Calibration Algorithm/Heuristics Topics for the EVLA

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Themes

- Interdependence of (interference between?) calibration and imaging effects
  - "All calibration is relative" to prior calibration ("ACIR") (propogation of errors poorly understood)
  - Generalized self-cal: revise more than just gain
  - A systematic approach to high dynamic range: sort limiting effects
  - How are imaging algorithms limited by calibration?
  - Can we rely on carefully balanced symmetries---some introduced by poor calibration partitioning---to 'cancel' subtle effects?
- Balanced strategy
  - High DR approach (big, bright sources, wide fields)
  - Simpler, broader scientific utility approach(modest sources, narrower fields)
  - Need to (re-)discover boundaries here

Topics

- Calibration Models, old and new
- Bandpass calibration now general
- Phase → Delay (self-)calibration
- Some ~quantitative examples
  - Switched power calibration
  - Delay clunking
  - Instrumental polarization
- Efficacy of uv continuum subtraction vs. deconvolved continuum model

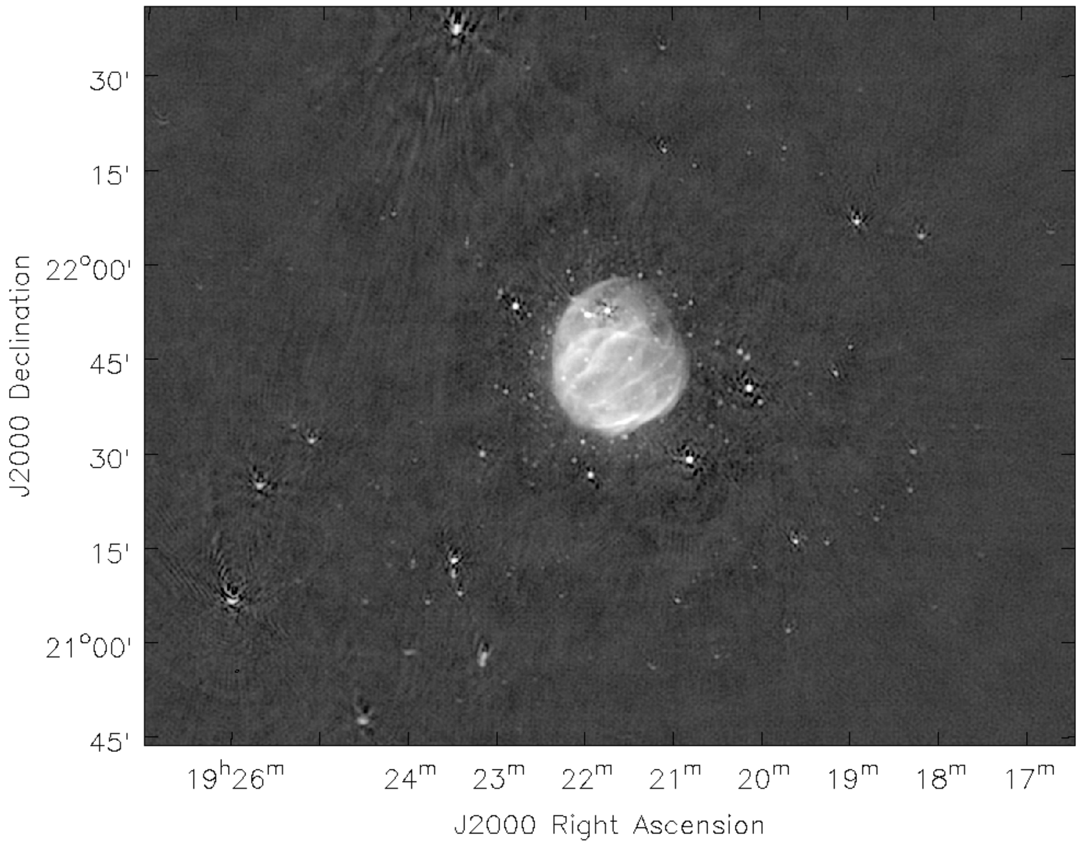
Traditional Calibration Model

- Serialized, generally scalar, calibration solves (image at earliest convenience)
  1. Gain
  2. Bandpass (if relevant)
  3. Instrumental polarization (if relevant)
  4. Baseline-based calibration (if necessary, to cope with closure errors)
- Motivations (perhaps partly in hindsight)
  – It basically works, and made VLA a very productive instrument
  – Easy to communicate to most users (but many users fail to comprehend, alas)
  – Circular feed basis conveniently enables essentially scalar approach (hides polarization, unless needed)
  – (Compare VLBA: enough additional complexity to frustrate?)

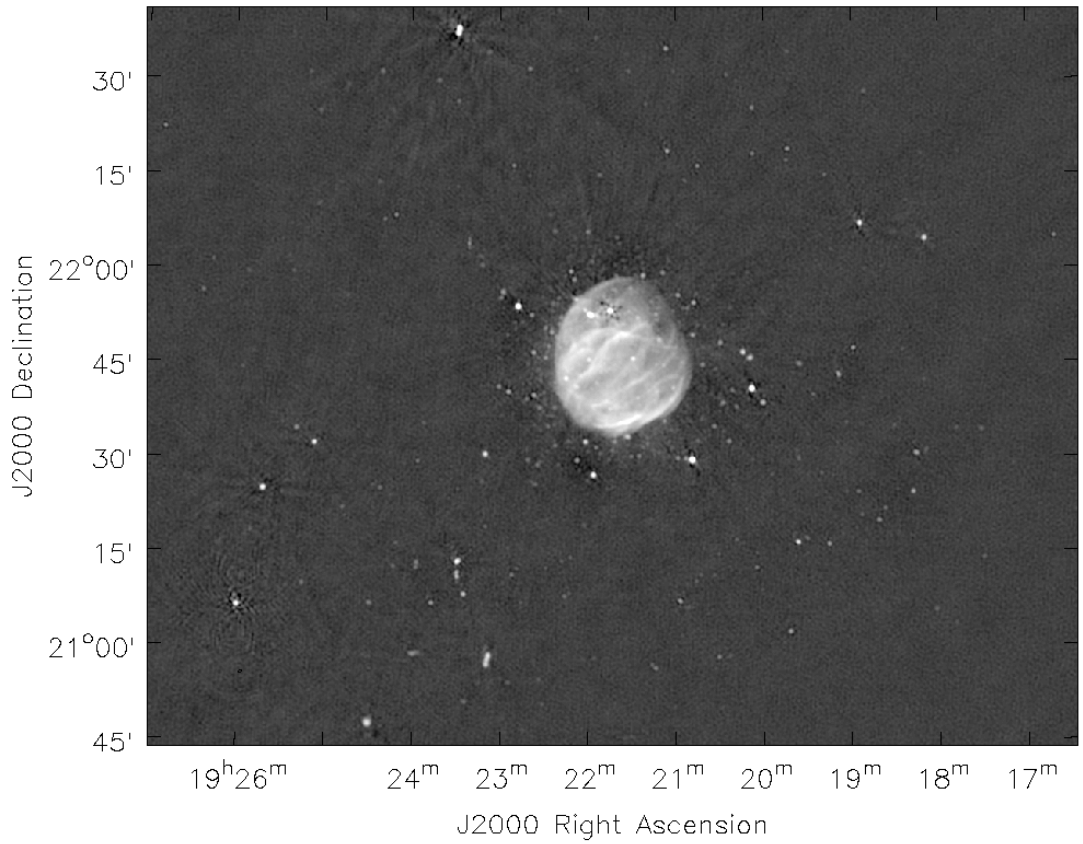
Traditional Calibration Model (cont)

- Self-cal generally limited to Gain
- Best work includes use of specific priors to fully leverage designed instrumental stability and otherwise maintain the standard serialized approach ("ACIR")
  - Pointing (online)
  - Opacity, gaincurve corrections and standard calibrator models enable stable measure of electronic gain among sources for accurate flux density scale transfer
  - Ionosphere corrections enable stable measure of electronic R-L phase for transfer among sources
  - Zenith delay (VLBA), antenna position corrections enable phase-referencing with minimal systematics between calibrator(s) and target

MS-Clean only



MS-Clean + MFS + W-proj



How is visibility calibration relevant to the remaining residuals?

Modern Calibration Model

- Acknowledge interdependence of solved-for calibration terms
  - "All calibration is relative" to all previous terms (some provisional)
  - This is generalized self-cal: improve instrument model as well as source model
  - Compare: Iterative imaging algorithms gain leverage via accurate geometric model of fringe
- Explicit non-scalar treatment
  - Polarized effects (instrumental polarization, squint, etc.) are important
  - EVLA sensitivity vastly improved, but some systematics, e.g., instrumental polarization same (or a bit worse?)
- New priors
  - Switched-power calibration (a practical feature of EVLA, cf VLA)
  - Instrumental polarization? (simple, stable enough?)
  - Bandpass?
- A more complete partitioning of effects, in general
  - Systematic approach to high dynamic range (discourage blcal!)
- Challenge: maintain comprehensibility!
  - NB: Traditional approach supplemented, *not excluded*, by this view

Bandpass Calibration Now General

- Including delay
  - Explicit delay solution vs. implicit treatment via conventional bandpass ("ACIR")
- Iterate bandpass with gain(t) calibration to optimize both ("ACIR")
- Calibrator models important
  - Spectra (including *visibility*)
  - Frequency coverage of f.d. models
- Instrumental polarization is frequency-dependent
  - Also, R-L phase (position angle calibration) is literally a bandpass phase (including a delay, in general)
- Averaging over an underlying bandpass mismatch no longer an important closure error contributor

Phase → Delay (self-)calibration

- Troposphere is the least stable calibration effect
  - It is a delay, treat it like one
  - (Ionosphere requires *1/f* model)
- Leverage full bandwidth
  - Maximize self-cal SNR
  - Access weaker calibrators
- Inter-band calibration
  - Calibrate one band with another ("ACIR")
  - VLA was limited here by lack of band-relative *instrumental* stability
  - (Critical calibration strategy for ALMA)

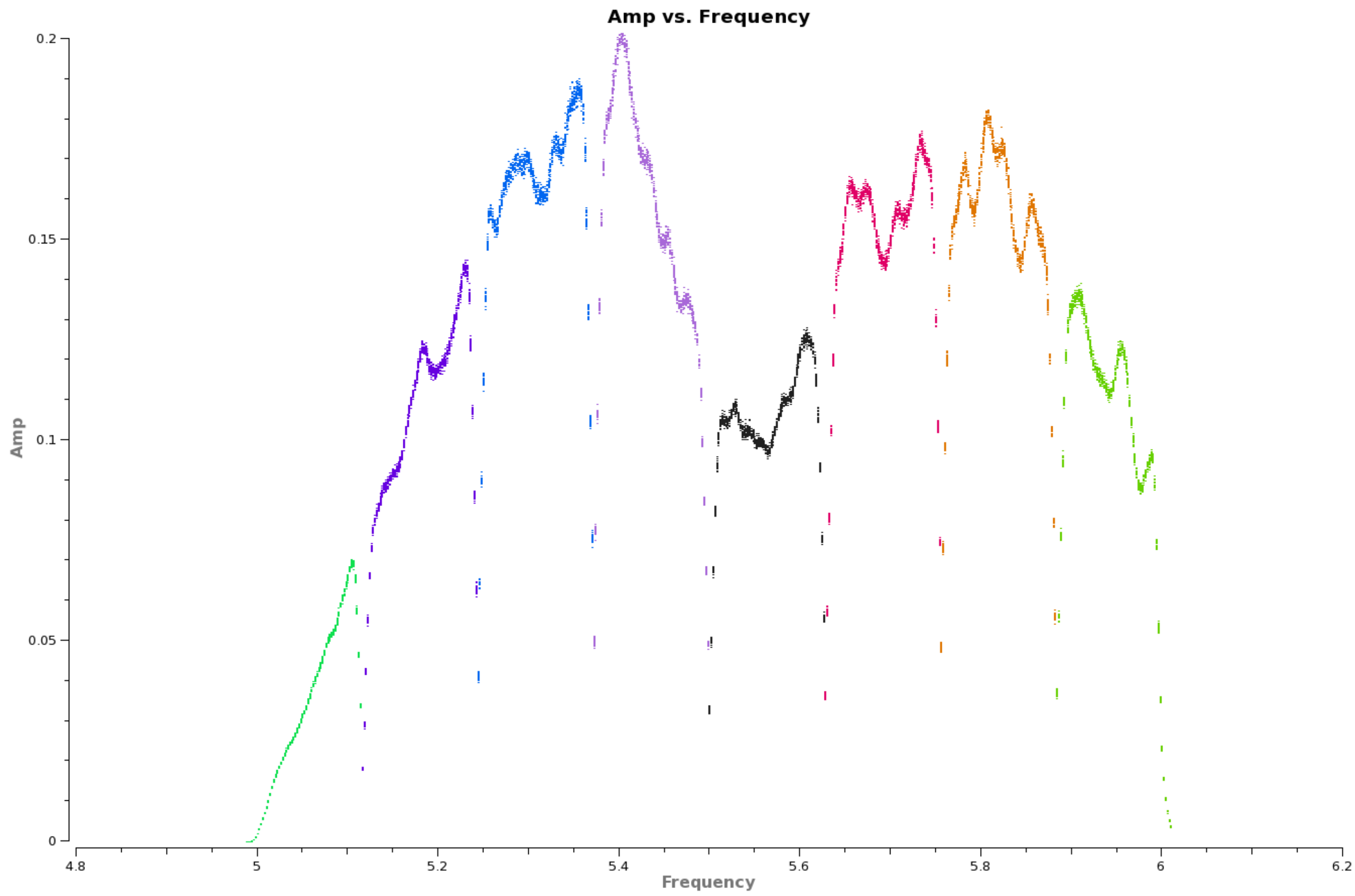
Switched Power Calibration

- EVLA correlations not normalized
  - for fixed input radio source signal (i.e., no gain curve, opacity effects, etc.), mean output visibility is constant, even if T_{sys} varies. Visibility noise varies according to T_{sys}.
  - Delivered weights uniform (=1.0); do not reflect inverse variance of the data
  - Recall VLA: visibility amplitude is normalized fraction of total power, so decreases with increasing T_{sys}. Raw noise (and weights) constant. Corrected via 'nominal sensitivity' *(~T_{sys})* calibration (same for VLBA, ALMA)
- Fundamentally, SNR is set at the amplifier
  - observed bandpass shape mainly introduced downstream by baseband filters and other sampling-related scale effects
  - SNR(freq) (as set by 'forward' sensitivity properties) remains essentially constant in passage through post-amplifier electronics, except at band edges where filter's noise contribution begins to dominate (i.e., signal and noise ~equally 'filtered')

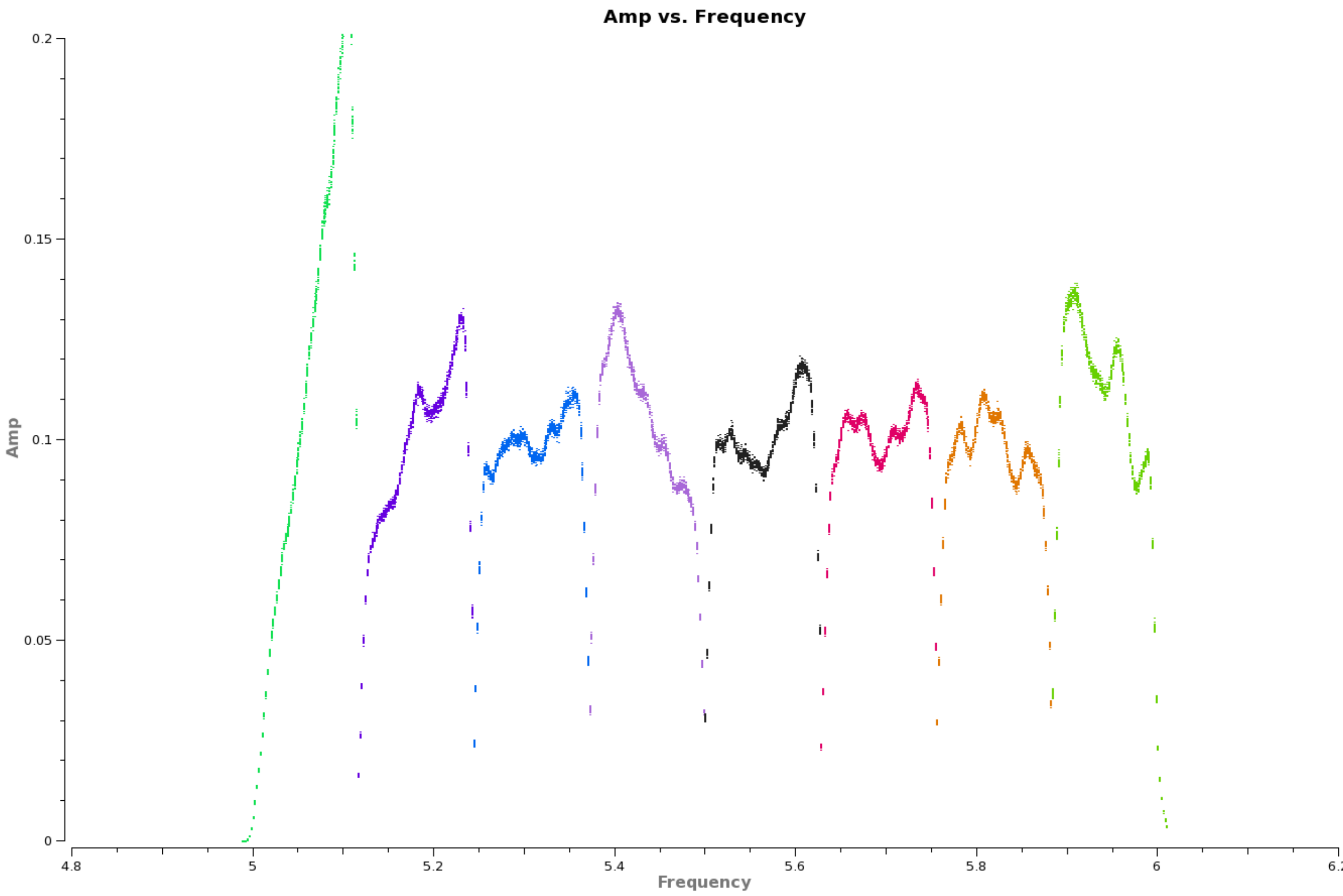
Switched Power Calibration (cont)

- Measure antenna-based total power (T_{sys}) at correlator inputs with and without injected T_{cal} contribution
  - Captures all post-amplifier scale changes; per subband
- Correct visibility amplitude by T_{cal} response (switched power difference)
  - Reconciles inter-subband amplitude scale (to ~K)
- Correct weights by $1/sqrt(T^i_{sys} T^j_{sys})$
- Compare to ordinary 'gain calibration'
  - $V_{corr} = G\ V_{obs}$
  - $wt_{corr} = wt_{obs}/|G|^2$ ($wt_{obs} \sim 1/\sigma^2_{obs}$; 'calibrate σ')
  - Assumes V_{obs} & wt_{obs} in consistent units

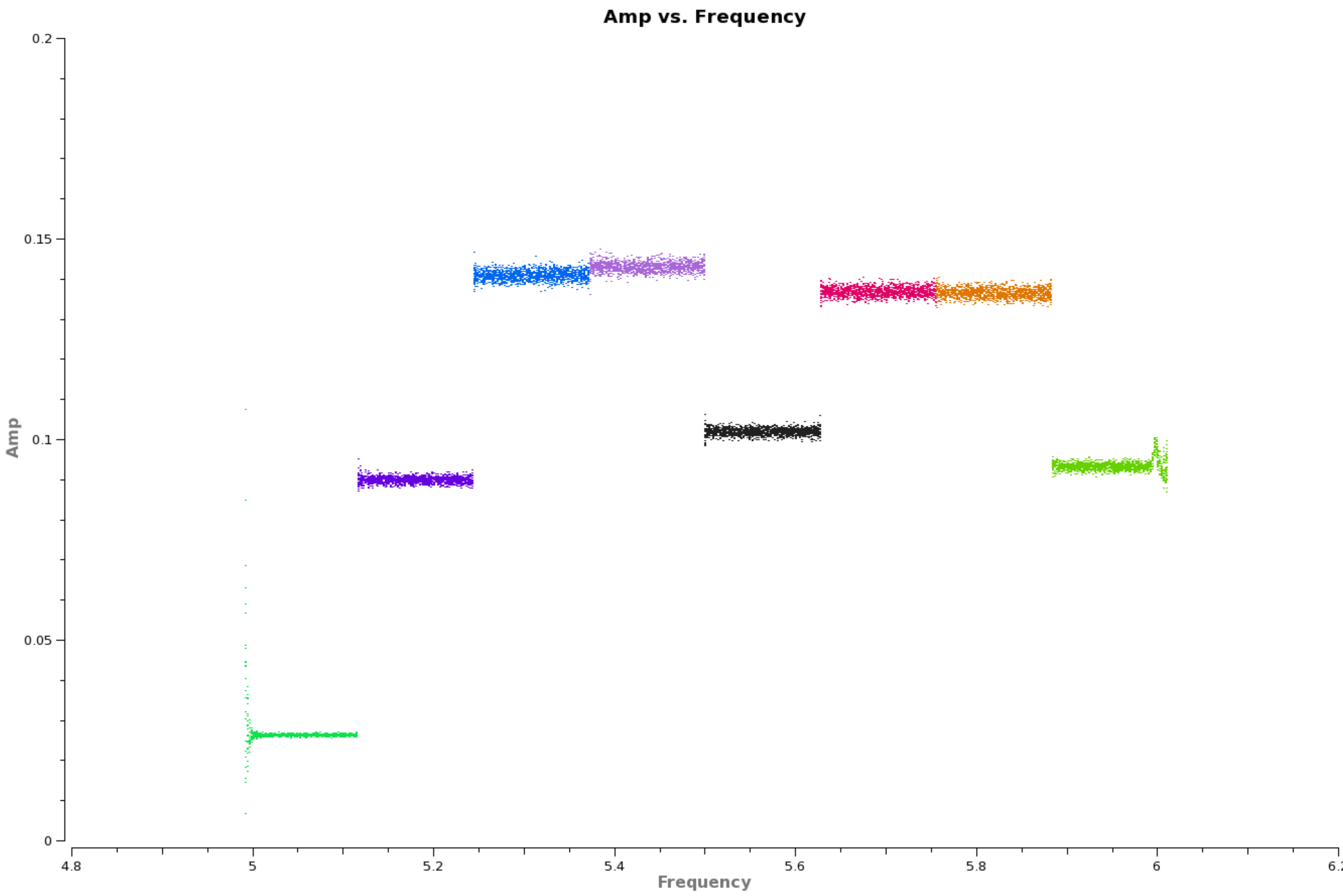
Switched Power Calibration (cont)



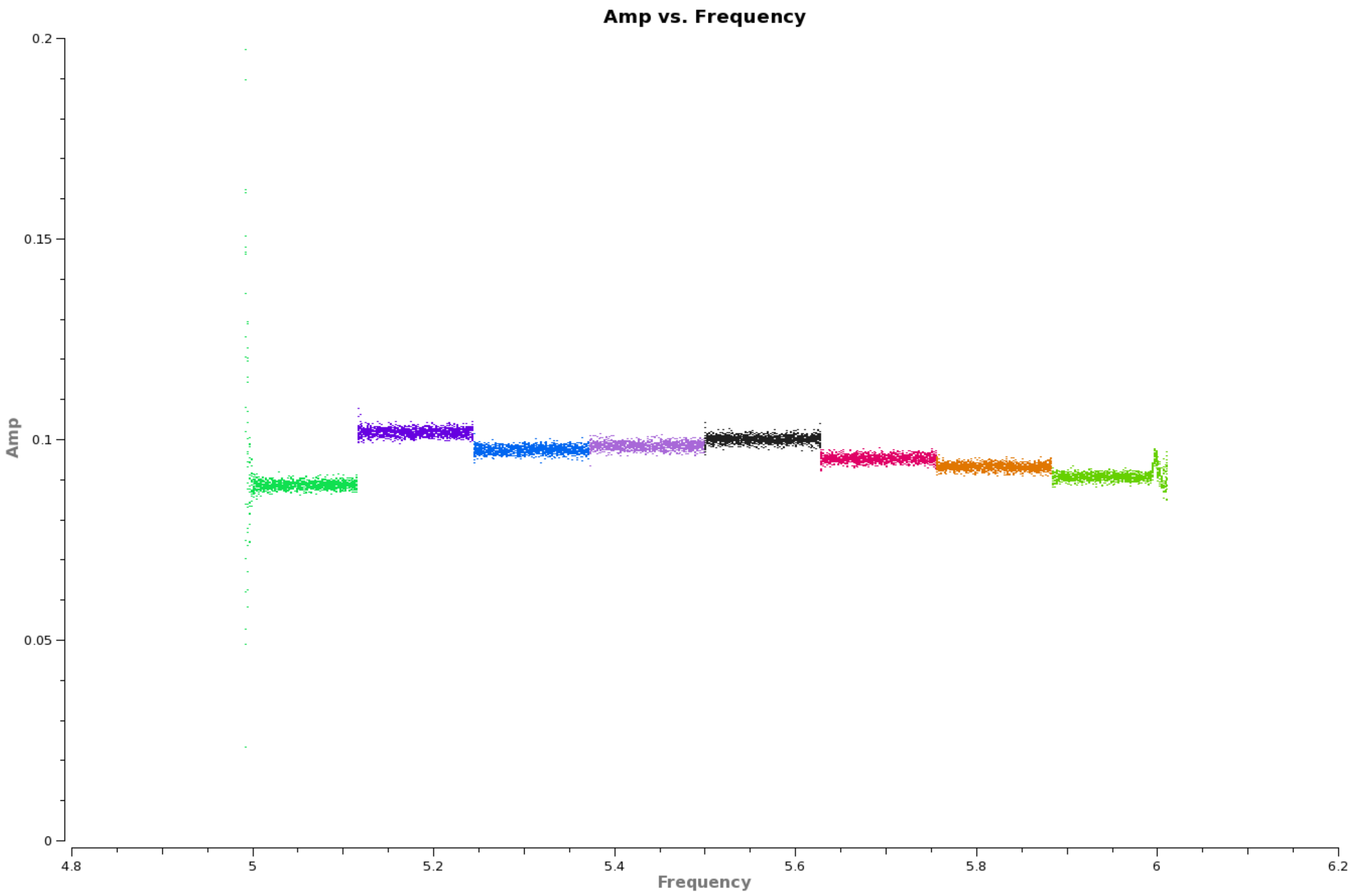
Switched Power Calibration (cont)



Switched Power Calibration (cont)



Switched Power Calibration (cont)



Switched Power Gotchas

- (Compression issues under investigation…)
- Ordinary gain calibration only (with weight calibration) will down-weight low-amplitude subbands relative to high-amplitude subbands ("ACIR")
- Fractional switched power gain error (per integration) adds significant (antenna-based) noise to corrected visibilities
  - Small T_{cal} signal response is difference of single-baseline (single dish) power measurement (vs. $sqrt(N_a\text{-}1)$ advantage of ordinary gain calibration)
  - Correctable via self-cal at timescale of switched-power correction
  - Avoidable via smoothing (bounded at attenuator or other changes)

Delay Clunking

- AKA "fractional bit-shift error"
- A temporary effect for the early EVLA
- Voltage samples finite (0.5nsec for 8-bit sampling) and correlator delay registration finite, but true delay actually changes continuously
  - Sawtooth delay residual of +/- 0.25 nsec (+/-5.5 deg peak jitter at 128 MHz subband edges)
  - Period follows the delay rate: slow near transit and within North arm
- 'Averages down (zero mean) over long observation to relative negligibility…'

Delay clunking (cont)

- …or does it?
- Bandpass calibration scan may not have time to average down efficiently, so its (non-zero) clunking delay residual becomes the zero point of the clunking average for all bandpass-calibrated observations ("ACIR!")
- Suppose a rms (over baselines) delay residual of ~0.1nsec
  - *Net* rms (baseline-based) coherence loss ~0.00026 (over 128 MHz)
  - Best case via *sqrt(351)* is DR < 70000:1
  - Averaging over subbands doesn't help (?)

Instrumental Polarization

- Traditionally, instrumental polarization calibration only used for source polarization measurements (cross-hands):

$$RL_{ij} = (Q + iU)e^{i(-\phi_i - \phi_j)} + D_{iR}D^*_{jL}(Q - iU)e^{i(+\phi_i + \phi_j)}$$
$$+ D_{iR}(I - V)e^{i(+\phi_i - \phi_j)} + D^*_{jL}(I + V)^{i(-\phi_i + \phi_j)}$$

- But it affects total intensity, too ("ACIR"):

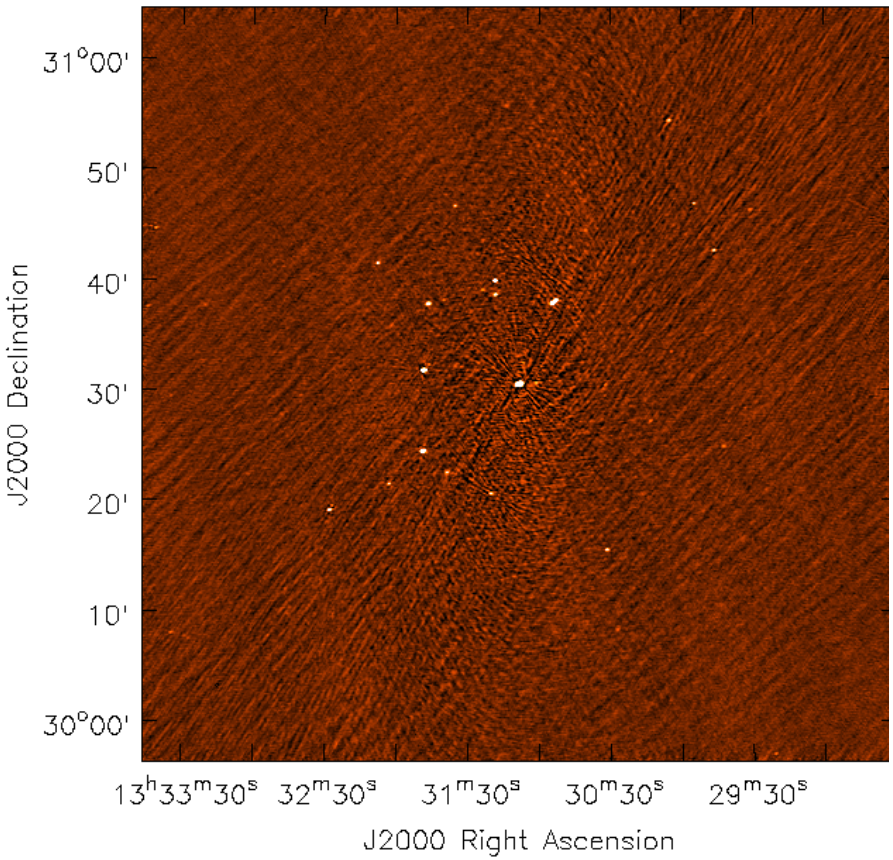
$$RR_{ij} = (I + V)e^{i(-\phi_i + \phi_j)} + D_{iR}D^*_{jR}(I - V)e^{i(+\phi_i - \phi_j)}$$
$$+ D_{iR}(Q - iU)e^{i(+\phi_i + \phi_j)} + D^*_{jR}(Q + iU)^{i(-\phi_i - \phi_j)}$$
$$= I\left(1 + D_{iR}D^*_{jR}\right) + D_{iR}(Q - iU)e^{i2\phi} + D^*_{jR}(Q + iU)^{-i2\phi}$$

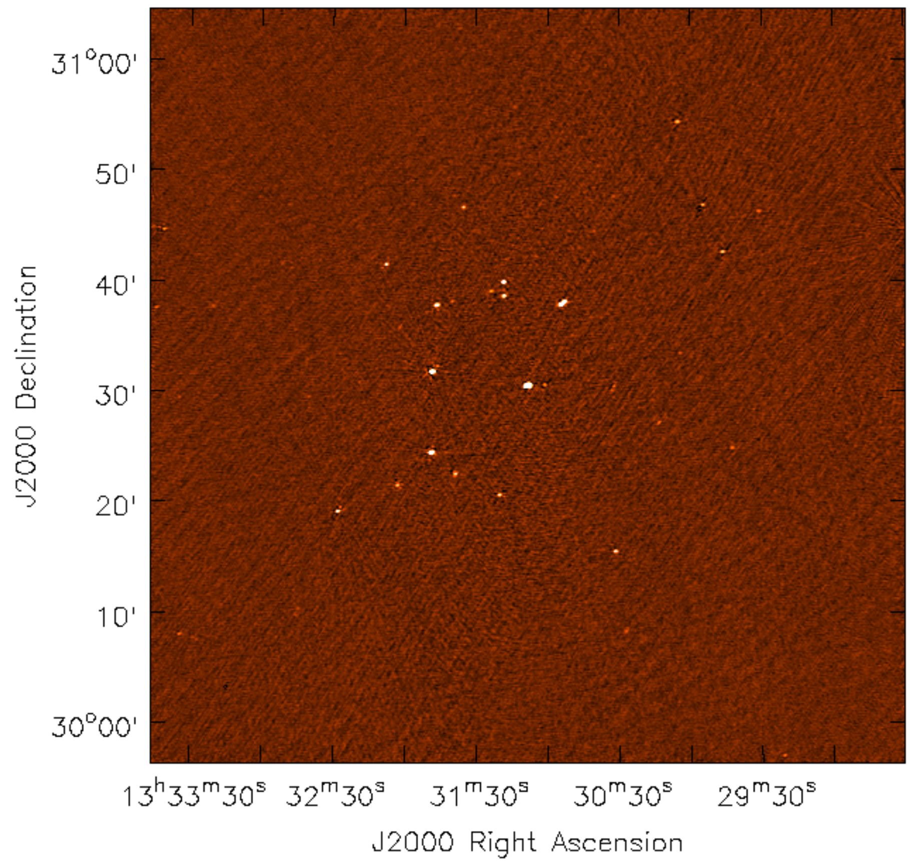
(V~0, small array)

Instrumental Polarization (cont)

- Some (anecdotal?) evidence of limited dynamic range already
  - Constant blcal on unpolarized source works well (DD term)
  - Constant blcal on long integration of polarized source works less well (time-variable DP terms)
  - (narrow field-of-view)
- Prototype WIDAR correlator closure phase averaging tests were probably limited by instrumental polarization

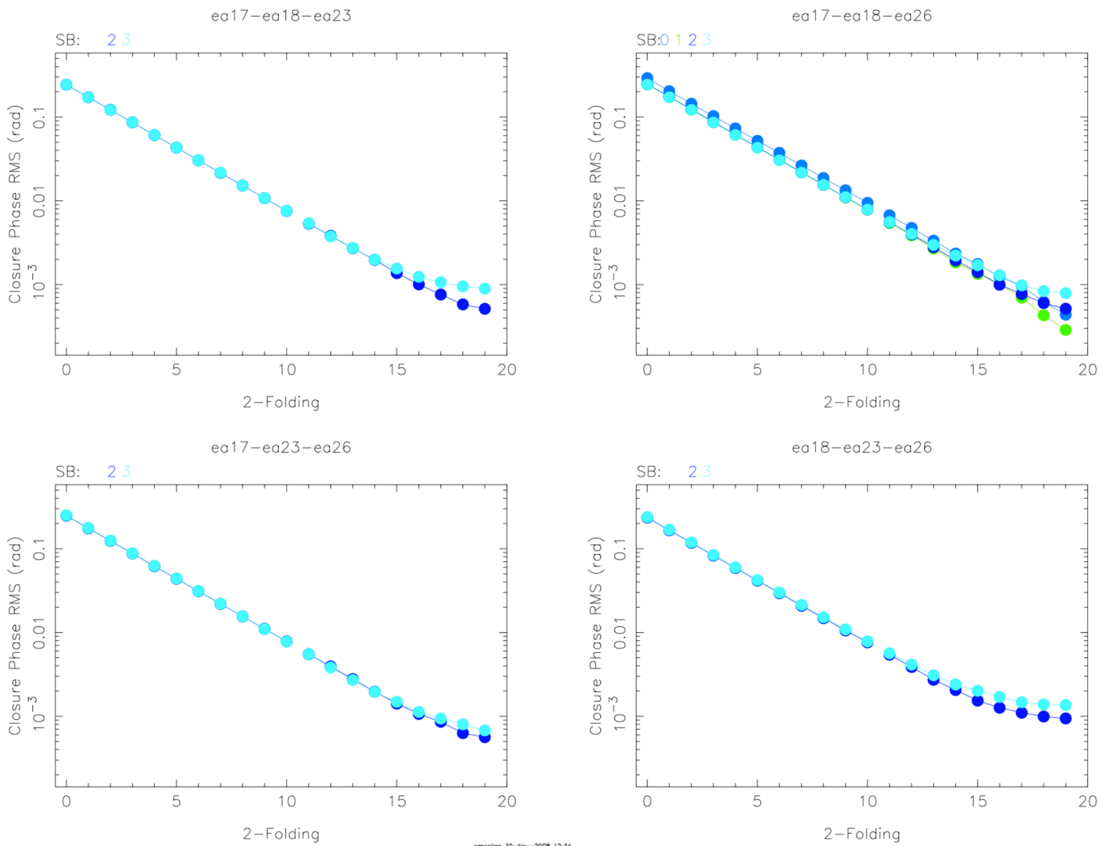
Baseline-based Visibility Calibration





~short integration on 3c286 (~10% polarized)

PTC Closure Phase Tests



Pairwise averaging, first over channel, then time

Instrumental Polarization (cont)

- Prototype correlator closure phase averaging RMS (w.r.t. zero) systematically limited to 0.0005-0.001 rad (0.03-0.06 deg)
  - Non-zero closure phase
- Plausible causes: source structure, correlator problems, instrumental polarization
  - D=2-3% (per antenna, randomly distributed phase) will *necessarily* cause closure phase errors at the observed level, just from the constant DD term (imaginary part)
- Dynamic range will be limited
  - DD~0.0004-0.0009, ~random over baselines
  - Best case, via sqrt(351), DR< 21000-47000
  - Small (not just stable) instrumental polarization desirable
- How does gain calibration respond? (“ACIR”)

Instrumental Polarization (cont)

- Conventional instrumental polarization determination limited to a relative solution for a small array
  - No differential parallactic angle within array
  - Second order terms difficult to leverage
- Absolute solution desirable
  - Linear feed basis (ALMA, EVLA < 1 GHz) provides leverage using linearly polarized calibrator, with *(I+/-Q)* multiplying *D* (rather than *(I+/-V)* with *V~0)* ....stay tuned....
- Application of relative solution should be adequate for total intensity (at least)
  - Yields an *orthogonal* basis (sufficient for formation of Stokes I), just not *pure*
  - Gain calibration should be reconciled ("ACIR")
  - QUV will be distorted, possibly correctable with appropriate calibrator assertions (*V~0,* etc*)*

UV Continuum Subtraction

- An additive blcal calibration (baseline-based solution subtraction)
- Claim: works better than subtracting deconvolved continuum model
  - Subtracting noise?
  - Indiscriminately subtracting un-modeled effects along with continuum?
- Lesson: If you are going to partition effects, must do so completely!