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ICRAR

Sensitivity of CRAFT Fly's Eye searches for FRBs

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Thanks to CRAFT & ACES teams

ICRAR / Curtin Institute of Radio Astronomy / CAASTRO

www.caastro.org

Australian Government

Australian Research Council

Government of Western Australia
Department of the Premier and Cabinet
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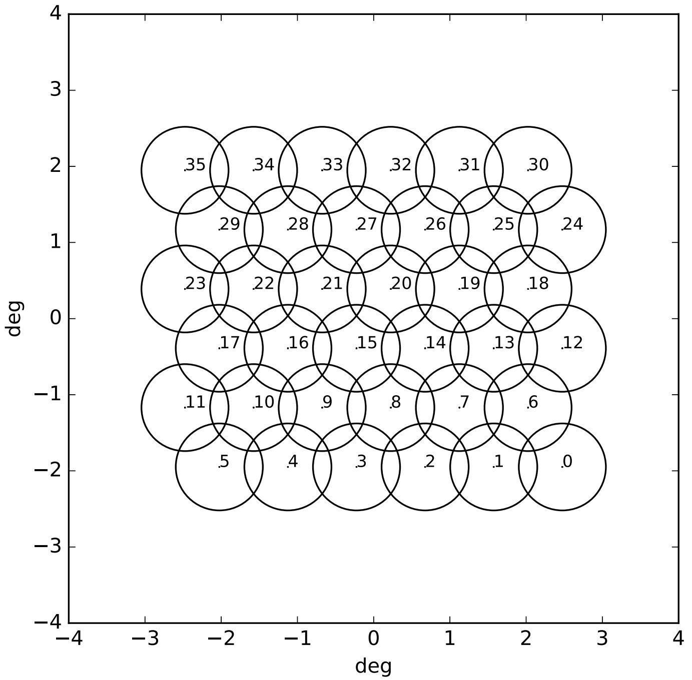
ASKAP

› Closepack configuration
  - 36 beams, triangular grid
  - 0.9 degree spacing
  - Overlap at ~half power points (1132-1468 MHz)



› CRAFT data
  - 336 1 MHz channels / beam / antenna
  - XX+YY integrated for 1500 samples
  - 1.265 ms resolution

Processing (reminder)

- “Fredda”:
  - Fast (incoherent) dedispersion transform
  - Performs some other functions (nicens data, flags bad things)
  - May or may not work properly (Harry Qiu)
  - See K. Bannister 2017 (in preparation) for further details
  - Returns base SNR of each candidate (threshold: 7 sigma)
- Friends of friends:
  - Groups raw Fredda candidates (in width, DM, time)
  - Selects strongest candidate (manageable rate)
- Visual inspection (well-trained algorithm called “Ryan”):
  - Removes obvious RFI
  - Find candidates over 9.5 SNR in a single beam

Fly's Eye strategy

Understand the system!

- Fly's eye search (independent galactic plane fields, ~57 mins)
- Pulsar check: all antennas view pulsar w. central beam (~3 minutes)
- Pulsar cal: all antennas scan beams 1-36 through pulsar, ~2 minutes per beam

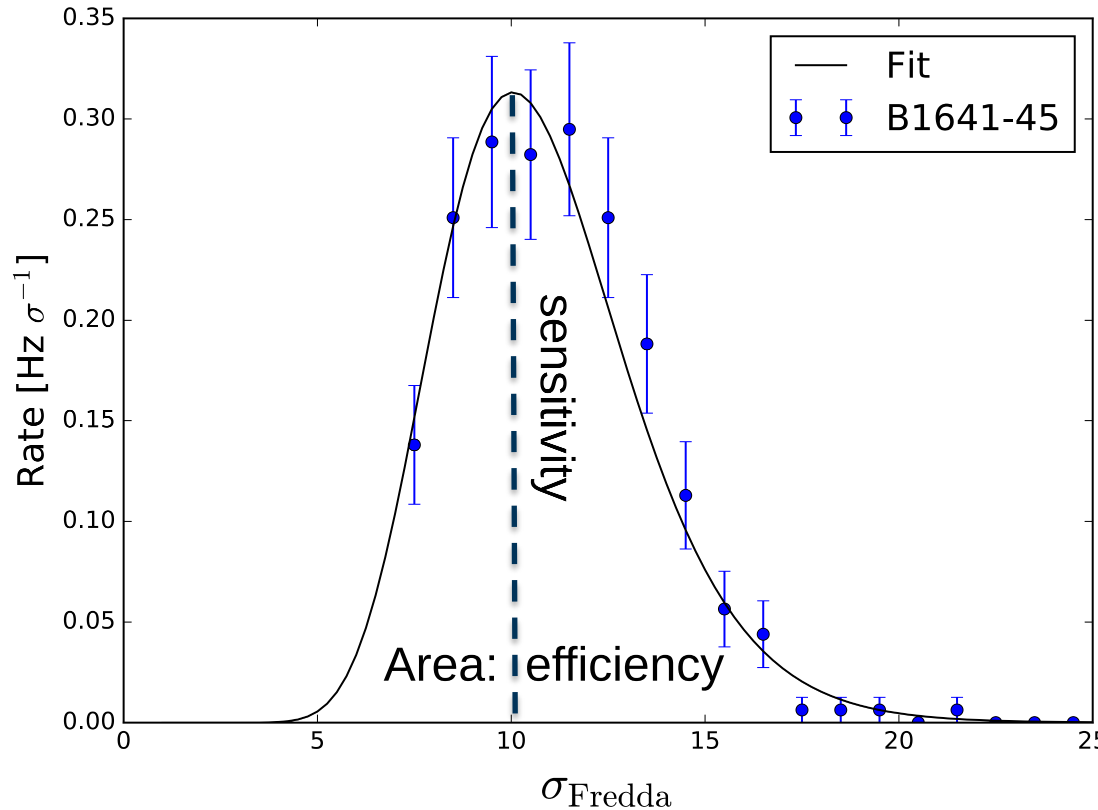
- Early observations: used commissioned antennas ('ak'), frequency, beam configuration varied
- Since ~June 2017: used commissioning ('co') antennas, constant configuration, increasing antenna number
- Apply processing pipeline on pulsar calibration runs to characterise sensitivity

Pulsar calibration data

- Histogram signal to noise for each antenna/beam for each scan
- Fit B1641-45 (J1644) & B0833-45 (Vela/J0835) using lognormal fits

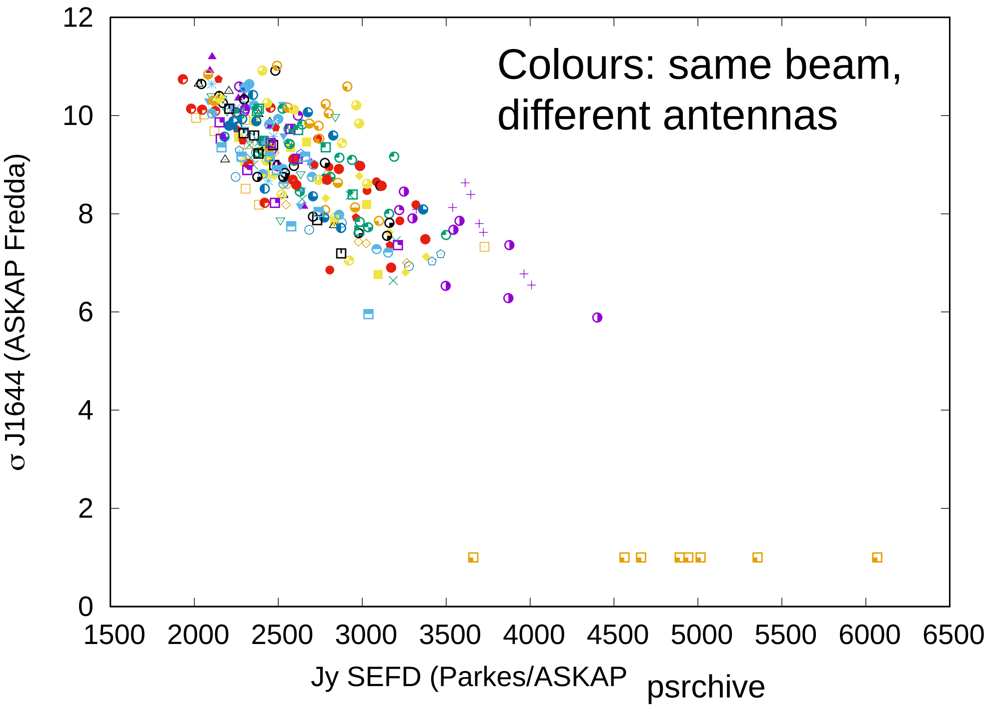
317	J0835-4510	lvm68	11.1946499395	5	dml02	67.99	1	dml02
1101	J1644-4559	kac+73	2.19751350054	5	smd93	478.8	8	dmk+93

- Fits calibrate data:
  - Peak: ~ sensitivity
  - Integral: ~ efficiency
- Repeat for each:
  - Beam
  - Antenna
  - Cal run
- O~10k data points

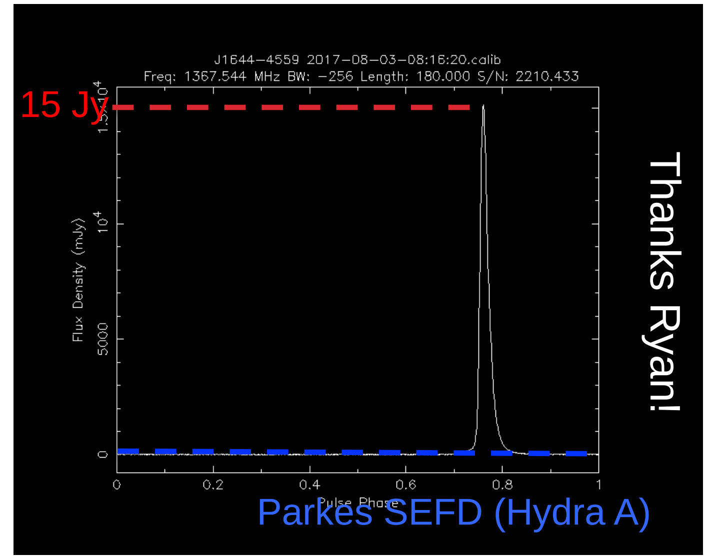


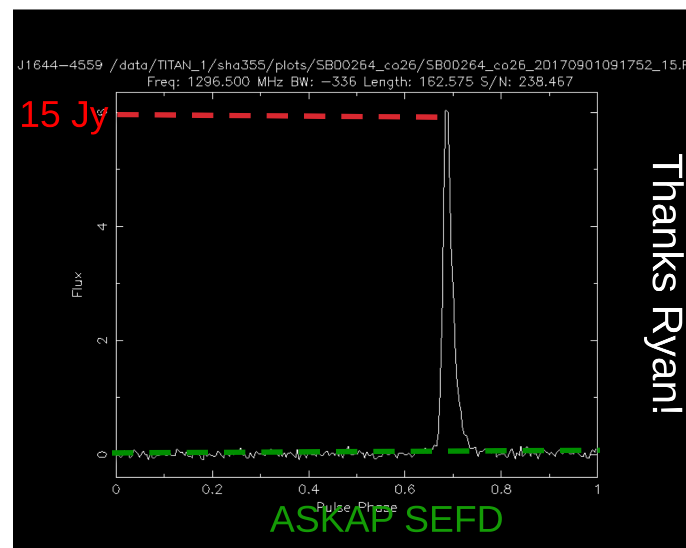
Absolute sensitivity

- Simultaneous Parkes observations
  - J1644 (B1641): analyse with PSRCHIVE
  - Set ASKAP SEFD, compare with Fredda σ



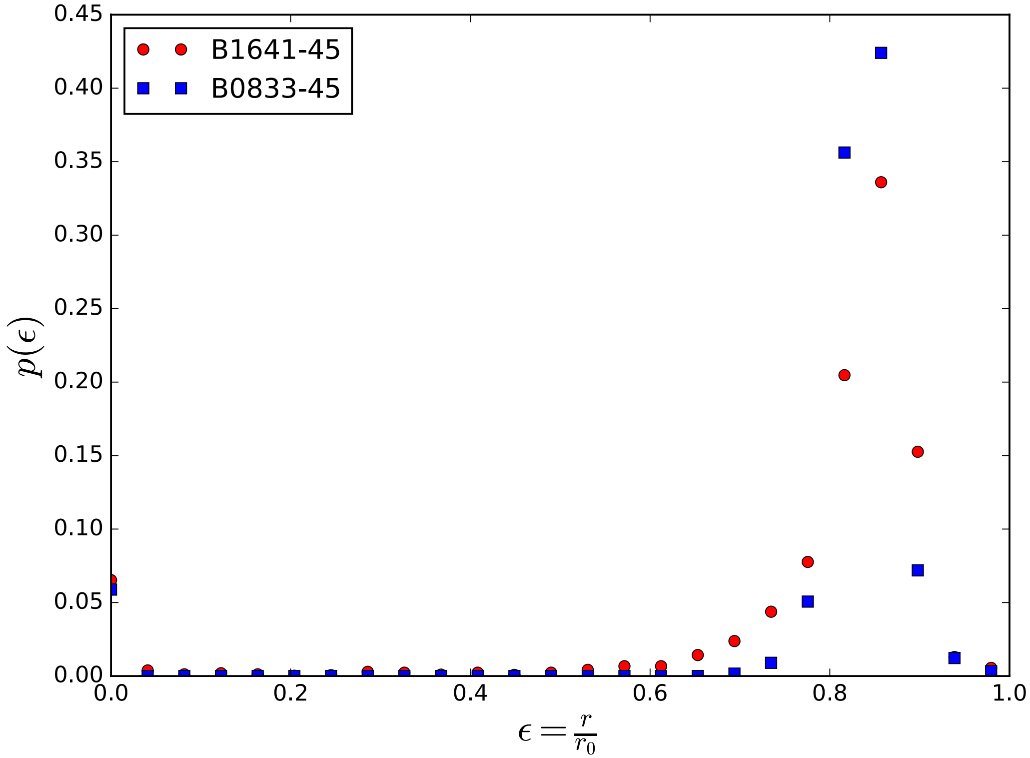
  - Recover nominal 2000 Jy SEFD (11 σ Fredda)
  - Scatter: Fredda vs PSRCHIVE?
  - Check w. analytic calc!





Efficiency

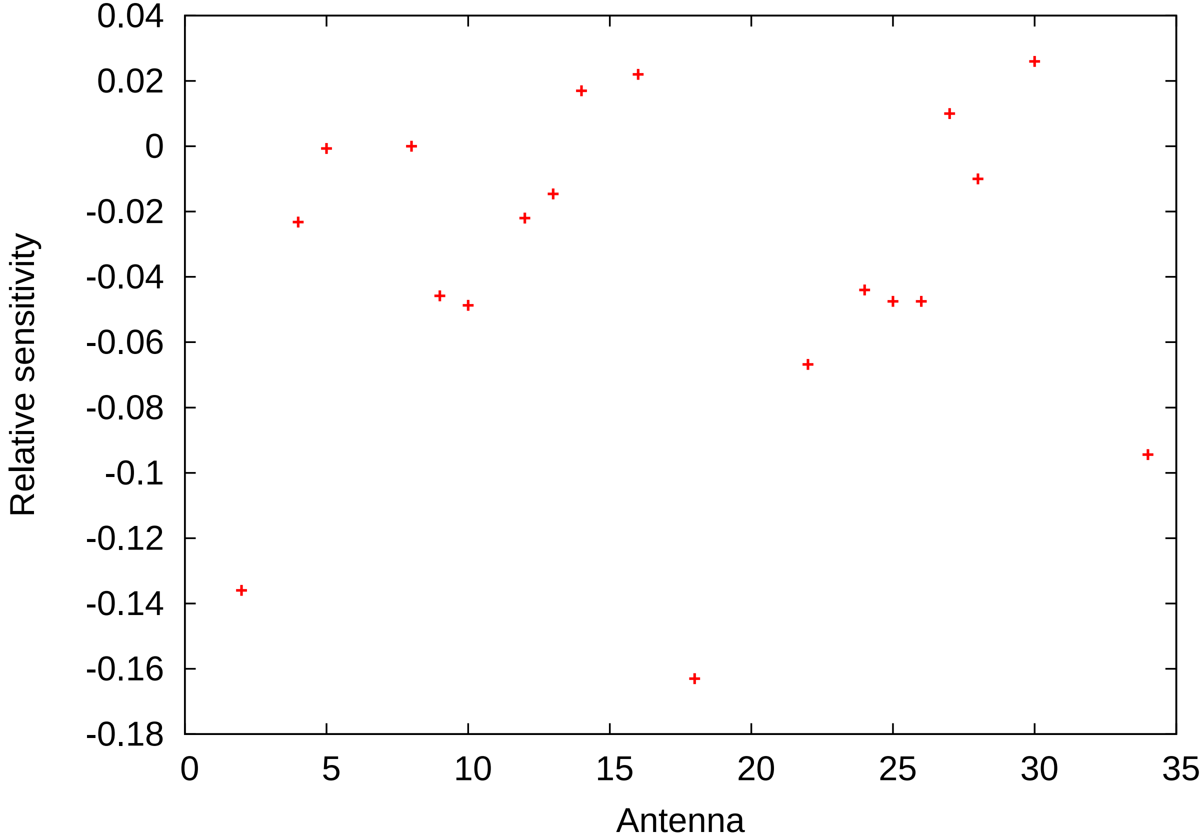
- Mean efficiency ignoring zeroes: (of Fredda / ASKAP): 0.82/0.84
  - Variation: RFI, 300Hz issue, different antennas/beams
  - Different behaviour for Vela and J1644
  - Due to DM (Vela: 68, 1644: 479) and LST (Vela obs more at night in this period)



Antenna variation

› Fit mean sensitivity: $\mu_\sigma = p_{\text{pulsar}} a_{\text{antenna}} b_{\text{beam}} f\left(n_{300\,\text{Hz}}\right)$

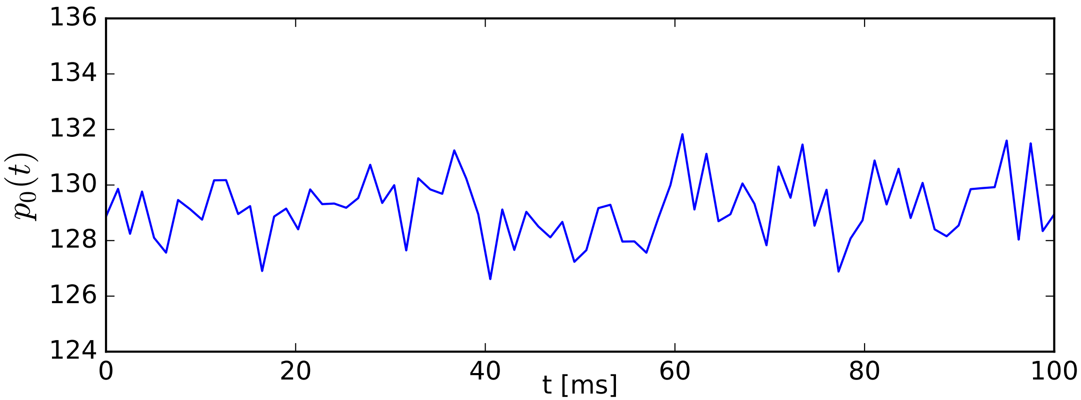
- Pulsar 'strengths' (as seen by Fredda: 1.265ms x 336 x 1 MHz)
- Antenna effects
- Beam strengths
- '300 Hz' noise

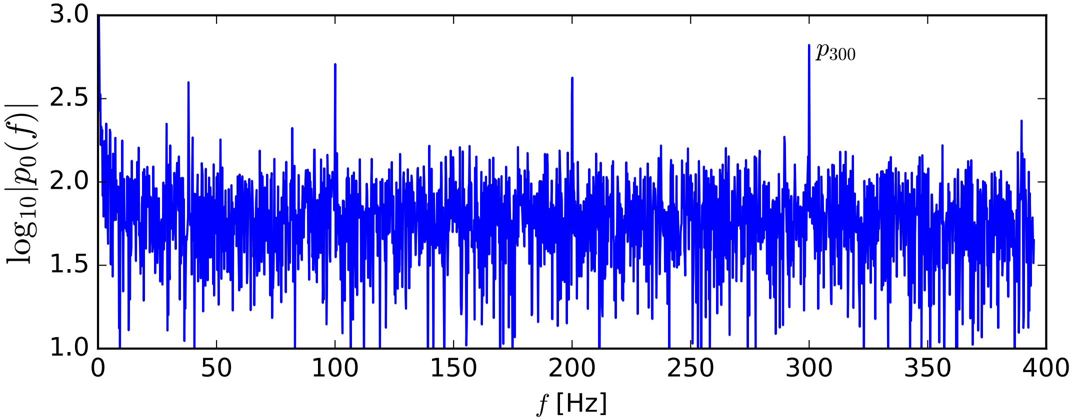


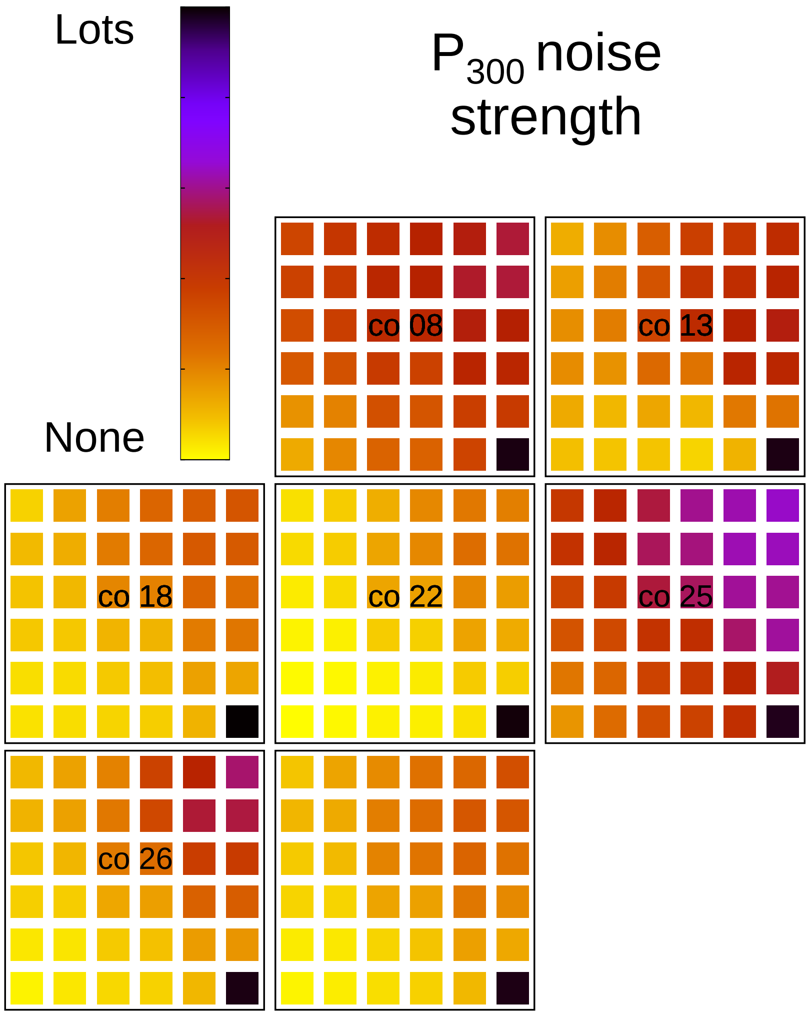
- +- 5% antenna by antenna sensitivity variation (consistent with ACES measurement)

“300 Hz” noise

- Power fluctuations
  - Vary with time, antenna, beam (=PAF!)
  - All due to power distribution

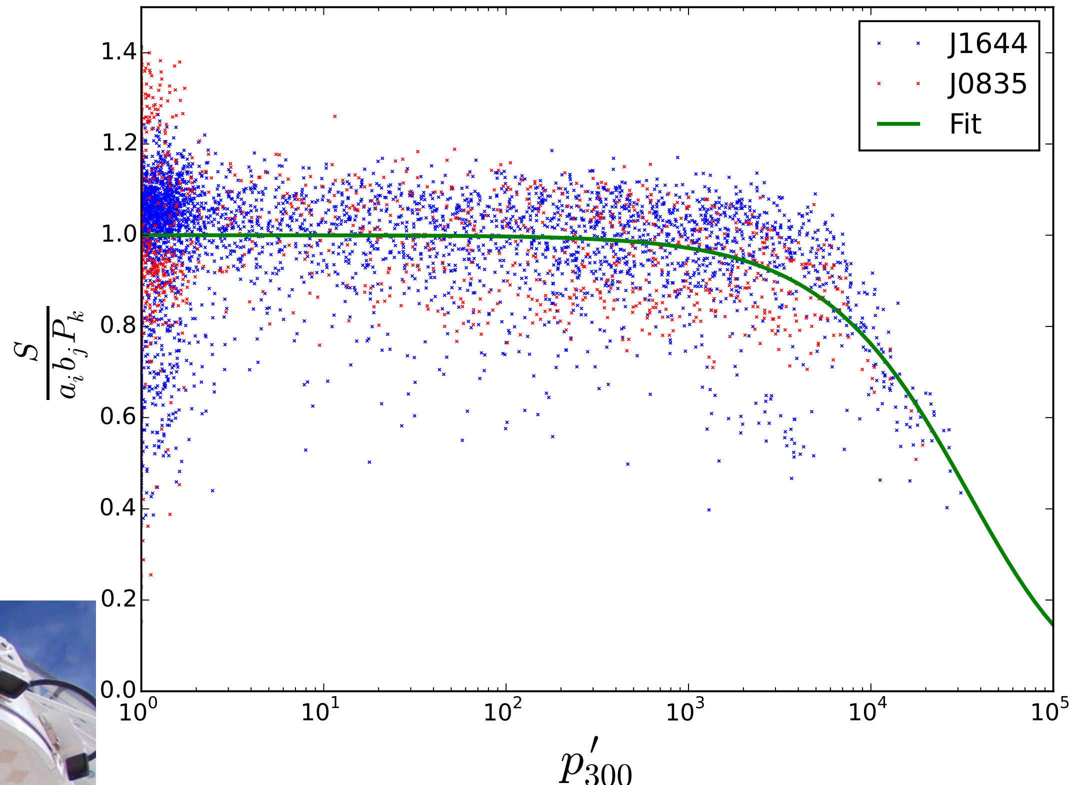


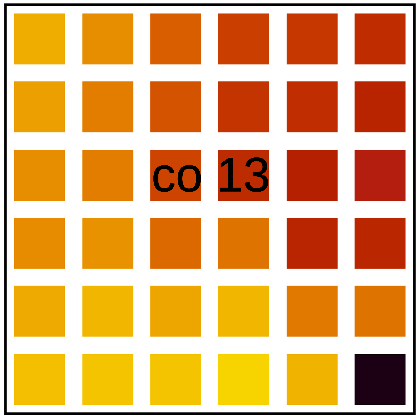


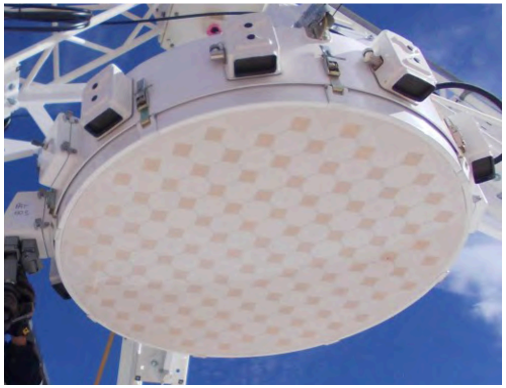


Sensitivity – 300 Hz noise

- Base model: $\mu_\sigma = p_{\text{pulsar}} a_{\text{antenna}} b_{\text{beam}} f\left(n_{300\,\text{Hz}}\right)$
- Effects of noise vary with FDMT parameters magic
  - Normalise power to N(0,1) – but over what timescale?
- Effects kick in SEFD ~doubles
  - Makes sense...
  - Except that getting rid of it does not help SNR



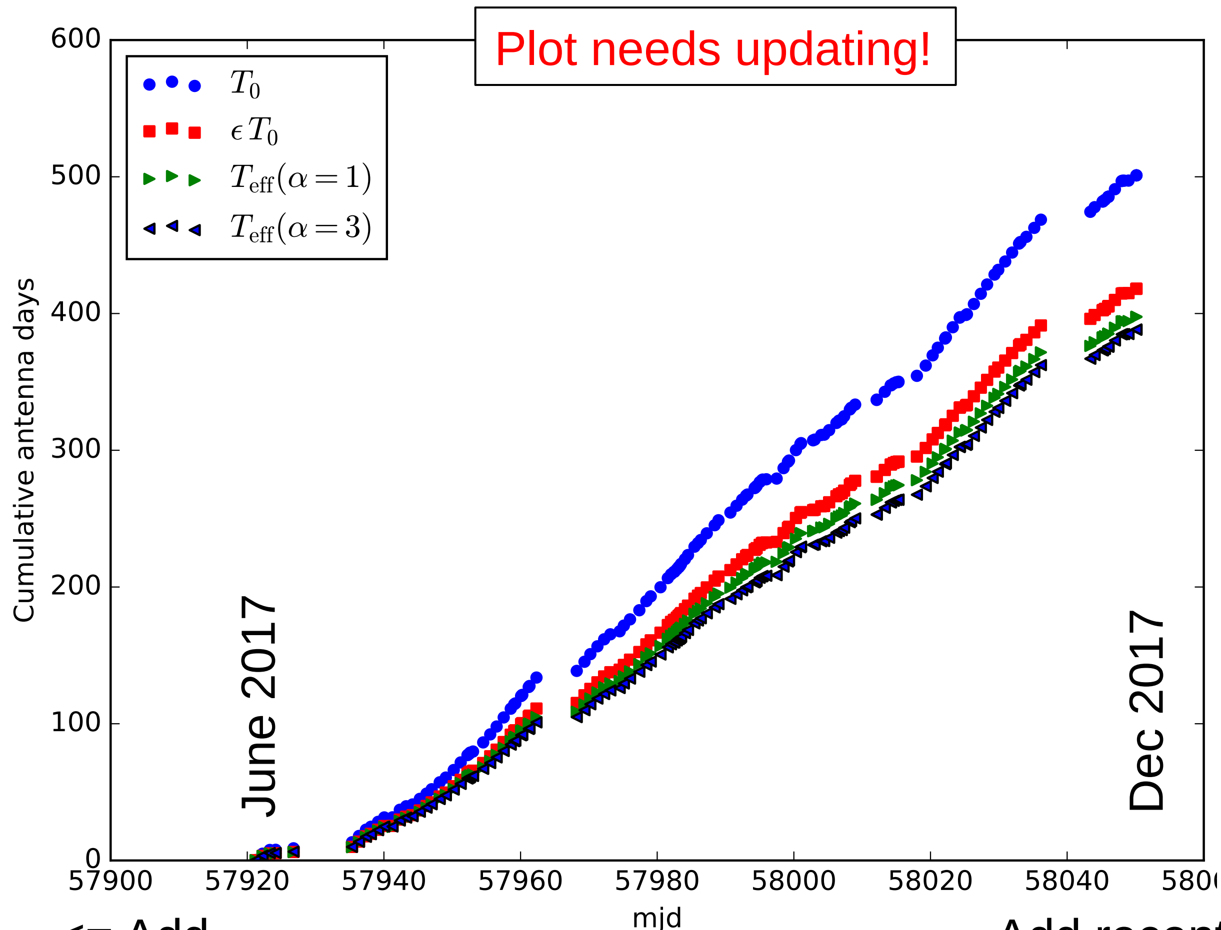




Antennas x noise

- Evolution of sensitivity
  - Lots of book-keeping!
  - Different antenna sensitivity
  - Time-varying noise
- Effective sensitivity depends on source statistics

$$R \sim S^{-\alpha} \quad \left(\frac{dR}{dS} \sim S^{-\alpha-1} \right)$$

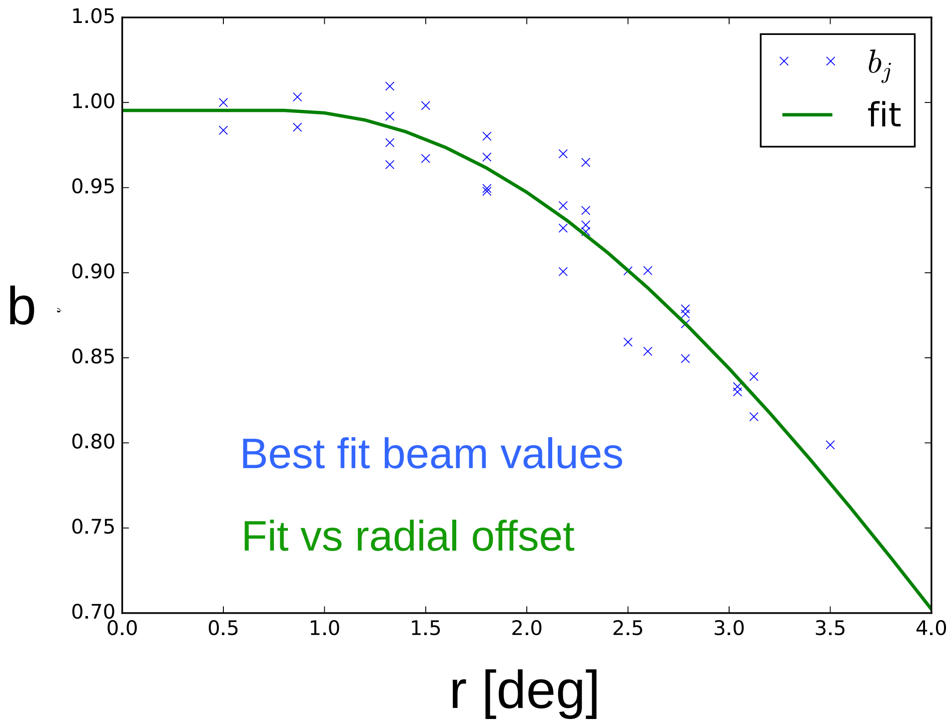


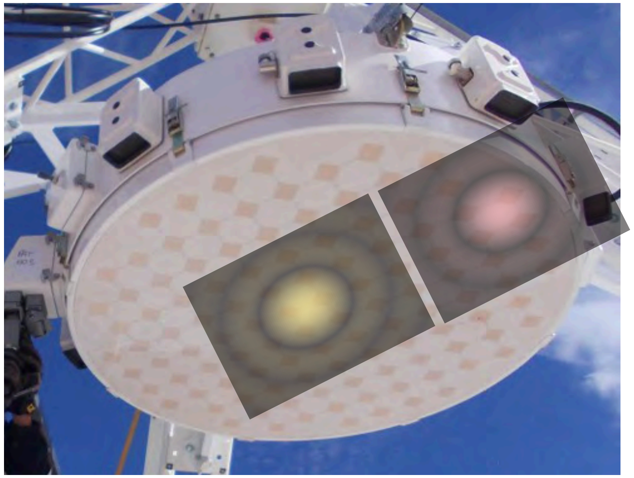
<= Add preliminary obs

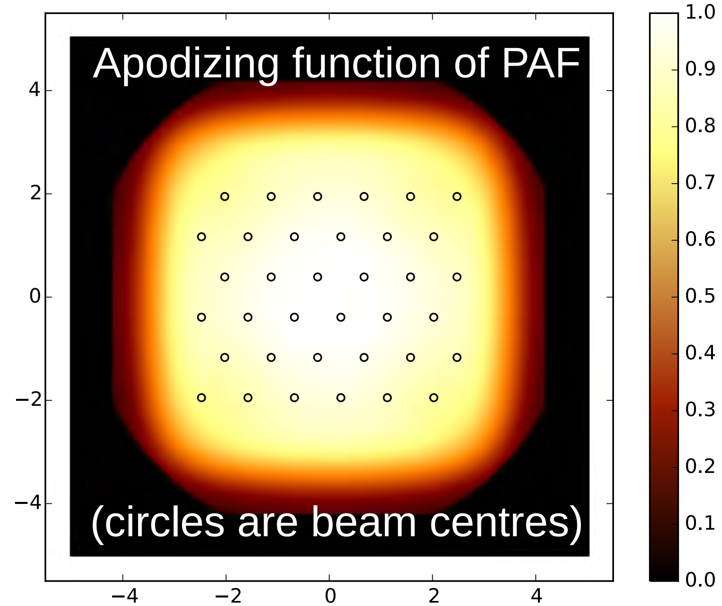
Add recent obs=>

Sensitivity - beams

- Base model: $\mu_\sigma = p_{\mathrm{pulsar}} a_{\mathrm{antenna}} b_{\mathrm{beam}} f\left(n_{300\,\mathrm{Hz}}\right)$





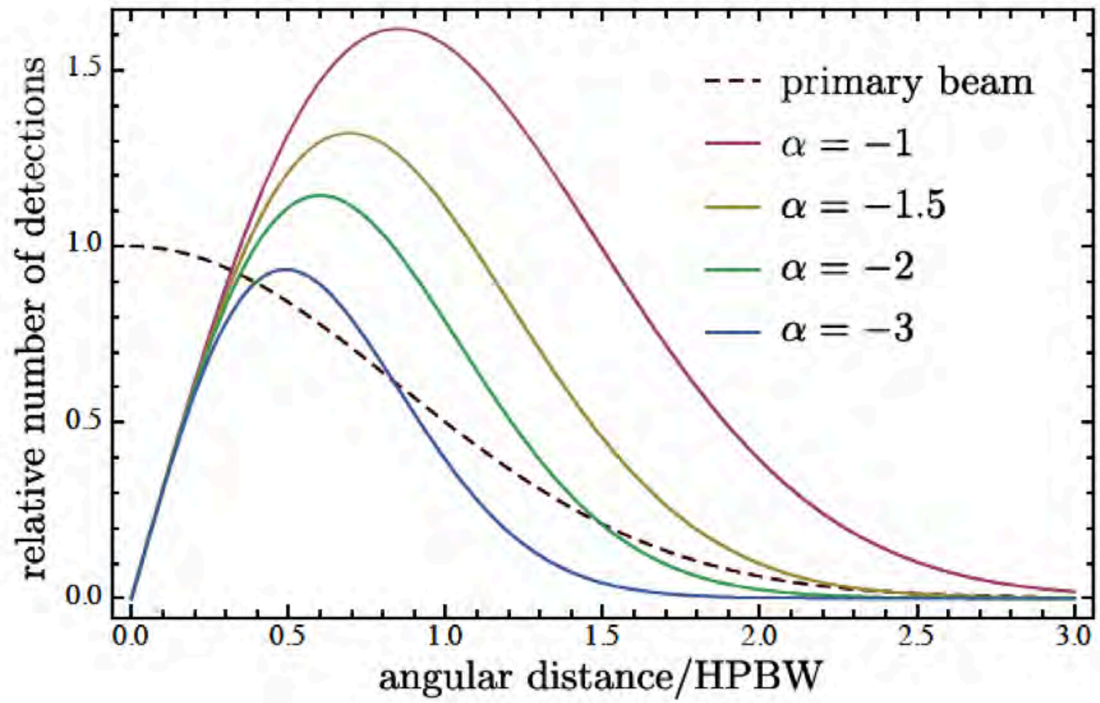


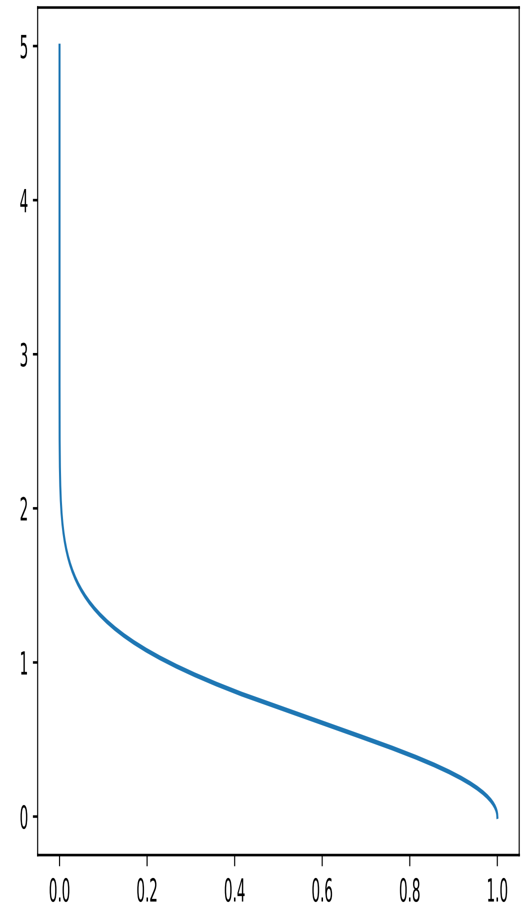
- +- 10% explicable/systematic variation
- +- ~2% 'inexplicable' variation
- Apodizing function does not provide better fit than simple radial model

Beam effects

- Ekers & Macquart: MNRAS 474 (2017) 1900
  - beam shape affects FRB population statistics measurer

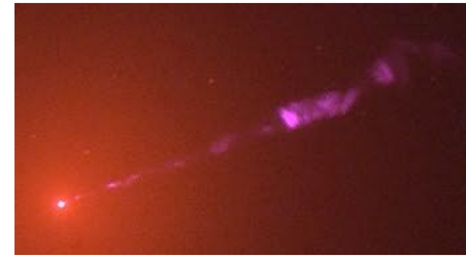
$$R \sim S^{-\alpha} \quad \left(\frac{dR}{dS} \sim S^{-\alpha-1} \right)$$



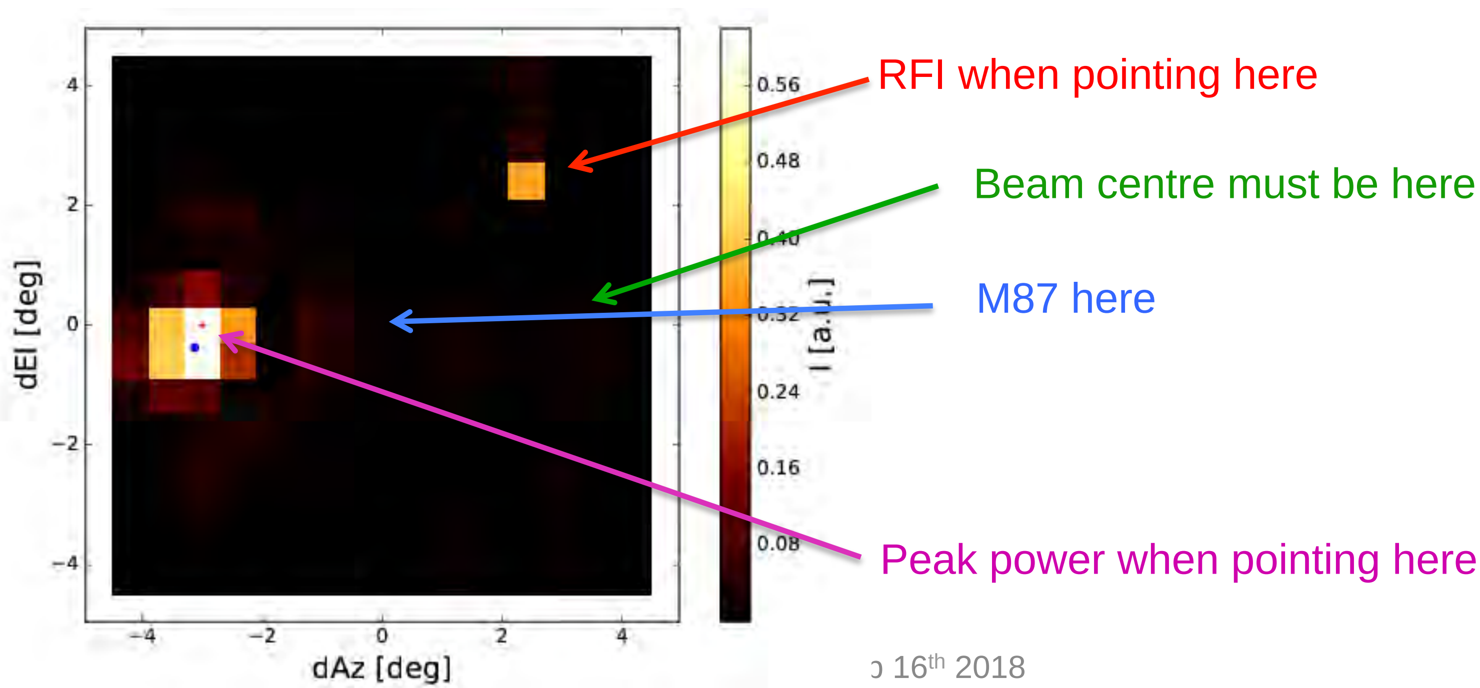


  - Better view: solid angle view at each sensitivity
  - What does this look like for CRAFT?

Holography observations



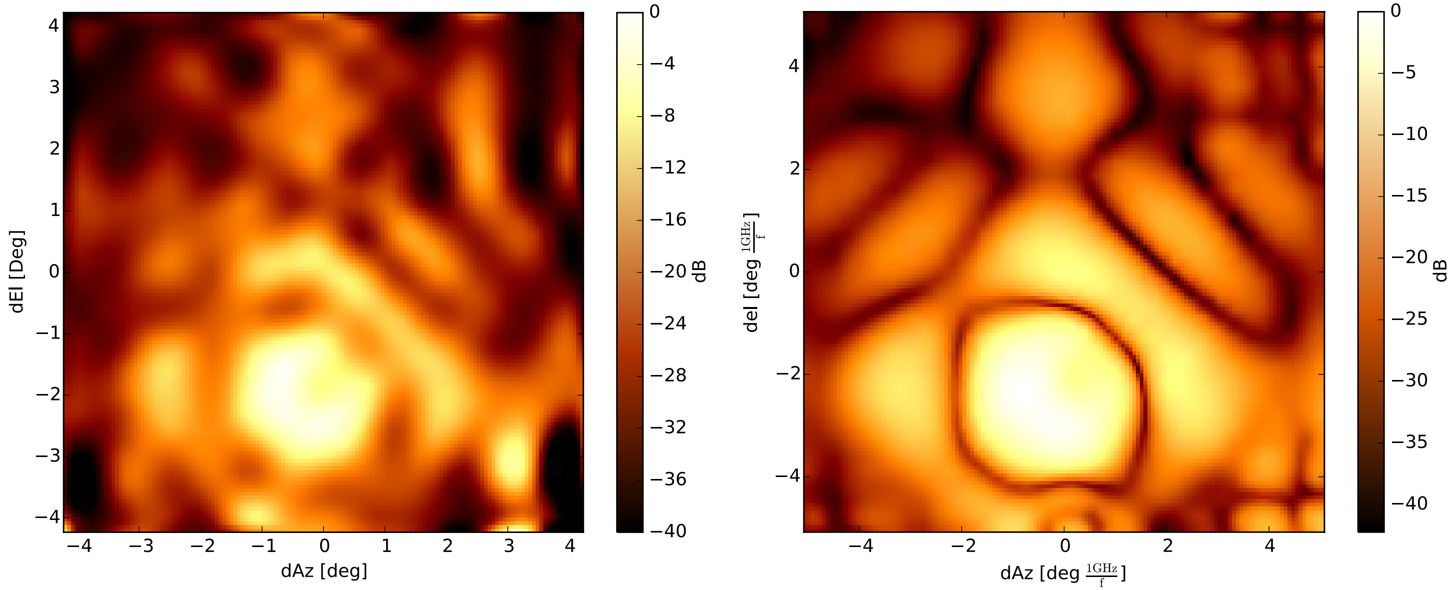
- Method
  - Fix reference antenna to M87
  - Scan other antennas through 15x15 grid of pointings
  - Measure XX,XY,YY correlations between reference and scan antennas
  - Data processed by A Hotan to extract mean XX/XY/YX/YY products



Beam calibration

› Method

- Create a spline interpolation in each of X and Y
- ASSUME: beam is identical at all frequencies except 1st order scaling about beam centre

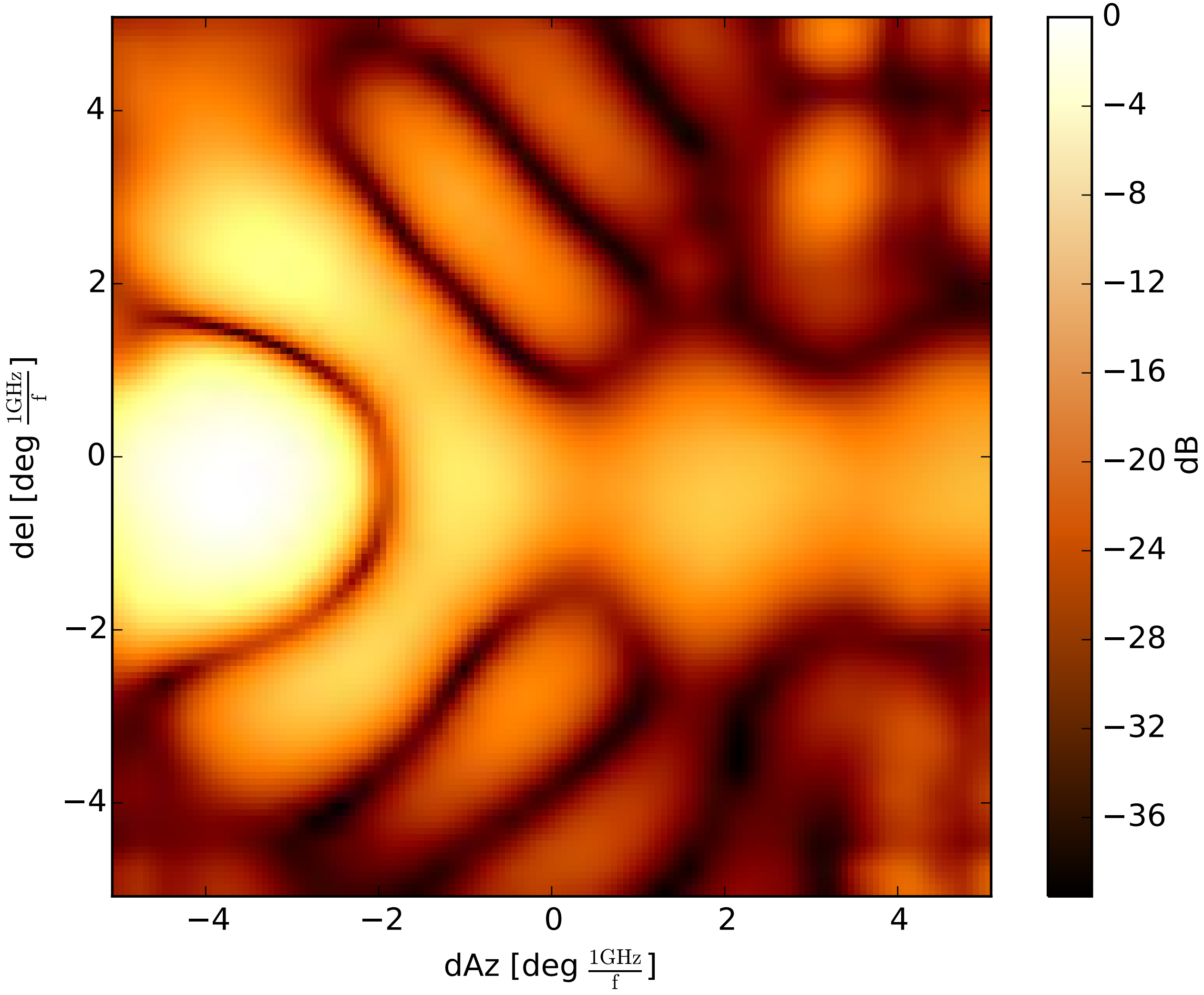


› Noise: must come from particular holography scan

› For CRAFT: it doesn't matter very much, because it's there

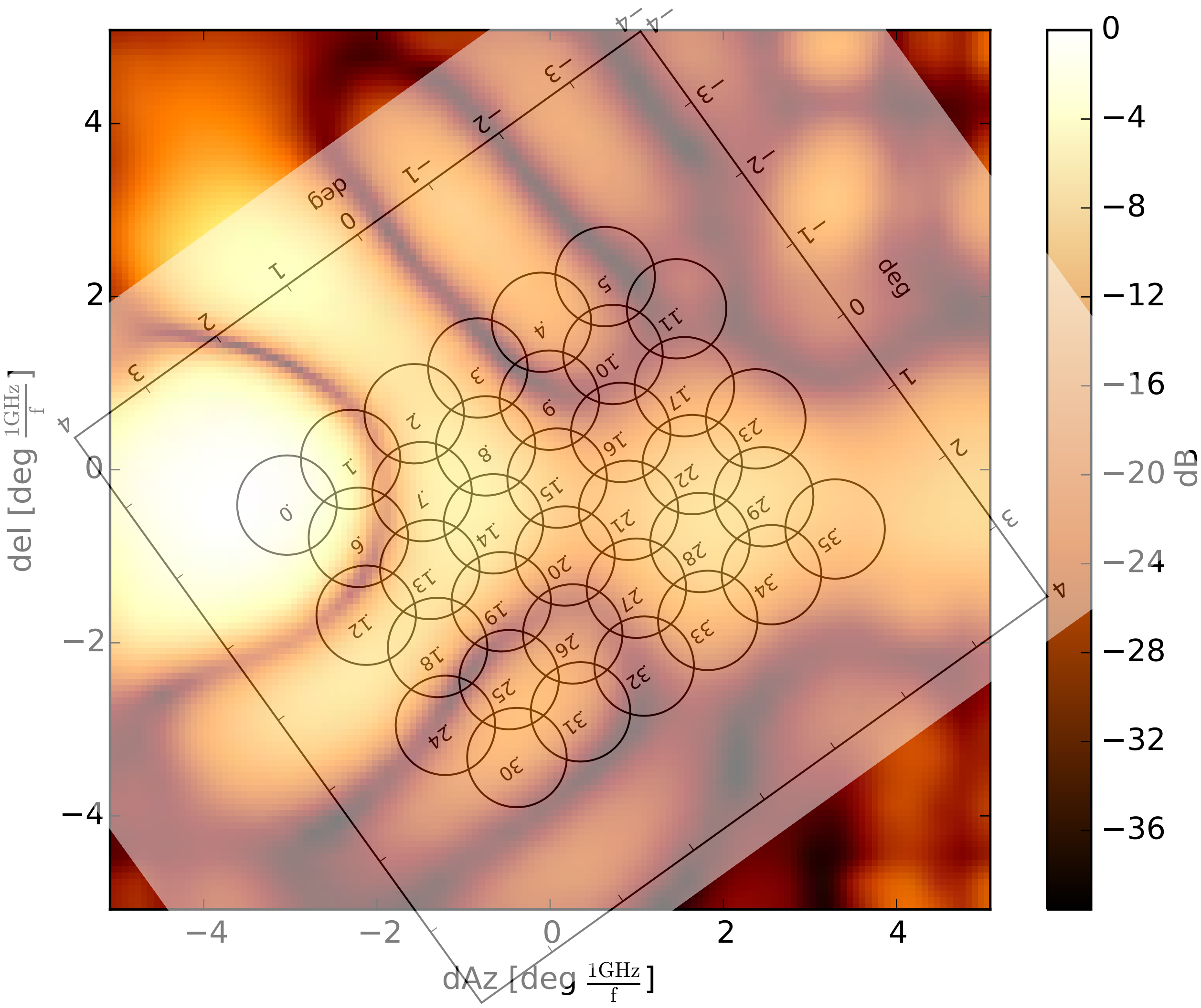
More beams

- Outer beams not well sampled by holography grid



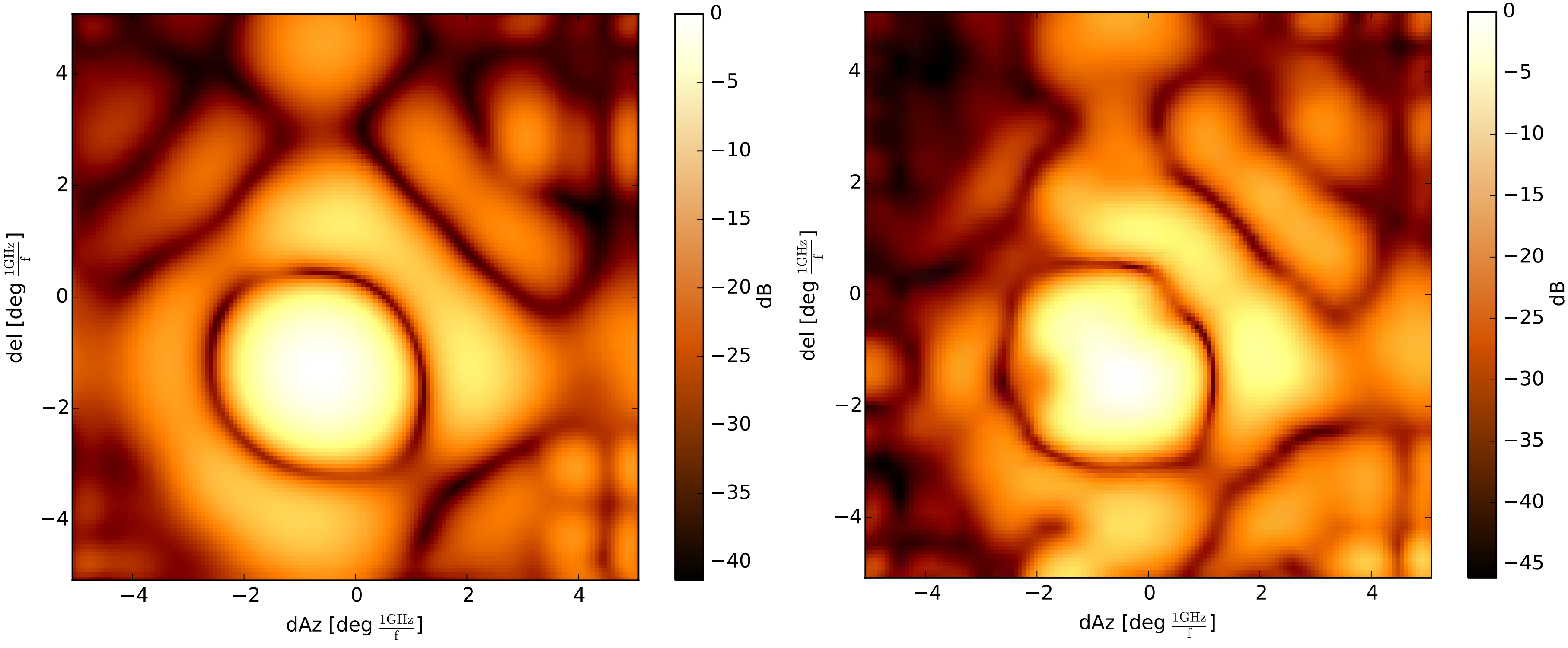
More beams

› PAFs rotated 45 degrees on sky; holography grid is not



More beams!

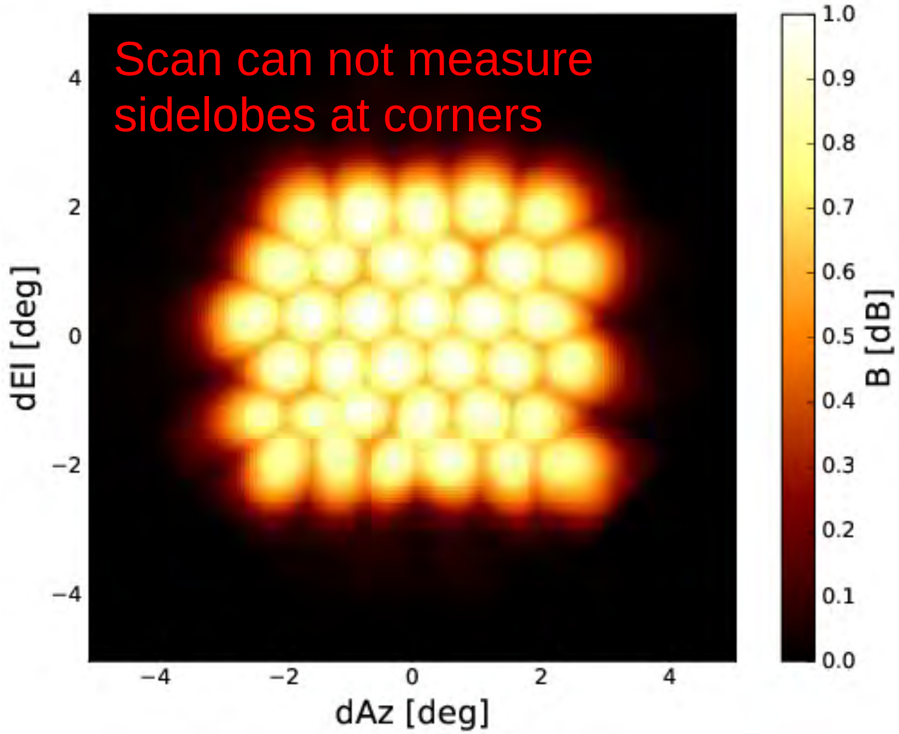
- Variation between antennas:
  - ‘bad’ antennas/beams? Long baselines resolving M87?

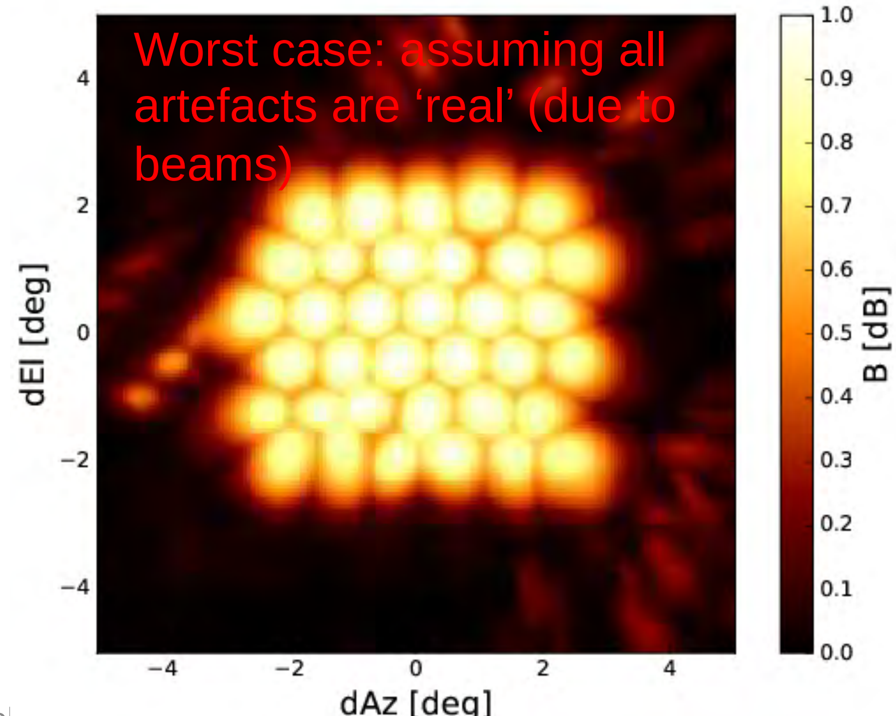


  - Ambiguity: 300 Hz noise ~ power distribution network

Closepack beamshape

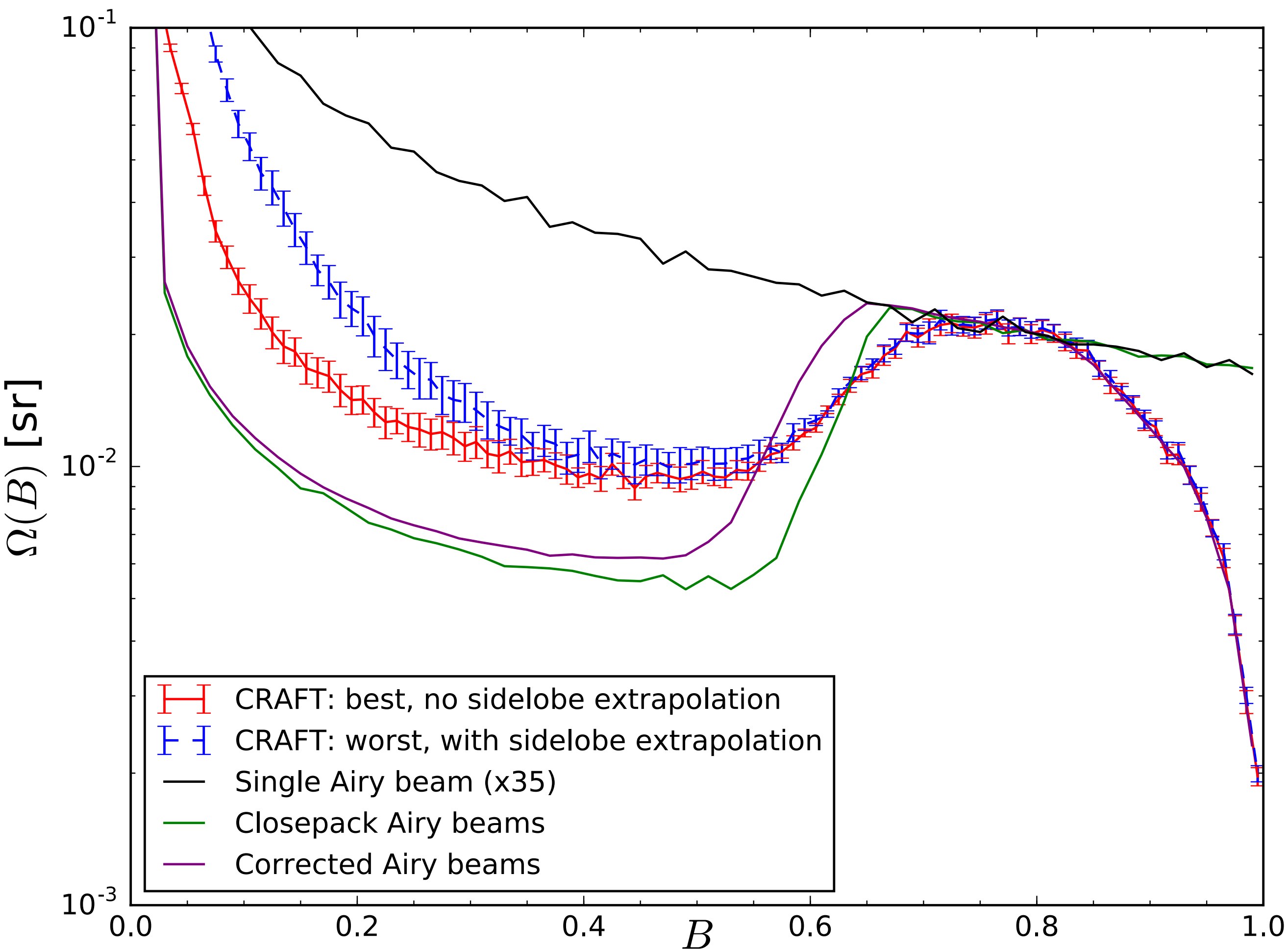
- CRAFT searches:
  - ‘FREDDA’ scans each beam independently
  - Threshold common on all beams: sensitivity is MAX() over all beams
  - Ignores double chance for noise to bump beams above threshold (matters near the beam intersection)
  - Add individual beam sensitivity from pulsar fits; remove beam 35 by hand

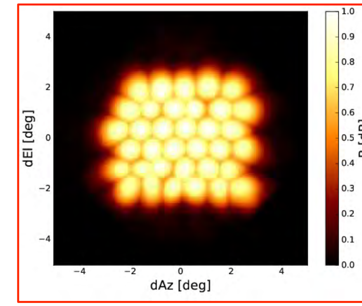


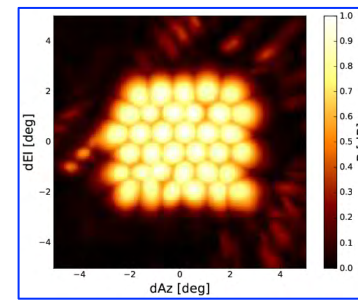


CRAFT

› CRAFT solid angle at given sensitivity



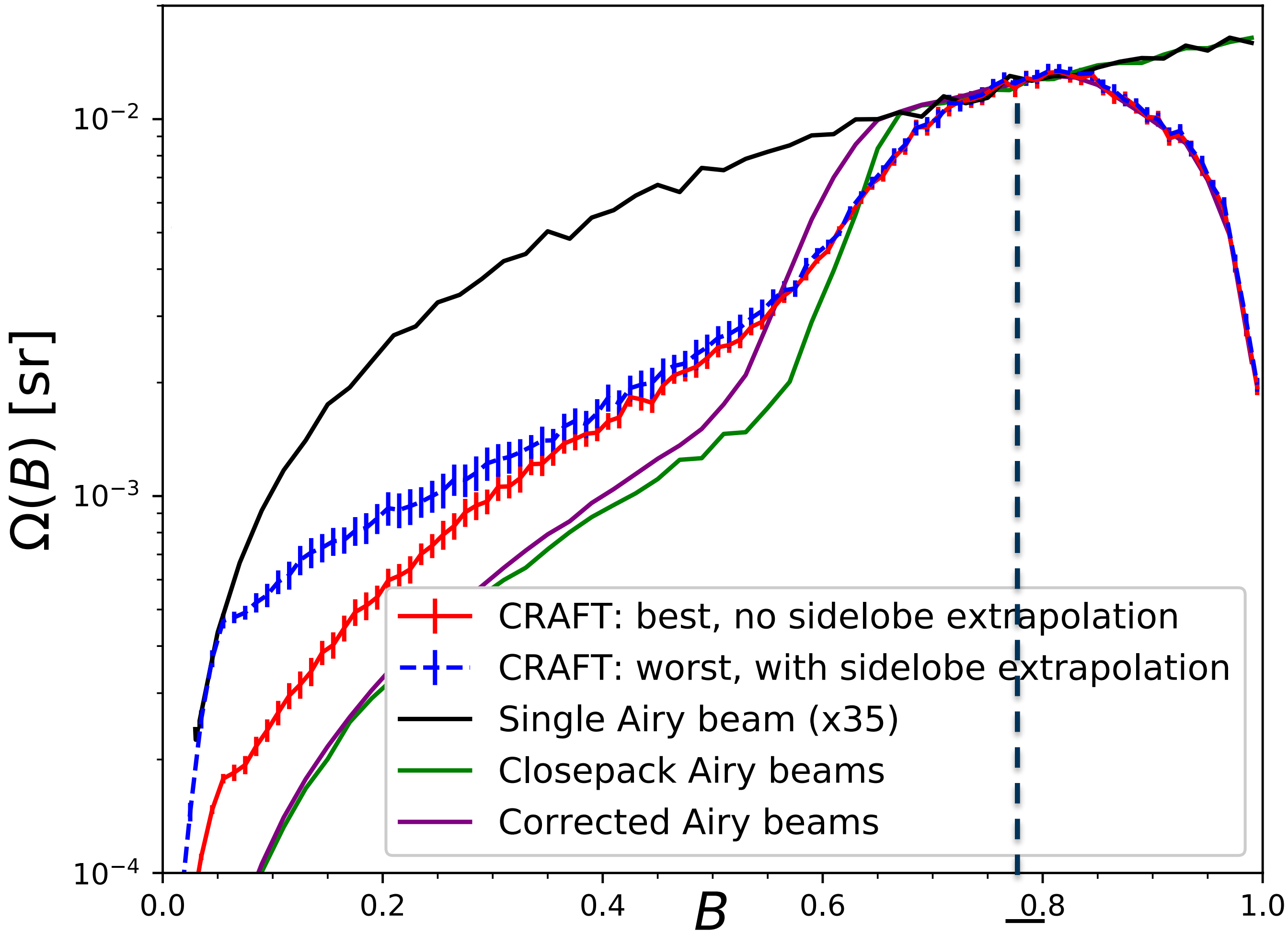




Beamshape

› CRAFT beamshape: weighted for α=2

$$R \sim S_{\text{thresh}}^{-\alpha} \left(\frac{dR}{dS} \sim S^{-\alpha-1} \right)$$



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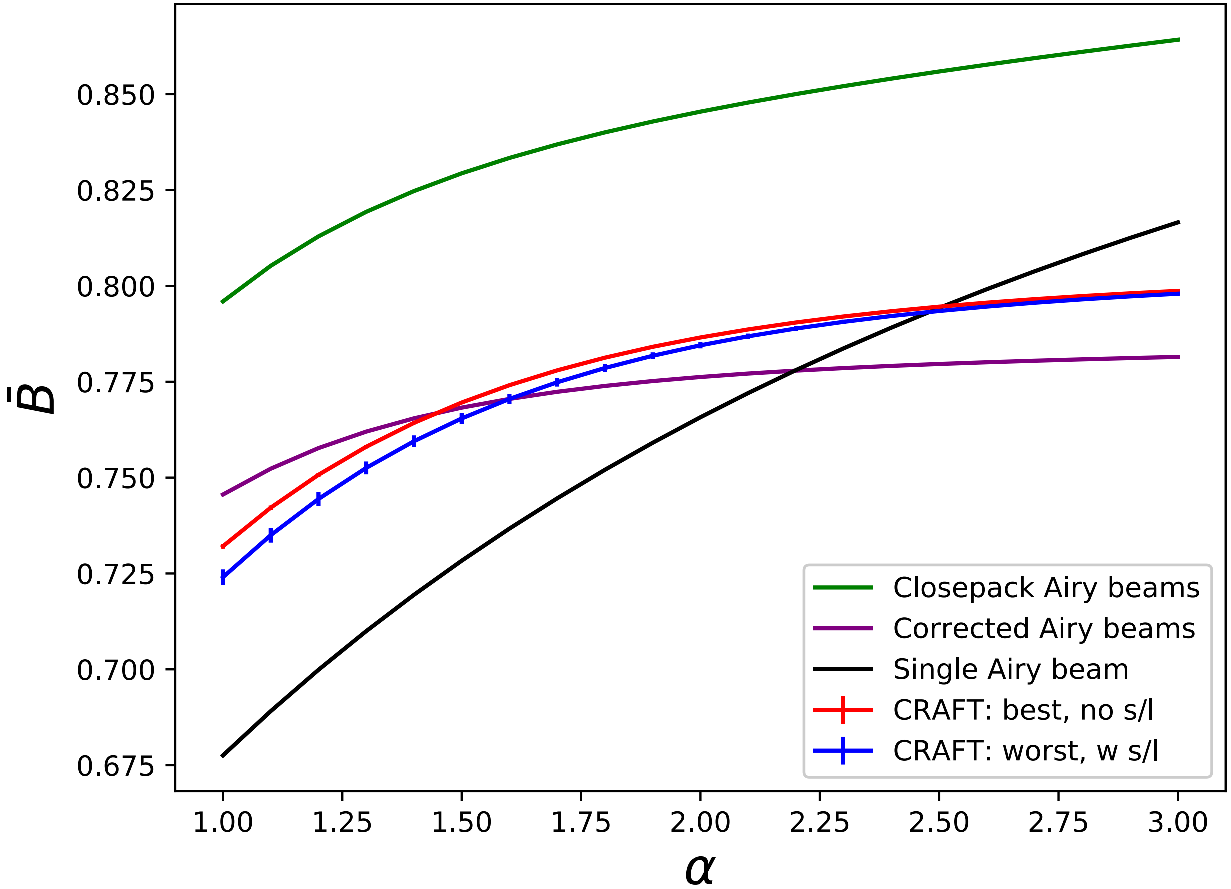
Beamshape

› Mean fluence correction factor: not very dependent on slope of source

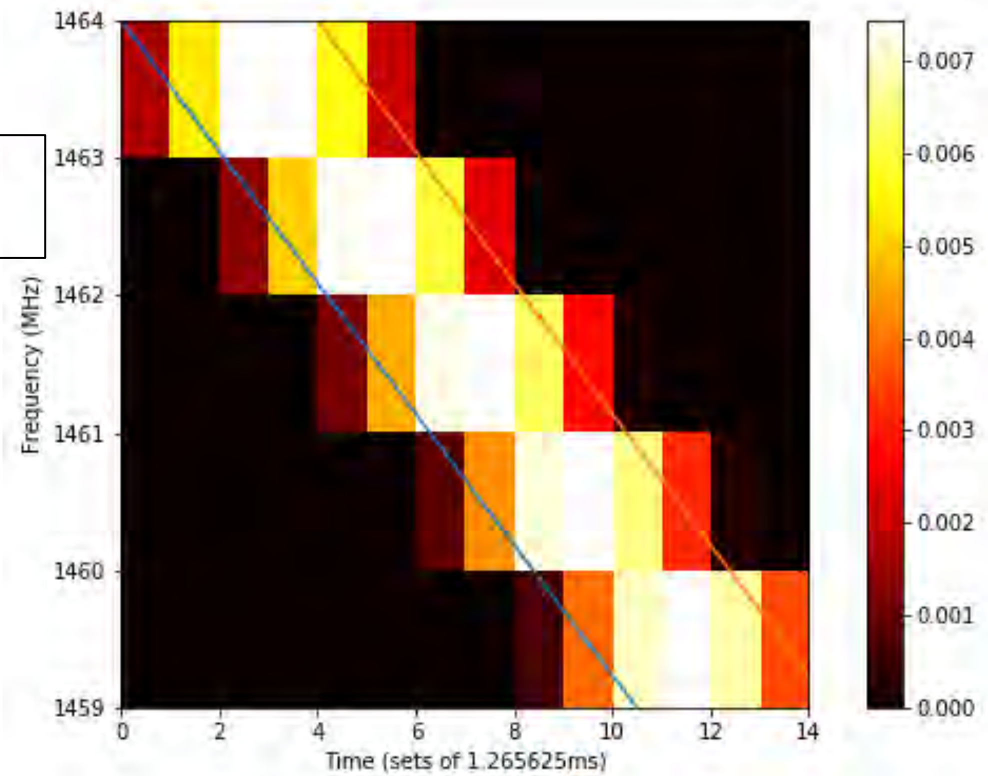
› Systematics do not matter very much − difference with Airy ideal maters at 5% level



FDMT effects

- ‘Fredda’ FDMT
  - Incoherent dispersion search
  - 336 x 1 MHz channels
  - 1.265 ms time resolution
  - Searches in DM and width space
  - NO interpolation/weighting

Diagonal DM: ~320



- Project by Mawson Sammons
  - Boxcar pulse shape
  - Uniform spectrum

- Three sensitivity measures:
  - “Intrinsic sensitivity” [coherent dedispersion]
  - FDMT sensitivity
  - Theoretical best (matched filter) sensitivity

NOT “Fredda” − use python mock-up of incoherent search algorithm

FDMT effects

- ‘Fredda’ FDMT
  - Incoherent dispersion search
  - 336 x 1 MHz channels
  - 1.265 ms time resolution
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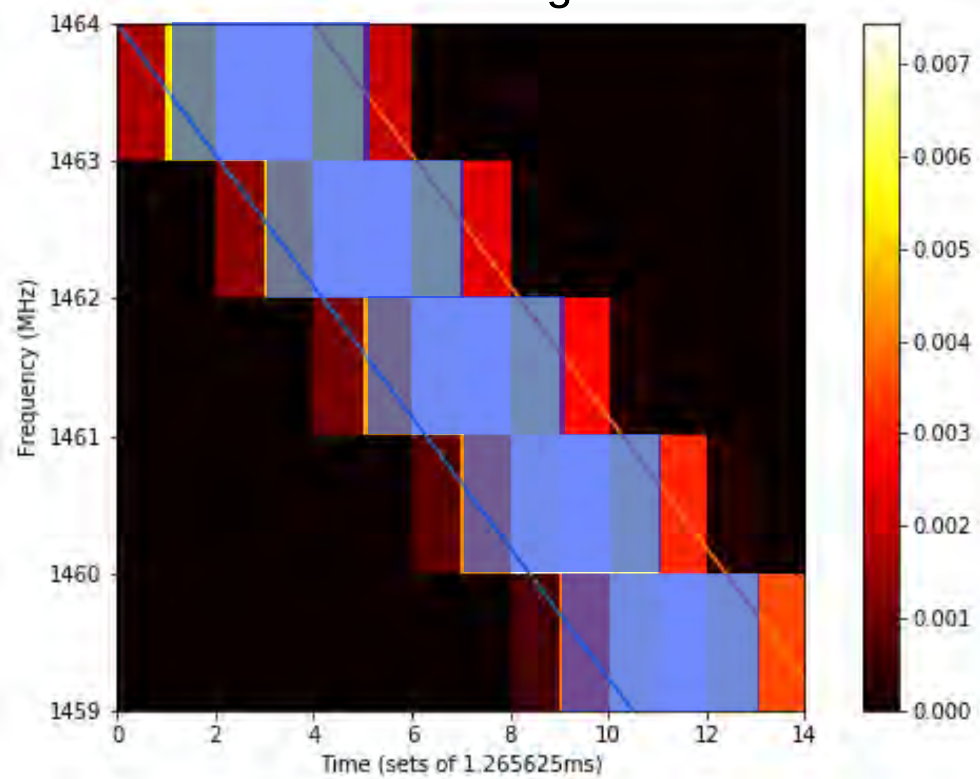
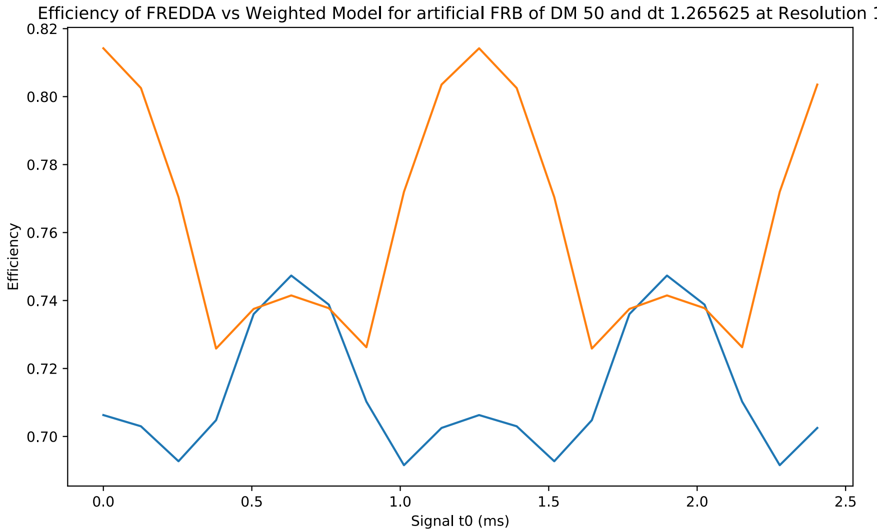


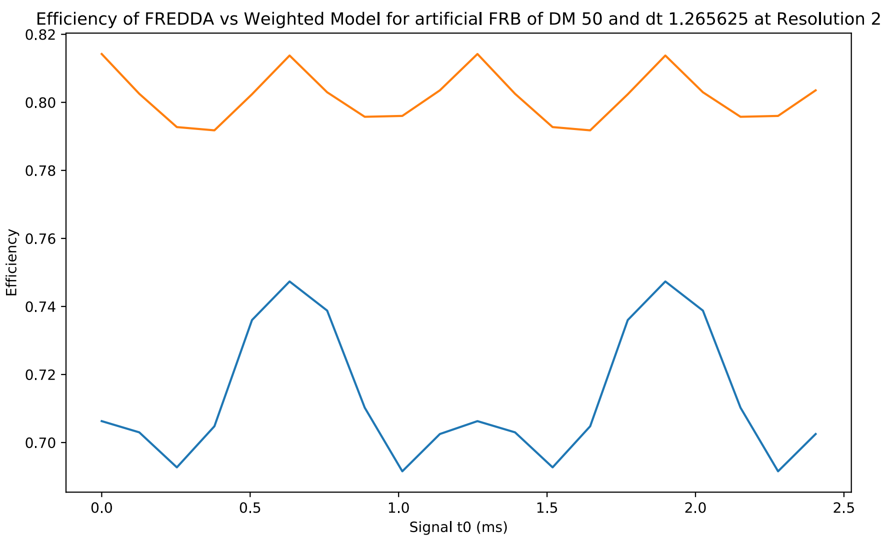
- Three sensitivity measures:
  - “Intrinsic sensitivity” [coherent dedispersion]
  - FDMT sensitivity
  - Theoretical best (matched filter) sensitivity given CRAFT data

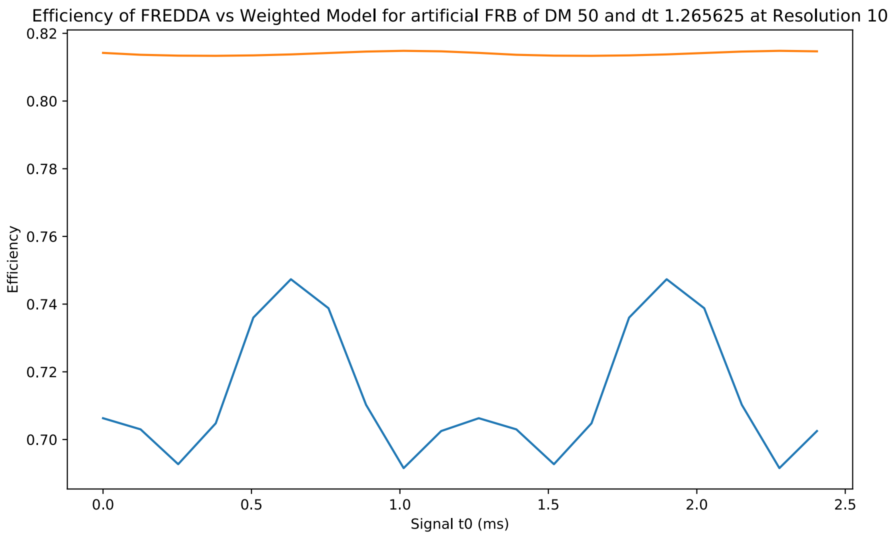
Diagonal DM: ~320

Testing efficiency

- EXAMPLE
  - Pulse width 1.265 ms (one time bin)
  - DM 50 (well within diagonal)
  - Vary start time from 0 to 2x1.265 ms
- FREDDA: search units 1.265 ms, DM 0.95
- MatchedFilter: use fractional start times
- X-axis: signal start time in bin
- Y-axis: recovered signal to noise





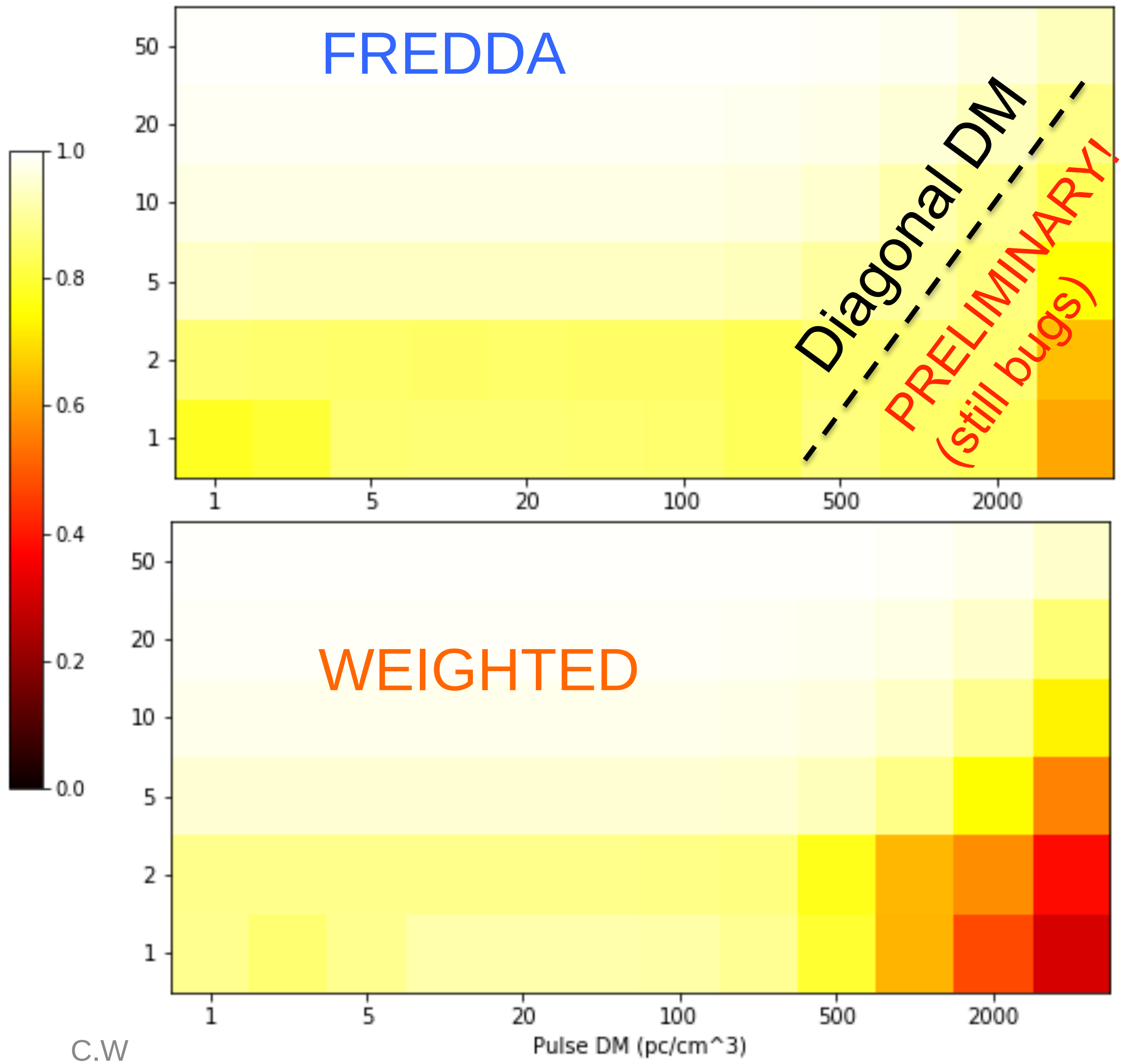


Results

PRELIMINARY!
(still bugs)

- Wider pulses:
  - less “edge effects”
  - More filled bins
- High DM:
  - ‘diagonal DM’ smearing
- Low DM:
  - start time matters

- TO DO:
  - Fix bugs
  - Investigate t<1.265ms
  - Realistic pulse shapes!
  - Improve reconstruction
- Q: can we fit FRB shape as
  - Gaussian + exp tail?



C.W

Conclusion

- Calibrating sensitivity is fun!:
  - Lots of effects governing CRAFT sensitivity
  - Beamshape, RFI/other variance, antenna sensitivity,
  - FDMT search method
  - "You don't need a complete sample, you need to understand your bias"
- To-Do:
  - Check FDMT implemented properly (Harry)
  - Add early and recent observations
  - Investigate different pulse shapes
  - Write in terms of absolute calibration
  - Analyse frequency dependence
  - Understand FRBs...

Understand the system

Where is the end-to-end system simulation?