SPECTRAL LINE VLBI

Loránt Sjouwerman

"Spectral line VLBI"

all VLBI = spectral line VLBI

- Observed bandwidth at **sky** frequency
- Correlated with number of "**lags**" – time shifts – to be able to account for "**delay"** – change of phase with frequency – due to
  - ***Atmosphere (ionosphere/troposphere)***
  - ***Individual telescope positions/electronics***
  - ***Clock/correlator model imperfections***

WHAT IS SO SPECIAL?

- "Spectral line VLBI" is ***not*** fundamentally different from regular "continuum VLBI"
  - ***Need to calibrate delay and rate***
- "Spectral line VLBI" is ***not*** fundamentally different from connected element (e.g. VLA) spectral line observations
  - ***Need to calibrate bandpass***
- "Spectral line VLBI" is just a combination
  - ***Lectures by C.Walker, M.Rupen, J.Hibbard***
  - ***But with some nitty-gritty details***
- *Requires to **be ready** before submitting proposal!*

SPECTRAL LINE

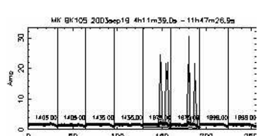
Two different interpretations:

- Science does not depend on frequency but **use** "spectral line" during processing
  "pseudo-continuum"
- Science depends on frequency
  "spectroscopy"
- Bandpass calibration becomes important!
- You have to choose correlator parameters

PSEUDO-CONTINUUM

Science does not depend on frequency, but keeping data in spectral line is useful to:

- ***Avoid limitations of spectral averaging;*** ***bandwidth smearing, "wide field" imaging, MFS***
- ***Recognize, flag, and account for Radio Frequency Interference (RFI)***



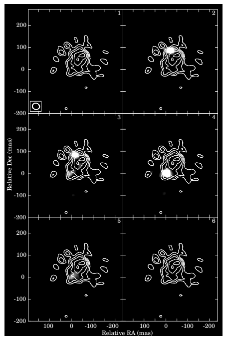
SPECTROSCOPY

Science depends on frequency:

- ***Emission lines***
  - Object only emits/visible at certain frequencies
- ***Absorption lines***
  - Object only visible at certain frequency because it is in front of absorbed background emission
- ***"Doppler lines"***
  - Emission/absorption line reveals velocity of object
- Line profiles may vary from *sub*-km/s emission line structure to *hundreds* of km/s wide, spatially distributed emission and absorption profiles

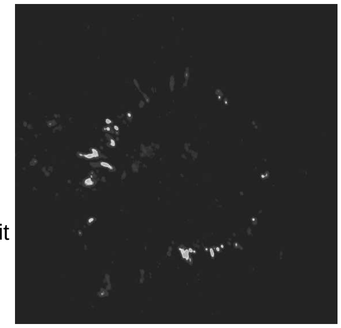
EXAMPLE EMISSION LINE

- Continuum source at 1667 MHz (contours)
- Six **different small frequency** bands
- Some frequencies show **extra emission** (white gray scale blobs)
- Extra emission from **different locations** in the continuum source
   - *Image courtesy: Ylva Pihlström*



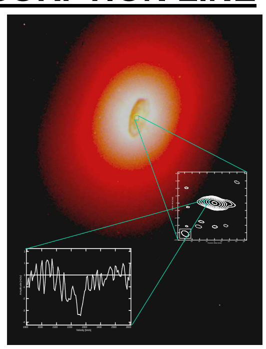
EXAMPLE EMISSION LINE

- 43 GHz SiO maser emission around a star
- **No continuum** emission at all
- Actually many frequencies with masers; composit
- Cool movie!
   - *Image courtesy: Phil Diamond & Athol Kembal*



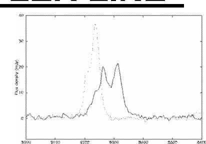
EXAMPLE ABSORPTION LINE

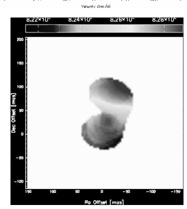
- Optical (HST) image of an elliptical galaxy with a **dust torus**
- Contains a radio continuum jet (inset)
- Dust torus absorbs radio continuum on **one side of the jet** only
- Geometry known, no need for optical data
   - *Image courtesy: Ylva Pihlström*



EXAMPLE "DOPPLER LINE"

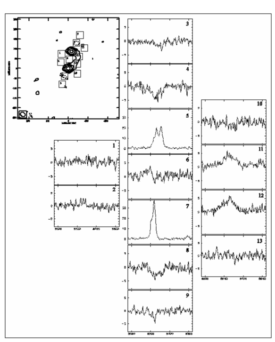
- Different parts of the source show different line profiles
- Dotted line: **blue-shifted** emission – moves toward us
- Solid line: **red-shifted** emission – moves away
- Gradient: fit to **solid body** rotation, some kind of disk
   - *Image courtesy: Ylva Pihlström*





EXAMPLE "ALL OF THE ABOVE"

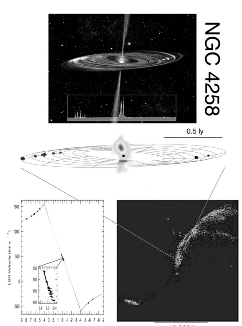
- Can get very messy!
- Continuum subtracted
- Maser lines, both narrow and wide
- Absorption too
- Used to model the components and their velocity structure
   - *Image courtesy: Ylva Pihlström*



ULTIMATE "ALL OF THE ABOVE"

- Galaxy with disk
- Radio continuum jet
- Jet on one side obscured
- Continuum amplifies maser emission (in green)
- Tangential to disk maser emission – faint red & blue spots at Keplerian (point mass) **rotation**
- First real measurement of **nuclear Black Hole mass**
- Add time dimension (4D): **geometric distance!**
   - *Image courtesy: Lincoln Greenhill*

NGC 4258



THE DETAILS: SOURCES

A limitation for detecting a source with VLBI is its brightness temperature, in particular for a spectral line source: $T_b \geq 10^9$ K

- ***Generally <u>not</u> neutral hydrogen, thermal molecules nor radio recombination lines***
- ***Usually <u>only non-thermal</u> sources:***
  - *Masers – OH, H_2O, SiO, CH_3OH, ..*
    - *Galactic as well as extra-galactic*
  - *Background AGN – HI and OH absorption*
    - *Galactic as well as extra-galactic*
  - *Human-made – satellites and orbiters*

DETAILS: PRE-PROPOSAL

<u>Get your frequencies right!</u>

- VLBI stations observe the same **sky frequency, ν_{obs}**
- Doppler corrections: source ***z, $V_{l.o.s.}$***, and **rest-frame**
  - Also: ***radio velocity definition*** versus ***optical velocity definition***
- **Frequency coverage** differs per VLBI station
- Select **maximum** and **minimum** frequency range
  - Fiddle with time averaging to meet correlator restrictions

SOME RELATIONS

- Radio versus optical velocity definition:
  - Radio / Optical : $V_{radio} / V_{optical} = \nu_{obs} / \nu_{rest}$
- Doppler velocity/frequency relation:
  - $V_{l.o.s.} / c = (\nu^2_{rest} - \nu^2_{obs}) / (\nu^2_{rest} + \nu^2_{obs})$

*For velocity $V_{l.o.s.}$ << **c**, redshift **z** << 1:*

- Frequency shift [MHz] = $V_{l.o.s.}$ [km/s] . ν [GHz] / 300
- Spectral resolution [km/s] = 0.3 $\Delta\nu$ [kHz] / ν [GHz]
- Velocity range [km/s] = 300 BW_{tot} [MHz] / ν [GHz]
- Optical velocity [km/s] = 3×10^5 . ***z*** ***BEWARE!***
- Do not miss the line in the observed bandwidth

REST-FRAMES

Correct for	Amplitude	Rest frame
Nothing	0 km/s	Topocentric
Earth rotation	< 0.5 km/s	Geocentric
Earth/Moon barycenter	< 0.013 km/s	E/M Barycentric
Earth around Sun	< 30 km/s	Heliocentric
Sun/planets barycenter	< 0.012 km/s	SS Barycentric (~Helioc)
Sun peculiar motion	< 20 km/s	Local Standard of Rest
Galactic rotation	< 300 km/s	Galactocentric

PRE-PROPOSAL ADVICE

- Get your source's definition from the paper
  - Check with other sources – SIMBAD, NED, other papers
- Redo your calculations at multiple occasions
  - Old programs exist (mostly FORTRAN); dopper/dopset
  - Check definitions of <u>band edge</u> versus <u>band center</u>
  - Some stations (VLA!) are more difficult to calculate
  - Ask someone else (e.g. your co-I) to check your results
- Check availability of receivers, known RFI
- Restrictions; band edge or RFI/seasons, bandwidth filter
- *Keep these handy for when proposal gets approved*

PRE-PROP: CORRELATION

All correlators have limitations in number of operations and data flow rate

- ***Spectral range: maximum bandwidth***
  - Number of BBCs and their (total) bandwidth
  - May have to overlap BBCs for shape of filter
- ***Spectral resolution: minimum width***
  - Number of channels/lags per BBC
- ***Field-of-view: correlator integration time***
  - Bandwidth smearing – usually not the problem
  - Time-average smearing – usually the trade-off
- ***Volume of the data set may get <u>GIGANTIC</u>***

AVAILABLE HELP

- Standard books, e.g. your own copy of
  - ***Synthesis imaging in radio astronomy (II)***
    - ALSO look at chapters for VLBI as well as spectral line
- Web pages for documents, programs
  - ***Observational status summaries***
  - ***Sensitivity calculators***
- Run latest SCHED to try out your parameters
  - ***General/rough preliminary VLBI schedule***
  - ***Frequencies, station limitations***
  - ***Correlator parameters, data volume***

At any stage you can ask for help!

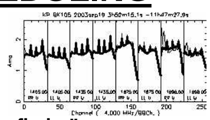
But remember to ask well in time (prefer ~ weeks)

DETAILS: PRE-OBSERVING

PI is responsible for a correct schedule

- Before scheduling, most proposals get a ***'local contact'*** and email addresses to ask for help
- Follow (obey) the rules given by the scheduler
  - **Finish the schedule about two weeks in advance**
  - **Do not deposit a schedule you know to be wrong**
- If you need help, ask well (=weeks) in advance!
- Schedules only get "checked" if you specifically ask for it – don't rely on checker to do your work

DETAILS: SCHEDULING



- **Switch off pulse-cal!**
  - ***And maybe add a note in the cover letter***
  - ***Pulse-cal tone interferes with line source***
- Include at least one bright **"fringe-finder"** (per 2 hours)
  - ***To be used for "manual p-cal"***
    - Calibrate "instrumental delay" on a continuum source
    - Spectral line source cannot be used for delay
- Include at least one (two) bright **bandpass calibrator(s)**
  - ***To be used for complex bandpass calibration***
    - May be same continuum source as the "fringe-finder"
    - Observe bandpass calibrator at the same sky frequency
    - Check that the source is **line-free** at these frequencies
- Use **2-bit sampling** for more sensitivity on the line

SCHEDULING

- Use SCHED on UNIX/LINUX platforms
  - ***Latest version available from NRAO***
  - ***Extensive (including some spectral line) documentation***
  - ***Very similar to scheduling a continuum observation***
- Scheduling takes time! In particular spectral line obs.
- Include "fringe-finder" and bandpass calibrators
  - ***Relatively strong, compact and line-free source***
  - ***Disperse over observing run (not only at start)***
  - ***Apply target Doppler tracking to all calibrators***
    - To observe calibrators at same sky frequency as target
    - Saves trouble of fiddling with spectra afterwards
- Again: use the correct frequency. If in doubt ask for help

DETAILS: POST-OBSERVING

- Data reduction follows continuum observations (delay, rate, and phase-referencing, self-cal)

Differences:

- **Data editing** – be sure to remove all RFI!
- **Calibration** – "manual p-cal", bandpass
- **Corrections** – Doppler shifts, self-cal on line
- **Imaging and analysis** – data cubes, line(-free) channels, frequency and l.o.s. velocity axis

DELAY CALIBRATION

- Because pulse-cal is (hopefully) switched off, it cannot be used to calibrate the time-independent "instrumental delay"
  - ***"manual p-cal" uses a short scan on a strong continuum source to calibrate "instrumental delay" (although small time dependencies may remain)***
  - ***In AIPS, one uses FRING instead of PCAL***
  - ***No big deal***

BANDPASS CALIBRATION

Small corrections for the amplitude and phase for each individual data path

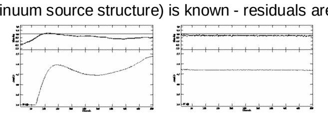
- Place where things can go wrong
- Place where people may differ in opinion; <u>my view:</u>
  - ***<u>Always</u> apply (complex) bandpass calibration***
  - ***Two step spectral line bandpass calibration***
    1. <u>Amplitude bandpass</u> calibration
       before Doppler corrections (skip for continuum observations)
    2. <u>Complex bandpass</u> calibration (amplitude and <u>**phase**</u>)
       after continuum (self-)calibration of the bandpass calibrators

BANDPASS AMPLITUDE

- Two different methods:
  - ***Strong line source, use autocorrelation spectra***
    - Per antenna determine <u>total power</u> of the line source
    - Compare with an on-off "template spectrum" of the line from your most sensitive and best calibrated antenna
    - Should be most accurate
  - ***Weak line source, use bandpass calibrator***
    - This step, correct for scalar **amplitude only**
- Calibrate amplitude before Doppler shift corrections

COMPLEX BANDPASS

- After final continuum calibration (fringe-fit, maybe self-cal) of the calibrators, good "cross-correlation continuum data" exists
- Use the **"bandpass calibrator"** to correct individual channels for small *residual phase* variations (and amplitude if step 1 omitted)
- The bandpass calibrator *must be calibrated* so its visibility phase (continuum source structure) is known - residuals are system



  - ***Bandpass calibrator must be <u>line-free and without RFI</u>***
    - Check your bandpass calibrator – cannot always anticipate
    - Fringe-finder or delay/phase-reference calibrator alternatives
  - ***Reduces closure errors, also for continuum observations***

ADDITIONAL CORRECTIONS

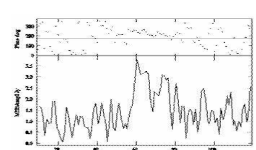
- **Doppler shifts**: if you did **not** use <u>Doppler tracking of your line source on your bandpass calibrator</u>, your spectra will shift during the observations due to Earth rotation. Recalculate with CVEL in AIPS – this shifts flux amongst frequency channels, thus you will want to do step 1 of the bandpass calibration (amplitude only) first
- **Self-cal on line**: you can use a bright spectral-line peak in one channel for a <u>one-channel self-cal</u> to correct antenna based **temporal phase and amplitude fluctuations** and apply the corrections to all channels (after applying the complex bandpass correction)

IMAGING AND ANALYSIS

- *<u>Treat the same as non-VLBI spectral line data</u>*
- Difference with continuum VLBI: *3D data cubes*
  - ***2D sky coordinates (R.A. and Dec.)***
  - ***"Channels", frequency (velocity) axis***
  - ***Channels with and without line features***
    - Emission: line-free channels usually are "empty"
    - Absorption: continuum source in all channels
- Need to view 3D structures
  - ***Imaging/analysis is the same, but per channel***
  - ***Extra programs for 3D display and analysis***
  - ***Easy swap between frequency and l.o.s. velocity***

CONTINUUM SUBTRACTION

- Line-free channels define (empty) "continuum"
- May want to subtract from the visibility data to speed up imaging considerably
- Watch out for "features"
  - Non-existing structures
  - Absorption in emission
    - Not line-free
    - Display only



- Also in image plane

CONCLUSION

- "Spectral line VLBI" is ***very similar*** to continuum VLBI and connected element spectral line observations and/or data sets
- Most of the differences ***already start*** with planning, proposing and scheduling, which is most of the work, and continue in calibration, imaging and data analysis
- ***Not*** much more difficult (really!)
- ***Help is abundant*** and "always" available