International Centre for Radio Astronomy Research

Investigations on MultiView VLBI for SKA

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1- ICRAR/UWA
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3- OAN/IGN

Curtin University

The Government of Western Australia

The University of Western Australia

VLBI in the Era of SKA

SKA will have 100-times the collecting area of current telescopes.

⇒ Baselines to SKA will have 10-times the collecting area ($\surd A_{ska} A_{tel}$)

SKA Mid and Low will be centred at frequencies around 1000 and 300 MHz, respectively

⇒ The new science will come at these frequencies

Science targets will be newly discovered compact objects.

⇒ VLBI will provide _dynamical_ information; the proper-motions, the relationship to other parts of the hosts, the distances

All astrometry — but astrometry at 1GHz and below is very hard

Astrometric VLBI at low Frequencies

Maria Rioja has covered the new methods for low frequency phase referencing. The errors arise from the static ionospheric component:

$$14.5\left(\frac{\nu}{8\mathrm{GHz}}\right)^{-1}\frac{\Delta I}{6\mathrm{TECU}}\left[\frac{\Delta\theta}{2^{o}}\frac{\cos(41^{o})\tan(Z)}{\cos(Z)\tan(41^{o})}\right]$$

Improvement come from:

Reducing the ionosphere error,

higher frequency, ensuring high Zenith angle,

or reducing the source-calibrator separation.

With dense GPS measurements we may be able to improve from a residual of 6TECU to 3TECU.

But this is equivalent to a _metre_ of residual path length (20mm/o)

c.f. 30mm of residual tropospheric path length (0.5mm/o)

for 35μ as we require ~1mm/o error on 6000km baseline

$\Rightarrow$ For significant improvements we need closer calibrators.

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Units: differential ΔTEC normalised per degree converted to mm delay per degree

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Population Estimates

In-beam Phase Referencing addresses this directly:

e.g. PSR-π, which has typical separations of 0.2 degrees, $\Rightarrow \sigma_{\rm epoch} \sim 100\,\mu{\rm as}$

Possible for L-band, as usually find sources with-in VLBA beam;

PSR-π, 60 out of 70 sources had in-beams — high success rate

arvix-1808.09046

Rare for other frequencies as primary beam are smaller …

Nevertheless for significant improvements we need even closer calibrators

SKA-VLBI will be an order of magnitude more sensitive: $\sigma_{thermal} \sim 10 - 1\mu{\rm as}$

so we are looking for a calibrator order of magnitude closer, searching an area two orders of magnitude smaller: $N \propto S^{-0.9} \sim 8$

$$\sigma_{\rm global\ j} \sim 30 - 80\mu{\rm Jy} : N \sim 10^2/^o = 1 \text{ per } 6'$$

Godfrey SKA Memo 135

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Well short of required 1 per 1′

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Multi-View Review

Maria Rioja has covered this, yesterday .. so I will summarise:

- Use Multiple Simultaneous Beams around the target.
- Fit a planar surface for each antenna.
- Solve for Ionospheric screen, at the line of sight of the target.

$$\Rightarrow \Delta\theta = 0$$

All error terms will be zero (static/dynamic, tropo-/ionosphere)

Perfect phase-referencing

Demonstrated in Rioja '16 (visibility-based) & Reid '17 (image-based)

Used in Immer etal. 2018, Sakai etal. in-prep (virtual quasar)

solves for Static Ionospheric Wedge over array

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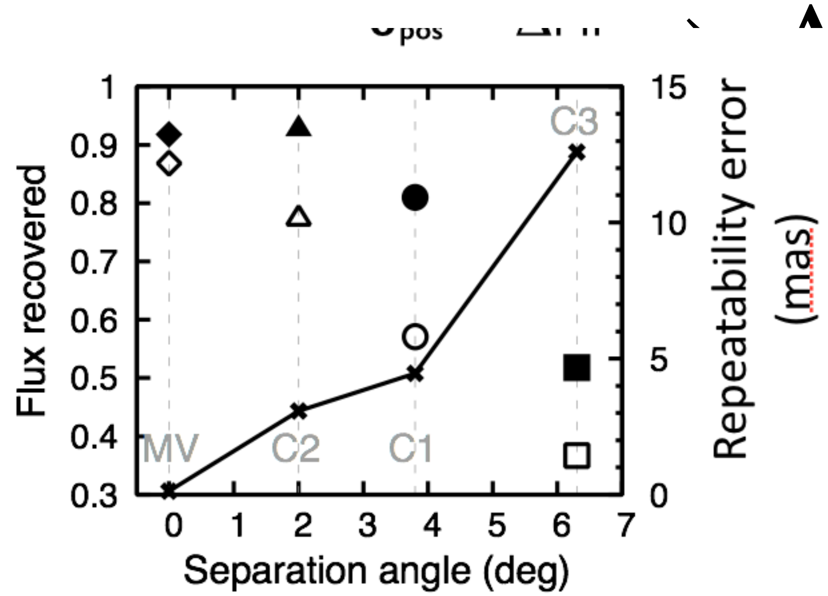

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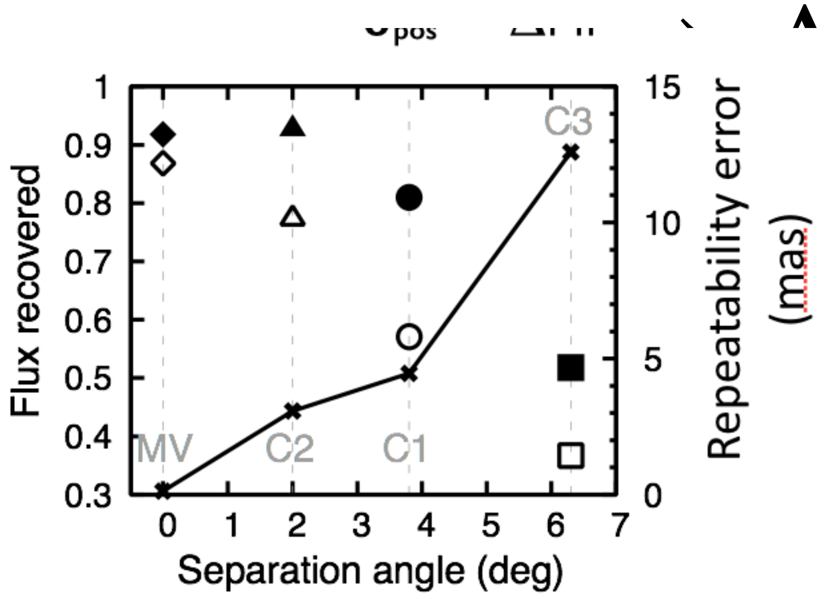

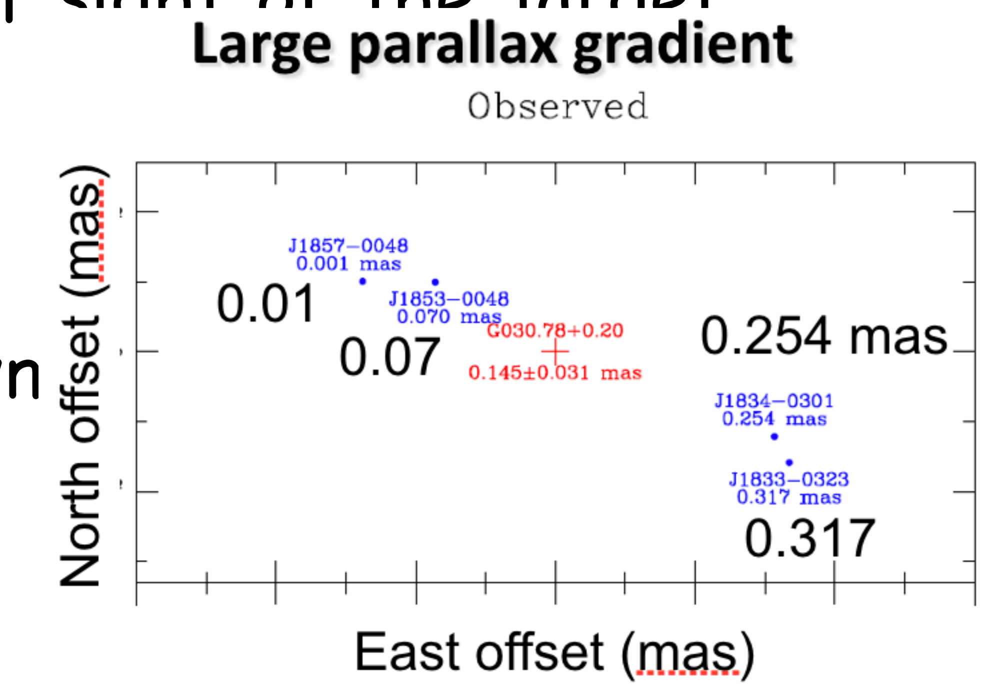

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How many Beams needed?

These are the crucial design question for SKA-VLBI:

- How many beams are needed?

  Is it a function of frequency?
- Can we assume that the phase surface is flat?
- Would more beams allow fitting a curved surface?
- Would more beams allow contemporaneous checks on calibrators?
- Would more beams allow new science goals?

MWA - RTS System

Dan Mitchell (Mitch) designed the Real Time System for EOR studies with Murchison Widefield Array (MWA). Chris Jordan used this to characterise MWA Phase-1 (3km baselines) ionospheric behaviour: Jordan etal. 2017, MNRAS

Image-shift measurement for all visible sources, every 8-sec $\Rightarrow \Delta\mathrm{TEC}(t, \Delta\vec{l})$

Has been used to classify types of weather:

weak (1), moderately correlated (2),

highly correlated but weak (3), highly correlated and strong (4)

We used these measurements to derive the change in gradient w. angle

source shifts $\propto \Delta\mathrm{TEC}/^{o}$

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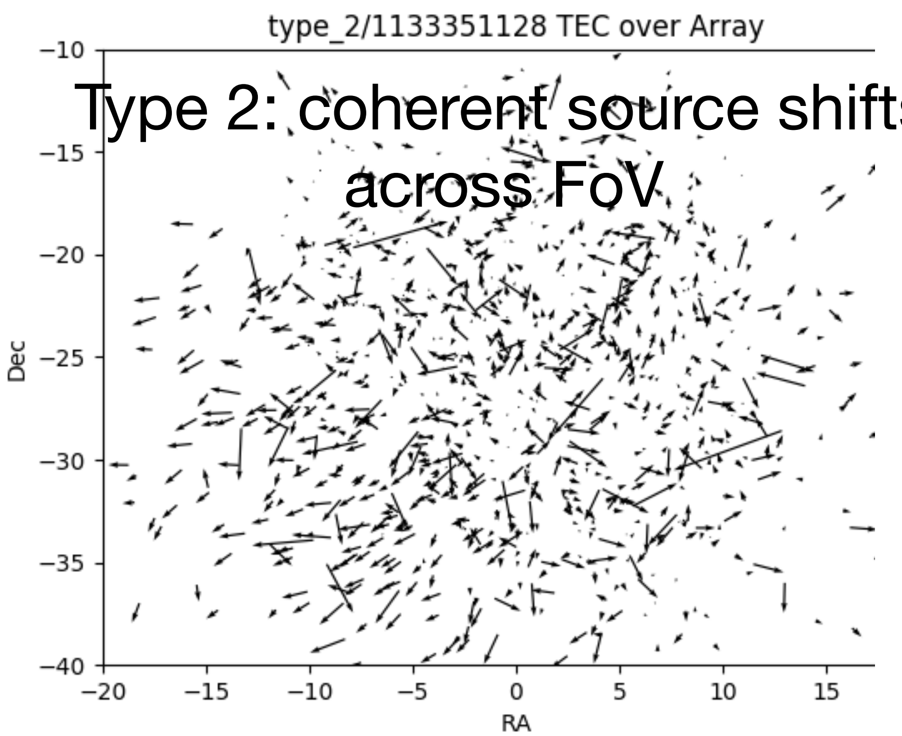

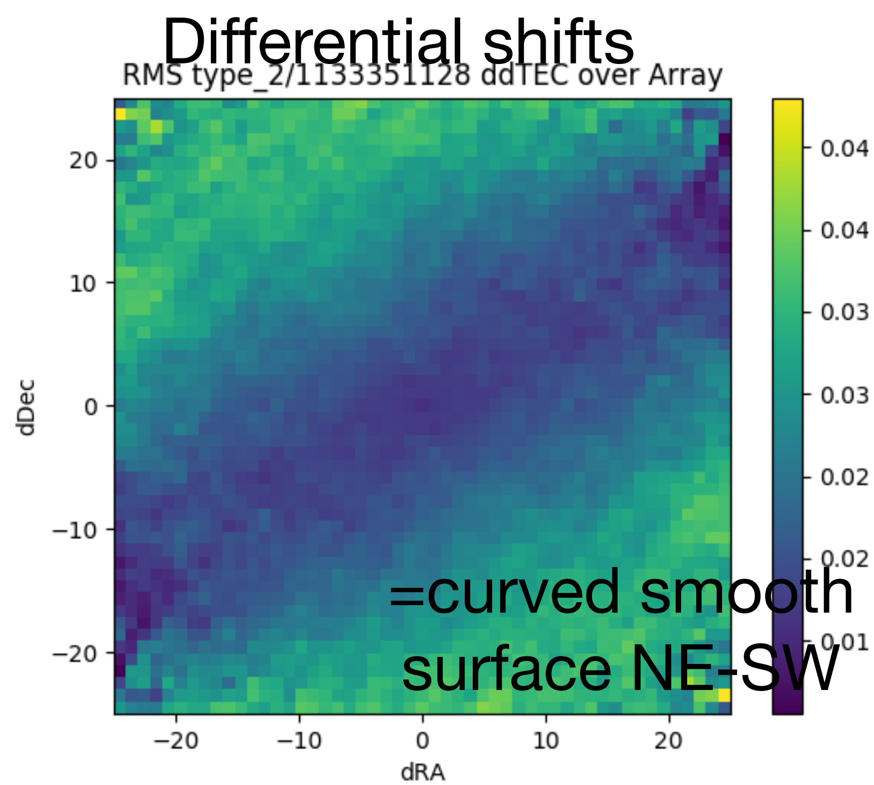

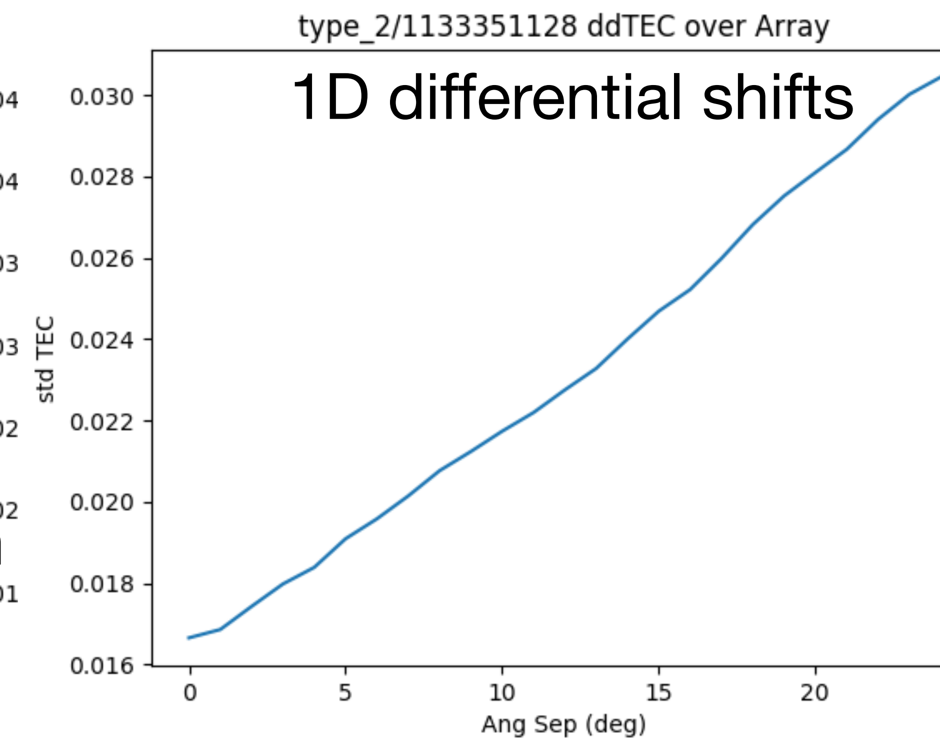

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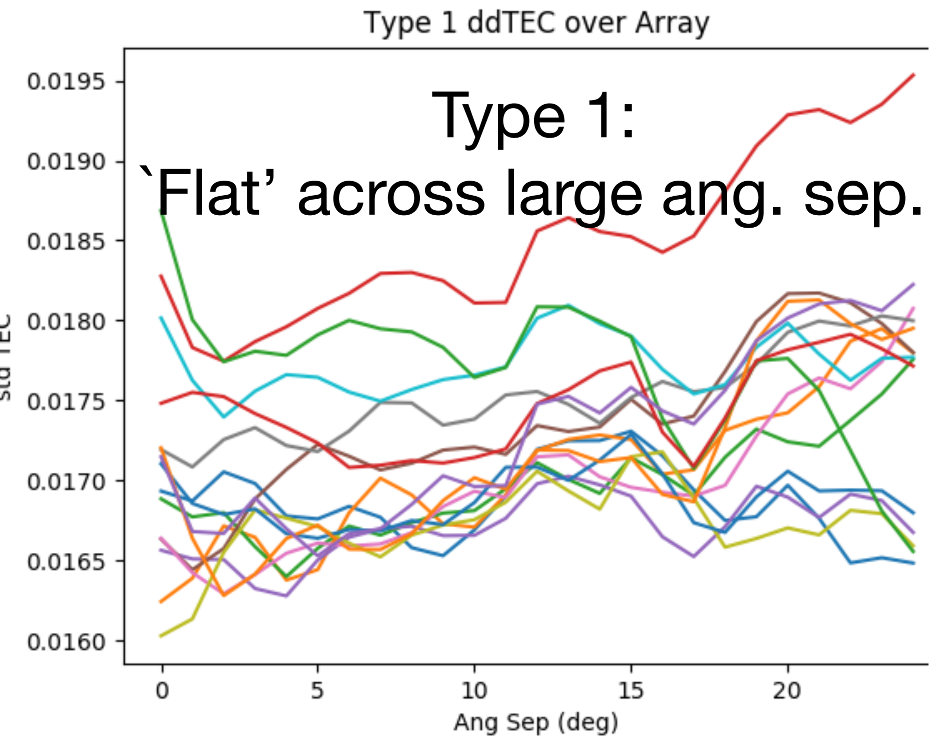
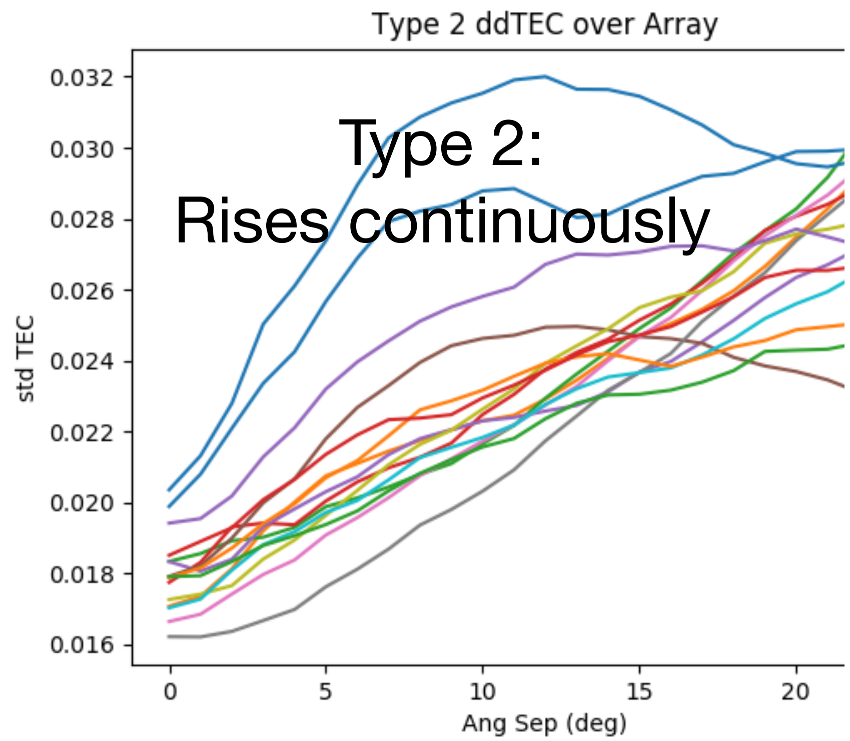
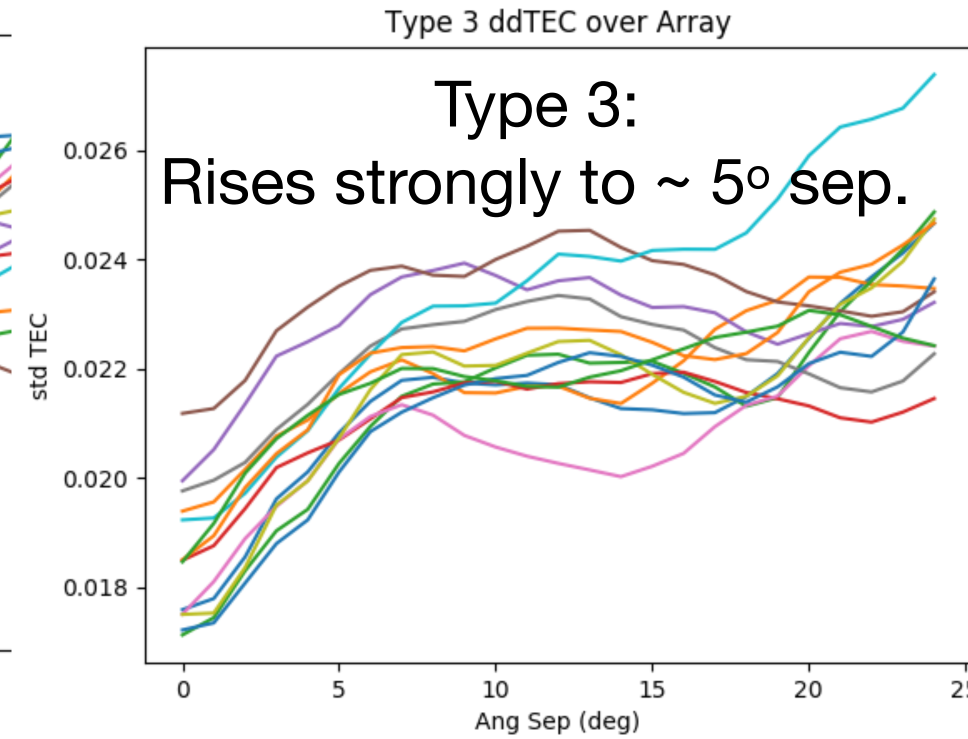




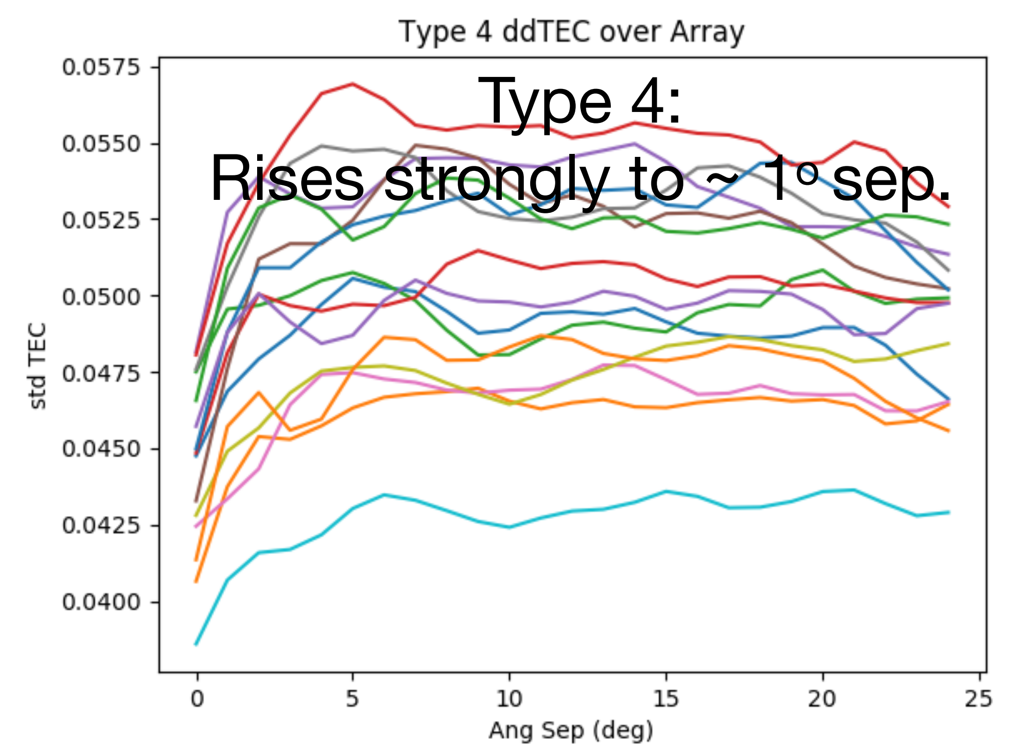


In most cases (0.02dTEC/º) residual path at 1.5GHz is ~4mm for calibrators at 1º (0.02*1*400*1.5^-2)

$\Rightarrow$ 100μ as

whereas, for BeSSeL-South (@6.7GHz)

MV Calibrators with 3º sep. would be acceptable in all weathers (0.05*3*400*6.7^-2)



ICRAR

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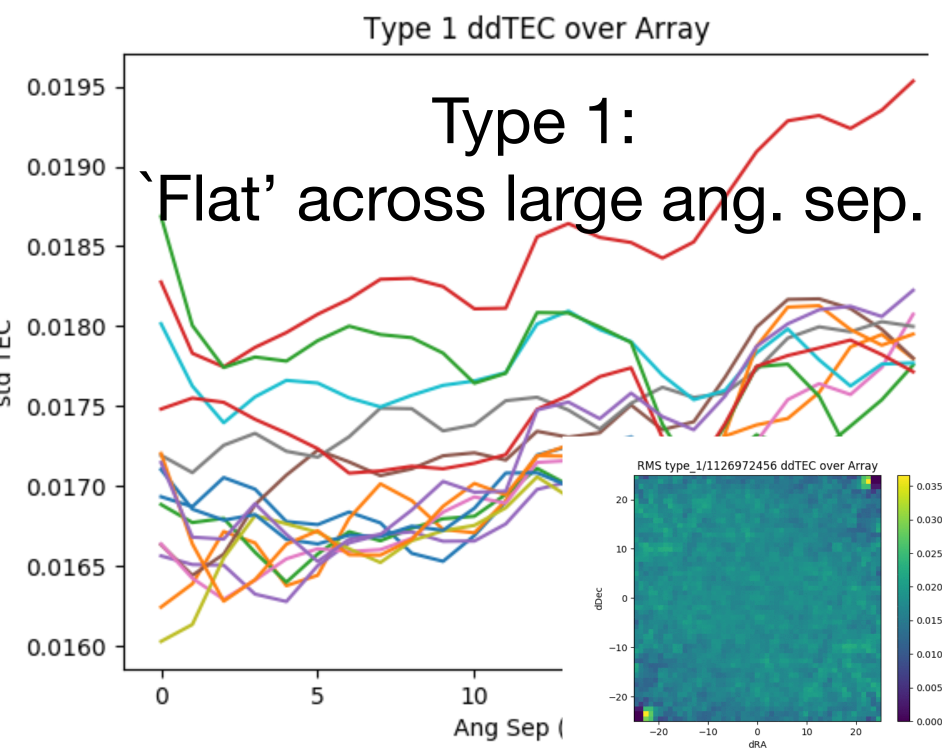

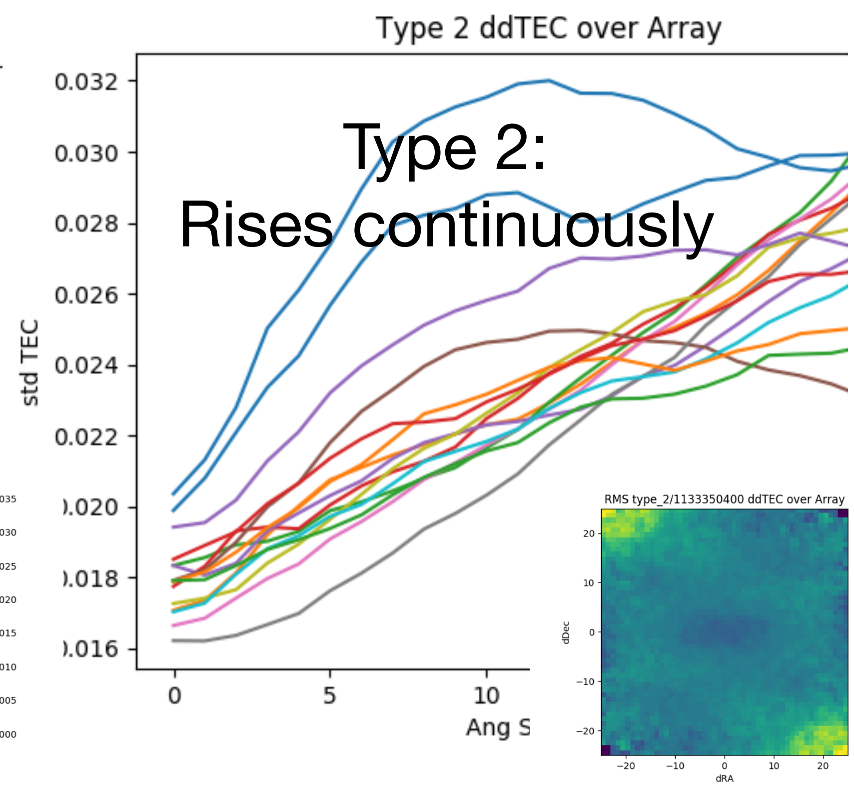

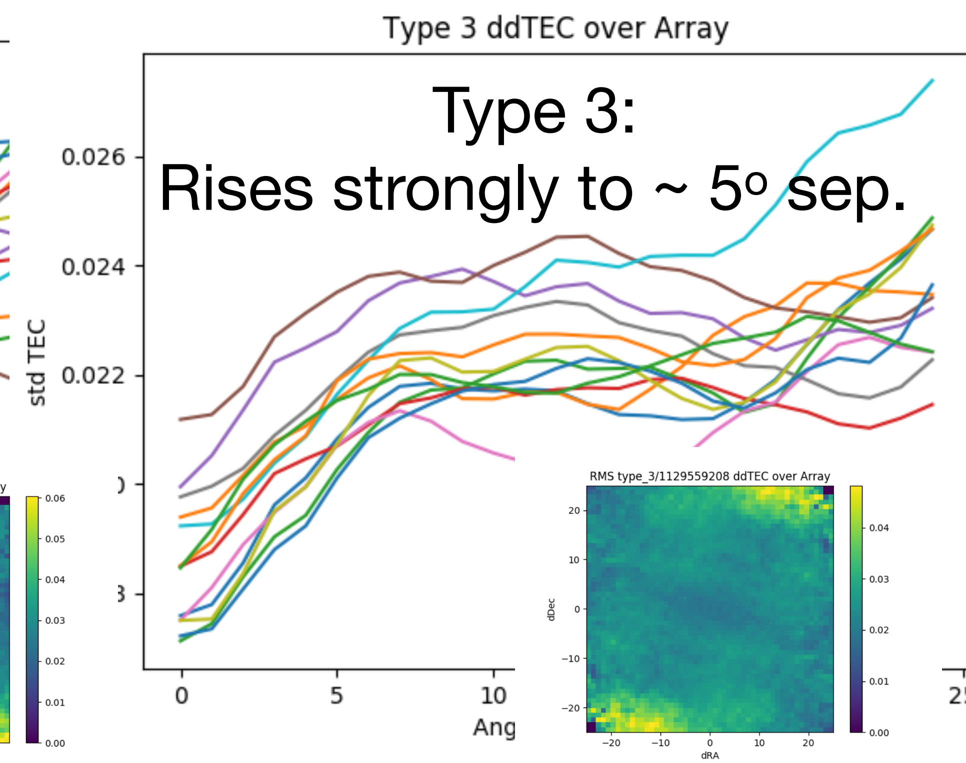

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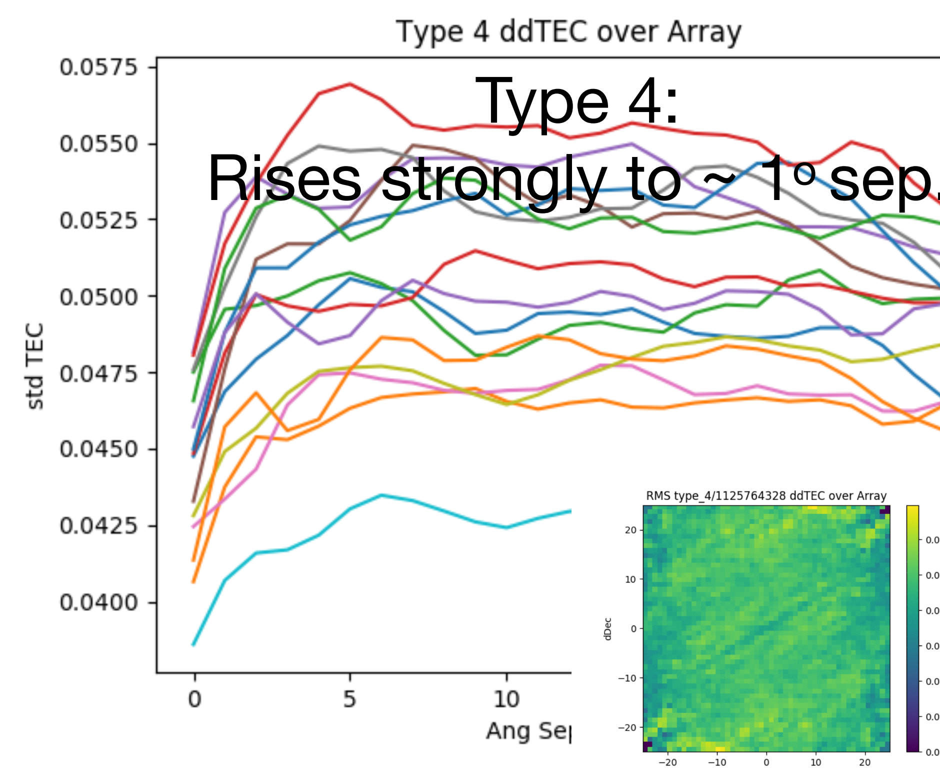

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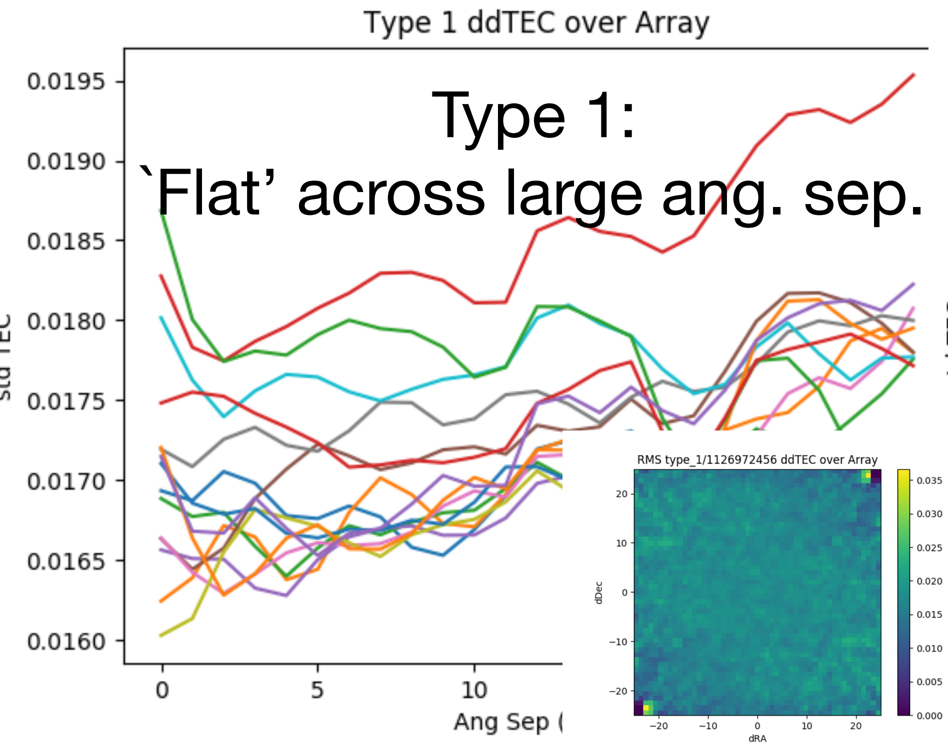

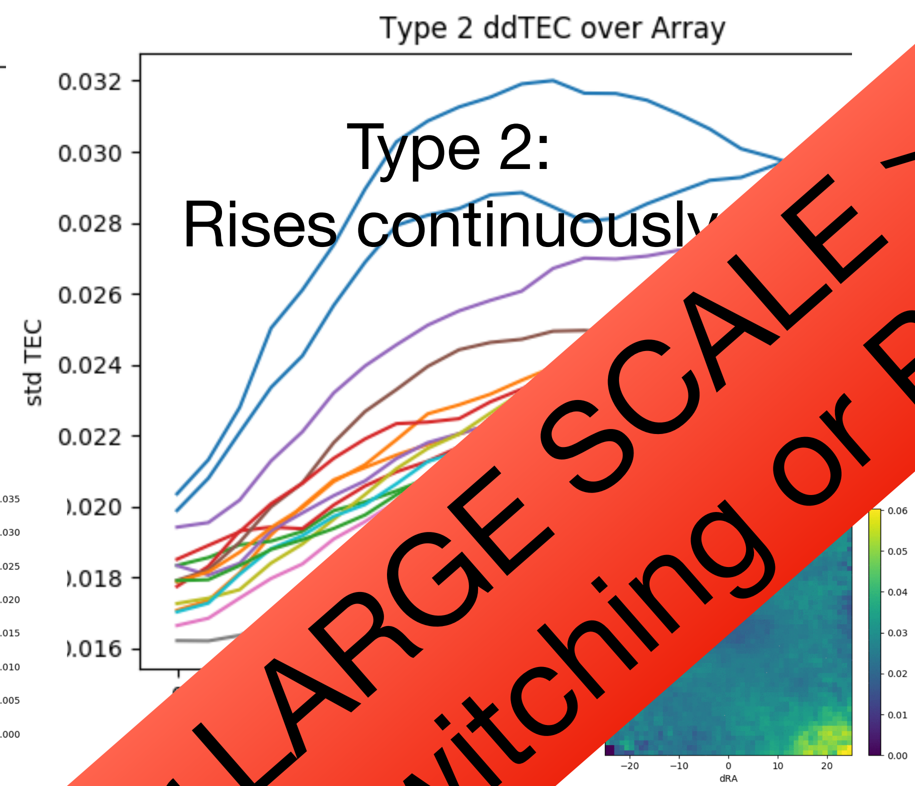

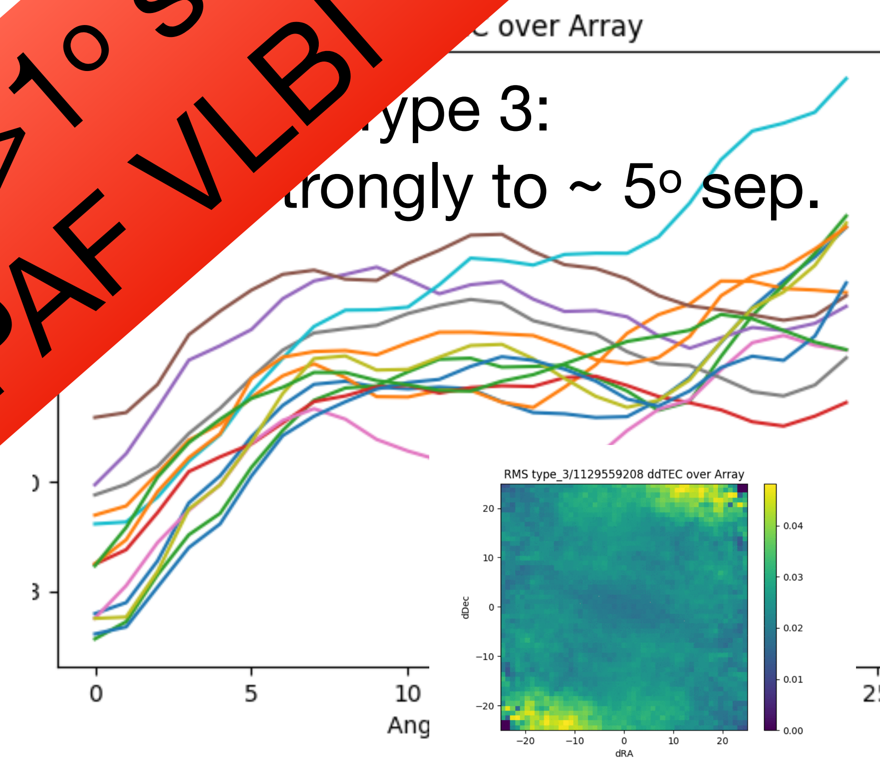

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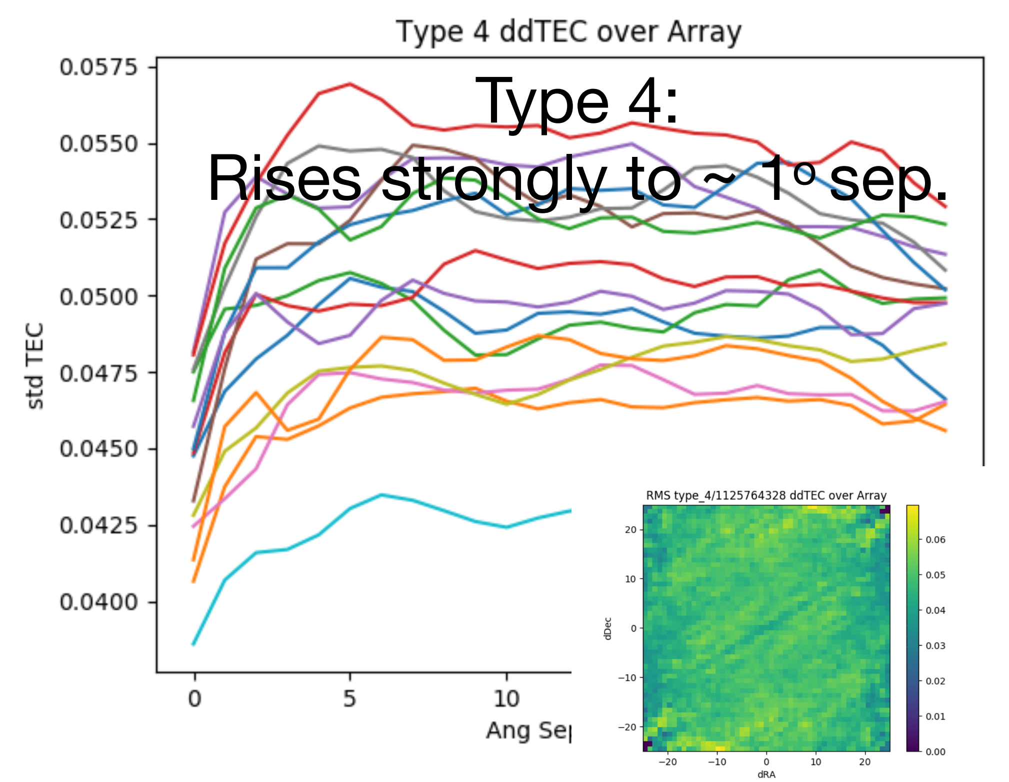

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Applicable for switching or PAF VLBI

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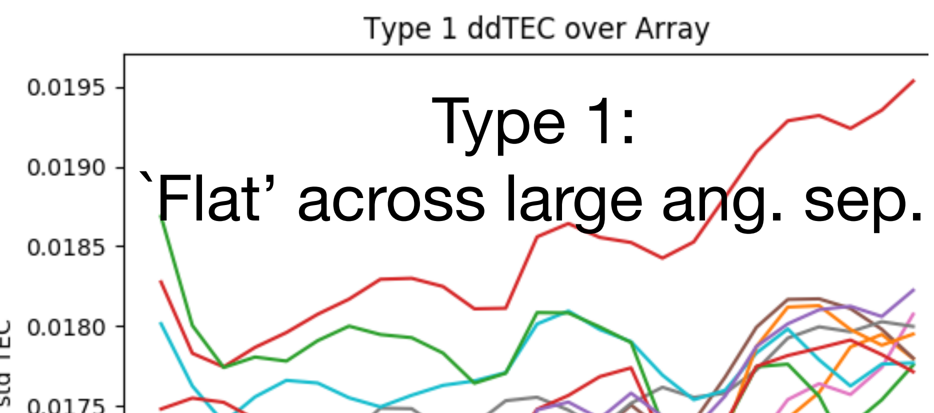

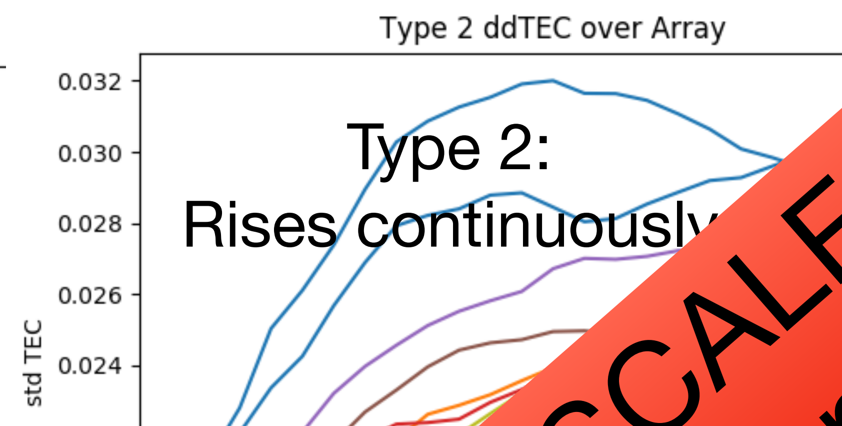

MultiView

Will <u>match in-beam</u> at L-band with ~1º cals

Will <u>exceed in-beam</u> above L-band

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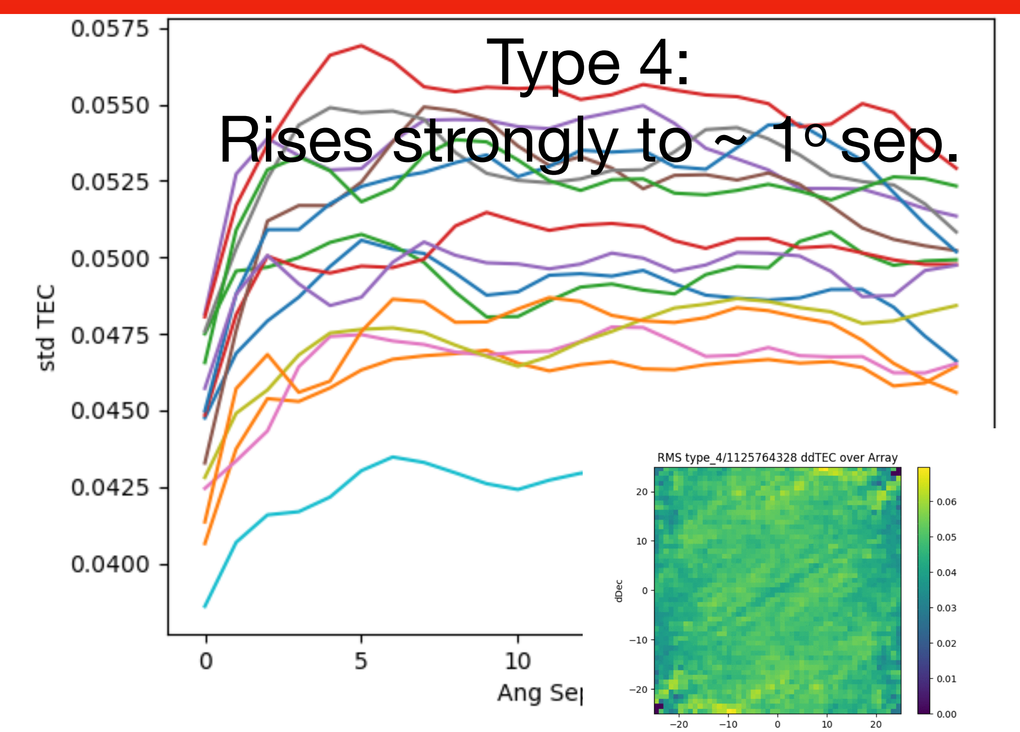

LEAP: Actual Phase Screens

MWA had no direction dependent calibration scheme;

The initial assumption was that the DI would be sufficient.

This was not …. so image-based, rubber-sheet, corrections were implemented. Similar to the field-based calibration (Cotton etal `99)

But these apply an array-wide linear shift per (snapshot) image.

LEAP (Low-frequency Excision of Atmosphere in Parallel) (Rioja etal `17) provides a station-based direction dependent visibility correction.

From this extracted a fine-scale (10-3000m) phase measurement across the array; probing the ionosphere to discover flatness of phase screens

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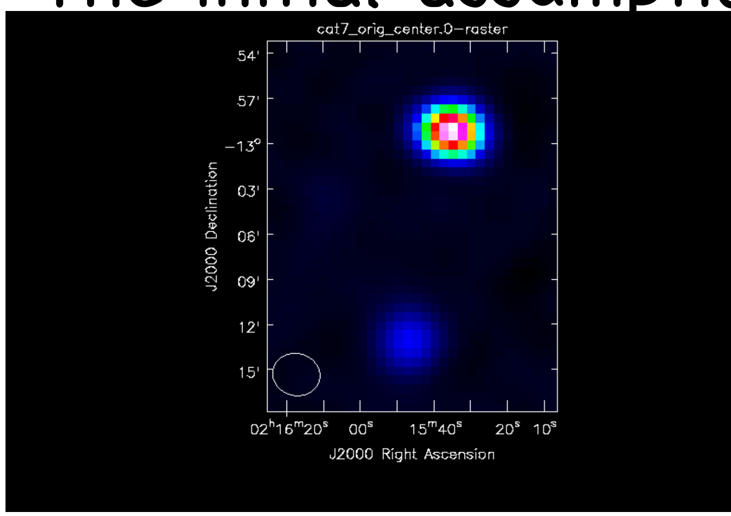

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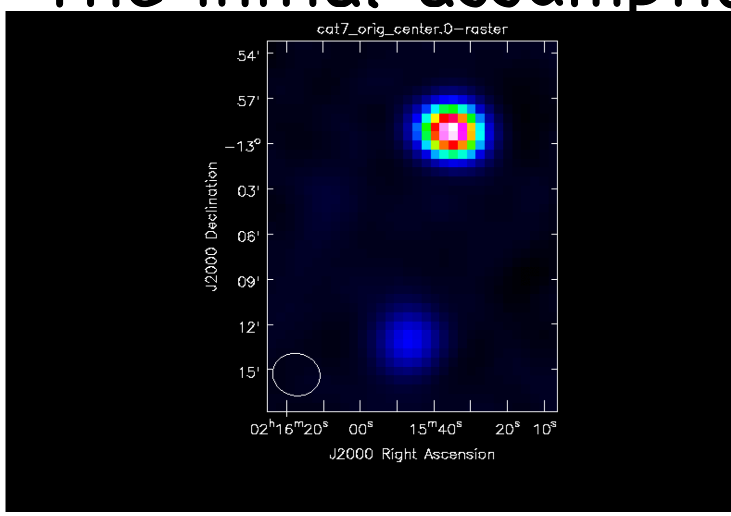

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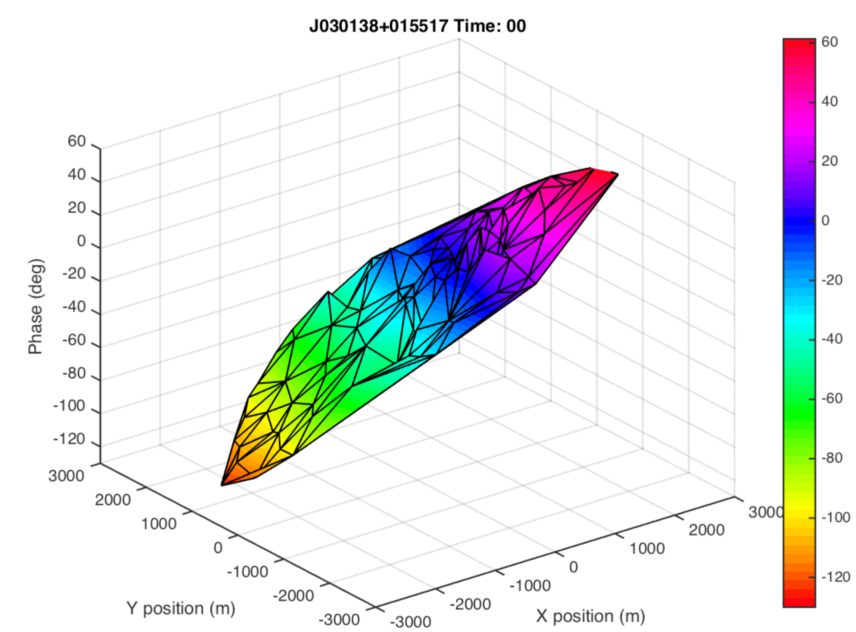
MWA-2 phase surface worst case



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MWA Phase-2 (6km baselines) shows much more `interesting' behaviour

Could be the longer baselines, but also different point in solar-cycle.

Phase slopes across array ~ $\pm 60^o$ — at 150MHz

Matching RTS image shifts.

Residual Phase Noise after linear fit (non-thermal) ~ 4^o — at 150MHz

< 1milli-TECU, or 0.1mm

Would allow calibrators to be anywhere across FoV (30-60′)

Would allow >1:1000 astrometry at 1.5GHz (<10μ as)

10% of phase screens show significant curvature

(>10% change w higher order)

— but linear approx often acceptable

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Many showed fast (~10sec) changes in phase surface require stronger & in-beam cals.

How many Beams needed?

- Can we assume that the phase surface is flat?

  For angular sep < 0.5^{o} > 1^{o}

  of an acceptable level for 4 μ as/epoch 100 μ as/ep.

- Would more beams allow fitting a curved surface & contemporaneous checks?

  Of course. Latter being more important.

- How many beams are needed?

  Minimum is 4 - target plus linear surface

  Greatest risk is poor stability in weak calibrators

  Multiple (6 or more) calibrators allows curved surfaces and internal consistency checks, averaging down of errors

- Would more beams allow new science goals?

  100's of continuum sources should be detectable

  Core-SKA to largest single dish would be covered with ~100

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at L-band. High freq. better
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Issue is cost

i.e. the budget?

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Conclusions

- Astrometric requirements key driver for SKA-VLBI
- MWA measurements of SKA site phase screens

  show: range of ionospheric behaviours and classes

  suggest: acceptably linear over SKA-core

  implies: excellent performance of in-beam MultiView
- Suggested number of beams:

  6 (minimum), 10 (lower goal) & 100 (maximum goal)

Lower will lower systematic contributions to parallax to μ as level

Upper will allow deep phase referenced observations of every source in beam

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