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Magnetic field structure in the jet acceleration and collimation zone of quasar 3C273

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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 2021 observing campaign by the Event Horizon Telescope (EHT). The 2021 campaign was the third 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)). New telescopes joining the EHT in this campaign were the IRAM NOEMA Observatory and the Kitt Peak 12-meter Telescope. 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 processing carried out on this L1 data delivery is largely the same as for the EHT 2018 April observations as described in Event Horizon Telescope Collaboration et al. (2024). Aspects that are the same as the EHT 2017 April campaign are described in more detail in Event Horizon Telescope Collaboration et al. (2019). For scientific results derived from the EHT 2021 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 IRAM 30m telescope, the phased Submillimeter Array (SMA), the South Pole Telescope (SPT), the Greenland Telescope (GLT), the IRAM NOEMA Observatory and the Kitt Peak 12-meter telescope. More information about the facilities used for these observations can be found in Event Horizon Telescope Collaboration et al. (2024). 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 AGN 3C273 at high resolution. The specific goal of the ALMA observations in this project as given in the abstract of the proposal are:

> High Faraday rotation measure of $5.0 \times 10^5 \mathrm{rad/m^2}$ has been recently observed in the nearby radio-loud quasar 3C273 within ALMA Band 6. This has opened up a new window for studying the magneto-ionic medium in and around the jet base in active galactic nuclei. Here we propose one 8-hr long track of Band 6 VLBI observations of 3C273 with the EHT+ALMA array in order to make the first ever map of in-band Faraday rotation at 1.3mm. Our aim is to constrain the spatial distribution of the high rotation measure plasma in and around the jet base at a resolution of 100 Schwarzschild radii. The proposed observations would provide constraints on the poorly known magnetic field structure in the jet acceleration and collimation zone. For example, if significant gradient in the Faraday rotation measure in direction transverse to the jet is seen, this would provide strong evidence for the existence of an ordered toroidal magnetic field component. Furthermore, observing Faraday rotation measure from the jet acceleration and collimation zone provides a way to make more direct comparisons with the magnetohydrodynamic jet formation simulations than what is possible through emission maps.

2. CONTENT OF THE DATA DELIVERY

The following file naming conventions have been used throughout the EHT 2021 April Observation Campaign 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-eht2021metadata_v1.2.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: `b1-b4` representing the 213.1 GHz, 215.1 GHz, 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_X1528_X20b.ec_doeleman.e21a14-1-b2-sgra-NRAO530-fits.tgz` refers to the visibility data in FITS format of the VLBI scans of the SGRA ALMA project that observed target NRAO530 in track '`a`' of the EHT observations on April 14th 2021.

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

Table 1. Station codes used in this data delivery

Station	HOPS code	FITS-IDI code
ALMA	A	Aa
APEX	X	Ax
SMT	Z	Mg
JCMT	J	Mm
IRAM 30m	P	Pv
SMA	S	Sw
SPT	Y	Sz
GLT	G	Gl
NOEMA	N	Nn
Kitt Peak	K	Kt

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). Table 1 lists the station codes used in this data release for both data formats.

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 2021. This includes a priori estimates of station sensitivity for all EHT 2021 scans in ANTAB format (Issaoun et al. 2017), as well as validation plots and auxiliary files produced by the metadata processing pipeline and the raw input data for that pipeline. This metadata package is described in detail in Romero-Cañizales et al. (in preparation). 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 (submitted for publication).

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`.

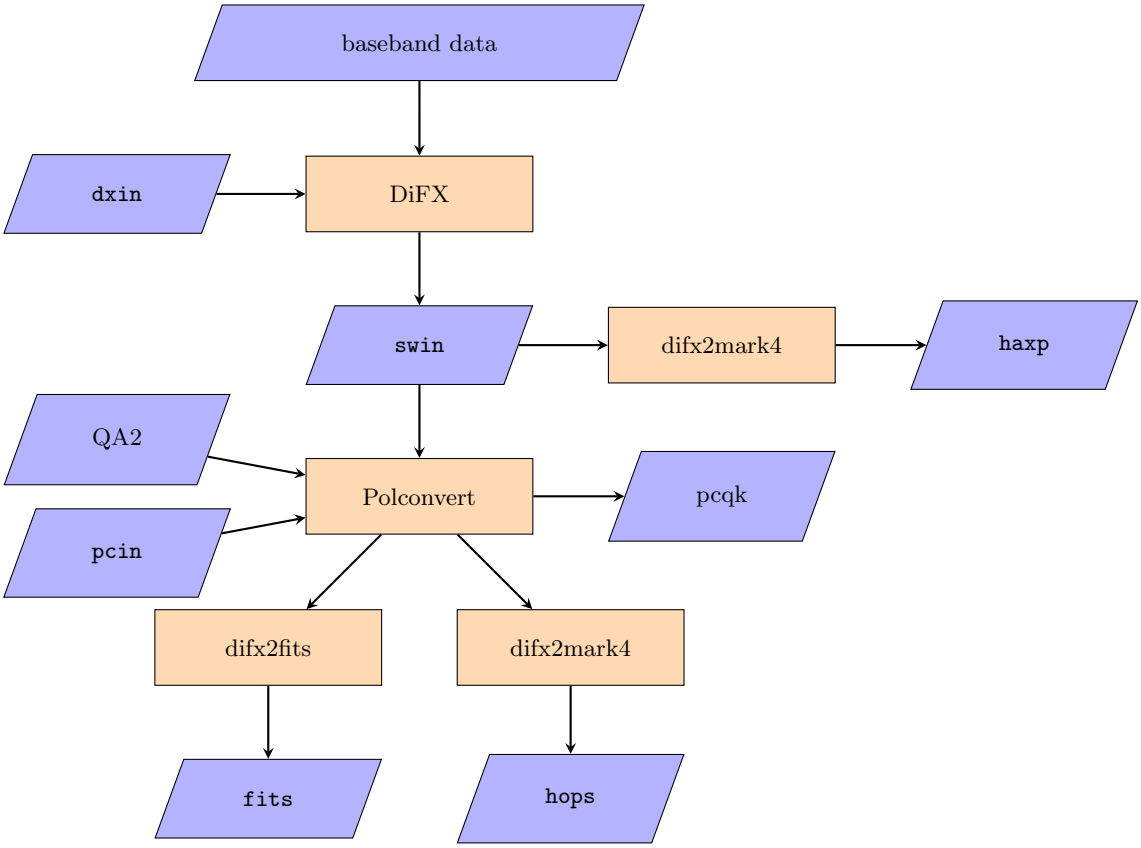
All telescopes of the EHT array, except for ALMA, observed circular polarizations. ALMA instead uses receivers that provide linear polarizations. This results in mixed pol correlation output. This mixed pol output is converted into a circular basis using `Polconvert` v1.7.9 (Martí-Vidal et al. 2016). 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`.

The 2021 EHT observations were the first to include NOEMA. Due to some issues in the signal processing pipeline of NOEMA's PolyFix correlator, phase jumps of a multiple of 90° may occur at the edge of each native 64 MHz channel[1]. These phase jumps can change every time the PolyFix backend gets reset, which may happen in the middle of an EHT observing track. Since ALMA uses native channels of 58 MHz, the edges of the NOEMA channels typically do not align with the edges of the ALMA channels. As the channelization of this data release is based on the ALMA channelization, this means the phase jumps will appear in the middle of a channel. These phase jumps will have to be accounted for in further processing of the EHT 2021 data products from this data delivery. More details, as well

[1] These channels are sometimes referred to as spectral windows or IFs depending on the data processing software used

Figure 1. Data processing flow



as a description of a calibration strategy for CASA and the rPICARD pipeline can be found in von Fellenberg et al. (2025).

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 two different pipelines. This includes fringe validation, checks on thermal error consistency and closure quantities. Details can be found in section 3.3 of Event Horizon Telescope Collaboration et al. (2024) and section 8 of Event Horizon Telescope Collaboration et al. (2019).

4.1. *Summary of major data issues*

The list below provides a summary of major data data quality issues during the EHT2021 observations for each track. In addition to these issues some stations missed a small number of individual scans.

- `e21b09`: ALMA and IRAM 30m did not observe. APEX observed with linear polarisation and wobbler enabled, which requires flagging.
- `e21e13`: NOEMA did not observe. APEX observed with wobbler enabled for part of the scan, which requires flagging.
- `e21a14`: No major issues.
- `e21d15`: High opacity at IRAM 30m with pointing issues in the 2nd half of the scan.

- `e21a16`: Only SPT, SMT, Kitt Peak, JCMT, and SMA observed.
- `e21a17`: No major issues.
- `e21e18`: SPT did not observe.
- `e21f19`: No NOEMA in sub-band b4.

The mount type for APEX is encoded incorrectly into the FITS files. Additional mirrors in the optical path mean that the effective mount type for this telescope is "Right" Nasmyth instead of "Left". It is important that the correct telescope mount type is used to apply the appropriate parallactic angle correction.

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