Calibration and direct validation of station embedded element patterns for SKA-Low prototype stations AAVS2 and EDA2

International Centre for Radio Astronomy Research

Randall Wayth

Curtin University

THE UNIVERSITY OF WESTERN AUSTRALIA

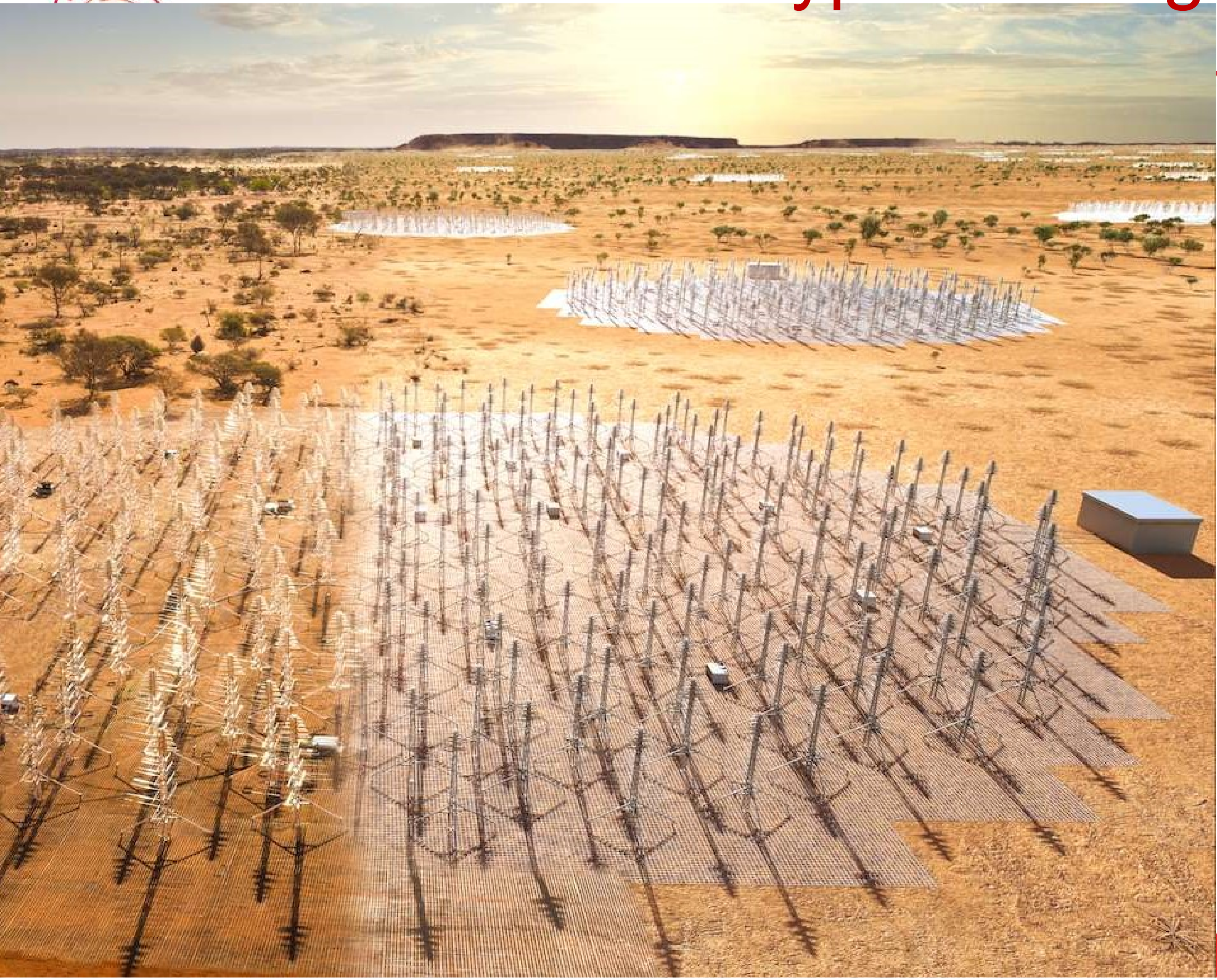
Government of Western Australia
Department of the Premier and Cabinet
Office of Science


Murchison Shire Boundary
Inyarrimanha Ilgari Bundara
(operated by CSIRO)
Population Density: 0.002 km⁻²
Geraldton
Perth
~200 km

Brief history of SKA-Low prototypes

- 2014: AAVS0.5 (Sutinjo et al.,2015)
  - 16 antennas analogue BF -> MWA
- 2016: EDA1 (Wayth et al., 2017)
  - 256 MWA antennas, hybrid beamformer
- 2017-2019: AAVS1 (Benthem et al. 2021)
  - 256 SKALA2 antennas
  - RFoF long distance signal transport
  - Full digital backend
  - Initial focus on basic functionality
  - Subsequent focus on calibration & stability

SKA-Low Prototypes – 2nd generation



SKA1-Low specs:

- 512 stations
- 256 antennas / station
- 50-350 MHz
- Full digital beamforming
- 300 MHz instantaneous bandwidth
- Current prototypes:
  - EDA2
  - AAVS2
  - Called “Bridging Arrays”

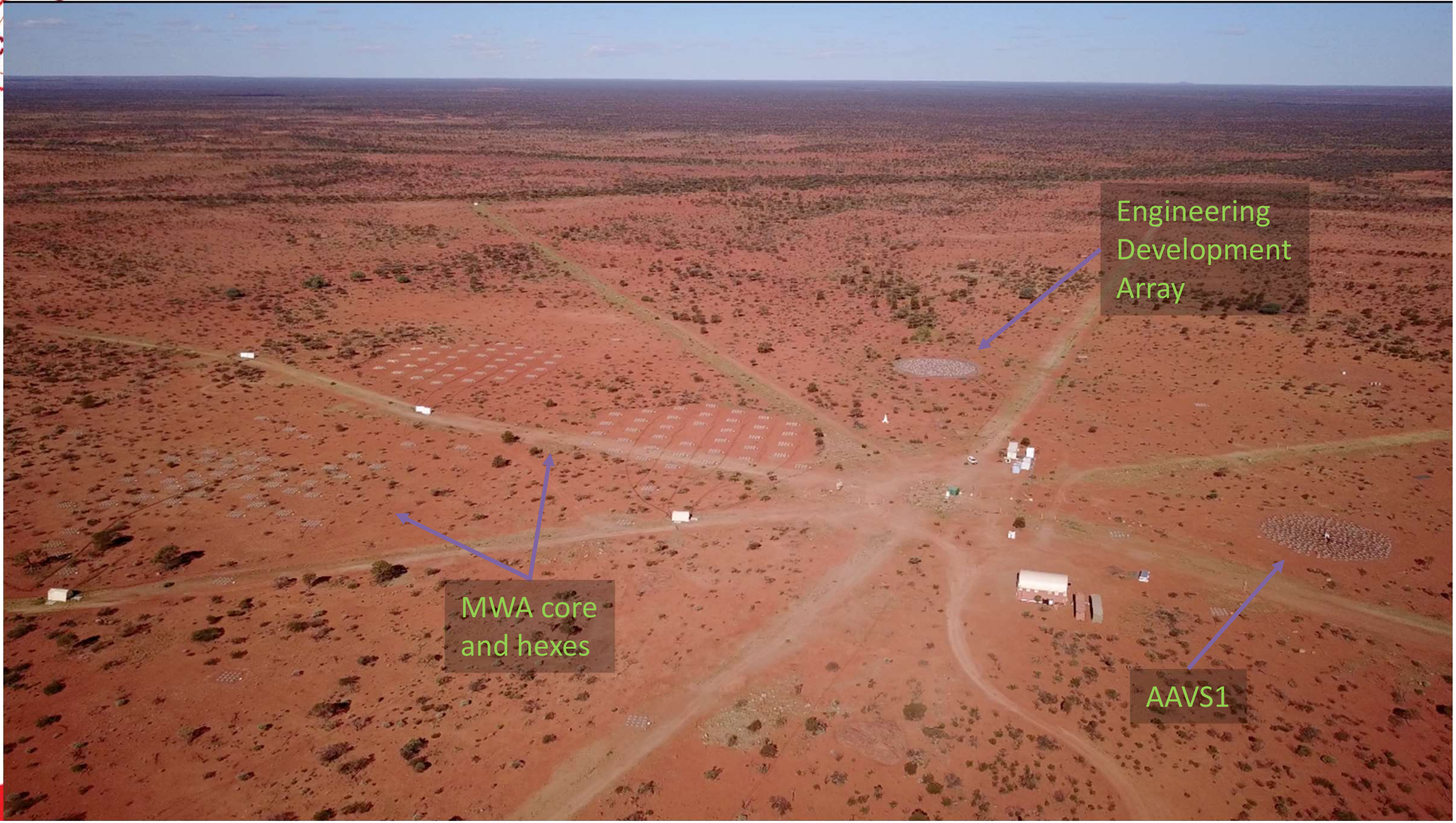
Engineering Development Array 2 – Completed June 2019

EDA2 facing north-east
Wayth et al, 2021. SPIE JATIS.

Aperture Array Verification System 2

van Es et al. ,2020. Proc SPIE.
Macario et al., 2021. SPIE JATIS.

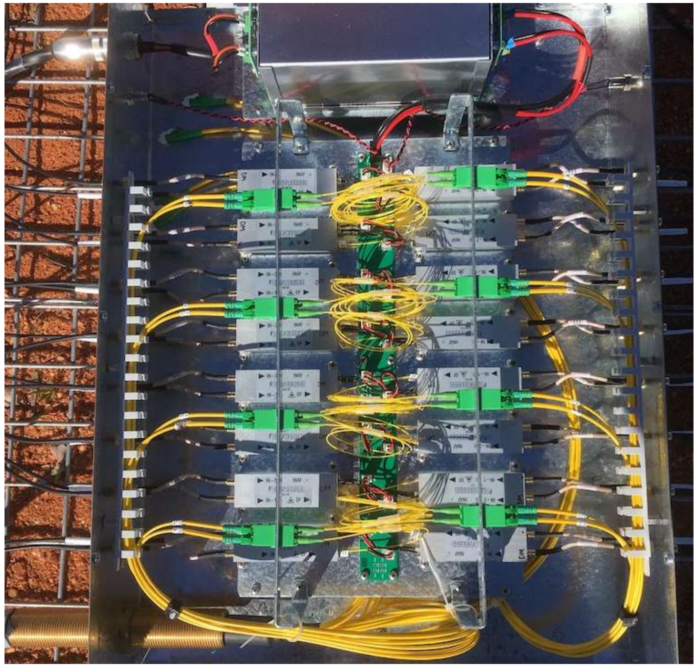
Hosted within MWA, using some MWA and Observatory infrastructure



Goals for the 2nd generation "bridging" arrays

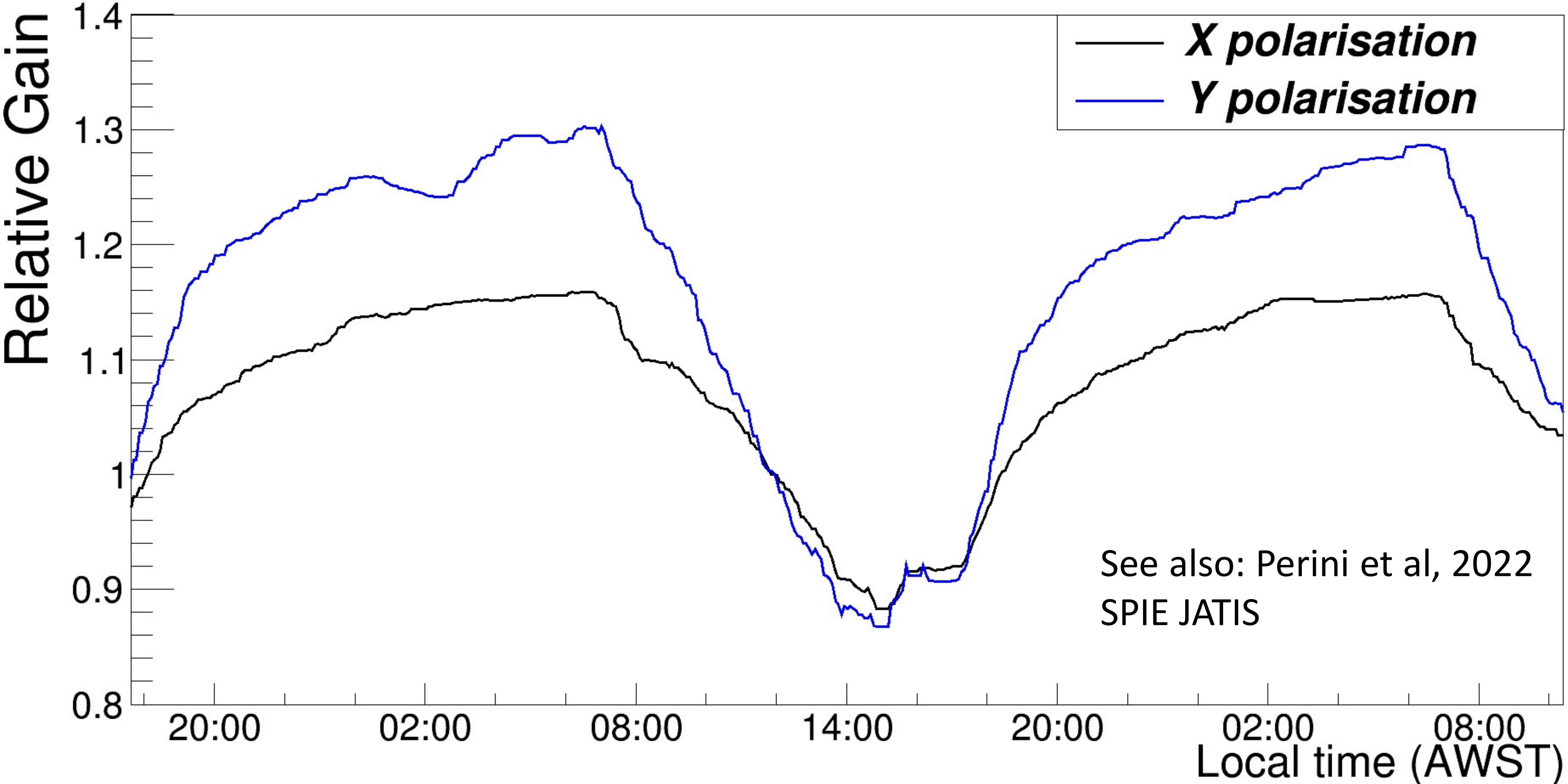
- **Calibration accuracy**: can we calibrate the arrays to sufficient accuracy?
  - Evaluation of two antenna types with different electromagnetic mutual coupling and optimisations.
- **Calibration stability**: what is the timescale required for (re)calibration?
- **On-sky sensitivity**: measure it
- Exercise the firmware & software backends for monitor and control
- Understand the realities of deployment at scale on site

A significant change from the 1st generation system (AAVS1) moved the optical transmitters out of the antenna apex.

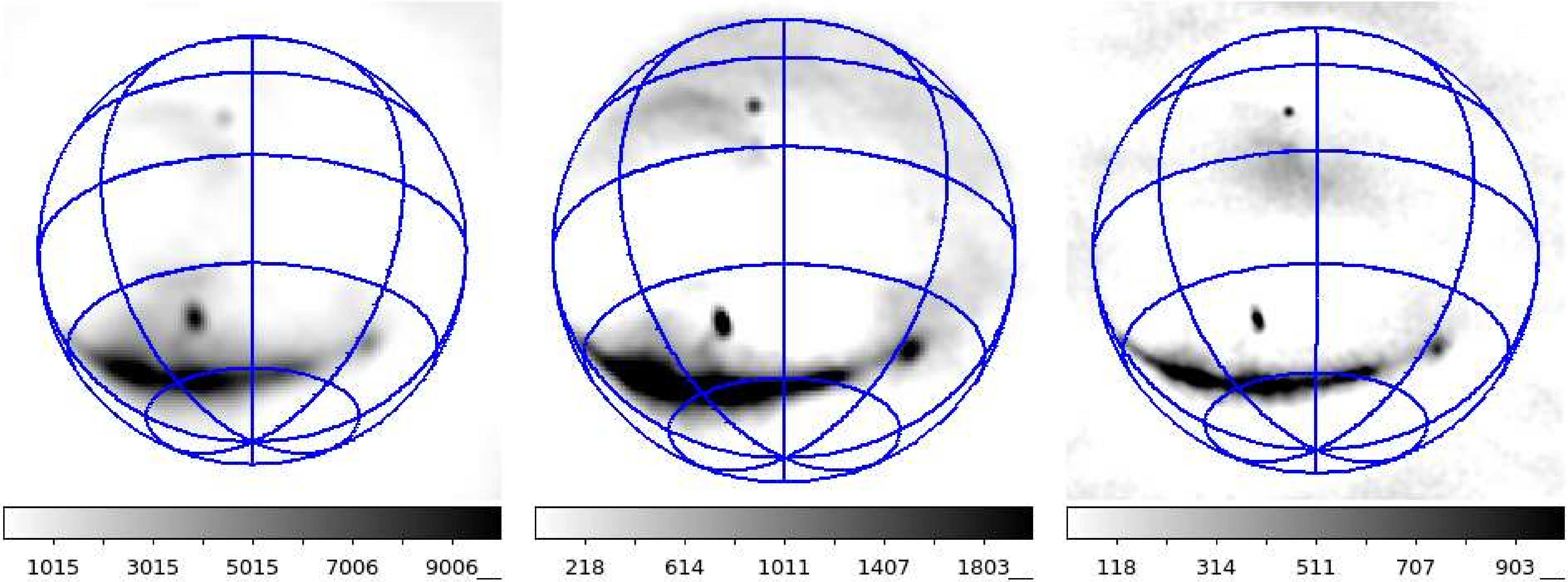


Inside a "SMART" box. 16 antennas electrical -> optical

Results: temperature dependent gain effect



Outputs: all-sky images, every 2 seconds



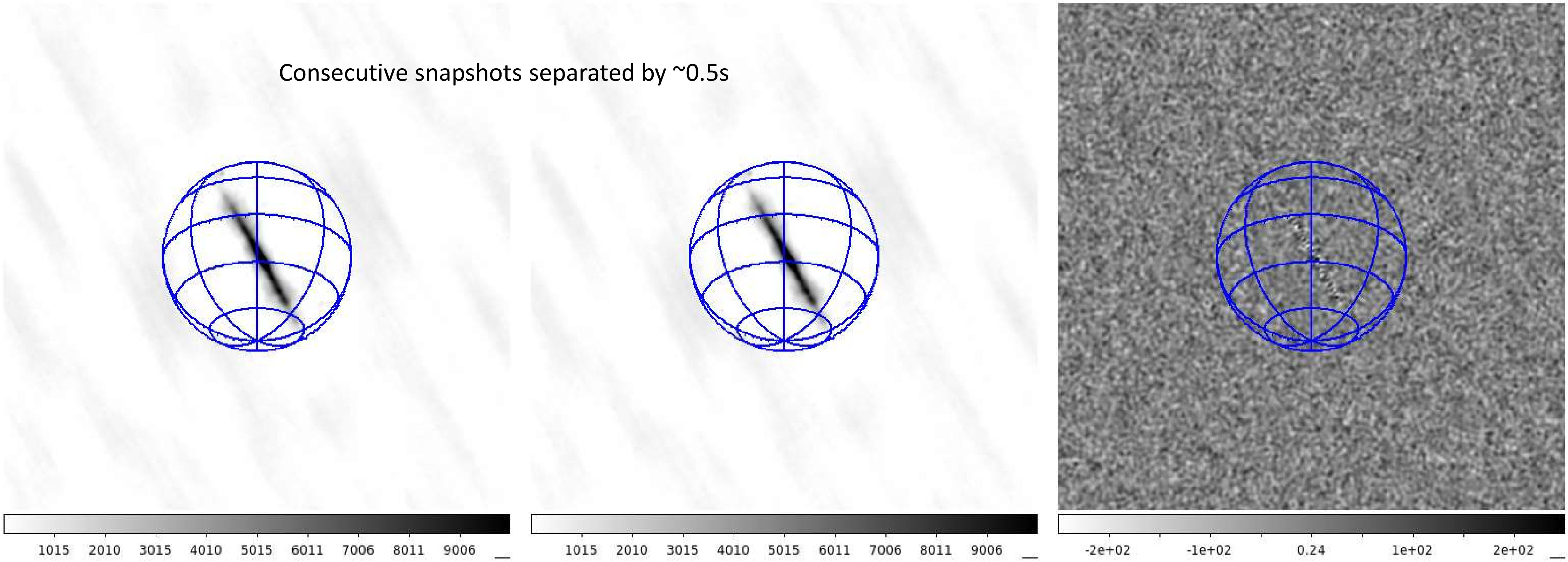
110 MHz | 159 MHz | 230 MHz

Science output: all-sky monitor with 2s timescale. Sokolowski et al., 2020.

Rate/strength of RFI sources in FM band: Tingay et al, 2020.

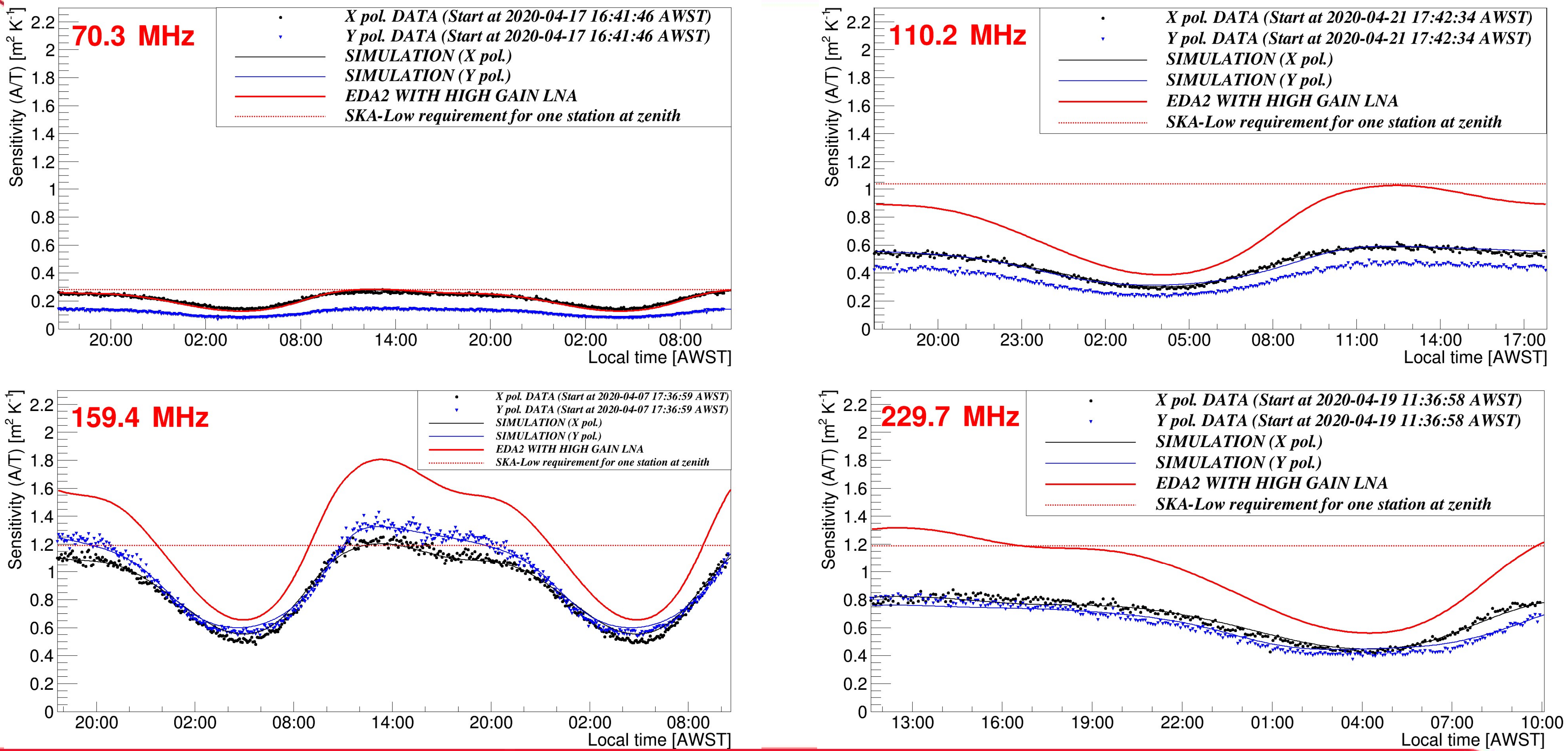
Results: sensitivity

- Snapshots are confusion limited, but difference images are noise-like
- This allows *direct measurement* of the on-sky array System Equivalent Flux Density (SEFD) from calibrated images



Results: EDA2 sensitivity

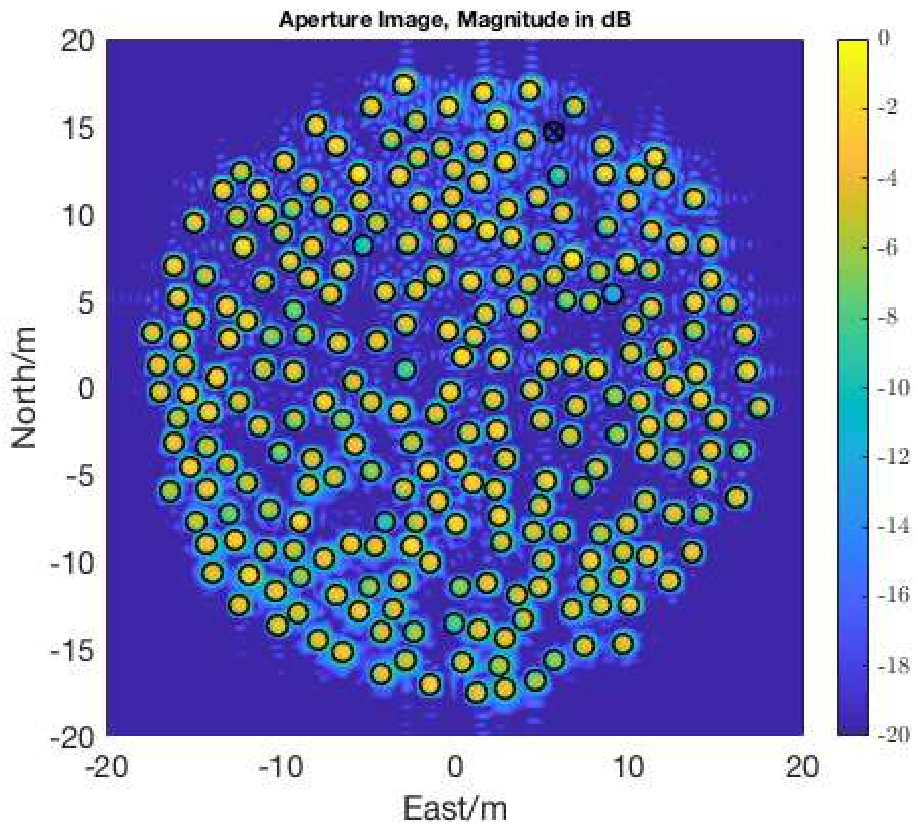
Wayth et al., 2021. SPIE JATIS.

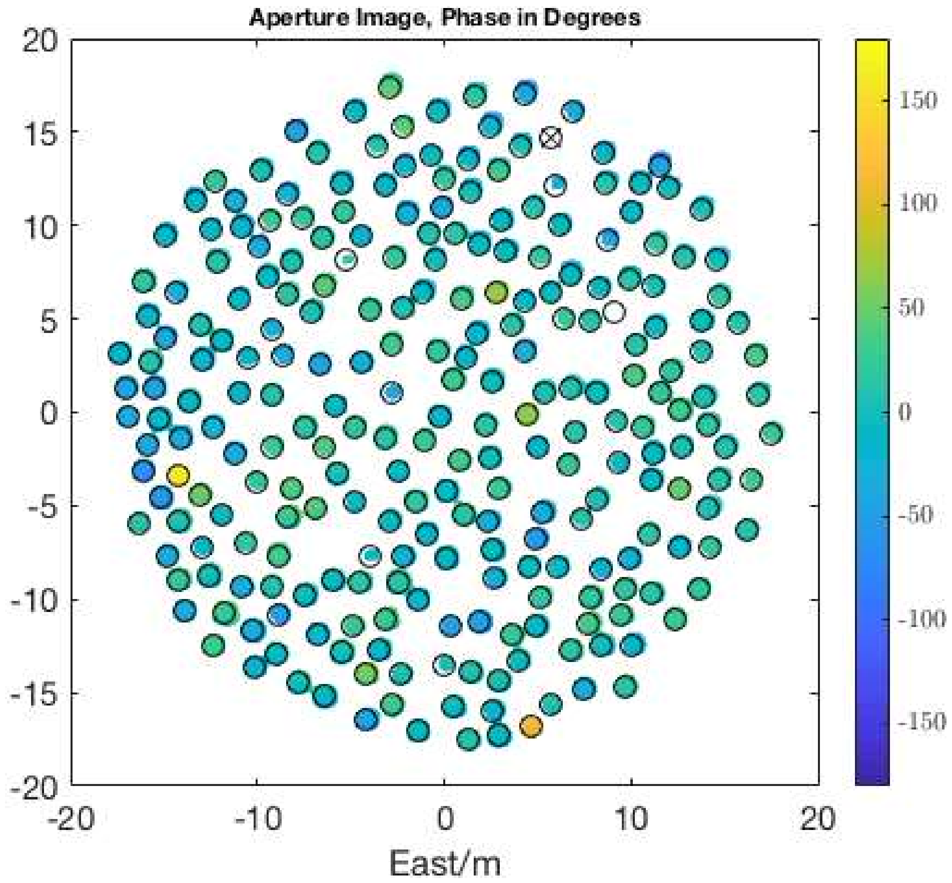


Aperture images – self holography

150 MHz EDA2 data.

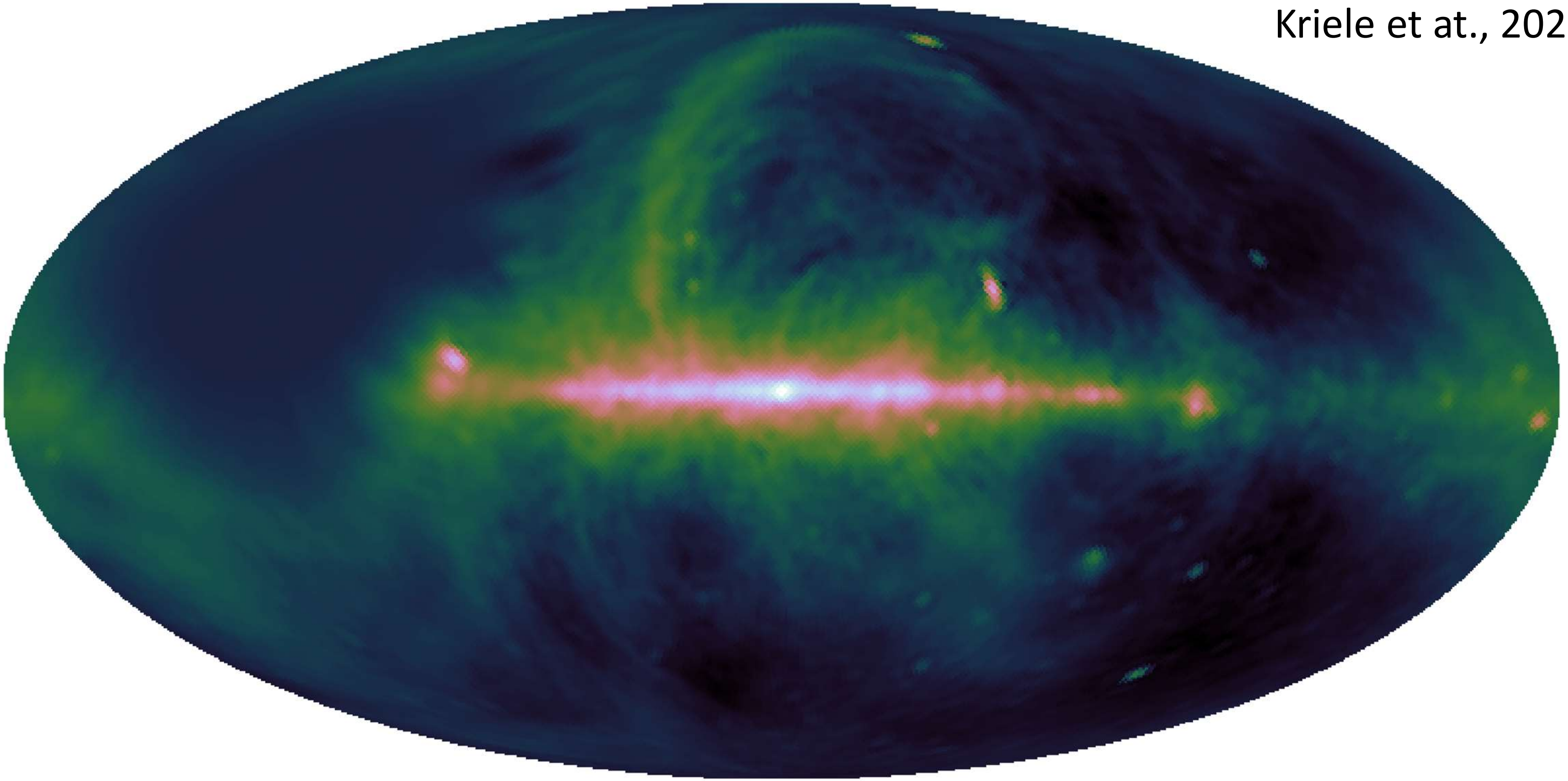
Kiefner et al, 2021. RadioScience





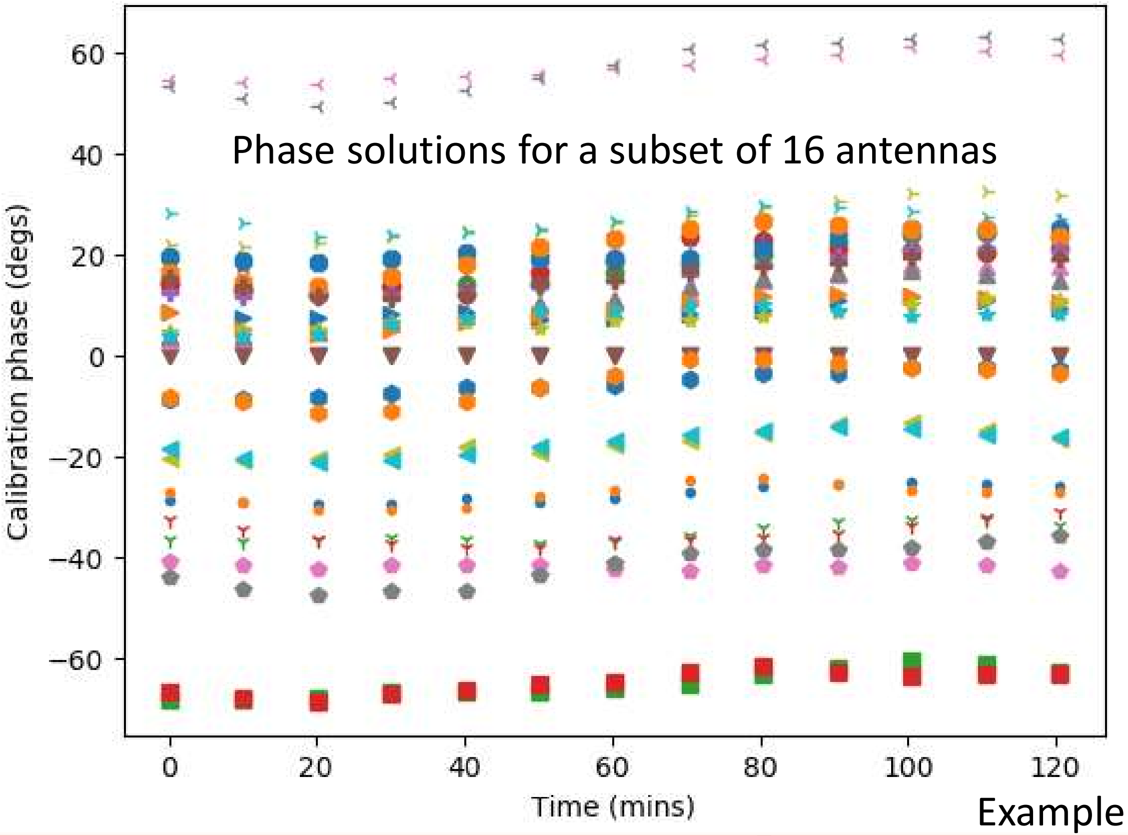
Outputs: All-sky map generated by EDA2 @ 160 MHz using the m-mode technique from 24hr drift scan

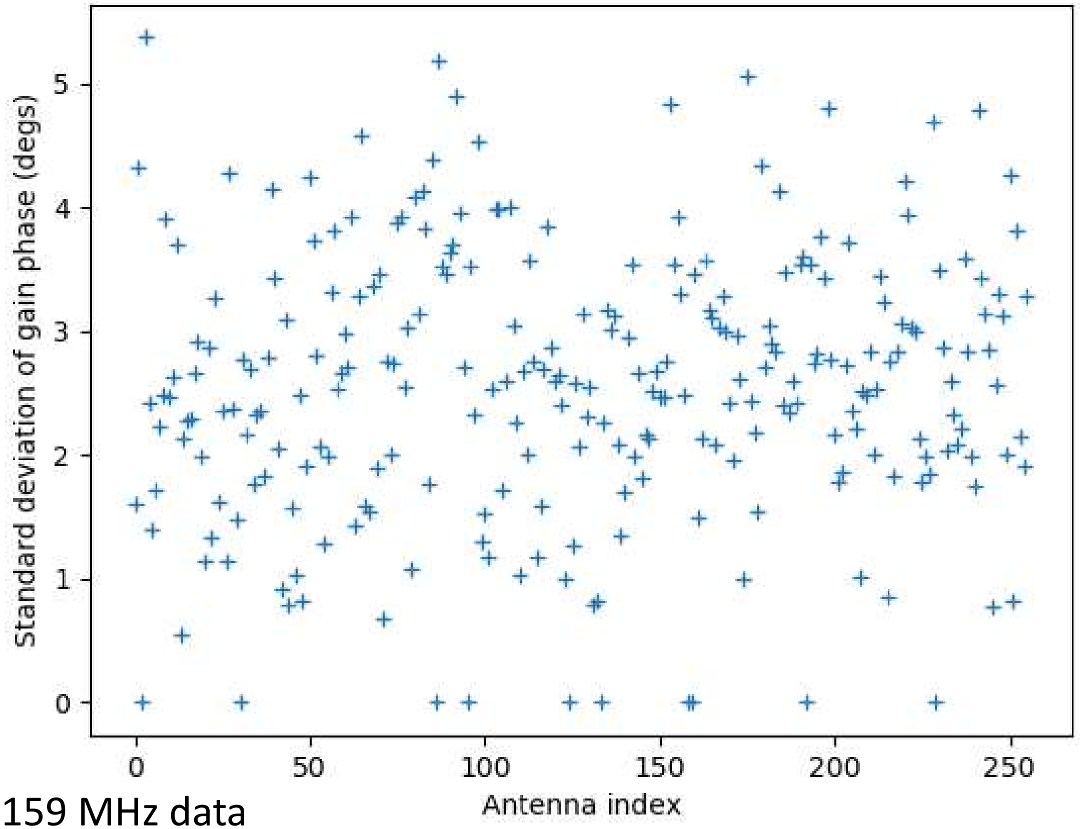
Kriele et at., 2022.



Results: calibration stability

Cal phase stddev: < 5 degs over 2 hours for EDA2. ~10 degs for AAVS2

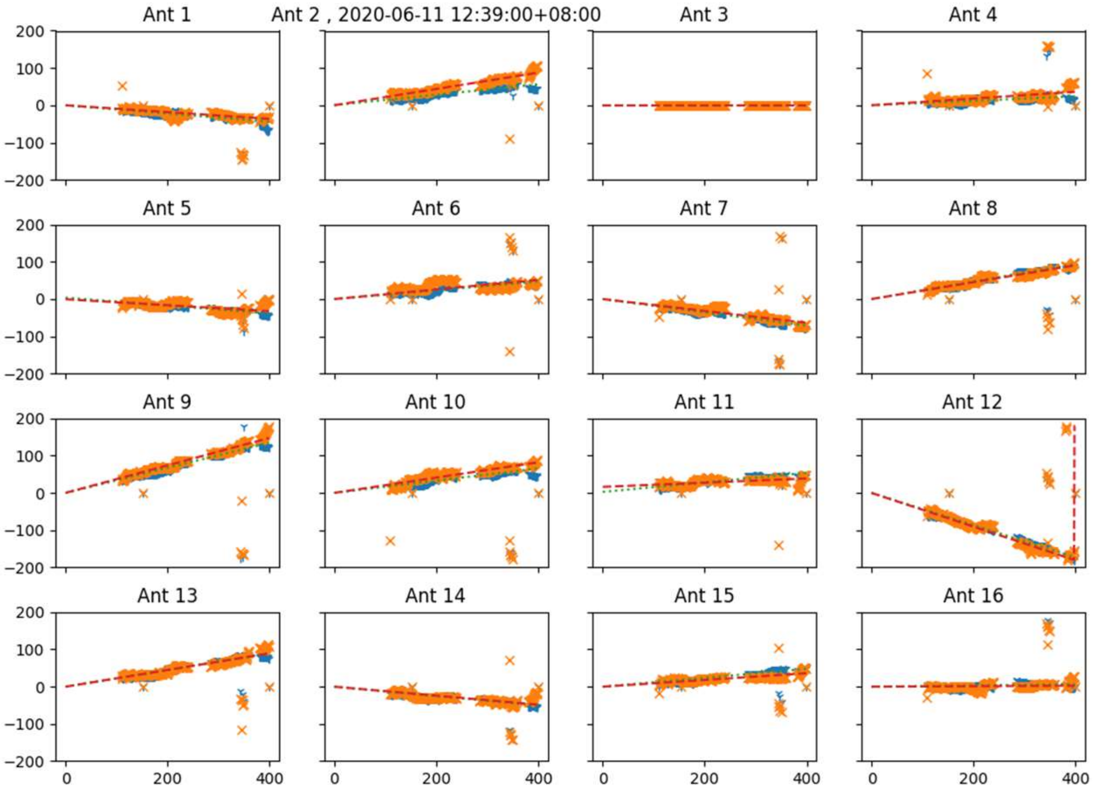




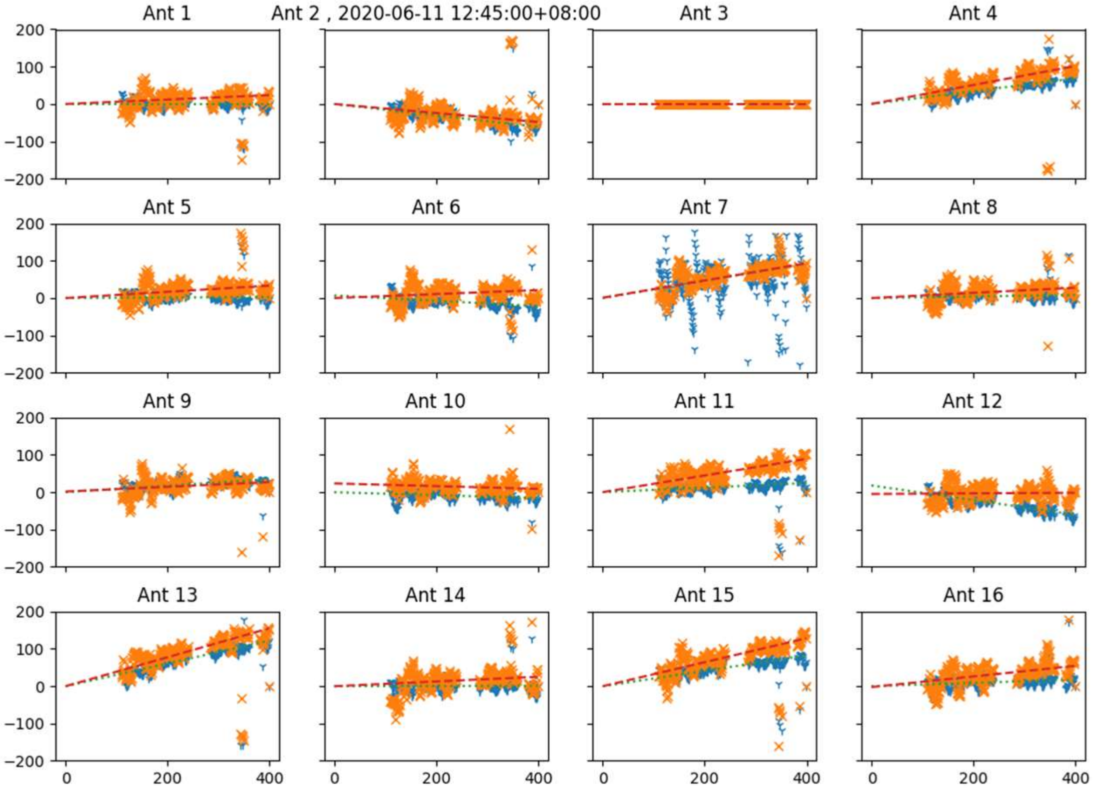
Example 159 MHz data

Calibration (around midday) in all frequency channels every few days

Used to measure and correct antenna *delays*. Required for real-time beamforming.

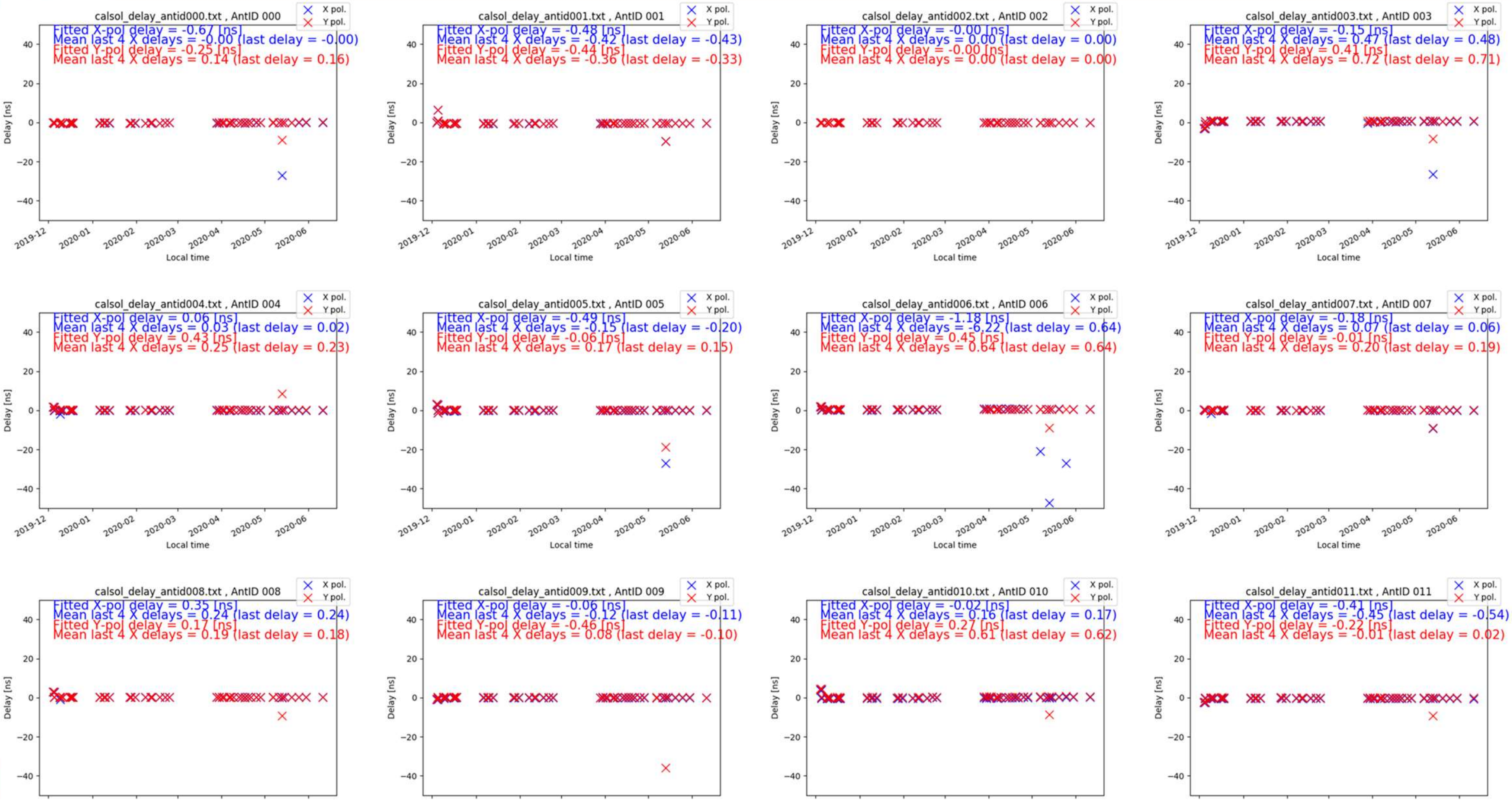


EDA2



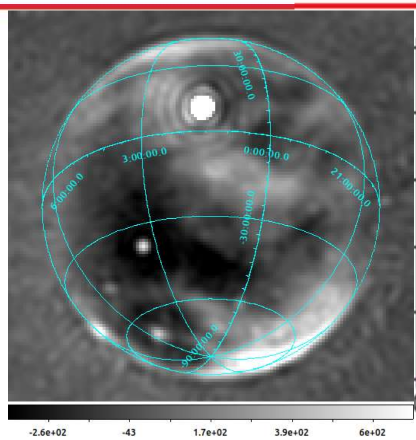
AAVS2

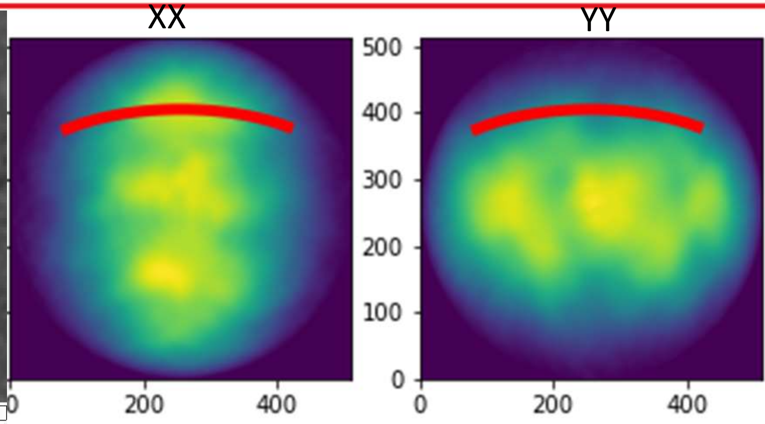
Monitoring the stability of delay solutions - AAVS2



Results: Verification of FEE patterns via solar calibration

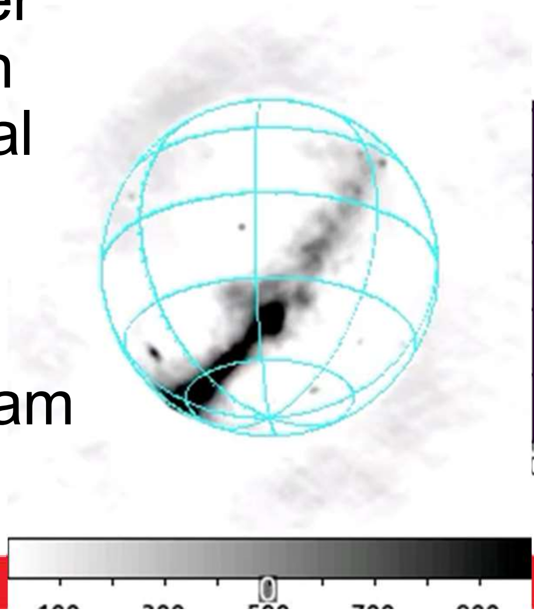
- FEKO full EM simulations for AAVS2 and EDA2
- Probe beam by using sun as calibrator over ~6 hours, with 10min cal interval, when Gal Centre has set
- Provides a direct measure of each beam at each cal time

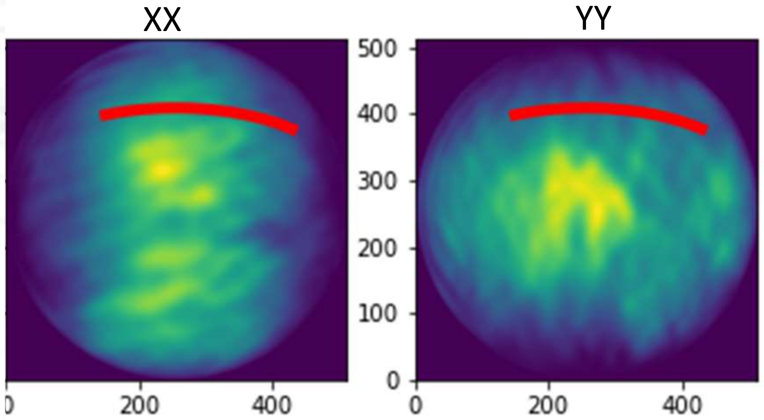




EDA2 ant 0 power, orthographic linear scale

Track of sun through EDA2 beam @ 230 MHz

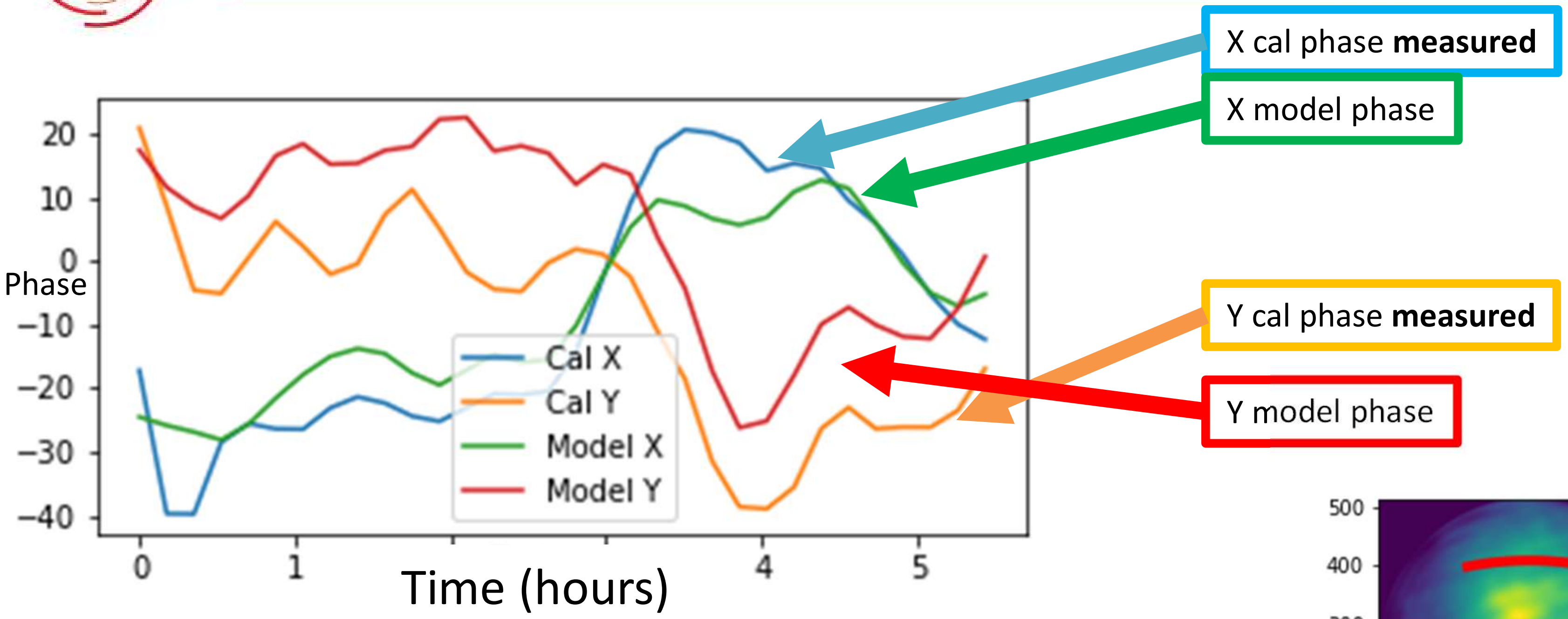


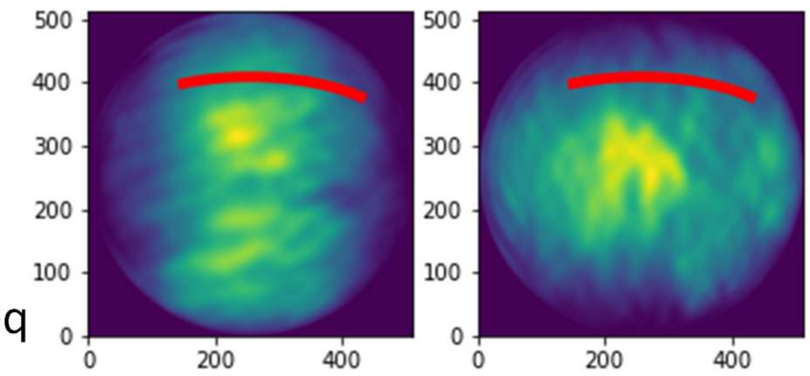


AAVS2 ant 0 power, orthographic linear scale

Track of sun through AAVS2 beam @ 110 MHz

AAVS2 110 MHz results: cal vs model

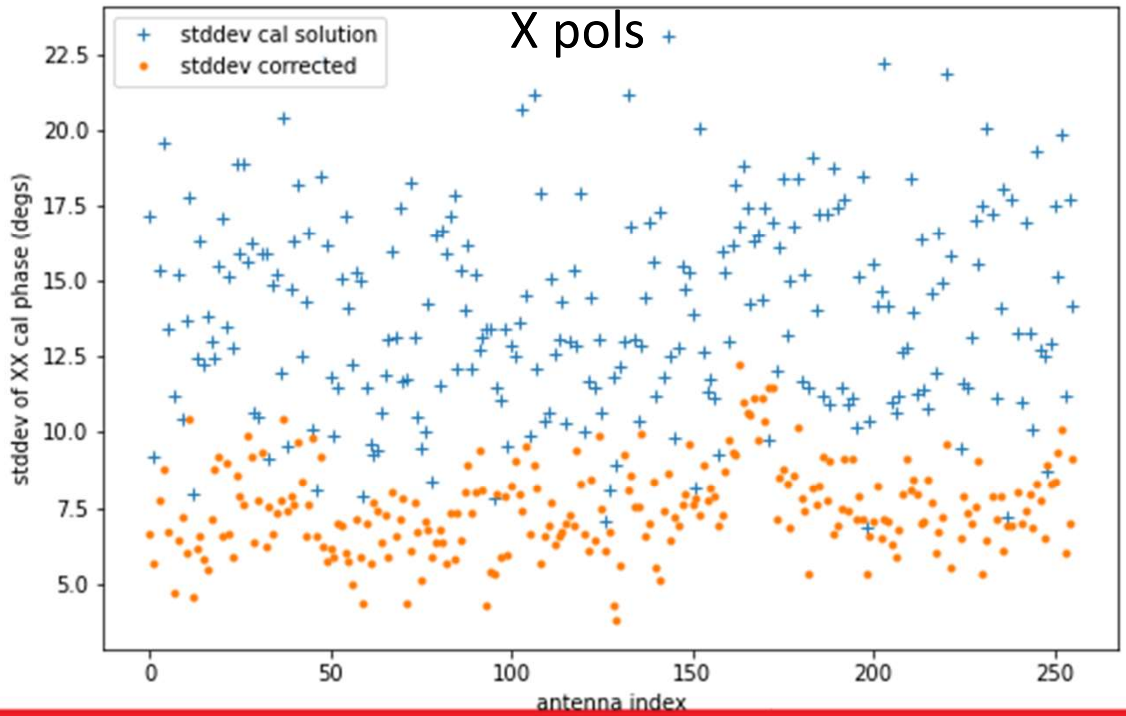


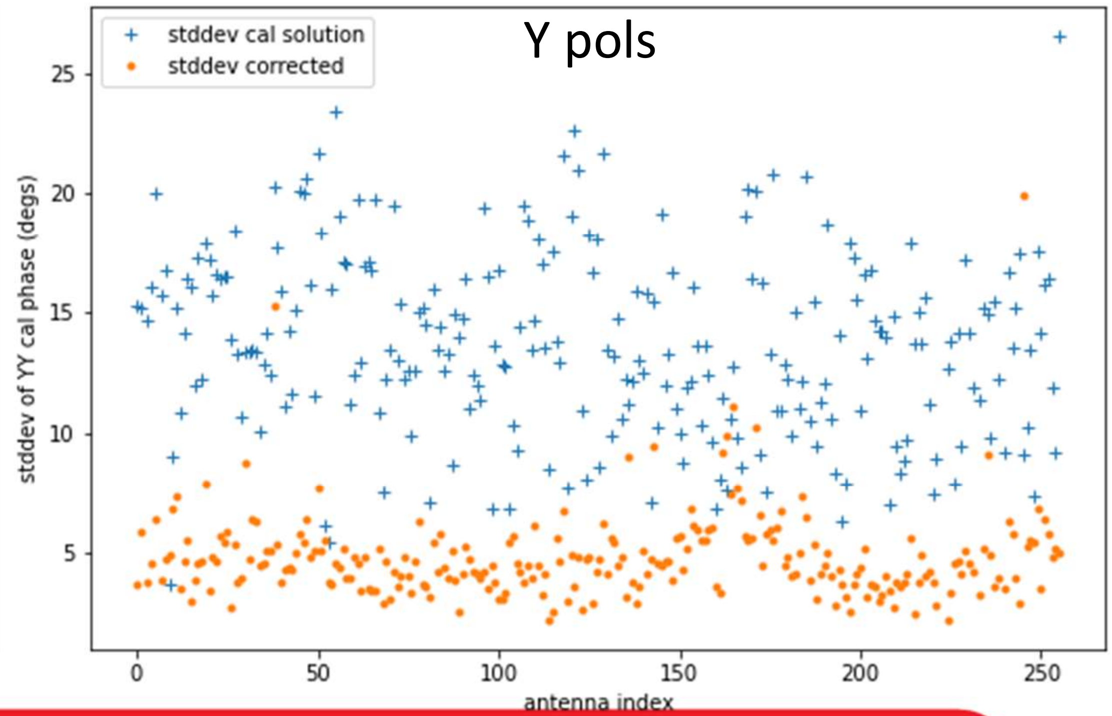


Without mutual coupling, all model phases would be **zero**.
FEE models predict phase variations +/- 10 degs depending on freq
Actual data shows **very good agreement** with model.
(There is one of these for all 256 antennas… too much to show.)

Stddev over time for each antenna – **AAVS2** 110 MHz

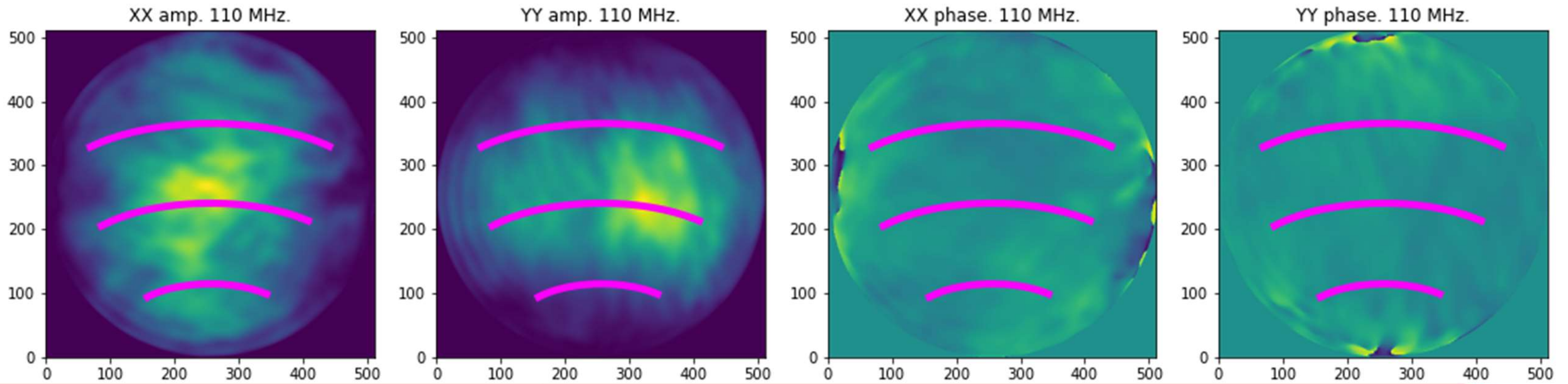
- Apply FEE model to data. A perfect model would result in zero phase.
- Residual phase variation over time is 5-7 degs after applying FEE beam correction
- This is **direct validation of FEE models from an astronomical source**. Residuals are from many possibilities, but at an acceptable level.



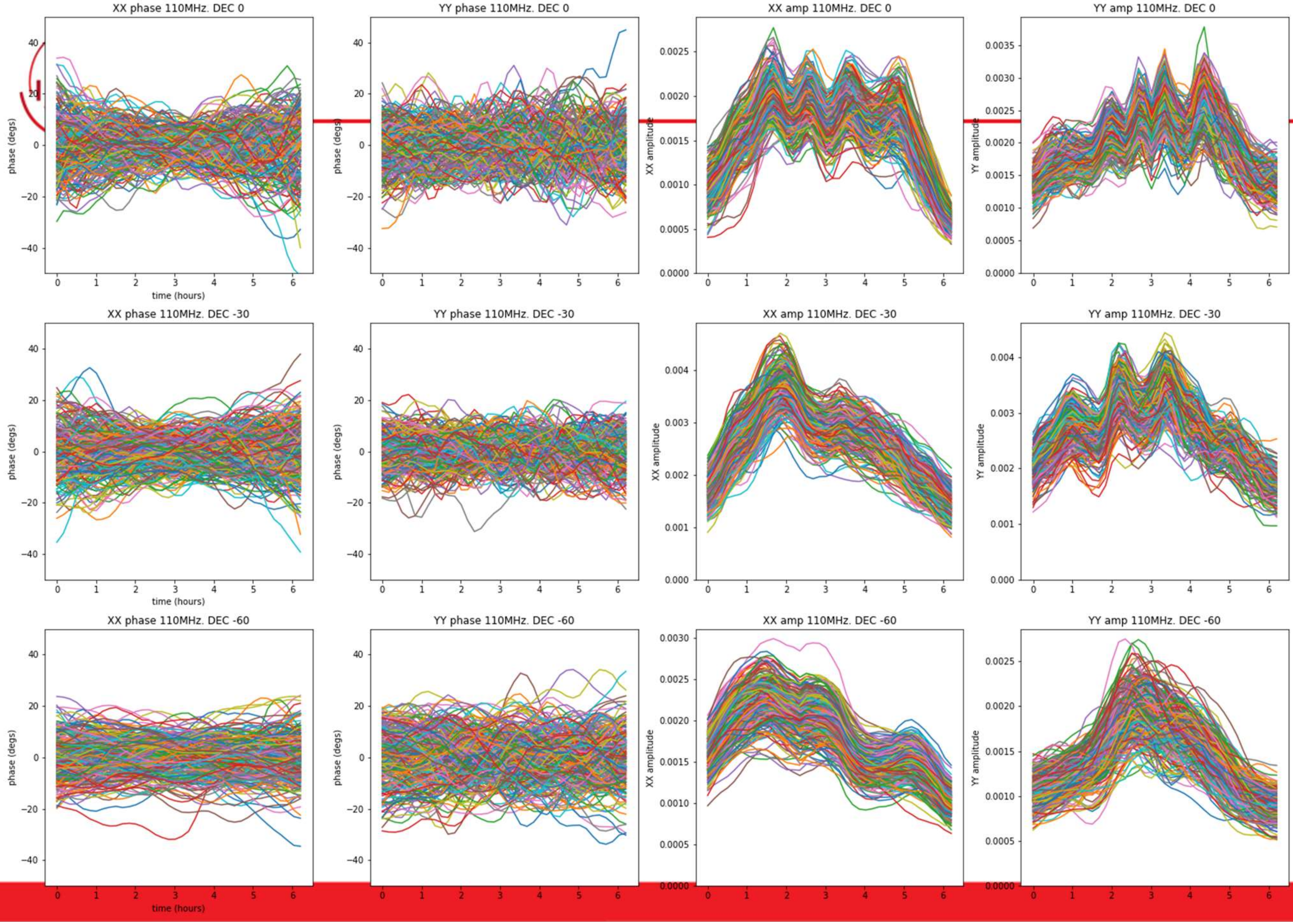


Predicting beamforming errors from FEE models

- Station beamforming is performed using geometric corrections only, differences in phase/amp between station antennas turn into beamforming errors
- We can use the same FEE models to predict the level of beamforming errors, as a function of frequency, *assuming ideal calibration*
- We take 3 representative 6-hour tracks on sources at 0, -30 and -60 degs DEC.



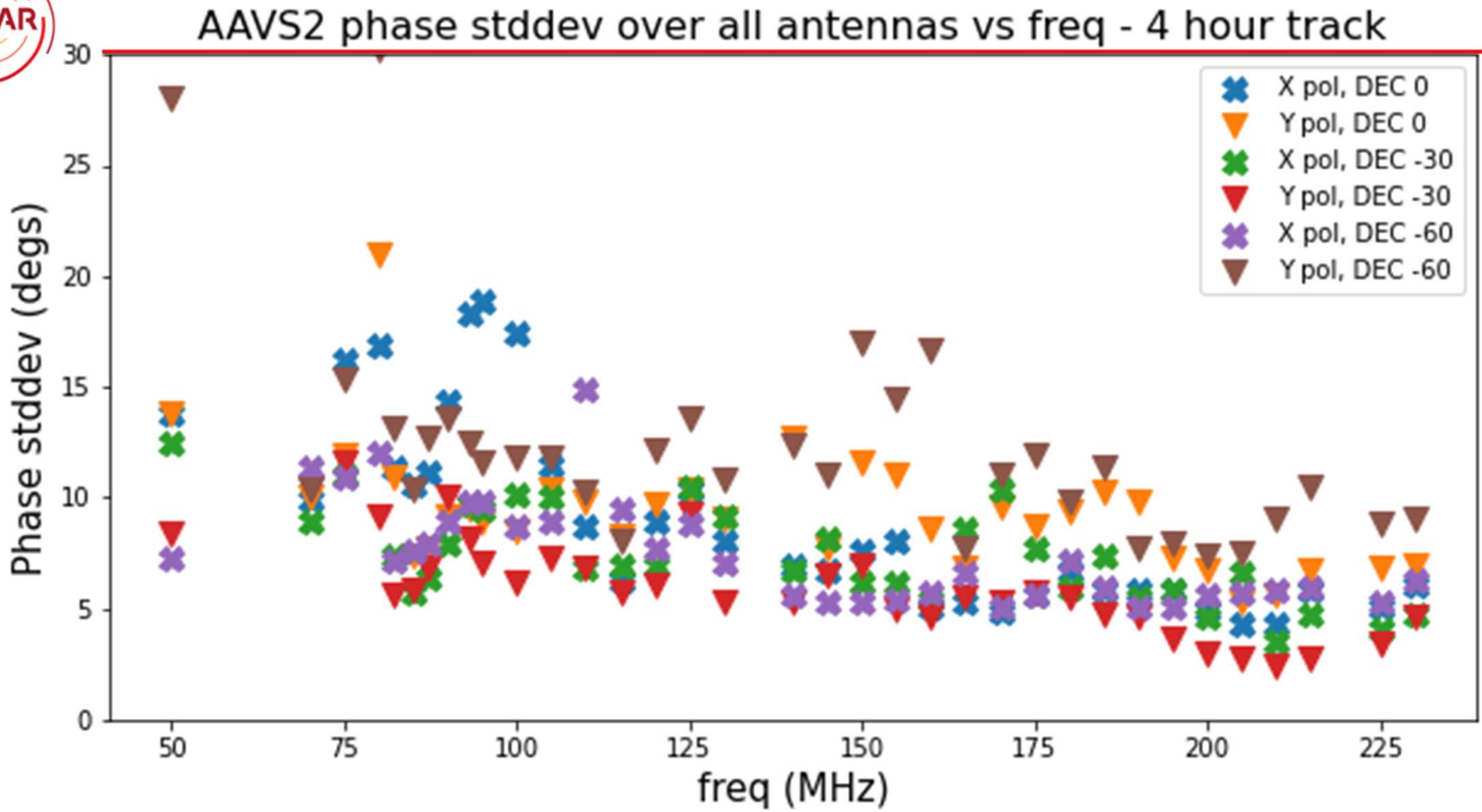
E.g. AAVS2 110 MHz



Declination 0

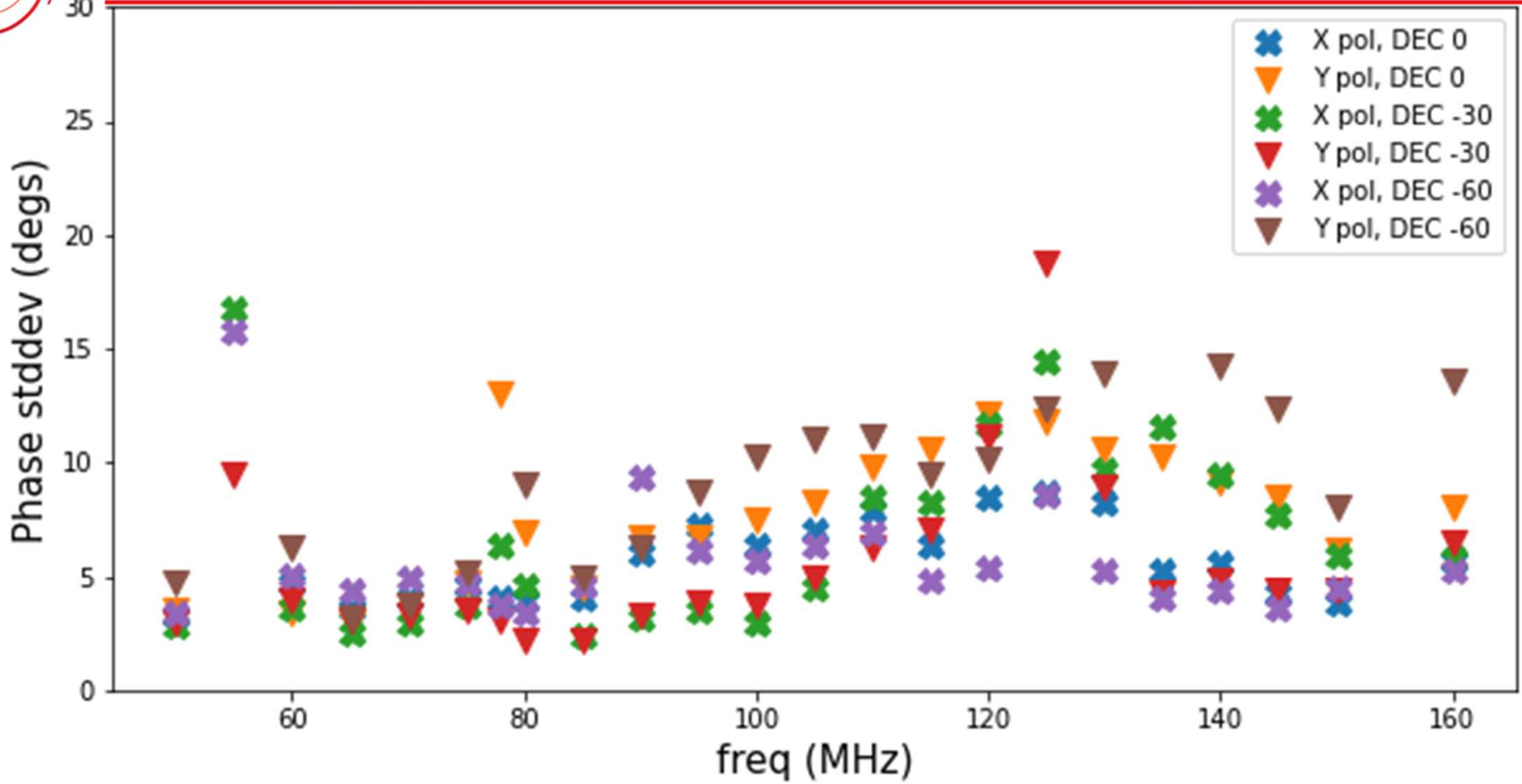
Declination -30

Declination -60


AAVS2 phase stddev over all antennas vs freq - 4 hour track
Phase stddev (degs)
freq (MHz)
X pol, DEC 0
Y pol, DEC 0
X pol, DEC -30
Y pol, DEC -30
X pol, DEC -60
Y pol, DEC -60
0
5
10
15
20
25
30
50
75
100
125
150
175
200
225

* Preliminary *

AAVS3 vogel phase stddev over all antennas vs freq - 4 hour track



Summary

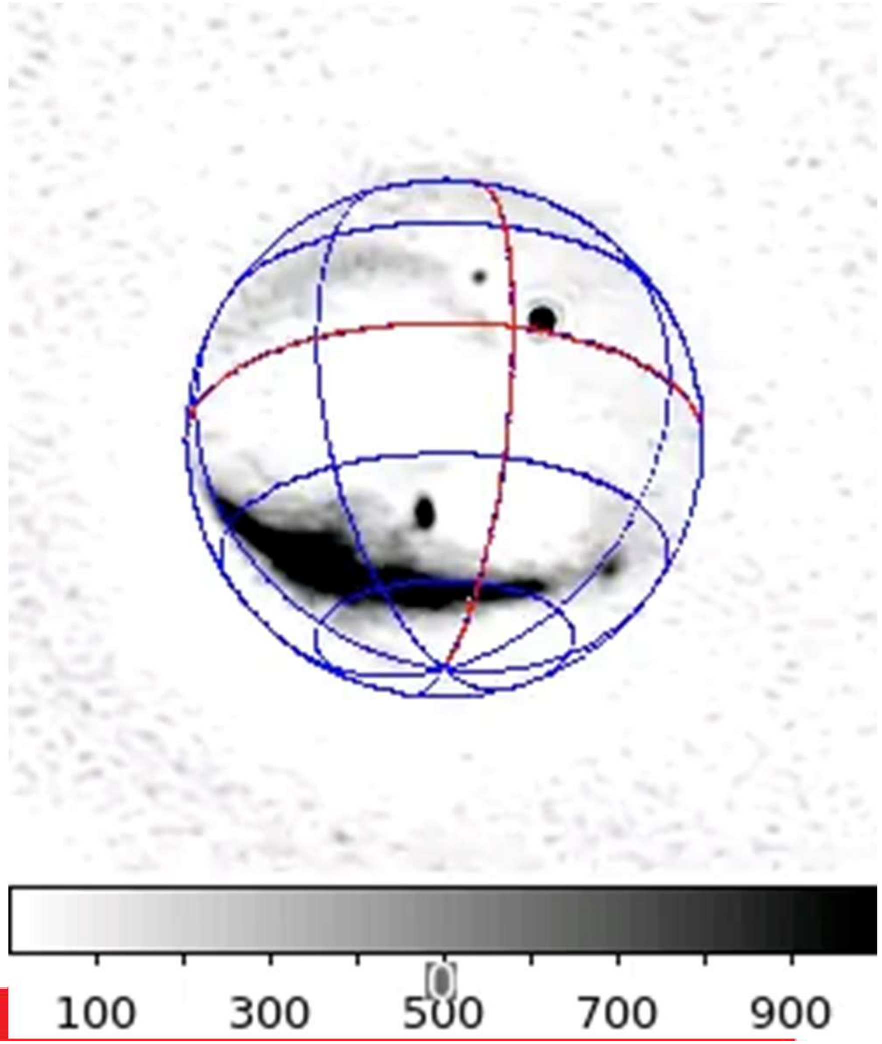
Macario et al., 2021. SPIE JATIS. (for AAVS2)
Wayth et al., 2021. SPIE JATIS. (for EDA2)
Sokolowski et al, 2020.
van Es et al. ,2020

- AAVS2 and EDA2 running since mid 2019
- Calibration phase stability shown to be stable over months

- Sensitivity measured at 5 reference frequencies
- Arrays being used for all-sky and transient science

- Direct verification of FEE beam models using astronomical source

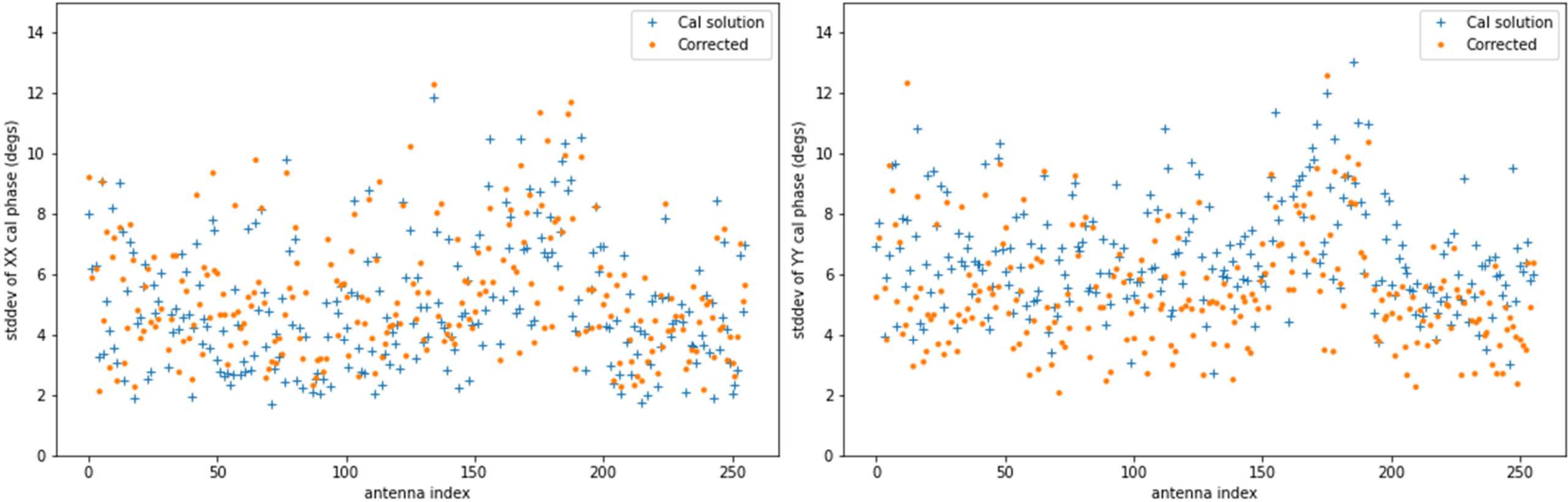
- Predicted beamforming errors (sensitivity loss) due to coupling over large freq range

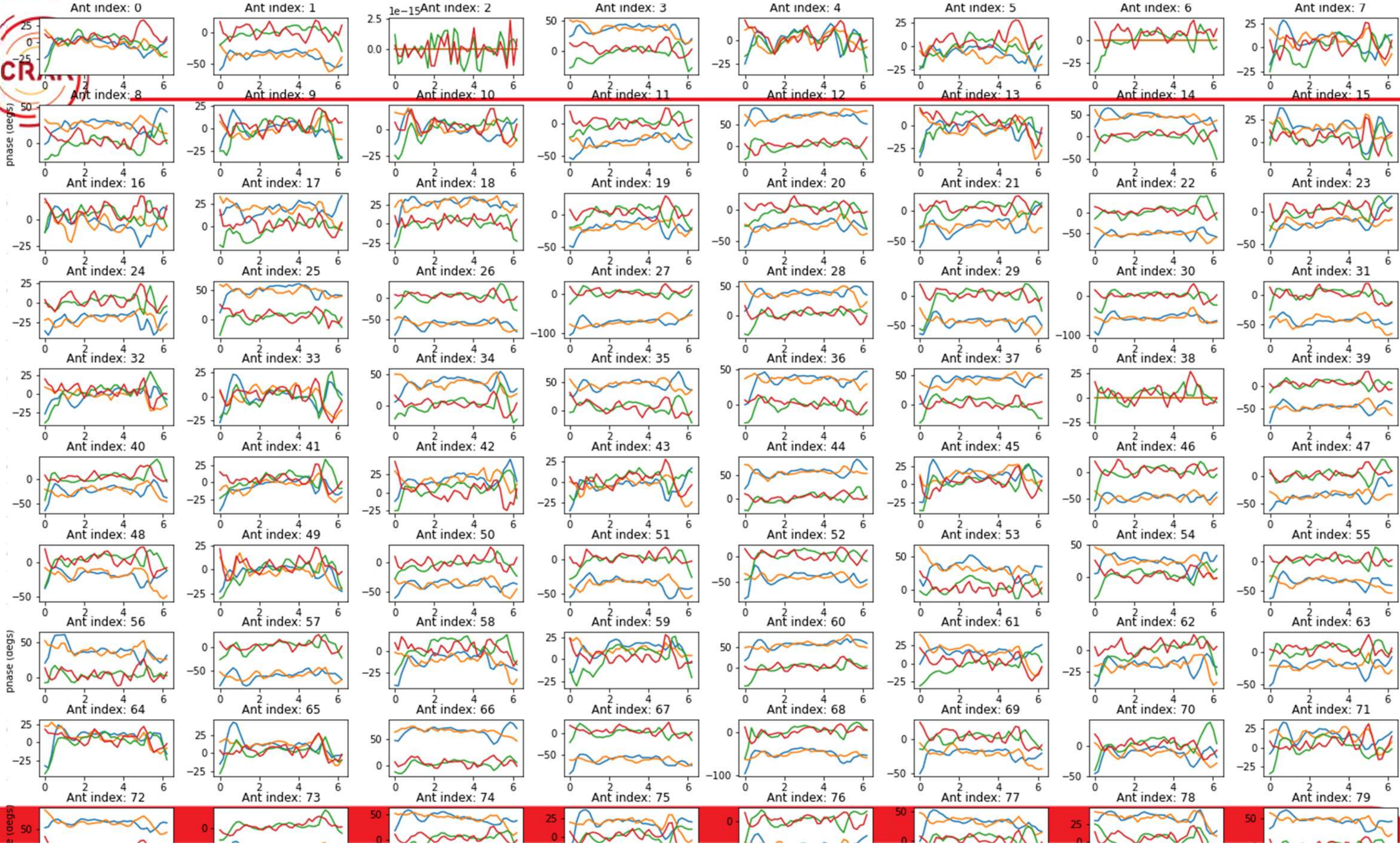


Stddev over time for each antenna – **EDA2** 230 MHz

Intrinsic phase variation over time is 4-7 degs (at this freq).
Corrections make negligible difference.

X pols Y pols




Ant index: 0
Ant index: 1
Ant index: 2
Ant index: 3
Ant index: 4
Ant index: 5
Ant index: 6
Ant index: 7
Ant index: 8
Ant index: 9
Ant index: 10
Ant index: 11
Ant index: 12
Ant index: 13
Ant index: 14
Ant index: 15
Ant index: 16
Ant index: 17
Ant index: 18
Ant index: 19
Ant index: 20
Ant index: 21
Ant index: 22
Ant index: 23
Ant index: 24
Ant index: 25
Ant index: 26
Ant index: 27
Ant index: 28
Ant index: 29
Ant index: 30
Ant index: 31
Ant index: 32
Ant index: 33
Ant index: 34
Ant index: 35
Ant index: 36
Ant index: 37
Ant index: 38
Ant index: 39
Ant index: 40
Ant index: 41
Ant index: 42
Ant index: 43
Ant index: 44
Ant index: 45
Ant index: 46
Ant index: 47
Ant index: 48
Ant index: 49
Ant index: 50
Ant index: 51
Ant index: 52
Ant index: 53
Ant index: 54
Ant index: 55
Ant index: 56
Ant index: 57
Ant index: 58
Ant index: 59
Ant index: 60
Ant index: 61
Ant index: 62
Ant index: 63
Ant index: 64
Ant index: 65
Ant index: 66
Ant index: 67
Ant index: 68
Ant index: 69
Ant index: 70
Ant index: 71
Ant index: 72
Ant index: 73
Ant index: 74
Ant index: 75
Ant index: 76
Ant index: 77
Ant index: 78
Ant index: 79
phase (degs)
1e−15

Calibration approaches

Dominant compact source (sun)

- Better at higher freqs. No good <~ 100 MHz

Delay calibration

- Fit linear phase ramp vs freq for each pol. -> delay
- Successfully doing this since AAVS1

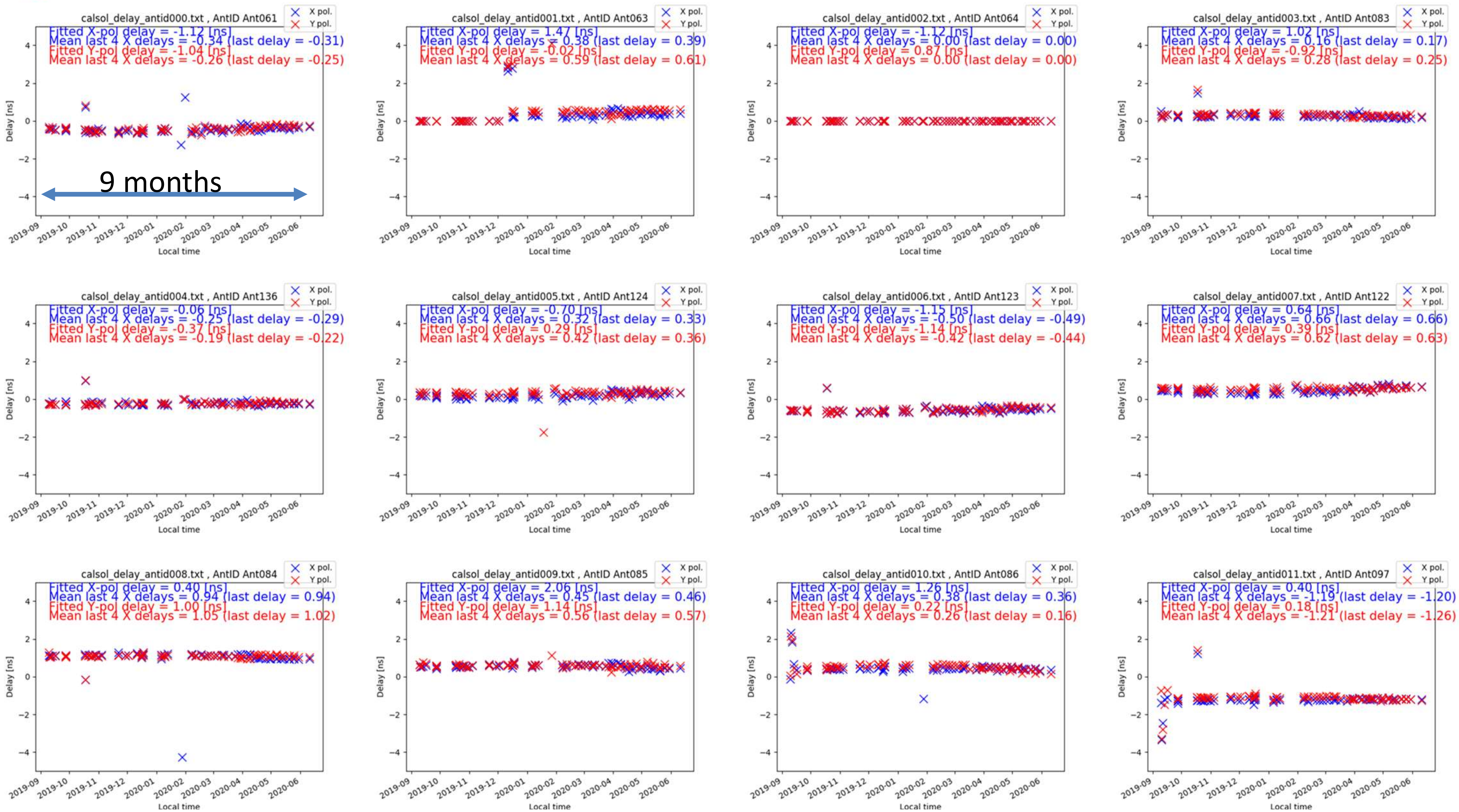
All-sky model: Average Element Pattern

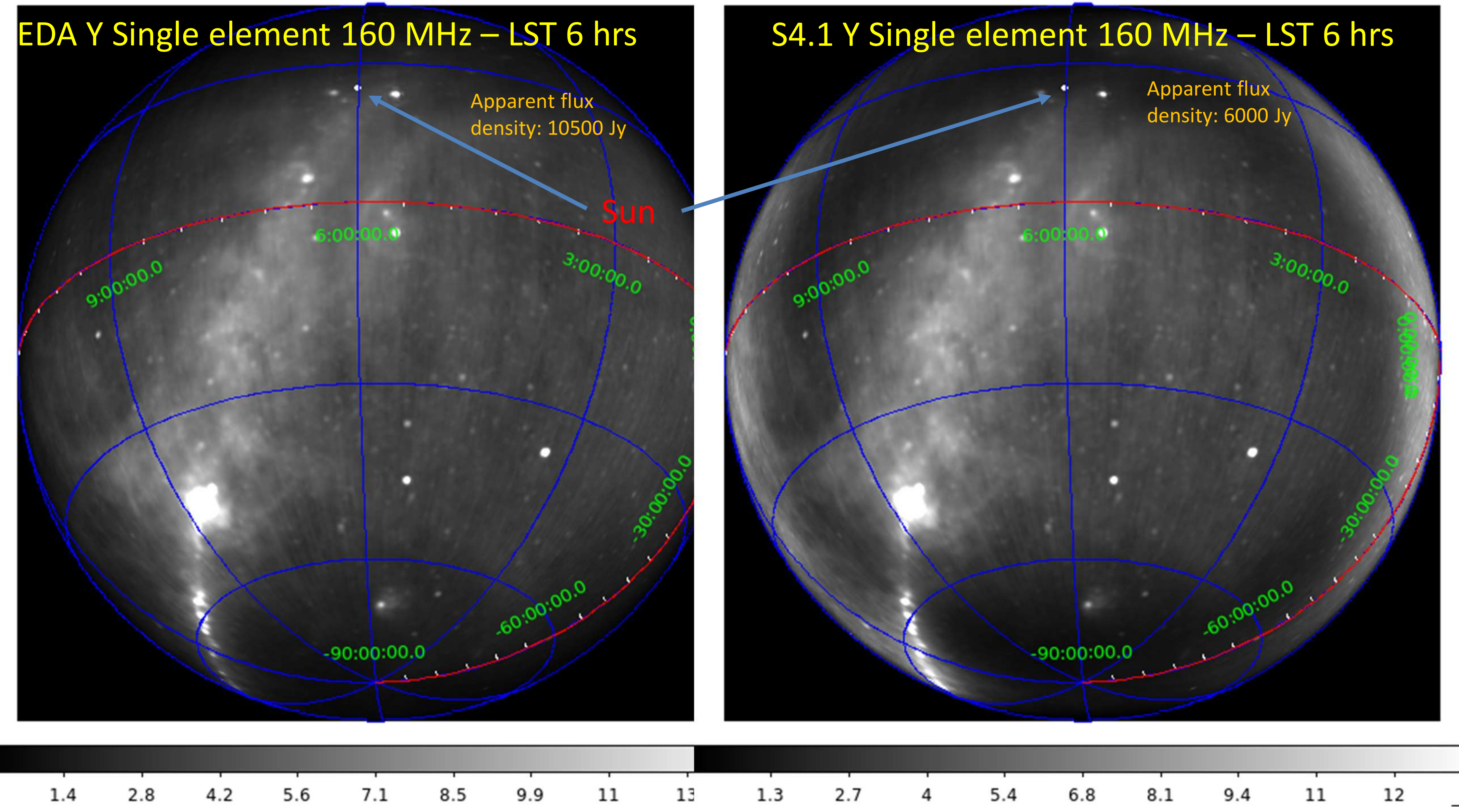
- Use rescaled Haslam and beam model including the Sun
- Successfully doing this since AAVS1

All-sky model: Full element patterns

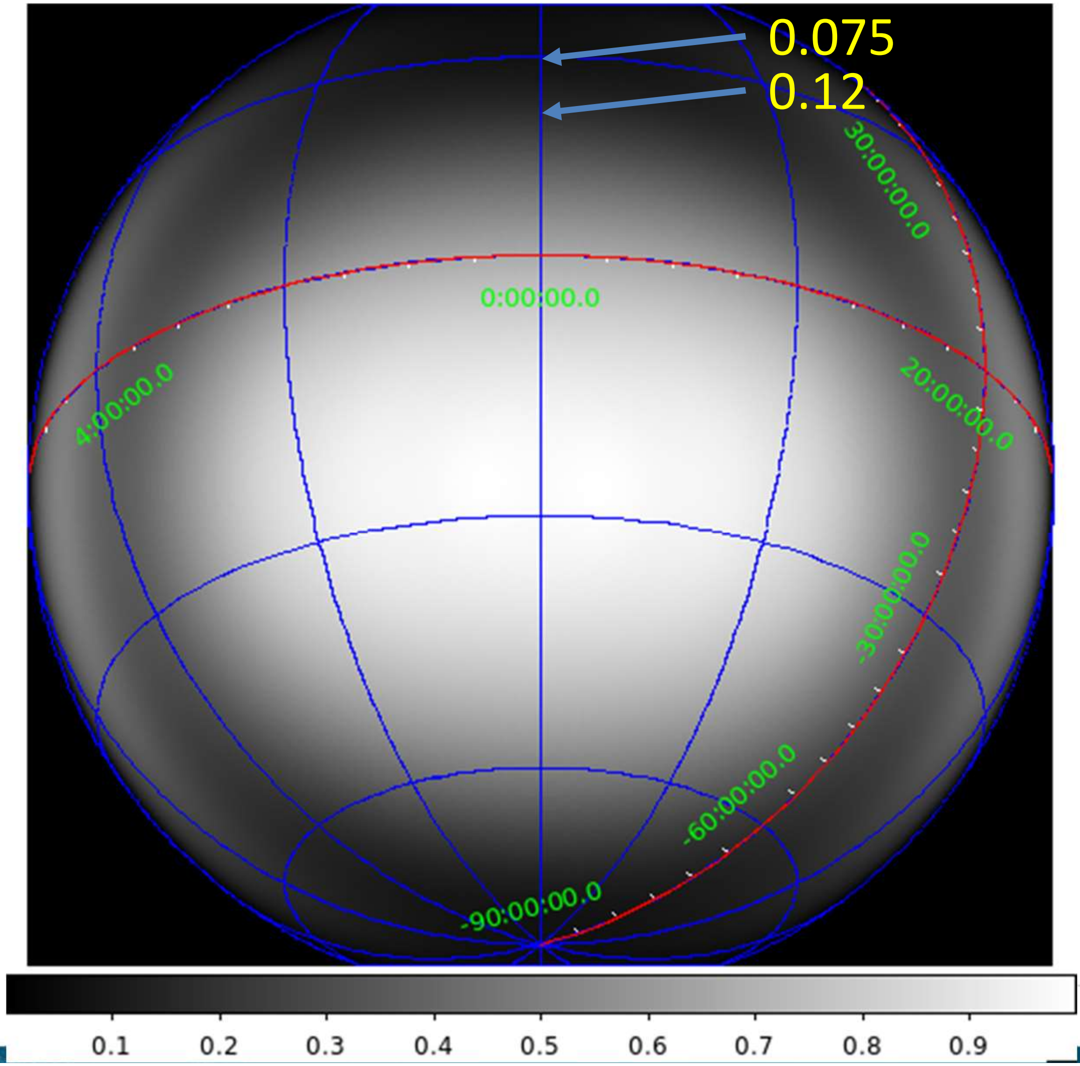
- Done in simulations, looking at applying to AAVS2 now

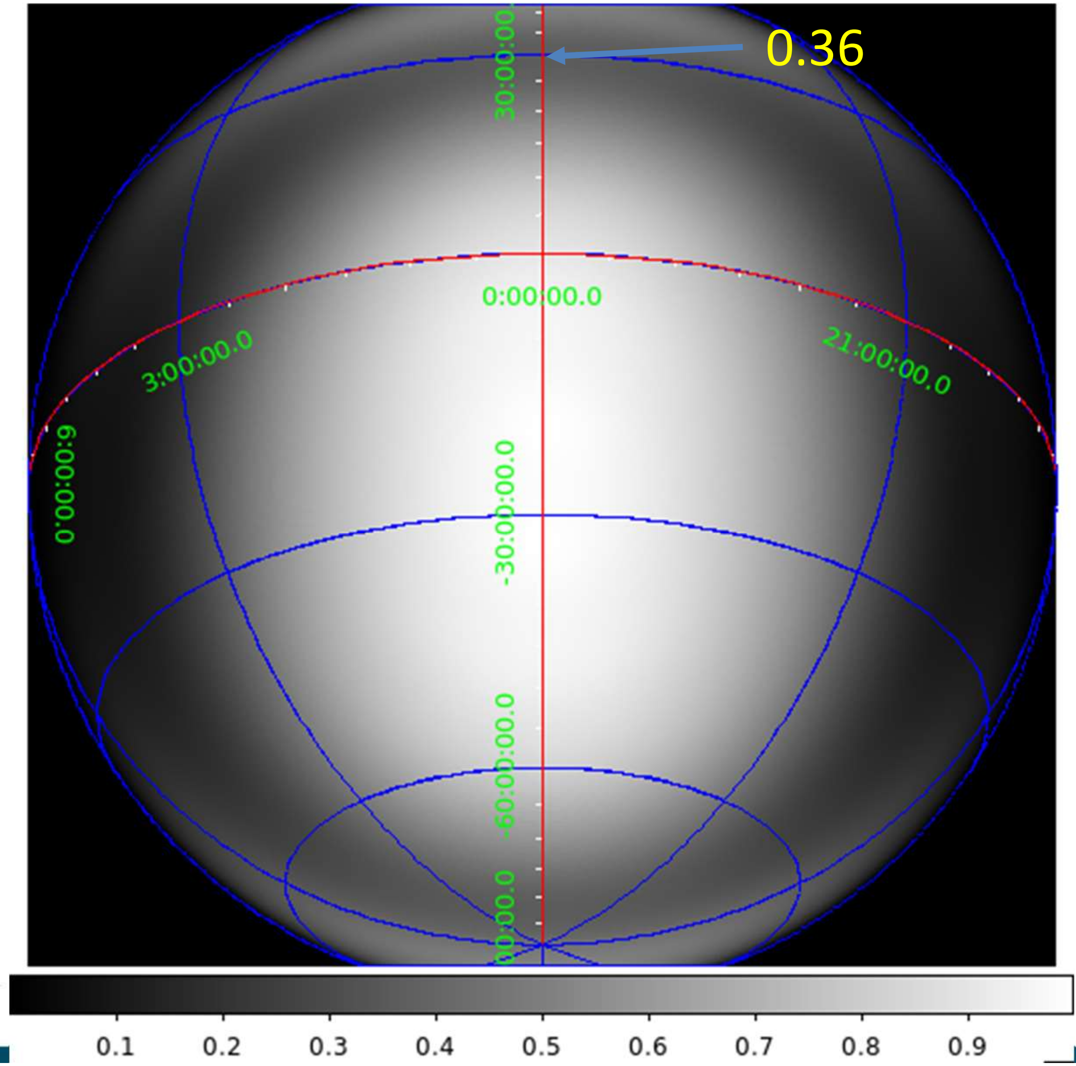
Results: stability of delay solutions - EDA2




EDA Y Single element 160 MHz – LST 6 hrs
S4.1 Y Single element 160 MHz – LST 6 hrs
Apparent flux density: 10500 Jy
Apparent flux density: 6000 Jy
Sun
6:00:00.0
9:00:00.0
3:00:00.0
-30:00:00.0
-60:00:00.0
-90:00:00.0
1.4
2.8
4.2
5.6
7.1
8.5
9.9
11
1.3
2.7
4
5.4
6.8
8.1
9.4
11
12

SKALA4 YY vs XX at large zenith angle (160 MHz)





Status

Dominant compact source (sun)

- Better at higher freqs. No good <~ 100 MHz
- During March-April timeframe, gives unambiguous data

Delay calibration

- Fit linear phase ramp vs freq for each pol. -> delay
- Successfully doing this since AAVS1

All-sky model: Average Element Pattern

- Use rescaled Haslam and beam model including the Sun
- Successfully doing this since AAVS1

All-sky model: Full element patterns

- Done in simulations, looking at applying to AAVS2 now
- Still combines the imperfect sky model with beam model. Hard to deconvolve.