Fringe-Fitting:

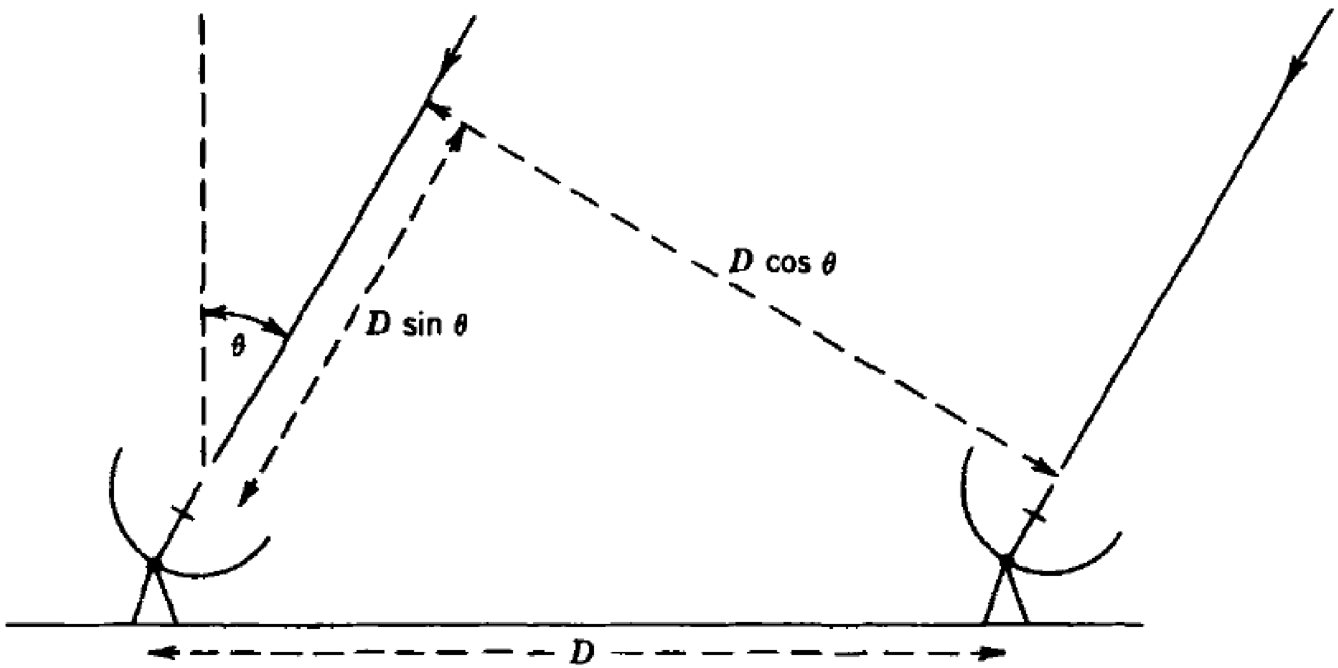
Correcting for delays and rates

Summary

- Radio signals detected by an interferometer are affected by a delay
- Wavefront of signal will arrive at each antenna at a different time (i.e. different delays)
- Correlator corrects for the changes in the delays, but the model will have errors
- Due to the large distances, this error changes significantly with time and frequency
- Corrected using the Fringe-Fitting technique

Introduction

Let us start with a simple 2 element radio interferometer



- Wavefronts of a signal from a distant source, arrives at one antenna with a geometrical delay, τ_{obs} = D/c sinθ
- $\Phi = 2\pi\nu\tau_{obs}$ (interferometer phase)
- τ_{obs} changes with time → fringe rates

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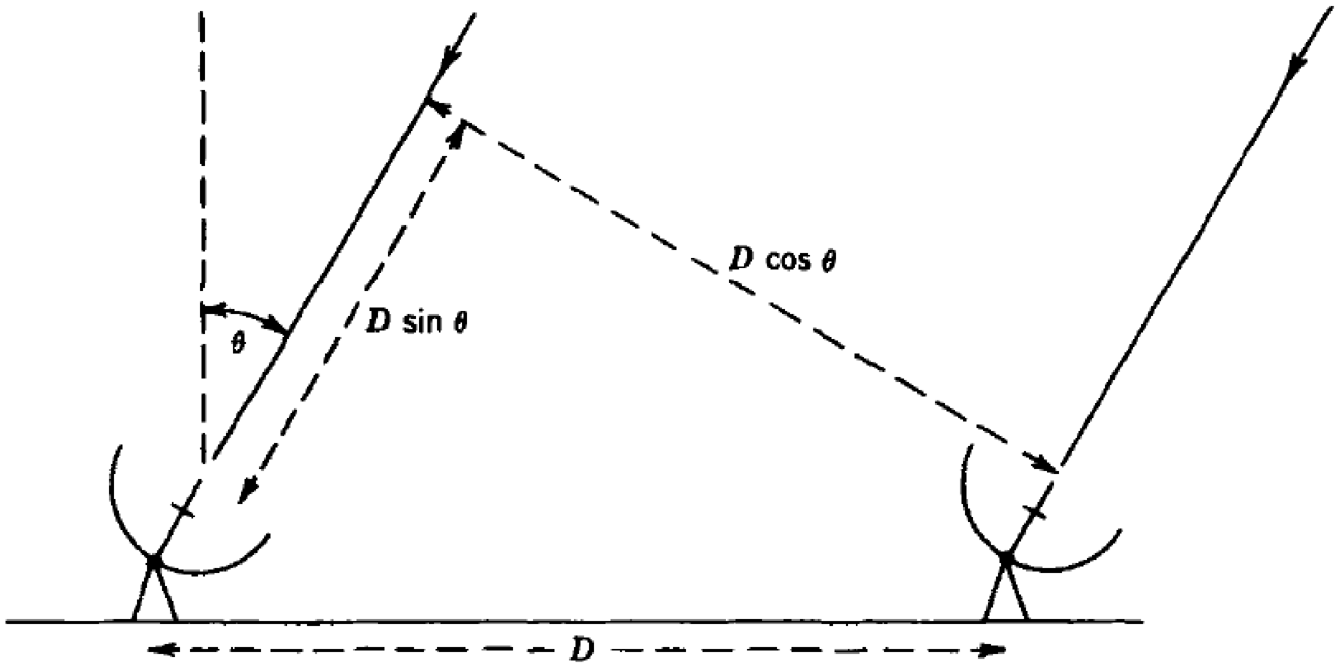
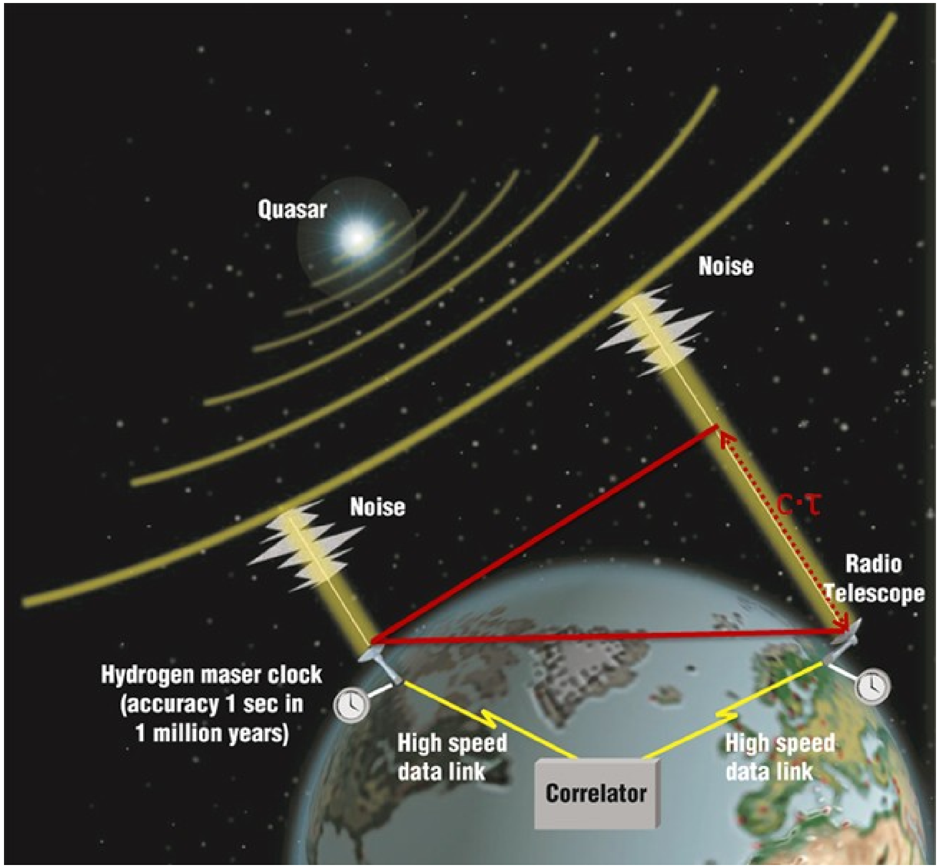


- Signals from both antennas are combined in a correlator
- Correlator estimates and corrects for τ_{obs}
- For connected arrays e.g. JVLA, ATCA, KAT-7 this simple geometrical delay is sufficient ... not so for VLBI

VLBI vs shorter-BI

- Just interferometry
- Longer baselines (100's to 1000's km)
  - → very high resolution
  - → sensitive to compact sources with high surface brightness
  - → increased time and bandwidth smearing
  - → less data averaging and larger data size for same FOV



- Independent clocks and equipment → phase/delay errors
- The delay and rate of the wavefronts are affected by different effects
- Must be estimated and removed during correlation

VLBI Geometric Model

Table 22–1. Terms of a VLBI Geometric Model [a]

Item	Approx max Magnitude [b]	Time scale
Zero order geometry.	6000 km	1 day
Nutation	$\sim 20''$	< 18.6 yr
Precession	~ 0.5 arcmin/yr	years
Annual aberration	$20''$	1 year
Retarded baseline	20 m	1 day
Gravitational delay	4 mas @ 90° from sun	1 year
Tectonic motion	10 cm/yr	years
Solid Earth Tide	50 cm	12 hr
Pole Tide	2 cm	$\sim$1 yr
Ocean Loading	2 cm	12 hr
Atmospheric Loading	2 cm	weeks
Post-glacial Rebound	several mm/yr	years
Polar motion	$0.5''$	~ 1.2 years
UT1 (Earth rotation)	Random at several mas	Various
Ionosphere	~ 2 m at 2 GHz	seconds to years
Dry Troposphere	2.3 m at zenith	hours to days
Wet Troposphere	$0 - 30$ cm at zenith	seconds to seasonal
Antenna structure	<10 m. 1cm thermal	—
Parallactic angle	0.5 turn	hours
Station clocks	few microsec	hours
Source structure	5 cm	years

[a] Adapted from Sovers, Fanselow, & Jacobs 1998

[b] For an 8000 km baseline, 1 mas $\leftrightarrow$ 3.9 cm. $\leftrightarrow$ 130ps

- Terms that affect the delay delay > few cm
- Most radio astronomers don't have to worry about these effects
- The most dominant would be the atmosphere
- if not corrected for will introduce large pase errors and decorrelate the signals

Did you know?: by observing very distant bright compact Quasars, VLBI can monitor the changes due to many of these effects … including the motion of the tectonic plates!

Table from Walker 1999, Ch. 22, the White Book

Residual Delay & Rate Errors

- Correlator model isn't perfect
  - Residual phase, delay and rate errors
  - Mainly from atmospheric fluctuations, clock errors
- Recall the interferometer phase → $\Phi = 2\pi\nu\tau_{obs}$
  - $\tau_{obs} = \tau_g + \tau_{str} + \tau_{trop} + \tau_{iono} + \tau_{instr} + \ldots + \varepsilon_{noise}$
  - Phase error will depend on the delay error
- Linear phase model (first order expansion):

$$\Delta\phi(t,\nu) = \boxed{\phi_0} + \left(\boxed{\frac{\delta\phi}{\delta\nu}\Delta\nu} + \boxed{\frac{\delta\phi}{\delta t}\Delta t}\right)$$

Phase error at reference time and freq + delay + delay rate

Some cases (e.g. space VLBI, mm-VLBI ??) may require higher orders

Errors are corrected by Fringe-Fitting

Fringe-Fitting

- Sources of delay and rate errors can be separated into contributions from each antenna
- Baseline depndent errors → difference of antenna dependent errors
- Phase errors for baseline i,j

$$\Delta\phi_{ij} = \phi_{i0} - \phi_{j0} + \left(\left[\frac{\partial \phi_i}{\partial \nu} - \frac{\partial \phi_j}{\partial \nu} \right] \Delta\nu + \left[\frac{\partial \phi_i}{\partial t} - \frac{\partial \phi_j}{\partial t} \right] \Delta t \right) .$$

- Fringe-fitting involves solving the above equation, to obtain the errors
- Via observations of a bright calibrator → phase referencing
- Assumes source is a point source at the phase centre
- Can be done per baseline or global (i.e. combine all baselines)
- Without, cannot average in phase and time
  - Worse for weaker targets

Baseline Fringe-Fitting

- Baseline fringe-fit:
  - FT to the delay-rate domain (data is in t-ν domain)
  - FT each baseline independently
  - Peak in delay-rate domain, gives the error for that baseline
  - Must detect the source on all baselines
  - Does not maintain antenna based or closure relationships
  - Not useful for weaker sources

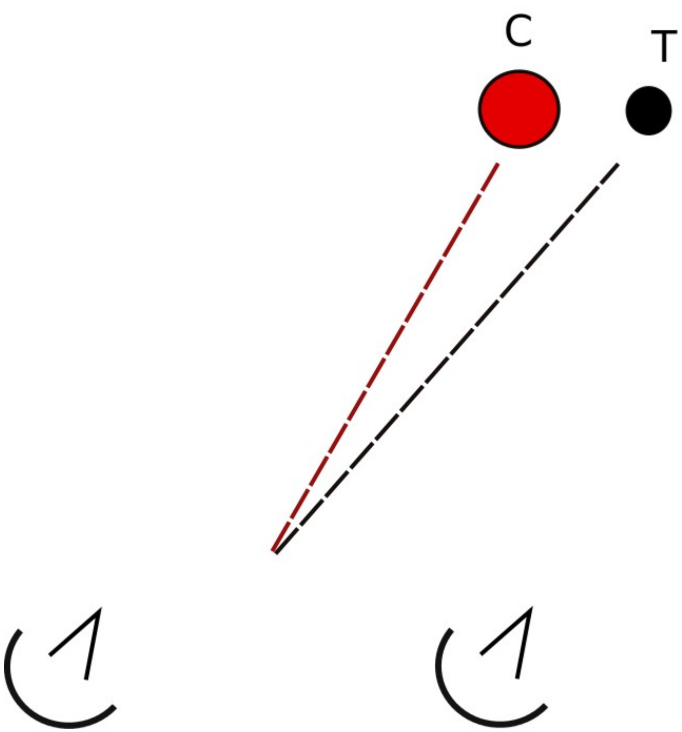
Global Fringe-Fitting

- Use all baselines to jointly estimate the antenna phase, delay and rate relative to a reference antenna
- Solves the baseline phase error equation, with one of the antennas set to the reference antenna
- Delay, rate and phase residuals for reference antenna are set to zero
- Hence only measures difference, not absolute errors
- Assumes calibrator is a bright point source at phase center
- Similar to self-calibration as source structure is part of the model
- Implemented in AIPS

Global Fringe-Fitting

- Random atmospheric phase fluctuations
  - Different for each antenna
  - Baseline phase error equation only adequate for a limited time → coherence time
- Solution interval:
  - > coherence time: increases sensitivity, but decreases number of possible solutions and increases phase ambiguities
  - < coherence time: decreases sensitivity, increases number possible of solutions, decreases phase ambiguities
  - ideal: long enough to have high SNR, but short enough to decrease phase ambiguities
- Good starting: set solutions interval to have one solution per phase reference cycle

Phase Referencing

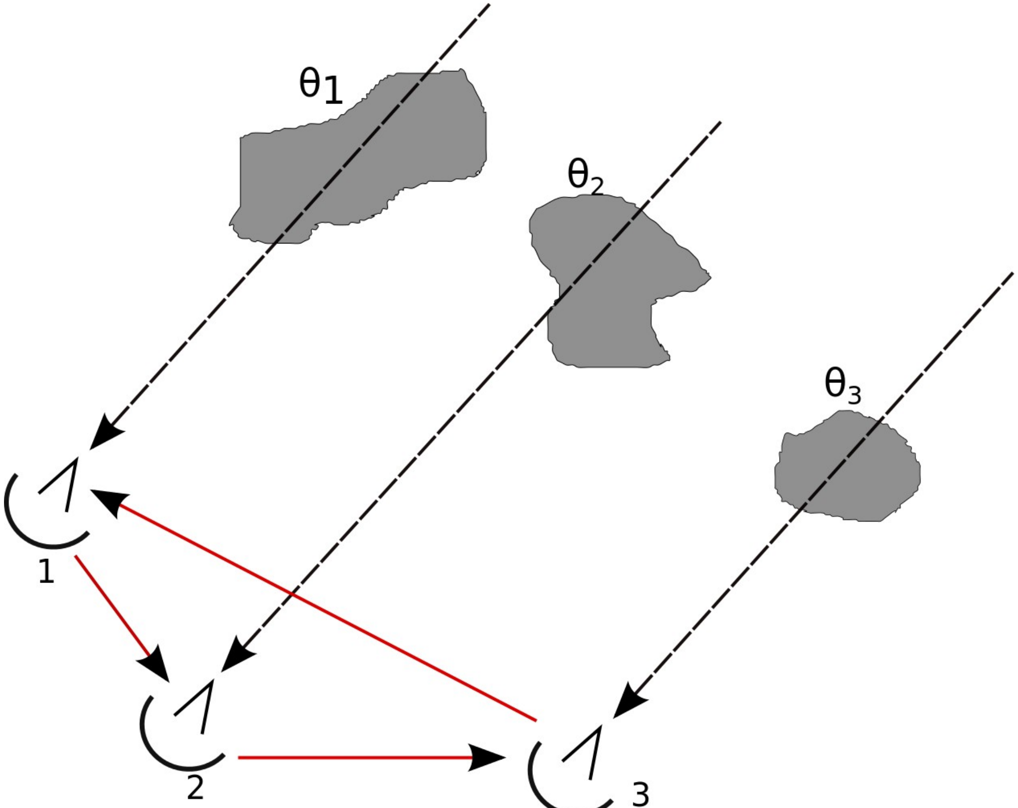


- Fringe-fitting requires observations of a bright, compact source → the phase-calibrator, C.
- Nodding between C and target (T)
- Cycle time must be shorter than the atmospheric fluctuations

  ~10 mins at 5 GHz; ~5 mins at 1.6 GHz
- C must be close to T (< 1 deg)
- Antenna positions must be known to within a few cm!
- Obtain solutions of the phase, rate and delay by applying the Fringe-fitting technique to C and interpolate to T
- Biggest problems

  - wet troposhere & fewer calibrators at high freq
  - Ionosphere at low freq

Closure Phase



Original ref: Rogers et al 1974, ApJ, 193, 293

Phase contributions from each baseline =
true phase + (difference between the random atm phases)

12-> $\Phi_{12} = \phi_{12} + \theta_1 - \theta_2$

23-> $\Phi_{23} = \phi_{23} + \theta_2 - \theta_3$

31-> $\Phi_{31} = \phi_{31} + \theta_3 - \theta_1$

Summing the total phases from each baseline, the phases from the atm cancels:

$$\phi_c = \Phi_{12} + \Phi_{23} \Phi_{31} + noise$$

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- All antennas have different random phase fluctuations due to atmosphere
- Closure phase, φ_c is the sum of simultaneously observed phases of a source on three baselines forming a triangle
- $\varphi_c = \varphi_{12} + \varphi_{23} + \varphi_{31}$ + noise
- Independent of station based phase errors
- phase errors due to different atmospheric variations are cancelled in the closed loop
- Fringe-fitting (and self-cal) uses this triangle to solve for the residual phases, rates and delay

Fringe-Fitting in practice

- Currently, fringe-fitting is implemented in the Astronomy Imaging Package (AIPS) via the task FRING
- AIPS was the standard radio reduction and imaging software
- Mostly used by VLBI astronomers (because of fringe-fitting) and people stuck in their old ways (like me!)

Typical AIPS User

- FRING is currently being written (or copied) for CASA (the new software)
- Until then you will need to use AIPS ...

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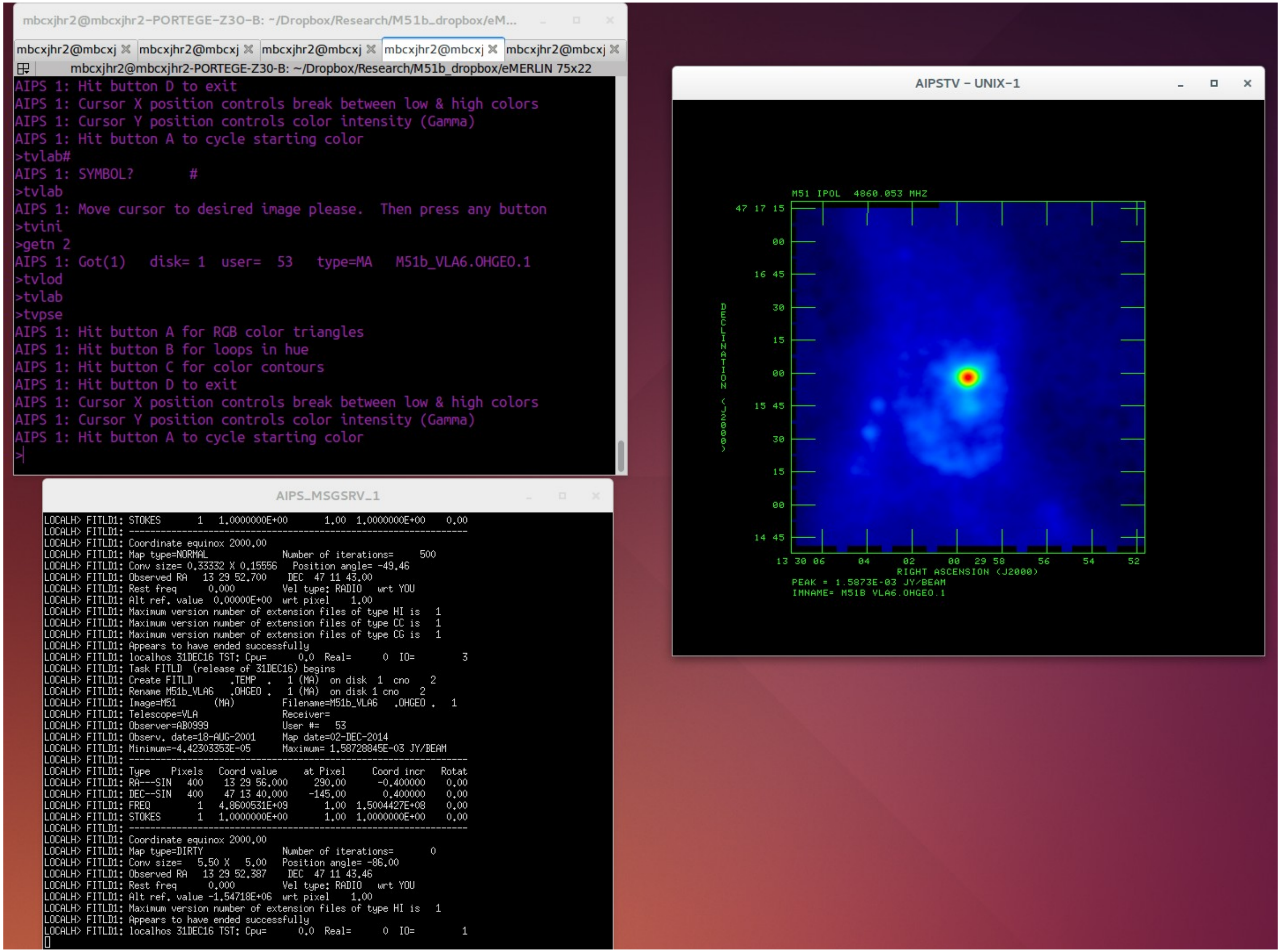
AIPS

- AIPS is written by the NRAO (US)
- ver 1 → 1978 in fortran (the user inteface hasn't changed in 38 years!)
- Composed of Tasks that are called in the terminal
- The user input values (or string commands) to keywords called parameters

User input terminal

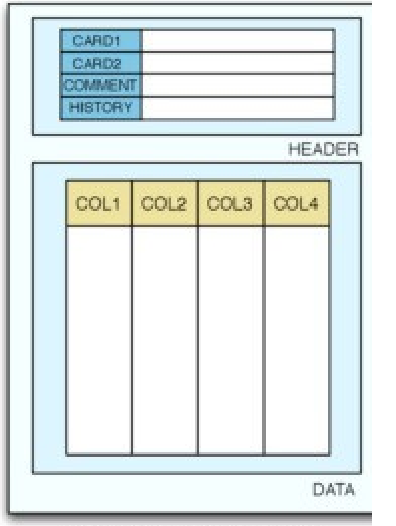
Image / plot viewer



Message window

UVFITS

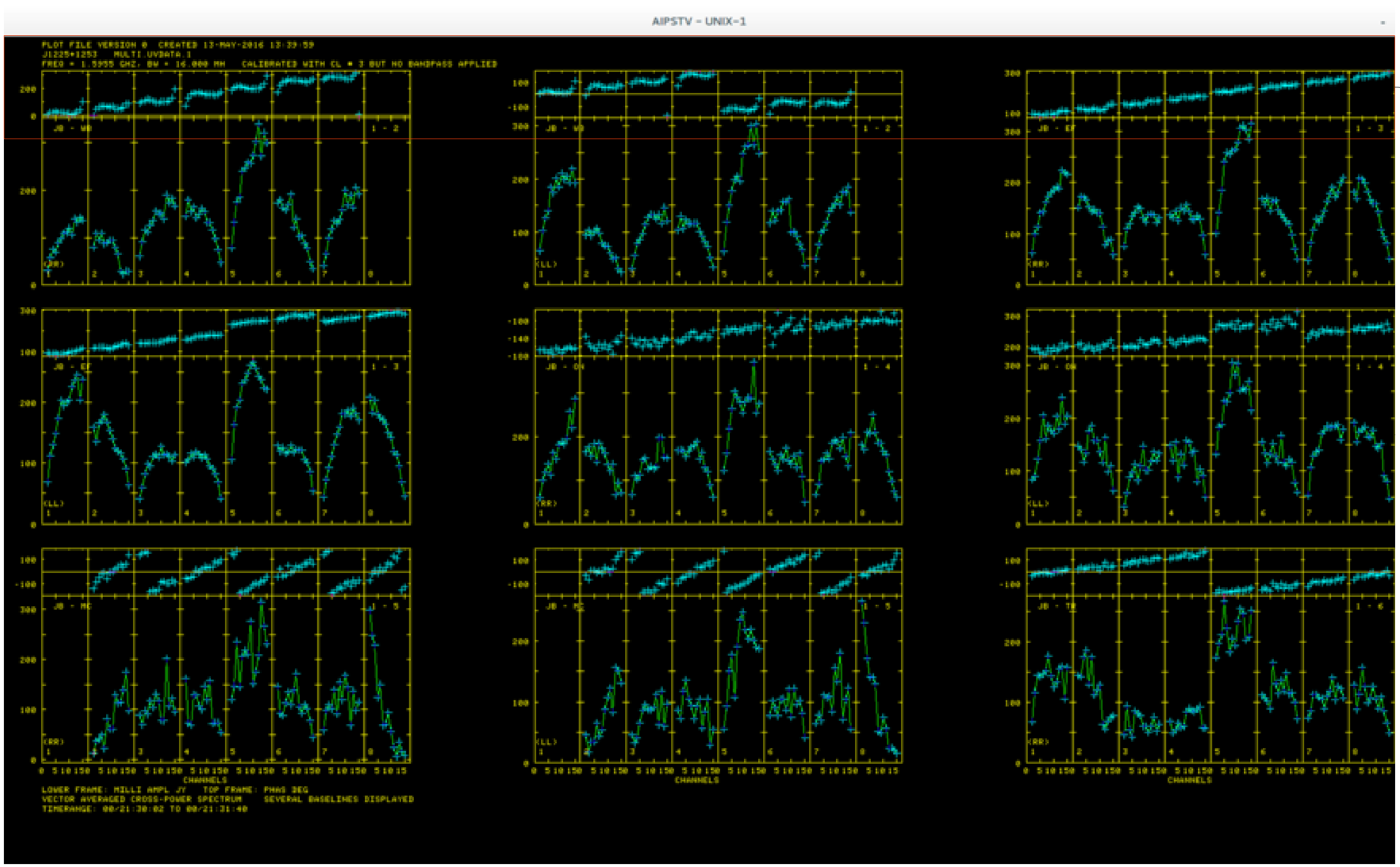
- UVFITS - AIPS input data format
- Composed of header tables and data columns
- Each table has records of specifc information (e.g.):
  - FQ: Frequency info; SU: Source position observed; AN: antenna info
- AIPS do not edit the data, but create tables that is appended (e.g.):
  - FG table: Flag tables (records of bad data to delete)
  - SN table: Calibration solutions obtained from calibrators
  - CL table: Calibration solutions applied to the targets
  - BP: instrument bandpass
- The information provided by these tables are only applied at the end of the calibration process via the task 'SPLIT'



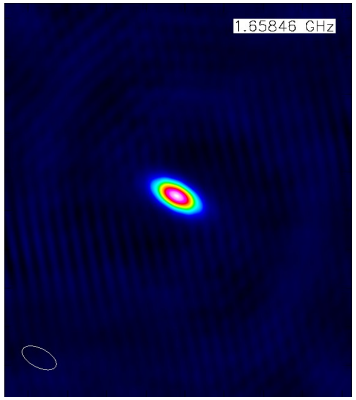
FITS HDU: HEADER DATA UNIT

Fringe-Fitting in practice

- Fringe-fitting will be done after amplitude calibration and correcting for instrumental delays (due to different path lengths of the various IFs)
- eg: 10 ant EVN @ 1.6GHz. Obs with 8 x 16 x 1MHz channels



- Phase vs frequecy on baselines to JB (the Lovell telescope)
- unresolved source: J1332+4722
- before Fring-fitting phase variations



- J1332+4722

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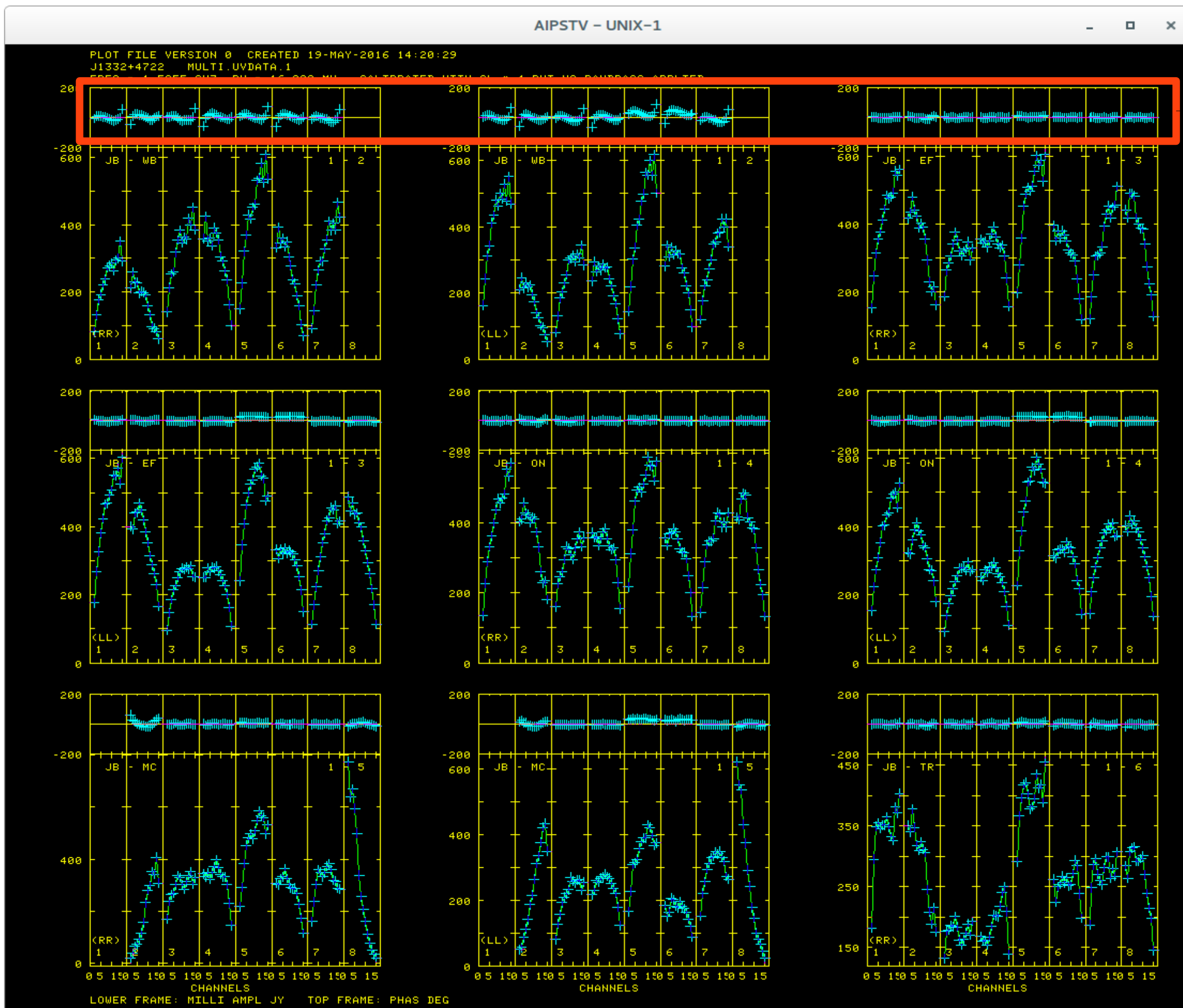

- Phase vs frequency post fringe-fitting
  - Phases zero +/1 noise for point source at phase centre
- Performed on each calibrator and applied to targets
- Reference antenna: Effelsberg (100m)
- Solutions interval = to one calibrator scan
- Note: this is Global Fringe-Fitting

Summary

- VLBI observations, due to an imperfect delay model will introduce residual phase, delay and rate errors
- These errors, changes with time and frequency and must be removed before imaging
- Discussed the fringe-fitting technique and explained phase referencing
- Quickly explained the practical application in AIPS


That's all Folks!