Toward Imaging 3000+ ICRF Sources From Closure Quantities From 1979–Present

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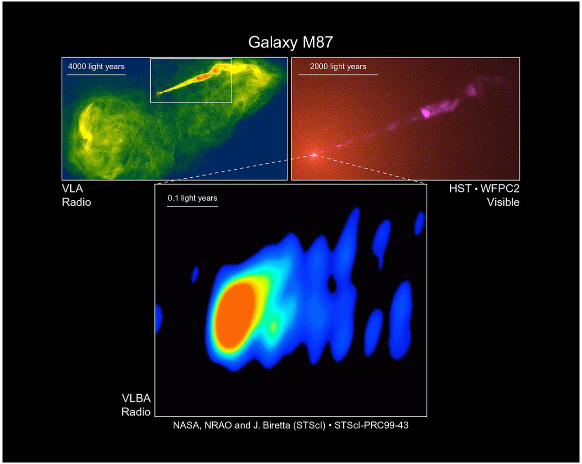
Outline

Introduction to ECORAS°2

Extension of the coordinate parameterization of radio sources observed by VLBI — second funding period (Heinkelmann & Schuh)

- 3 year project funded by the DFG Deutsche Forschungsgemeinschaft (German research foundation)
  - M. H. Xu arrived in Potsdam 2017 Dec officially started mid-2018
  - S. Lunz started 2018 Aug
  - J. M. Anderson started 2018 Oct
- Main Objectives
  - Determination of systematic deformations of the ICRF
  - Proper handling of frequency-dependent radio–radio and radio–optical (**Gaia**) ties, core shifts, and effects caused by source structure
  - Investigation of source structure effects on dispersive delays
- **This presentation provides a status update on ECORAS°2**

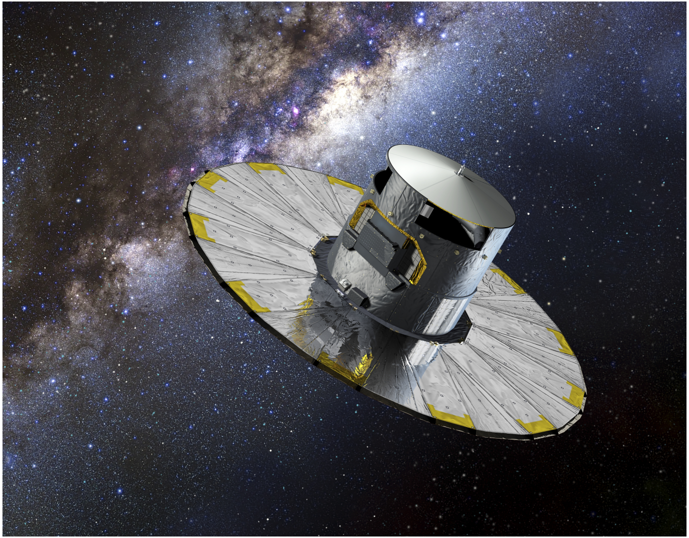
What Do We "See" at Radio Frequencies?



Credit: NASA (2006)

- Example of radio (and optical) emission from the AGN in the nearby galaxy M87
- Compact core region, plus an extended jet of emission, plus large radio lobes
- As an interferometric instrument, VLBI is only sensitive to emission on size scales sampled by the interferometer — long baselines only see compact structure near the core
  - But beware! Short baselines, such as those for co-located antennas, are sensitive to different, large scale, emission
- The jet structure near the core is finite in extent, both along and perpendicular to the jet direction

Gaia



- Will determine the position, parallax, and proper motion of $> 10^9$ objects with an accuracy of 20 µas at 15 mag and 200 µas at 20 mag
- Frame determination to a stability better than 1 µas yr^{-1}

What Does Gaia "See"?

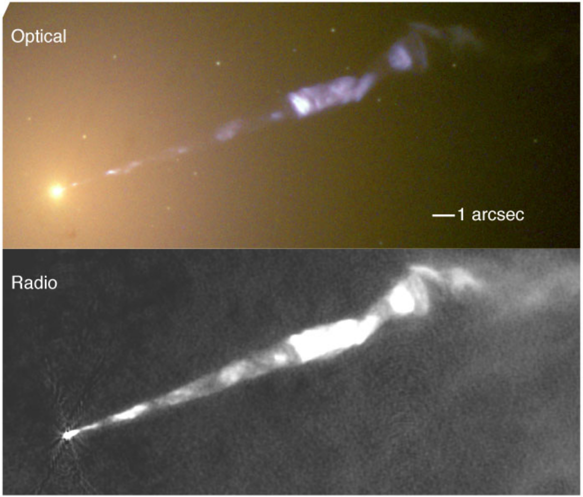
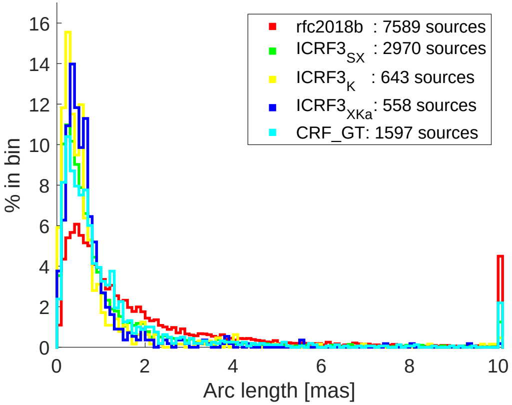


Fig 9.5 (J Biretta/HST) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

- Jets have emission at all frequencies, including radio, optical, and x-ray regions
- M87 (Virgo A) shown at left
- **Problem:**
  - Radio **interferometry** with Earth-diameter baselines resolves out large-scale features
  - As an imager, Gaia is sensitive to the **entire** optical structure of the object
  - This leads to position differences between geodetic VLBI and Gaia

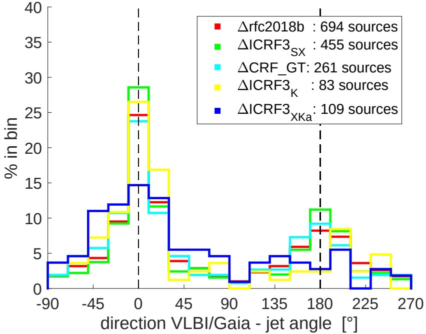
Significant Gaia–VLBI Position Offsets

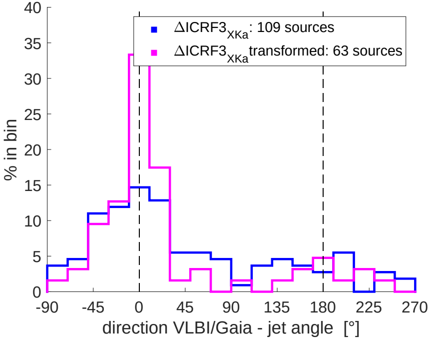


- Comparison of different radio catalog source positions to Gaia positions
    - rfc2018 refers to the Radio Fundamental Catalog version 2018b and CRF_GT is a GFZ catalog based on VLBI S/X observations made during the Gaia operations period
- Position offsets are much larger than allowed by the nominal catalog position uncertainties

For more information, see poster P310, S. Lunz et al., "Radio source position offsets among various radio frames and Gaia" this conference

Significant Gaia–VLBI Position Offsets Related to Source Structure





- Gaia offsets from VLBI positions are preferentially **along** the jet direction
- S/X has some Gaia positions upstream along the jet of the VLBI position
- X/Ka analysis consistent with no upstream offsets
- Source structure and frequency dependence must affect radio–Gaia and radio–radio (not shown) position offsets
- See poster P310, S. Lunz et al., this conference, Petrov et al. (2019), and references therein

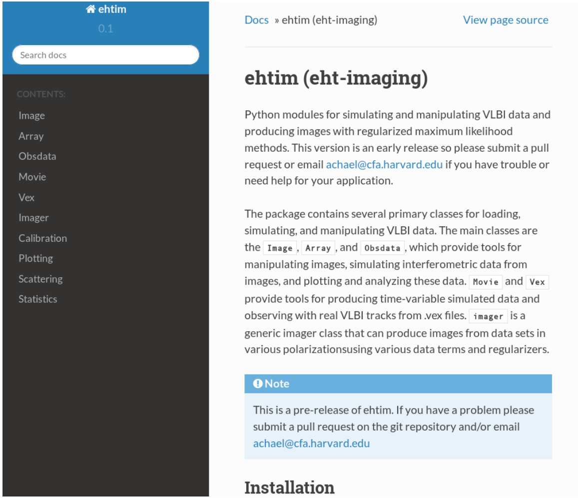
Goals for Source Structure Determination

- Develop an **automated** pipeline to determine source structure from geodetic measurements
  - **Determine source structure from the geodetic observations themselves in order to match the frequencies, baselines, and times observed by geodetic VLBI**
  - **Cover geodetic VLBI from 1979 onward**
  - Automatically update structure database as new session data are delivered by the correlators
- Provide structure information to correct measurements
  - For example, in the form of vgosDB-compatible corrections to multiband group delays
  - For the future, structure models to correct for source structure prior to fringe-fitting
- Apply source structure corrections to geodetic data to improve source positions and stability
  - Generally improve geodetic VLBI analysis results
  - Attempt to correct Gaia positions for source structure
  - Thereby improve the VLBI–Gaia and VLBI–VLBI frame ties

We Are Investigating Making Images From Geodetic Closure Data

- Visibility data are readily available (public FTP/HTTP) for only a few geodetic datasets
- **Visibility data may not exist at all (not archived) for the first many years of geodetic VLBI, so we must use the geodetic data**
- So we are forced to make images from non-visibility (that is, geodetic) datasets for a large fraction of geodetic sessions anyway
- Why do we attempt to make images from closures instead of phase and amplitude data? Because then we do not have to perform any calibration. We hope that this simplifies the development and operation of an automated imaging pipeline

Closure Imaging Software



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Python modules for simulating and manipulating VLBI data and producing images with regularized maximum likelihood methods. This version is an early release so please submit a pull request or email achael@cfa.harvard.edu if you have trouble or need help for your application.

The package contains several primary classes for loading, simulating, and manipulating VLBI data. The main classes are the `Image`, `Array`, and `Obsdata`, which provide tools for manipulating images, simulating interferometric data from images, and plotting and analyzing these data. `Movie` and `Vex` provide tools for producing time-variable simulated data and observing with real VLBI tracks from .vex files. `imager` is a generic imager class that can produce images from data sets in various polarizationsusing various data terms and regularizers.

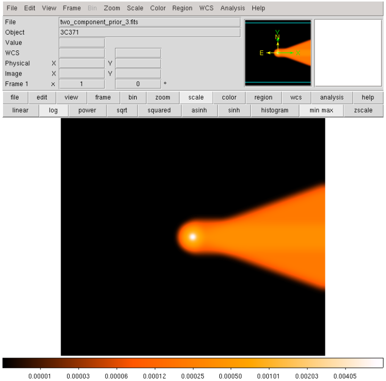
Note

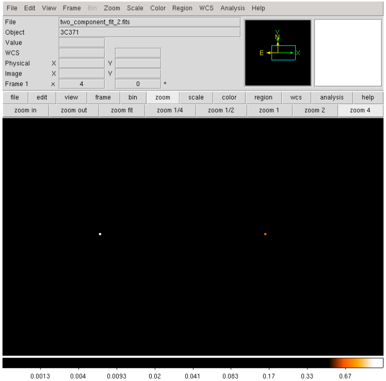
This is a pre-release of ehtim. If you have a problem please submit a pull request on the git repository and/or email achael@cfa.harvard.edu

Installation

- We are using the **ehtim** Python package for imaging closure data (Chael et al. 2016; Chael et al. 2018)
  - EHT: Event Horizon Telescope, (sub)mm-VLBI
- Many software modifications needed
  - Ability to read in data from geodetic datasets
  - Develop Bayesian priors that are reasonably jet-like
  - Develop Bayesian priors from our GFZ-internal structure models
  - Generalize code to work for non-EHT interferometers (for example, show spatial scales of mas instead of μas)

Simple Test Cases Work Fine



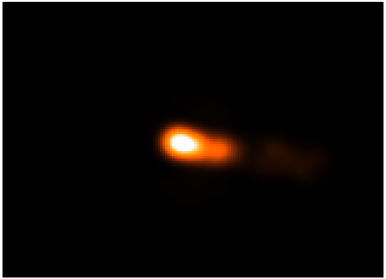


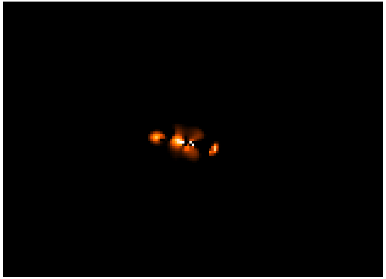
- Left: can form a reasonable prior for a jet with a position angle of −90°
- Right: can image a test dataset, in this case a two-component model with a bright core and a weaker jet component

Imaging Geodetic Data From Closures — Work in Progress

- We have made closure quantities from all publicly available IVS datasets starting from 1979 (see M. H. Xu et al., submitted to A. J. Suppl. Series)
- After our initial round of semi-automated and manual flagging, we have > 3000 sources with at least 100 closure phases and 100 closure amplitudes
- We are now working on developing our automated imaging pipeline to make time-resolved images

X-Band Imaging of 3C371 From Closure Phase and Closure Amplitude

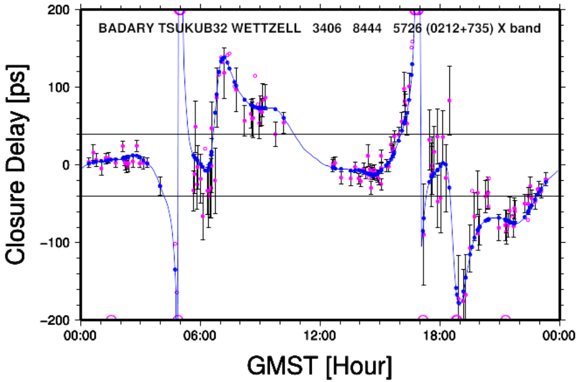




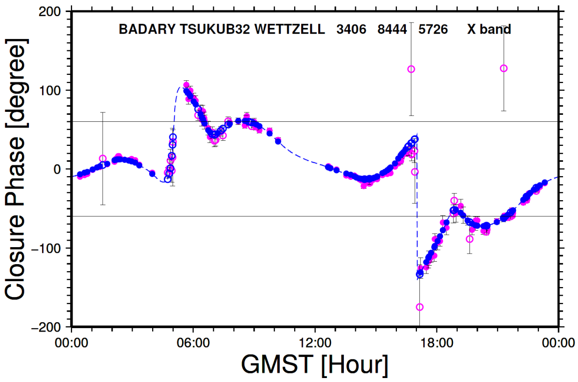
- 3C371 has significant, but relatively stable, structure
- We have good images of 3C371 from our visibility imaging of CONT14 (left)
- Perform closure imaging on geodetic closures from the same time period
- Initial closure imaging results are not very good
  - Position angle of $\sim -100^\circ$ correct
  - Structure does not look like what I expect

Geodetic Closure Errors

We Use Geodetic Closure Phases Instead of Closure Delays



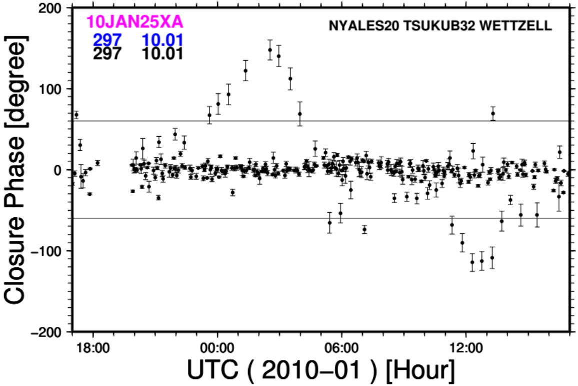
Credit: Anderson & Xu (2018)



Credit: Anderson & Xu (2018)

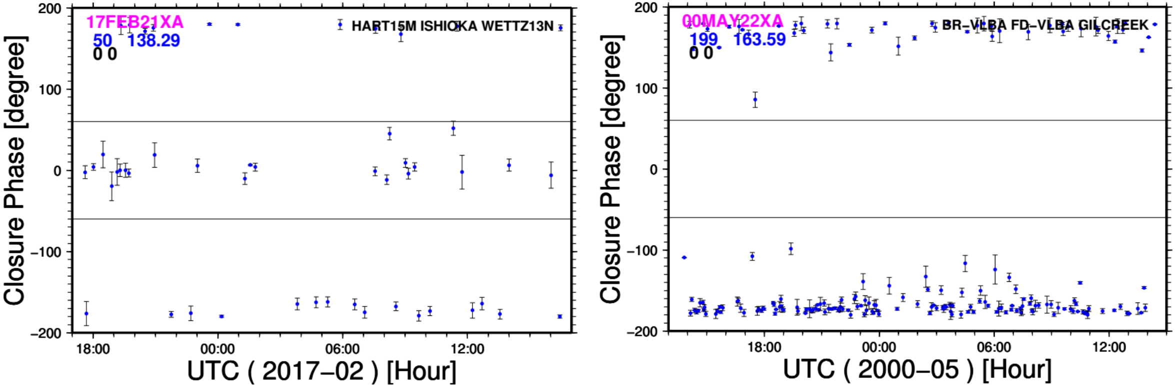
- Phase should be more precise than delay (example above from CONT14)
- ehtim does not yet support closure delays or closure rates (on my TODO list)

How **Should** Geodetic Closure Phases Behave?

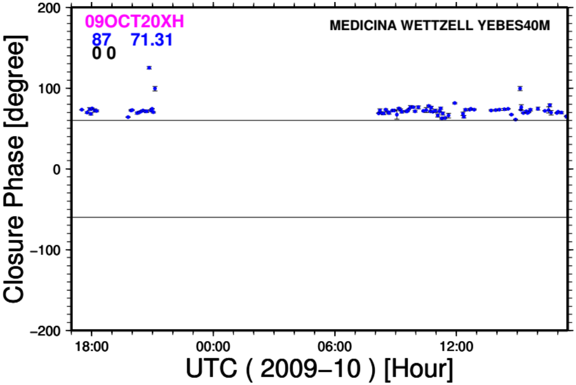


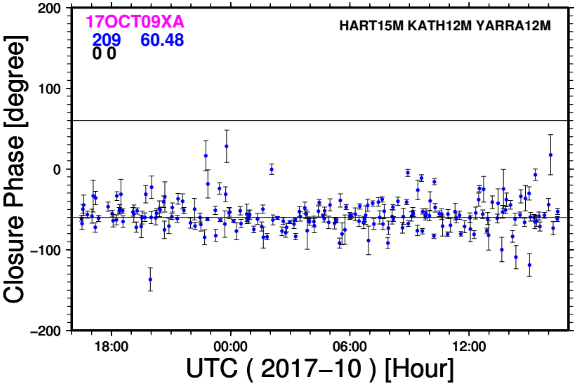
- Closure phase for **all** sources for **one** triangle for **one** session
- Most measurements should be near zero (compact sources) with a modest amount of scatter
- A few measurements from sources with significant structure deviate from zero

Geodetic Closure Phase Errors: 180° Phase Offsets

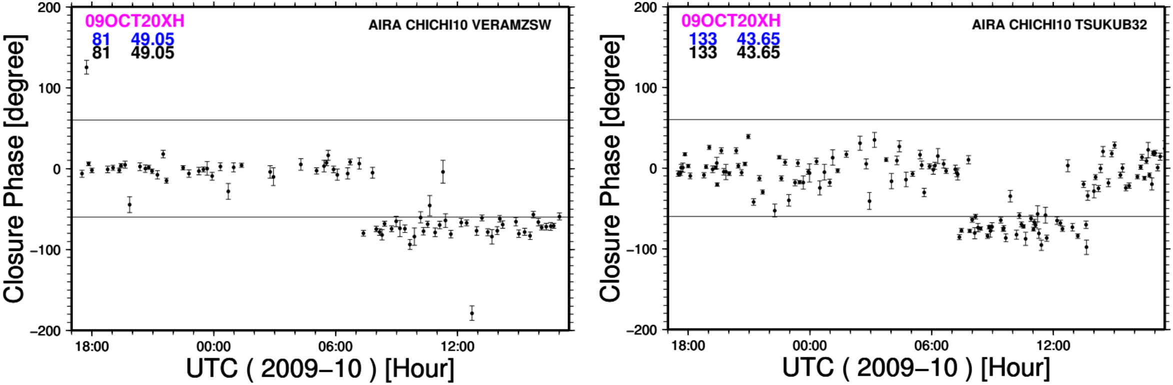


Geodetic Closure Phase Errors: Other Phase Offsets

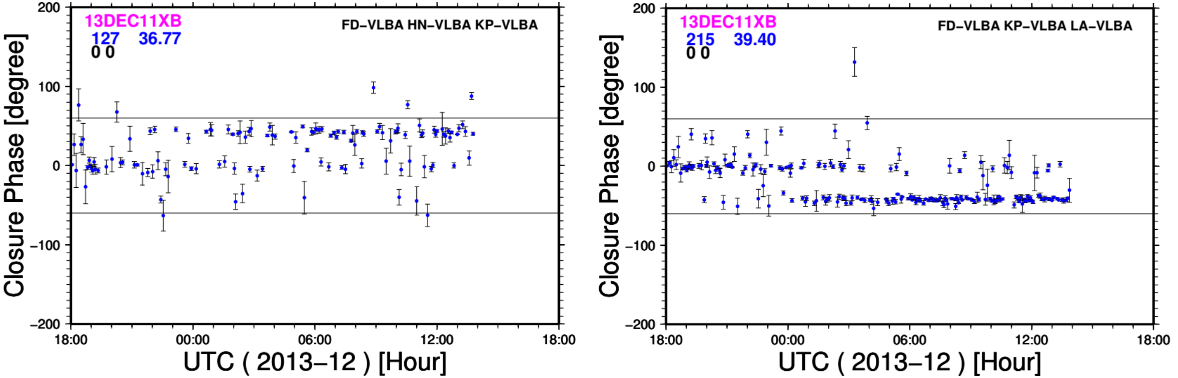




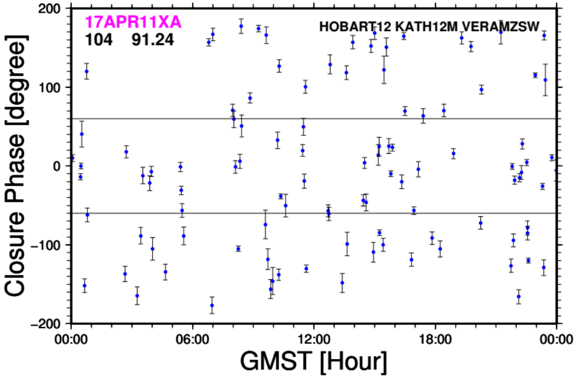
Geodetic Closure Phase Errors: UTC-Dependent Phase Offsets

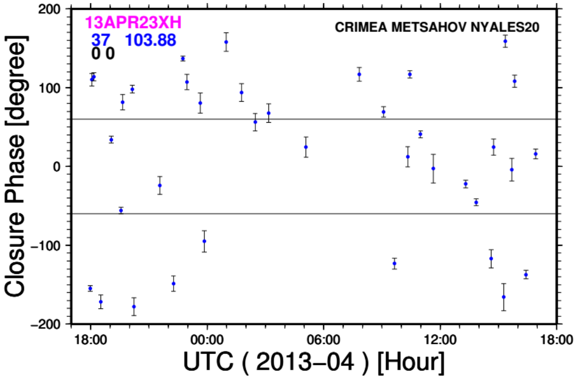


Geodetic Closure Phase Errors: UTC-Overlapping Phase Offsets



Geodetic Closure Phase Errors: Random Phase Offsets



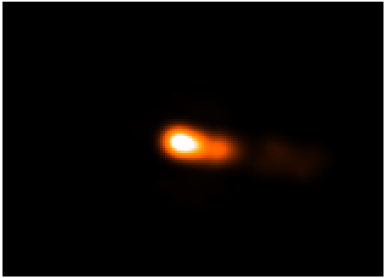


Geodetic Closure Phase Errors

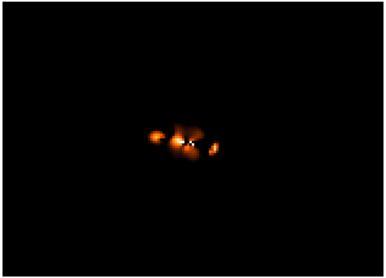
- Labor intensive to find and flag bad closure data sessions — bad for automated imaging
- Spot checks examining (FITS) visibility data obtained from the Bonn correlator **do not show these problems**
  - Therefore, the problem must arise in the geodetic fringe-fitting software or the software that generated the geodetic databases from the fringe-fitting results

More X-Band Imaging of 3C371

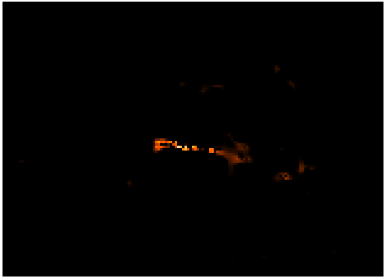
Visibility



Closure Phase & Amp



Closure Amplitude Only



Better than amplitude and phase data together, but also more noise in surrounding area

Summary

- Our development of an automated imaging pipeline based on geodetic closure data is underway
  - Additional data flagging should bring significant improvements over the next months of development work
- There are severe errors in the phases in geodetic datasets
- Visibility-based imaging still yields the best quality results at this point
  - We would like to encourage the IVS community to make the visibility data more readily available for analysis
  - FITS, DiFX, MarkIV, MeasurementSet, and other visibility data formats could all be accommodated

The End

Thank you for your attention

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NASA (2006). (2006). Credit: NASA, National Radio Astronomy Observatory/National Science Foundation, John Biretta (STScI/JHU), and Associated Universities, Inc., url: https://en.wikipedia.org/wiki/File:Close-Up_Look_at_a_Jet_Near_a_Black_Hole.jpg (visited on 09/25/2018)

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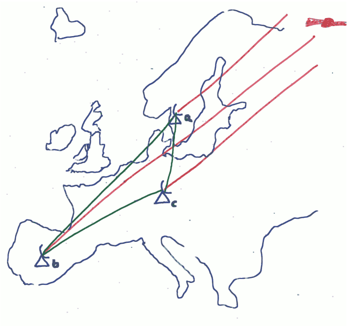
What Is a Closure Triangle



- Take 3 stations, a, b, and c, that are observing the same sourc simultaneously
- Form the closure abc by going around the triangle of baselines, $ab + bc + ca$
- The closure delay is $\tau_{\text{grp},abc} \equiv \tau_{\text{grp},ab} + \tau_{\text{grp},bc} + \tau_{\text{grp},ca}$
- The measured delay on baseline ab is $\tau_{\text{grp},ab}^{\text{measured}} = \tau_{\text{grp},ab}^{\text{reference-point}} + \tau_{\text{grp},ab}^{\text{structure}} + \epsilon_{\tau_{\text{grp},ab}}^{\text{measured}}$
- Going around the triangle, the source reference point delays cancel exactly (the delay to each station from the reference poin appears once positively and once negatively), so we have $\tau_{\text{grp},abc} = \left(\tau_{\text{grp},ab}^{\text{structure}} + \tau_{\text{grp},bc}^{\text{structure}} + \tau_{\text{grp},ca}^{\text{structure}}\right) + \left(\epsilon_{\tau_{\text{grp},ab}}^{\text{measured}} + \epsilon_{\tau_{\text{grp},bc}}^{\text{measured}} + \epsilon_{\tau_{\text{grp},ca}}^{\text{measured}}\right)$

Closures Are Fantastic for Studying VLBI Source Structure

Image credit: Max-Planck-Institut für RadioAstronomie (2017)

- Closures eliminate most things geodecists normally deal with:
  - Tropospheric delay error
  - Ionospheric delay error
  - Station position error
  - Earth orientation parameter error
  - Station clock error
  - Station cable length error
  - Station gain (phase, amplitude, delay) errors
  - Station thermal expansion
  - Relativistic delay model errors
  - Source reference point errors
  - ...

The only things that remain in closure quantities are (relative) **source structure**, **measurement noise**, and **non-closing errors** (such as bandpass mismatch and polarization leakage that, lo and behold, are also source-structure dependent!)