On-sky testing of the C-band cryo-PAF: Pharos2

Michael D'Cruze[1], Keith Grainge[1] , Michael Keith[1], Simon Melhuish[1], Mark McCulloch[1], Bob Watson[1], Alessandro Navarrini[2] , A. Melis[2], G. Naldi[2], G. Pupillo[2], G. Comoretto[2], P. Ortu[2], A. Ladu[2], R. Concu[2], P. Marongiu[2], A. Poddighe[2], R. Chiello[3]
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[2] INAF-OAC, Cagliari, Italy
[3]The University of Oxford, UK

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The original Pharos…

- Originally conceived c.20yrs ago as C-band cryoPAF concept receiver, consisting of:
  → 10x11 array of 4—8GHz Vivaldi antennas in each pol
  → 20K LNAs designed in-house
  → Analogue BF utilising liquid crystal delay lines to form four beams with on-the-fly phase adjustment

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- Intended as general tech demonstrator; eventual deployment on LT for C-band obs and integration into eM

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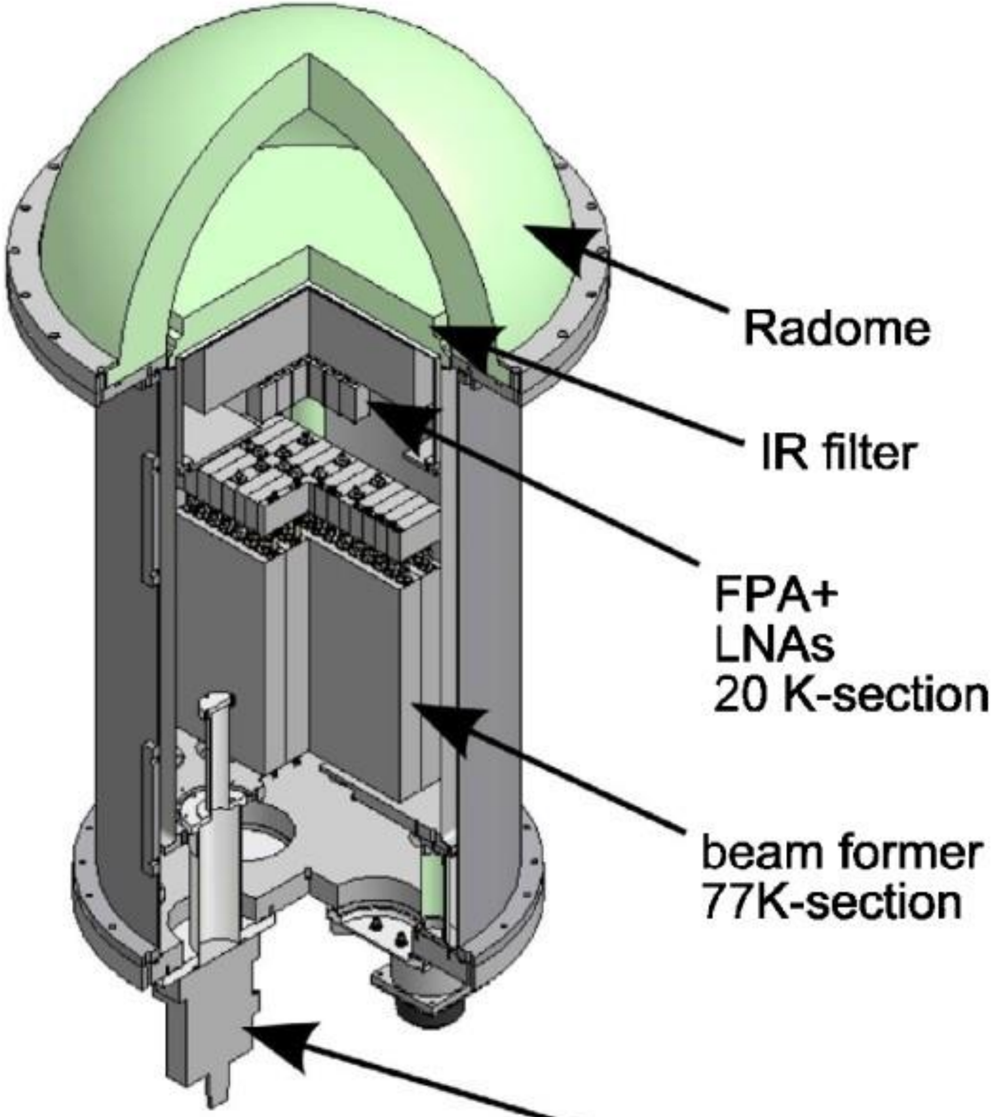

Figure 7. Preliminary cryostat design indicating the RF sections immediately behind the vacuum window.

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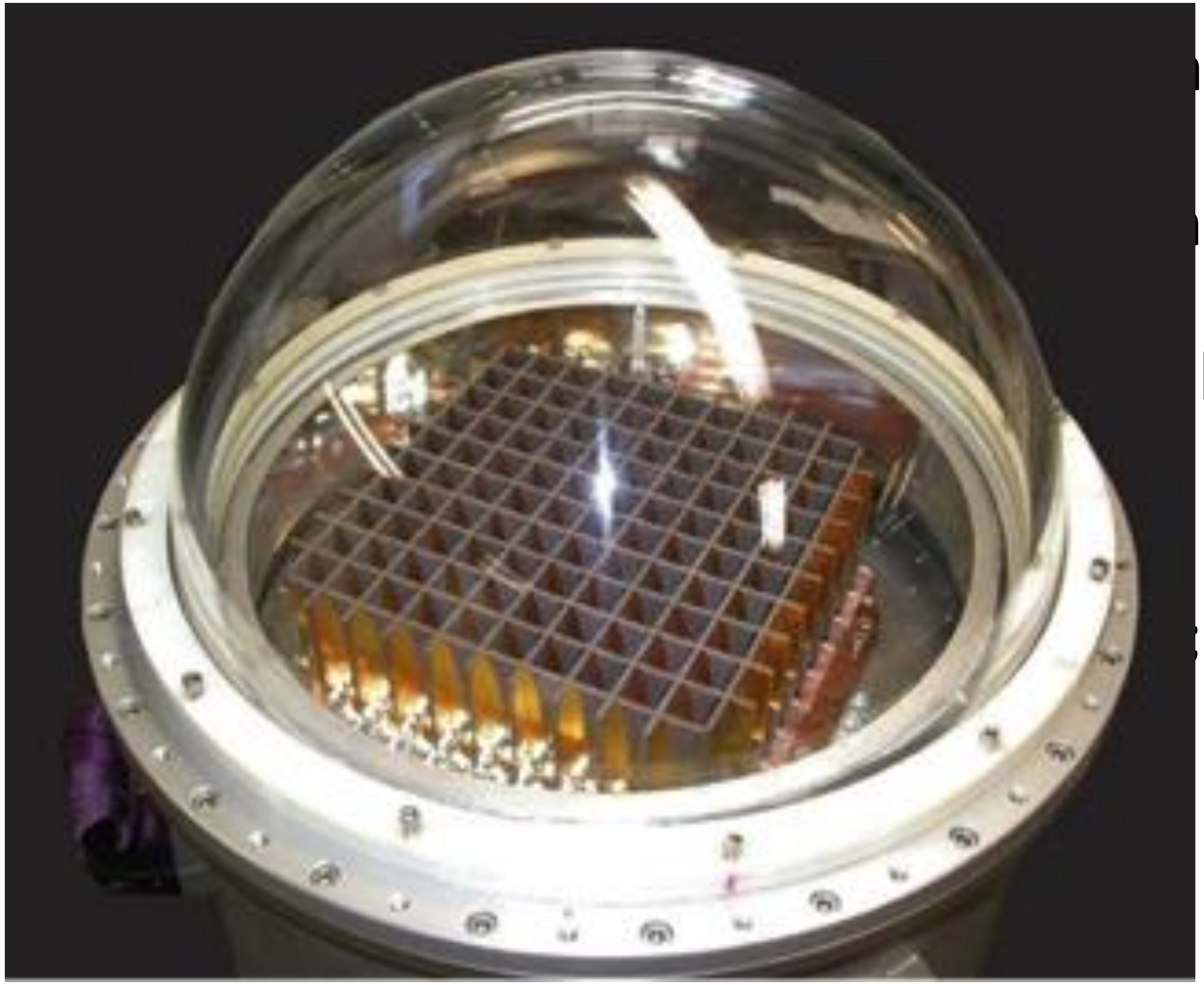
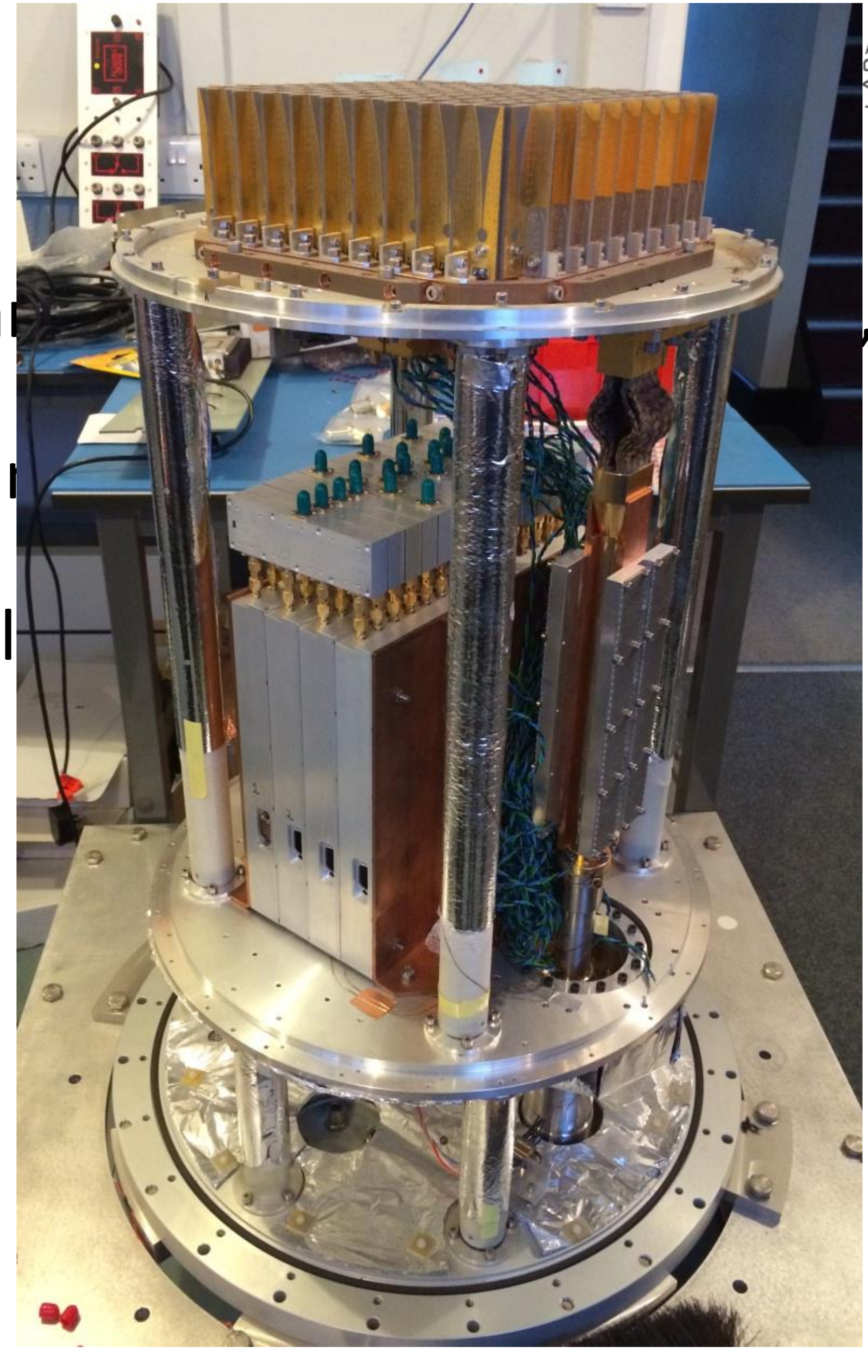
The original Pharos...





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The Pharos2 upgrade

- Pharos2 funded through SKA PAF AIP as demonstrator and pathfinder for potential future SKA-Mid PAFs
- Aim primarily to match single-pixel SEFD for boresight beams; form clean, stable beams off-axis

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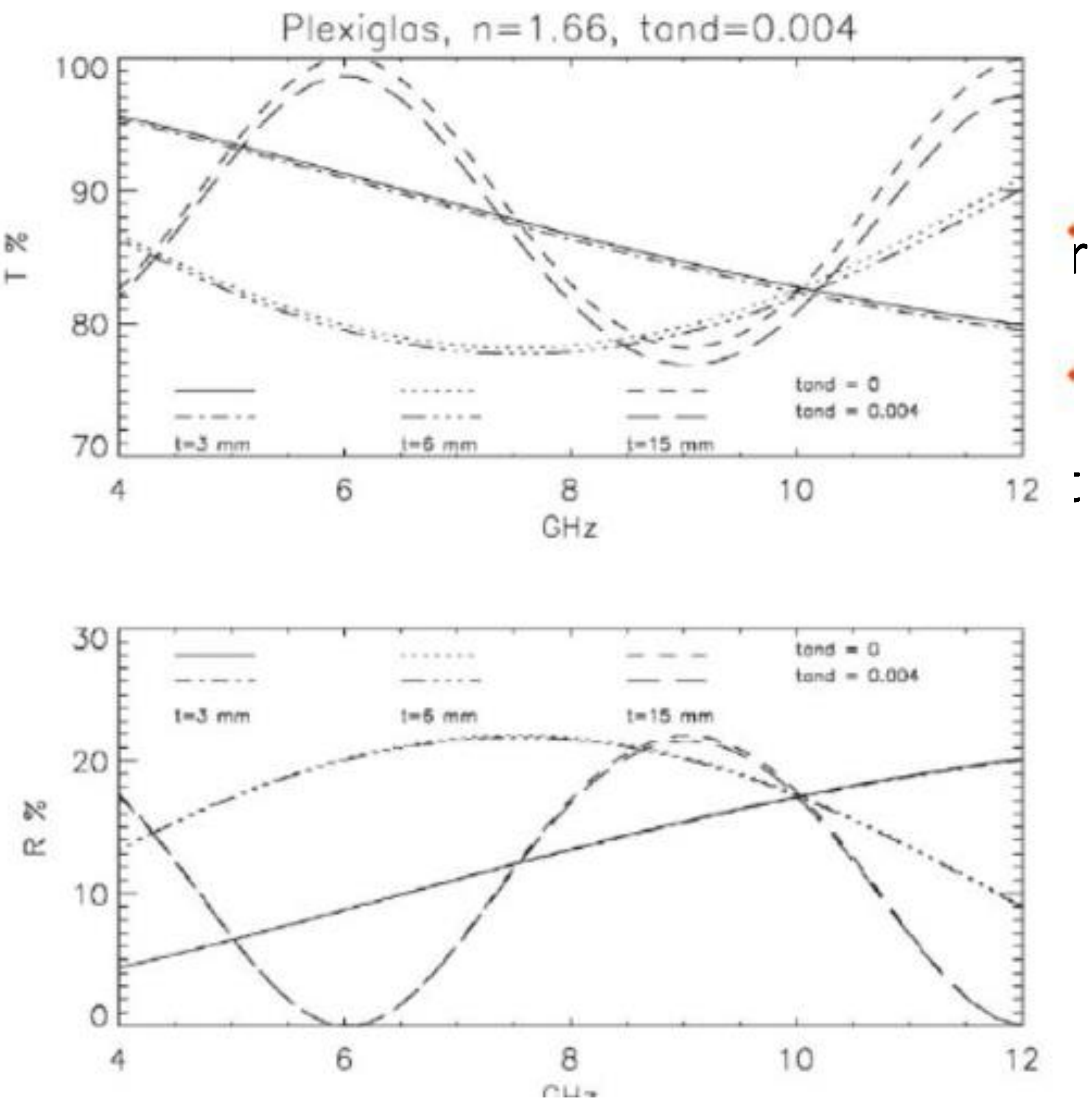

- Pharos2 fu … r and pathfinder
  for potenti
- Aim prima … : beams; form
  clean, stab
- Substantia
  -- Lower-lc

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- Aim primarily to r ght beams; form clean, stable bear

- Substantial upgra
  -- Lower-loss and)
  -- Custom multi-la

FIG. 6: A test foam stack of foam disks. In this case the material is Rohacell 51HF. Note the use of staggered *buttons* to separate layers.

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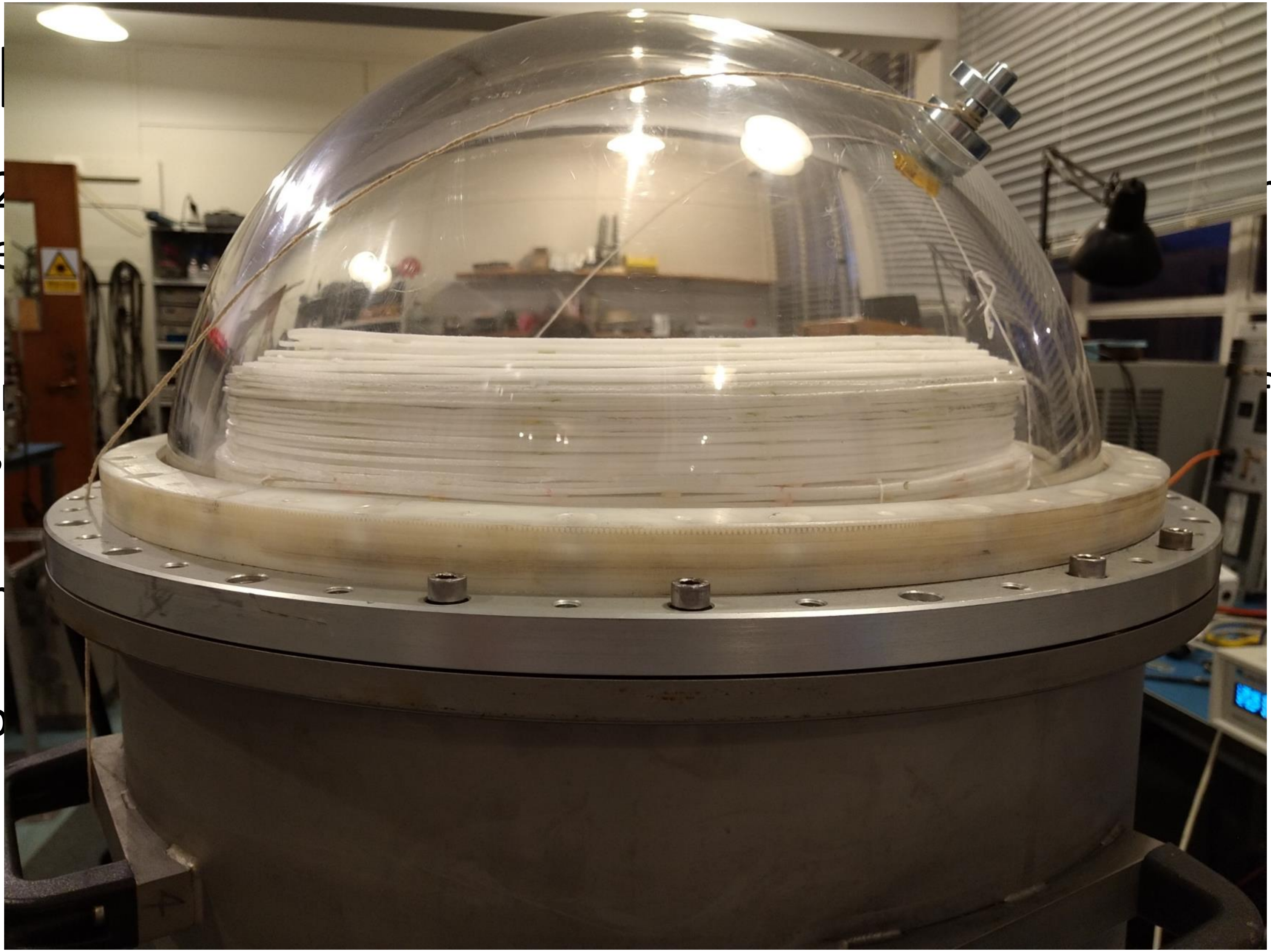

- Pharos2 … nfinder for pote…
- Aim pri… form clean, s…
- Substan…
  -- Lowe…
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The Pha

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- Aim prima ... s; form clean, stab

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  -- Lower-l
  -- Custom

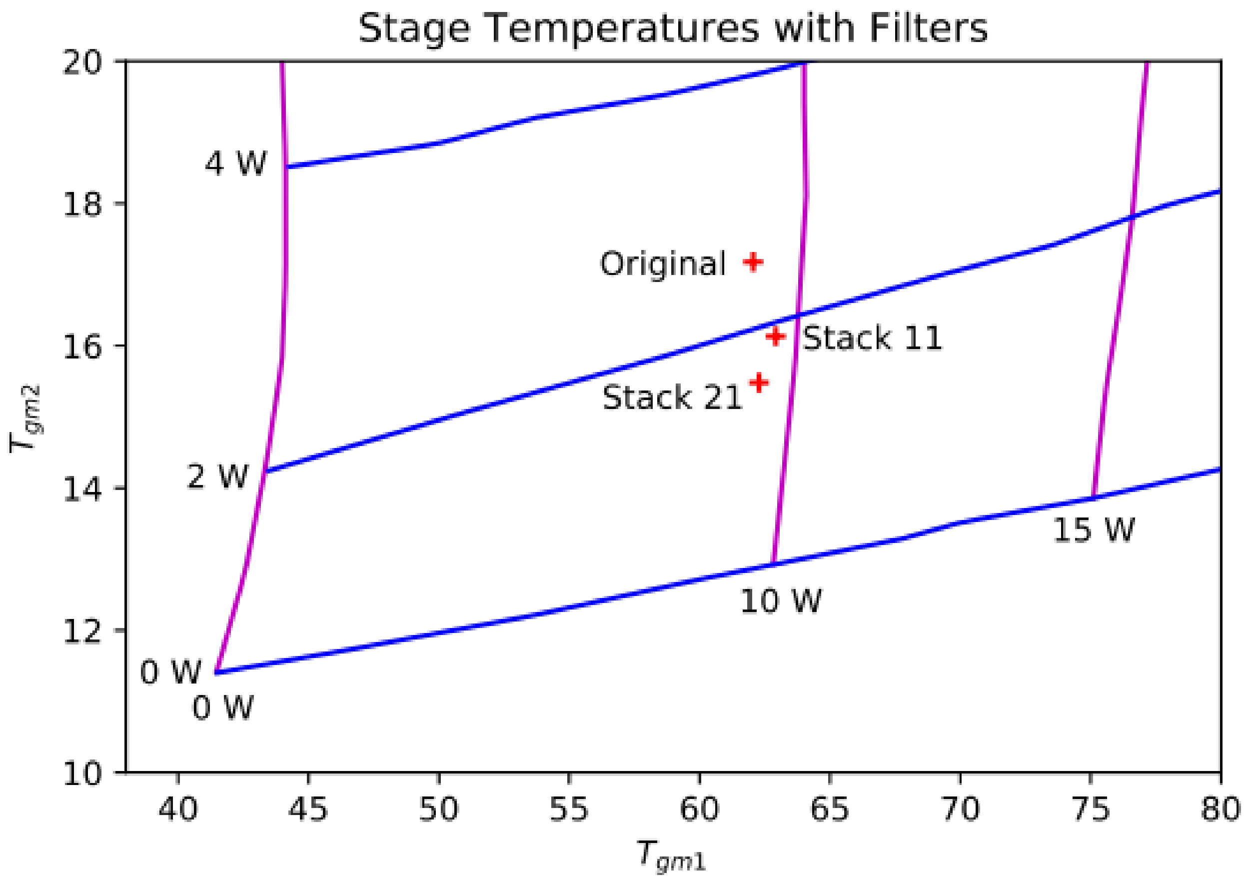

FIG. 14: Equilibrium temperatures using the original filter and multi-disk filters, shown over part of the cold head capacity map (magenta – 3 levels of 1st-stage power, blue – 3 levels of 2nd-stage power).

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The Phar

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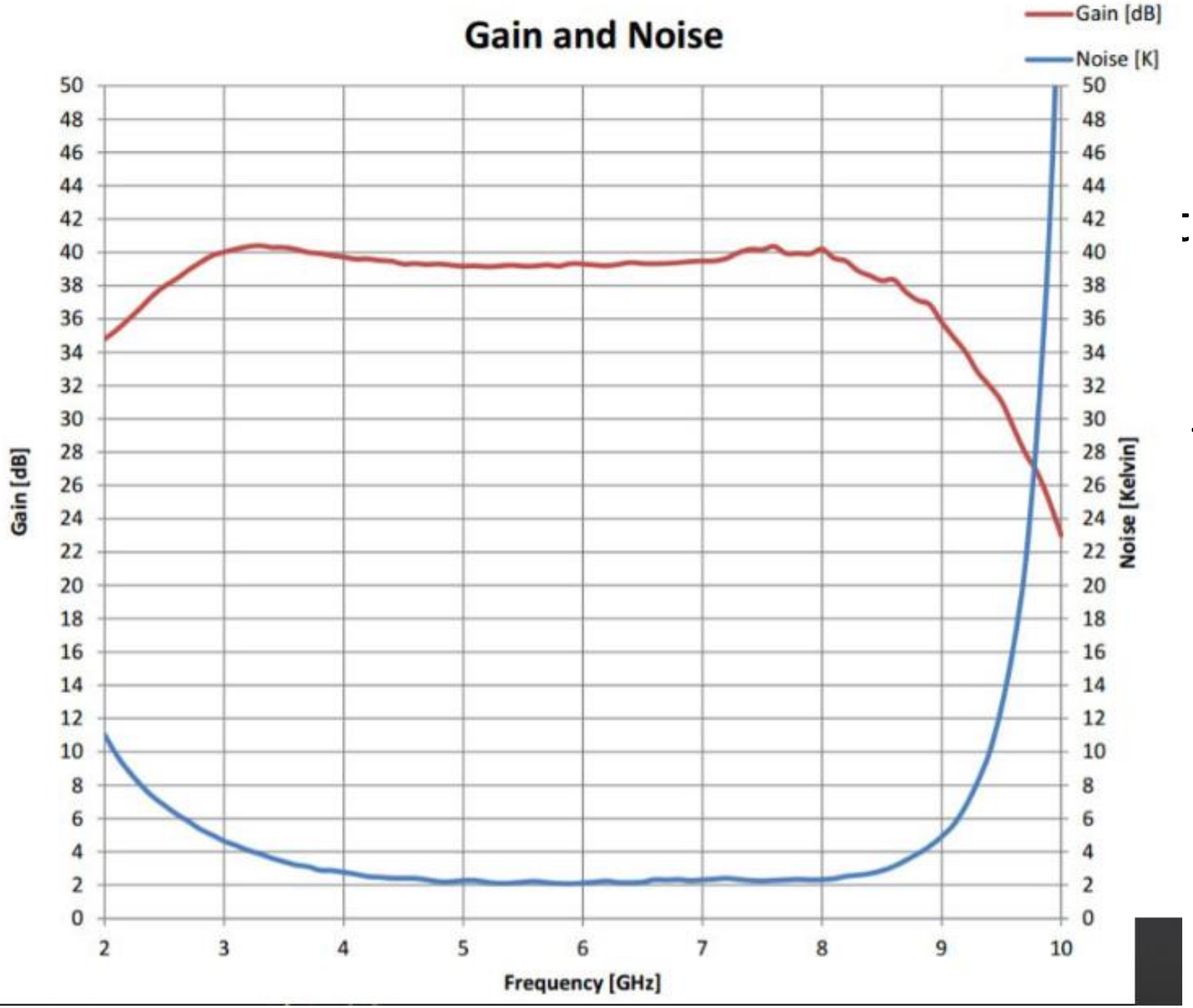
- Aim primari form clean, stable
- Substantial
  -- Lower-los
  -- Custom m
  -- 2—3K LN



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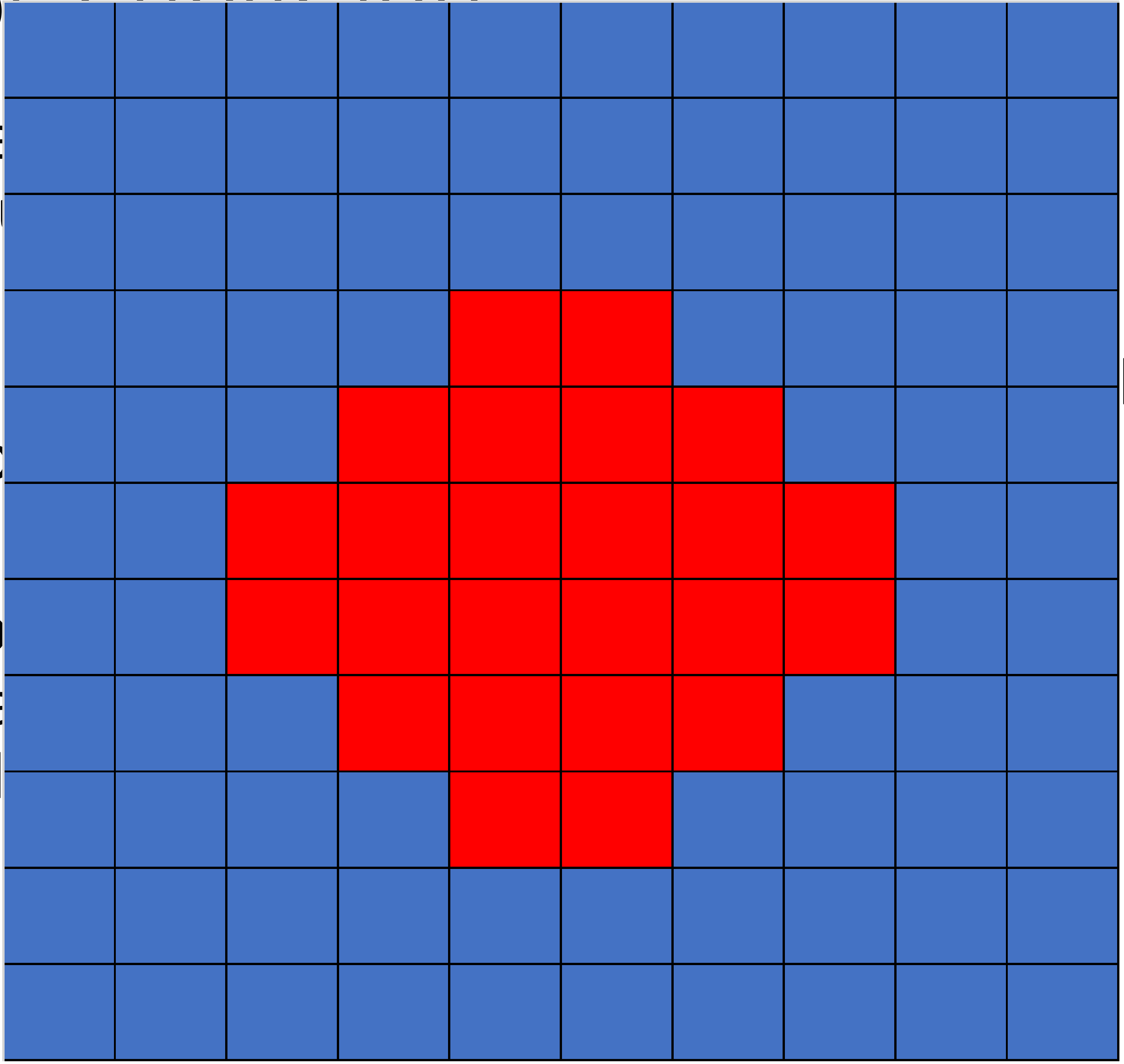
The Pharos2 upgrade



- Pharos2 funde … and pathfinder for potential f…
- Aim primarily … beams; form clean, stable b…
- Substantial up…
  -- Lower-loss a…
  -- Custom mul…
  -- 2—3K LNAs

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  -- Replacement of ABF with INAF-supplied SKA-LOW prototype DBF unit configured for four beams

The

- Phar hfinder
for p

- Aim form
clean

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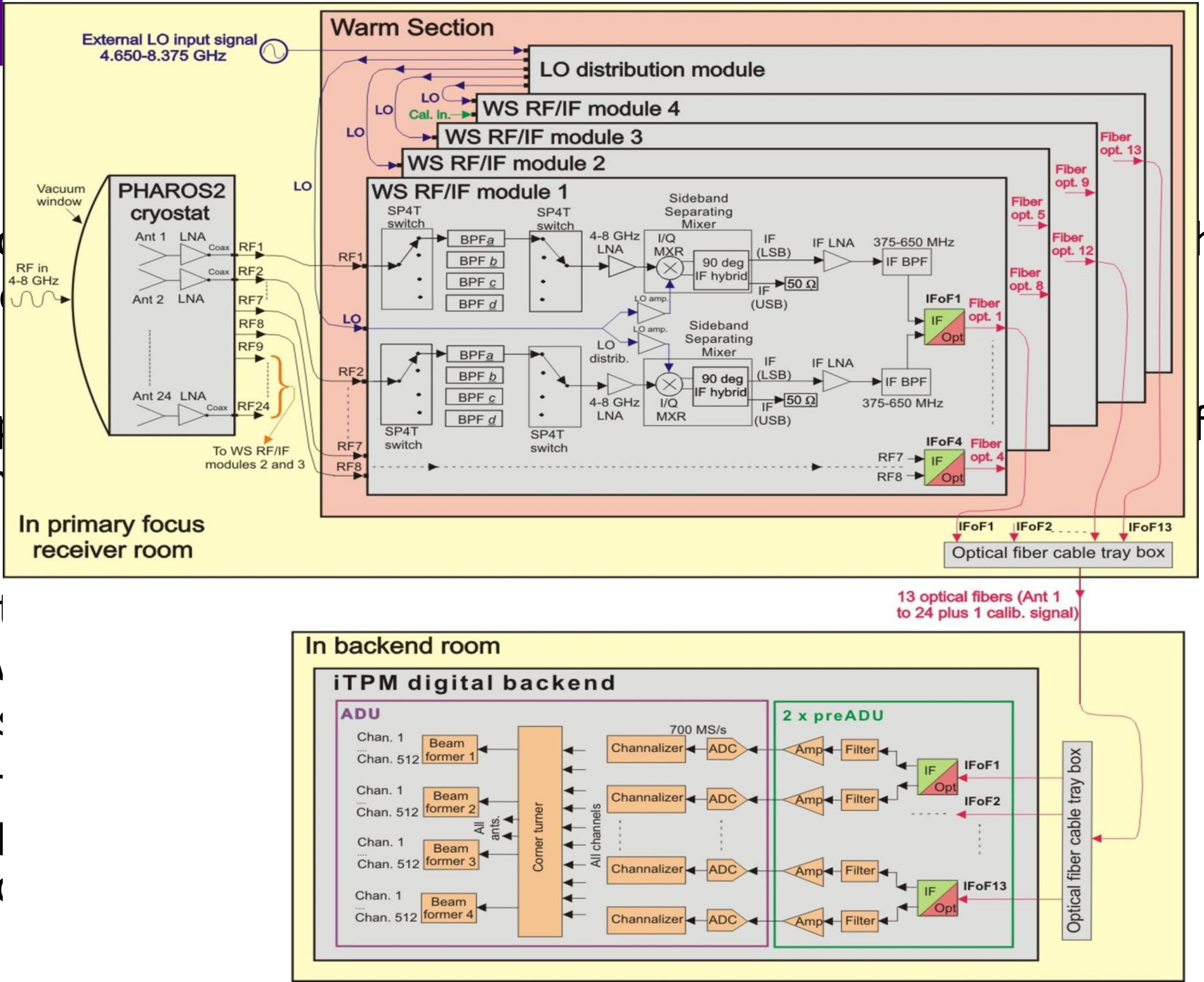

2018—9: Initial testing

- First outdoor tests performed using ABF prior to delivery of INAF WS & DBF, immediately showing the benefit of the new LNAs…

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- First outdoor t y of INAF WS & DBF, immed As…

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2018

• First
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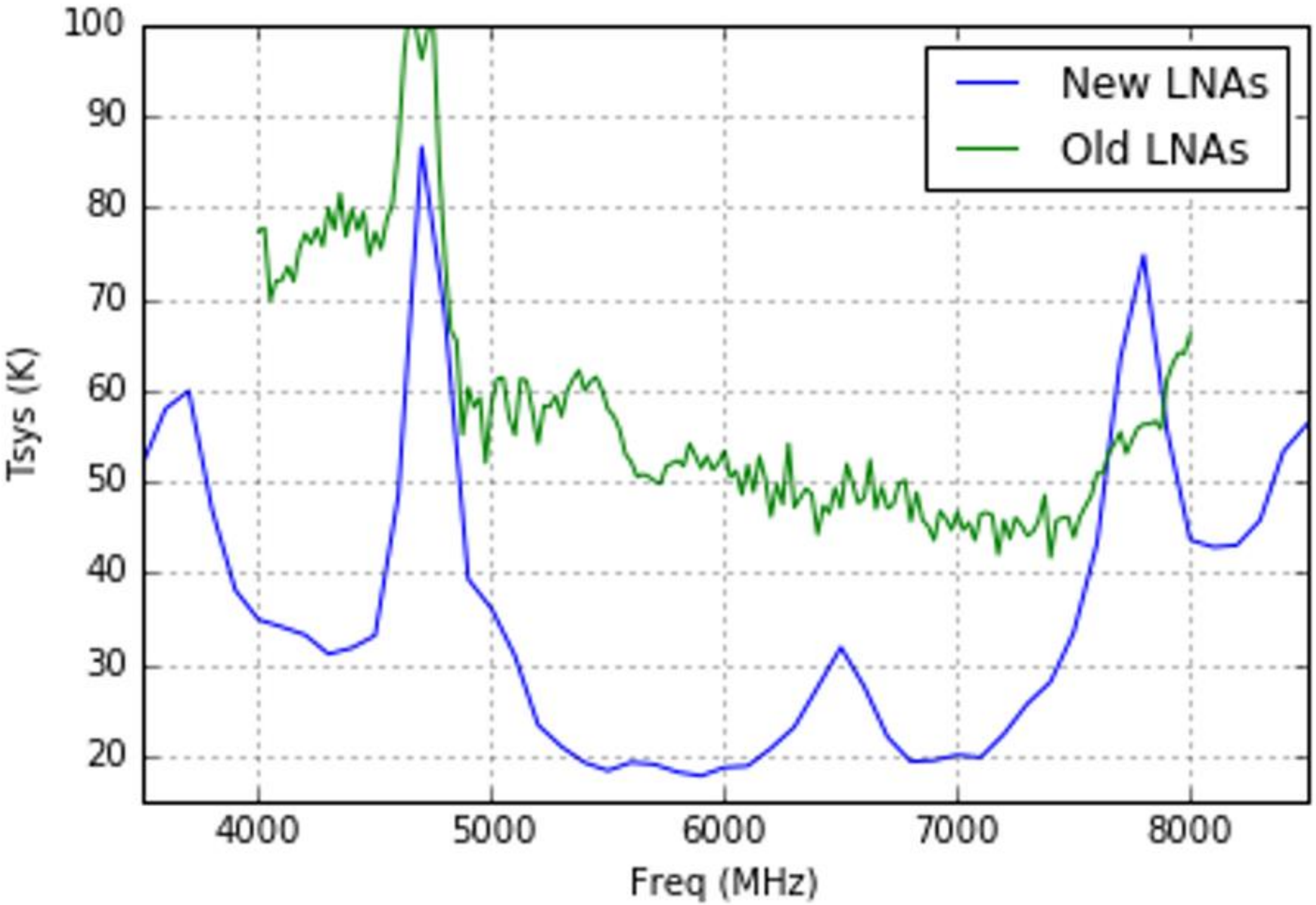
AF WS



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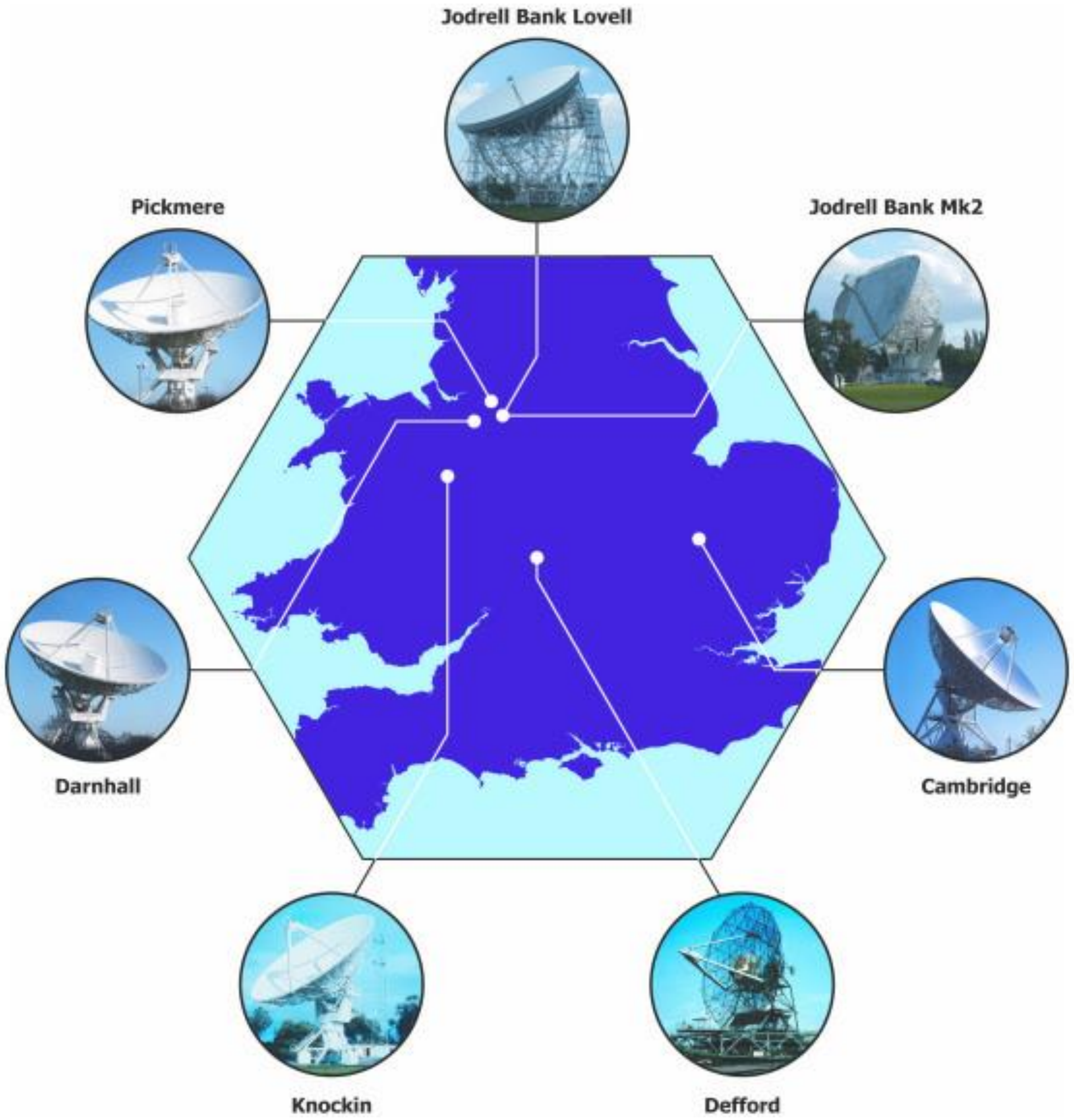

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- Lots of challenges:
  -- Recommission prime focus operation
  -- Cryo, power, LO + maser ref. signal, install fibres etc.
  -- No real certainty as to mechanical limitations re: installation & focusing
  -- eM took some convincing re: restoration of telescope following test period…

2019—20: Ground testing

- INAF deliver WS & DBF autumn 2019, enabling ground testing

2019—20: C

- INAF deliver WS

nd testing

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2019—20

- INAF deliver W ound testing

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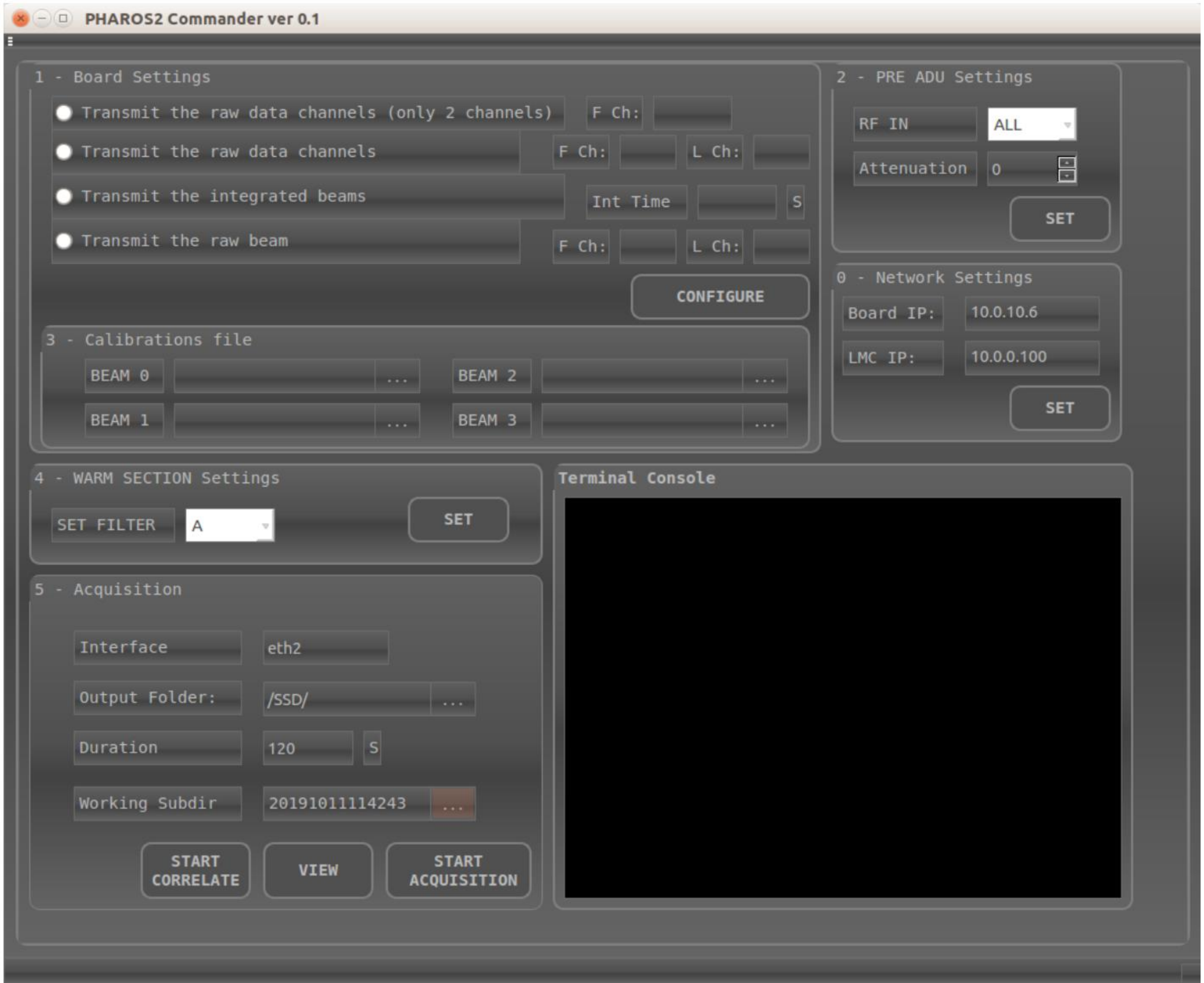

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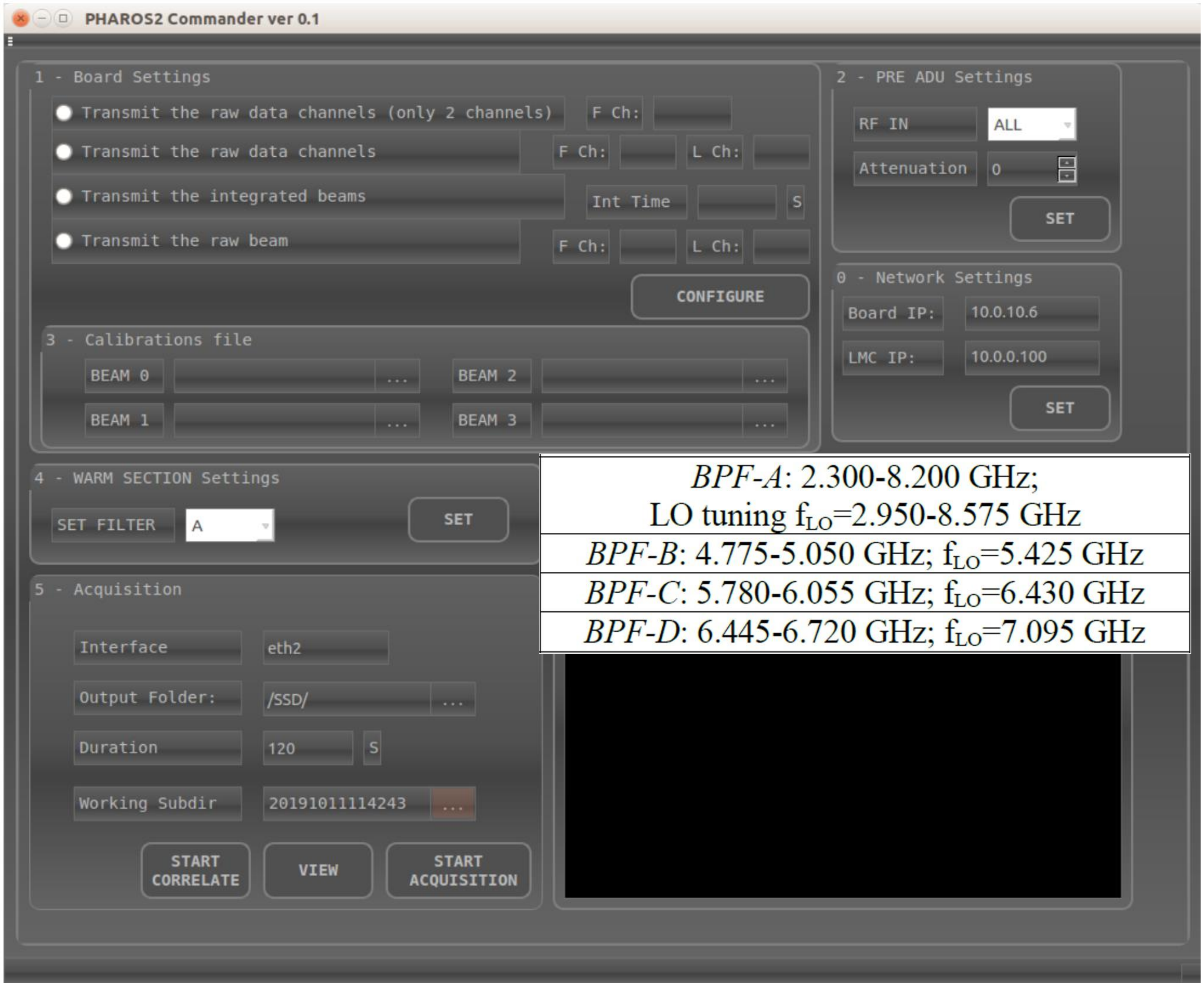

BPF-A: 2.300-8.200 GHz; LO tuning f_{LO}=2.950-8.575 GHz
BPF-B: 4.775-5.050 GHz; f_{LO}=5.425 GHz
BPF-C: 5.780-6.055 GHz; f_{LO}=6.430 GHz
BPF-D: 6.445-6.720 GHz; f_{LO}=7.095 GHz

2019—20: Ground testing

- INAF deliver WS & DBF autumn 2019, enabling ground testing

- Outfitting of focus box complete, inc. packaging & shielding of control & comms hardware:
  -- strong focus on minimising RFI in component selection
  -- media converters triple-shielded

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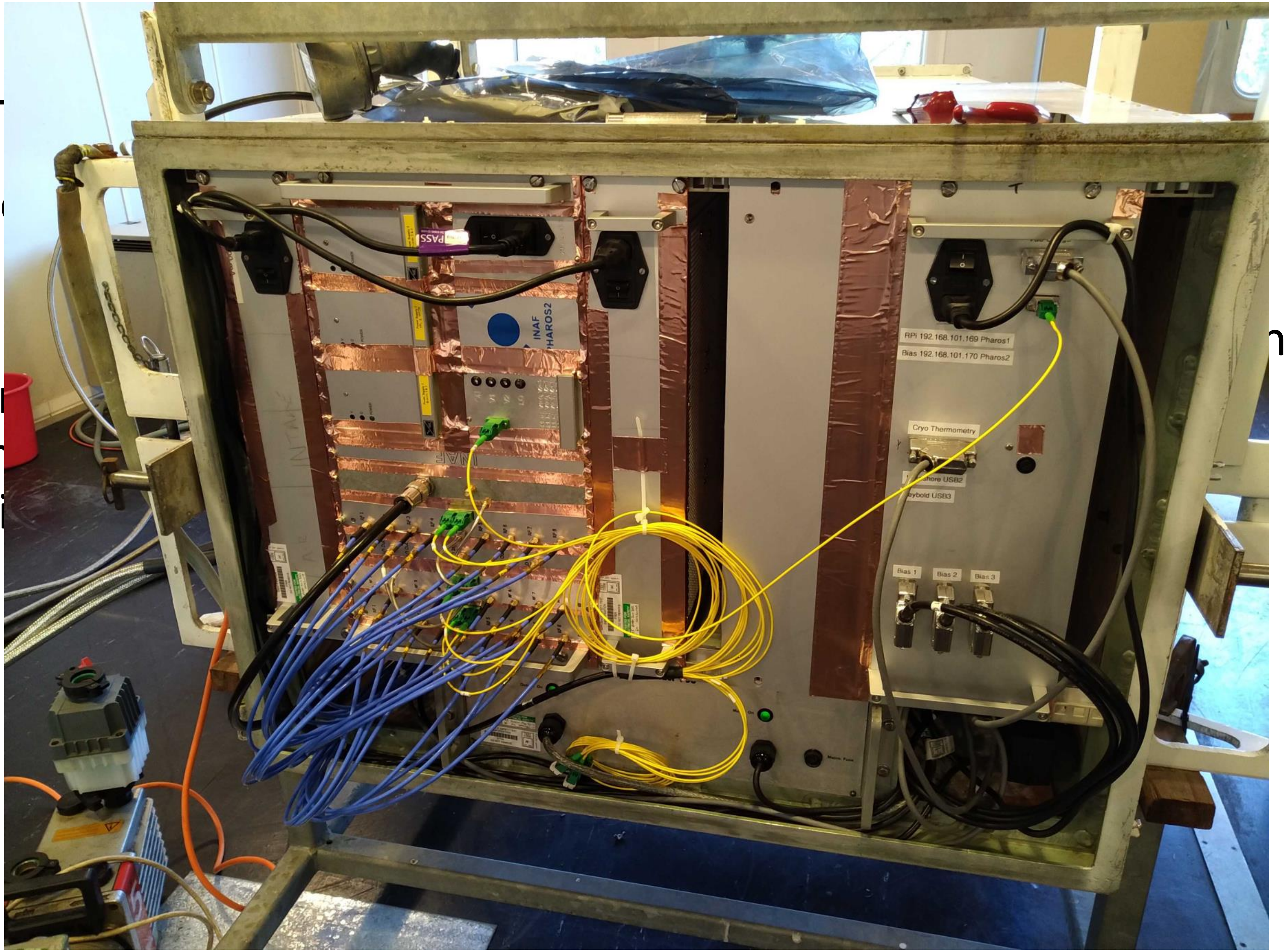

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  -- strong focus on minimising RFI in component selection
  -- media converters triple-shielded

- Obs plan assembled:
  -- Bulk of testing against Cyg A, Cas A, also 3C sources, NGC7027 etc.
  -- Also consider spectral line sources e.g. W3OH, M42

2019—20: Ground testing

- Former SKADS mount recommissioned and populated focus box mounted, enabling AzEl control; DBF operating from nearby hut.

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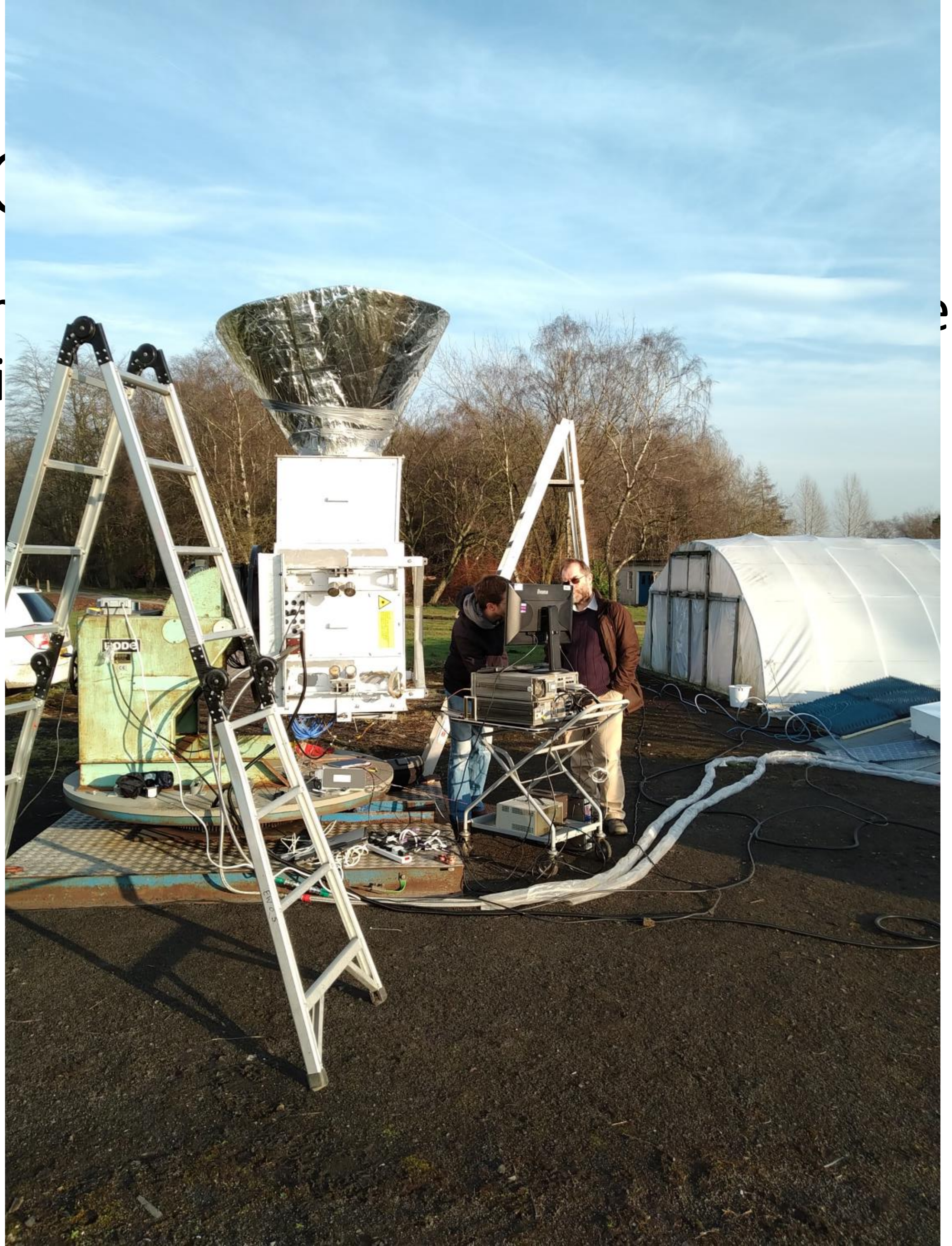
2019—20: C

- Former SKADS m ed focus box mounted, enabli nearby hut.



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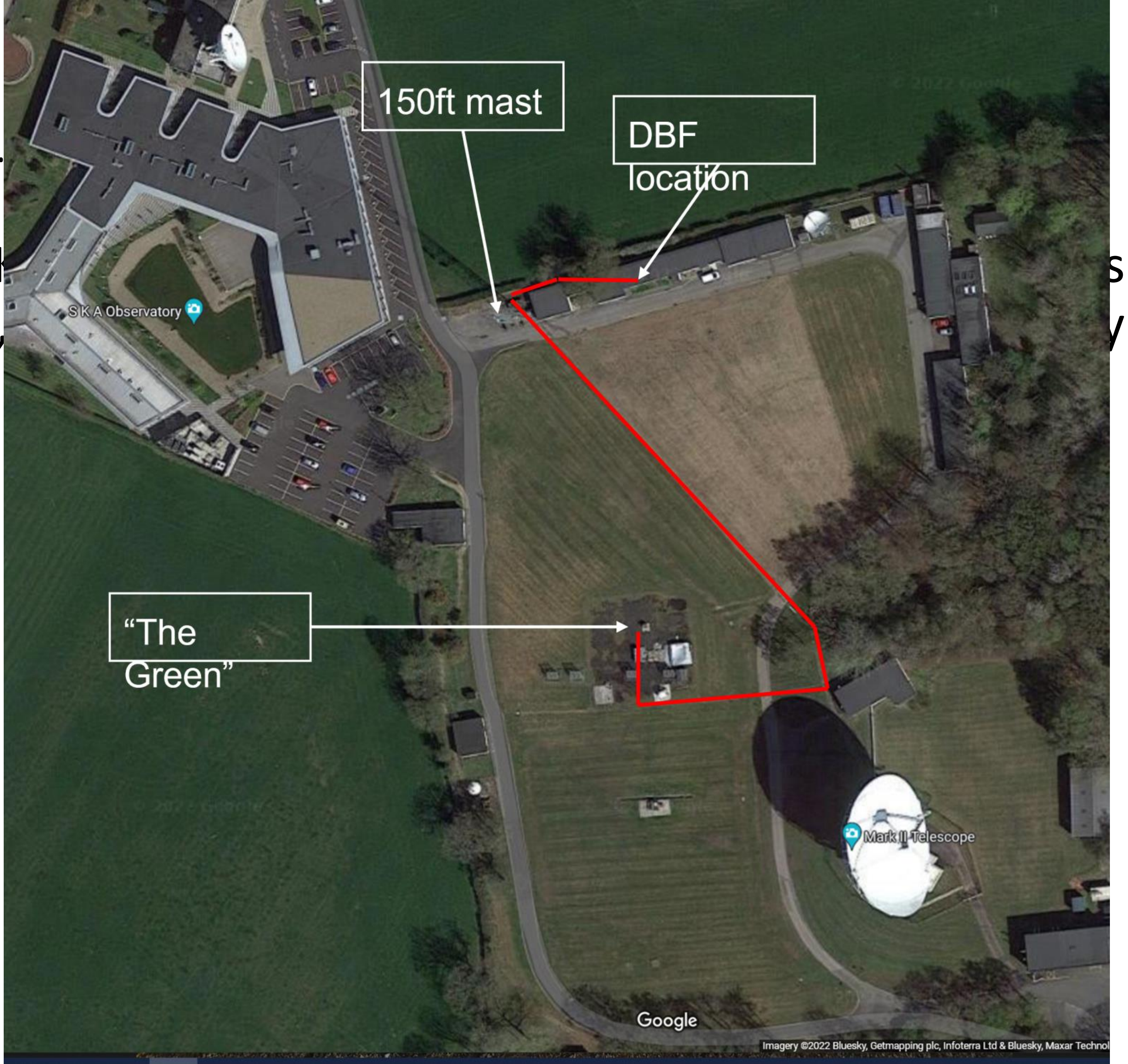

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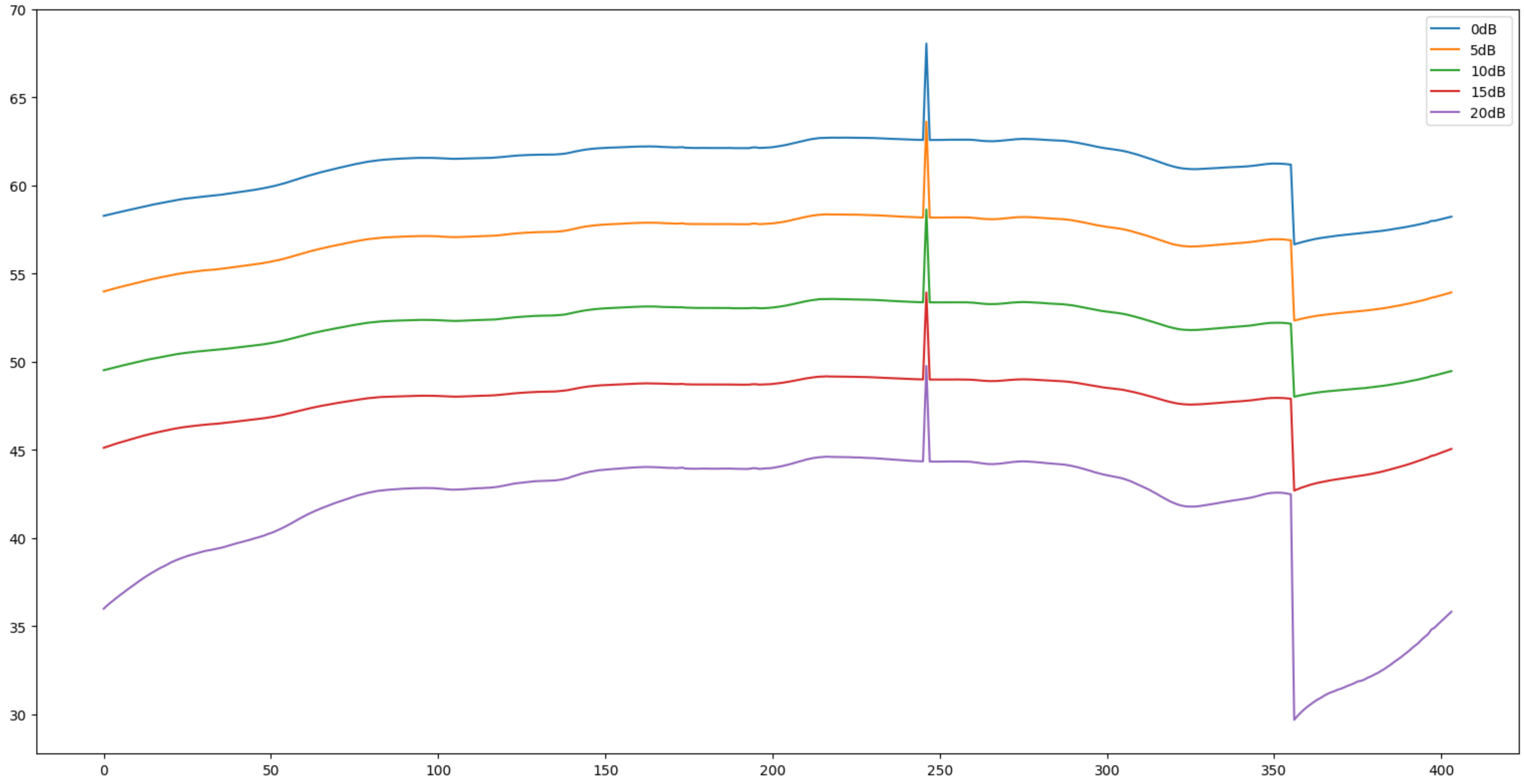

0dB
5dB
10dB
15dB
20dB
70
65
60
55
50
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40
35
30
0
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100
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200
250
300
350
400

2019—20: Ground testing

- Former SKADS mount recommissioned and populated focus box mounted, enabling AzEl control; DBF operating from nearby hut.
- Hot/cold load tests showed curious disparity between ABF & DBF TRx…

2019—20: Ground testing

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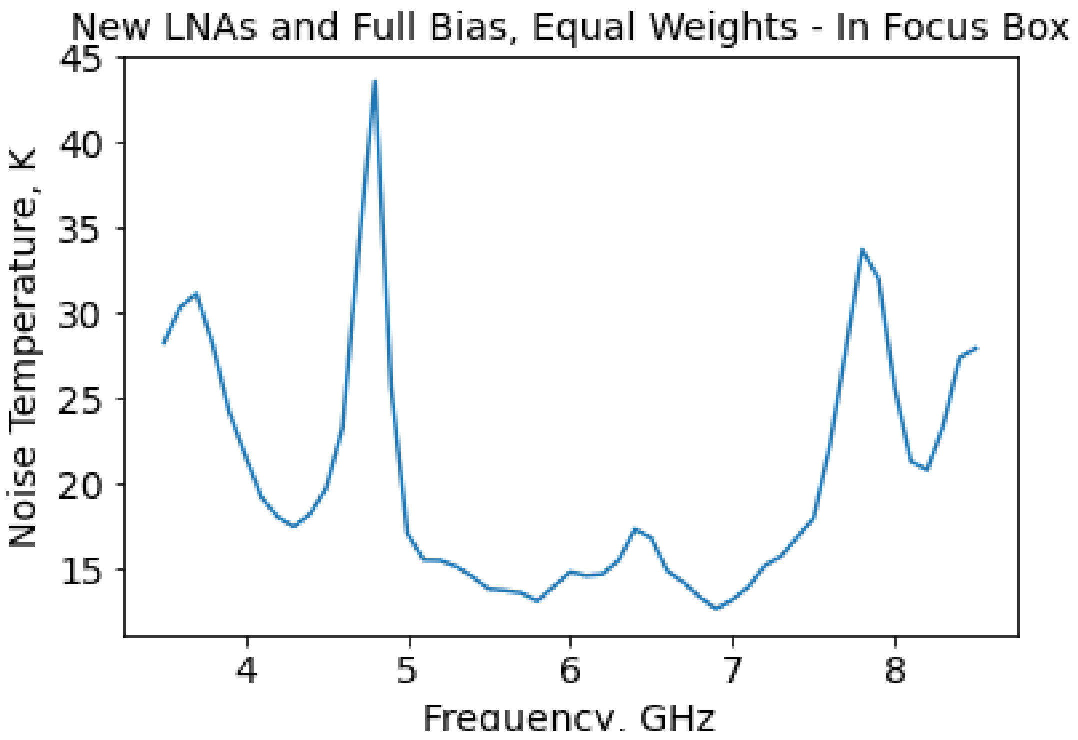

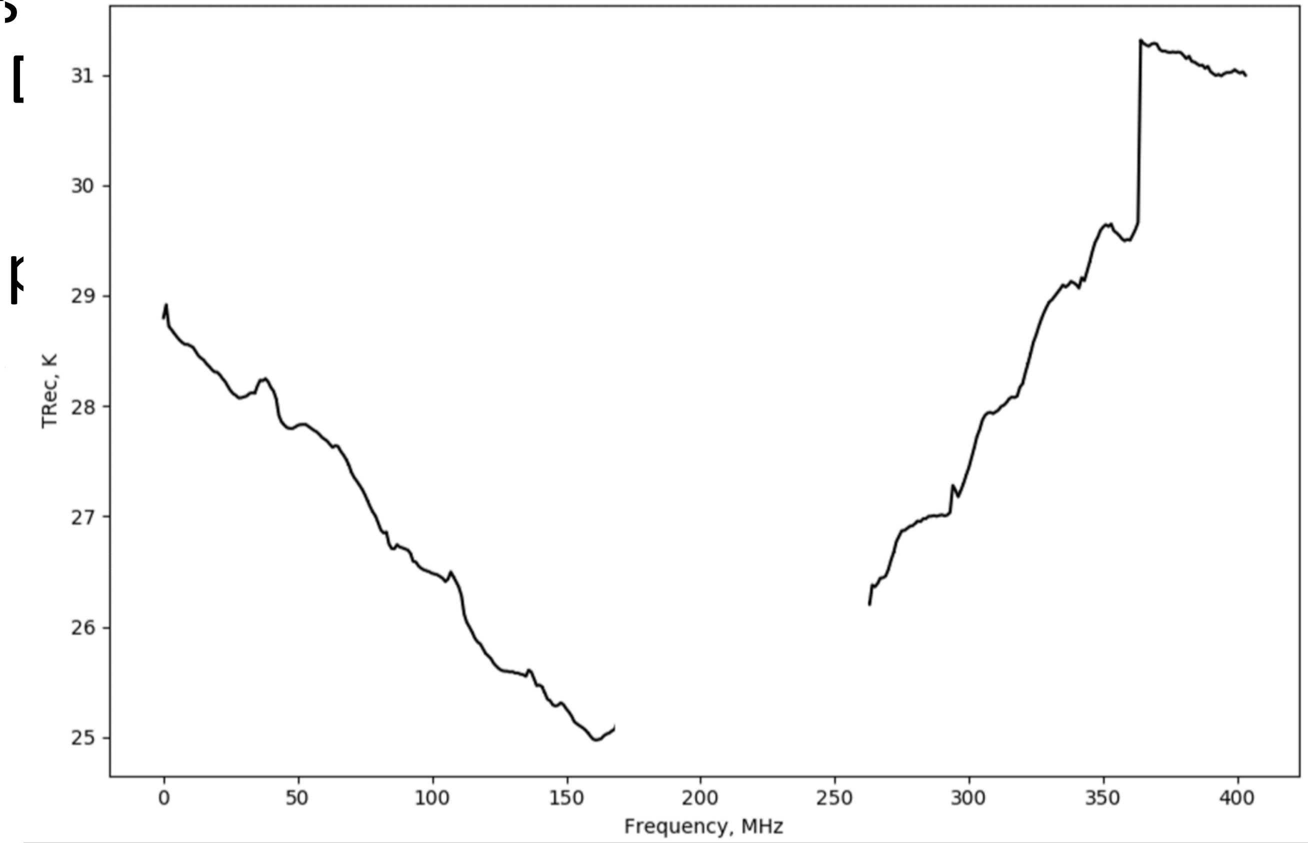

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- Nevertheless, TSys c.25K informs SEFD = 250Jy target on 25m Pickmere telescope.

2020: The Pickmere Test

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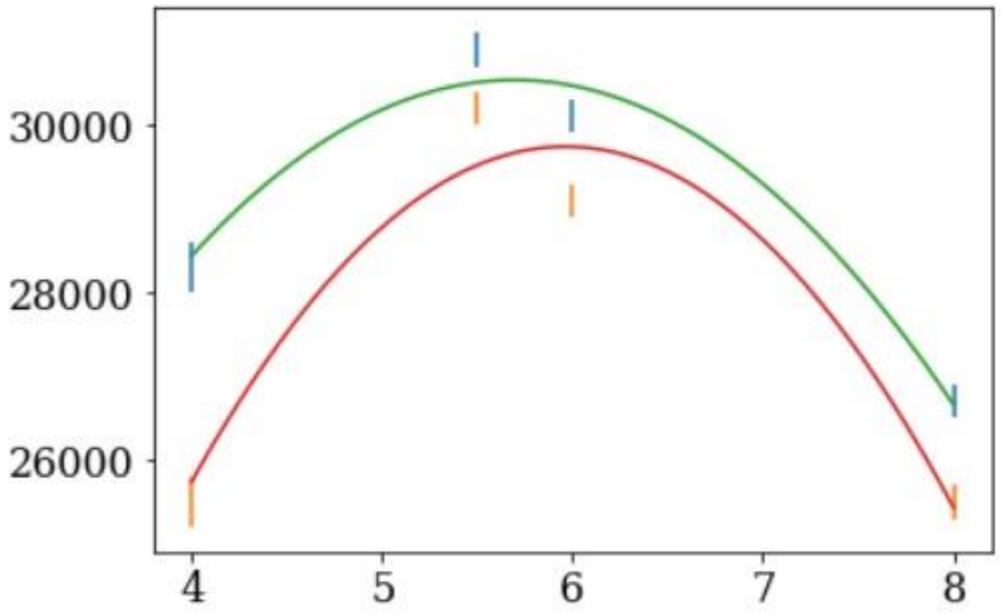
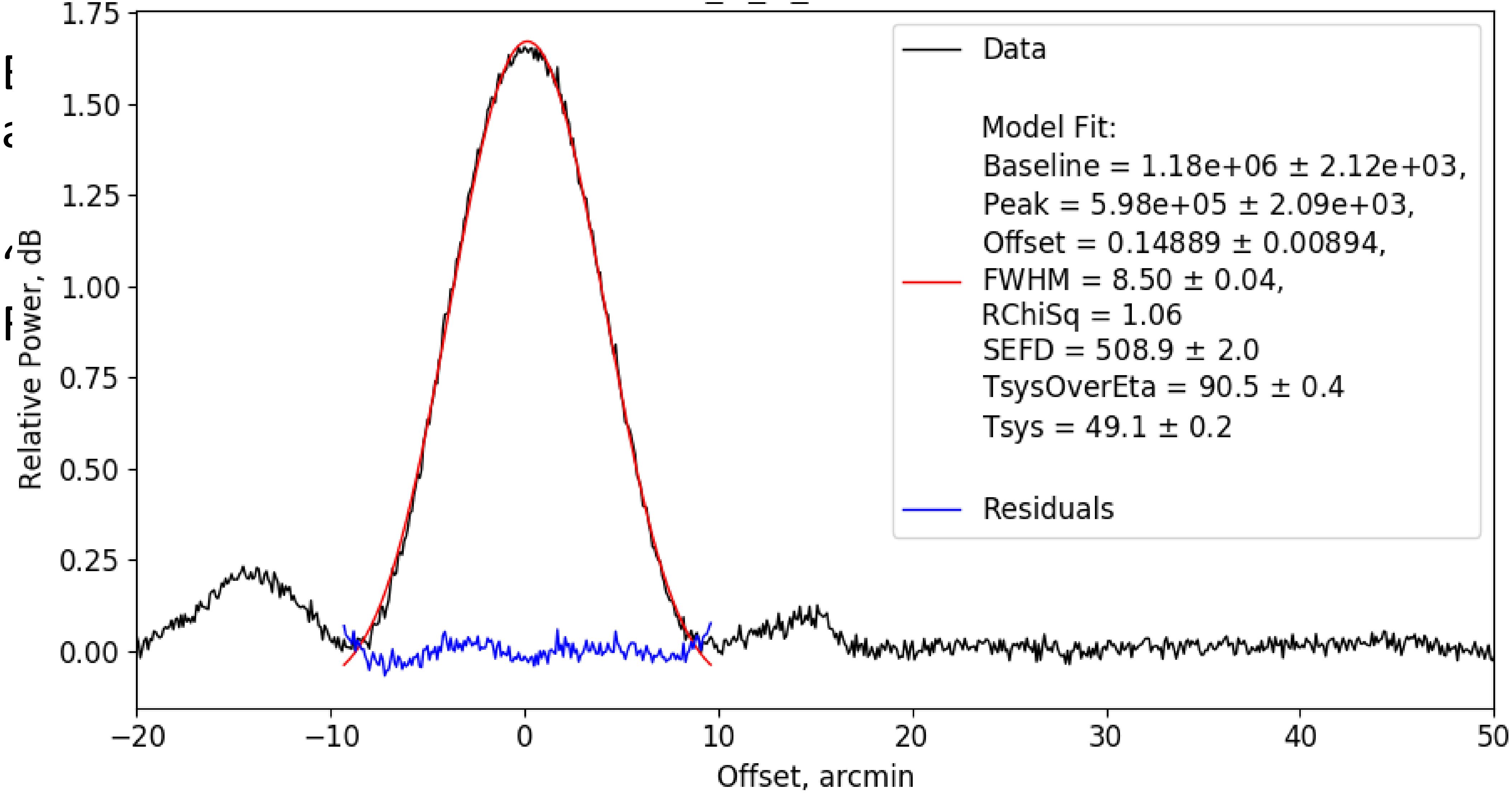
- Initial focusing tests showed adjustment required…



2020: The Pickmere Test

- Initial focusing tests showed adjustment required…
- “First light” achieved using Cyg A to calculate SNRMax weights at Filter D sub-band centre (6.5GHz), followed by azimuthal sweep

2020: The Pickmere Test



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2020: The Pickmere Test

- Basic plan for three weeks' testing. Initial focusing tests showed adjustment required…

- "First light" achieved using Cyg A to calculate SNRMax weights at Filter D sub-band centre (6.5GHz), followed by azimuthal scan

- Clean beam formed, but…
  -- Strong gaussianity even down to first minimum
  -- FWHM wider than expected
  -- SEFD x2 higher than expected…

- Attempts to test further scuppered by compressor failure.

2020: The Pickmere Test

- Five days remaining to gather as much useful obs as possible…

- Form some beams off-axis…

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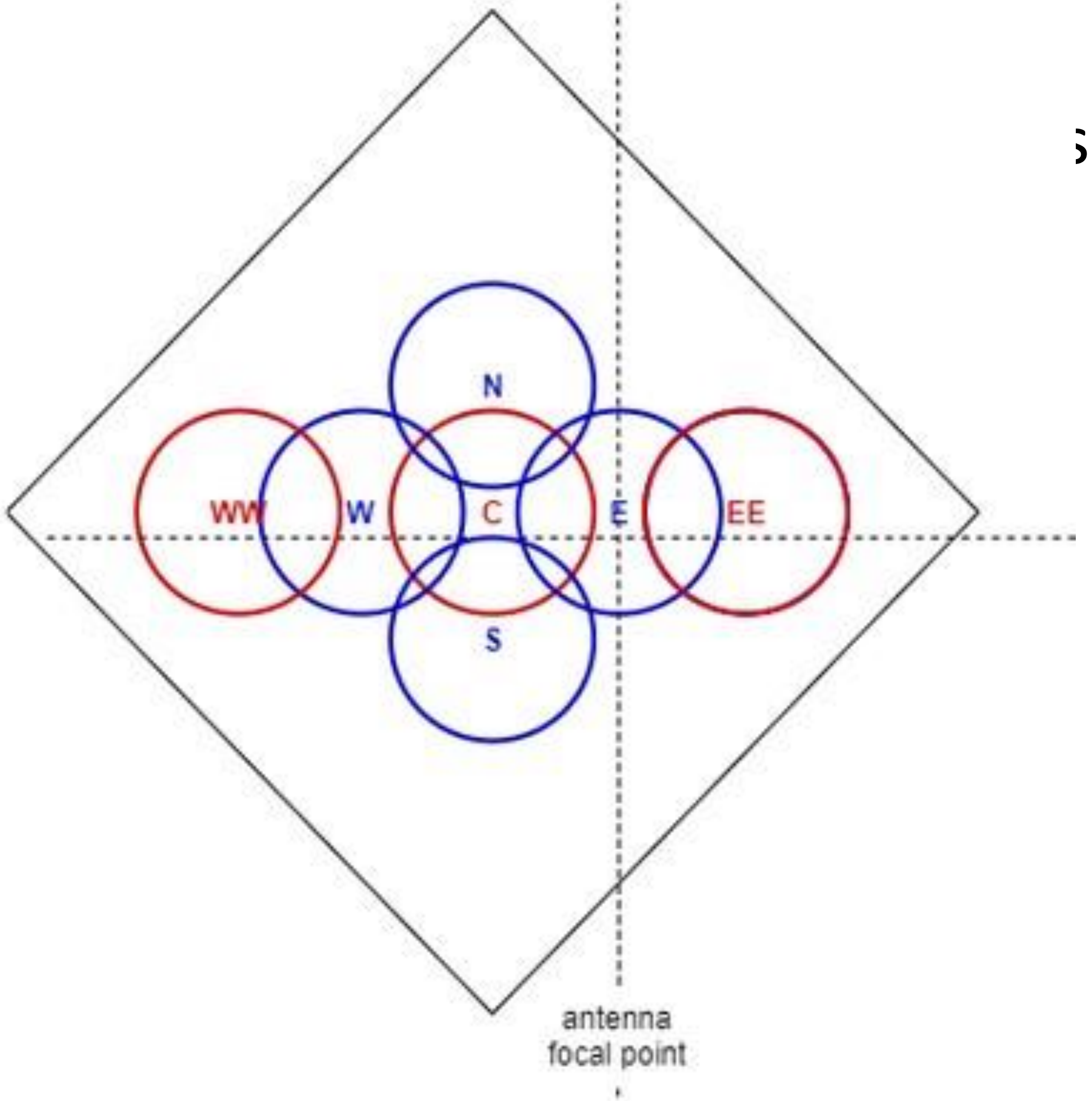
2020: The Pickmere Test

- Five day … s possible…
- Form so



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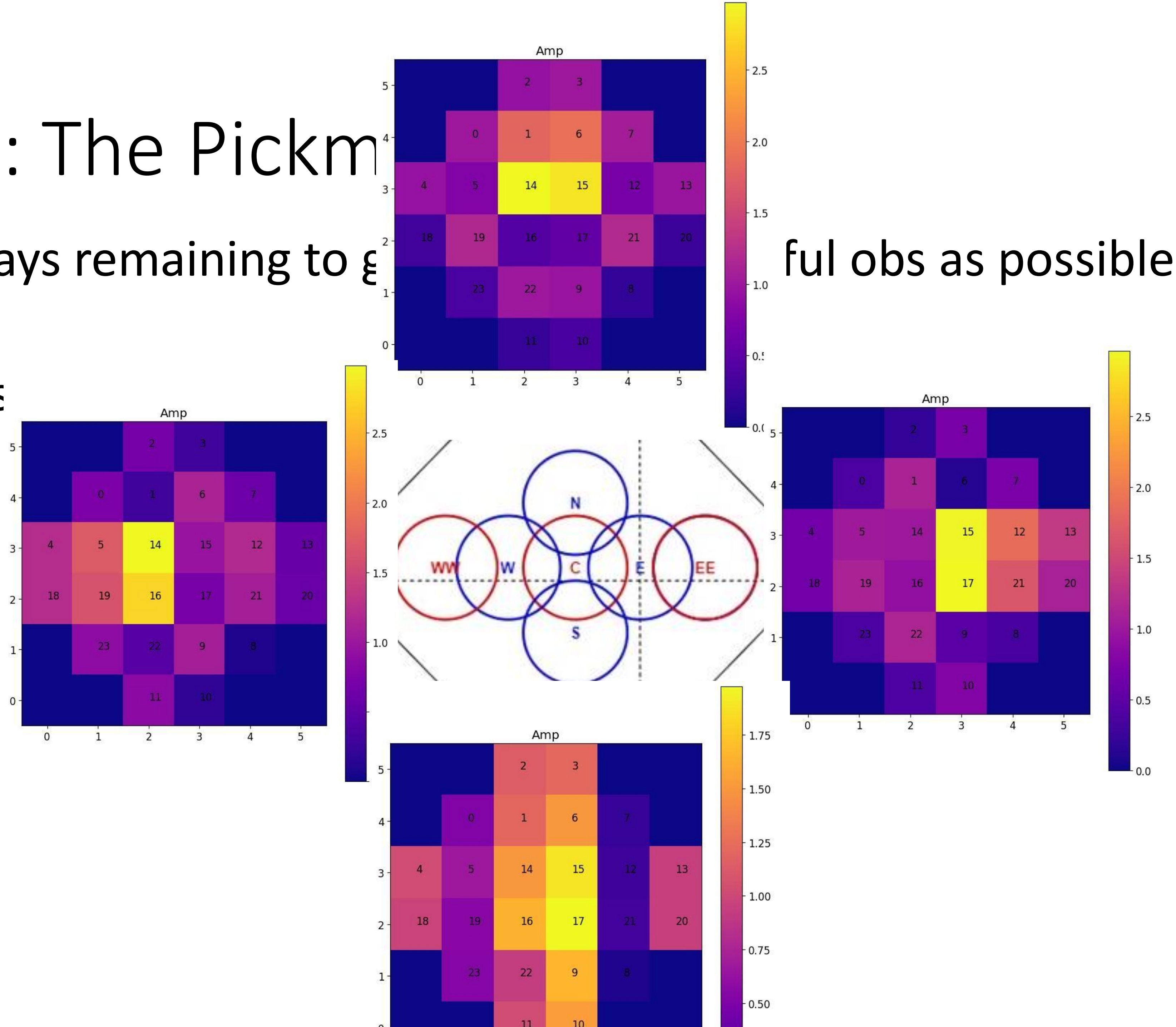
- Form s



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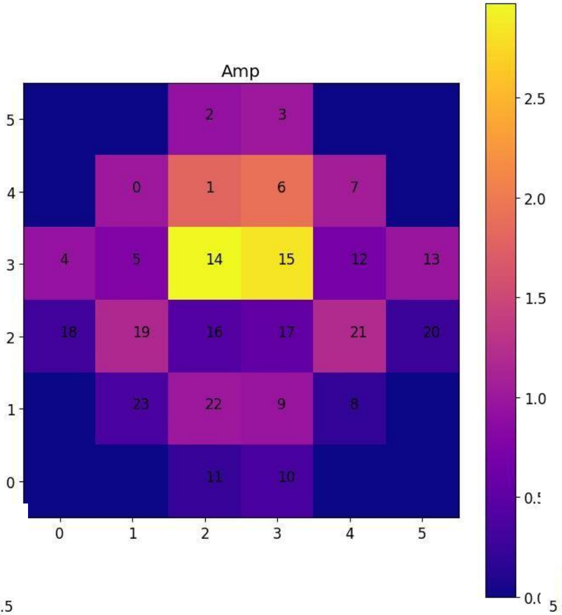

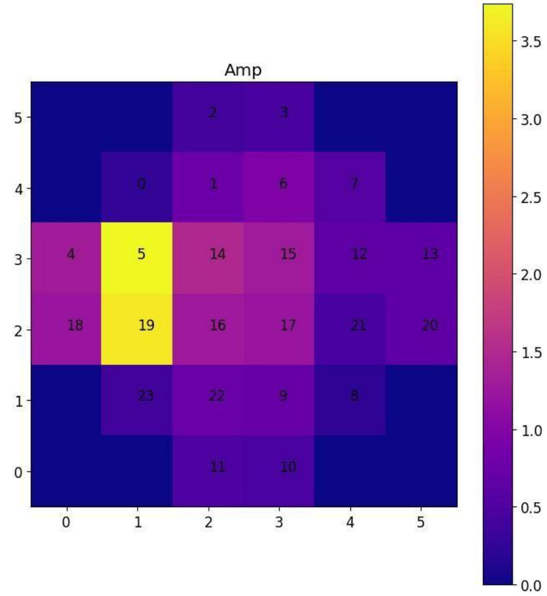

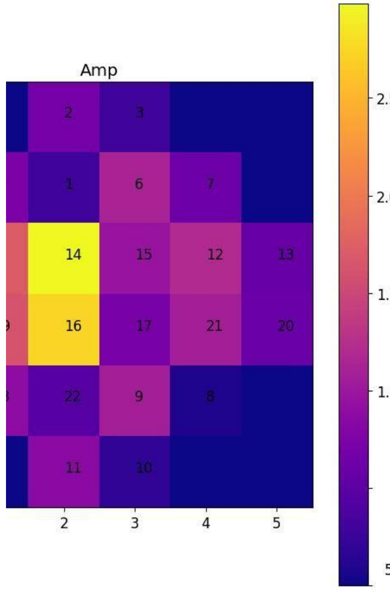

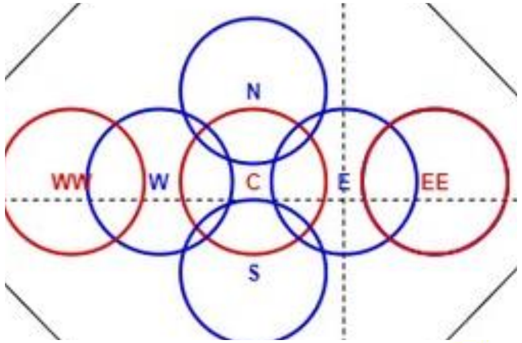

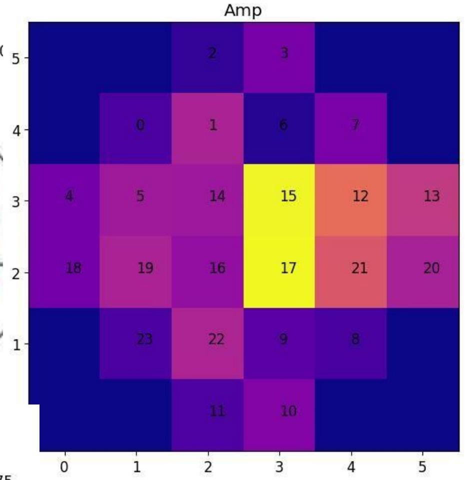

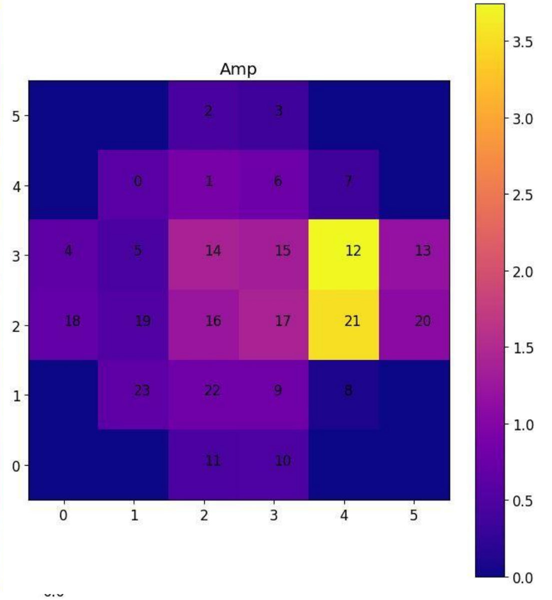

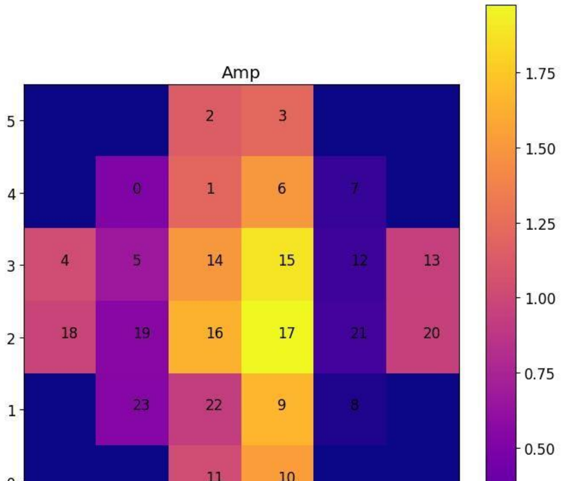

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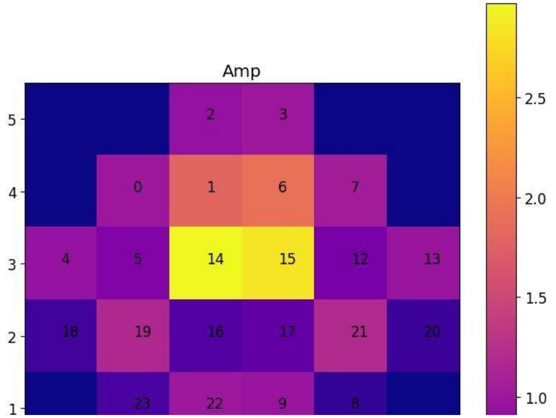
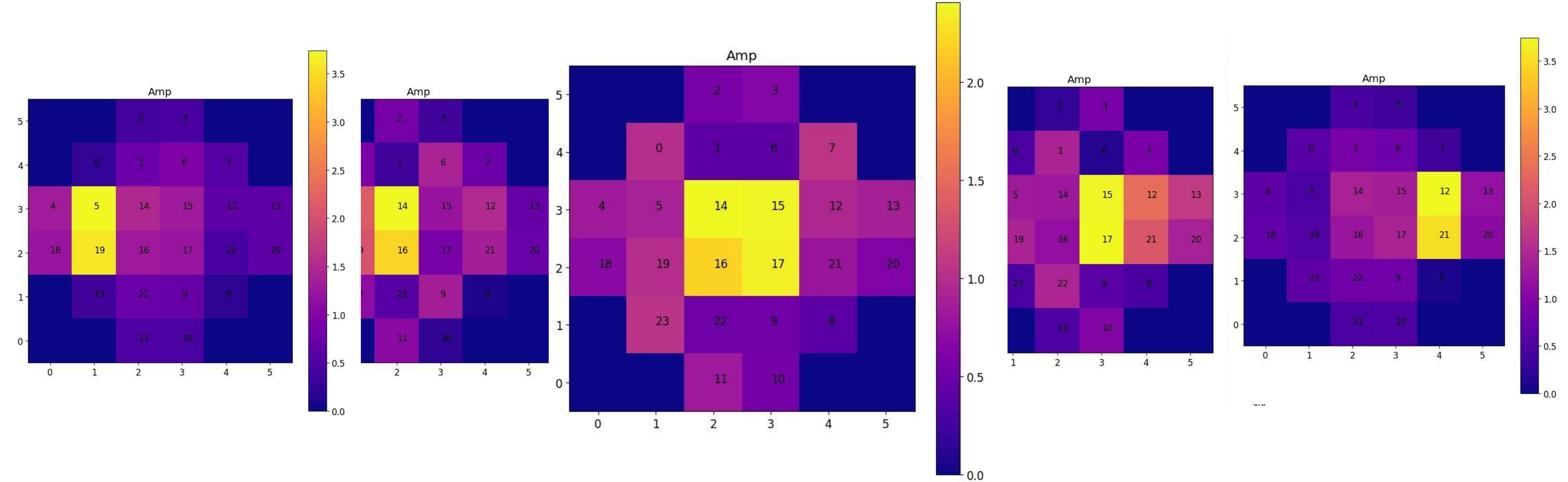
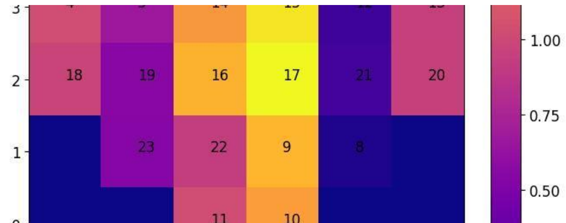
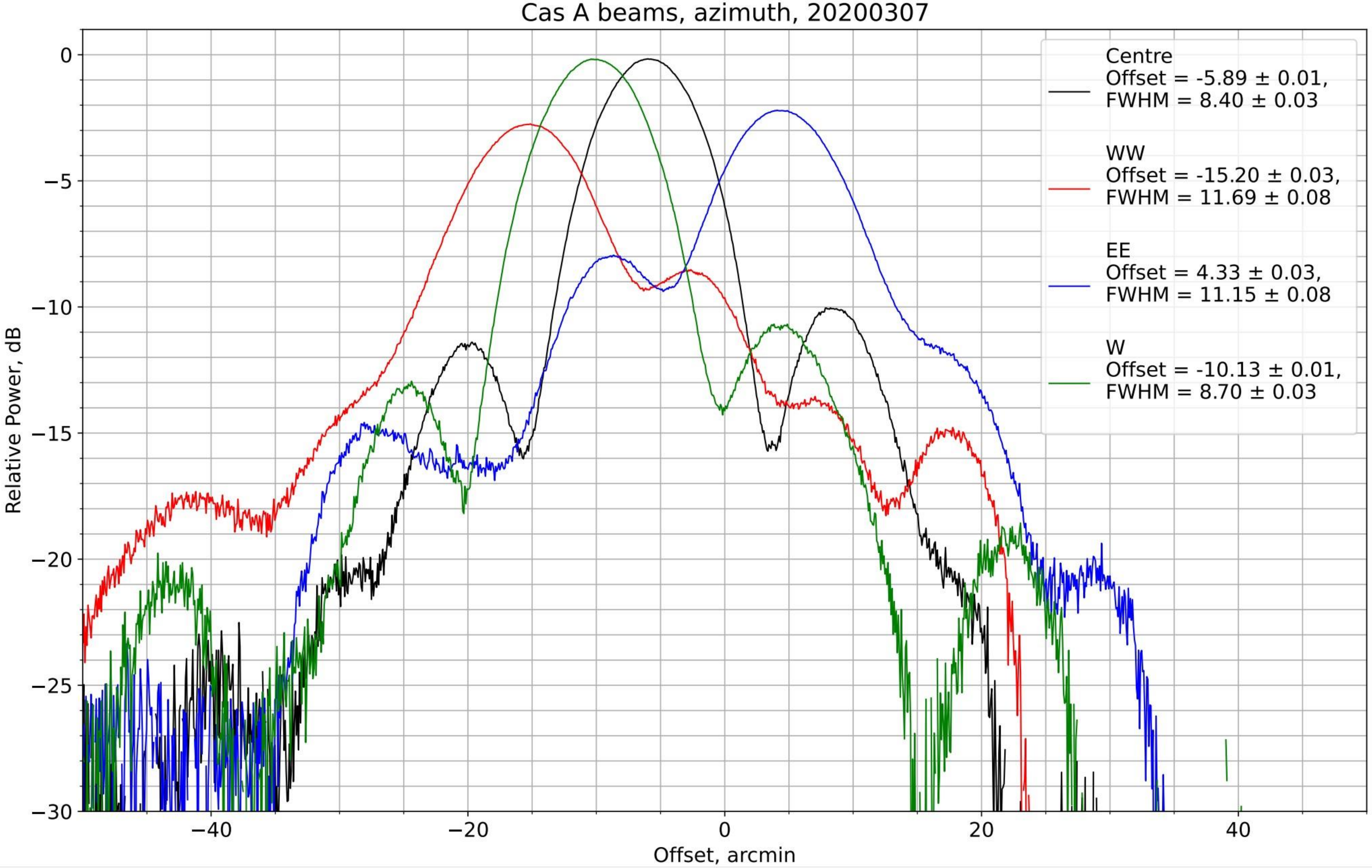


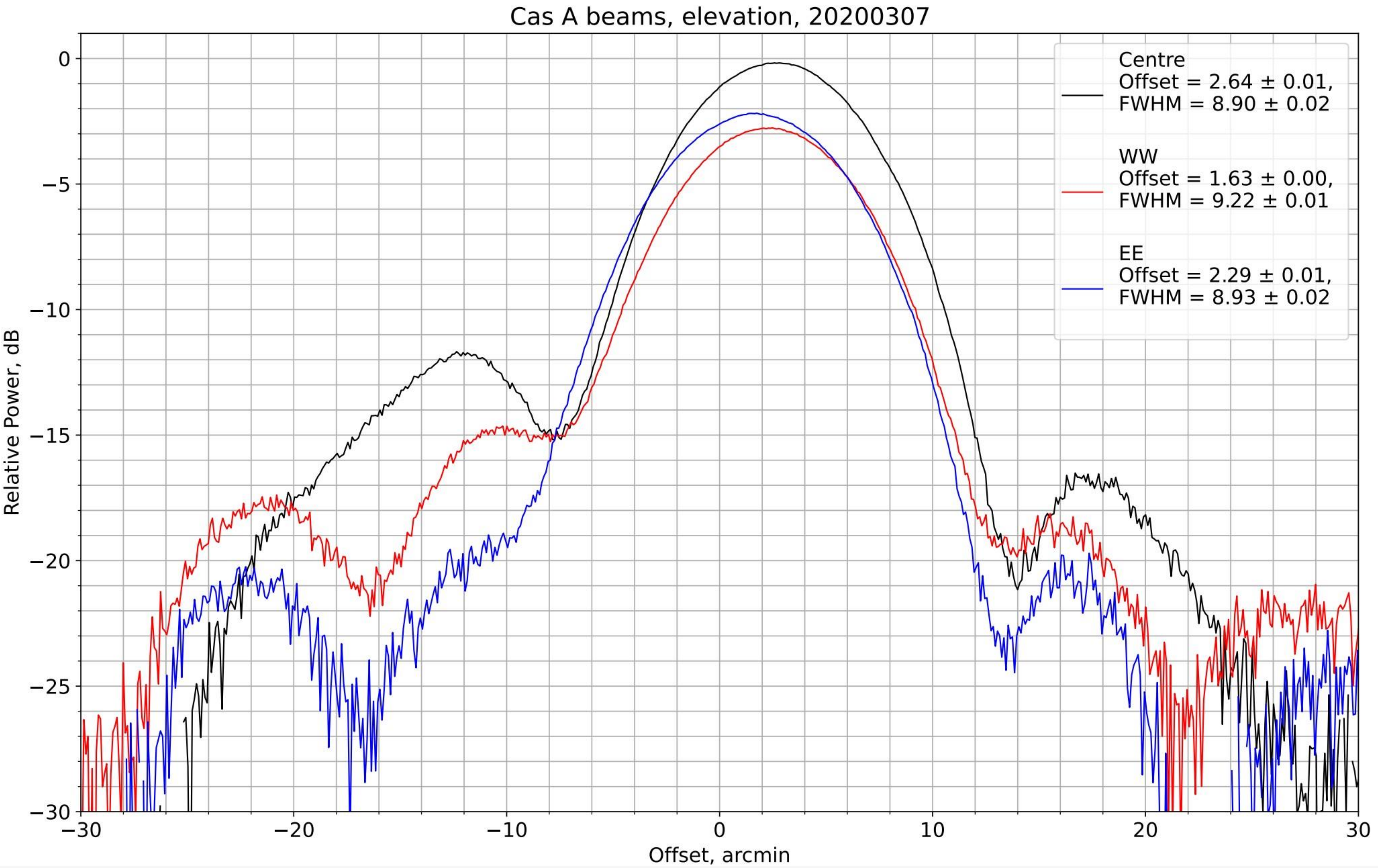




2020: The Pickmere Test

- Five days remaining to gather as much useful obs as possible…
- Form some beams off-axis using Cyg A…
- Amplitudes look encouraging… test beams against Cas A


Cas A beams, azimuth, 20200307
Relative Power, dB
Offset, arcmin
0
−5
−10
−15
−20
−25
−30
−40
−20
0
20
40
Centre
Offset = -5.89 ± 0.01,
FWHM = 8.40 ± 0.03
WW
Offset = -15.20 ± 0.03,
FWHM = 11.69 ± 0.08
EE
Offset = 4.33 ± 0.03,
FWHM = 11.15 ± 0.08
W
Offset = -10.13 ± 0.01,
FWHM = 8.70 ± 0.03



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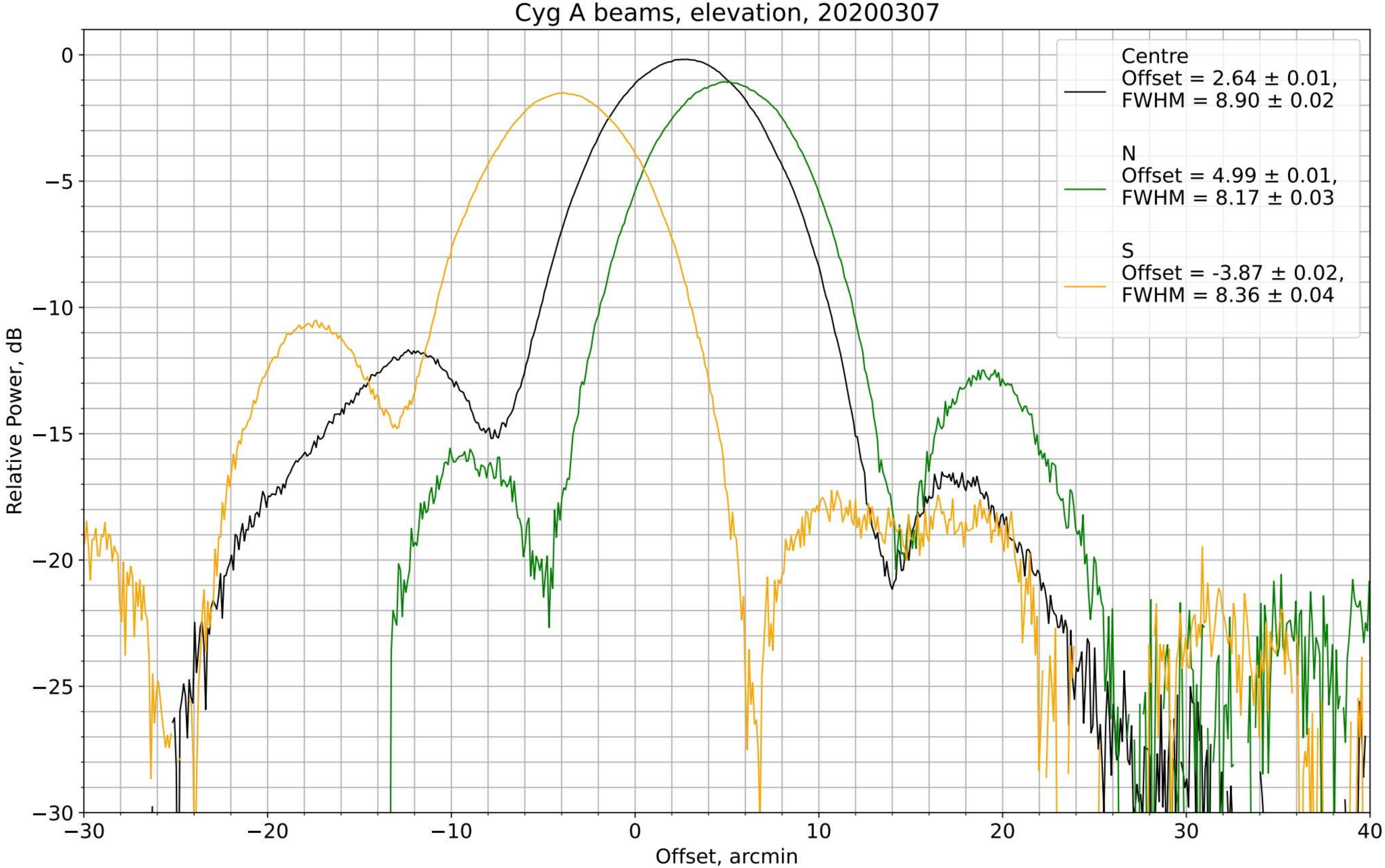

Cyg A beams, elevation, 20200307
Centre
Offset = 2.64 ± 0.01,
FWHM = 8.90 ± 0.02
N
Offset = 4.99 ± 0.01,
FWHM = 8.17 ± 0.03
S
Offset = -3.87 ± 0.02,
FWHM = 8.36 ± 0.04
Relative Power, dB
Offset, arcmin
0
−5
−10
−15
−20
−25
−30
−30
−20
−10
0
10
20
30
40

2020: The Pickmere Test

- Five days remaining to gather as much useful obs as possible…
- Form some beams off-axis using Cyg A…
- Amplitudes look encouraging… test beams against Cas A
- We have beams!
  -- Central beams well-formed, strongly gaussian but with higher sidelobes than expected
  -- Off-axis beams suffer considerable degradation in sensitivity and profile
  -- Elevation beams show particularly uneven sidelobes

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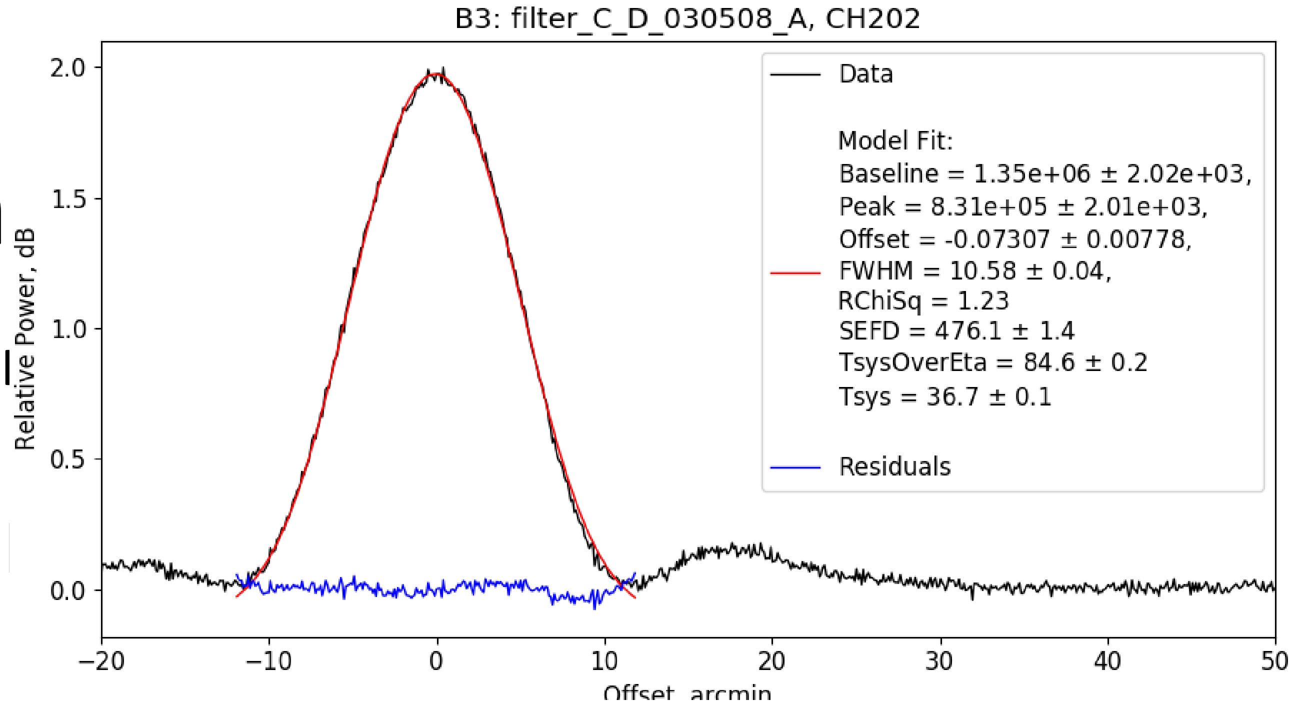
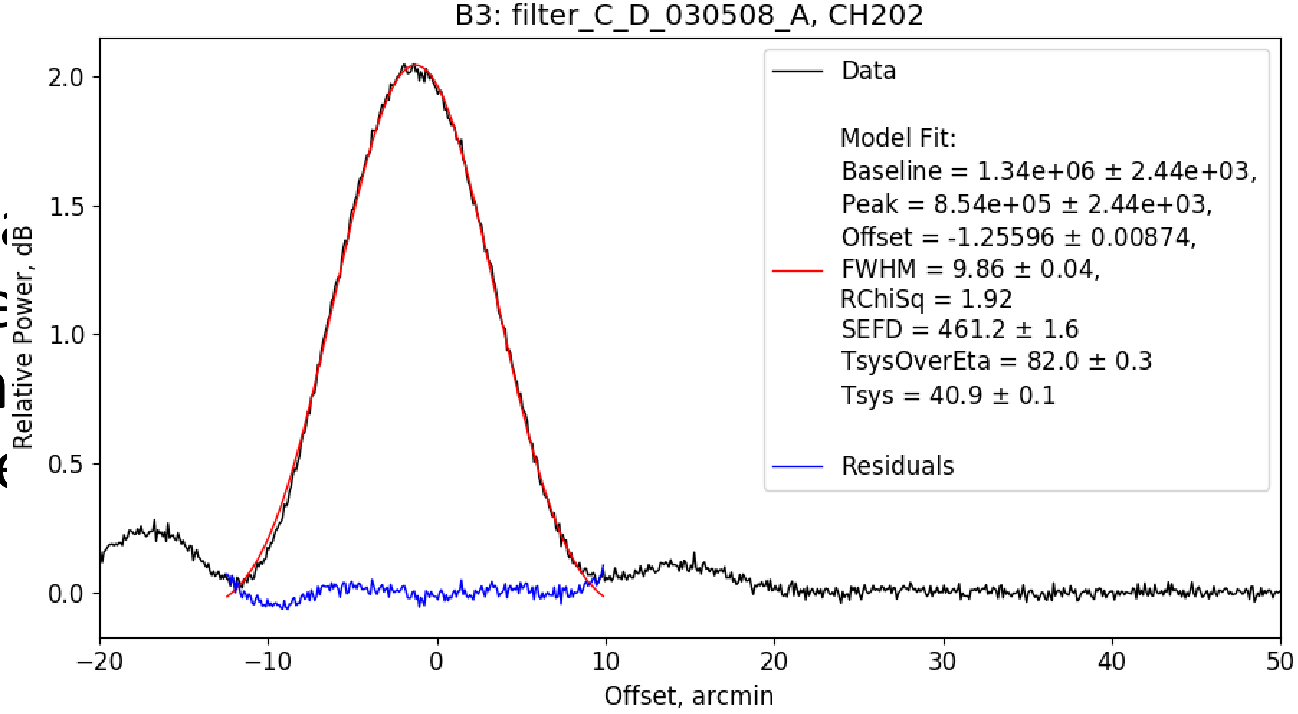


- Five days re ssible...
- Form some
- Amplitudes A

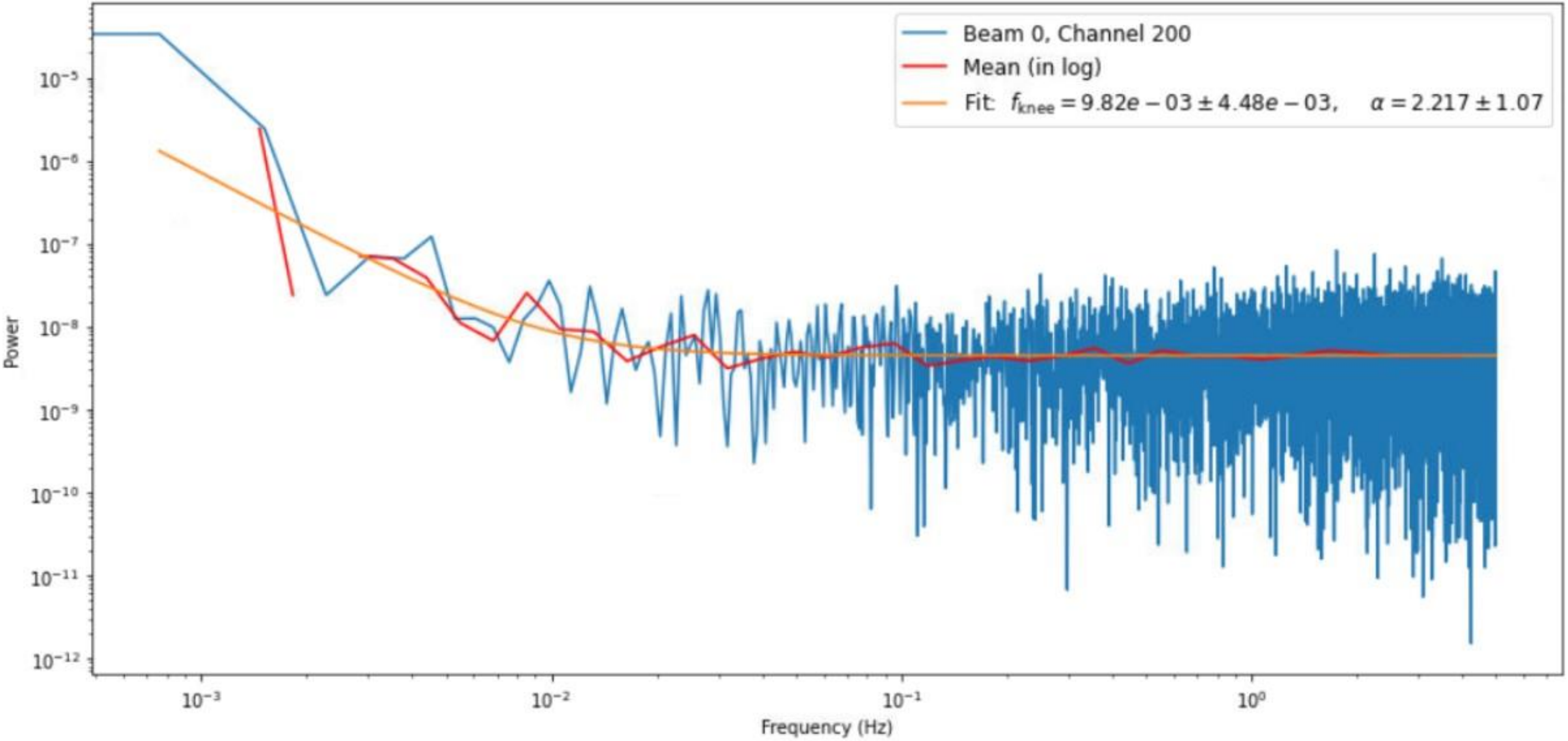


- We have bea
  -- Central be th higher sidelobes th
  -- Off-axis be nsitivity and profile
  -- Elevation

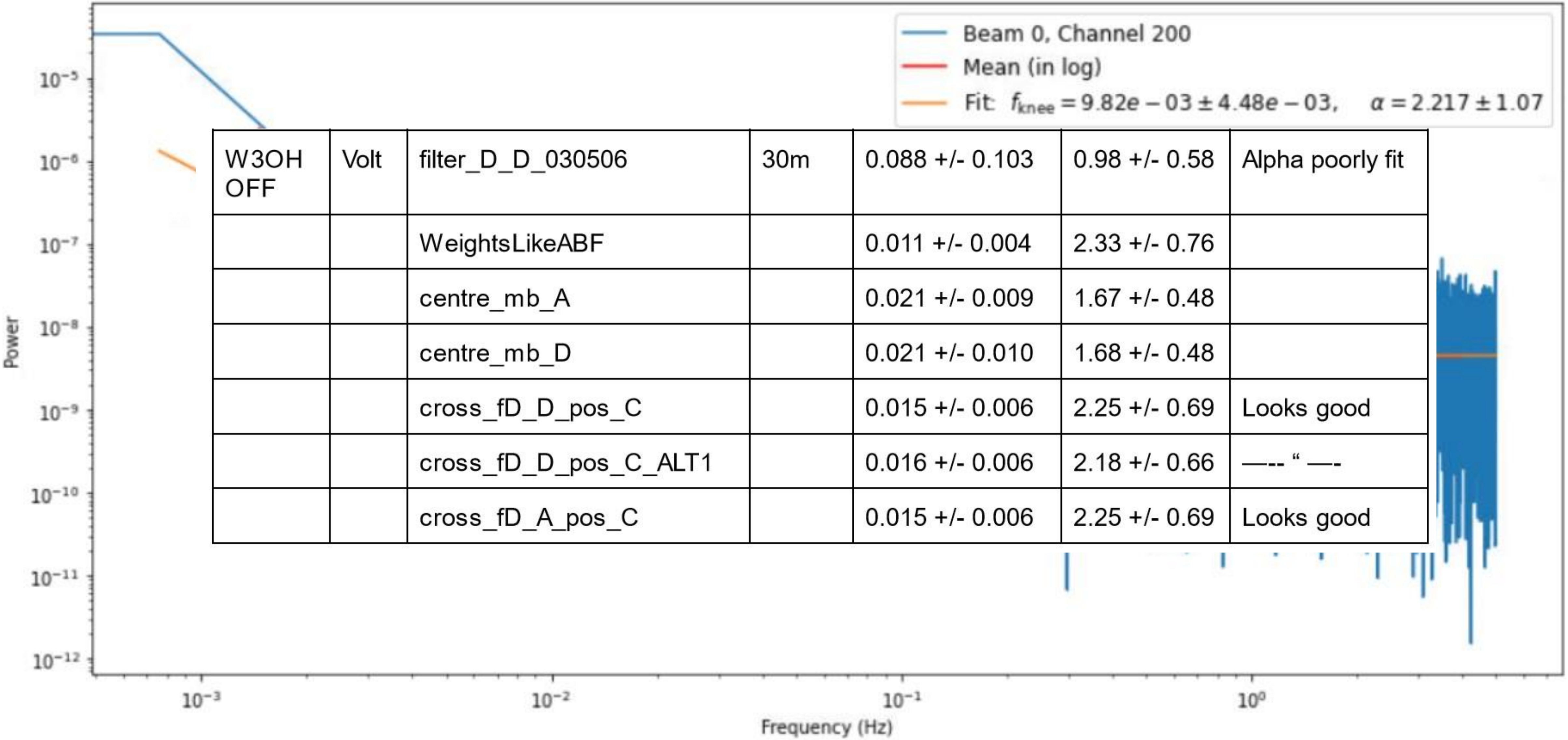
2020: The Pickmere Test

- Clutching at straws to explain low sensitivity…
- Gain variations…?

2020: The Pickmere Test



2020: The Pickmere Test



W3OH OFF	Volt	filter_D_D_030506	30m	0.088 +/- 0.103	0.98 +/- 0.58	Alpha poorly fit
		WeightsLikeABF		0.011 +/- 0.004	2.33 +/- 0.76	
		centre_mb_A		0.021 +/- 0.009	1.67 +/- 0.48	
		centre_mb_D		0.021 +/- 0.010	1.68 +/- 0.48	
		cross_fD_D_pos_C		0.015 +/- 0.006	2.25 +/- 0.69	Looks good
		cross_fD_D_pos_C_ALT1		0.016 +/- 0.006	2.18 +/- 0.66	—-- “ —-
		cross_fD_A_pos_C		0.015 +/- 0.006	2.25 +/- 0.69	Looks good

2020: The Pickmere Test

- Clutching at straws to explain low sensitivity…
- Gain variations…?
  →Nope.

- Test TSys direct using Moon
  → Fills beam
  → Almost constant 216K load across lunar disc
  →Direct comparison of DBF-acquired sensitivity with “offline beamforming”

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2020: The

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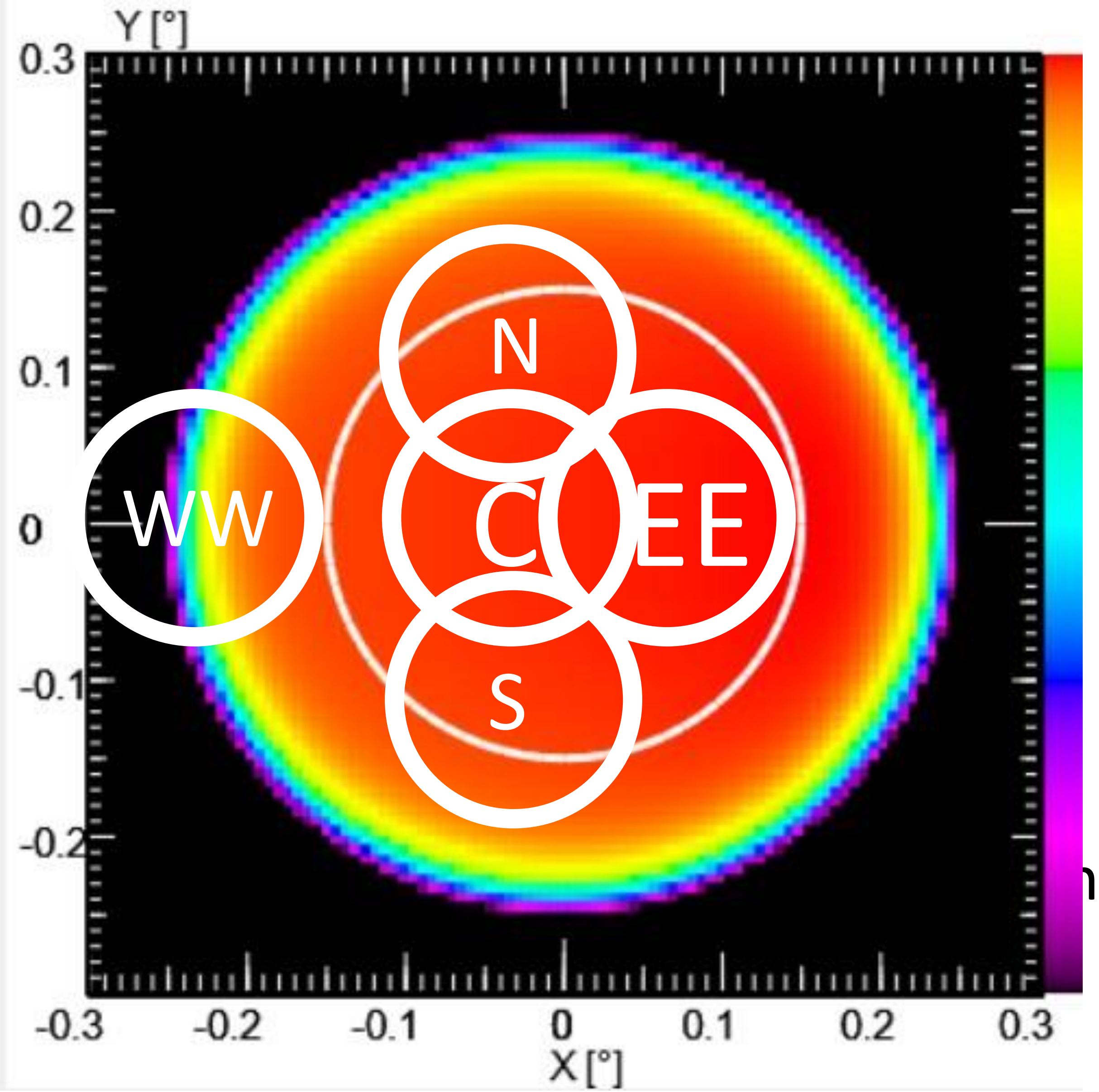
- Test TSys dire
  → Fills beam
  → Almost co
  →Direct com n "offline beamforming



- https://portia.astrophysik.uni-kiel.de/~koeppen/JS/LunarRadioMaps.html

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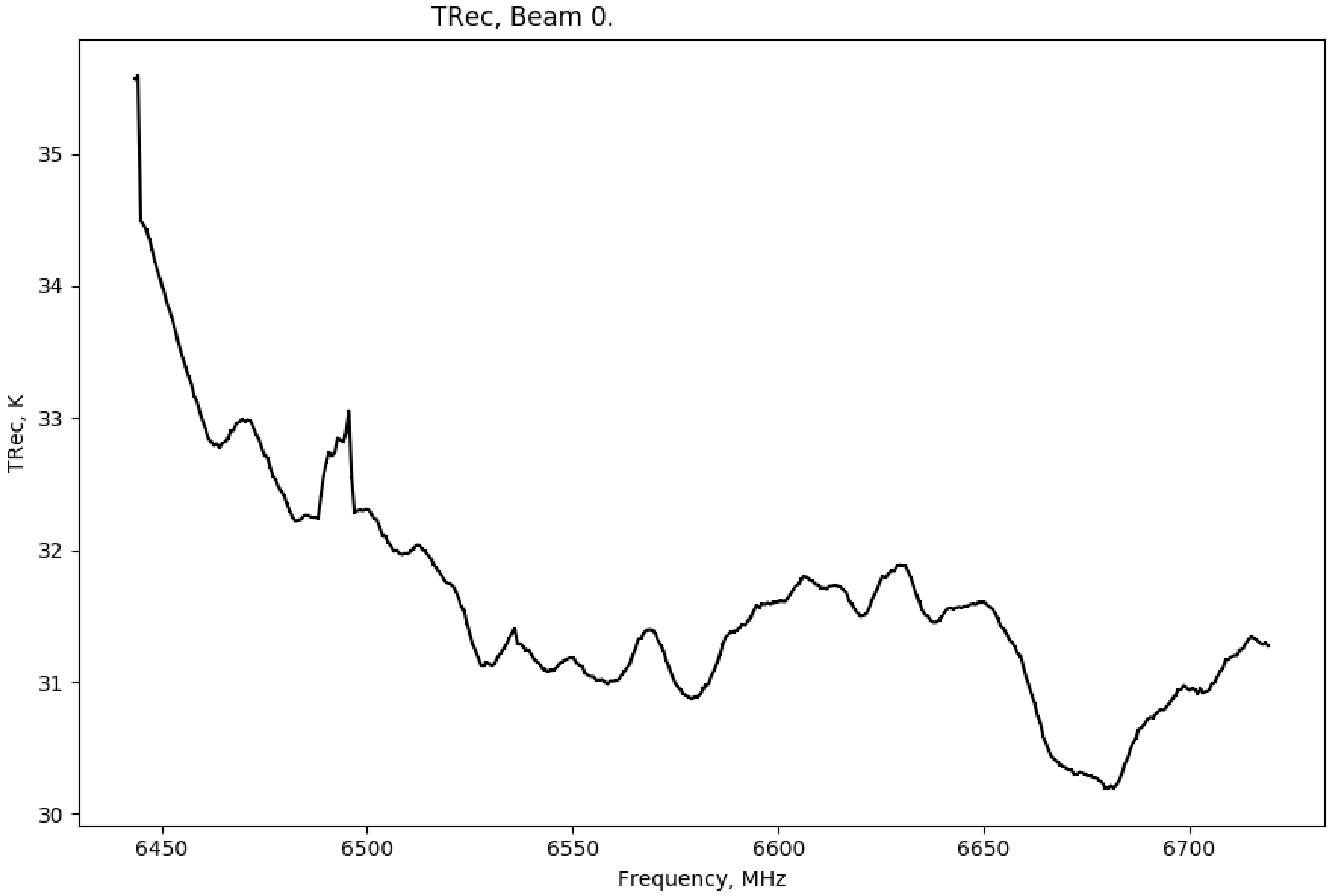
2020: The Pickmere Test

Weights set	TRx	Uncertainty
D_pos_C	23.64	0
	23.66	0
D_pos_N	29.02	
	29.03	
D_pos_S	27.27	
	27.49	
D_pos_E	24.30	
	24.34	
D_pos_EE	28.51	
	28.49	
D_pos_W	29.05	
	29.05	
D_pos_WW	56.66	
	56.74	



2020: The Pickmere Test

- Clear disparity between online and offline BF sensitivities.
  → sensitivity tests must be made using offline BF
  → go back and apply weights offline to raw voltage obs…

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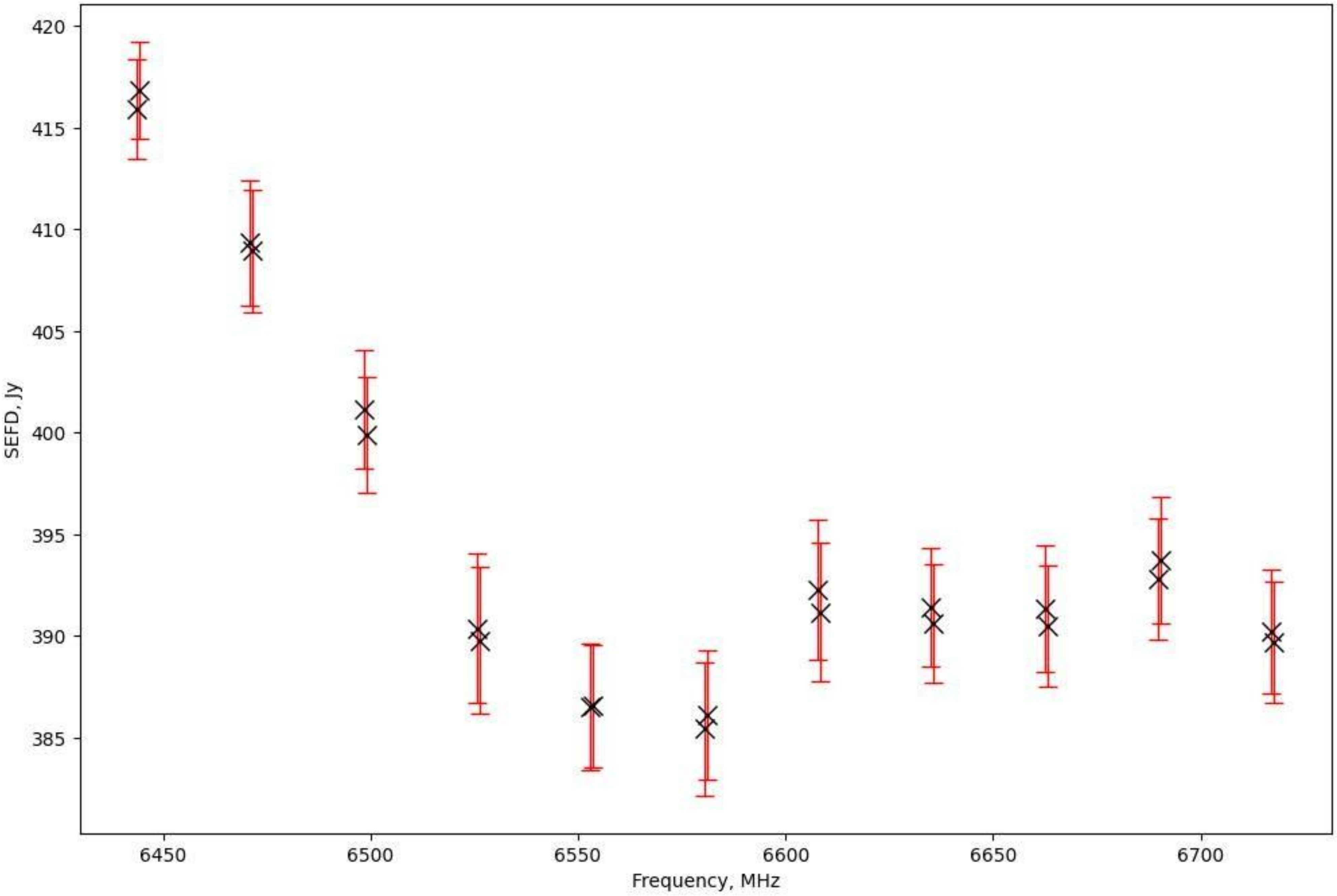
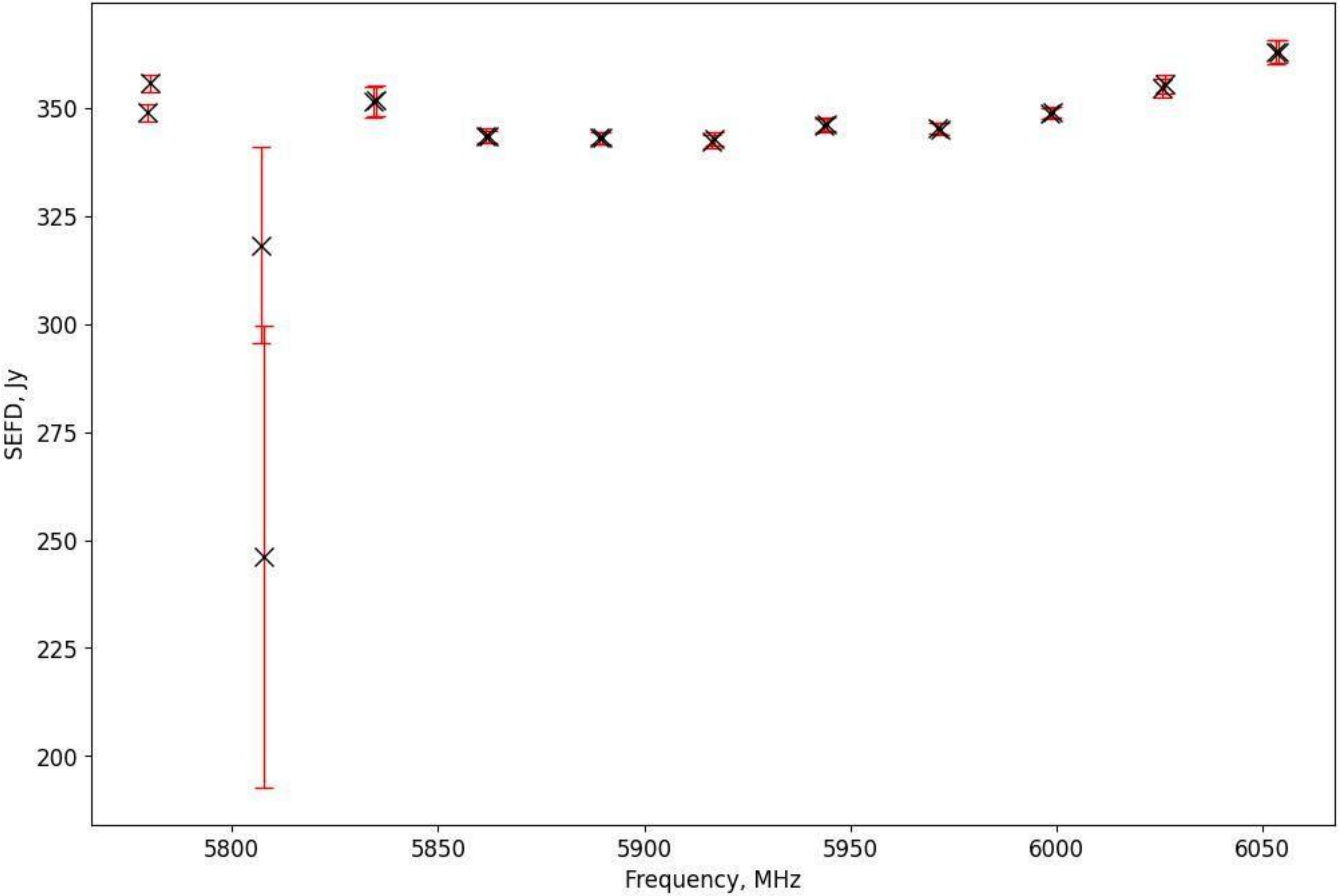
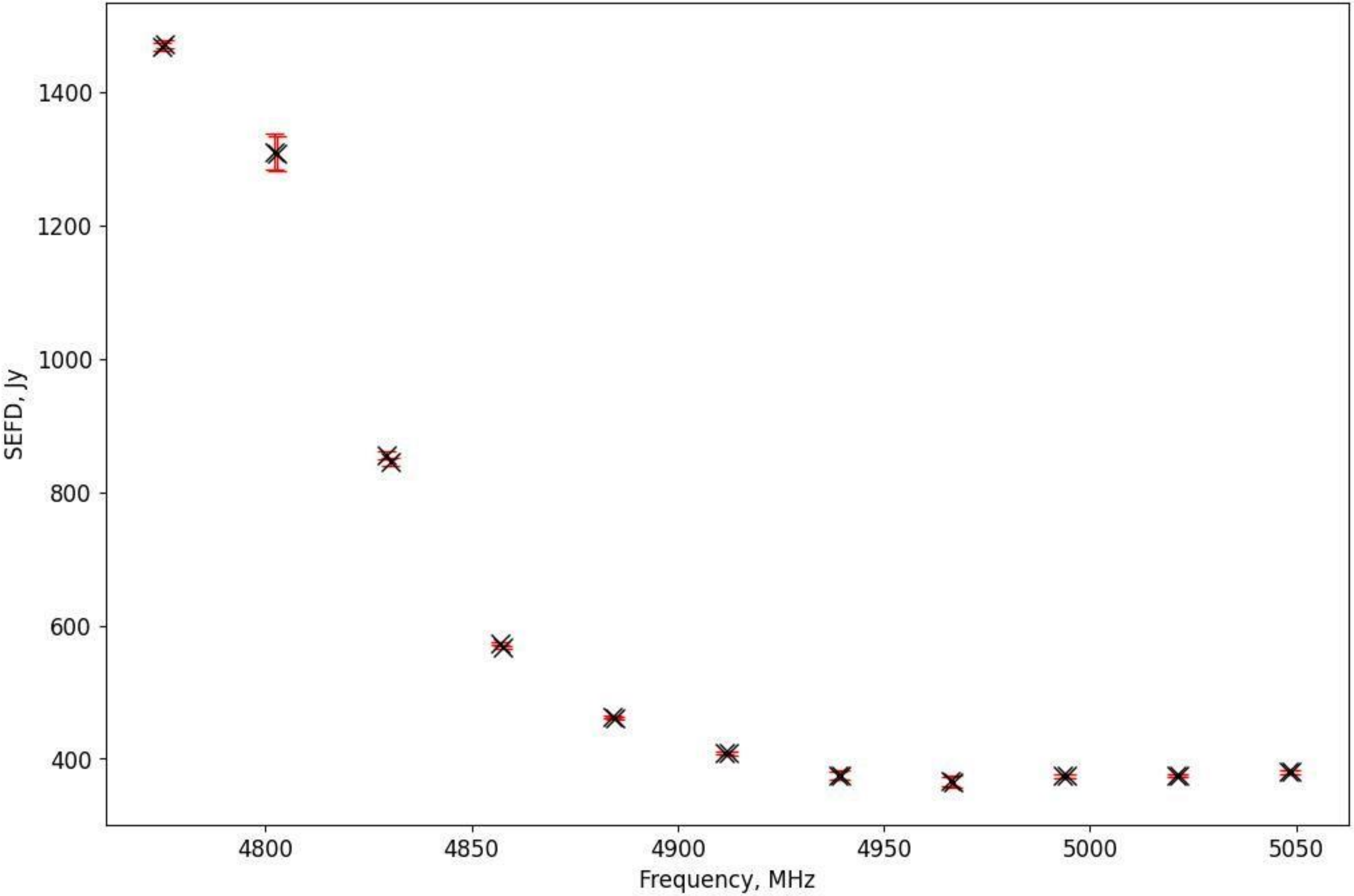



SEFD, Jy
350
325
300
275
250
225
200
5800
5850
5900
5950
6000
6050
Frequency, MHz

2

- (


SEFD, Jy
1400
1200
1000
800
600
400
4800
4850
4900
4950
5000
5050
Frequency, MHz

2020: The Pickmere Test

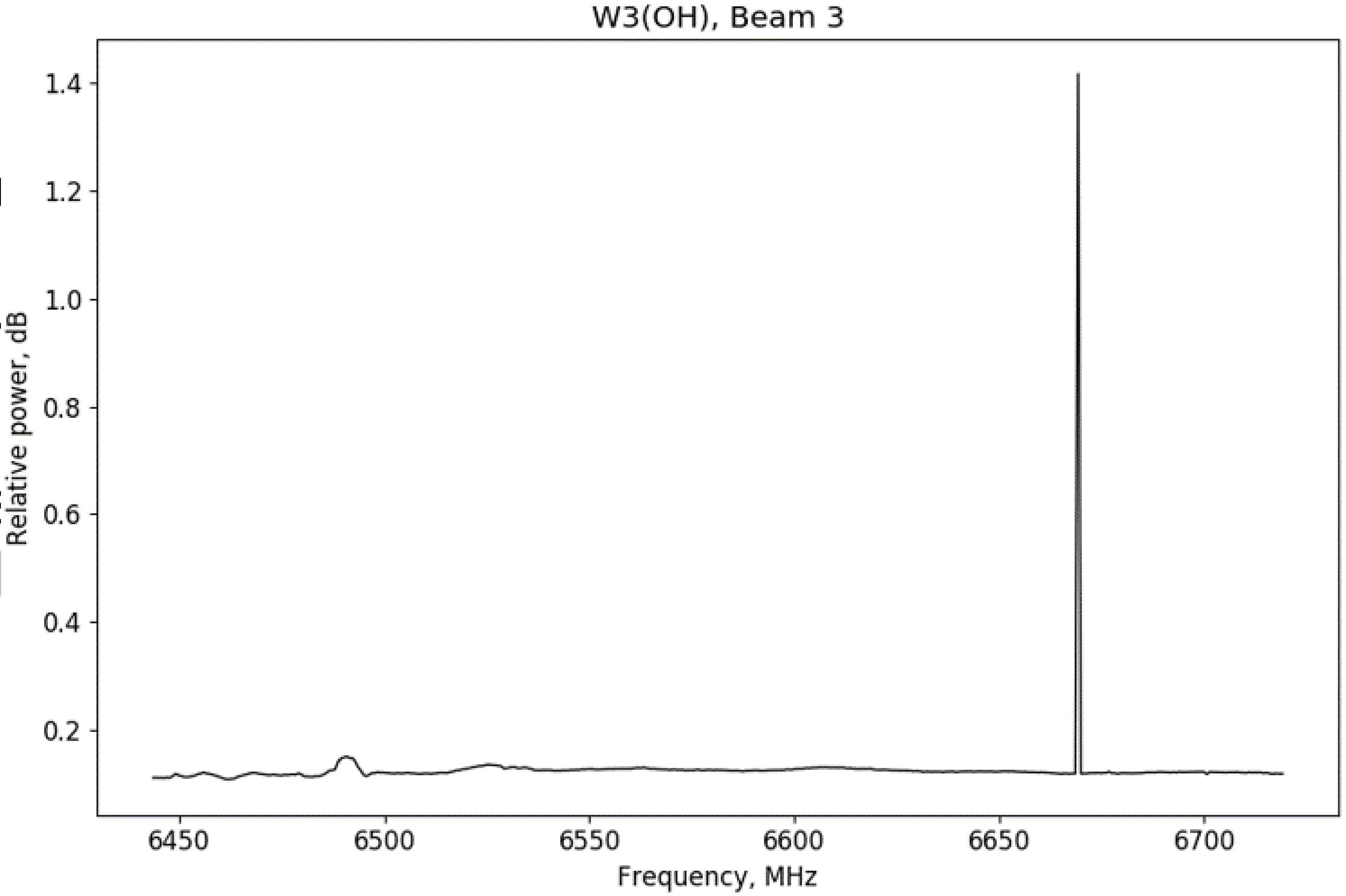
- Clear disparity between online and offline BF sensitivities.
  → go back and apply weights offline to raw voltage obs…
  → 20—30% improvement c.f. online BF, but still below target 250Jy

- Final tests: spectral lines
  → demo line capability e.g. W3OH 6.67GHz maser…

2020: The Pickmere Test

- Clear disp
  → go bac
  → Similar ...)Jy

- Final tests
  → demo



2020: The Pickmere Test

- Clear disparity between online and offline BF sensitivities.
  → go back and apply weights offline to raw voltage obs…
  → Similar 20—30% improvement, but still below target 250Jy

- Final tests: spectral lines
  → demo line capability e.g. W3OH 6.67GHz maser…
  → obs of weaker lines more challenging
  → Tests noise and bandpass quality across relatively long periods

2020: The Pickmere Test

- Choose Orion KL (M42) and H/He recombination lines in Filter D
  → source readily visible from Pickmere
  → 400Jy source swamps minor systematics
  → spectral line physics well-understood

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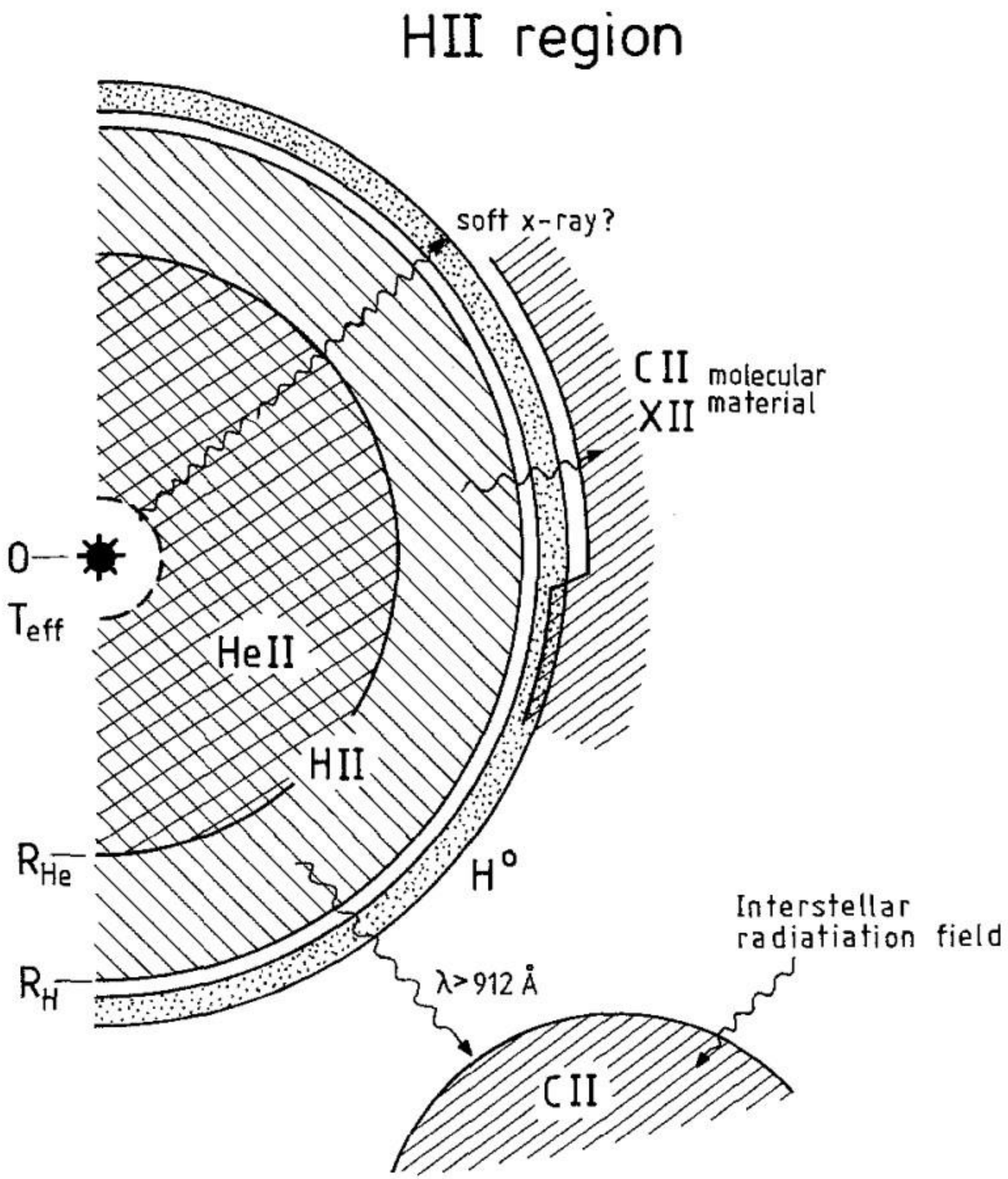
2020: The

- Choose Orior   Filter D
  - → source rea
  - → 400Jy sou
  - → spectral li



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2020: The Pickmere Test

- Choose Orion KL (M42) and H/He recombination lines in Filter D
  → source readily visible from Pickmere
  → 400Jy source swamps minor systematics
  → spectral line physics well-understood

- Start from Draine 2011 free-free absorption coefficient…

$$\left(\frac{\kappa_{ff}}{\mathrm{cm}^{-1}}\right) = \frac{4}{3}\left(\frac{2\pi}{3}\right)^{1/2} \frac{e^6}{m_e^{3/2}\sqrt{kT}hc\nu^3}[1 - e^{-h\nu/kT}]Z_i^2 n_i n_e \langle g \rangle ,$$

… derive equation for line intensity

$$\frac{T_L}{T_C}\Delta v_{\mathrm{km/s}} = \frac{10530}{\langle g \rangle}\frac{\nu_9}{T_e}\frac{1}{1+0.08},$$

2020: The Pickmere Test

- Expect H99a and H100a lines 5% of 400Jy continuum
  → easily detectable.
  → Beta, Gamma, Delta lines also available, also He alpha, beta

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2020: The Pickmere Test

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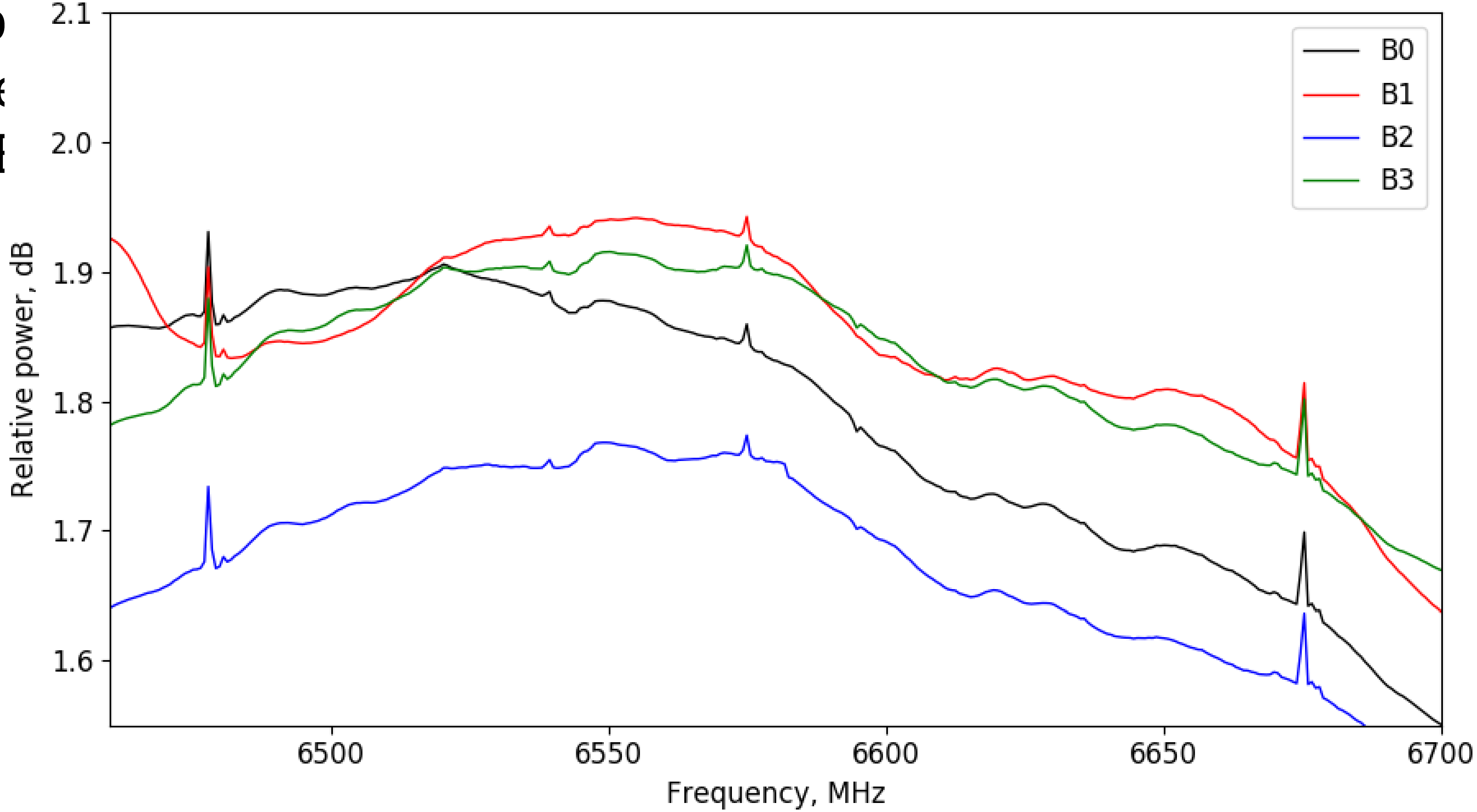
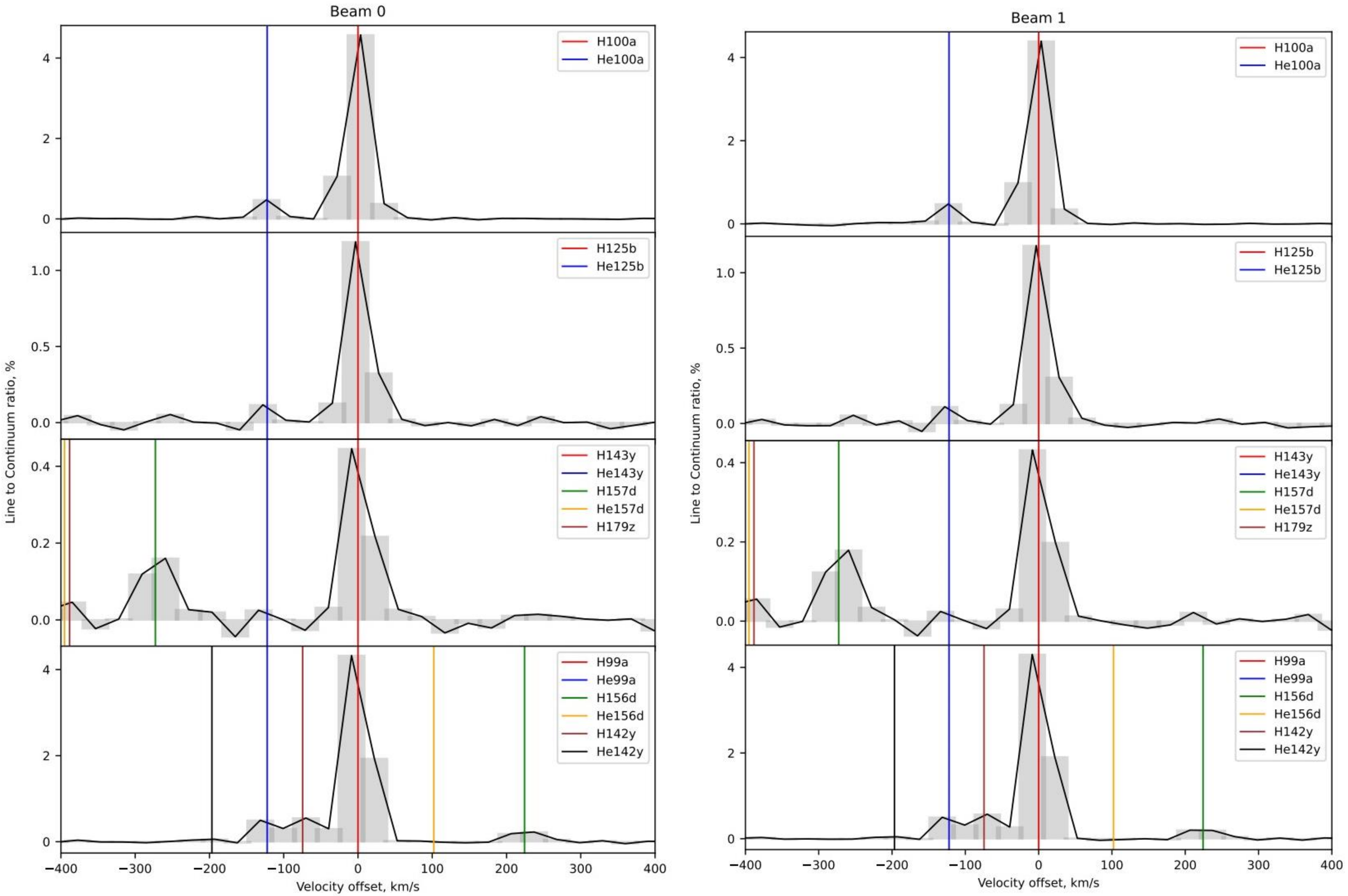


2020: The Pickmere Test

- Expect H99a and H100a lines 4—5% of 400Jy continuum
  → easily detectable.
  → Beta, Gamma, Delta lines also available, also He alpha

- Considerable effort required to subtract remaining bandpass…
  → LSq cubic spline chosen with extreme care re: overfitting



Beam 0
Beam 1
H100a
He100a
H125b
He125b
H143y
He143y
H157d
He157d
H179z
H99a
He99a
H156d
He156d
H142y
He142y
Line to Continuum ratio, %
Velocity offset, km/s

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2020: The Pickmere Test

- Expect H99a and H100a lines 4—5% of 400Jy continuum
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- Results show line intensities very close to expectation

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2020: -

- Expect H
  → easily
  → Beta,

- Consider ...s...
  → LSq cu

- Results s

Line	Beam	T_L/T_C (%)	T_e (K)
H100α	0	5.17 ± 0.26	8000 ± 420
	1	4.89 ± 0.25	8400 ± 430
	2	5.07 ± 0.26	8000 ± 420
	3	5.08 ± 0.25	8050 ± 400
H99α	0	5.33 ± 0.27	8000 ± 400
	1	5.29 ± 0.27	8000 ± 400
	2	5.37 ± 0.28	7900 ± 400
	3	5.30 ± 0.27	8000 ± 400

Table 1 – Measured line-to-continuum ratios of the Hα lines, and electron temperatures determined therefrom; these compare well with the literature values.

Line	Beam	T_L/T_C (%)	N(He)/N(H) (%)
He100α	0	0.49 ± 0.14	9.80 ± 0.50
	1	0.50 ± 0.11	10.50 ± 0.55
	2	0.48 ± 0.16	9.65 ± 0.50
	3	0.48 ± 0.14	9.80 ± 0.50

Table 2 – Relative helium abundance determined from the 100α lines. The measured values compare well with the Poppi et al. 2007 literature value of 10.0 ± 0.8 %.

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2020: The Pickmere Test

- Expect H99a and H100a lines 4—5% of 400Jy continuum
  → easily detectable.
  → Beta, Gamma, Delta lines also available, also He alpha

- Considerable effort required to subtract remaining bandpass…
  → LSq cubic spline chosen with extreme care re: overfitting

- Results show line intensities very close to expectation…

- Ratios of line intensities also very close to theory
  → very encouraging result
  → demo of noise reliability at arbitrary points across bandpass

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  → Beta
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  → LSq (
- Results
- Ratios c
  → very
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Lines	Menzel 1969 ratio	Beam	Observed ratio
H100α/H99α	0.9780	0	1.012$\pm$0.086
		1	0.970$\pm$0.071
		2	1.005$\pm$0.100
		3	1.010$\pm$0.092
H125β/H143γ	2.820	0	2.515$\pm$0.085
		1	2.603$\pm$0.078
		2	2.908$\pm$0.099
		3	2.552$\pm$0.084
H143γ/H157δ	2.101	0	2.444$\pm$0.078
		1	2.172$\pm$0.071
		2	2.241$\pm$0.071
		3	2.233$\pm$0.078

Table 3 – Comparisons between example line ratios, showing good agreement between theoretical values using the Menzel 1969 approximation, and the observed values in each beam.

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2020: The Pickmere Test

- Explanation for low sensitivity…? Look back to Simons et al. 2006 array design paper…

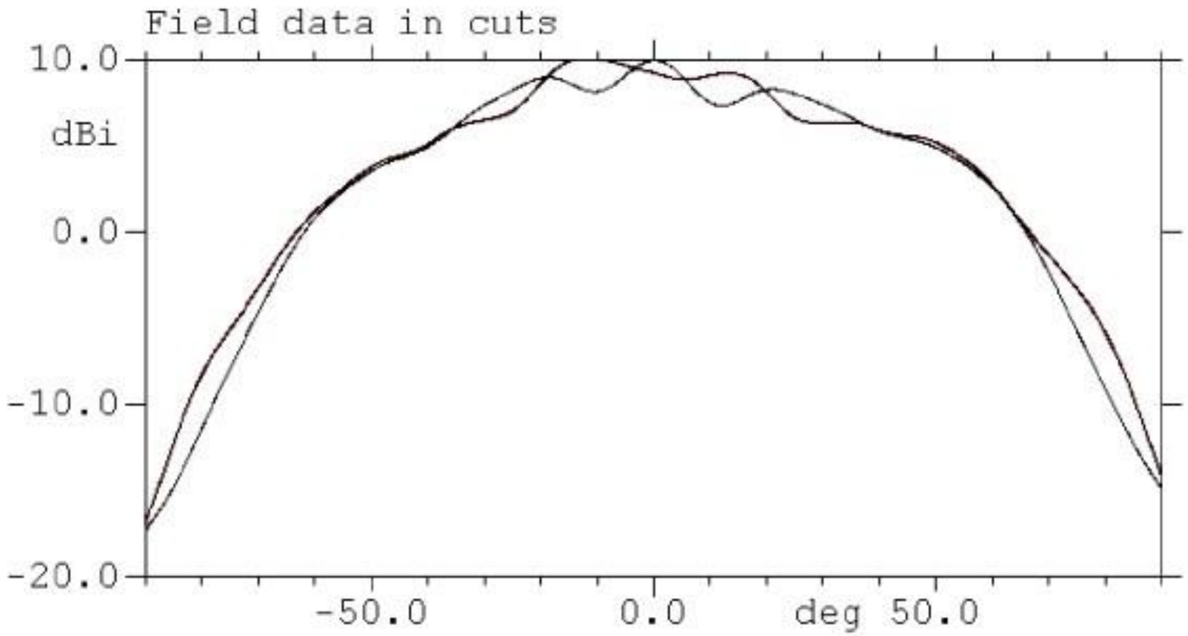
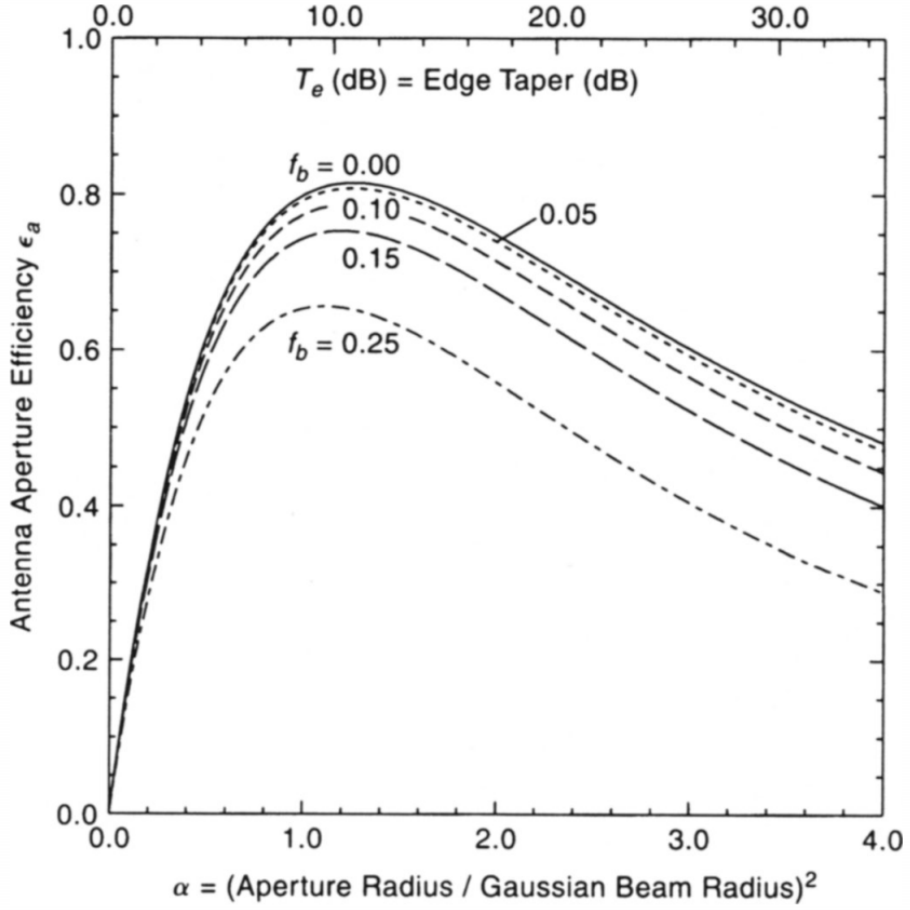


Figure 9: Physical optics simulations of the effect of a well positioned radome near the FPA antenna.

2020: The Pickmere Test

- Explanation for low sensitivity…? Look back to Simons et al. 2006 array design paper… compare with theory (Goldman 1998)



2020: The Pickmere Test

- Explanation for low sensitivity…? Look back to 2006 paper… compare with theory (Goldman 1998)

- Simply, ASTRON array poorly optimized for Pickmere dish
  → Weights heavily focused on single central element, possibly explaining strongly gaussian beam shape and low sensitivity
  → need larger f/D to overilluminate dish, enabling weights calculation to distinguish between on-source and off-source phases

Conclusions

- Successfully formed stable beams using Pharos2 Rx and iTPM DBF
  → Sensitivity 30—50% lower than expectation with online beamforming
  → offline beamforming shows better results, closer to eM SEFD…

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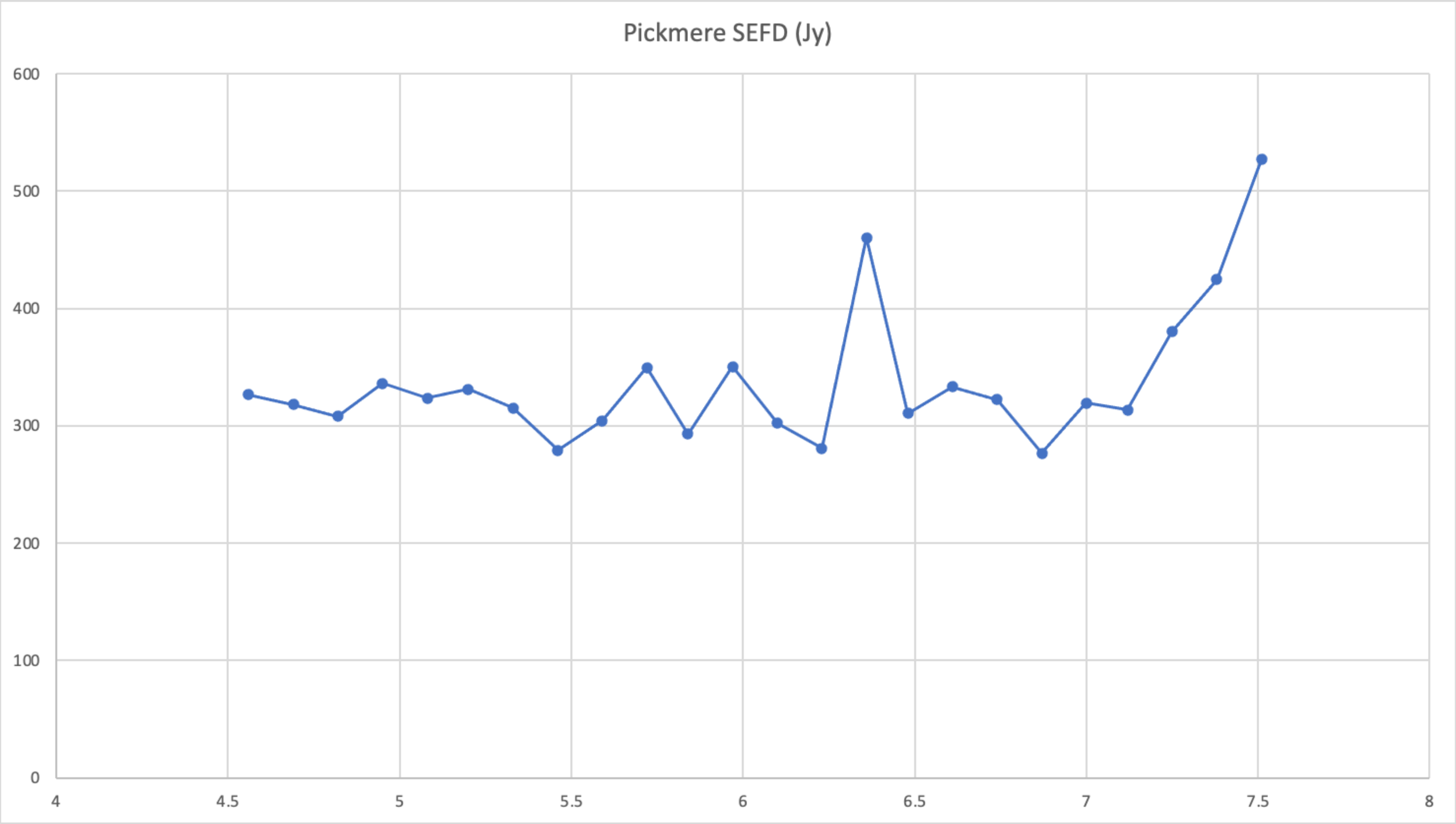

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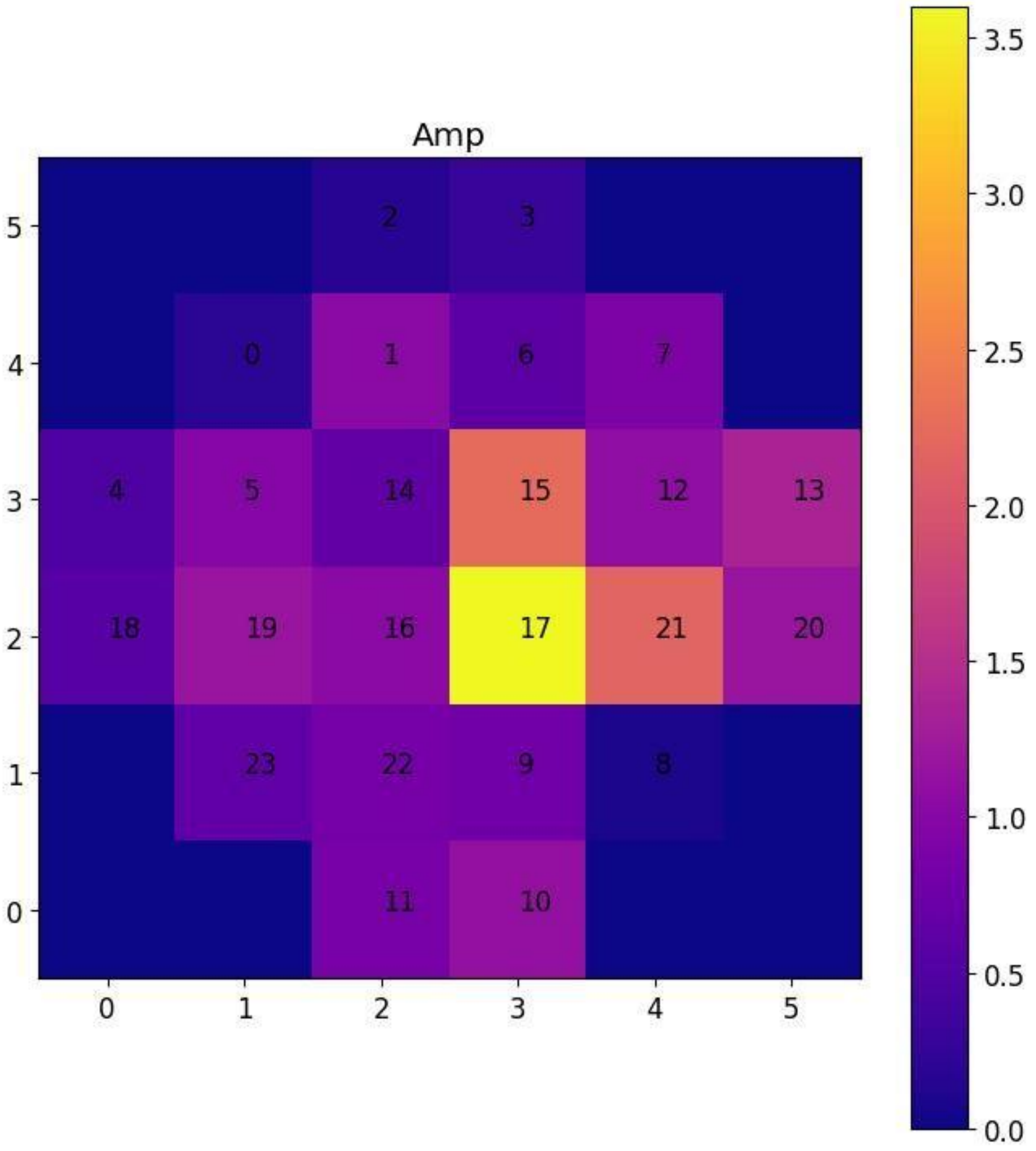
Conclusions

- Successfully formed stable beams using Pharos2 Rx and iTPM DBF
  → Sensitivity x2 lower than expectation with online beamforming
  → offline beamforming shows better results, closer to eM SEFD…
  → should have spent more time exploring other filters; obs under heavy time pressure

- Clear need to optimize array for antenna design
  → At 6.5GHz clearly sub-optimal
  → Lower frequencies show better illumination but radome cuts in, SEFD still >400Jy

Conclusio



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  → Sensitivity eamforming
  → offline bea ɔ eM SEFD…
  → should hav ;s; obs under
  heavy time pı

- Clear need to
  → At 6.5GHz
  → Lower frec dome cuts in,
  SEFD still >40

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Conclusio

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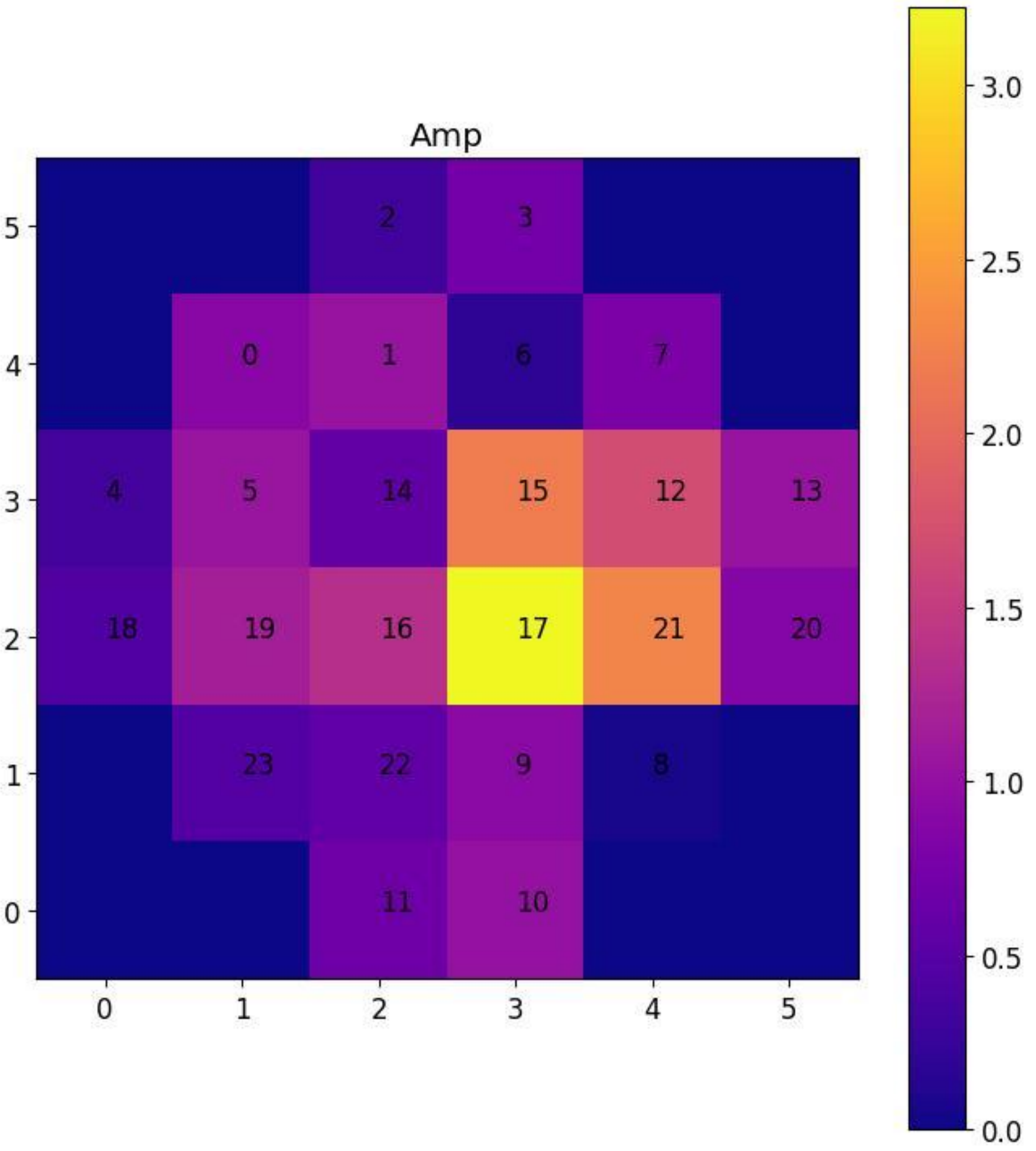
  heavy time p ...



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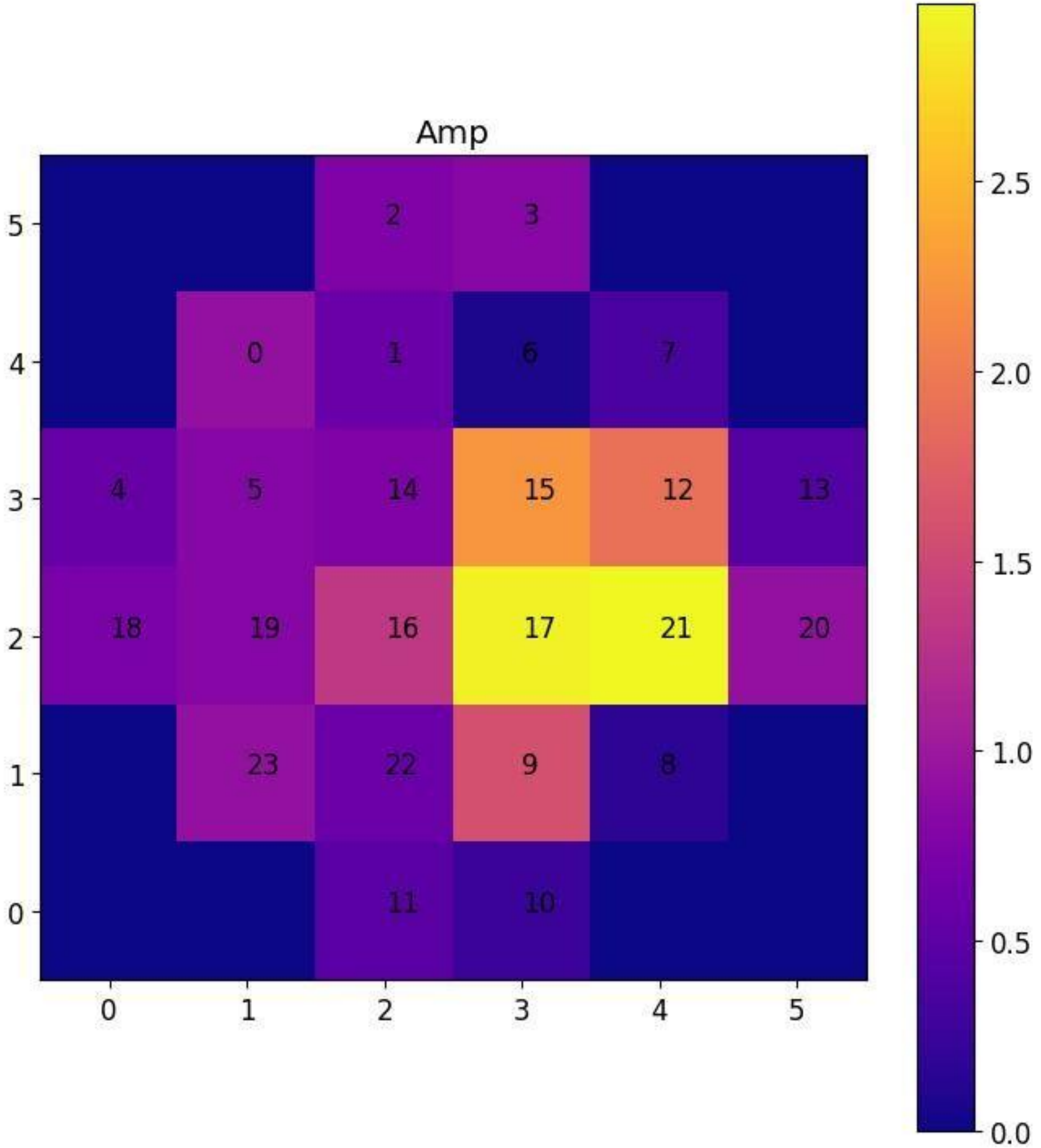

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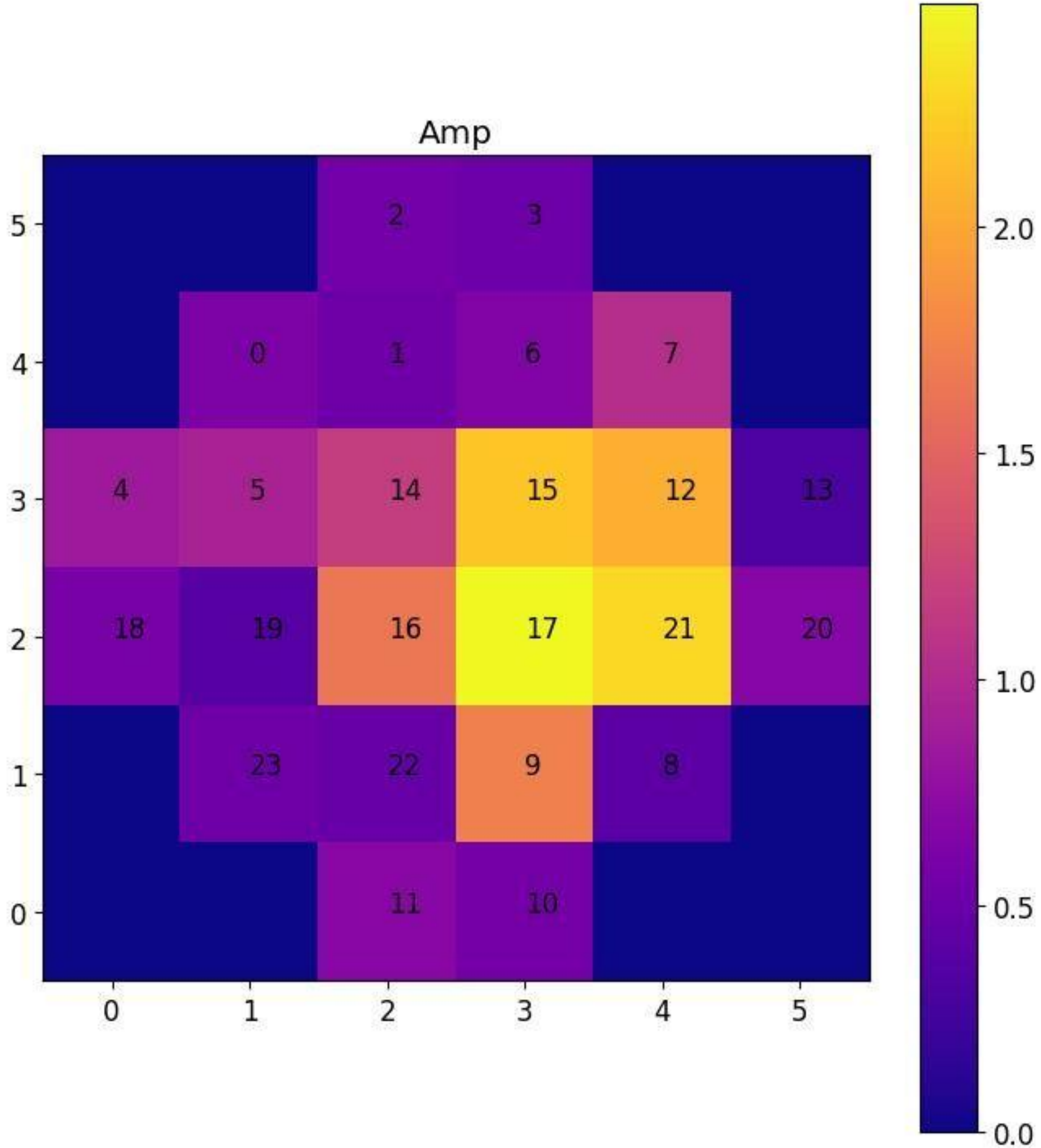

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Conclusions

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- Clear need to optimize array for antenna design
  → At 6.5GHz clearly sub-optimal
  → Lower frequencies show better illumination but radome cuts in, SEFD still >400Jy

- Future: Pharos2 concluded; publication soon!
  → Need to lower costs: LNAs £5k each! Can't populate 250 elements