Sensitivity of CRAFT Fly’s Eye searches for FRBs
Clancy W. James,
Thanks to CRAFT & ACES teams
ICRAR / Curtin Institute of Radio Astronomy / CAASTRO
www.caastro.org
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

C.W. James, Feb 16th 2018
Fly’s Eye strategy

- 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

Fits calibrate data:
- Peak: ~ sensitivity
- Integral: ~ efficiency

Repeat for each:
- Beam
- Antenna
- Cal run

O~10k data points

C.W. James, Feb 16th 2018
Simultaneous Parkes observations
- J1644 (B1641): analyse with PSRCHIVE
- Set ASKAP SEFD, compare with Fredda $\sigma$
  - Recover nominal 2000 Jy SEFD ($11 \sigma$ Fredda)
  - Scatter: Fredda vs PSRCHIVE?
  - Check w. analytic calc!

C.W. James, Feb 16th 2018
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)
Fit mean sensitivity:
- Pulsar ‘strengths’ (as seen by Fredda: 1.265ms x 336 x 1 MHz)
- Antenna effects
- Beam strengths
- ‘300 Hz’ noise

\[ \mu_{\sigma} = p_{\text{pulsar}} a_{\text{antenna}} b_{\text{beam}} f(n_{300\text{Hz}}) \]

- +- 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

C.W. James, Feb 16\textsuperscript{th} 2018
Sensitivity – 300 Hz noise

- Base model: $\mu\sigma = p_{\text{pulsar}} a_{\text{antenna}} b_{\text{beam}} f(n_{300Hz})$

- 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

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

- Base model: \( \mu_\sigma = p_{pulsar} a_{\text{antenna}} b_{\text{beam}} f(n_{300\text{Hz}}) \)

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

Best fit beam values

Fit vs radial offset

Apodizing function of PAF (circles are beam centres)
Beam effects

  - beam shape affects FRB population statistics measurer

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

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

![Graph showing M87, beam centre, RFI, and peak power points.

- M87 here
- Beam centre must be here
- RFI when pointing here
- Peak power when pointing here]
Method

- Create a spline interpolation in each of X and Y
- ASSUME: beam is identical at all frequencies except 1\text{st} 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
CRAFT searches:

- ‘FREDDA’ scans each beam independently
- Threshold common on all beams: sensitivity is \( \text{MAX}(\cdot) \) 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

Scan can not measure sidelobes at corners

Worst case: assuming all artefacts are ‘real’ (due to beams)
CRAFT solid angle at given sensitivity

- CRAFT: best, no sidelobe extrapolation
- CRAFT: worst, with sidelobe extrapolation
- Single Airy beam (x35)
- Closepack Airy beams
- Corrected Airy beams
CRAFT beamshape: weighted for $\alpha=2$

$$R \sim S_{\text{thresh}}^{-\alpha} \left( \frac{dR}{dS} \sim S^{-\alpha-1} \right)$$
› Mean fluence correction factor: not very dependent on slope of source
› Systematics do not matter very much – difference with Airy ideal matters at 5% level
‘Fredda’ FDMT
- Incoherent dispersion search
- 336 x 1 MHz channels
- 1.265 ms time resolution
- Searches in DM and width space
- NO interpolation/weighting

Project by Mawson Sammons
- Boxcar pulse shape
- Uniform spectrum

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

Diagonal DM: ~320

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
  - Searches in DM and width space
  - NO interpolation/weighting

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

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

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?
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?

C.W. James, Feb 16th 2018