Line-VLBI Observations

Ciriaco Goddi
BlackHoleCam Project Scientist

Institute for Mathematics, Astrophysics and Particle Physics (IMAPP) ,
Radboud University, Nijmegen, Netherlands
Allegro, ALMA ARC node, Leiden Observatory, Netherlands

Radboud Universiteit Nijmegen

BLACK HOLE CAM

erc

ALMA
EUROPEAN ARC
ALMA Regional Centre || Allegro

Why do spectral line VLBI at mm waves?

- Science driven: science depends on frequency! (spectroscopy)

- Gives you a 3rd axis

…..Which implies lots of extra information:

- velocity information (kinematics and dynamics)
- Column density (amount of gas)
- Excitation conditions (temperature and density)
- Chemical history (gas composition)
- And magnetic fields, distances, etc.

What kind of mm spectral lines for VLBI?

- Emission: non-thermal, i.e. ***masers*** :
  - H_2O, SiO, CH_3OH,.....(*Humphreys et al. 2007*)
  - Galactic star-forming regions and evolved stars, AGNs

- Absorption against continuum :
  - HCO^+, HCN, HC_3N, ... (*Muller et al. 2011*)
  - Cosmological sources/ high-redshift galaxies

Preparing Line Observations

- **Doppler/Redshift**: Know the velocity/redshift of your target and set the observing frequency
  - *For high-redshift sources, is the line within the available receivers' bands?*
  - *For galactic sources, is the line frequency well centred in your narrow-band?*
- **Spectral resolution**: enough to sample and fully cover the line (+ line-free channels for cont.)
  - maser lines can be very narrow, 0.5 km/s: this requires Dv~0.1 km/s or **80 KHz** at 230 GHz
  - absorption features can be very broad, 300 km/s: this requires **BW>200 MHz** at 230 GHz
- **Sensitivity**: ask for enough time to reach the required sensitivity on target ***per spectral channel***(*NOT* per entire bandwidth)
- **Scheduling** your line experiment:
  - include scans on continuum calibrators (fringe-finders, bandpass, phase-reference)
  - 2 passes of correlation:

    continuum ("broad-band") for *calibrators and* **line** ("narrow-band") for *target*

Line Data Calibration

- Spectral line observations use several channels over a total BW

  => *much like continuum but with more channels!*

- *Absorption* line data is processed like cont. except ignoring line channels

- For *emission* lines (masers) a few additional elements must be considered

  a. Presence of RFI. *More important*

  b. Fringe-fitting. *Different techniques*

  c. Bandpass calibration. *More important*

  d. Doppler corrections. *Unique to line*

  e. Continuum subtraction. *Unique to line*

  f. Self-calibration . *Different techniques*

  g. Imaging of a data *Cube*. *Unique to line*

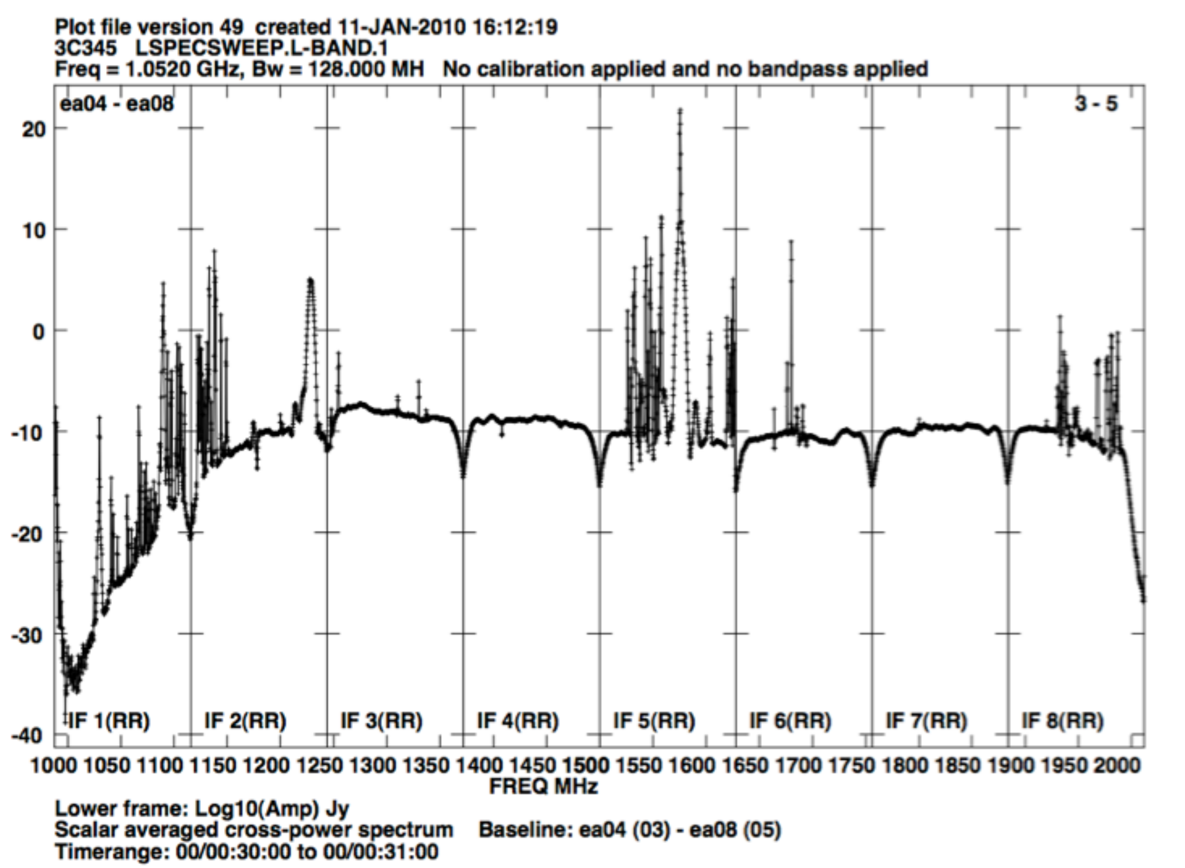
Line Data Calibration

a) Editing spectral line data

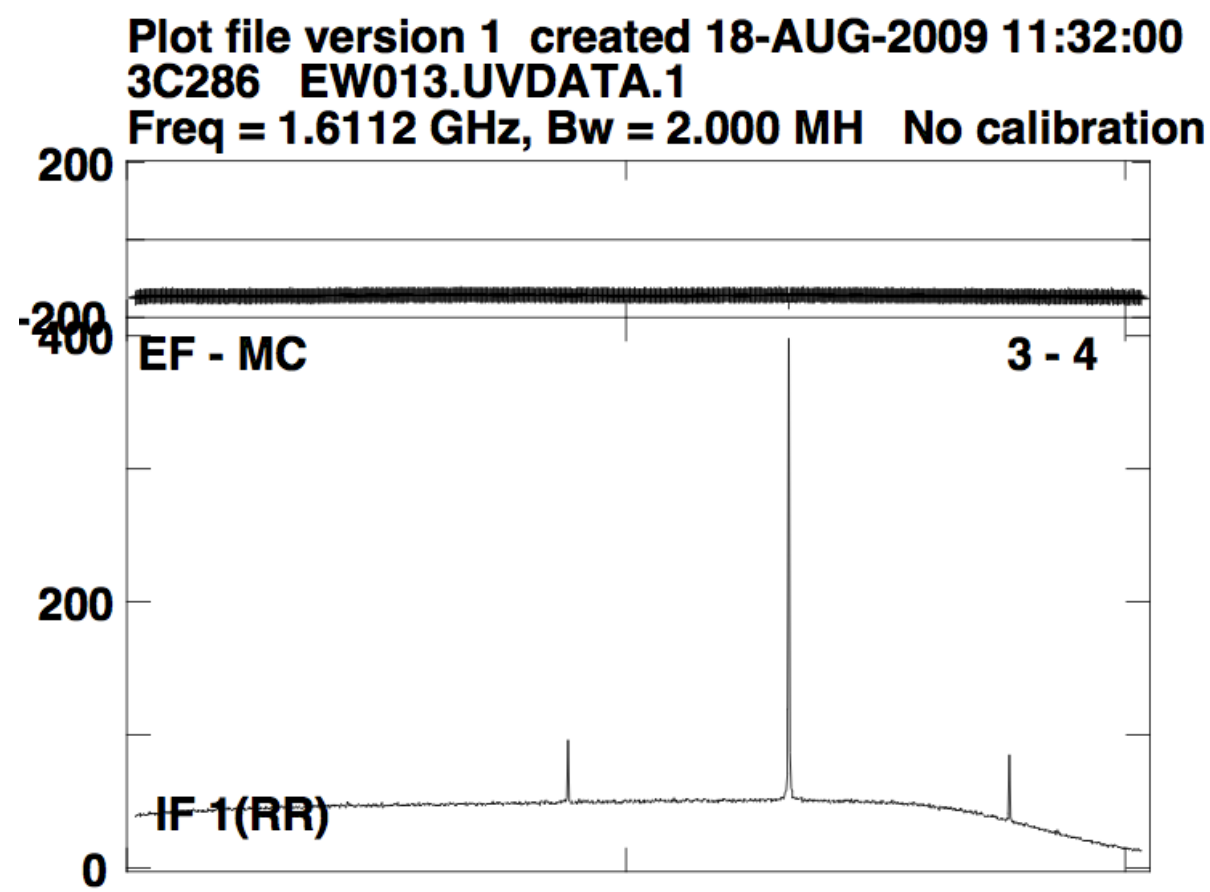
(as a function of ν)

Produce scalar-averaged cross-power spectra of calibrators (i.e. _continuum_ sources) to spot narrowband RFI.

RFI at the JVLA L-Band



RFI at the EVN L-Band

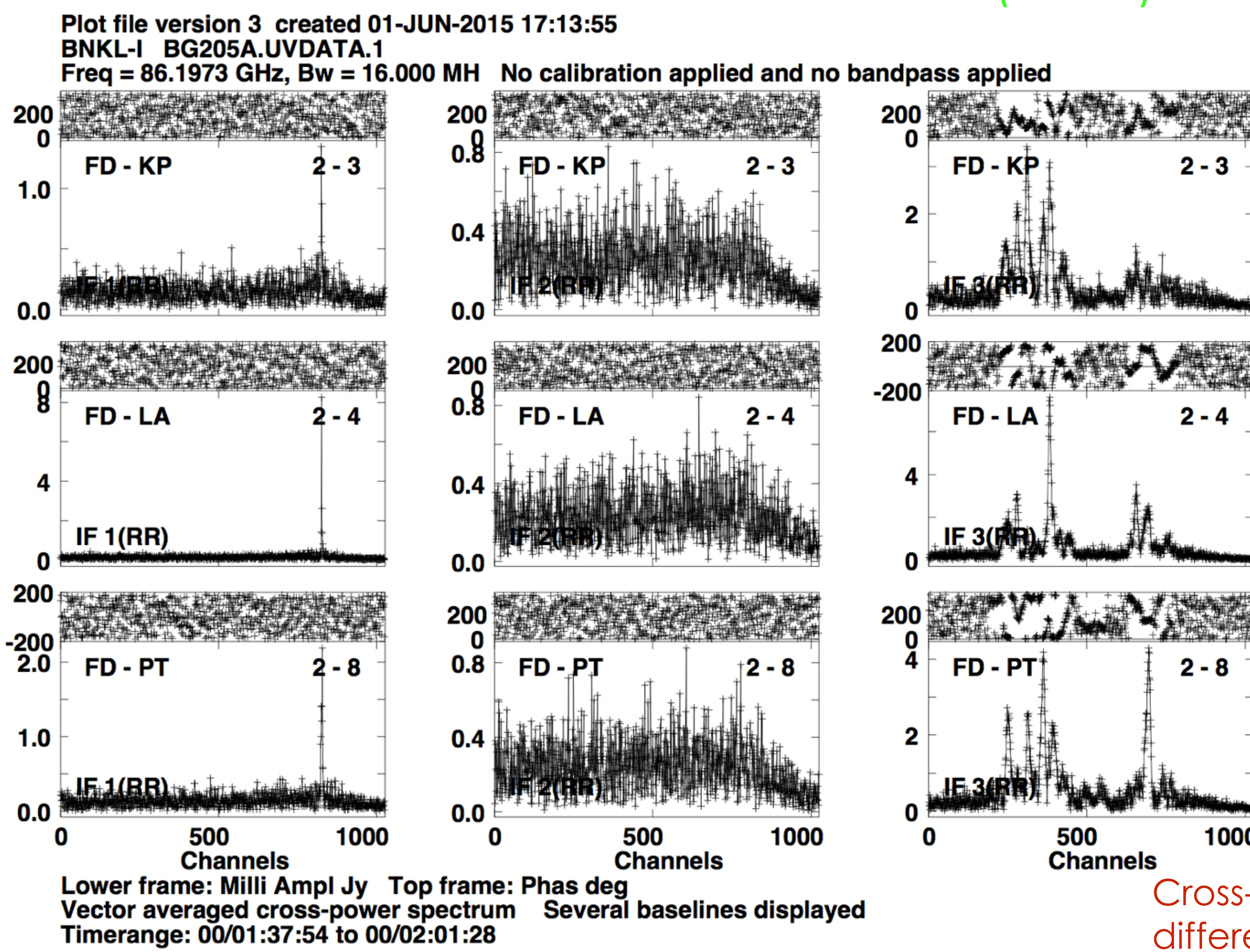


Flagging RFI: Primarily a low frequency problem

Line Data Calibration

a) Editing spectral line data

3mm SiO maser line (VLBA)



Cross-power spectra on different VLBA baselines

RFI No-Line SiO-Line

Line Data Calibration

b) Fringe-fitting: *Delays*

- Independent clocks, atmospheric propagation, and geometric errors in the earth model at the correlator cause delay residual errors

- *No pulse cal system for line observations!*
  =>need "manual" phase-calibration
  =>Fringe-fit the data to calibrate your delays! *FRING* in AIPS

- Cannot determine delay errors from line source (i.e. the target maser)

- Delay calibration requires a continuum calibrator
  => fringe fit a scan on a strong continuum source and apply delay corrections to all scans/sources

Line Data Calibration

b) Fringe-fitting: (Residual Delays +) *Rates*

"Global" fringe-fitting: *FRING* or *KRING* in AIPS

1. For weak lines, use a nearby ($<1^0$ for $\nu>43$GHz) strong continuum calibrator source to calibrate phases, delays, rates (*phase-reference*)

2. *For strong line emission (i.e., maser), do fringe-fitting on the target itself*
   - maser emission consists of many individual bright and compact "spots"
   - a spectral channel with a single strong spot is an excellent calibrator
   - fringe-fit to derive the rates and remove from all other spectral channels
   - could also apply target solutions to phase-reference calibrator for astrometry (*indirect phase-reference*)

Line Data Calibration

c) Bandpass computation

Definition: Given the visibility $V_{ij}(t,v)_{obs} = V_{ij}(t,v)\, G_{ij}(t)\, \mathbf{B_{ij}(t,v)}$

Bandpass calibration is the process of deriving the *frequency-dependent* part of the gains, $\mathbf{B_{i\,j}(t,v)}$

- In theory, $\mathbf{B_{i\,j}(t,v)}$ for each baseline can be estimated from the frequency spectrum of the visibilities of a flat-spectrum calibrator
  => but this requires very high S/N.

- Most corruption of the bandpass is linked to individual antennas
  => *solve for antenna-based gains instead of baselines*:
  $B_{i\,j}(t,v) \approx \mathbf{B_i(t,v)\, B_j(t,v)^*} = b_i(t,v) b_j(t,v) \exp[i\,(ph_i(t,v) ph_j(t,v))]$

- Given N antennas, now only N complex gains to solve for compared with $N(N - 1)/2$ for a baseline-based solution.
  => less computationally intensive
  => improvement in S/N of ~ $\mathrm{sqrt}[(N-1)/2]$

Line Data Calibration

c) Bandpass computation

How BP calibration is performed?

Commonly used method :

- Uses a strong calibrator whose data is divided by a source model or continuum (Channel 0), which removes any source structure effects and any uncalibrated continuum gain changes
- The antenna-based gains are solved for as free parameters channel-by-channel.

AIPS task BPASS. *No task in HOPS? Limited to a BW< 500 MHz?*

Modified approach:

- For VLBI, compact strong cont. sources to detect with high S/N on all baselines are rare

=> use autocorrelation spectra to calibrate the amplitude part of the bandpass

- Signal-to-noise too low to fit channel-by-channel?

=> try polynomial fit across the band. AIPS task CPASS

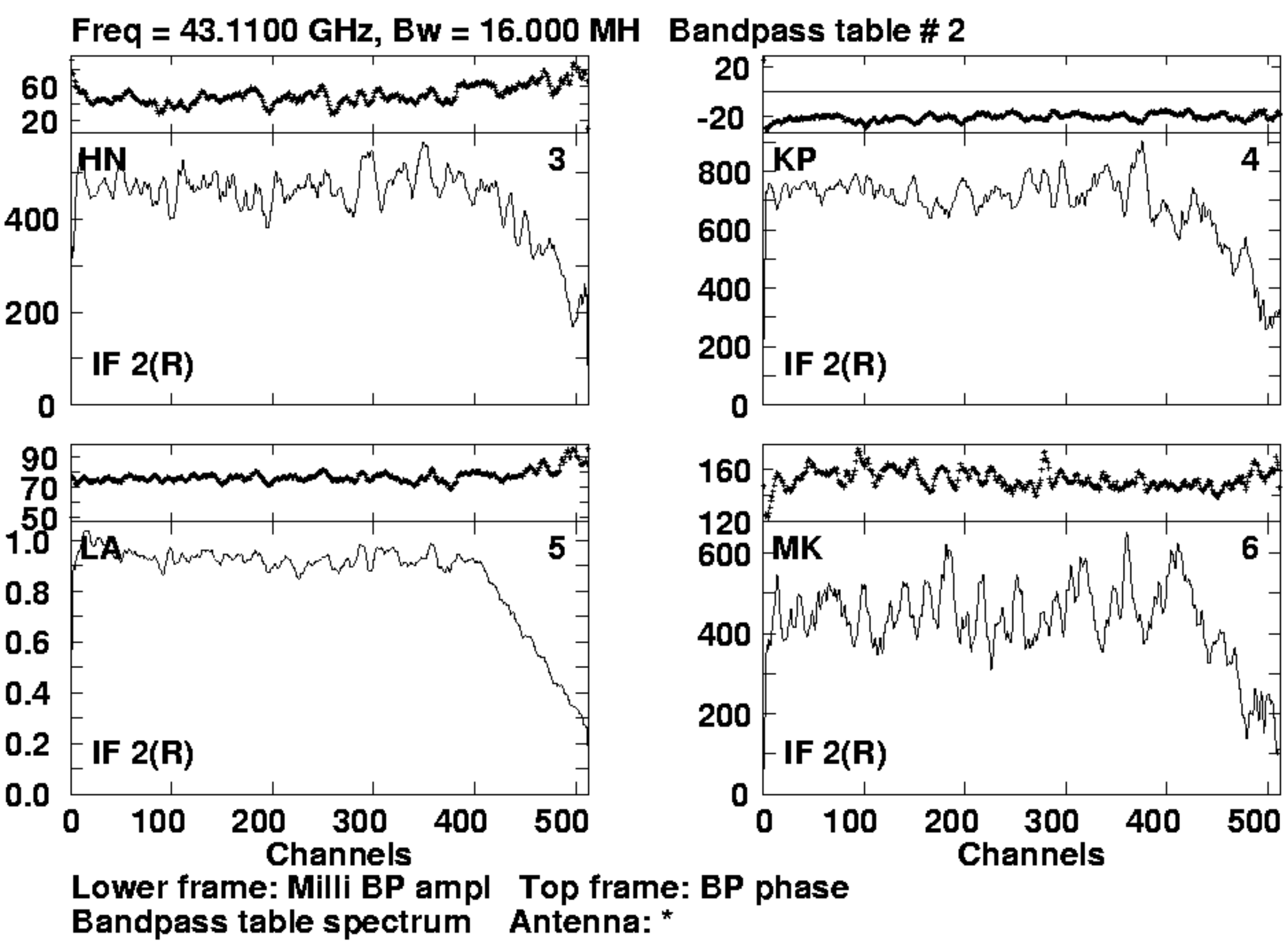
- At mm wavelengths, strong continuum sources are rare.
  - polynomial fit across the band?
  - use artificial noise source? ✗

Line Data Calibration

c) Bandpass computation

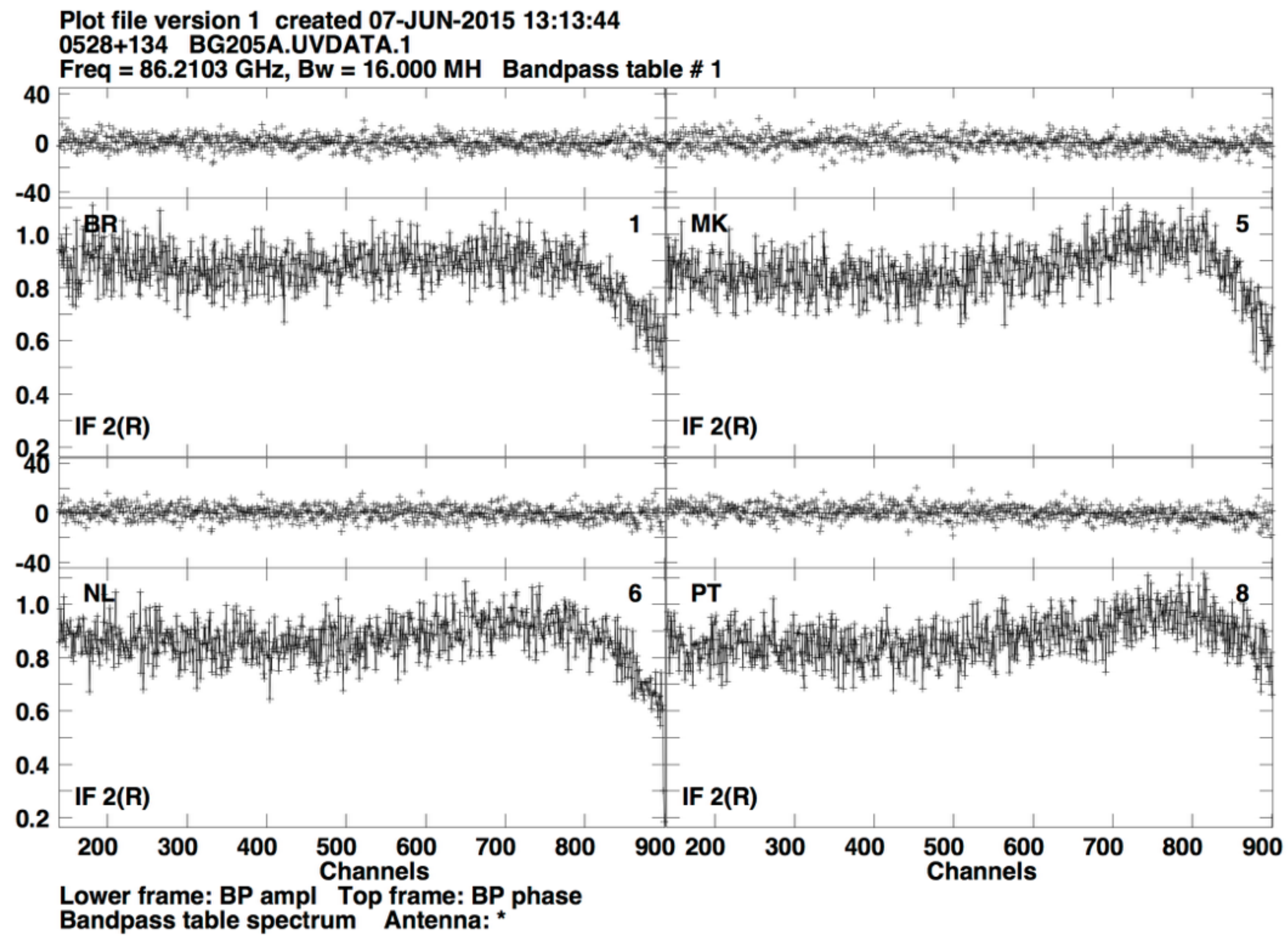
Assessing the Quality of the Bandpass Calibration

<u>Poor-quality bandpass solutions</u>



- Amplitude has different normalization for different antennas
- Noise levels are high, and are different for different antennas

<u>Good bandpass solutions</u>



- Solutions look comparable for all antennas.
- Mean amp~1 and ph~0 across useable portion of the band
- No sharp variations in amp or phase (not noise-dominated)

Line Data Calibration

d) Doppler Correction

- The velocity/redshift of a source is a crucial number as this dictates what sky frequency a line is observed.
- Source velocities need to be corrected relative to a rest frame
- Observing from Earth, our velocity with respect to astronomical sources is not constant in time or direction.

Line observing frequency: Rest Frames

Correct for	Amplitude	Rest frame
Nothing	0 km/s	Topocentric
Earth rotation	< 0.5 km/s	Geocentric
Earth around Sun	< 30 km/s	Heliocentric
Sun peculiar motion	< 20 km/s	Local Standard of Rest
Galactic rotation	< 300 km/s	Galactocentric

Conventions:

Radio-LSR $V_{radio}/c = (\nu_{rest}-\nu_{obs})/\nu_{rest}$ - Mainly Galactic work

Optical-heliocentric $V_{opt}/c = (\nu_{rest}-\nu_{obs})/\nu_{obs} = cz$ - Extragalactic work

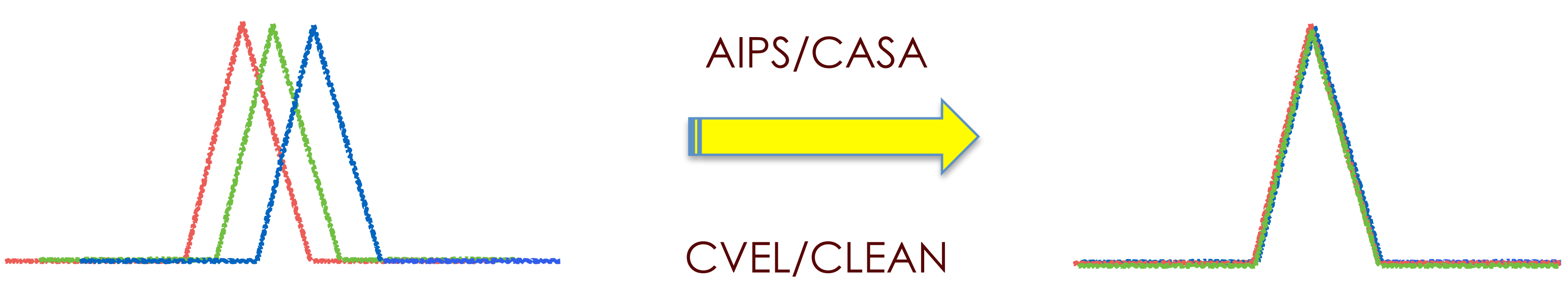
(approximations to relativistic formulas, differences become large as redshift increases)

Line Data Calibration

d) Doppler Correction

- ***Doppler tracking*** can be applied in real time to track a spectral line in a given reference frame, and for a given velocity definition (e.g., radio vs. optical)
- Note that the BP shape is really a function of *frequency*, not velocity!
  - Applying Doppler tracking introduces a time-dependent and position dependent frequency shift
- VLBI is done with *fixed frequency* (***Doppler setting*** not *tracking*)

=> The spectra must be shifted in frequency to correct for constant velocity



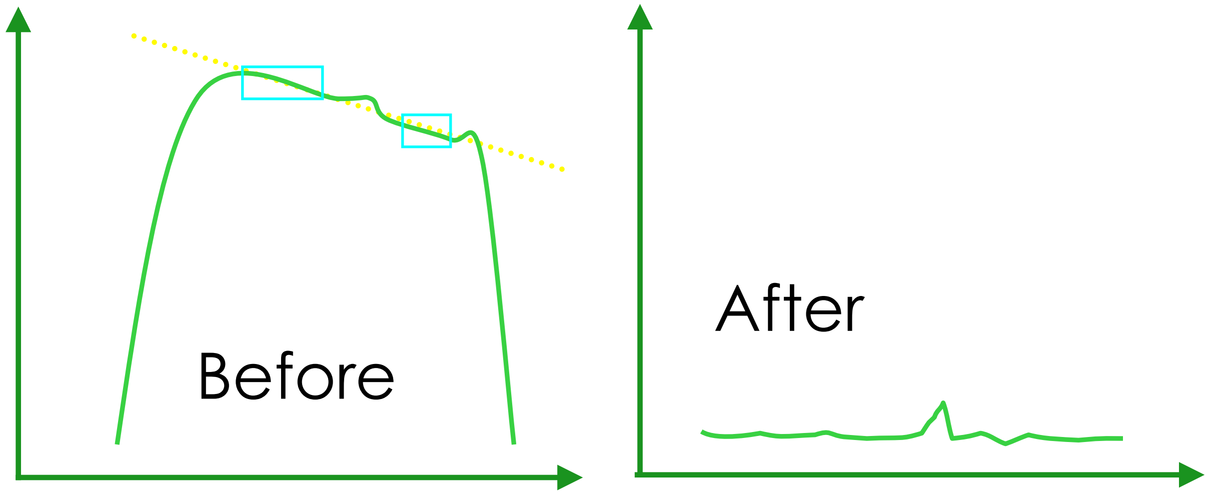
Line Data Calibration

e) Continuum subtraction

Basic concept

- Spectral-line data often contain continuum sources (either from the target or from nearby sources in the field of view) as well as line data.

- This continuum emission should be subtracted in your spectral-line data set
  - use line-free channels to estimate the continuum level
  - Subtract this continuum model from all channels
  - Iterate if necessary



<u>Only necessary if strong continuum presents</u>

- rarely an issue for maser emission
- very important for weak absorption lines

Line Data Calibration

f) Self-calibration

Same as continuum, but two cases (like in the fringe-fitting):

- *Strong line emission (i.e. maser)*
  - Self-cal the "reference channel" used for the global fringe fitting and apply solutions to all other channels
  - Allows imaging of weak continuum with >snr

- *Weak line and strong continuum phase-reference source*
  - Self-cal the continuum source and apply solutions from the continuum to individual channels
  - Allows imaging of weak lines with >snr

Line Data Calibration

g) Imaging: *Cleaning and Deconvolution*

- Deconvolution of spectral line data often poses special challenges:

  - Cleaning many channels is *computationally expensive*

  - Emission *distribution* & *structure* change from channel to channel
    => *labour-intensive* (setting clean boxes, interactive cleaning, etc)

- One is often interested in *both* high sensitivity (to detect faint emission) and high spatial/spectral resolution (to study kinematics)
  => cannot smooth your data to boost your sensitivity

Line Data Calibration

g) Imaging: *Line Cubes Data Analysis*

- After mapping all channels in the data set, we get not a ***map*** but a 3D data ***cube*** (RA, Dec, Velocity)

- The price to pay is more complexity to handle (large data sets, visualisation methods/softwares, etc.)

- To visualize the information we usually make 1-D or 2-D projections:

  - Line profiles (1-D slices along velocity axis)

  - Channel maps (2-D slices along velocity axis)

  - Movies (2-D slices along velocity axis)

  - Position-vel. plots (slices along spatial dimension)

  - Moment maps (integration along the vel. axis)

Random points for discussion

1. Data volumes output from the correlator for processing
2. Data Calibration:
   - Bandpass necessary for the wide-band data?
   - Amplitude calibration with auto-correlation spectra on strong maser lines?
3. Fringe-fitting: line-sources (i.e. masers) as calibrators?
4. Data Analysis: continuum subtraction for (weak) absorption lines
5. …….

Extra Slides

Amplitude calibration with auto-correlations

- Autocorrelation spectra of strong masers can be used to calibrate variations in antenna gain, Tsys, etc.

- Use template spectrum (from most sensitive telescope) to fit scaling to others

<u>Pros</u>:

- Excellent relative amplitude calibration (good within 1%)

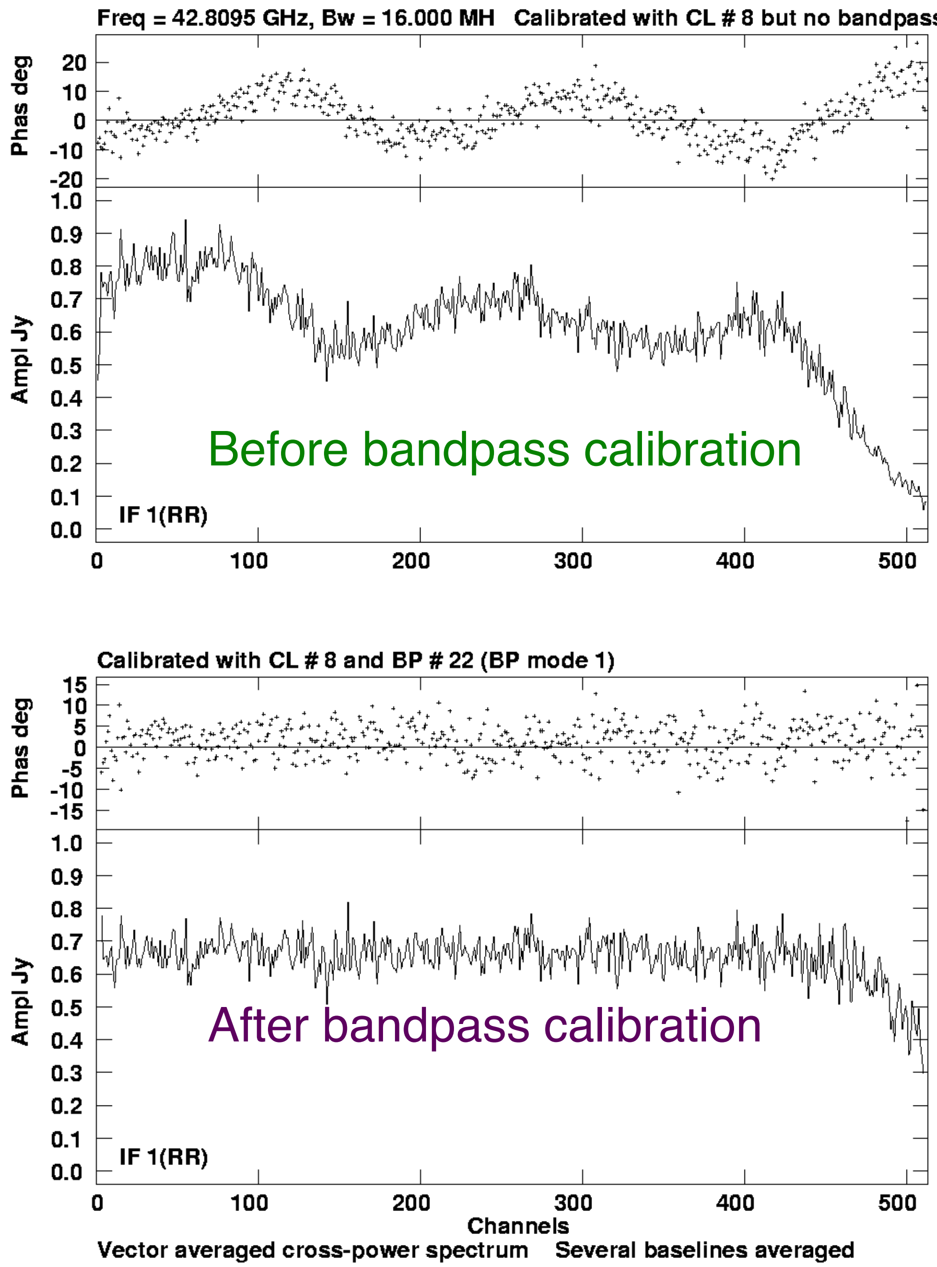
<u>Cons</u>:

- Absolute calibration depends on accuracy of flux scale for template

Line Data Calibration

c) Bandpass computation

Bandpass quality: apply to a continuum source



Before accepting the BP solutions, apply to a continuum source and use cross-correlation spectra to check:

- That phases are flat across the band
- That amplitudes are constant (for continuum sources)
- That the noise is not increased by applying the BP
- Absolute flux level is not biased high or low

How long to observe a BP calibrator?

- Applying the BP calibration means that every complex visibility spectrum will be divided by a complex bandpass, so noise from the bandpass will degrade all data.

- Need to spend enough time on the BP calibrator so that SNR_{BPcal} > SNR_{target}. A good rule of thumb is to use

SNR_BPcal > 2*SNR_target

which then results in an integration time:

*t*_BPcal = 2(*S*_target /*S*_BPcal)2 *t*_target

(Sub)mm Maser Lines in Alma Bands

Band	$\theta_{B(16km/1km)}$ (mas)	H_2O (GHz)	SiO (GHz)	HCN (GHz)
3	40 / 650	96		
5	20 / 320	183		177
6	16 / 250	232	214, 216, 257, 259	
7	10-15 / 160-240	293, 321, 325, 336, 354	300, 302, 336*, 343, 345	
8	9 / 145	437, 439, 471		
9	6 / 100	658		
10	5 / 80		*isopotomer	805, 891