Time and Frequency Requirements for Radio Astronomical Interferometry

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Radio Interferometry

- A virtual radio telescope, where resolution increases with the distance between the dishes, and the observing frequency.

- Phase / delay measurement can be transformed back into a radio ‘image’ of the sky.

- Requires identical or at least very stable clocks at each receiver.
  - ‘Connected Interferometers’ distribute a single clock.
  - VLBI (Very Long Baseline Interferometry): stations at (inter)continental distances, each with its own H-maser.

- VLBI provides unsurpassed resolution (sub milli-arcsecond).
Stability Requirement

- Stable to within a fraction of the phase at the observing frequency
  - 10 GHz: period is 100ps

- Integration time limited by ionosphere / troposphere
  - 1000s at 10 GHz requires ~1E-14 ADEV @ 1000s
  - Requires active H-maser (or better…)

- To mitigate against ionospheric effects, we use ‘phase referencing’
  - Iterate between a strong, compact radio source, and the science target
  - Cycling period of just a few minutes
  - Also removes reference frequency errors

- ‘Clocks searching’ at start of observation by looking at strong source
  - Calibrate initial H-maser time and frequency offset, and drift
The Asterics Project

- Operated by ASTRON
- Member of EVN
- Hydrogen Maser

ASTRONS is a project supported by the European Commission Framework Programme Horizon 2020 Research and Innovation action under grant agreement n. 653477
1. Low Jitter Daughterboard (M. Rizzi e.a., https://www.ohwr.org/projects/wrs-lowjitter)
2. Cleanup Oscillator
3. Use of DWDM stabilised laser SFPs, and external DWDM filters
WR in a DWDM Network

- Bi-directional WR traffic on conventional (two fiber) DWDM
- Wavelengths outside of C-band get demuxed
  - Normally used for the ‘Optical Supervisory Channel’
- Insert CWDM filters to separate out the two WR wavelengths in the OSC path
  - We used 1511.05 nm / 1511.81 nm
- Bi-Directional Optical amplification of WR
  - SOA: Semiconductor Optical Amplifiers
• Three parallel links:
  • DWDM (169km)
  • 2x Dark Fibre (35km)
  • LOFAR core connected to Groningen

• DWDM Link: 2x 67 km + 35 km = 169 km
• On SURFnet production network SN8

• Dark Fibre Link: 35 km
Link Performance (2x 67km)

Phase Noise measured using MicroSemi 3120A between H-Maser and 10 MHz output of WR switch with cleanup oscillator

PPS measured on SR620

Red: 50 Hz
Blue: 0.5 Hz
Grey: 3120A Noise Level
Brown: Cleanup Osc.
Green: PPS (SR620)
Black: H-maser nominal performance
At longer timescales: ADEV limited by ionosphere, atmosphere

Observations are not simultaneous, so different atmospheric contribution

No significant performance difference between 35km and 169km link
LOFAR 2.0

• Upgrade to the 38 Dutch LOFAR stations
• Design phase complete, starting roll-out
• Adds sensitivity, more simultaneous bandwidth
• T&F distribution using WR
  • ASTERICS link from WSRT H-maser to LOFAR core (132 km)
  • WR link over dark fiber to the stations
• Replaces many GPS locked Rb clocks
  • Difficult to calibrate, high failure rate
  • Large upgrade to image quality
T&F distribution in VLBI

ELSTAB
- Polish system, links up to 350km
- 2 UTC(k) labs, a Sr clock
- Torun Radio Telescope
- Local H-maser vs. Remote H-maser
  - Same performance
- Remote Sr optical clock
  - Improved VLBI RMS phase noise
- Replaced failing H-maser

LIFT
- Italian system
- Coherent optical transfer
- INRIM UTC(k), H-masers & Yb clock
- Medicina Radio Telescope (550 km)
- Matera Radio Telescope (1800 km)
- Local H-maser vs. Remote H-maser
  - Same performance
- Two telescopes on the same clock
- Expanding to Noto and Sardinia

(see last slide for references)
VLBI Requirements

- Network Bandwidth: 1 - 4 Gb/s per station (with future increases)
- Frequency Stability: Active H-Maser level or better
  - Lower observing frequencies will work with higher ADEV
  - Lower ADEV can improve observation, but limited by ionosphere/troposphere
- Timing accuracy: 1 µs (not critical for VLBI)
  - Other use cases, e.g. pulsar timing, require ns level timing
- Redundancy / Availability / Performance Monitoring
  - Availability has to be comparable to using a local clock
- Remote locations, long optical links
  - Radio telescopes are usually far away from cities and industry
  - ‘Last Mile’ challenge
References

Asterics Project

• D5.4 Hardware for masers-level time & frequency distribution in public networks

• D5.6 Tools and methods for delay calibration before installation and in situ

• D5.7 Time Transfer in SURFnet/LOFAR Network & general design rules

• D5.14 Demonstration of VLBI Synchronization via the SURFnet/LOFAR network

LIFT

• A VLBI experiment using a remote optical clock via a coherent fiber link
  https://www.nature.com/articles/srep40992

ELSTAB

• Fiber-optic delivery of time and frequency to a VLBI station