Draft version May 6, 2022
Typeset using LaTeX default style in AASTeX631

Imaging the Black Hole Shadow and Jet Launching Region of M87

PI: Event Horizon Telescope Consortium

Project: 2016.1.01154.V

1. INTRODUCTION

This data delivery contains what is defined by the Event Horizon Telescope Collaboration (EHTC) as L1 data for the Very Long Baseline Interferometry (VLBI) 1-mm 2017 observing campaign by the Event Horizon Telescope (EHT). 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 (APP; (Doeleman 2010; Fish et al. 2013; Matthews et al. 2018)). 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. (2019a). The paper 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 https://eventhorizontelescope.org/publications. Additional data products derived from this L1 data can be found at https://eventhorizontelescope.org/for-astronomers/data.

This data delivery includes data 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 the facilities used for these observations can be found in Event Horizon Telescope Collaboration et al. (2019b).

The overall goal of the observations is to image the supermassive black holes M87* (M87) and Sagittarius A* (SGRA) at event horizon scales and to image the AGNs OJ287, 3C279, CENA, and NGC1052 at high resolution. The specific goal of the ALMA observations in this project as given in the abstract of the proposal are:

> The supermassive black hole at the heart of the Virgo A galaxy (M87) powers one of the most well-studied relativistic jets in the sky. Due to its high mass and close proximity, it presents us (along with SgrA* in the Galactic Center) with the opportunity to resolve the shadow cast by the black hole event horizon against the backdrop of surrounding hot plasma. The Event Horizon Telescope (EHT) Consortium has previously used a 1.3mm three-station VLBI array to measure a size of the jet base in M87 to be just 5.5 Schwarzschild radii. With this important confirmation of horizon-scale structure, we propose two tracks of Band 6 VLBI observations with the EHT+ALMA. An ALMA-anchored EHT array can detect the shadow feature, which would provide the strongest evidence for the existence of supermassive black holes and enable new tests of strong-field GR. Through full polarimetric imaging, the relativistic jet and black hole magnetosphere can be mapped, testing models of jet launch from spinning black holes at the event horizon. In sum, we aim to connect the smallest objects predicted by Einstein's GR to galactic-scale outflows that impact large-scale structure in the Universe.

2. CONTENT OF THE DATA DELIVERY

The following file naming conventions have been used throughout the EHT 2017 April Observation Compaign data deliveries:

- `*-fits.tgz`: Final correlation output (FITS)
- `*-hops.tgz`: Final correlation output (HOPS)

- `*-4fit.tgz`: Sample Fourfit Fringe files (4FIT)
- `*-dxin.tgz`: Correlator `DiFX` input files
- `*-haxp.tgz`: Mixed Pol ALMA-only correlations (HOPS)
- `*-pcin.tgz`: PolConversion input files
- `*-pcqk.tgz`: PolConversion processing artifacts
- `*-swin.tgz`: Correlator `DiFX` output files (SWIN)
- `*-logs.txt`: Observing track processing logs
- `*.app_deliverables.tgz`: ALMA QA2 data
- `*.metadata-2020-d02-01.tgz`: Observing metadata

Some of these are quite large and have been split into multiple files to get more manageable pieces. These typically group VLBI scans on a single target together. The partition is based on:

- experiment: The unique $EXPER reference label of the VLBI schedule VEX file; typically `e` followed by the last two digits of the year, followed by a track label (`a-z`) followed by two digits of day of month
- revision: Revision number; monotonically increasing with time
- sub-band: `lo` or `hi` representing the 227.1 GHz and 229.1 GHz bands (representing the band center at ALMA)
- project: A short "nickname" corresponding to the primary target of the ALMA project; `na` refers to observations not involving ALMA
- target: The name of the target of the VLBI scans

All files are prefixed with the ALMA group uid for the project and an ALMA large project "nickname". So for example `group.uid__A001_X11b3_X30.ec_eht.e17c07-7-lo-sgra-J1733-fits.tgz` refers to the visibility data in FITS format of the VLBI scans of the SGRA ALMA project that observed target J1733 in track '`c`' of the EHT observations on April 7th 2017.

The *Correlator DiFX input files* are the control input files for the `DiFX` software correlator that were used to correlate the data. This includes the correlator model that was used for correlation. This does not include the baseband (voltage) data from the individual telescopes as these have not been retained (as is normal practice for VLBI observations) due to the large size of this data.

The *Correlator `DiFX` output files* are the raw correlator output in the so-called SWIN format. This data is in mixed polarization basis and is provided to make it possible to the redo the conversion into circular polarization basis. The result will have to be converted into FITS or HOPS format using the appropriate tools from DiFX for further processing.

The *PolConversion input files* are the control input files for the `Polconvert` package (Martí-Vidal et al. 2016).

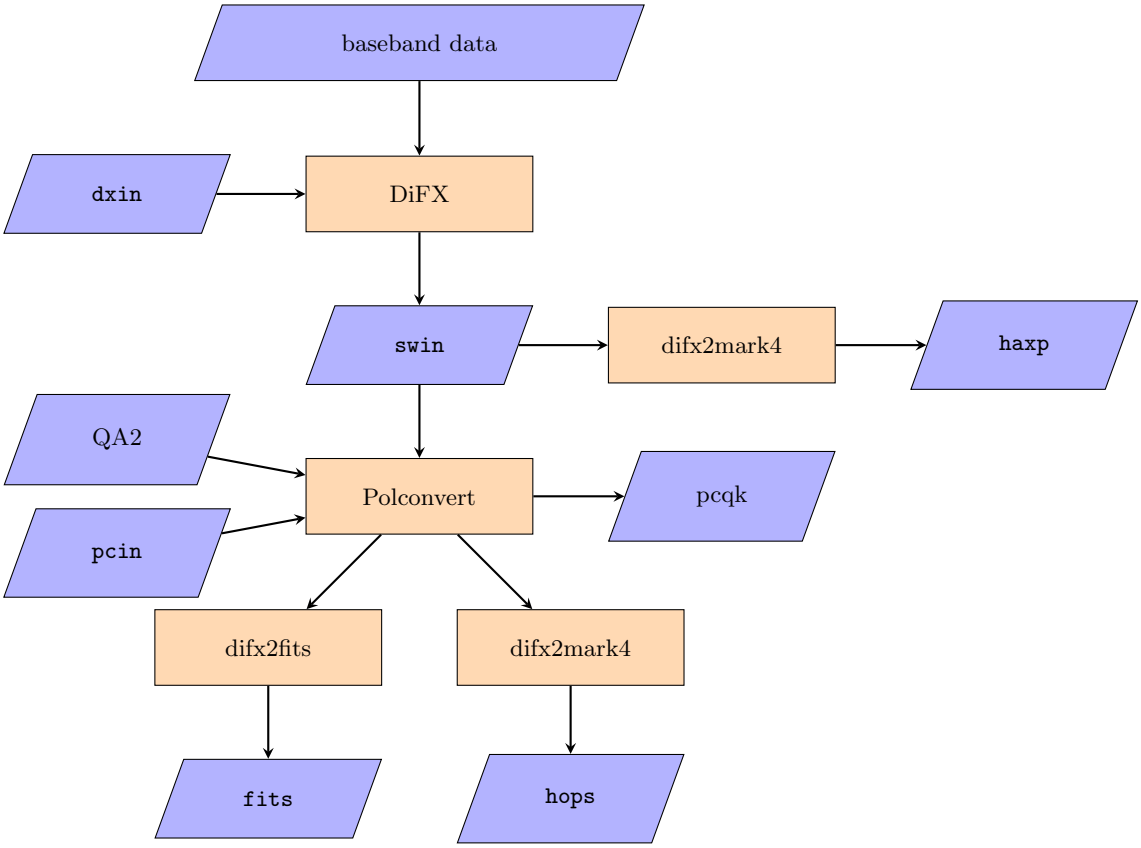
The *PolConversion processing artifacts* provide various diagnostic plots produced by `Polconvert` that provide a means to assess the quality of the conversion from a mixed basis into circular basis.

The *Sample Fourfit Fringe files*.

The *Mixed Pol ALMA-only correlations* are a subset of the correlator output in Mk4 fileset (HOPS) format in mixed polarisation basis generated without running `Polconvert`. This subset contains only the files for the baselines that contain ALMA as the files for other baselines have identical content to the ones provided in the *Final correlation output*.

The *Final correlation output* is provided in two different formats: FITS and HOPS. This data is in circular polarization basis. The FITS files follow the FITS-IDI convention as documented in Greisen (2009) and can be loaded into radio-interferometry data reduction software packages like `AIPS` and `CASA`. The HOPS files are in the Mk4 fileset format for further processing with the `HOPS` software package that is often used for mm-VLBI (Whitney et al. 2004).

Figure 1. Data processing flow



The *Observing track processing logs* contain output from the top-level data processing and archiving process. These are provided for completeness.

The *Observing metadata contains* is a collection of metadata to accompany all the EHT Observations taken in April 2017. This includes a priori estimates of station sensitivity for all EHT 2017 scans in ANTAB format (Issaoun et al. 2017), as well as control codes for configuring and reducing EHT data in the `CASA` and `HOPS` radio interferometry software environments. Metadata in this package can be used as auxiliary information to process original EHT correlator output in FITS-IDI or HOPS format. Data that has already been reduced and calibrated are provided in accompanying EHT publications, see for example Event Horizon Telescope Collaboration et al. (2019a).

The data processing flow and the data products produced by it are illustrated by figure 1.

3. DATA PROCESSING METHODS

The VLBI baseband data (including ALMA VLBI output) was correlated using the `DiFX` software correlator (Deller et al. 2011), using zoom bands to account for differences in observation bands and sampling rates used at the various stations that form the EHT. The input parameters for the correlation as well as some of the intermediate parameter descriptions are provided in the `*-dxin.tgz` files. This includes the observed schedule in VEX format (`*.vex.obs`) which includes the clock model and the earth orientation parameters (EOPs) that were used for correlation. The main correlation parameters are provided in the `*.v2d` files. From these files the intermediate parameter files are generated. These are provided in the `*.input` and `*.calc`. files. The latter is then used to generate the correlator model, which is provided in the `*.im` files using the `CALC11` code bundled with `DiFX`.

All telescopes of the EHT array, except for ALMA, observed circular polarizations. ALMA instead uses receivers that provide linear polarizations. This results in mixed pol correlation output. This mixed pol output is converted into a circular basis using `Polconvert` (Martí-Vidal et al. 2016). This was done using the version of `Polconvert` as bundled with `DiFX` using the ALMA QA2 data (`*.app_deliverables.tgz`) as auxiliary input (Goddi et al. 2019).

Finally the output from `Polconvert` is converted into FITS format using the difx2fits tool and converted into HOPS format using the difx2mark4 tool bundled with `DiFX`.

4. QUALITY ASSESSMENT

Initial quality assessment of the correlated data was performed by an initial fringe-fit using the `fourfit` tool that is part of the `HOPS` package. These results are included in this data release in the `*-4fit.tgz` package.

Quality assessment of the polarization conversion: `Polconvert` produces diagnostic plots; these plots are included in the `*-pcqk.tgz` files.

The final quality assessment has been done on both the FITS and HOPS data using three different pipelines. This includes fringe validation, checks on thermal error consistency and closure quantities. Details can be found in section 8 of Event Horizon Telescope Collaboration et al. (2019a).

REFERENCES

Deller, A. T., Brisken, W. F., Phillips, C. J., et al. 2011, PASP, 123, 275, doi: 10.1086/658907

Doeleman, S. 2010, in 10th European VLBI Network Symposium and EVN Users Meeting: VLBI and the New Generation of Radio Arrays, Vol. 10, 53

Event Horizon Telescope Collaboration, Akiyama, K., Alberdi, A., et al. 2019a, ApJL, 875, L3, doi: 10.3847/2041-8213/ab0c57

—. 2019b, ApJL, 875, L2, doi: 10.3847/2041-8213/ab0c96

Fish, V., Alef, W., Anderson, J., et al. 2013, arXiv e-prints, arXiv:1309.3519. https://arxiv.org/abs/1309.3519

Goddi, C., Martí-Vidal, I., Messias, H., et al. 2019, PASP, 131, 075003, doi: 10.1088/1538-3873/ab136a

Greisen, E. W. 2009, The FITS Interferometry Data Interchange Convention – Revised, Tech. rep., AIPS Memo Series

Issaoun, S., Folkers, T. W., Blackburn, L., et al. 2017, A conceptual overview of single-dish absolute amplitude calibration, Tech. rep., Event Horizon Telescope Memo Series

Martí-Vidal, I., Roy, A., Conway, J., & Zensus, A. J. 2016, A&A, 587, A143, doi: 10.1051/0004-6361/201526063

Matthews, L. D., Crew, G. B., Doeleman, S. S., et al. 2018, PASP, 130, 015002, doi: 10.1088/1538-3873/aa9c3d

Whitney, A. R., Cappallo, R., Aldrich, W., et al. 2004, Radio Science, 39, RS1007, doi: 10.1029/2002RS002820