ngVLA Calibration Strategies and Options

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Outline

• What’s different about ngVLA?
• Calibration challenges: pointing
• Calibration challenges: amplitude
• Calibration challenges: phase/delay
• Misc. topics

…indebted to many talks & papers, esp. those by Crystal Brogan, Bryan Butler, Chris Carilli, Barry Clark, Ed Fomalont, Mark Holdaway, Maria Rioja, and the ALMA & KVN teams
What’s different about the ngVLA?

• **High frequencies**: 100+ GHz (ALMA Band 3)
  • >= 4x SKA1_Mid

• Wide bandwidths
  • Up to 30 GHz (vs. 8 GHz ALMA, EVLA; 5 GHz SKA1_Mid)

• **Long baselines** (2x SKA1_Mid) & lots of antennas
  * Fixed stations
  * Groups of antennas

➤ Huge spatial dynamic range, *all the time* (as SKA1)

➤ More stable antennas?

➤ Range of atmosphere & weather across the array

➤ High sensitivity
  * 100 GHz: ~8x ALMA
  * 15 GHz: ~ 3x SKA1_Mid
What’s different about the ngVLA?

• Following ngVLA memos (Carilli, Clark, Owen, …) I concentrate on high frequencies & long baselines
  • Focus is on new & different– e.g., self-cal is important but barely mentioned here
• Very few details/numbers – too little time, too easy to bog down

• High sensitivity also creates issues
  • High dynamic range imaging: e.g., SKA1_Mid interested in pointing self-cal, wide-area pol’n response
  • Fast mapping: e.g., dealing with pointing errors during on-the-fly mapping
Calibration challenges: pointing

- 18m FoV at 100 GHz ~30 arcsec $\rightarrow$ 3x < VLA 43 GHz

$\Rightarrow$ Avoid the problem
- VLA, ALMA, …
- wait for good weather
- is this practical across the southwest?
- good-weather subarrays?
Calibration challenges: pointing

- Referenced pointing
  - transfer from lower frequency
    …different scan: VLA
    …simultaneous: cf. VERA
  - pointing self-cal: SKA1_Mid
    …probably not needed

- Better intrinsic pointing
  - stiff dishes, tiltmeters, optical telescopes, … (ALMA, NOEMA, …)
Calibration challenges: amplitudes

- Opacity

- Emission (noise) & absorption (lower signal)
- Varies with time, frequency, and location
- Elevation dependence
Calibration challenges: amplitudes

- Opacity
  - Scheduling: cal/src at ~same elevation
  - Tipping scans (aka sky dips): measure opacity directly
  - Tsys corrections: track fast changes
    - ALMA Amp.Cal.Device (hot/cold load) measured every 5-15 mins
    - VLA: switched noise diodes
Calibration challenges: amplitudes

- Flux scale
  - Calibrators are few & highly variable

Quasars: ALMA B3, B7
Calibration challenges: amplitudes

- Flux scale
  - Calibrators are few & highly variable
    \(\Rightarrow\) \textit{a priori} calibration: VLBI, many mm instruments
    - Tsys & efficiency measurements
    - sampler corrections: ACCOR
  \(\Rightarrow\) different types of calibrators at different frequencies
    - red giants, asteroids, etc.: ALMA
Calibration challenges: phases (delays)

- Fast phase variations, primarily (but not entirely!) troposphere & water at high frequencies
  - ALMA: PWV changes delay by up to 0.3 mm/s (30 degs @ 90 GHz)
  - Fundamentally delays so solve for those, not phases!
  - Different atmosphere over different sites
    - See discussion on pointing

- Fewer, more variable, and fainter calibrators

→ Avoid the problem: “Go/Nogo”
  - But how often do we have good weather everywhere?
→ Self-cal: but average flux < 50 microJy…
Water Vapor Radiometers

- Measure PWV by looking at water lines
- CARMA, NOEMA: 22 GHz
- ALMA, SMA, CSO-JCMT: 183 GHz
  - Measured @ 1 Hz
  - WVR can make things worse: clouds, ice (<10% of time @ 1 Hz)

![Graphs showing phase variation over time for short and longer baselines](image)

Nikolic 2011
• Have to account for other terms as well: e.g., CALC dry term
Fast switching

- 1.44mm PWV, 7 m/s; 1.3 degs., 20s cycle time
Fast switching

- Lovely but…
  - Requires fast moving & settling
- Spend ½ or more of time calibrating
- Requires dense grid of calibrators

Figure 3. The histogram of the target–calibrator separation from the ALMA catalogue on 1 January 2014. The probability distribution for the minimum separation of a random position in the sky from the nearest Band 3 calibrator is shown. The median separation is 3.5° and there is a 90% probability of finding a calibrator within 7° of a random target.

Median 3.5degs
90% w/in 7 degs

ESO msg 2014
Fast switching

• Lovely but…
  • Requires fast moving & settling
  • Spend $\frac{1}{2}$ or more of time calibrating
  • Requires dense grid of calibrators
  → real-time search for calibrators?
Simultaneous calibrator/source observations

• Multiple, steerable receivers: VERA

• Paired antennas
  • Wastes 25-50% of collecting area (and uv-coverage)
  • Or use cheaper calibration antennas
  • Does anyone actually do this regularly?
Frequency scaling

- Fast phase variation is tropospheric (non-dispersive) delay, so phase goes as frequency
- Solve for phase at low frequency & apply at high
- Fast-switch in frequency, slow-switch in position
- ALMA “band-to-band” transfer for Bands 8-10
Frequency scaling

• Multiple receivers: Korean VLBI Network (KVN): 3 dishes, 22, 43, 87, 130 GHz, 300-500km (K Q W D)

How important are integer frequency ratios?
Frequency scaling

- Multiple receivers: Korean VLBI Network (KVN): 3 dishes, 22, 43, 87, 130 GHz, 300-500km (K Q W D)

- Coherence loss vs. flux recovered
- 43 → 130 GHz phase transfer
- Just freq switching
- Plus source switching (3min)
Frequency scaling

• Paired high/low freq arrays (Carilli, Owen)
  …need to separate dispersive/non-dispersive effects
Other phasing approaches

• Pulse cals: inject tones at the antenna to align subbands & polarizations, and to track electronic delays
  • VLBA does this
• Correct for coherence losses in amplitude when phase can’t be fixed
  • OVRO, BIMA, …
• Correct phases statistically (i.e., deconvolve with PSF smoothed with “average” atmosphere) – Holdaway et al.
  • Does this cover an interesting parameter space?
• Separate observations of dispersive term (cf. VLBA/Reid)
Misc. topics
Polarization & bandpass calibration

• Polarization
  • Still early days
  • GMVA calibration approach seems quite similar to VLA/VLBA
  • Artificially polarized noise source with rotatable signal? (ALMA)
  • Squint will continue to be an issue

• Bandpass
  • Again similar but need very strong source
  • Past arrays have injected broadband signals with known bandpass
Living with bad weather/data

- Antenna-based weighting likely to be more important
- Could imagine subarrays with different calibration schemes depending on local conditions
  …either intrinsically different, or solve for subset of antennas in multiple passes
- Fair-weather dishes? Save power in lousy conditions
Lessons from VLBI

• A priori calibration where possible (amplitudes, delays)
• Delays rather than phases: model the physical effects
• Weighting of antennas: L1 and beyond
• Sifting & smoothing of calibration solutions: range of solution, SNR, consistency
• Split solutions into subarrays (i.e., separate solutions for different groups of antennas)
Conclusions
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- Can drive array design, but probably not computationally expensive (for post-processing)
- Exception: pointing & “normal” self-cal
- What do we do about the weather?
- Consider relative importance of highest frequencies
  - Do we trade dishes for stiffness? Fast switching? Multiple receivers? WVRs? Which gives the best benefit/$?
  - Do we only observe high frequencies under perfect conditions?
Comments?

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