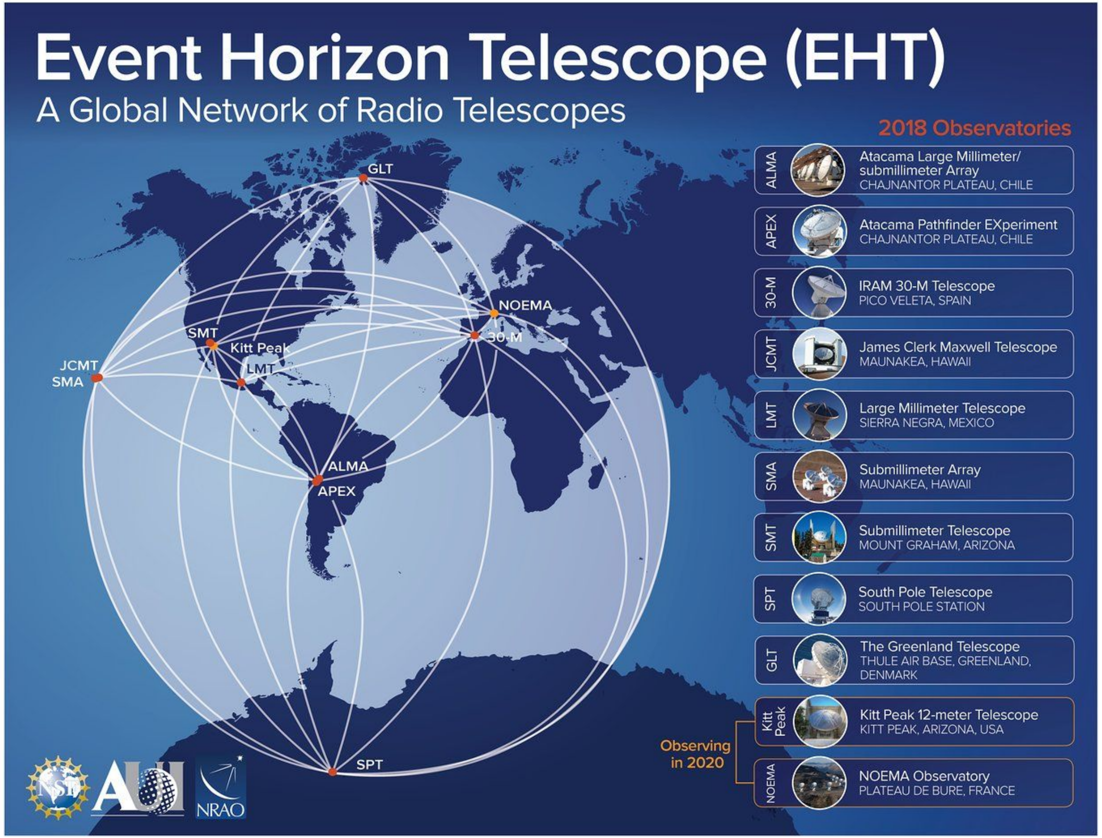
Outline

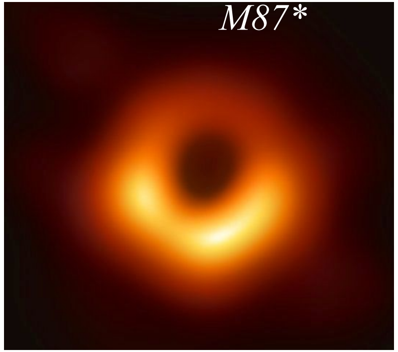
1. Getting public EHT data from the archive
2. How to calibrate GMVA+ALMA data
3. How to calibrate EHT+ALMA data
4. Details on the calibration pipeline

214 & 228, 253 & 267, 336 & 348 GHz. (ALMA b6, b7)

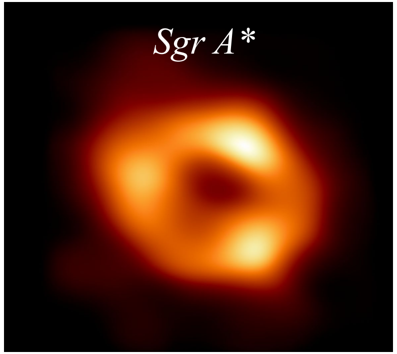
15 μas.

Correlation in Bonn and Haystack.





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



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

Quick reminder on how to propose for EHT observations

See VLBI I-ITRAIN I for details

eventhorizontelescope.org/for-astronomers/proposals

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EHT Proposals

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- Meetings and Events

News and documentation for the next proposal deadline:

- ALMA Cycle 12 (2025/2026) Pre-Announcement (20-Dec-2025)
- **Special notes for Cycle 12 EHTC Proposals:**
  - Flux limits for phase calibrators have been lower by about sqrt(8) to 180 mJy in band 6 and 270 mJy in band 7. Passive-phasing with a nearby calibrator is being offered for targets below these limits.
  - For Cycle 12 in addition to regular VLBI proposals, the EHT for the first time will support **multi-epoch monitoring** for proposals spanning March through April, with a possible extension into May.
    Notes (*See the section Proposal Preparation and Submission for additional details*):
    - The ALMA Proposal tool limits requests for ALMA time to 50 hours. Proposals can ask for additional EHT sessions without ALMA in the Technical Justification. Observations are restricted to ALMA band 6 and an LO of 221.1 GHz and depending on resources may only use two of the four subbands centered at 213.1 and 229.1 Ghz, respectively.
    - Observations are limited to night time LSTs at ALMA. Note that the LMT may also have limited ability to observe in daytime. Projects extending into May can expect to increasingly be impacted by deteriorating weather conditions.
    - The minimum interval between VLBI sessions is three days. Contrary to the flexible schedule during a regular campaign, monitoring observations will be executed on a pre-set fixed schedule but one that can be irregular.
    - Each session will have an identical schedule (except possibly for a 4 min/day sidereal shift [tbd]) for a single, contiguous VLBI block. As a result not all allocated projects may be schedulable.

ALMA AOT

EHT archival data

eventhorizontelescope.org

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- Publications
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  - EHT 2017 Data Release
- EHT Proposals
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The Event Horizon Telescope is an international collaboration capturing images of black holes using a vir

EHT NEWS BLOG

[Peering into the heart of a distant quasar with the Event Horizon Telescope]

February 8, 2023

A global collaboration of scientists used the Earth-size virtual radio telescope, the Event Horizon Telescope (EHT), to see the innermost parts of the quasar NRAO 530. Quasars are extremely powerful sources of radiation located in the centers of distant galaxies. Their central engines are supermassive black holes, funneling accelerated particles and radiation into bright thin jets. Astronomers are trying to understand the complicated...

Read more

EHT ON TWITTER (@EHTELESCOPE)

Follow the EHT on Twitter!

EHT IN THE MEDIA

Images of a black hole reveal how cosmic beasts change over time

Wednesday, September 23, 2020

Scientists Predict Countless Rings of Light Encircle Black Holes, Reports Sky &

https://eventhorizontelescope.org/for-astronomers/data

9:40 AM 8/30/23

EHT Data Products

EHT Data Product Code	Title	Author(s)	Last Updated	Access Link(s)	Reference
2022-D02-03	Multi-wavelength Observations of Sgr A* During the 2017 EHT Campaign	The EHT MWL Science Working Group et al.	12 May 2022	CyVerse Data Commons (DOI: 10.25739/26fq-k306)	The EHT Collaboration et al. 2022b (Sgr A* Paper II)
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2022-D01-01	2017 EHT Observations: Complete L1 Data Products	The EHT Collaboration et al.	9 May 2022	ALMA Science Portal and CyVerse Data Commons (DOI: 10.25739/kat4-na03)	The EHT Collaboration et al. 2019c (M87 Paper III) & 2022c (Sgr A* Paper III)
2021-D03-01	EHT observations of Centaurus A: Calibrated Data	The EHT Collaboration et al.	19 Jul 2021	CyVerse Data Commons (DOI: 10.25739/kejs-2n22)	Janssen et al. 2021, Nat. Astro.
2021-D02-01	Multi-wavelength Observations of M87 During the 2017 EHT Campaign	The EHT MWL Science Working Group et al.	14 Apr 2021	CyVerse Data Commons (DOI: 10.25739/mhh2-cw46)	The EHT MWL Science Working Group et al. 2021, ApJL, 911, L11
2020-D03-01	EHT Visibility Amplitude Data of M87* in 2011-2013	The EHT Collaboration et al.	23 Sep 2020	CyVerse Data Commons (DOI: 10.25739/daft-jz11)	Wielgus et al. 2020, ApJ, 901, 67
2020-D01-01	First 3C279 EHT Results: Calibrated Data	The EHT Collaboration et al.	12 Aug 2020	CyVerse Data Commons (DOI: 10.25739/vty0-ve39)	Kim et al. 2020, A&A, 640, A69
2019-D01-02	First M87 EHT Results: Imaging Pipelines	The EHT Collaboration et al.	24 Apr 2019	https://github.com/eventhorizontelescope/2019-D01-02	The EHT Collaboration et al. 2019d (M87 Paper IV)
2019-D01-01	First M87 EHT Results: Calibrated Data	The EHT Collaboration et al.	10 Apr 2019	CyVerse Data Commons (DOI: 10.25739/g85n-f134)	The EHT Collaboration et al. 2019c (M87 Paper III)

MWL data

Calibrated data (no pol)

L1: Raw correlator output

Calibrated data (no pol) different source

Imaging scripts

eventhorizontelescope.org/for-astronomers/data

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L1: Raw correlator output: let's check out the ALMA portal first

almascience.eso.org/almadata/ec/eht/

Index of /almadata/ec/eht

ALMA txt archive difficult to browse (ALMA-only interferometric data is accessible from the normal ALMA archive, see previous talk by Kazi)

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almascience.eso.org/almadata/ec/eht/2016.1.01114.V/

Index of /almadata/ec/eht/2016.1.01114.V

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L1: Raw correlator output: let's check out Cyverse now

CyVerse Data Commons has a nice interface

About Data Store Discovery Environment

shared / commons_repo / curated / EHTC_2017L1_May2022 / 2016.1.01114.V

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datacommons.cyverse.org/browse/iplant/home/shared/commons_repo/curated/EHTC_2017L1_May2022

Data Commons

About Data Store Discovery Environment

shared / commons_repo / curated / EHTC_2017L1_May2022

Public Data Release of the Event Horizon Telescope 2017 Observations

DOI: 10.25739/kat4-na03

Creator: The Event Horizon Telescope Collaboration

Description: The Event Horizon Telescope Collaboration (EHTC) and Joint ALMA Observatory (JAO) announce the public data release of the Very Long Baseline Interferometry (VLBI) 1-mm 2017 observations by the Event Horizon Telescope (EHT). The overall goal of the observations is to image the supermassive black holes M87* and Sagittarius A* at event horizon scales and to image the AGNs OJ287, 3C279, CENA, and NGC1052 at high resolution. This data delivery contains what is defined by the EHTC as L1 data for the 2017 observing campaign. The 2017 campaign was the first where the Atacama Large Millimeter Array (ALMA) participated as a phased array, a capability that was developed by the ALMA Phasing Project. The EHT L1 data encompasses the VLBI correlator output, converted into circular polarization basis, as well as the calibration information from the participating telescopes. For ALMA this includes their quality assurance (QA2) output that is used for the polarization basis conversion. The primary reference for the data from the EHT 2017 April observation campaign is Event Horizon Telescope Collaboration et al. 2019, ApJL, 875, L3 (doi: 10.3847/2041-8213/ab0c57) which in detail discusses the processing carried out for the current L1 data delivery. For scientific results derived from the EHT 2017 April Observation Campaign see eventhorizontelescope.org/publications. Additional data products derived from this L1 data can be found at eventhorizontelescope.org/for-astronomers/data. This data delivery includes observations from the following facilities: ALMA, the Atacama Pathfinder Experiment (APEX), the Submillimeter Telescope (SMT), the James Clerk Maxwell Telescope (JCMT), the Large Millimeter Telescope Alfonso Serrano (LMT), the IRAM 30m telescope, the Submillimeter Array (SMA), and the South Pole Telescope (SPT). More information about these facilities can be found in Event Horizon Telescope Collaboration et al. 2019, ApJL, 875, L2 (doi: 10.3847/2041-8213/ab0c96).

Publisher: CyVerse Data Commons

Publication Year: 2022

Rights: This data is made available under the Public Domain Dedication and License v1.0 whose full text can be found at http://www.opendatacommons.org/licenses/pddl/1.0/

Citation: The Event Horizon Telescope Collaboration (2022). Public Data Release of the Event Horizon Telescope 2017 Observations. CyVerse Data Commons. DOI 10.25739/kat4-na03

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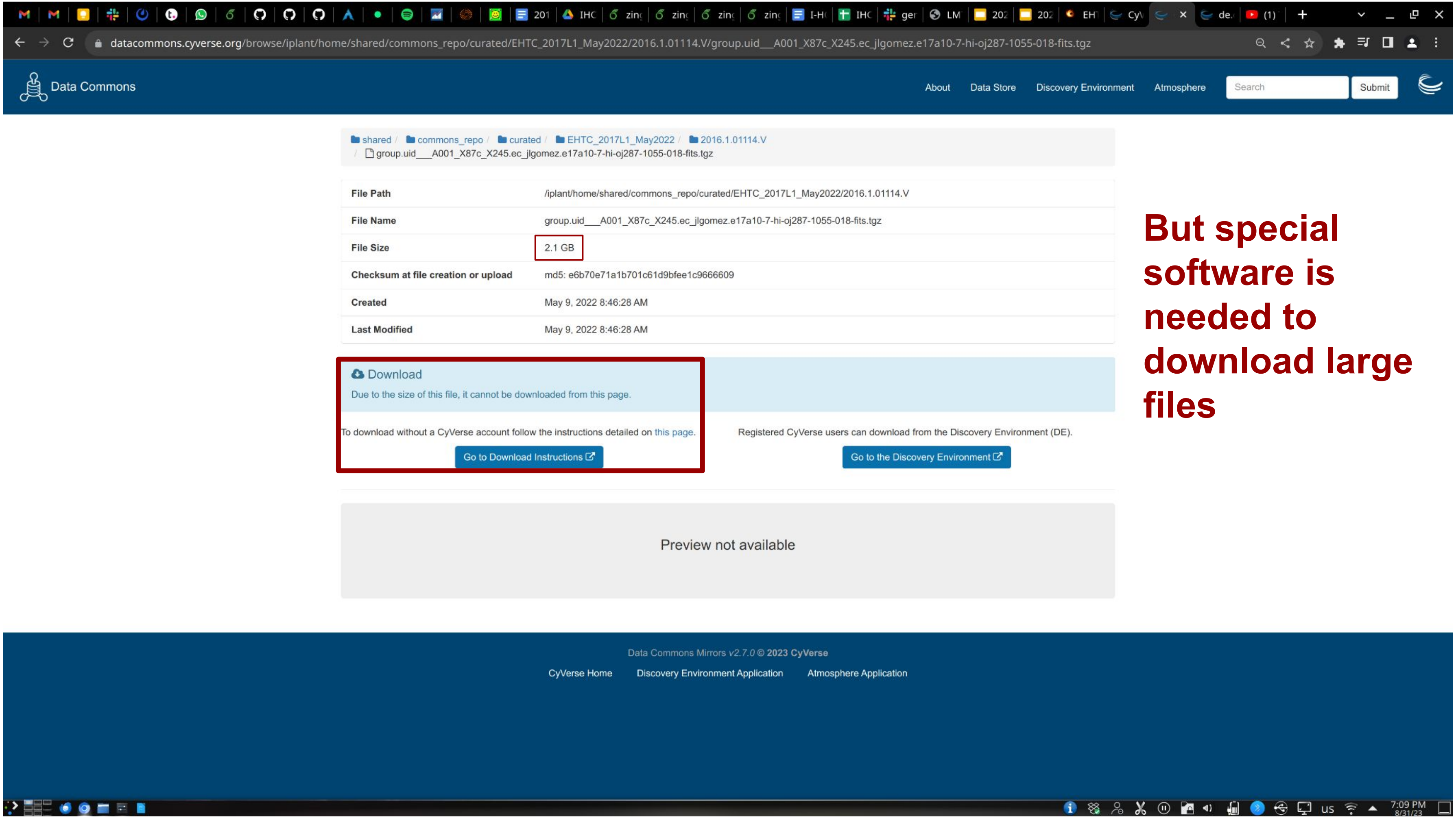
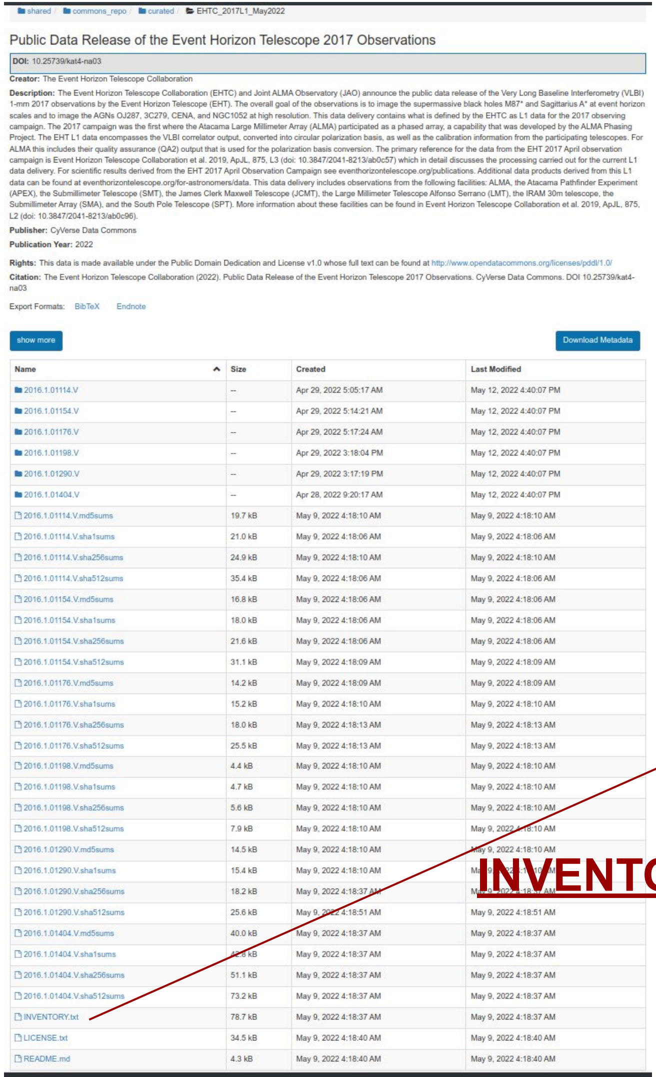
Name	Size	Created	Last Modified
2016.1.01114.V	--	Apr 29, 2022 5:05:17 AM	May 12, 2022 4:40:07 PM
2016.1.01154.V	--	Apr 29, 2022 5:14:21 AM	May 12, 2022 4:40:07 PM
2016.1.01176.V	--	Apr 29, 2022 5:17:24 AM	May 12, 2022 4:40:07 PM
2016.1.01198.V	--	Apr 29, 2022 3:18:04 PM	May 12, 2022 4:40:07 PM
2016.1.01290.V	--	Apr 29, 2022 3:17:19 PM	May 12, 2022 4:40:07 PM
2016.1.01404.V	--	Apr 28, 2022 9:20:17 AM	May 12, 2022 4:40:07 PM



But special software is needed to download large files

Let's get an index of all files from CyVerse


shared / commons_repo / curated / EHTC_2017L1_May2022

Public Data Release of the Event Horizon Telescope 2017 Observations

DOI: 10.25739/kat4-na03

Creator: The Event Horizon Telescope Collaboration

Description: The Event Horizon Telescope Collaboration (EHTC) and Joint ALMA Observatory (JAO) announce the public data release of the Very Long Baseline Interferometry (VLBI) 1-mm 2017 observations by the Event Horizon Telescope (EHT). The overall goal of the observations is to image the supermassive black holes M87* and Sagittarius A* at event horizon scales and to image the AGNs OJ287, 3C279, CENA, and NGC1052 at high resolution. This data delivery contains what is defined by the EHTC as L1 data for the 2017 observing campaign. The 2017 campaign was the first where the Atacama Large Millimeter Array (ALMA) participated as a phased array, a capability that was developed by the ALMA Phasing Project. The EHT L1 data encompasses the VLBI correlator output, converted into circular polarization basis, as well as the calibration information from the participating telescopes. For ALMA this includes their quality assurance (QA2) output that is used for the polarization basis conversion. The primary reference for the data from the EHT 2017 April observation campaign is Event Horizon Telescope Collaboration et al. 2019, ApJL, 875, L3 (doi: 10.3847/2041-8213/ab0c57) which in detail discusses the processing carried out for the current L1 data delivery. For scientific results derived from the EHT 2017 April Observation Campaign see eventhorizontelescope.org/publications. Additional data products derived from this L1 data can be found at eventhorizontelescope.org/for-astronomers/data. This data delivery includes observations from the following facilities: ALMA, the Atacama Pathfinder Experiment (APEX), the Submillimeter Telescope (SMT), the James Clerk Maxwell Telescope (JCMT), the Large Millimeter Telescope Alfonso Serrano (LMT), the IRAM 30m telescope, the Submillimeter Array (SMA), and the South Pole Telescope (SPT). More information about these facilities can be found in Event Horizon Telescope Collaboration et al. 2019, ApJL, 875, L2 (doi: 10.3847/2041-8213/ab0c96).

Publisher: CyVerse Data Commons

Publication Year: 2022

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Citation: The Event Horizon Telescope Collaboration (2022). Public Data Release of the Event Horizon Telescope 2017 Observations. CyVerse Data Commons. DOI 10.25739/kat4-na03

Export Formats: BibTeX Endnote

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Name	Size	Created	Last Modified
2016.1.01114.V	--	Apr 29, 2022 5:05:17 AM	May 12, 2022 4:40:07 PM
2016.1.01154.V	--	Apr 29, 2022 5:14:21 AM	May 12, 2022 4:40:07 PM
2016.1.01176.V	--	Apr 29, 2022 5:17:24 AM	May 12, 2022 4:40:07 PM
2016.1.01198.V	--	Apr 29, 2022 3:18:04 PM	May 12, 2022 4:40:07 PM
2016.1.01290.V	--	Apr 29, 2022 3:17:19 PM	May 12, 2022 4:40:07 PM
2016.1.01404.V	--	Apr 28, 2022 9:20:17 AM	May 12, 2022 4:40:07 PM
2016.1.01114.V.md5sums	19.7 kB	May 9, 2022 4:18:10 AM	May 9, 2022 4:18:10 AM
2016.1.01114.V.sha1sums	21.0 kB	May 9, 2022 4:18:06 AM	May 9, 2022 4:18:06 AM
2016.1.01114.V.sha256sums	24.9 kB	May 9, 2022 4:18:10 AM	May 9, 2022 4:18:10 AM
2016.1.01114.V.sha512sums	35.4 kB	May 9, 2022 4:18:06 AM	May 9, 2022 4:18:06 AM
2016.1.01154.V.md5sums	16.8 kB	May 9, 2022 4:18:06 AM	May 9, 2022 4:18:06 AM
2016.1.01154.V.sha1sums	18.0 kB	May 9, 2022 4:18:06 AM	May 9, 2022 4:18:06 AM
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2016.1.01154.V.sha512sums	31.1 kB	May 9, 2022 4:18:09 AM	May 9, 2022 4:18:09 AM
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2016.1.01176.V.sha512sums	25.5 kB	May 9, 2022 4:18:13 AM	May 9, 2022 4:18:13 AM
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2016.1.01198.V.sha1sums	4.7 kB	May 9, 2022 4:18:10 AM	May 9, 2022 4:18:10 AM
2016.1.01198.V.sha256sums	5.6 kB	May 9, 2022 4:18:10 AM	May 9, 2022 4:18:10 AM
2016.1.01198.V.sha512sums	7.9 kB	May 9, 2022 4:18:10 AM	May 9, 2022 4:18:10 AM
2016.1.01290.V.md5sums	14.5 kB	May 9, 2022 4:18:10 AM	May 9, 2022 4:18:10 AM
2016.1.01290.V.sha1sums	15.4 kB	May 9, 2022 4:18:10 AM	[illegible]
2016.1.01290.V.sha256sums	18.2 kB	May 9, 2022 4:18:37 AM	[illegible]
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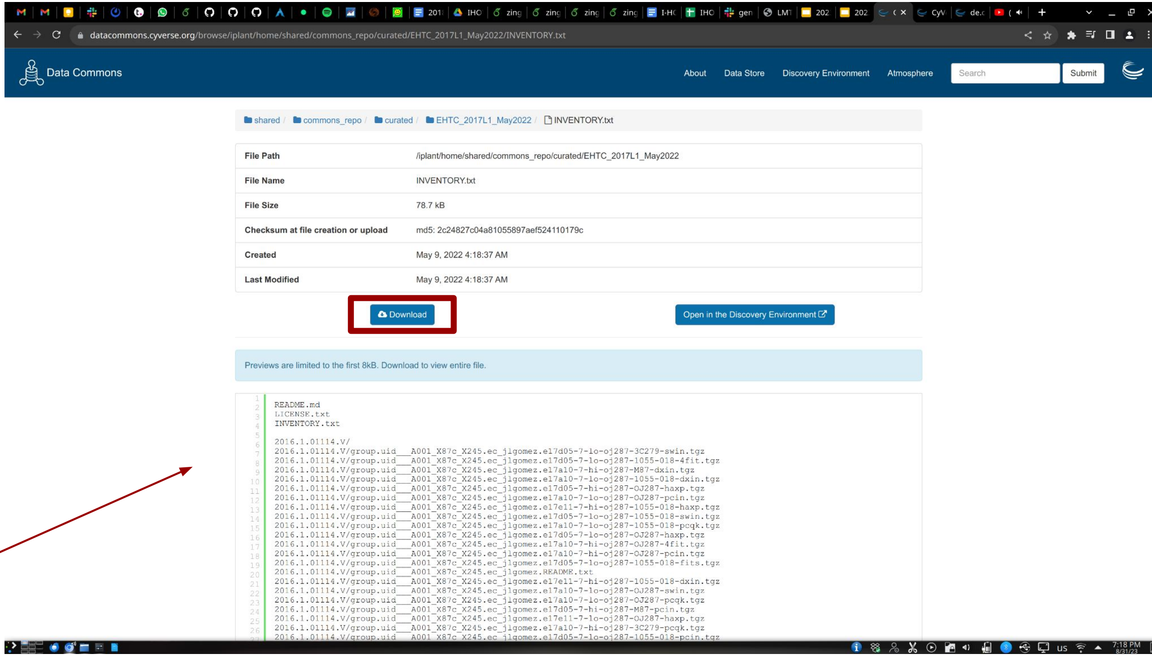
2016.1.01404.V.md5sums	40.0 kB	May 9, 2022 4:18:37 AM	May 9, 2022 4:18:37 AM
2016.1.01404.V.sha1sums	42.8 kB	May 9, 2022 4:18:37 AM	May 9, 2022 4:18:37 AM
2016.1.01404.V.sha256sums	51.1 kB	May 9, 2022 4:18:37 AM	May 9, 2022 4:18:37 AM
2016.1.01404.V.sha512sums	73.2 kB	May 9, 2022 4:18:37 AM	May 9, 2022 4:18:37 AM
INVENTORY.txt	78.7 kB	May 9, 2022 4:18:37 AM	May 9, 2022 4:18:37 AM
LICENSE.txt	34.5 kB	May 9, 2022 4:18:40 AM	May 9, 2022 4:18:40 AM
README.md	4.3 kB	May 9, 2022 4:18:40 AM	May 9, 2022 4:18:40 AM



INVENTORY.txt

d05: observing track D, day 05 (April) ; lo: lower frequency band / hi: higher frequency band ; 1055-018: sourcename ; -fits.tgz: FITS-IDI files (visibility data)

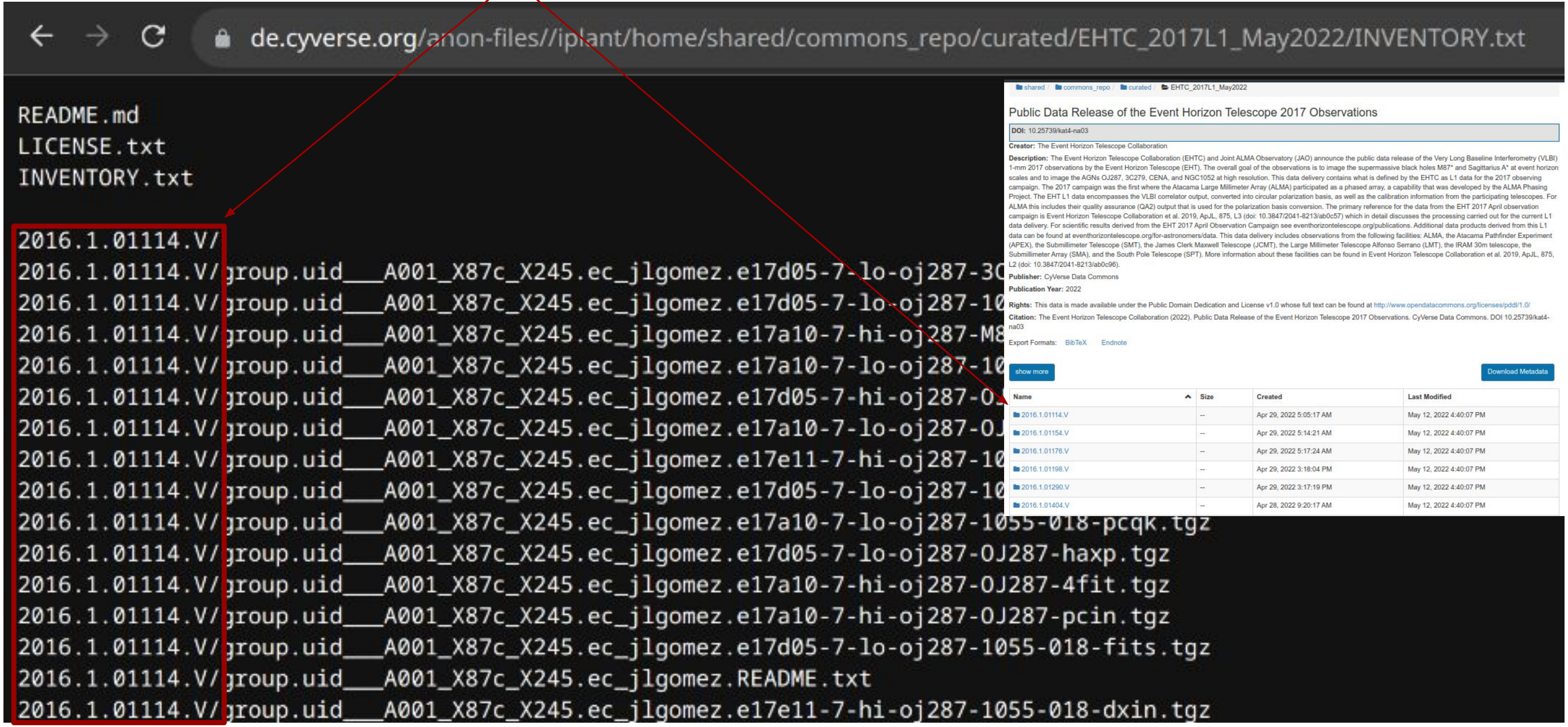
de.cyverse.org/anon-files//iplant/home/shared/commons_repo/curated/EHTC_2017L1_May2022/INVENTORY.txt

```
README.md
LICENSE.txt
INVENTORY.txt

2016.1.01114.V/
2016.1.01114.V/group.uid___A001_X87c_X245.ec_jlgomez.e17d05-7-lo-oj287-3C279-swin.tgz
2016.1.01114.V/group.uid___A001_X87c_X245.ec_jlgomez.e17d05-7-lo-oj287-1055-018-4fit.tgz
2016.1.01114.V/group.uid___A001_X87c_X245.ec_jlgomez.e17a10-7-hi-oj287-M87-dxin.tgz
2016.1.01114.V/group.uid___A001_X87c_X245.ec_jlgomez.e17a10-7-lo-oj287-1055-018-dxin.tgz
2016.1.01114.V/group.uid___A001_X87c_X245.ec_jlgomez.e17d05-7-hi-oj287-OJ287-haxp.tgz
2016.1.01114.V/group.uid___A001_X87c_X245.ec_jlgomez.e17a10-7-lo-oj287-OJ287-pcin.tgz
2016.1.01114.V/group.uid___A001_X87c_X245.ec_jlgomez.e17e11-7-hi-oj287-1055-018-haxp.tgz
2016.1.01114.V/group.uid___A001_X87c_X245.ec_jlgomez.e17d05-7-lo-oj287-1055-018-swin.tgz
2016.1.01114.V/group.uid___A001_X87c_X245.ec_jlgomez.e17a10-7-lo-oj287-1055-018-pcqk.tgz
2016.1.01114.V/group.uid___A001_X87c_X245.ec_jlgomez.e17d05-7-lo-oj287-OJ287-haxp.tgz
2016.1.01114.V/group.uid___A001_X87c_X245.ec_jlgomez.e17a10-7-hi-oj287-OJ287-4fit.tgz
2016.1.01114.V/group.uid___A001_X87c_X245.ec_jlgomez.e17a10-7-hi-oj287-OJ287-pcin.tgz
2016.1.01114.V/group.uid___A001_X87c_X245.ec_jlgomez.e17d05-7-lo-oj287-1055-018-fits.tgz
2016.1.01114.V/group.uid___A001_X87c_X245.ec_jlgomez.README.txt
2016.1.01114.V/group.uid___A001_X87c_X245.ec_jlgomez.e17e11-7-hi-oj287-1055-018-dxin.tgz
```

2017: lo, hi – 2GHz bands around 228 GHz
2018+: b1,b2,b3,b4 – e.g., 2GHz around 213, 215, 227, 229 GHz

Select *.e17<track>-*-{lo,hi}-*-<*-sourcename>-fits.tgz
Across projects! Easy to go through in INVENTORY.txt



The download is easy:

Say you have selected
2016.1.01114.V/group.uid___A001_X87c_X245.ec_jlgomez.e17a10-7-lo-oj287-M87-fits.tgz
2016.1.01176.V/group.uid___A001_X879_X3ef.ec_tkrichbaum.e17a10-7-lo-3c279-M87-fits.tgz
2016.1.01176.V/group.uid___A001_X879_X3ef.ec_tkrichbaum.e17a10-7-lo-3c279-3C279-fits.tgz
from the INVENTORY.txt file

Then you can download easily from the ALMA portal via the command line
$ wget https://almascience.eso.org/almadata/ec/eht/2016.1.01114.V/group.uid___A001_X87c_X245.ec_jlgomez.e17a10-7-lo-oj287-M87-fits.tgz
$ wget https://almascience.eso.org/almadata/ec/eht/2016.1.01176.V/group.uid___A001_X879_X3ef.ec_tkrichbaum.e17a10-7-lo-3c279-M87-fits.tgz
$ wget https://almascience.eso.org/almadata/ec/eht/2016.1.01176.V/group.uid___A001_X879_X3ef.ec_tkrichbaum.e17a10-7-lo-3c279-3C279-fits.tgz

A complete set of metadata (ANTAB files containing Tsys and gain information) is available for each project:
$ wget https://almascience.eso.org/almadata/ec/eht/2016.1.01114.V/group.uid___A001_X87c_X245.ec_jlgomez.metadata-2020-d02-01.tgz

Note the following convention after extracting:
2020-D02-01/antab/eht_2017_april_A_sideband1.EHT.AN

A – a10	B – b06	C – c07	D – d05	E – e11	(2017 data)
sideband 1 – lo		sideband 2 – hi			(2017 data)
sideband b*X* – antab/processed/*_b*X*_*					(2018+ data)

⇒ Needed only for 2017 ANTABs: combine *.AA.AN and *.EHT.AN into single files

extract with
`tar xvf`

Questions on how to get EHT archival data?

General notes on the calibration pipeline

CASA-based rPICARD VLBI pipeline:

https://bitbucket.org/M_Janssen/picard

rPICARD VLBI calibration pipeline

- Janssen et al., A&A, 626 (2019) A75, https://bitbucket.org/M_Janssen/picard
- Open source.
- Built-in MPI acceleration for all tasks.
- Set input parameters in text files.
- Many diagnostics to inspect.
  Easy to adjust strategy and re-run steps.
- Works for any VLBI array.

```
#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
```

rPICARD

- Performs a series of steps that can be re-run individually with the picard CLI.
  - First solving instrumental effects on *calibrator sources*. Then deep fringe searches on *science targets*.

- Input: FITS-IDI raw visibility data + metadata
- Output: calibrated data in UVFITS (`.uvf`) and CASA MS (`.ms.avg`) format.

```
The pipeline will execute the following steps for the
VLBAhi array in the given order:
   a : load models of observed sources (if present)
   b : use online flags from idi files (if present)
   c : use flags from metadata (if present)
   d : flag based on outlier detection from auto-correlations vs time
   e : flag based on outlier detection from auto-correlations vs frequency
   f : flag edge channels
   g : flag start and end segments of scans (quacking)
   0 : task_accor
   1 : task_scalar_bandpass
   2 : task_tsys_add_exptau
   3 : task_gaincurve
   4 : task_fringefit_single
   5 : task_fringefit_solint_cal
   6 : task_fringefit_multi_cal_short
   7 : task_complex_bandpass
   8 : task_rldelay
   9 : task_rlphase
  10 : task_dterms
  11 : task_fringefit_multi_sci_long
  12 : task_fringefit_solint_sci
  13 : task_fringefit_multi_sci_short
  14 : task_atmo_selfcal_startmod
   h : clear the calibrated data column of the MS from previous applycal runs
   i : apply all existing tables from all_calibration_steps
   j : print overview of flagged data (can be slow)
   k : make diagnostic plots of calibrated visibilities and create a calibration summary file
   l : average and export the calibrated data
```

Installing rPICARD (generic, for reference)

- `$ git clone https://bitbucket.org/M_Janssen/picard`
- `$ curl -L "$(cat picard/README.md | grep wget | cut -d' ' -f3)" -o CASA.picard.tar.xz`
- `$ tar xJf CASA.picard.tar.xz`
- `$ ./picard/setup.py -p .`
- `$ printf '\nexport PATH=$PATH:'"$(pwd)"'/picard/picard\n' >> ~/.bashrc`
- `$ printf '\nexport PYTHONPATH=$PYTHONPATH:'"$(pwd)"'/picard/picard\n' >> ~/.bashrc`
- `$ source ~/.bashrc`

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

- Or run containerized within Singularity(Apptainer)/Docker (for MacOS): https://bitbucket.org/M_Janssen/picard/src/master/README.md

```
$ singularity build casavlbi.pipe docker://mjanssen2308/casavlbi:latest
$ singularity run ./casavlbi.pipe
```

Setting up rPICARD (generic, for reference)

- Create a clean working directory and link input data there
  - Link (`ln -s`) to FITS-IDI, ANTAB, and (for GMVA) 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, EHT, …) and list of reference antennas.
    - See `/path/to/installation/picard/ picard/main_picard.py` for a list of array names.

Setting up rPICARD

- Minimally set parameters in input/observation.inp and input/array.inp:
  - Names of science target(s) and calibrators.
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#Bright calibrators for complex bandpass calibration.
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#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
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#Generally, this should be False for astrometry. It should be True when the calibrator is far away
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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
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#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
```

Running rPICARD (generic, for reference)

- `$ 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 -p -l e`	Load data, write listobs, exit
`$ picard -pq h,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

Questions on how to set up the pipeline?

Calibrating GMVA+ALMA data

With the **CASA**-based rPICARD VLBI pipeline:

https://bitbucket.org/M_Janssen/picard

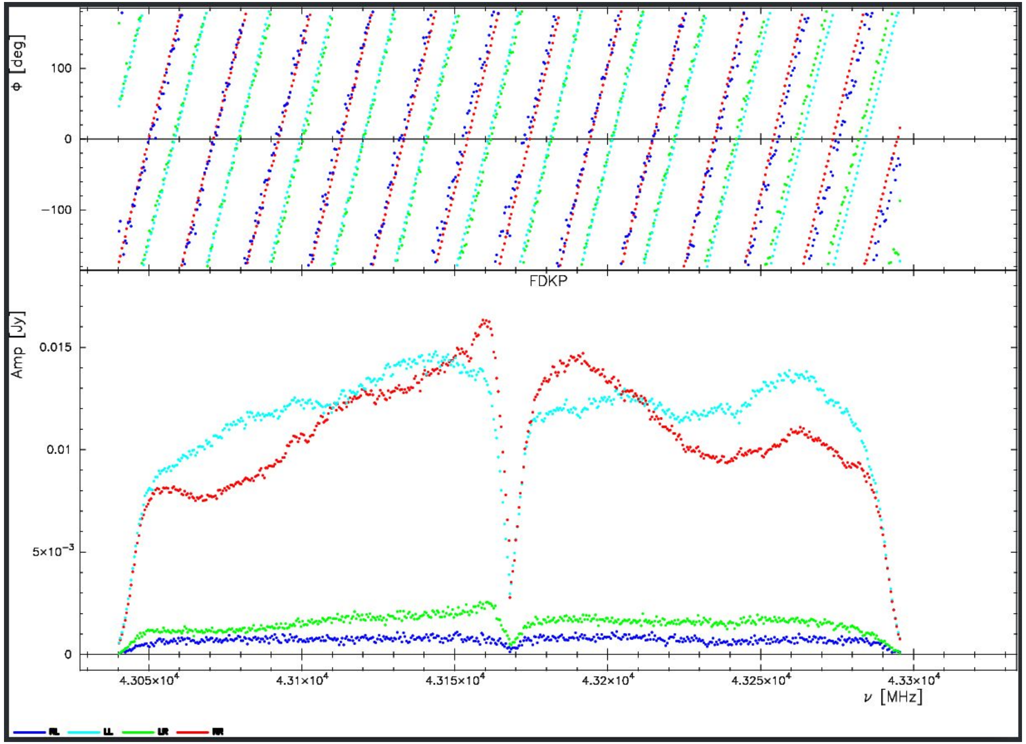
Calibrating GMVA + phased ALMA data

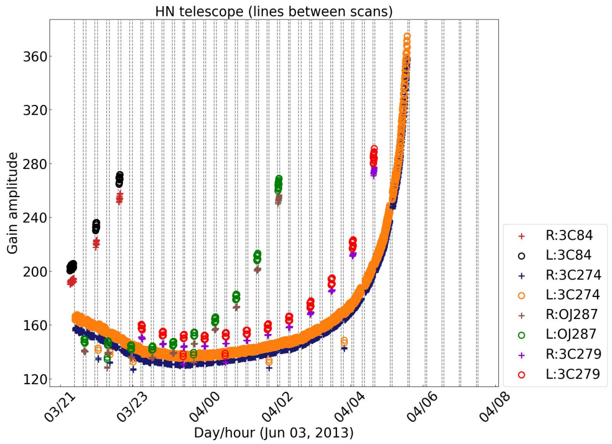
- `$ cd /path/to/working/dir`
  - *.fits   *.WX   *.antab
- `$ cp -r /path/to/installation/picard/input_template input`

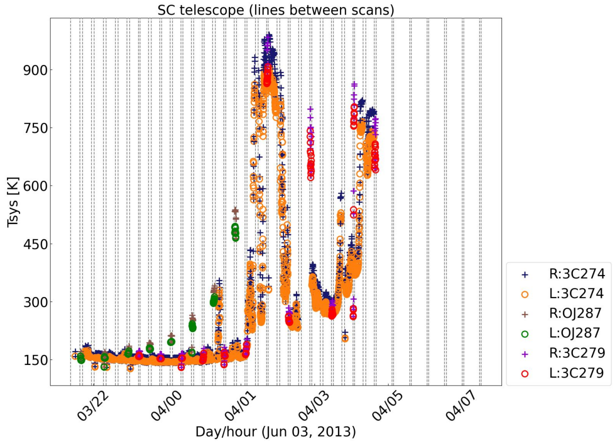
- `array.inp:` *array_type* = *GMVA*
- `array_finetune.inp`: *fringe_exhaustive_refant_search_islands* = *True*
  - S/N often low. Allows sub-arrays of antennas to be calibrated

- First create Tsys and raw visibility plots: **`$ picard -prq 2,h,k`**
  - Also make flag backup (`-r`)
  - Make refant list (usually AA first) and pick calibrator sources. <u>Example</u>:
    - `array.inp`:
      refant = AA, NN, EF, GB, LA, KY
    - `observation.inp:`
      science_target = M87
      calibrators_instrphase = 3C279, 3C273
      calibrators_bandpass = 3C279, 3C273

Visibility and tsys plots







After inputs are set

- Run the pipeline:

```
$ picard -p
```

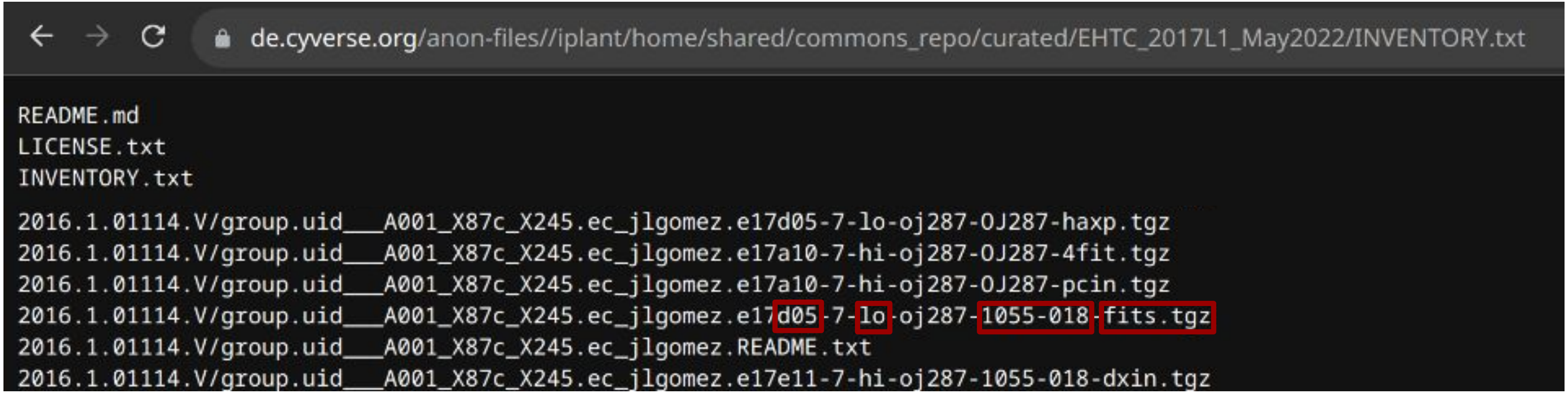
Calibrating EHT+ALMA data

With the **CASA**-based rPICARD VLBI pipeline:

https://bitbucket.org/M_Janssen/picard

Calibrating EHT + phased ALMA data

- git clone https://bitbucket.org/M_Janssen/casaeht
  - Has wrapper script to run picard efficiently on EHT data & example EHT input configurations
- `$ cd /path/to/working/dir`
  - *.fits/*.FITS   *.AN
  - No WX file as the ANTAB Tsys are already corrected for atmospheric opacities
- `$ cp -r /path/to/installation/picard/input_template input`


de.cyverse.org/anon-files//iplant/home/shared/commons_repo/curated/EHTC_2017L1_May2022/INVENTORY.txt

```
README.md
LICENSE.txt
INVENTORY.txt

2016.1.01114.V/group.uid___A001_X87c_X245.ec_jlgomez.e17d05-7-lo-oj287-OJ287-haxp.tgz
2016.1.01114.V/group.uid___A001_X87c_X245.ec_jlgomez.e17a10-7-hi-oj287-OJ287-4fit.tgz
2016.1.01114.V/group.uid___A001_X87c_X245.ec_jlgomez.e17a10-7-hi-oj287-OJ287-pcin.tgz
2016.1.01114.V/group.uid___A001_X87c_X245.ec_jlgomez.e17d05-7-lo-oj287-1055-018-fits.tgz
2016.1.01114.V/group.uid___A001_X87c_X245.ec_jlgomez.README.txt
2016.1.01114.V/group.uid___A001_X87c_X245.ec_jlgomez.e17e11-7-hi-oj287-1055-018-dxin.tgz
```

Calibrating EHT + phased ALMA data: input

- `observation.inp`: <u>EXAMPLE</u>
  science_target = M87, SGRA, OJ287
  calibrators_instrphase = 3C279
  calibrators_bandpass = 3C279

- `array.inp`:
  array_type = EHT
  refant = AA, LM, NN, PV, MM

  fringe_delay_window_initial = -150;150
  fringe_rate_window_initial = -10;10
  fringe_delay_window_mb_sci_short = 0.01
  fringe_rate_window_mb_sci_short = 0.05
  fringe_solint_optimize_search_cal = 0.0001;2;5;10;15
  fringe_solint_optimize_search_sci = 0.0001;2;5;10;15
  fringe_solint_mb_reiterate = 30;60;180;300;999

- `array_finetune.inp`:
  atmo_selfcal = both
  fringe_minSNR_sb_instrumental = 4.51
  fringe_minSNR_mb_coher = 3.1
  fringe_minSNR_mb_short_cal = 3.01
  fringe_minSNR_mb_long_sci = 3.05
  fringe_minSNR_mb_short_sci = 3.01
  fringe_minSNR_mb_shortFFT = 3.01
  fringe_minSNR_mb_reiterate = 3.01
  fringe_instrumental_method = interpolate
  sbd_no_stationflag = True
  fringe_exhaustive_refant_search_islands = True

- `constants.inp`:
  sigmascale = 1.031
  ff_mem_settletime = 100
  fringefit_mb_interpolate_over_flags = True

- `flagging.inp`:
  flag_edge_channels = False

After inputs are set

- Run the pipeline:
  `$ picard -p`

- Or:
  `$ /path/to/casaeht/bin/./process_eht /path/to/working/dir --mincores 25GB`
  - Optimizes usage of CPU cores against available memory for different pipeline steps
  - Two rounds of calibration. Treats all sources as *science targets* for deep fringe searches after instrumental effects are solved.
    - Might also be useful for GMVA data. This is what the process_eht script does:

```
$ rm -fr calibration_tables/ff_mb_cal_s.t
$ rm -fr calibration_tables/ff_mb_cal_c.t
$ rm -f fringe_params.stored.cal*
$ rm -f scan_refants.stored.cal*
```

& *science_target* = *<all>*, *calibrators_** = *None* in `observation.inp`

>GMVA steps are then `$ picard -prq x,0~10`→ `$ picard -prq x,11~99`

On polarization calibration with phased ALMA (1, 3, 7 mm)

- Absolute RL phase:
  - Need to correct for R-L phase offset of primary reference antenna

  - If source EVPA of calibrator is known (from single-dish observation):
    - `observation.inp:` set *calibrators_rldly* & *rldly_EVPAs_FE*
  - Otherwise, if you have phased ALMA:
    - Absolute RL phase known and RL delay already calibrated
    - Skip *rldly*
    - **90** degrees for **EHT** and **20** degrees for **GMVA**
      - Not part of pipeline, can use CASA polcal or https://gitlab.com/mjanssen2308/eht-postproc/-/blob/master/eht_postproc.py?ref_type=heads#L171

- Leakage / D-terms:
  - Not part of rPICARD calibration. To bes solved during imaging & self-calibration.

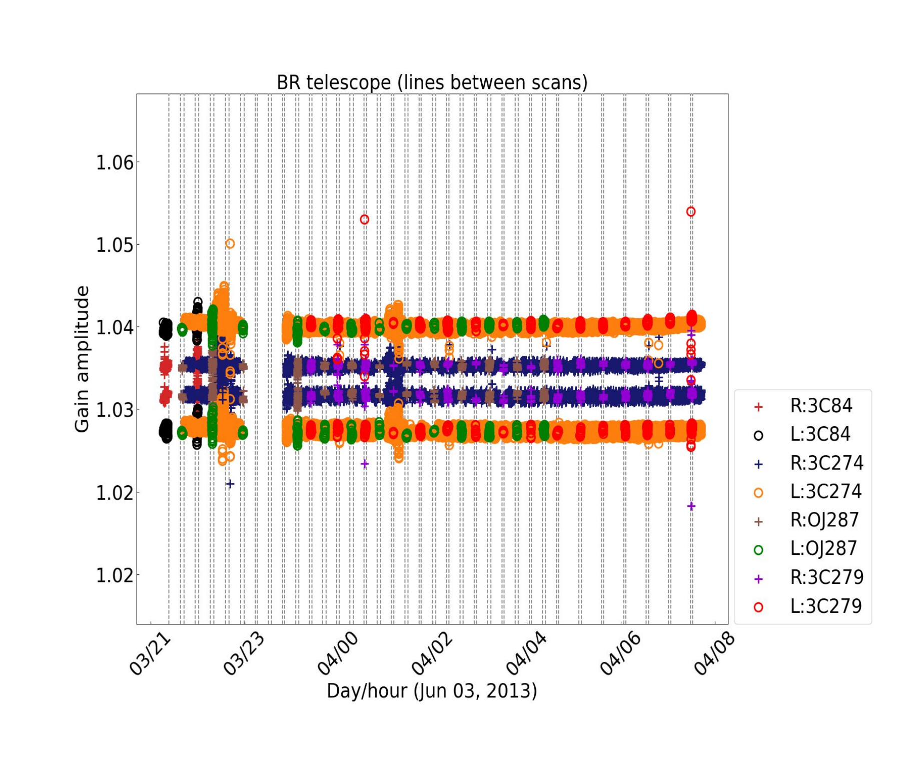
Questions on how to run rPICARD for GMVA and EHT data?

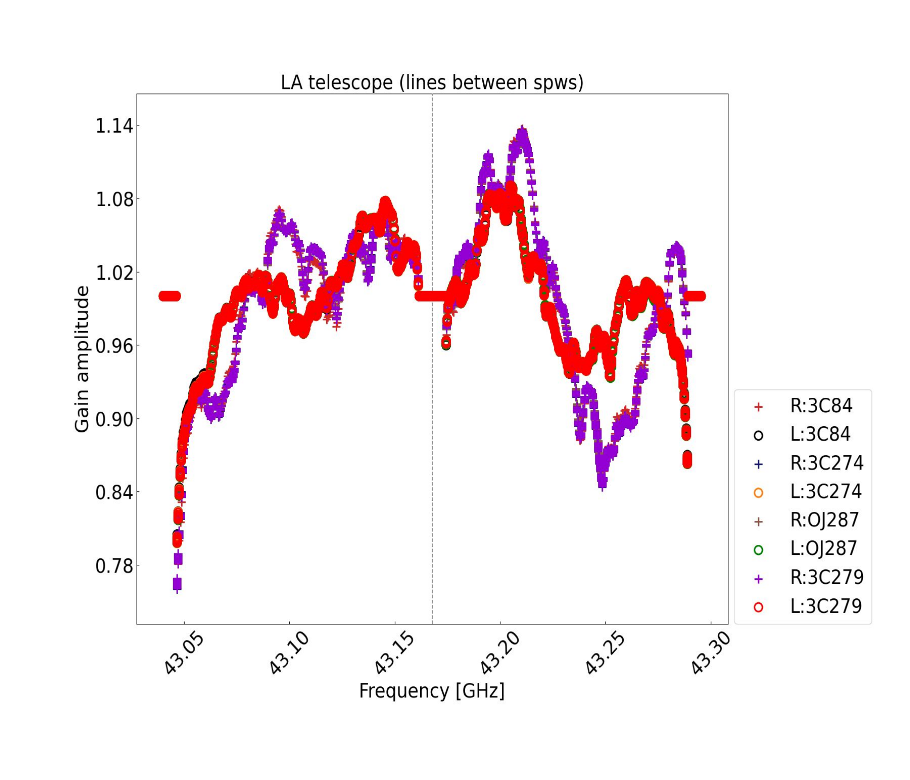
Pipeline details

How it works and what the automatically generated diagnostics tell you

Amplitude calibration

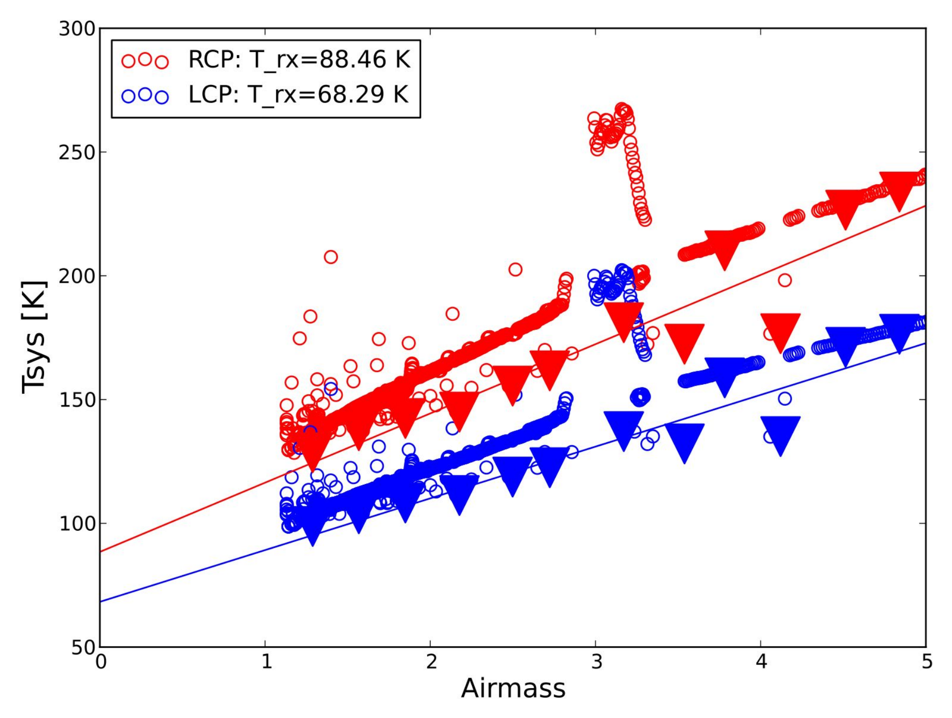
Accor & scalar bandpass

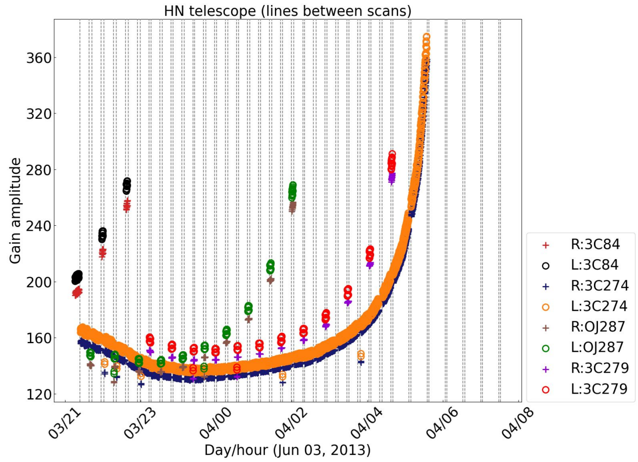


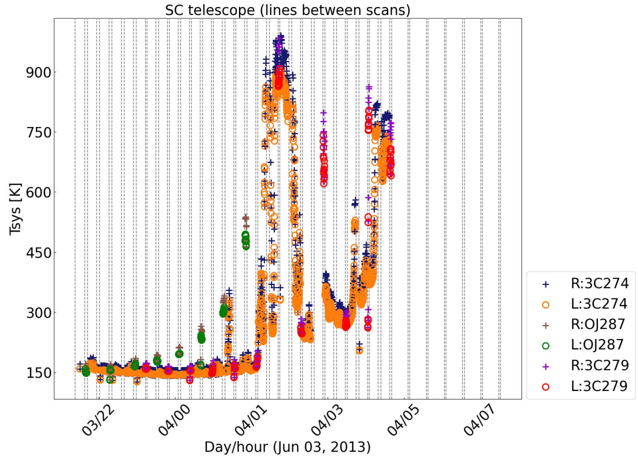


7mm VLBA data of M87. Project code: BW0106.

Tsys calibration





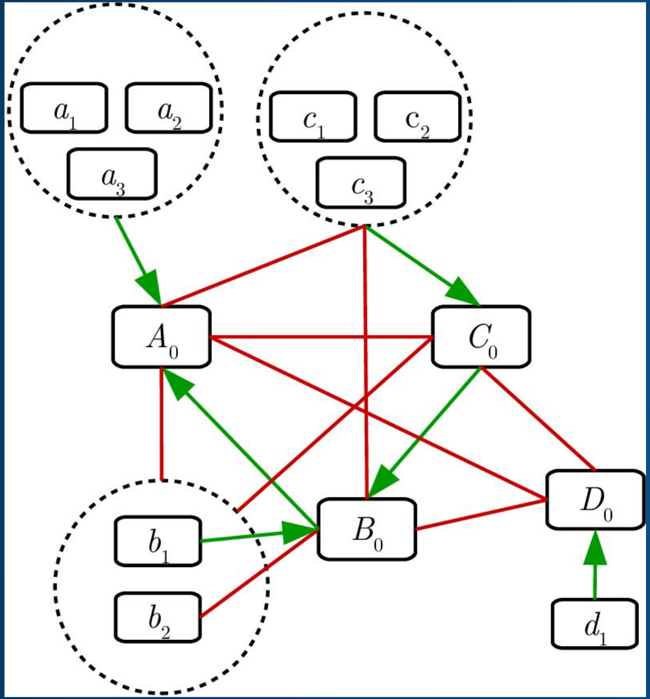


7mm VLBA data of M87. Project code: BW0106.

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

Phase calibration

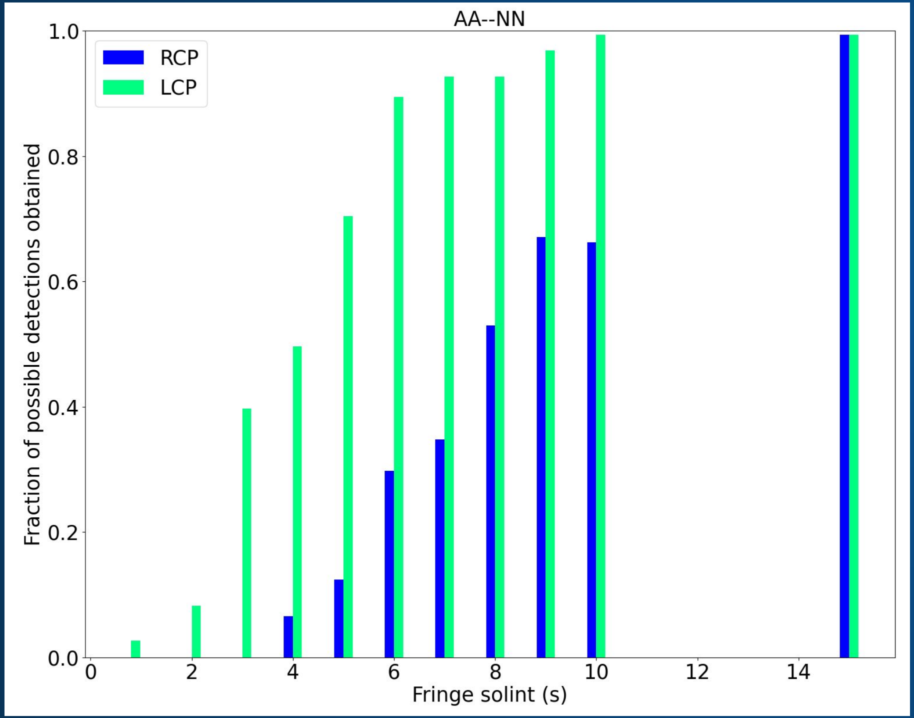
Intra-scan exhaustive fringe search

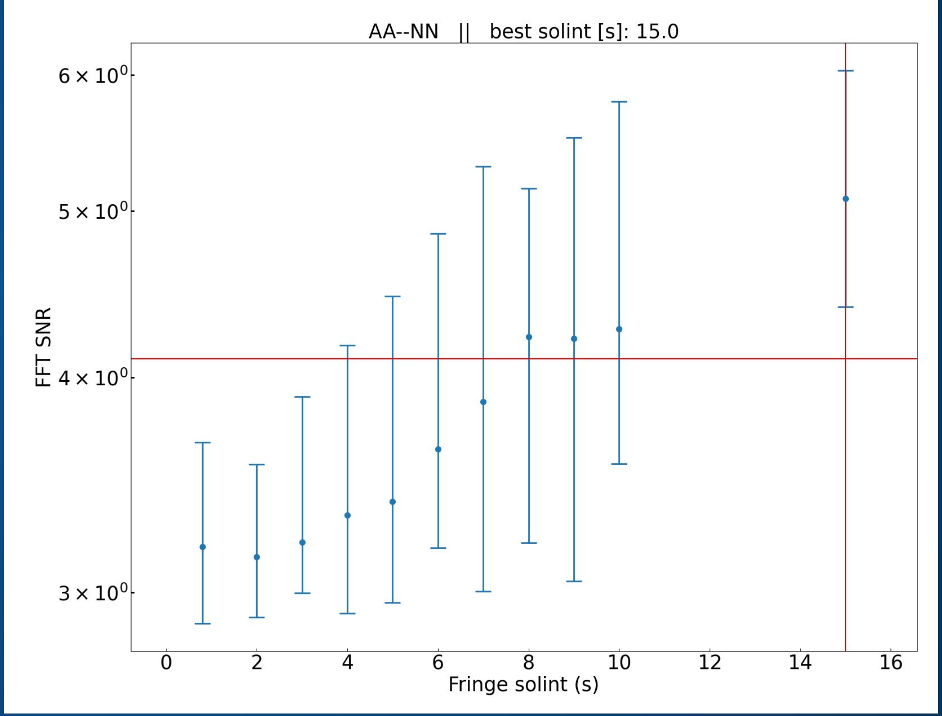


- A_0, B_0, C_0, D_0 list of prioritized reference stations.
- Green : detection.
- Red: Non-detection.
- b_1, C_0, c_i calibratable via re-referencing.

Solution interval estimation per ant/scan

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

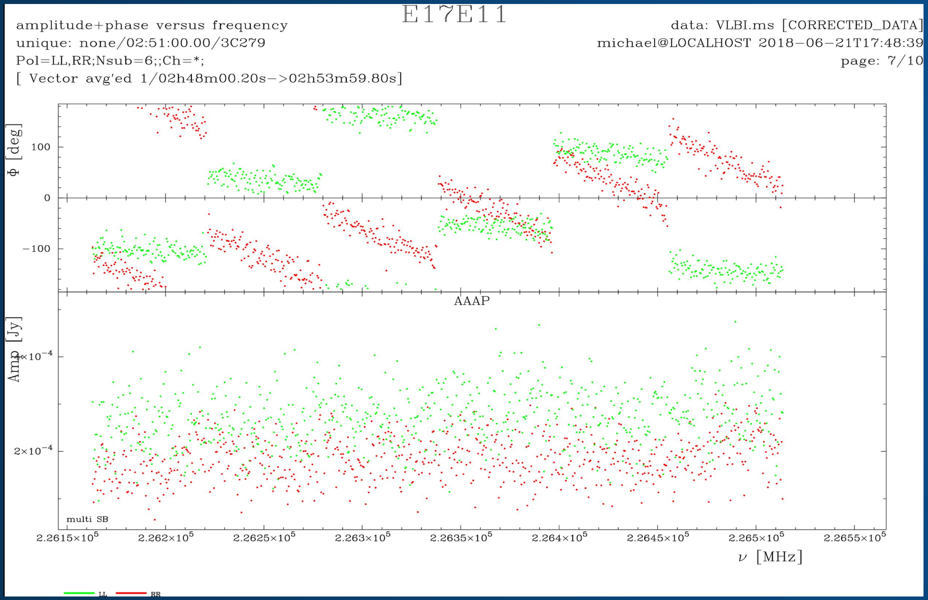


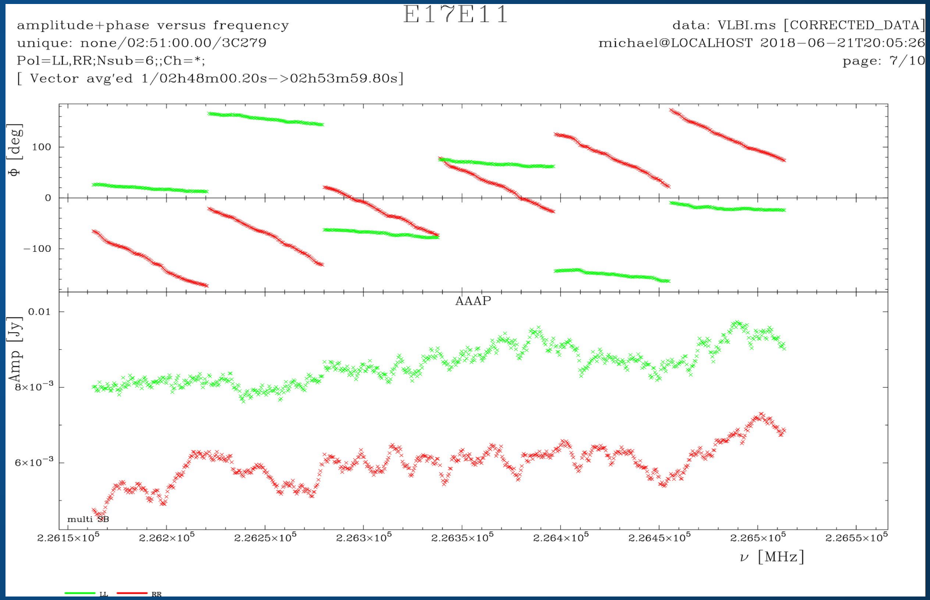


Coherence calibration

Atmospheric phase stabilization

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

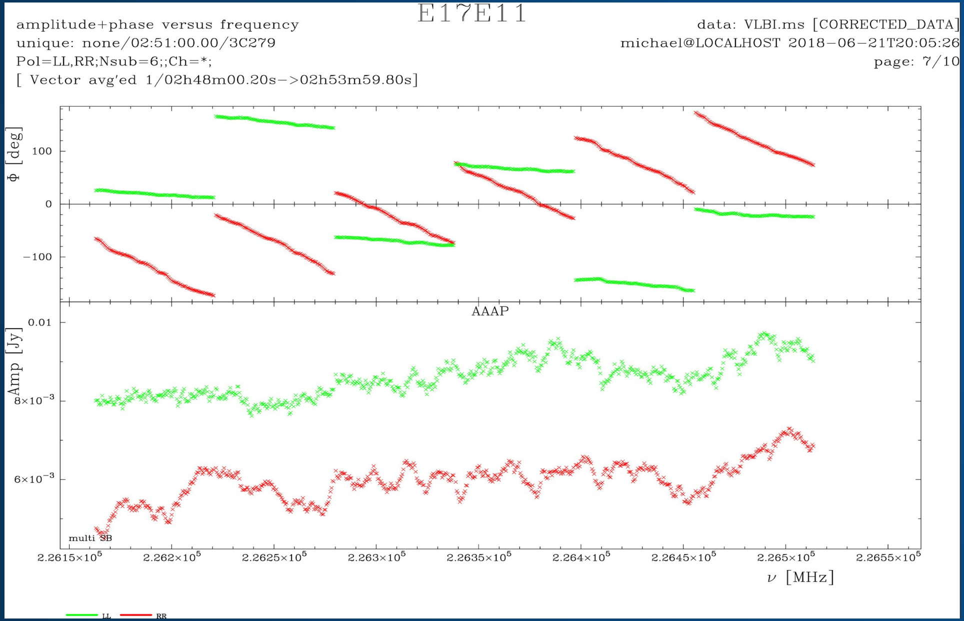


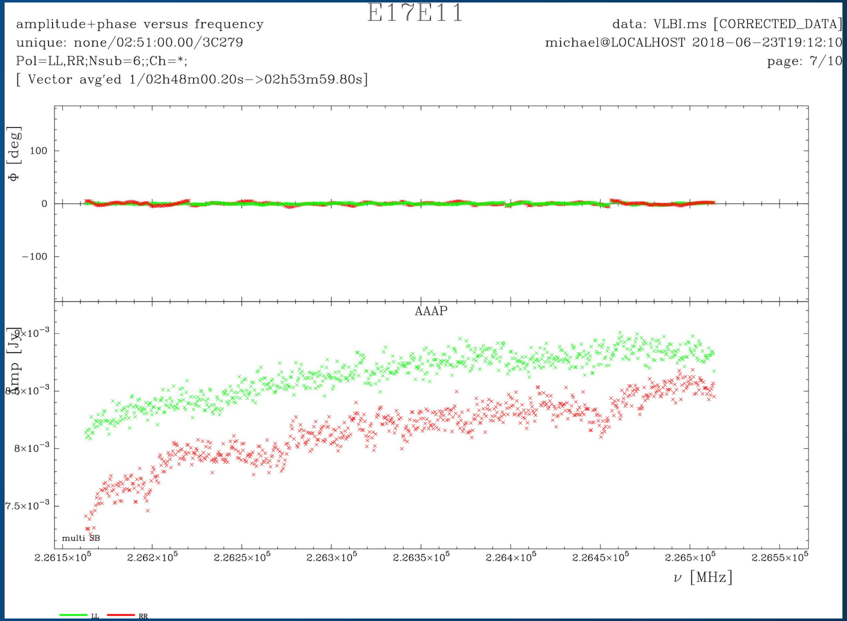


Instrumental phases and delays

Per-spw fringefit

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

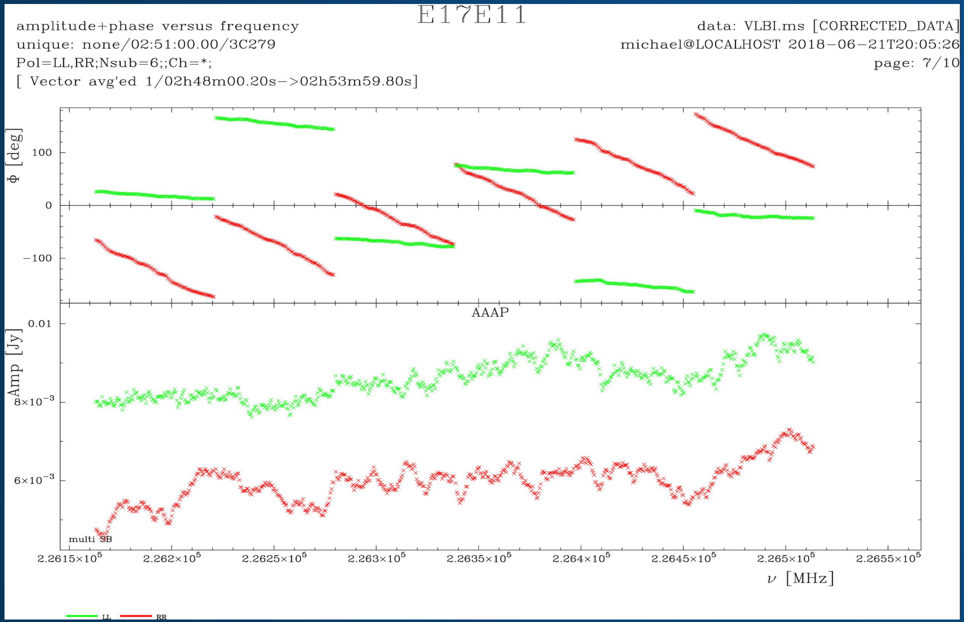


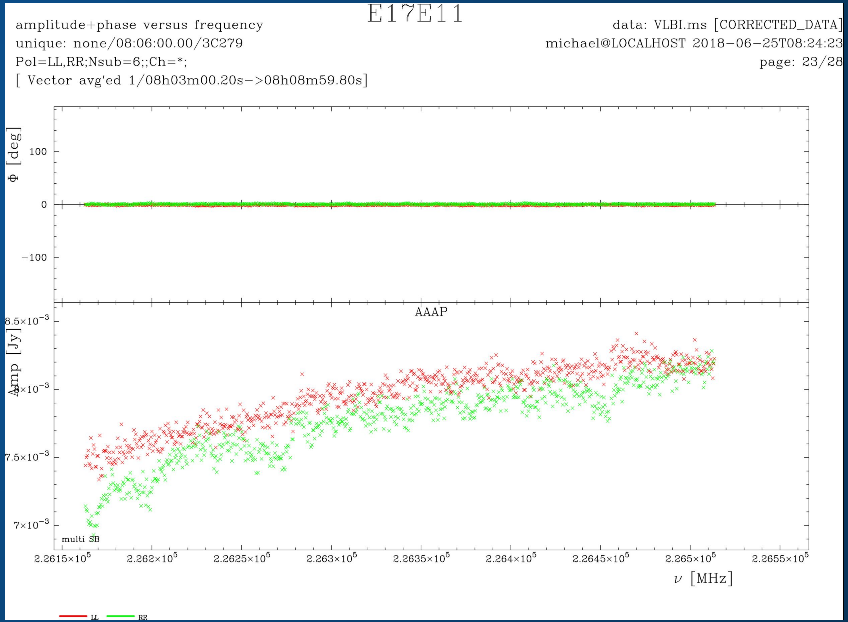


Instrumental phases and delays

Per-spw fringefit + bandpass

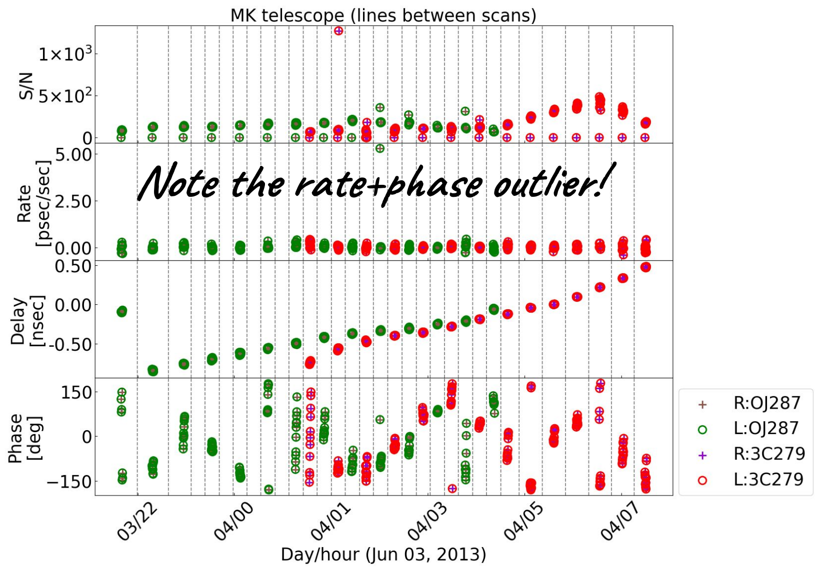
=========================>

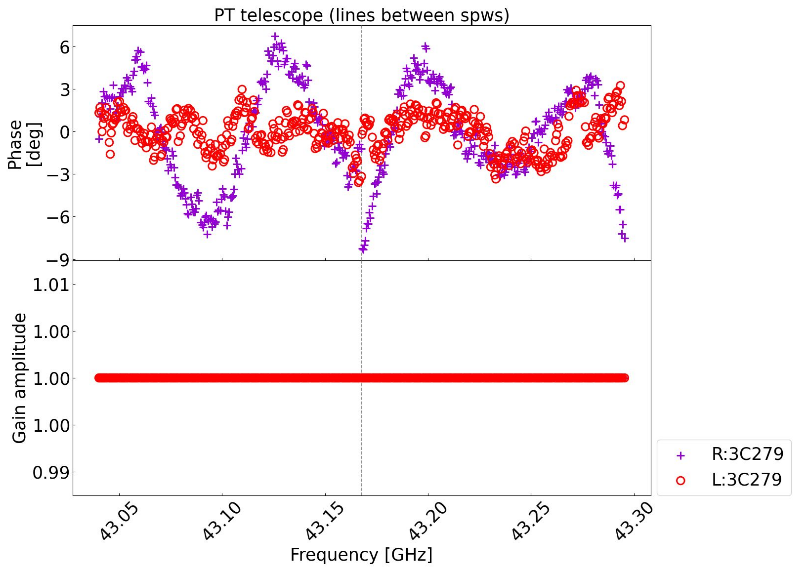




Multi-band fringe & complex bandpass

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





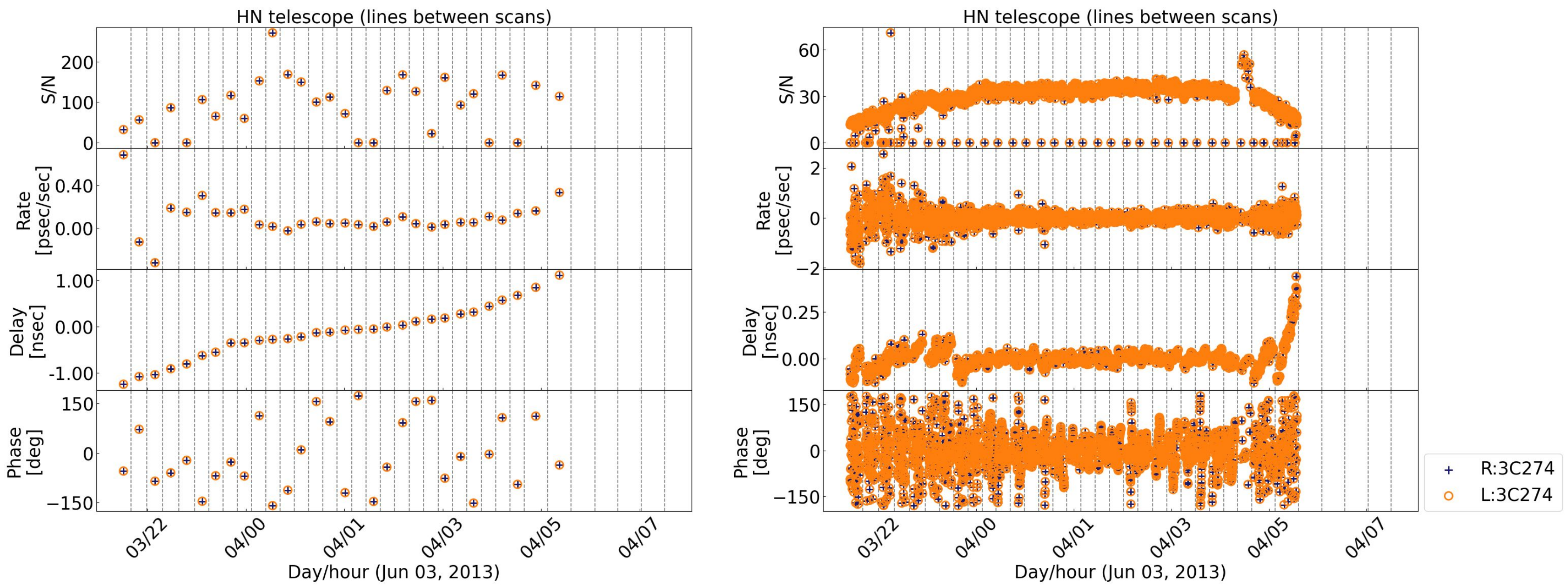
7mm VLBA data of M87. Project code: BW0106.

Last calibration steps: fringe-fit science targets

- 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.

- 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



Last calibration steps: fringe-fit science targets

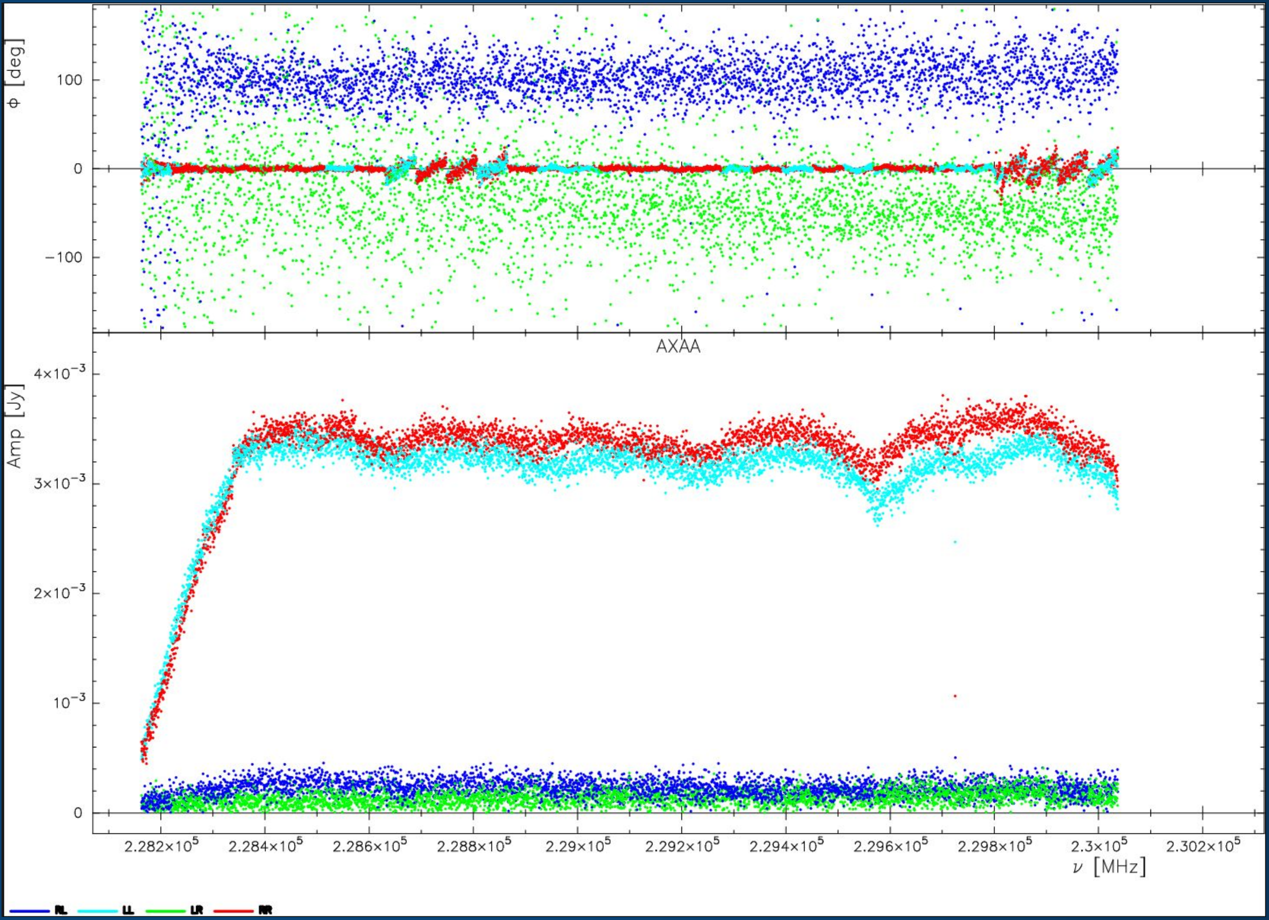
- First: long integration (entire scan) to take out bulk delay or rate with maximized SNR.
  → Source detected or not?
  Typically with open FFT search windows. Over aligned spws and correlation products (pols after RL phase+delay).

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

- 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.

Example visibility plot of the final calibrated data generated by the pipeline.

With some data issues.



Backup slides

Format metadata

```
tar xfz group.uid___A001_X87c_X245.ec_jlgomez.metadata-2020-d02-01.tgz

mv 2020-D02-01/antab/eht_2017_april_A_sideband1.EHT.AN .

echo "" >> eht_2017_april_A_sideband1.EHT.AN

sed -e s/FREQ=10,100000//g -i 2020-D02-01/antab/eht_2017_april_A_sideband1.AA.AN

cat 2020-D02-01/antab/eht_2017_april_A_sideband1.AA.AN >> eht_2017_april_A_sideband1.EHT.AN

mv 2020-D02-01/casa/config/eht.mounttypes .

mv 2020-D02-01/casa/flagfiles/lo.flags .

rm -rf 2020-D02-01

#> add antenna='SR' and antenna='SP' to lo.flags for speedup
```

Current spectral line processing implementation in rPICARD

- Can combine line and continuum correlations with overlapping frequency range into a single *MeasurementSet* as distinct spectral windows.
- Can use *mstransform* to shift frames (e.g., to LSRK).
- Cube imaging with *tclean.*
- Phase-referencing already implemented for cm VLBI and **should** work out of the box.
- Enable spectral line mode with `spectral_line` and `line_var` parameters in `observation.inp`.
  For `spectral_line=search` (simple peak search that uses auto-corrs), `line_var` limits how much the line peak is allowed to shift between scans.

Current spectral line processing steps

1. Pre-calibration:
    a. Gather and process metadata
    b. Load the data into a MeasurementSet
    c. Load source models
    d. Flag bad data

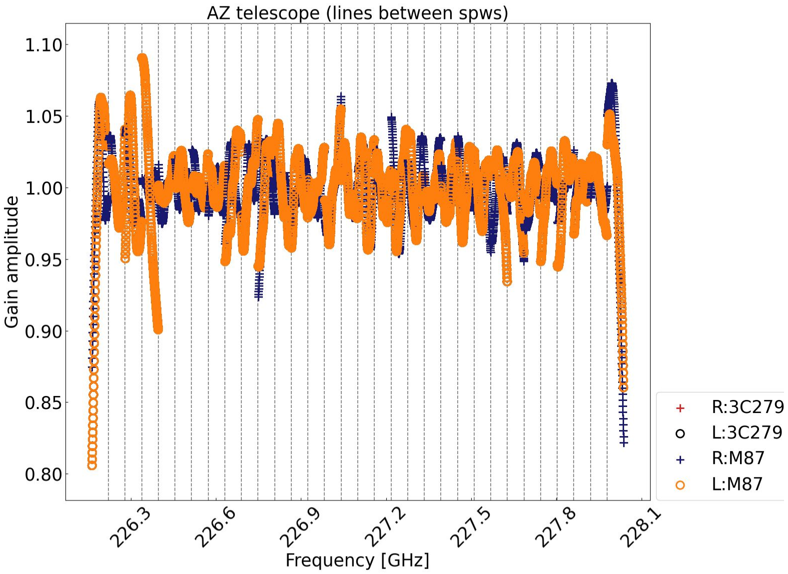
2. Calibration steps:
    a. Flux density
    b. Fringe-fit & phase calibration of calibrator sources
    c. Solve instrumental effects
        i. Align spws, bandpass, align correlation products (RL phase+delay)
    d. Fringe-fit science targets over VLBI scans, combine correlation products for max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

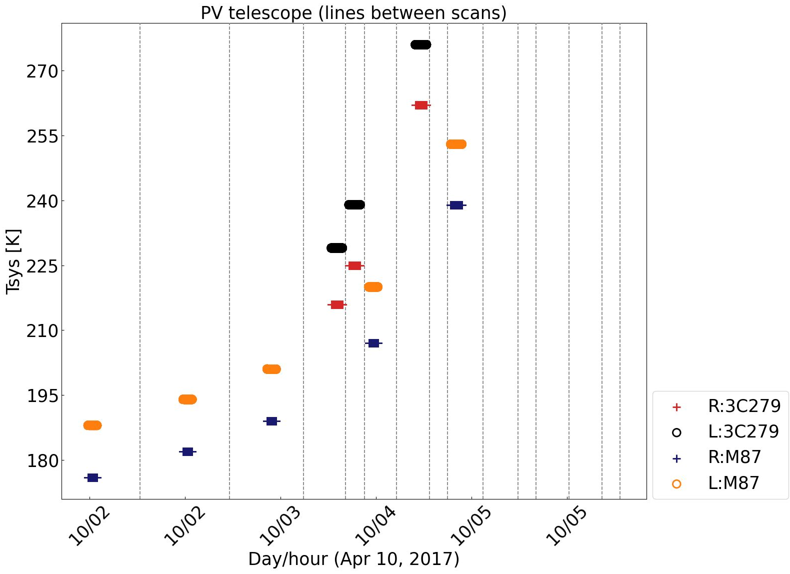
3. Post-calibration:
    a. Apply calibration solutions
    b. Plot the calibrated data
    c. Export averaged data as MS and UVFITS

Run the pipeline (using 8 CPU cores)

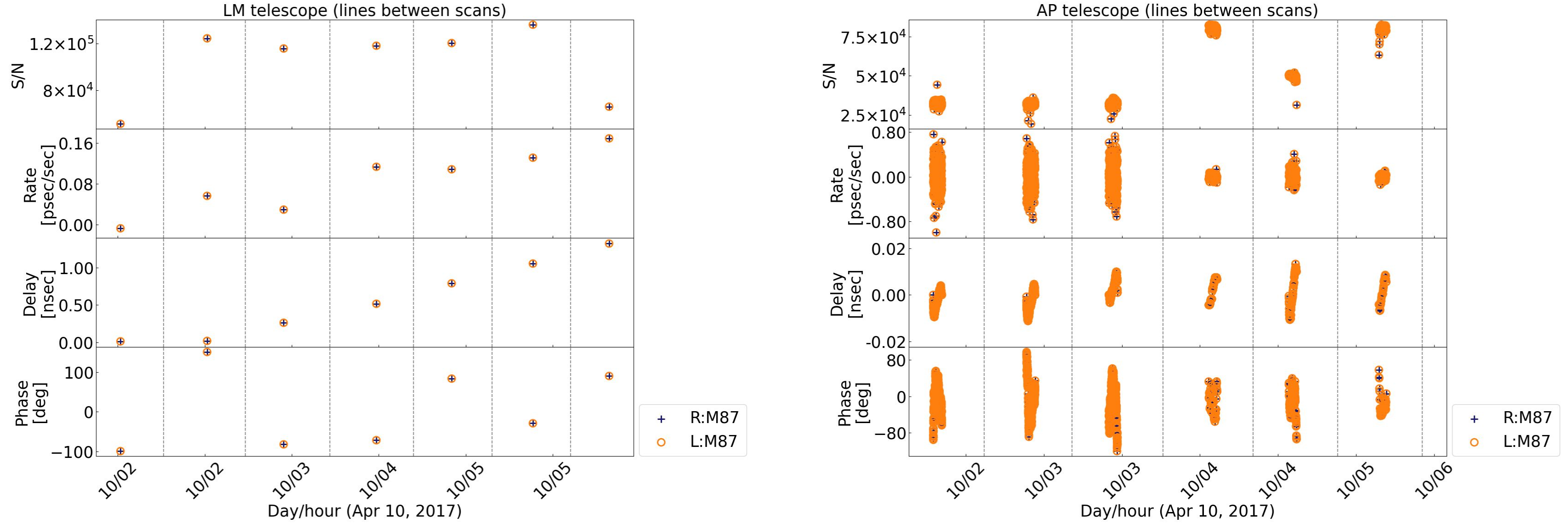
picard -p -n 8 > picard.out

Diagnostics from the EHT data calibration run

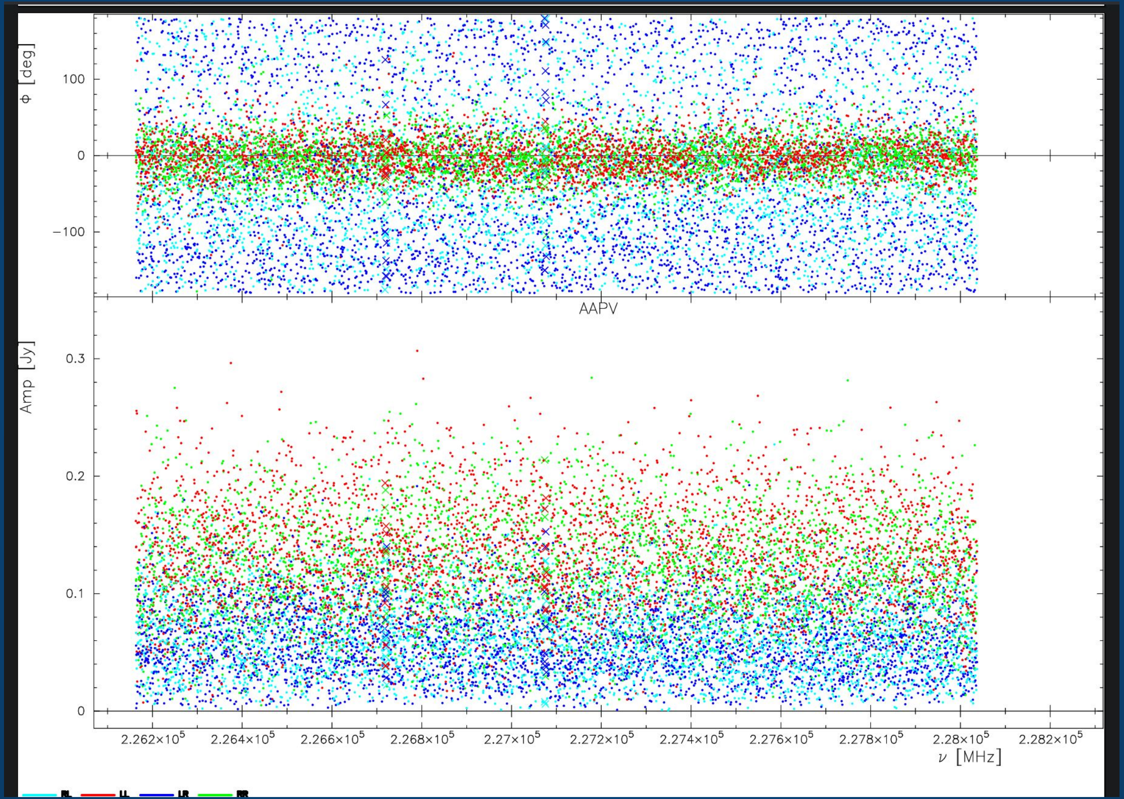




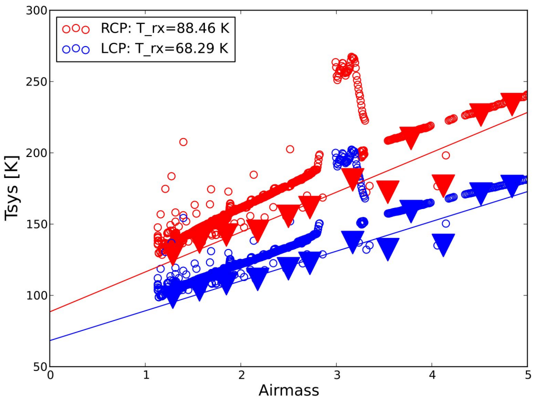
Diagnostics from the EHT data calibration run

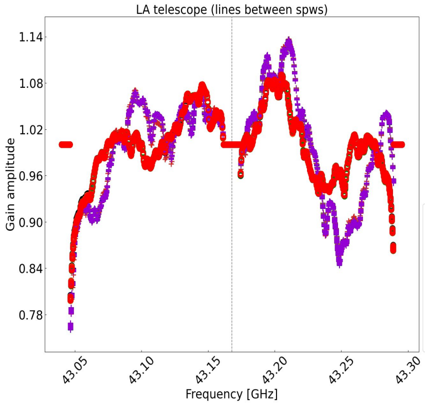


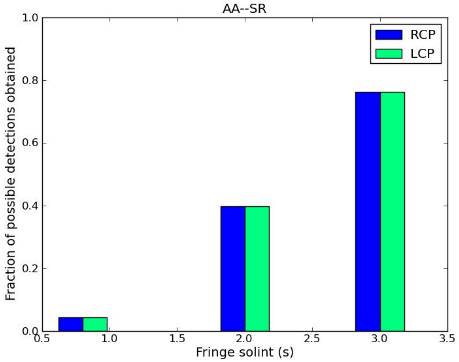
Diagnostics from the EHT data calibration run

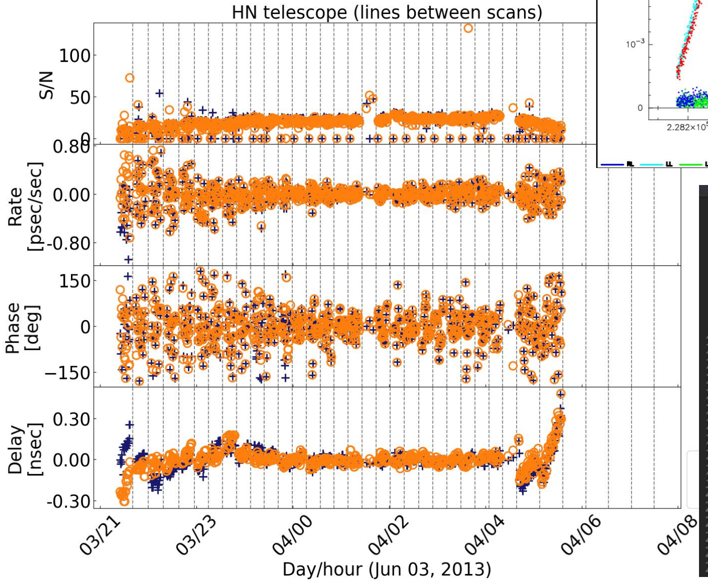


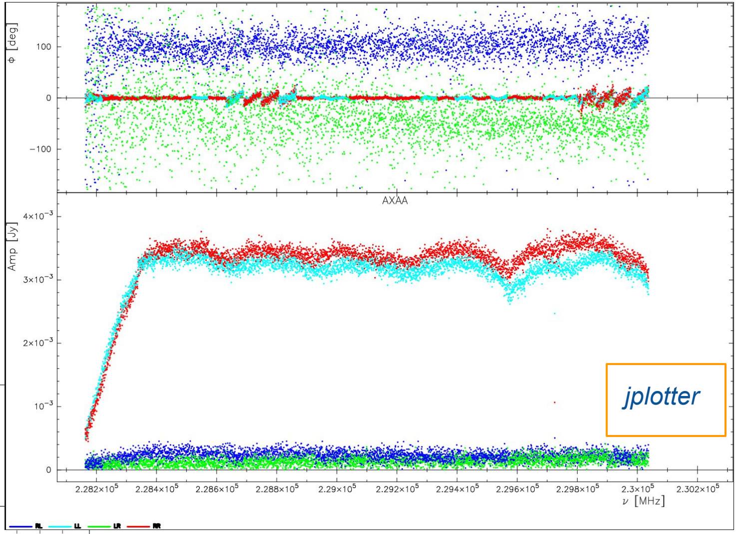
rPicard diagnostics












```
#Scan,Time,Source,Calibrator,Antenna1,Antenna2,PolarizationID,Detection,SNR,FFT-
4,4877013305.0,3C274,N,KP,BR,1,Y,50.657474517822266,0.0,-8.065732326825725e-15
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
4,4877013305.0,3C274,N,KP,HN,2,Y,40.48537826538086,0.0,0.0
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4,4877013305.0,3C274,N,KP,LA,2,Y,76.9952392578125,-0.0,-8.065938155831908e-15
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4,4877013305.0,3C274,N,KP,MK,2,N,0.0,0.0,0.0
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4,4877013305.0,3C274,N,KP,SC,2,Y,38.65174102783203,-0.0,-0.0
6,4877014416.0,3C274,N,KP,BR,1,Y,56.23532485961914,0.0,8.065938155831908e-15
6,4877014416.0,3C274,N,KP,BR,2,Y,56.23532485961914,0.0,8.065938155831908e-15
6,4877014416.0,3C274,N,KP,FD,1,Y,150.17469787597656,0.0,0.0
6,4877014416.0,3C274,N,KP,FD,2,Y,150.17469787597656,0.0,0.0
6,4877014416.0,3C274,N,KP,HN,1,Y,31.009220123291016,0.0,8.065938155831908e-15
6,4877014416.0,3C274,N,KP,HN,2,Y,31.009220123291016,0.0,8.065938155831908e-15
```

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

1. Pre-calibration:
    a. Gather and process metadata
    b. Load the data into a MeasurementSet
    c. Load source models
    d. Flag bad data

2. **Calibration <u>steps</u>:**
    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

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.