EHT Amplitude Calibration

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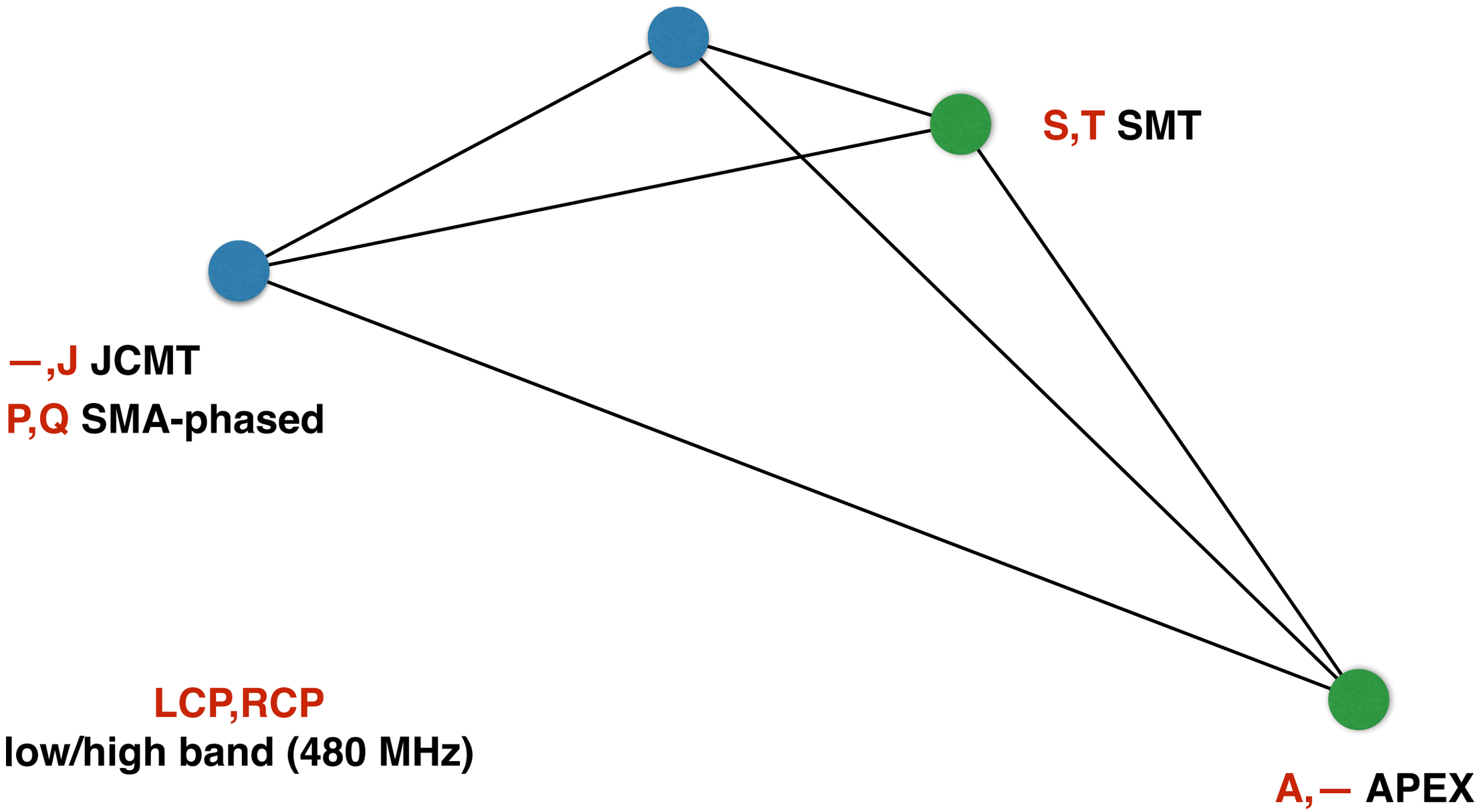
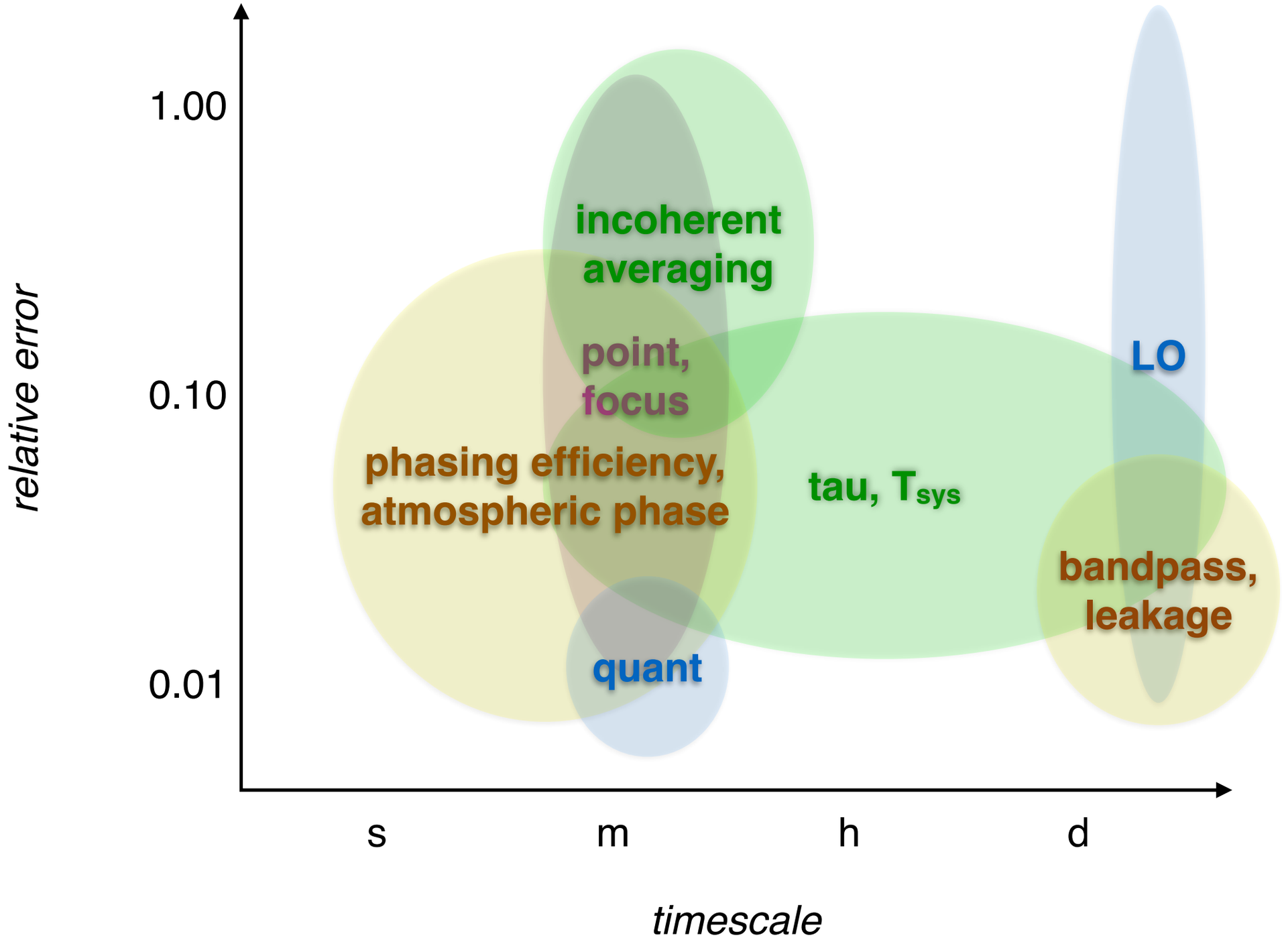
EHT Network (2013)



Amplitude systematics

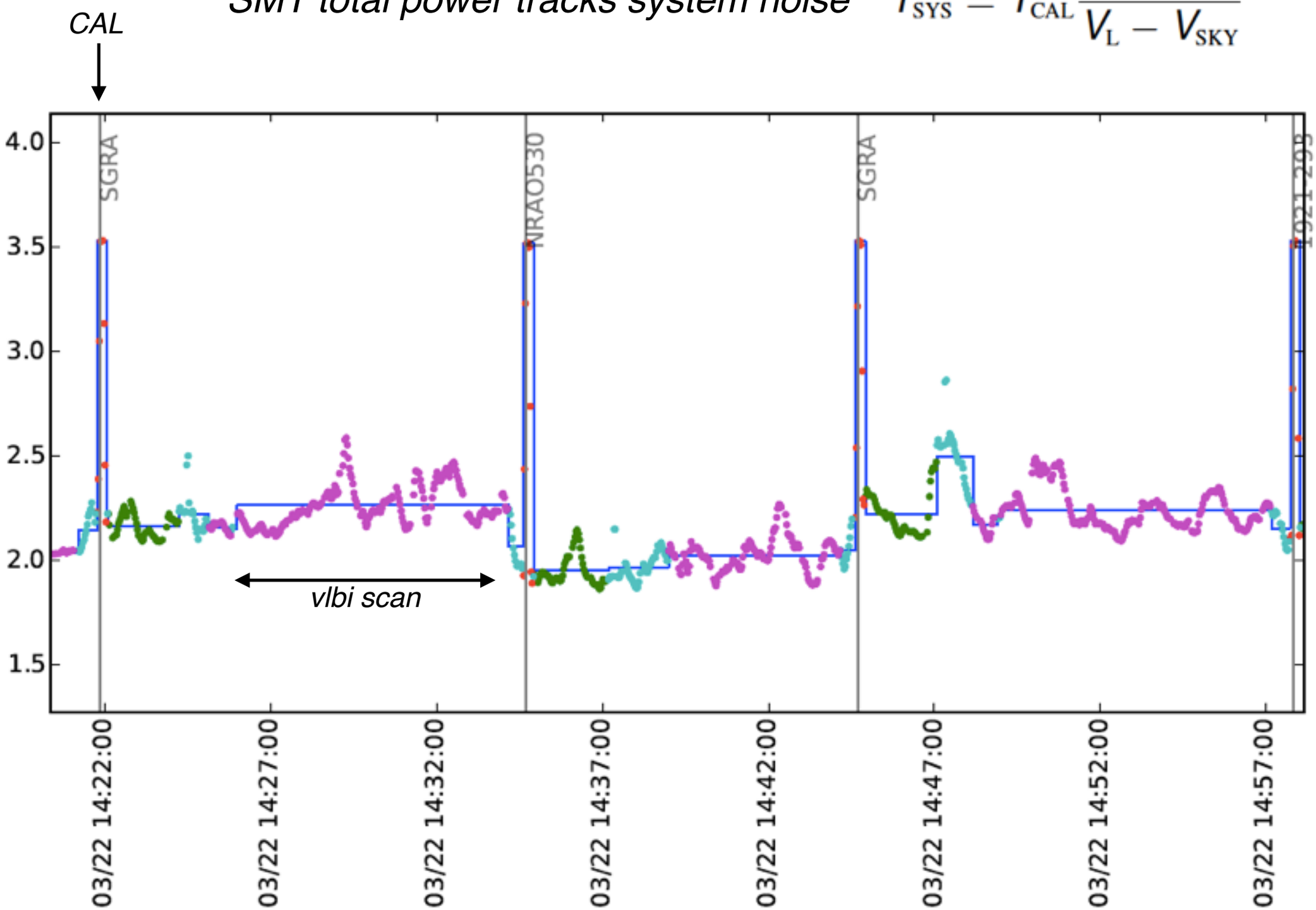
- **Single dish**
  - T_{sys} (T_{rx}, T_{atm}, T_{spill}, …)
  - atmospheric opacity
  - pointing, focus
- **Phased array**
  - phasing efficiency
  - common local noise
- **Correlation amplitude**
  - LO jitter
  - bandpass shape, colored noise
  - atmospheric phase
  - polarization leakage
  - incoherent averaging systematics

Amplitude systematics



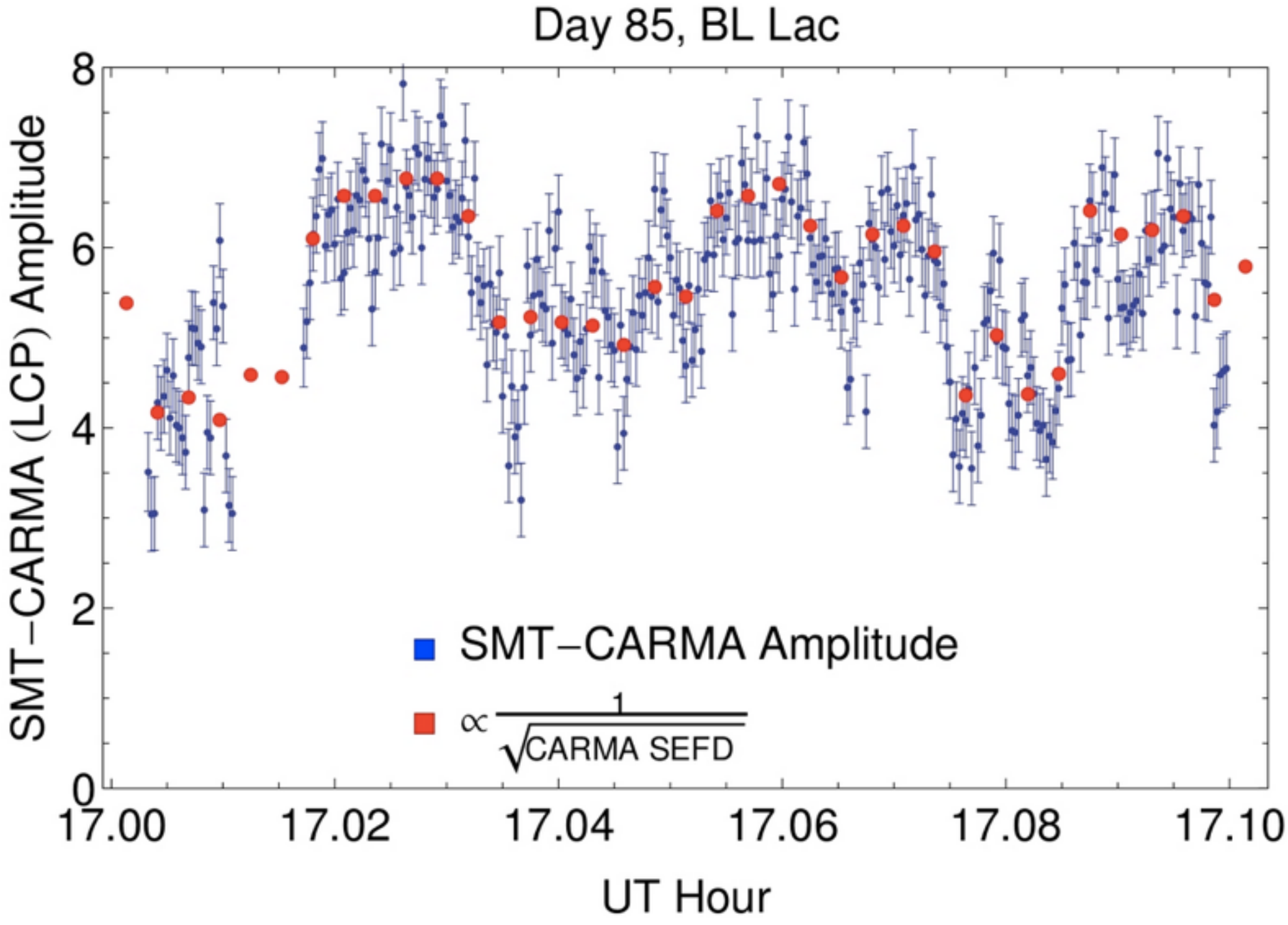
Single dish

SMT total power tracks system noise $T_{SYS} = T_{CAL} \frac{V_{SKY}}{V_L - V_{SKY}}$



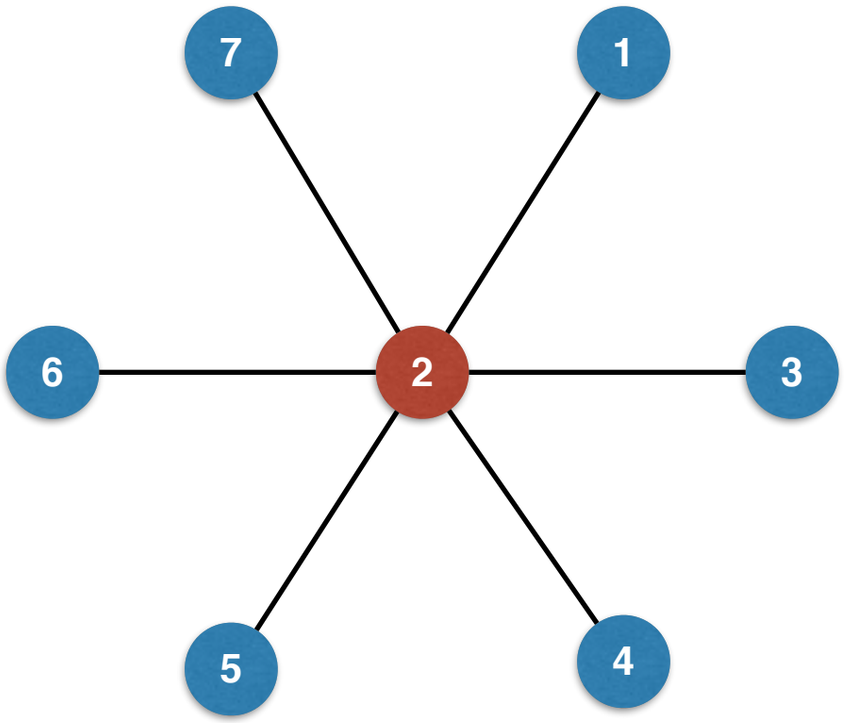
Phasing efficiency (CARMA)

visibility amplitude tracks sub-scan phasing efficiency variation at CARMA



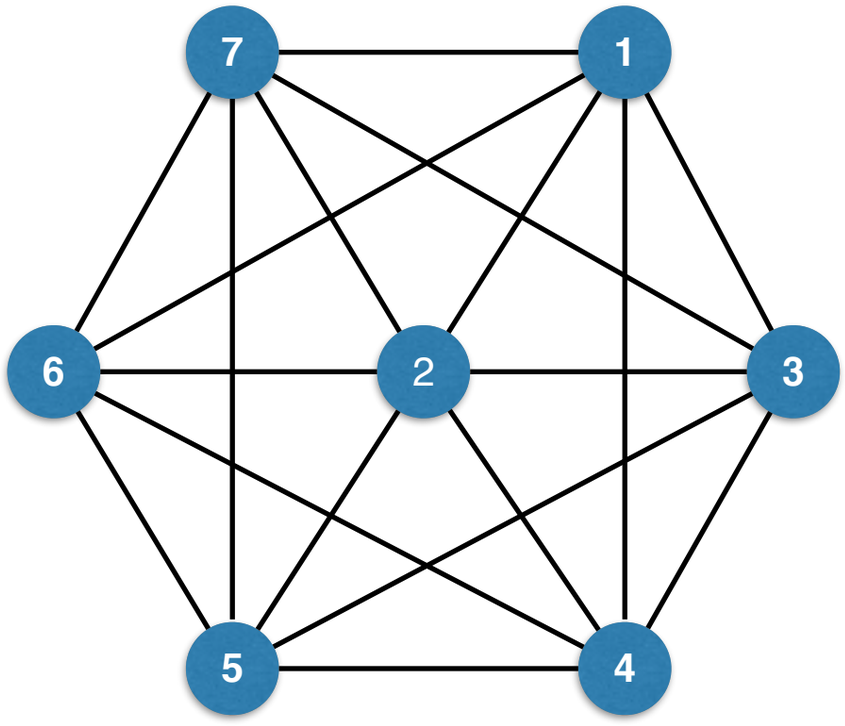
Phasing efficiency (SMA)

PhRInGES (2013)



- median efficiencies 83% (low band), 65% (high band)
- single reference antenna
- 30s averaging period
- 8 channels
- no auto-correlation

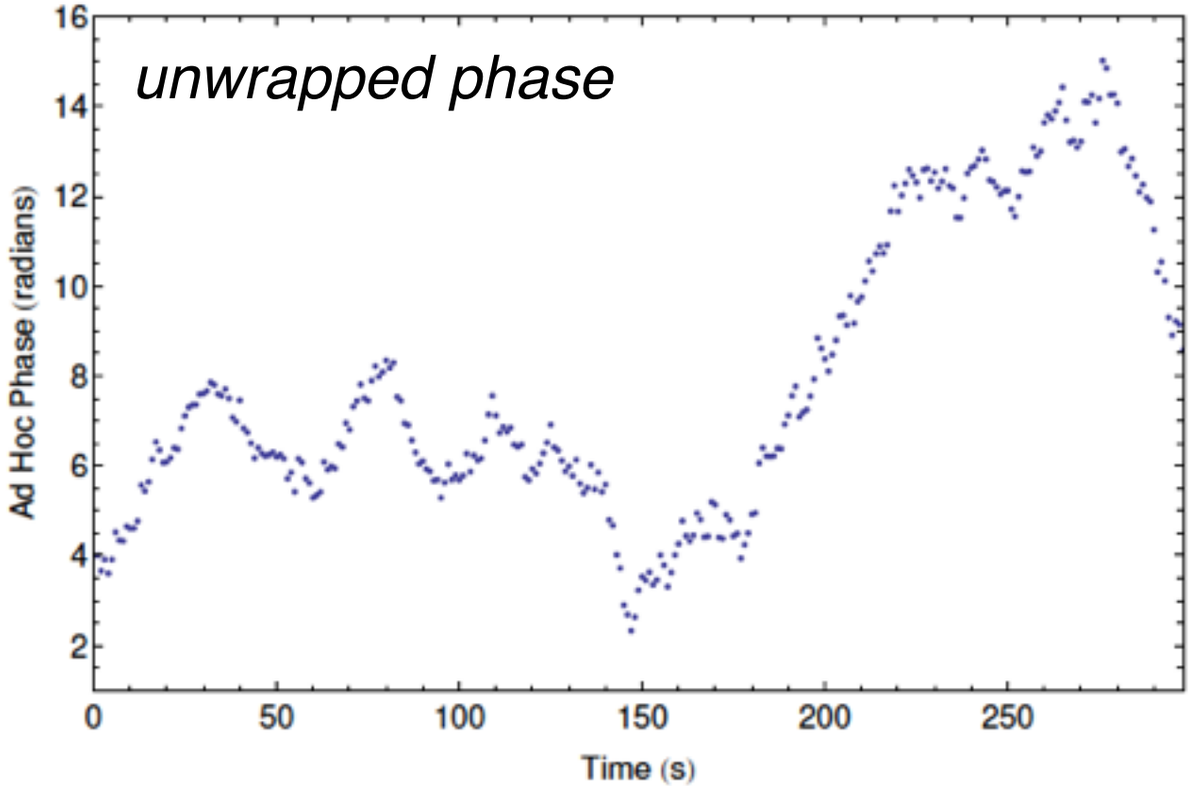
SWARM (2015)

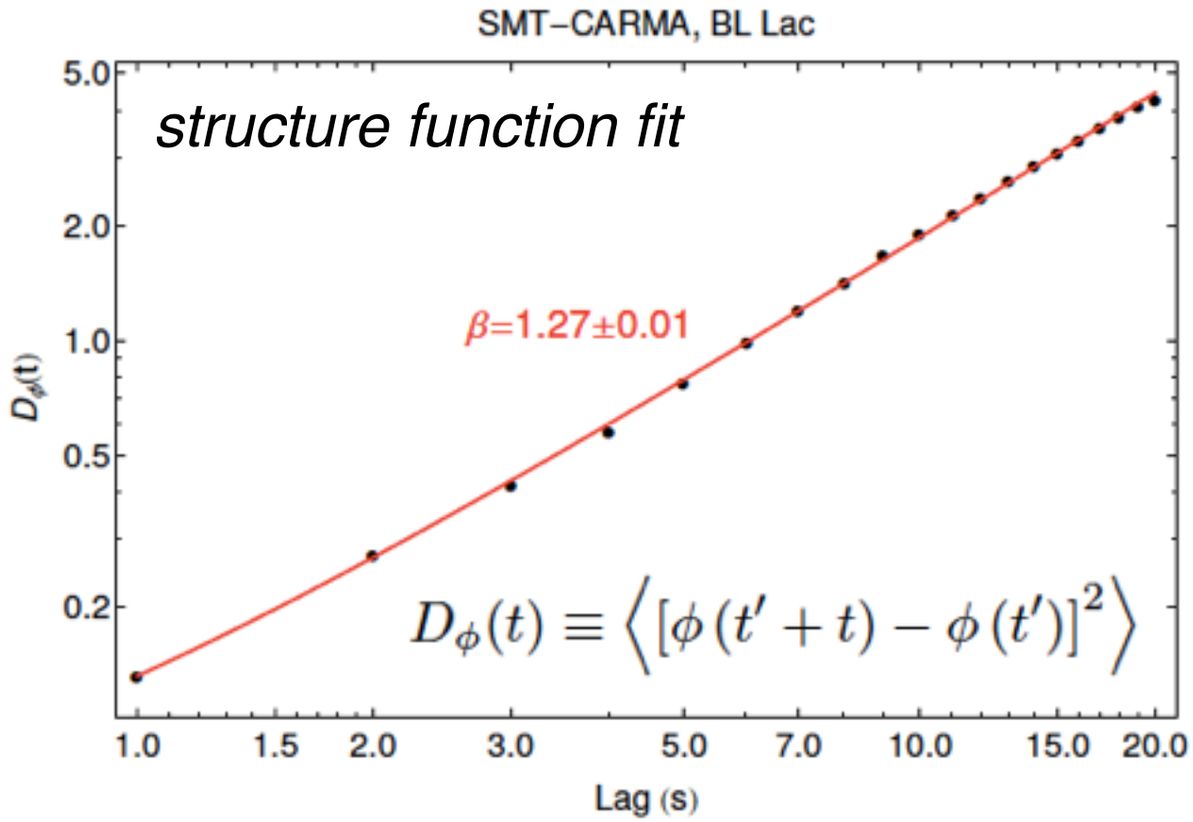


- high 90-% phasing efficiency
- full correlation network
- ~10s averaging period
- 16384 channels
- auto-correlation amplitudes

Atmospheric phase

predictable loss in amplitude due to phase variation within coherent average may be approximated by a gain factor

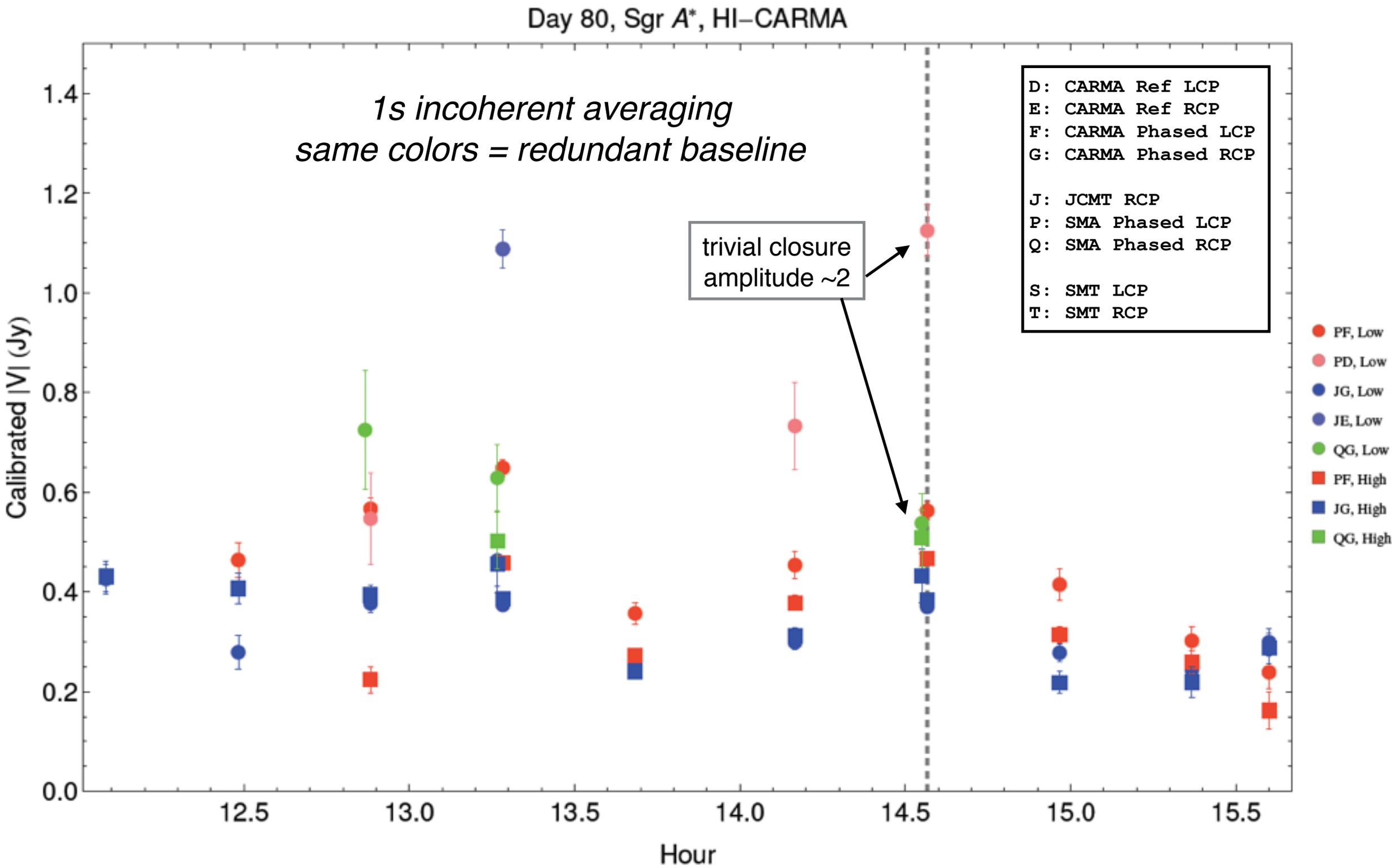




$$\sqrt{\left\langle |G_{\rm atm}|^2 \right\rangle} \approx 1 - \frac{1}{4+6\beta+2\beta^2}\left(\frac{t_{\rm acc}}{t_0}\right)^{\beta}$$

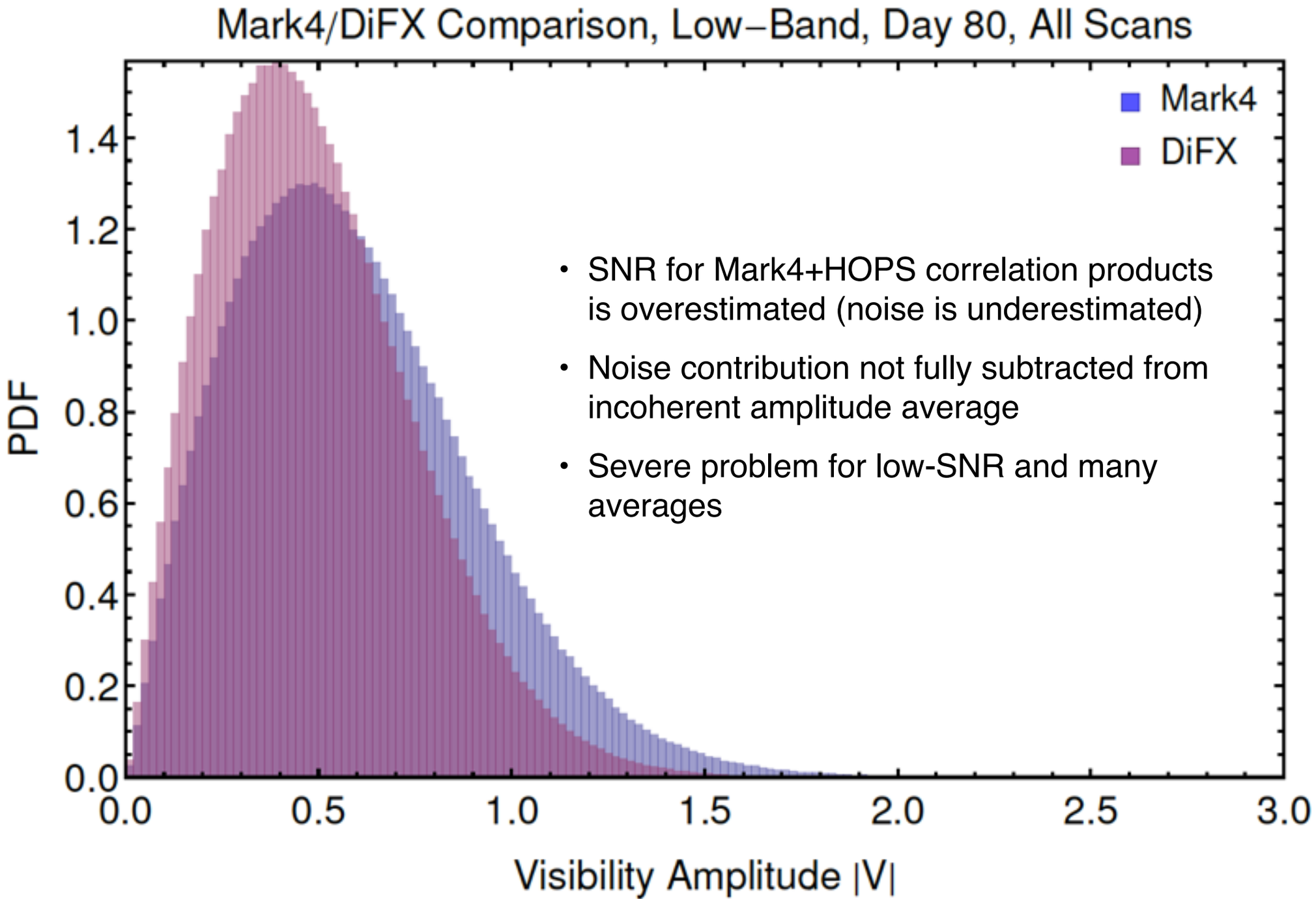
- pre-2013: try different averaging timescales until SNR is maximized
- post-2013: measure structure function coefficient on strong baselines, calculate ideal averaging timescale and amplitude correction factor

Network redundancy



DifX vs Mark4

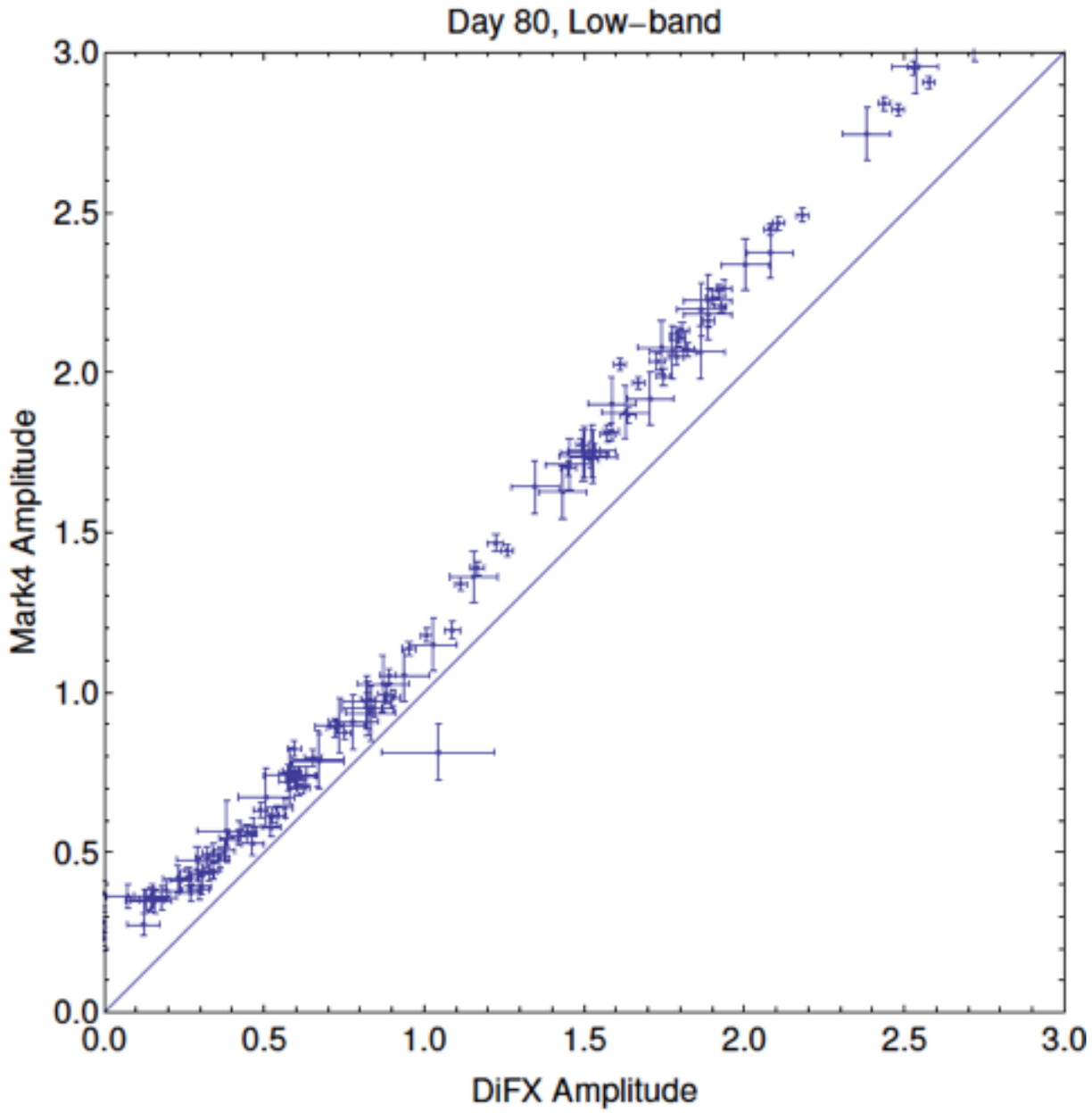
Noise only (off-fringe data)

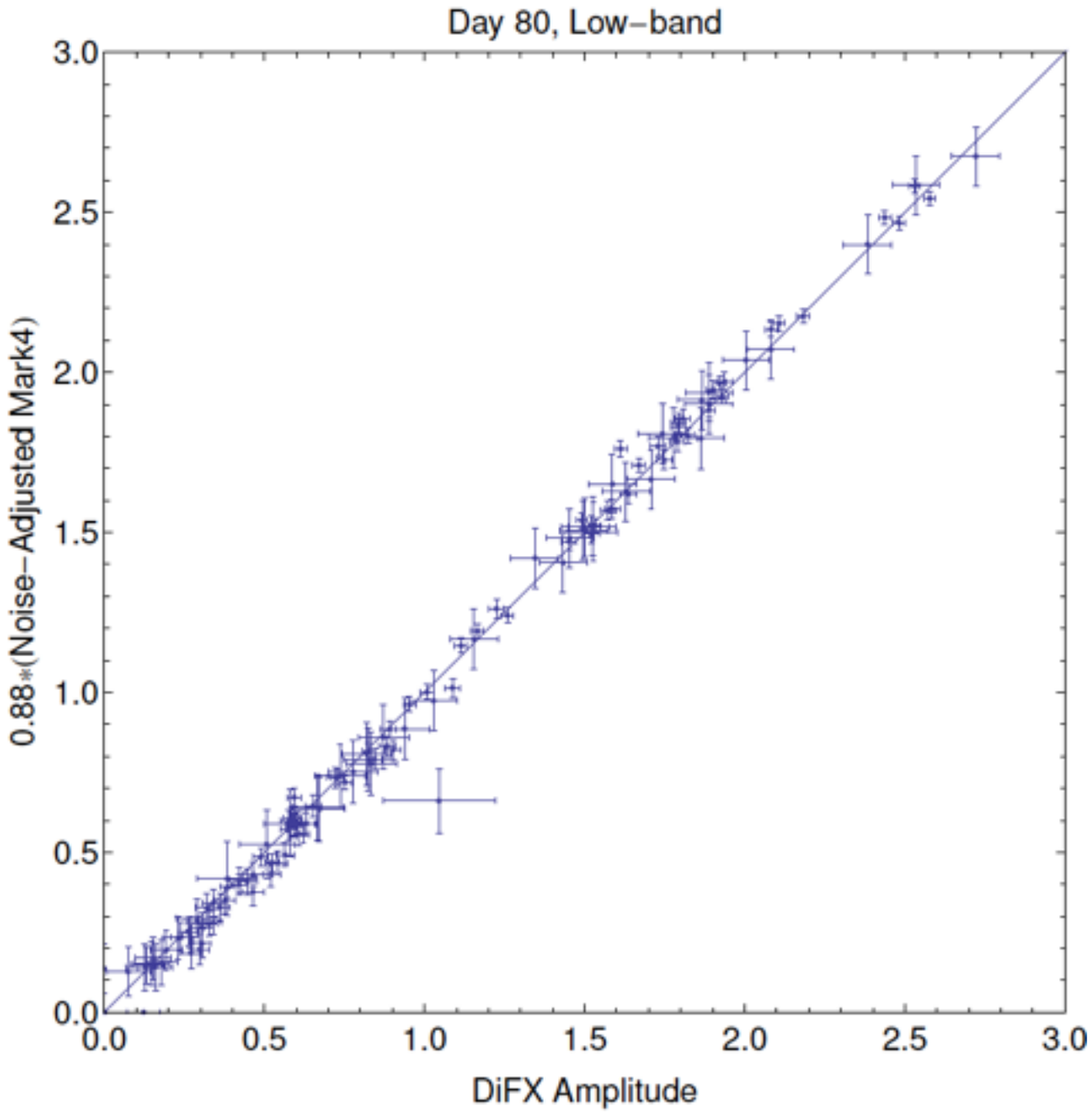


- SNR for Mark4+HOPS correlation products is overestimated (noise is underestimated)
- Noise contribution not fully subtracted from incoherent amplitude average
- Severe problem for low-SNR and many averages

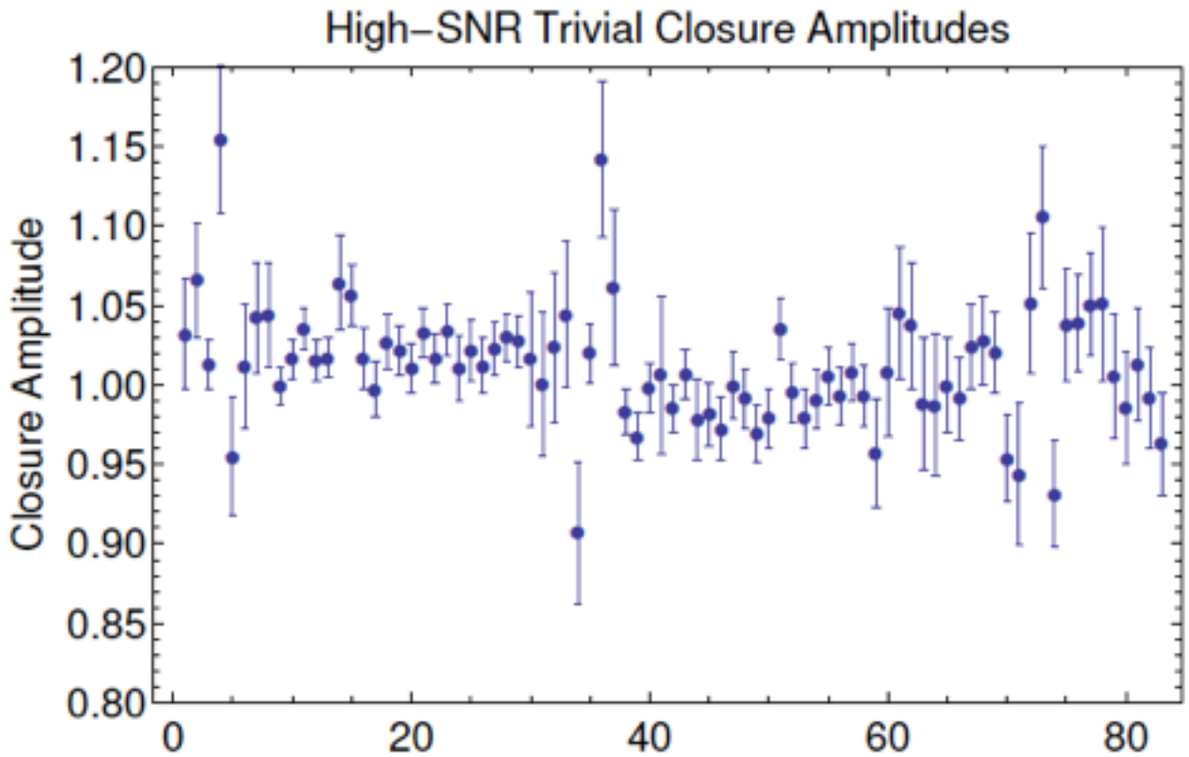
DifX vs Mark4

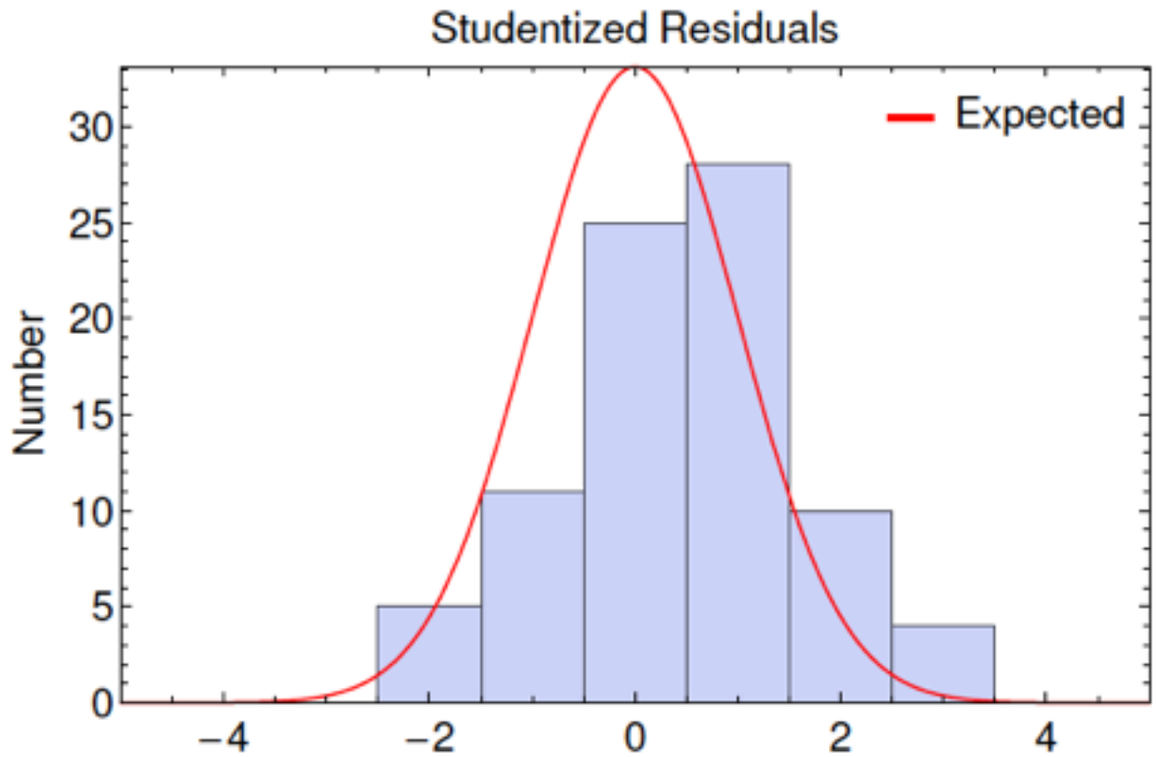
5% correction factor applied to Mark4 noise estimate
DifX not available for many scans (disk failure)

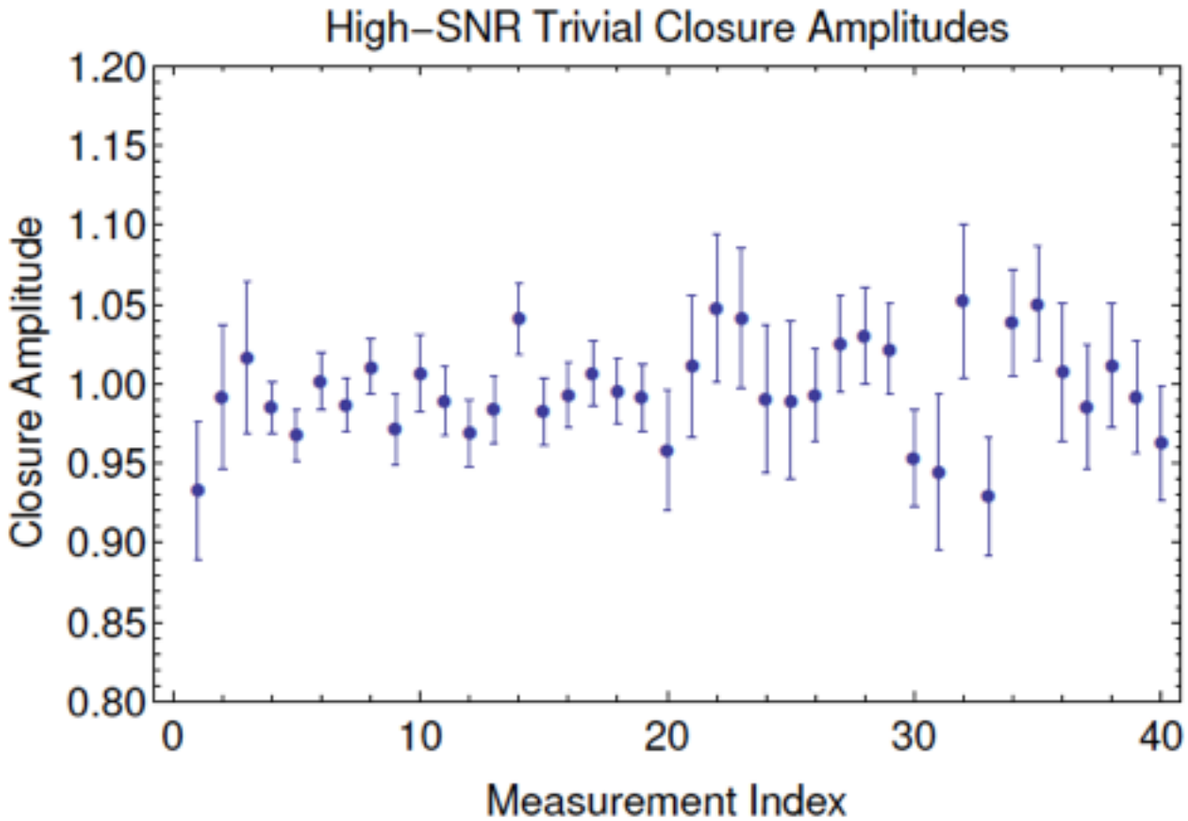


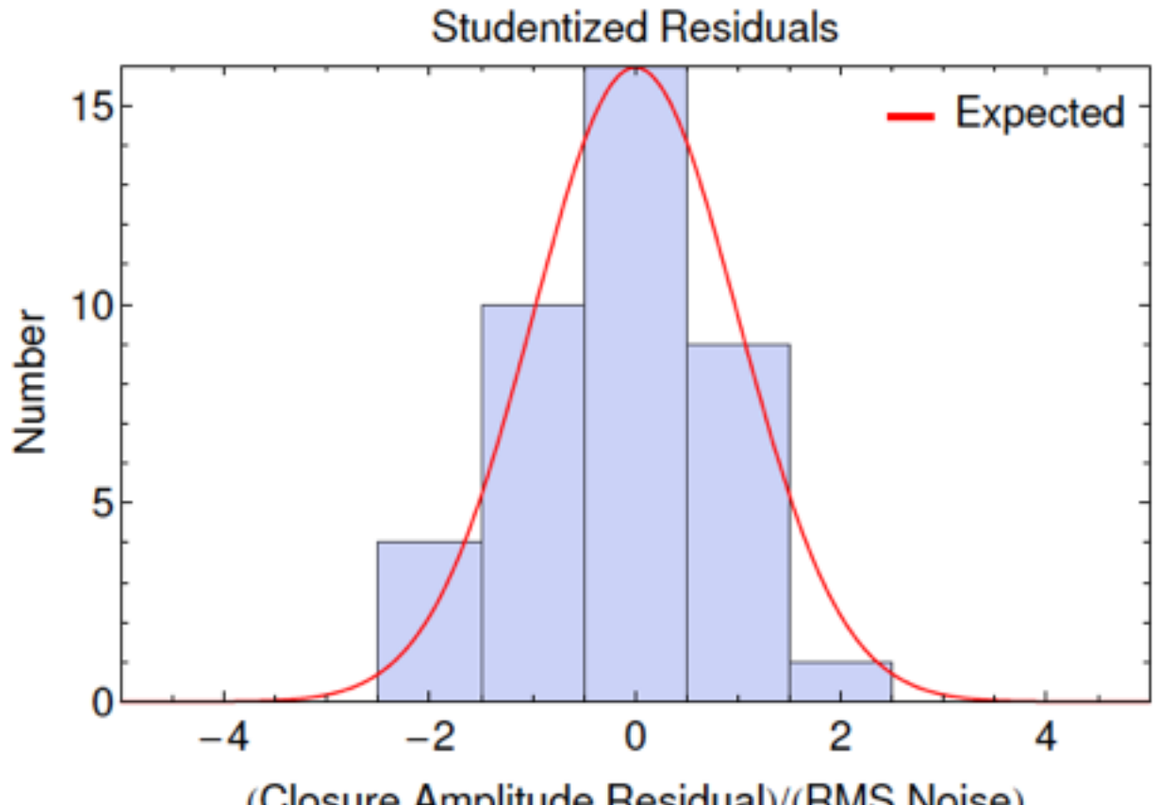


Trivial closure amplitude









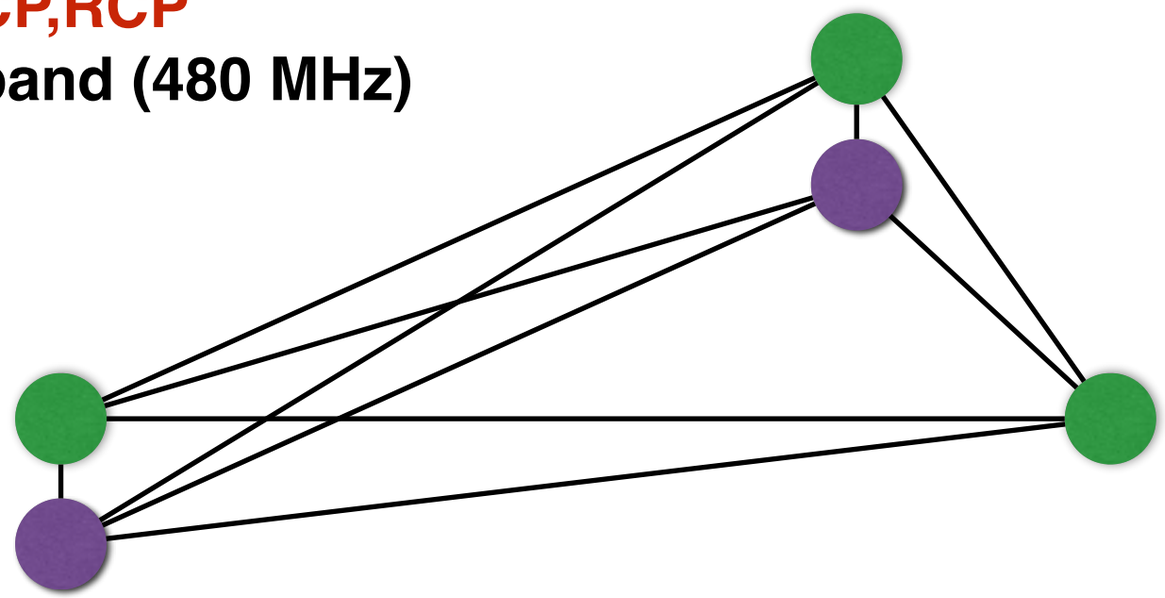
Network solution

D,E CARMA-reference

F,G CARMA-phased

LCP,RCP

low/high band (480 MHz)



- 5 sites
- 10 baselines

S,T SMT

—,J JCMT

P,Q SMA-phased

solve for site gain factors consistent with measured and modeled baseline visibility amplitudes

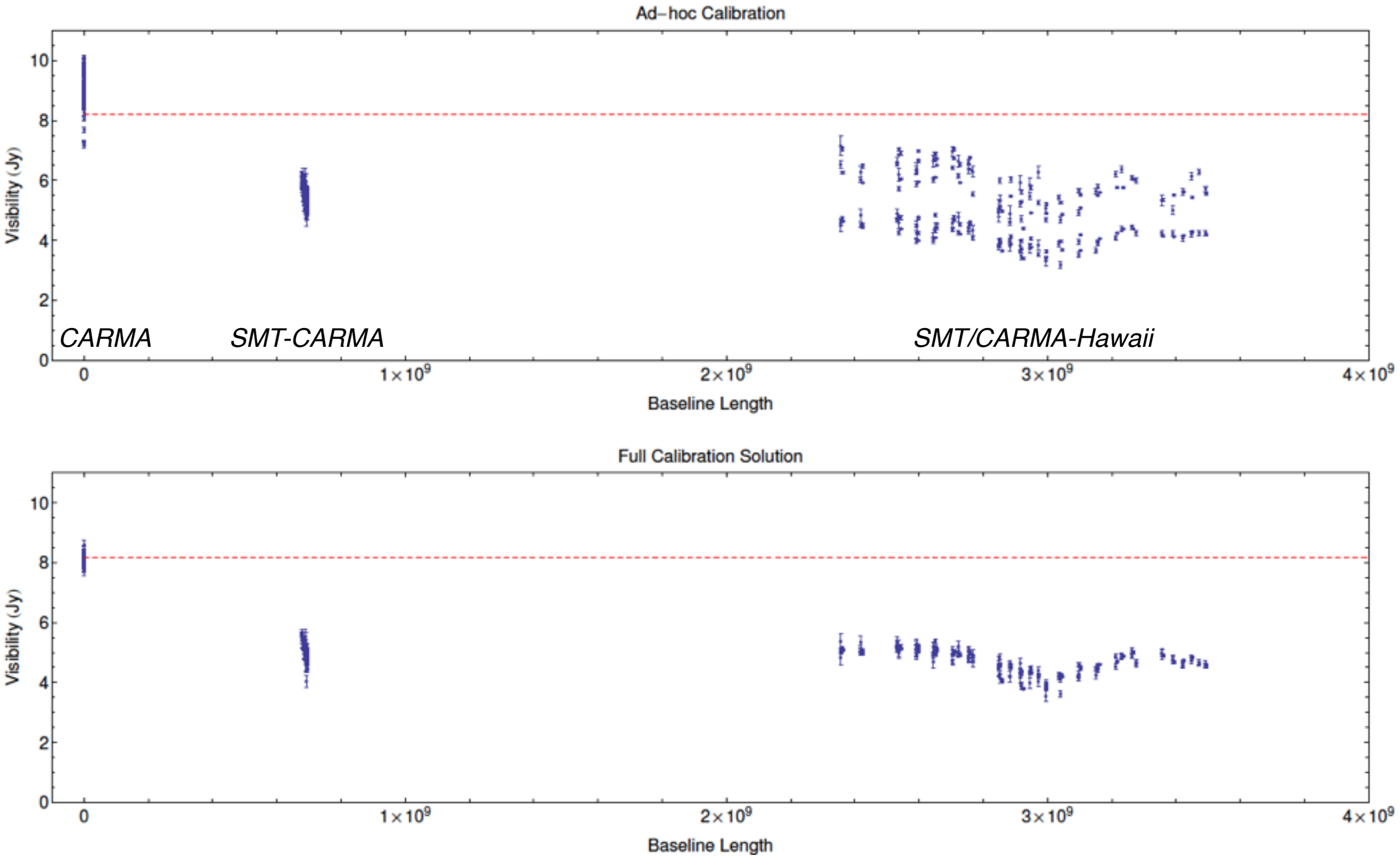
$$|V_{\mathrm{meas}}| = G_1 G_2 \, |V_{\mathrm{exact}}|$$

Connecting the array

- data cuts (few %):
  - SNR < 6
  - anomalous LCP/RCP gain ratio at CARMA Phased
  - >4σ inconsistency between high and low band amplitude
  - >4σ inconsistency between short and adjacent long scans
- daily:
  - LCP/RCP gain ratios estimated at each site
  - LCP/RCP ratio at SMA using adjacent P+Q scans and CARMA Phased, and assumed equal for high/low band
- per scan:
  - solve for site gain ratios and missing model baseline visibilities using measured and assumed model visibilities, with thermal + 2% systematic error added to measured values in χ^2 fit.
  - zero baseline (CARMA-CARMA, JCMT-SMA) assumed equal to CARMA-Phased estimate.
  - For SgrA* assume CARMA-SMT is close to zero-baseline
  - otherwise assume SMT calibration for absolute LCP gain

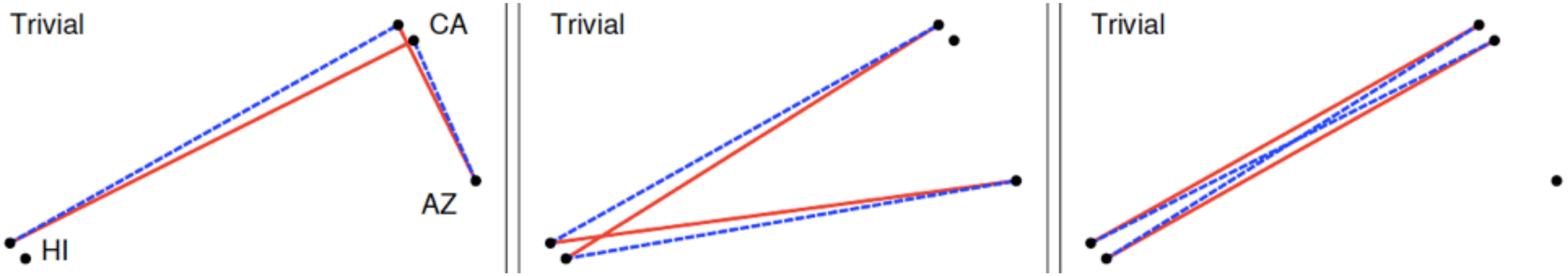
```
D: CARMA Ref LCP
E: CARMA Ref RCP
F: CARMA Phased LCP
G: CARMA Phased RCP

J: JCMT RCP
P: SMA Phased LCP
Q: SMA Phased RCP

S: SMT LCP
T: SMT RCP
```

Solution amplitudes

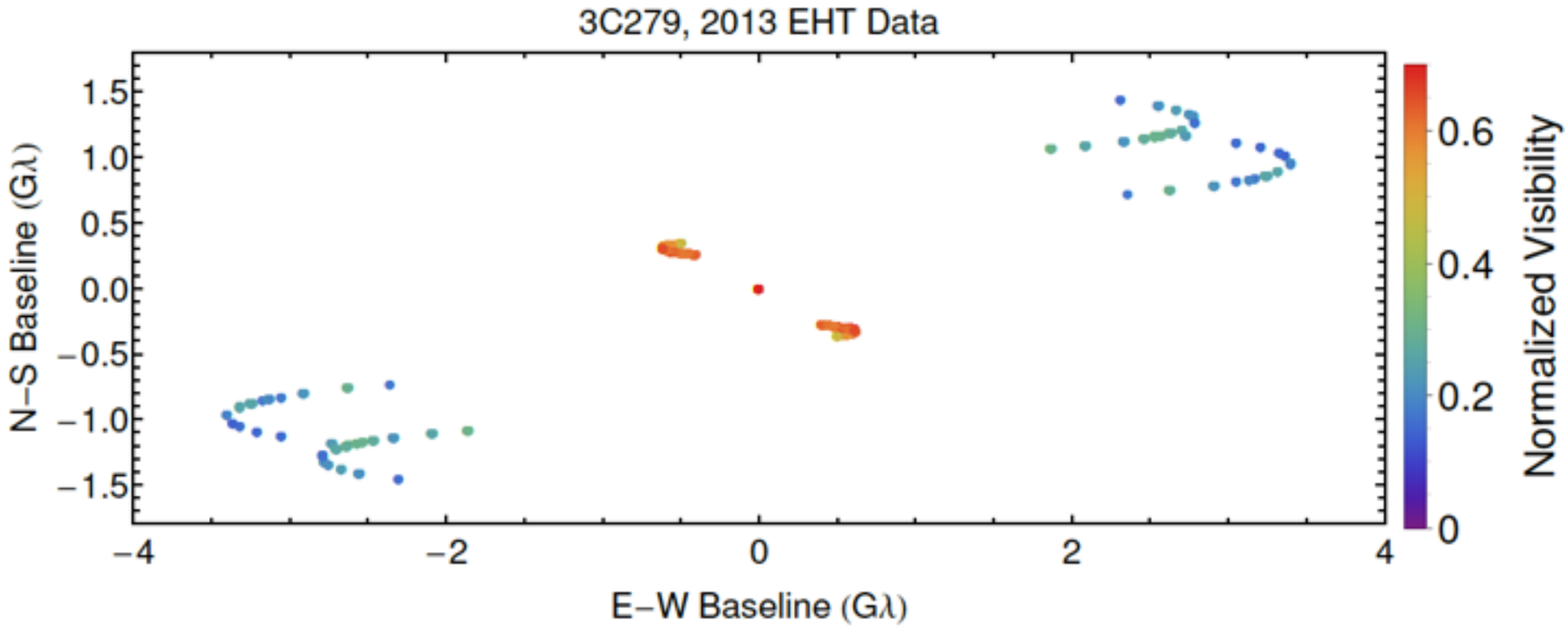


Calibration validation

- Trivial closure quantities

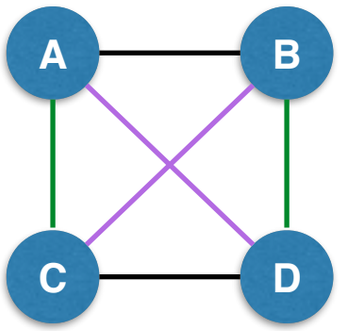


- Crossed or similar baselines



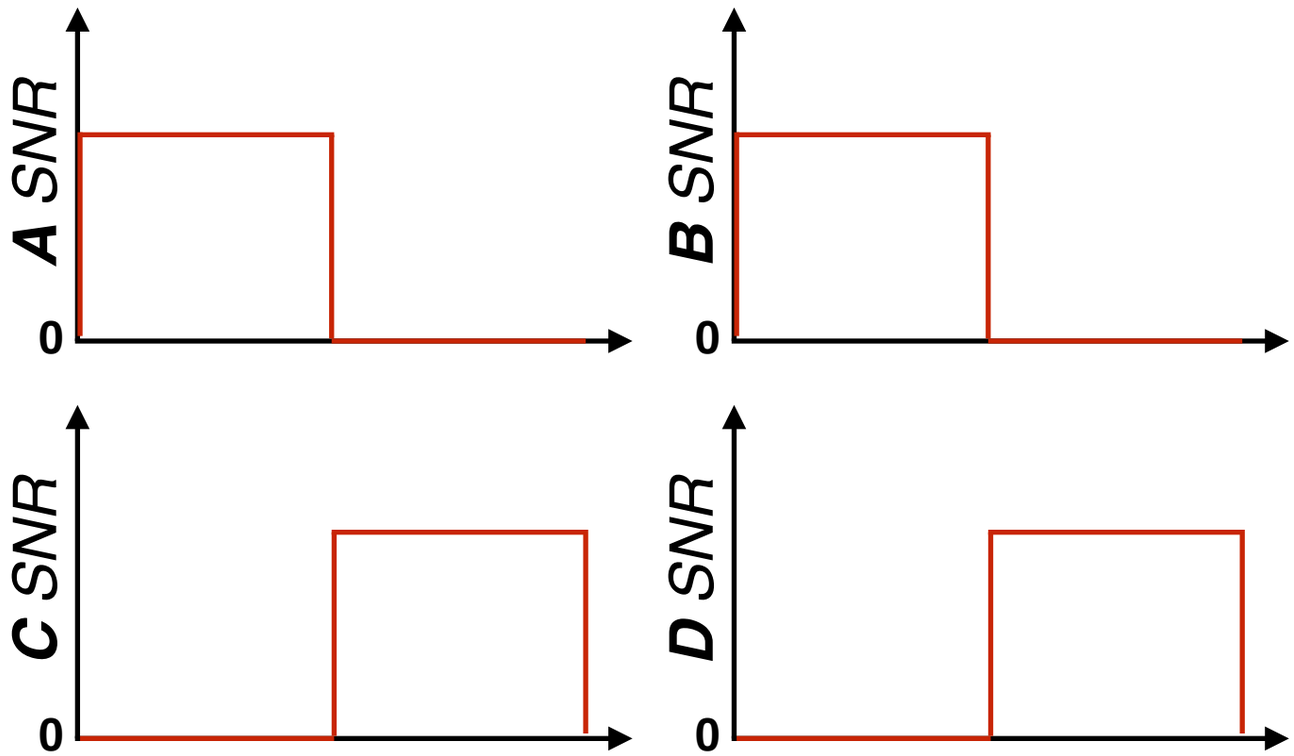
- Source-subtracted residuals

Averaging



closure amplitudes

$$\frac{AB \cdot CD}{AC \cdot BD} \qquad \frac{AB \cdot CD}{AD \cdot BC}$$



zero baseline..

$$\frac{1 \cdot 1}{0 \cdot 0} \neq 1$$

EHT 2015

- **2 GHz single-channel in time domain**
  - easier to correlate (no band matching)
  - bandpass effects (even if channelizing at correlation)
- **SMT**
  - severe slope in pass band
- **LMT single-dish site**
  - pointing uncertainty
  - new receiver
- **SWARM-correlator phased array at SMA**
  - new complicated frequency-domain data product
  - more stable phasing