ngVLA Calibration Strategies and Options

Michael P. Rupen

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Advanced Technology Program

Herzberg Astronomy & Astrophysics

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

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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

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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

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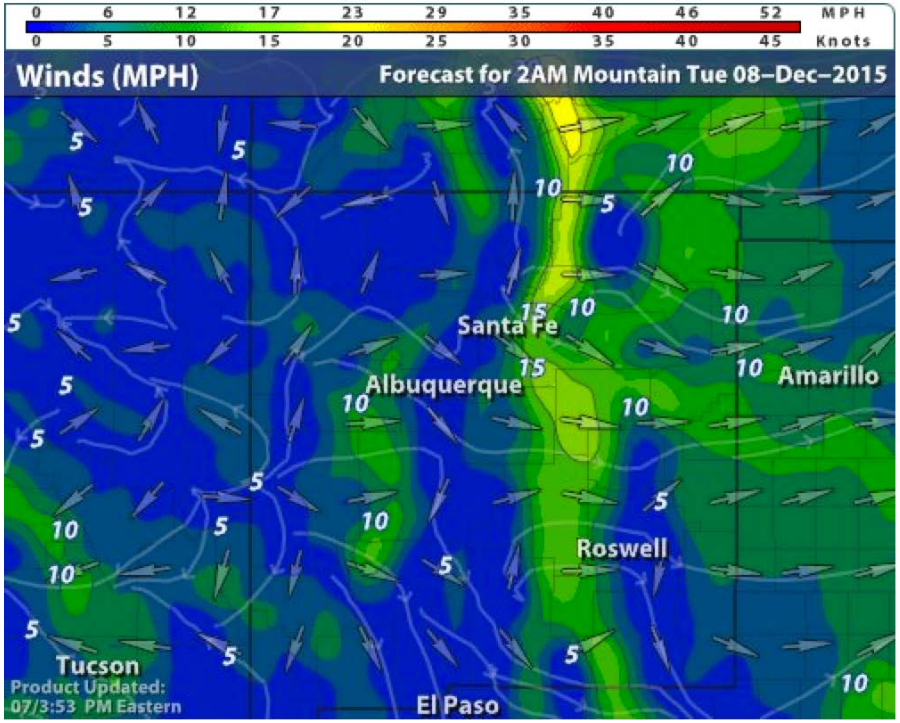
Calibration challenges: pointing

- 18m FoV at 100 GHz ~30 arcsec → 3x < VLA 43 GHz

➔ Avoid the problem

- VLA, ALMA, …
- wait for good weather
- is this practical across the southwest?
- good-weather subarrays?



Intellicast.com

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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, …)

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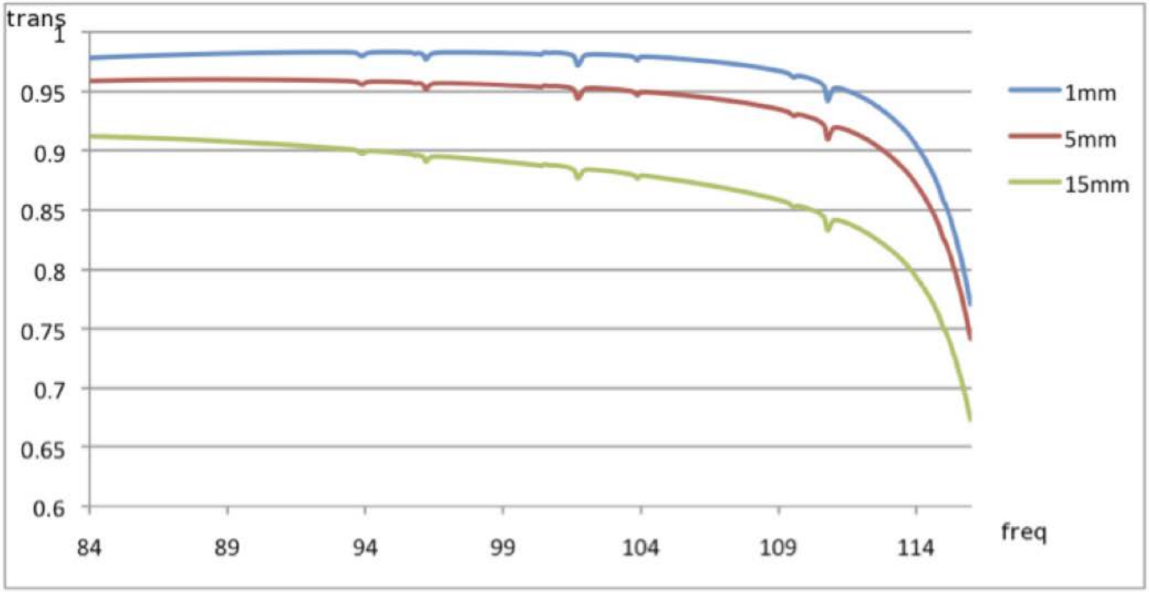
Calibration challenges: amplitudes

- Opacity



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

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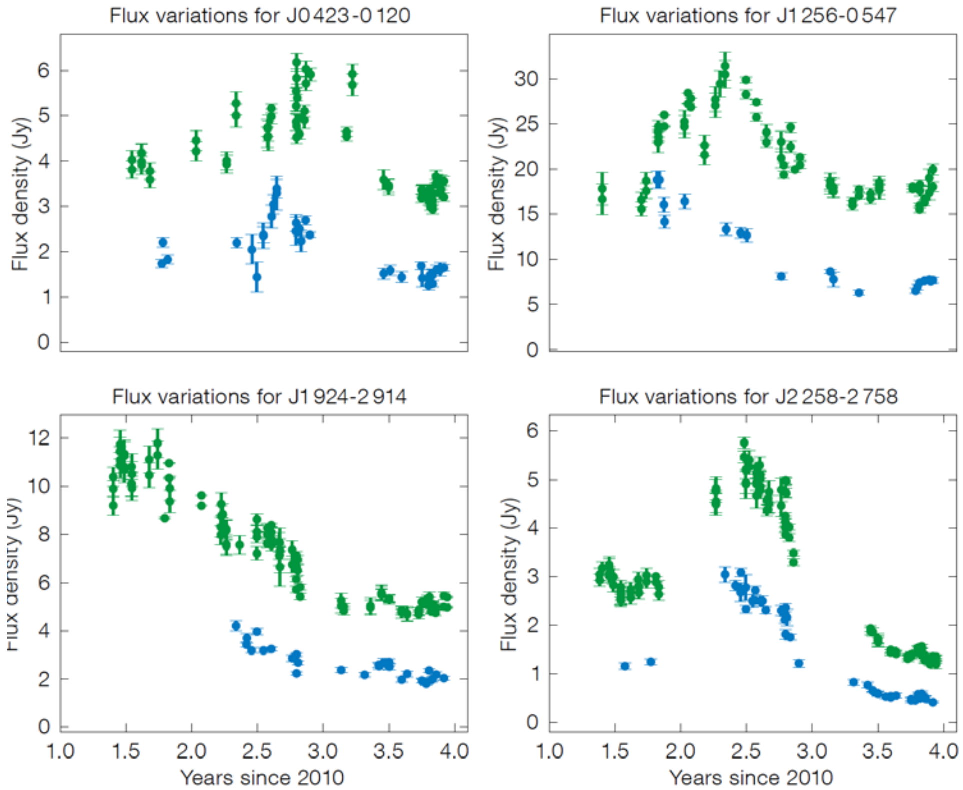
Calibration challenges: amplitudes

- 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

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Calibration challenges: amplitudes

- Flux scale
  - Calibrators are few & highly variable

  → *a priori* calibration: VLBI, many mm instruments
    - Tsys & efficiency measurements
    - sampler corrections: ACCOR

  → different types of calibrators at different frequencies
    - red giants, asteroids, etc.: ALMA

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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…

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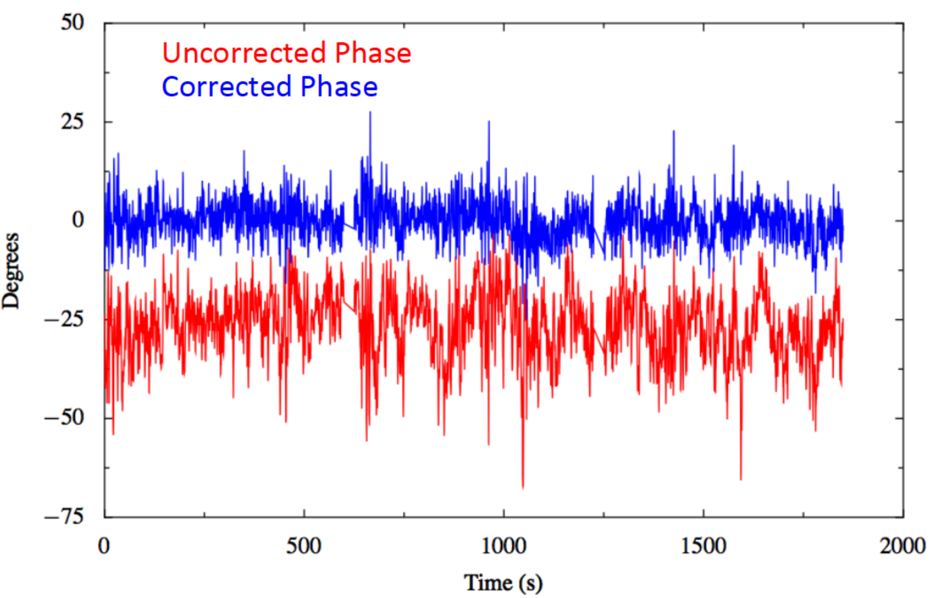
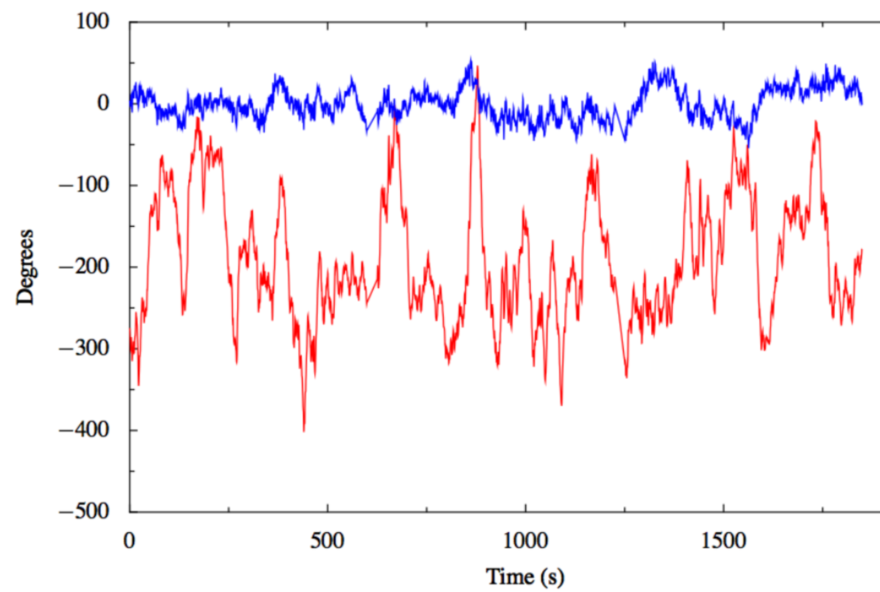
Water Vapor Radiometers

- 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 @



Short Baseline (≈50m)

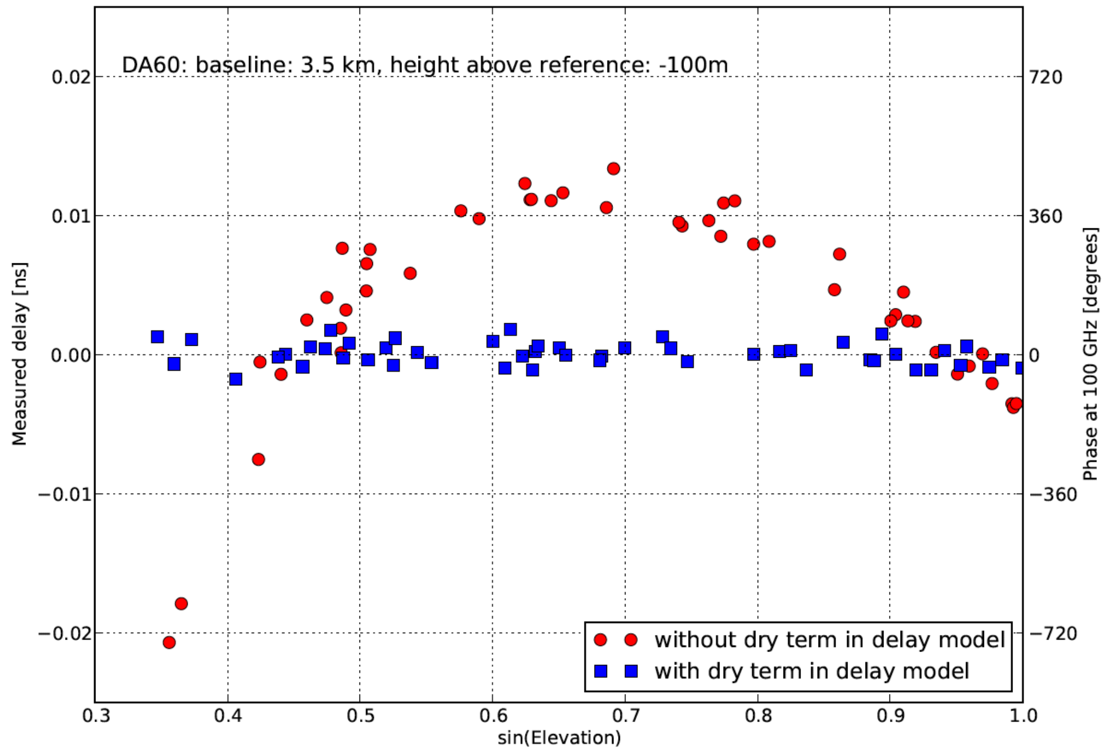


Longer Baseline (≈300m)

Nikolic 2011

Water Vapor Radiometers

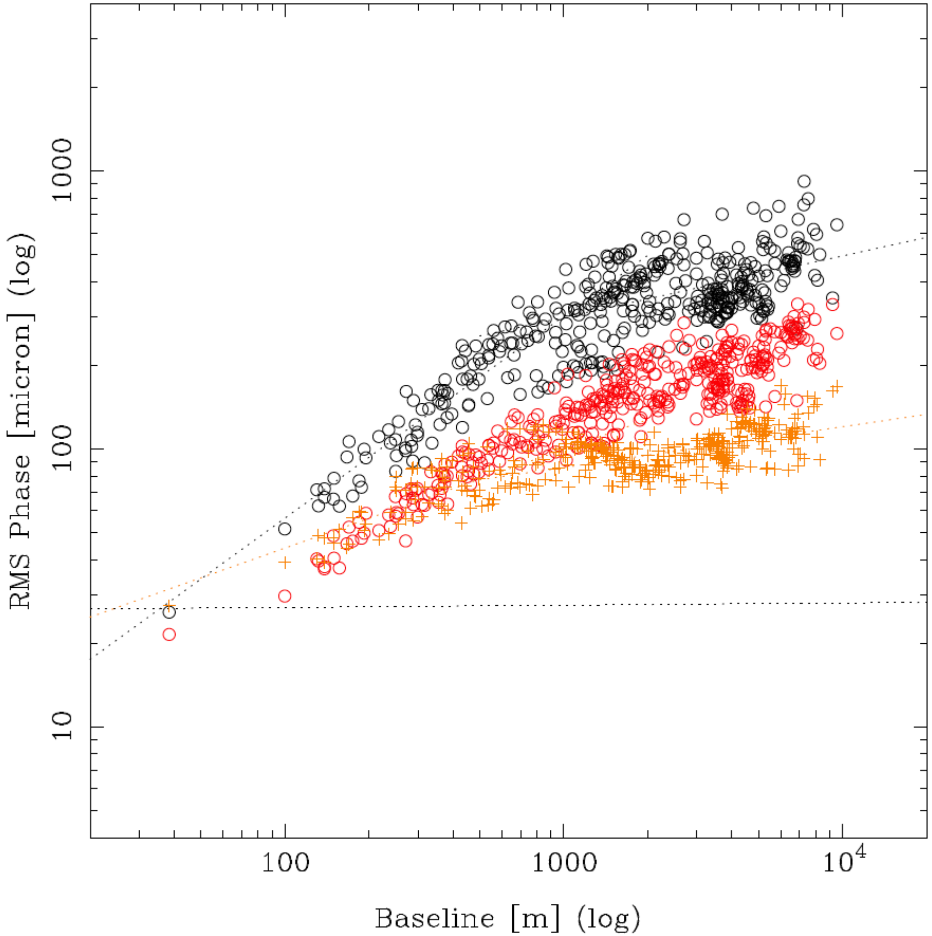
- Have to account for other terms as well: e.g., CALC dry term



APP 2015 (LBC)

Fast switching

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



Raw
WVR
WVR+fs

APP 2015 (LBC)

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Fast switching

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

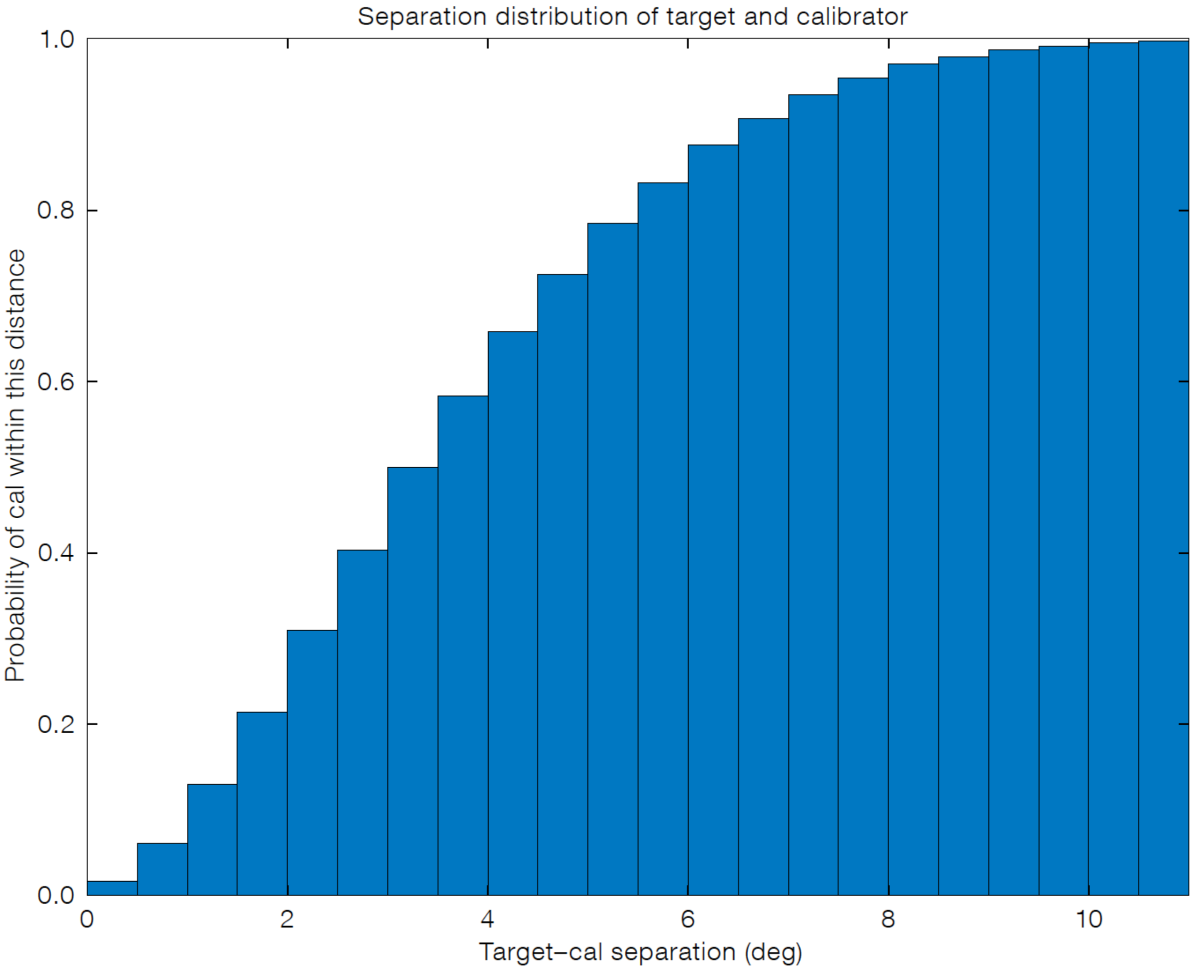

Figure 3. The histogram of the target–calibrator separation from the ALMA catalogue on 1 January 2014. The probability distribution for the minimum separation of a random position in the sky from the nearest Band 3 calibrator is shown. The median separation is 3.5° and there is a 90 % probability of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

Median 3.5degs
90% w/in 7 degs

ESO msg 2014

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Fast switching

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

    → real-time search for calibrators?

Simultaneous calibrator/source observations

- Multiple, steerable receivers: VERA

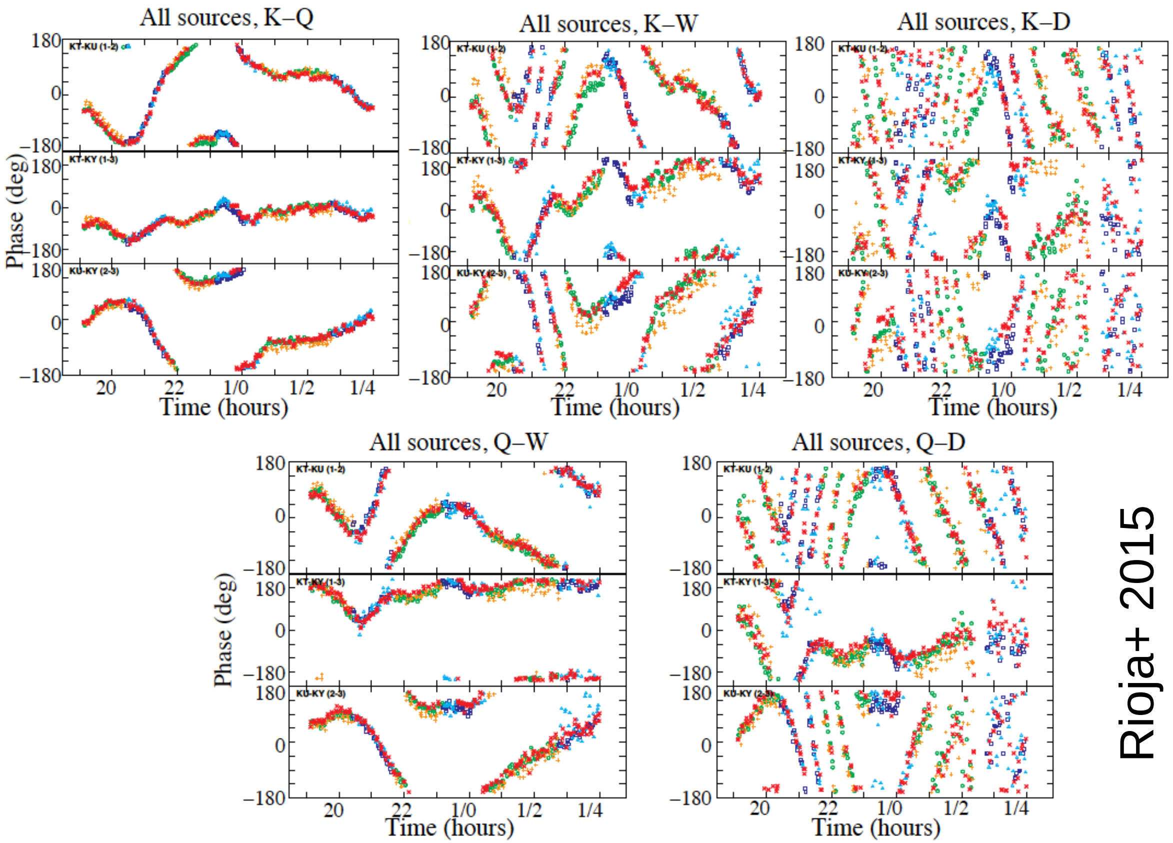
- Paired antennas
  - Wastes 25-50% of collecting area (and uv-coverage)
  - Or use cheaper calibration antennas
  - Does anyone actually do this regularly?

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?

Rioja+ 2015

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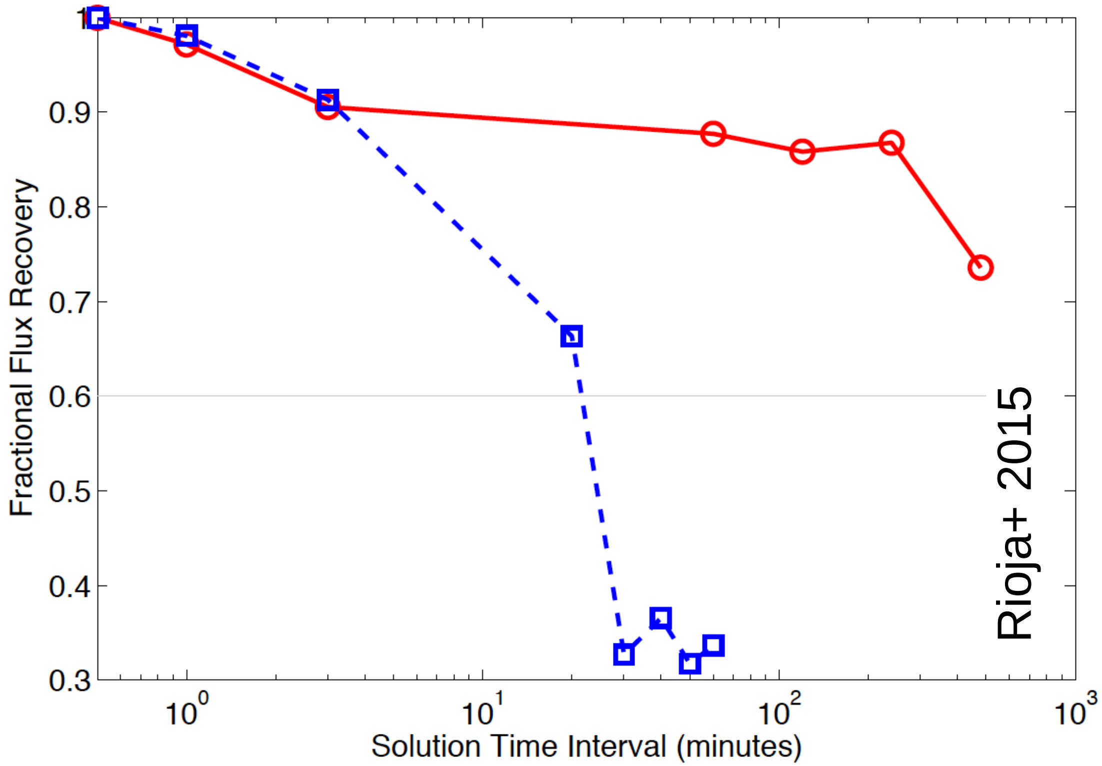
Frequency scaling

- 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

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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)

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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

Conclusions

- 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?

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Comments?

Michael Rupen
Senior Research Officer
Tel: 250 497-2307
Michael.rupen@nrc-cnrc.gc.ca
www.nrc-cnrc.gc.ca