CARMA Correlators

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CARMA Correlators Overview

- System Block Diagram
- Terminology and Technology
  - Spectra
  - Downconversion
  - Sideband separation
  - Delay tracking
  - Correlation
  - Continuum (Wideband) and Spectral modes
  - FPGAs
- Correlator Systems
  - 8-antenna wideband system
  - 15-antenna spectral line system
    - 15-antenna single+dual-polarization mode
    - 23-antenna single-polarization mode
- How it works
- Correlator Room Tour
Power-spectra (correlation)

Some magic occurs ...
CARMA Antenna Signal Path

- 15-antennas
- 8-bands
CARMA Antenna Signal Path

Antenna

\[ \tilde{\phi}_1 = \text{phase-switch and lobe-rotation correction} \]

\[ \sim 100\text{GHz or } \sim 270\text{GHz} \]

Sky spectrum

1GHz to 9GHz Receiver Output

Block Downconverter

1GHz to 5GHz Receiver Output

Enable

1GHz to 5GHz

5GHz to 9GHz Receiver Output

Downconverter

1GHz to 5GHz

Band selection

0.5GHz to 1GHz Downconverter Output

Digitizer

1GHz clock

8-bit ADC and 1:2 Demux

500MHz clock, 2 x 8-bits, real-valued

To digitizer board FPGAs
CARMA Antenna Signal Path

From digitizer

Digitizer interface FPGA

1:4 Demux

125MHz clock, 8 x 8-bits, real-valued

Whole nanosecond delay

Sub-nanosecond delay

Digitizer filter FPGA

$250\text{MHz} + \phi_2$

$\phi_2 = \text{secondary lobe-rotation correction}$

Digital filtering and decimation

Modulation to real-values $\frac{B}{2}$

$B = 500\text{MHz}, 250\text{MHz}, 125\text{MHz}, \ldots, 1.95\text{MHz}$

Requantization

180-degree phase-switch removal

Autocorrelation

Front-panel LVDS transmitters (to cross-correlator boards)
Antenna Signal Path Terminology

- Spectra

- Downconversion
  - Upper and Lower sidebands

- Sideband separation
  - (Walsh) Phase-switching

- Delay tracking
  - Phase-offset tracking (lobe rotation)
  - Phase-slope tracking
Spectra

- Provide information on signal power as a function of frequency

- Auto-spectra
  - Magnitude (power) only
  - Dominated by antenna noise component; used for diagnostics

- Cross-spectra
  - Magnitude (power) and phase (relative time or location)
  - Radio source information used for imaging

- Continuum (wideband) sources
  - Constant power over a wide range of frequencies

- Spectral-line sources
  - Power concentrated in a narrow range of frequencies
Downconversion

Most signal processing systems use an LO with both in-phase and quadrature components and two mixers.

- The CARMA telescopes use a single mixer and time-multiplex the LO between in-phase and quadrature:
  - 90-degree phase switching
**Downconversion and Lobe Rotation**

Relative arrival delay causes a phase-slope

Phase-offset added to first LO

Phase-offset Tracking = Lobe Rotation

$$\phi_{LR1} = -j2\pi f_{LO1}\tau$$
Sideband Separation

In-phase

\[ I(f) = \text{Sideband separation} = 90\text{-degree phase-switch demodulation} \]

Quadrature

\[ Q(f) \]

\[ jQ(f) \]

\[ U(f) = \frac{1}{2} \{ I(f) + jQ(f) \} \]

\[ L(f) = \frac{1}{2} \{ I(f) - jQ(f) \}^* \]
Power-spectra (correlation)

Imaging Plane

Different delays between each antenna

Vibration

Rotation

Some magic occurs ...
Cross-correlation (full-precision)

\[ \mathcal{N}(0, \rho) \times \mathcal{N}(0, 1-\rho) \]

\[ \mu_{\text{TOTAL}} = \rho \]
\[ \sigma^2_{\text{TOTAL}} = 1 + \rho^2 \]

\[ \mu = \rho \quad \sigma^2 = 2\rho^2 \]
\[ \mu = 0 \quad \sigma^2 = (1-\rho)^2 \]
\[ \mu = 0 \quad \sigma^2 = \rho(1-\rho) \]

K-sample average:

\[ \mathcal{N}\left(\rho, \frac{(1+\rho^2)}{K}\right) \]
Correlation

- **Lag (XF) correlator**
  - Measure the averaged product of pairs of antenna signals over a range of time delays
  - Fourier transform to get cross-power spectrum

- **FX correlator**
  - Fourier transform or digitally filter antenna-based signals into frequency-domain channels
  - Multiply and average in the frequency domain

- CARMA uses lag correlators
Lag Correlation

Cross-correlations are calculated for lags $-N/2$ to $N/2-1$

Auto-correlations are calculated for lags 0 to $N/2$
2-bit Sampling (Re-quantization)

- Thresholds:
  - The input amplitudes (values) at which output codes (quantization) decisions are made
  - Eg., whether an input value becomes 00b or 01b
  - The input amplitude is determined by the downconverters
  - Threshold optimization maximizes the correlator efficiency
2-bit Correlation

- 2-bit sampling (or filter output requantization)
- 2-bit by 2-bit multiplication
  - 4-input lookup table (LUT)
  - Nominal 4-bit multiplication result
  - Deleted inner product has 3-bit result (25% logic reduction for 1% loss in SNR)
  - Correlation estimate $N(\rho, 1.31/K)$
  - 87% efficiency relative to full-precision
Cross-correlation Spectra

Magnitude measures image pixel strength

Phase measures image pixel location (relative to pointing center)
Continuum vs Spectral-line Mode

500MHz continuum
(3C454)

500MHz line
(Upsilon Herculis
SiO maser)

62MHz line

Data taken: 11/24/2009
Optical and Radio Images

The Whirlpool Galaxy (M51)

(a) Hubble Space Telescope Image

(b) CARMA Radio Image
Solar Systems – Just like ours?
Planetary Formation

- Dust emission from a proto-planetary disk
- CARMA image (left) and Keck Infrared image (right)
- Is there a planet in the interior of the dust ring?
Radio Galaxy Morphology
Correlator Systems

- **Wideband (SZA)**
  - 8-antenna, 28-baselines, 8GHz bandwidth
  - 16 bands; fixed IF location
  - 500MHz bandwidth per band

- **Spectral-line (CARMA)**
  - 15-antenna, 105-baselines, 4GHz bandwidth
  - 8 bands; independently tuneable over the IF
  - 2MHz to 500MHz bandwidth per band
CARMA Correlator Systems

- Spectral Correlator:
  - 8 bands x 15-telescopes single-pol
  - 4 bands x 23-telescopes single-pol
  - 4 bands x 15-telescopes dual-pol

- Wideband Correlator:
  - 16 bands x 8-telescopes single-pol x fixed
  - 500MHz bandwidth
Replace/expand using a digital downconversion system
CARMA Digitizer/Correlator Board
CARMA Digitizer/Correlator Board

- 2-antennas input
- 500MHz bandwidth each input
- FIR filtering
- Digital Downconversion
- Digital Delay
- Auto/Cross Correlation

- DATA-FPGAs average correlation data
- SYS-FPGA coordinates real-time DMA of averaged data to PowerPC memory
- PowerPC runs Linux
- Processes the data in ‘sustained real-time’, i.e., it just has to keep up!

FPGA = Field Programmable Gate Array
COBRA Digitizer Board

- 2-antennas input
- 500MHz bandwidth each input
- FIR filtering (62MHz and lower)
- Digital Downconversion
- Digital Delay (whole-sample only)
- Auto/Cross Correlation

- DATA-FPGAs average correlation data
- SYS-FPGA coordinates real-time DMA of averaged data to DSP memory
- DSP runs uC/OS-II real-time OS
- DATA-FPGAs have 20K logic elements (versus 360K on CARMA digitizer)
COBRA Correlator Board

- Calculates 10 cross-correlations
- SYS-FPGA coordinates real-time DMA of averaged data to DSP memory
- DSP runs uC/OS-II real-time OS
- DATA-FPGAs have 50K logic elements (versus 520K on CARMA digitizer)
CARMA Dual-band Modes

- 4 bands
  - Independently tuneable over the IF
  - 2MHz to 500MHz bandwidth per band

- 15-antenna dual-polarization
  - 15-antenna, 105-baselines, 4-polarizations, 2GHz bandwidth

- 23-antenna single-polarization
  - 23-antenna, 253-baselines, 2GHz bandwidth

- There is 8GHz of bandwidth available
  - We need more correlator processing power!
Digitizer/Correlator Development

- 4-bits at 20Gbps ADC with 1:2 output demux
- Tested at a sampling frequency of 10240Mbps
- 8-bits at 5120Mbps transceiver lane rate into the FPGA
- FPGA receiver demux-by-32
- FPGA logic operating on 64 x 4-bit samples at 160MHz clock rate
That’s it for correlator ‘magic’

Time for a tour of the correlator room