Cyclic Imaging:
Interferometric Detection and Localisation of Wideband Engineered Signals

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Wide-field Wideband SETI

- Goal: real-time detection and localisation over the whole FoV

- Want:
  1. large FoV for survey speed
  2. high sensitivity for deep searches

- Array telescopes provide wide FoV, but to obtain maximum sensitivity, need either:
  - coherent tied-array beams, possibly thousands to tile the entire FoV, with separate detector pipelines on each beam output, or
  - interferometric imaging, which can detect compact sources at (nearly) the full array sensitivity
Wide-field Wideband SETI

- But a wide FoV image will contain thousands/millions of radio sources
  – how to discriminate natural and engineered sources?

Image credit: B. Saxton (NRAO/AUI/NSF); ALMA (ESO/NAOJ/NRAO); NASA/ESA Hubble.
Wide-field Wideband SETI

Narrowband SETI

- look for “unnaturally narrow” emissions
  BUT – impractical to image at ultrafine freq resolution → beamforming + high-res FFT
  → thousands of beams (computationally intensive) but detector on each beam is easy

Wideband SETI

- beamforming approach: requires the same beamformer computations, plus more complex detector processing on each beam
  BUT – for wideband SETI the imaging approach comes back into play
  BUT – only viable if there’s a means to differentiate natural and engineered sources
  → cyclic imaging
Cyclic Imaging

- Conventional imaging maps sky brightness as a function of RA and Dec
  - usually Stokes I (power flux), or other Stokes parameters
- Cyclic imaging maps a different metric: - cyclostationarity
  - only sources whose emissions contain cyclostationary power are visible

Cyclostationarity

- “a signal having statistical properties that vary cyclically with time” (Wikipedia)
- those properties can relate to voltages, powers and/or higher-order moments
- can apply to both coherent and incoherent emissions, but always there is time-coherence and specific cycle frequencies
  - correlation between signal components spaced regularly in time
Example Cyclostationary Sources

Natural

➢ pulsars
  • emission resembles broadband Gaussian noise with a time-varying power envelope that repeats on a characteristic timescale – the pulsar’s period

Engineered

➢ pulsed radar
  • regularly spaced bursts of power, typically sinusoids, chirps or pseudo-noise – not necessarily coherent


Image Credit: Bob Muro, Boonton.
Example Cyclostationary Sources

Engineered

- digitally-modulated communications signal
  - can exhibit envelope cyclostationarity (e.g. bandlimiting, repeating frame structure with header pattern)
  - BUT – envelope can be constant and still there is correlation between different symbols (when there is a finite symbol alphabet)
  - NOTE – different cyclostationary detection algorithms may not detect all forms of cyclostationarity!!
Conventional vs Cyclic Imaging
Conventional vs Cyclic Imaging

only
cyclostationary
sources

radar reflection
off aircraft

pulsars

reflection off
LEO space debris

satellite & aircraft
communications
signals
Conventional vs Cyclic Imaging

Expect all to be known pulsars/RRATs

only cyclostationary sources that are static on the sky
Conventional vs Cyclic Imaging

only cyclostationary sources that are static on the sky and not previously catalogued

unknown pulsar? ET?
Detecting Cyclostationarity

- Various techniques, including:
  1. Cyclic spectroscopy
  2. Autocorrelation
  3. Symbol-wise autocorrelation (SWAC)
  4. Karhunen–Loève Transform (KLT) (or any principle component analysis)
Detecting Cyclostationarity

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Appeal of SWAC:
- naturally extends to interferometric regime (from auto- to cross-correlations)
  → symbol-wise cross-correlation (SWCC) and “cyclic visibilities”
- does not rely on power envelope fluctuations
- maximises detection sensitivity for modulation types of interest
- incoherent accumulation of SWCC detection metric
  → no need to fully phase up and calibrate the array (for detection)
SWAC

\[ SWAC(\tau) = \sum_{n=1}^{M} \sum_{k=k_0+(n-1)\tau}^{k_0+n\tau} (y_k \cdot \bar{y}_{k+\tau}) \]

\[ D = \max_{\tau \in [\tau_1, \tau_2], k_0 \in [0, \tau]} SWAC(\tau) \]

\[ \hat{T}_S = \arg \max_{\tau \in [\tau_1, \tau_2], k_0 \in [0, \tau]} SWAC(\tau) \]
**SWAC**

**BENEFIT #1**
Deals with “random” modulation

**BENEFIT #2**
Can extend to cross-correlating multiple symbol pairs
→ sensitivity approaches matched filter

**BENEFIT #3**
Built-in null reference
SWAC Sensitivity

$M = 100,000$ symbols

**SWAC-1**

$S/N_{SWACSQR} = \frac{2M}{(WT_s)^2} \left( \frac{E_s}{N_0} \right)^4 + 2 \left( \frac{E_s}{N_0} \right)^3 + \left( \frac{E_s}{N_0} \right)^2$
SWAC With Beamforming/Tiling

beamformer 1 → SWAC 1
beamformer 2 → SWAC 2
beamformer 3 → SWAC 3
beamformer 4 → SWAC 4

beamformer N → SWAC N
Symbol-Wise Cross-Correlation (SWCC)

- Array telescopes provide multiple samplings of the same signal
  - independent receiver noise
  - lower SNR than tied-array output

- Correlate symbols from one antenna with symbols from all other antennas

- For $N$ antennas, there are $N(N+1)/2$ baseline pairs (including autos)
  - tied-array sensitivity scales with $N$
  - SWCC sensitivity scales with $\sqrt{\text{number of baselines}} \approx \frac{N}{\sqrt{2}}$
  - factoring in RFI, the advantage could swing to SWCC

Conclusion: should achieve similar sensitivity to SWAC-with-coherent-beamforming
    BUT over the same (much larger) FoV as incoherent beamforming
SWCC Cyclic Imaging – “CYCLONE”

SWCC – symbol-wise cross-correlation
Possible MWA Deployment

256 tiles
(each with 16 dipoles + analogue beamforming)

MRO

32 receivers
(each digitising + coarse channelising 8 tiles)

servers
(media conversion, packetisation)

UDP multicast

voltage capture

correlator/beamformer

imaging pipeline

Breakthrough
Listen servers

CYCLONE

Curtin/
Pawsey
Grant application currently in preparation
  - Australian Research Council, Discovery Project scheme
  - for funding commencing January 2020

Requesting ~US$300k over 4 years, including support for:
  - 1 x PhD student stipend
  - small cluster of GPU-accelerated compute servers

Principal investigators: Ian Morrison, Greg Hellbourg, David Davidson, Randall Wayth (all Curtin University)

External collaborators: University of New Mexico - LWA
Collaboration Opportunities

1. Provide design review input
2. Contribute to simulations and design
3. Contribute to implementation (GPU code)
4. Contribute GPU server hardware to enable a more powerful MWA prototype
5. Contribute GPU server hardware for a duplicate system on another telescope
6. Provide feedback as a beta user
7. Other?
Cyclic imaging could provide a useful capability at any current or future array telescope, supporting

- RFI mitigation
- space situational awareness
- wideband SETI

Will enable the first high sensitivity wide-field wideband SETI surveys

CYCLONE: a planned MWA prototype system aimed at demonstrating the value of cyclic imaging and exploring alternative implementation approaches

- bidding for an Australian government grant (PhD student and equipment)
- seeking collaborators to contribute expertise, coding effort or equipment
Questions?

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MWA Partner Institutions