PrepSKA WP 2.2.3.2 PAF Receiver Concepts for SKA Phase 1

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Summary
PrepSKA WP 2.2.3.2 PAF Receiver Concepts for SKA Phase 1

- Introduction
  - System Requirements
  - PAF system specifications
  - PAF receiver architectures

- PAF receiver assembly concepts
  - PAF receiver assembly (Concept 1):
    - Using RF-over-fibre signal transmission and direct sampling at RF but with switched narrowband anti-aliasing filters subassembly
  - PAF receiver assembly (Concept 2):
    - Using an integrated IQ mixer architecture subassembly
    - I/Q integrated receiver development
  - Analog-to-digital conversion subassembly
  - Receiver gain calibration subassembly
  - Digital Filterbank and data formatter subassembly
  - Digital transmission over optical fibre
  - Digital Beamformer subassembly

- Risks
The Dish Array Hierarchy

- Dish Array
  - PAF
    - PAF Feed Payload
      - PAF Array/Low-noise amplifiers
    - PAF Receiver
      - PAF Receiver Package
      - RF electronics
      - Digital electronics
  - Dish
  - Single Pixel Feeds

L5 Elements
L4 Sub systems
L3 Assemblies
L2 Sub assemblies
System Requirements

- The feed payload shall be designed to be compatible with the baseline SKA dish design.
- The feed payload shall be designed for rapid installation by two people using minimal equipment.
- The routine maintenance interval for a feed payload shall be a minimum of TBD years. 3 years
- The raw cross-polarization components in each output from the feed payload shall not exceed TBD relative to the co-polar output levels. -10 dB
- Polarization stability versus time TBD
- Polarization stability versus frequency. TBD
- The radio frequency gain in each polarization channel shall be a minimum of TBD across the band of operation. 30 dB
- The input -1 dB compression point of each polarization channel shall be TBD minimum. -20 dBm
- Feed payloads are required to cover the frequency range TBD. 600 MHz to 1.5 GHz.
- The feed payload shall provide a minimum aperture efficiency of TBD and a maximum system noise temperature of TBD across the full operating band when mounted on the baseline SKA dish. 60 % 35 Kelvins
- The feed payload shall meet all functional specifications over the full range of the system operational environmental specifications.
- The feed payload shall survive, without any damage to its functionality, any combination of environmental conditions specified in the system survival environmental specifications.
## PAF system specifications

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reflector diameter</td>
<td>15 m</td>
</tr>
<tr>
<td>Observing band</td>
<td>TBD</td>
</tr>
<tr>
<td>Instantaneous bandwidth</td>
<td>~ Observing bandwidth</td>
</tr>
<tr>
<td>System temperature</td>
<td>TBD</td>
</tr>
<tr>
<td>Antenna efficiency</td>
<td>TBD</td>
</tr>
<tr>
<td>Number of dishes</td>
<td>TBD</td>
</tr>
<tr>
<td>Survey speed</td>
<td>TBD</td>
</tr>
<tr>
<td>Field of view</td>
<td>TBD</td>
</tr>
<tr>
<td>Number of beams</td>
<td>TBD</td>
</tr>
<tr>
<td>Number of elements</td>
<td>TBD</td>
</tr>
</tbody>
</table>
Receiver architecture considerations

- Receiver architecture depends critically on:
  - RF (observing) band
  - IF (sampled) band
  - Sampled bandwidth is dependent upon digital processing capacity

- RF bandwidth
  - Up to 2.5:1 for Chequer-board array or Vivaldi array

Possible RF bands (2.5:1) are:

<table>
<thead>
<tr>
<th>Hi Redshift (z)</th>
<th>RF Band (MHz)</th>
<th>RF Bandwidth (MHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3 – 2.2</td>
<td>440 – 1100</td>
<td>660</td>
</tr>
<tr>
<td>0.1 – 1.8</td>
<td>500 – 1250</td>
<td>750</td>
</tr>
<tr>
<td>-0.1 – 1.4</td>
<td>600 – 1500</td>
<td>900</td>
</tr>
<tr>
<td>-0.2 – 1.0</td>
<td>700 – 1750</td>
<td>1050</td>
</tr>
</tbody>
</table>
Possible Receiver Architectures

• Double heterodyne

**ASKAP:** RF band 700 – 1800 MHz
IF 300 MHz bandwidth

**APERTIF:** RF band 1000 – 1750 MHz
IF 300 MHz bandwidth

• Direct RF sampling

**Receiver concept:**
*Direct optical high BW* (DRAO)
Possible Receiver Architectures

- **Direct RF sampling**
  - with switched anti-aliasing filters

  *PAF Receiver assembly concept utilising RF-over-fibre signal transmission (CSIRO)*

- **I/Q conversion**

  *PAF Receiver assembly concept utilising an integrated IQ mixer architecture (CSIRO)*
PAF Receiver assembly concept utilising RF-over-fibre signal transmission

- Allows digitisation to occur up to 10 km from the antenna.
  - Digitisation and digital processing of the signals from the antennas in the “core” and “inner” regions (for SKA Phase 1) could be at the central site;
  - for antennas in the “Mid” region, the digitisation and digital processing of signals from one or more “clusters” of antennas could be centralised in RFI shielded “bunkers” and the resulting data trunked to the central site.
SKA Phase 1 Array Distribution (Memo 130)

- 250 dishes total;
  - 175 in the core and inner regions,
  - 75 in the mid region.

- In the core and inner regions
  - Dishes are <2.5 km from centre

- In the mid region
  - (~200 km dia.)
  - there are 5 dishes per cluster
  - there are 25 clusters.
PAF Receiver assembly concept utilising RF-over-fibre signal transmission

PAF receiver assembly concept includes the following components:

- A set of two switched anti-aliasing filters to cover the whole 600 – 1500 MHz RF band,
- Transmission of the RF over fibre to the Analog-to-digital conversion block,
- Gain calibration to correct for minor variations in gain and phase of the RF channels,
- Analog-to-digital conversion using the EV8AQ160 or similar,
- Digital processing in the Filterbank/Beamformer, and
- Digital transmission within the Filterbank/Beamformer using optical fibre.
PAF Receiver assembly concept utilising RF-over-fibre signal transmission

- Cost competitive RF over Fibre systems are currently limited to at most octave bands due to second order intermodulation.
- The PAF covers more than an octave so this requires sub-octave band filters after LNA and RF amplification in the PAF

<table>
<thead>
<tr>
<th>RF Band</th>
<th>RF Band (MHz)</th>
<th>RF Bandwidth (MHz)</th>
<th>Sample rate (MS/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Band 1</td>
<td>600 – 1000</td>
<td>400</td>
<td>1100</td>
</tr>
<tr>
<td>Band 2</td>
<td>900 – 1500</td>
<td>600</td>
<td>1650</td>
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PAF Receiver assembly concept utilising RF-over-fibre signal transmission

- Single mode transmission of RF requires
  - good Optical Return Loss (ORL),
  - low back reflection connectors.
- Mass termination Multiple Parallel Optical (MPO) connectors are preferable.
  - Can be used in 12 wide MPO configurations with Angled Physical Contact (APC) high ORL ~ 60 dB (designed for single-mode ribbon fibre).
  - Multiple MPO connectors can be mounted in the same connector shell making for rapid field replacement of the PAF.
- Single mode fibre loose tube could also be used (rather than newer ribbon fibre based distribution)

600-1500MHz Duoband
Z = 50W

Link NF < 20 dB
SFDR > 110 dB.Hz $^{2/3}$
Link G > 0dB 18 dB
Flatness +/- 1 dB
PAF Receiver assembly concept utilising an integrated IQ mixer architecture

- Allows digitisation of the received signals at the antenna and the beamformer digital processing to occur up to 10 Km from the antenna
  - Beamforming of the signals from the antennas in the “core” and “inner” regions (for SKA Phase 1) could be at the central site;
  - for antennas in the “Mid” region, the processing of signals from one or more “clusters” of antennas could be centralised in RFI shielded “bunkers” and the beamformed outputs trunked to the central site.
• 250 dishes total;
  • 175 in the core and inner regions,
  • 75 in the mid region.

• In the core and inner regions
  • Dishes are <2.5 km from centre

• In the mid region
  • (~200 km dia.)
  • there are 5 dishes per cluster
  • there are 25 clusters.
PAF Receiver assembly concept utilising an integrated IQ mixer architecture

- PAF receiver assembly concept includes the following components:
  - An integrated “Receiver System-on-a-Chip” that includes RF gain, RF filters, I/Q direct quadrature down conversion, IF gain and anti-aliasing filters.
  - Analog-to-digital conversion using the EV8AQ160 or similar,
  - Gain calibration to correct for minor variations in gain and phase of the RF channels,
  - Digital Filterbank signal processing and data formatting for transmission to the Beamformer.
  - Transmission of the Filterbank digital output to the Beamformer over optical fibre,
  - Digital processing in the Beamformer, and
  - Digital transmission within the Beamformer using optical fibre.
PAF Receiver assembly concept utilising an integrated IQ mixer architecture

The critical CSIRO/Salinna Silicon-on-Sapphire chip specifications are:

- 250 MHz to 2500 MHz RF range.
- Onboard by-passable RF filters – 700 MHz HP and 1200/1800 MHz LP.
- 2 dB input noise figure.
- I/Q direct quadrature down conversion - selectable instantaneous bandwidth up to 600 MHz.
- 40 dB dynamic range due to tight I/Q amplitude and phase matching
- Onboard LO synthesiser and ADC driver.
- Plenty of RF and broadband gain adjustment:
  - 14 – 39 dB RF gain range, 5 dB steps.
  - 8 – 20 dB BB gain range, 2 dB steps.
- Compact, 6 mm square, QFN package.
I/Q integrated receiver development

- 0.25um Silicon on Sapphire process

- Direct-downconversion I/Q architecture with divide-by-2 LO
  - Single out of band LO required
  - I/Q amplitude and phase match expected to be adequate to ensure 40 dB image suppression

- Implementation of whole receiver - from LNA output to ADC input
  - Including LO synthesiser and all filters
  - Minimal external components and cost
  - LNA off-chip for minimum $T_n$ and maximum flexibility
  - Off-chip ADC to reduce development cost
  - Includes high power ADC drivers

- Maximum flexibility
  - RF and baseband gain adjustable
  - RF filter selection switches (including bypass)
  - Baseband filter selection
  - Power level monitoring in RF and baseband
This is only one of several chips

• We have test chips for:
  • Downconverter – filters – baseband attenuator – ADC drivers
  • Downconverter only
  • LO chain only
  • Filter – baseband attenuator – ADC driver  
    *(this is the one that has been tested thus far)*
  • ADC driver only
  • LO filter only.
I/Q integrated receiver development
I/Q integrated receiver development
• EV8AQ160 and EV10AQ190 (manufactured by E2V) meet the specification for a PAF

  • For the example the critical specifications of the EV8AQ160 Analog-to-digital converter are:
    • 8-bit;
    • 7.2 ENOB;
    • 4 samplers interleaved in one chip;
    • Max. Sample rate in dual channel mode: 2.5 GS/s;
    • Max. input Freq 2GHz (typ.), 1.5 GHz (min.)

<table>
<thead>
<tr>
<th>Max. Sample rate</th>
<th>Input bandwidth (MHz)</th>
<th>interleaved</th>
</tr>
</thead>
<tbody>
<tr>
<td>1250</td>
<td>600</td>
<td>1</td>
</tr>
<tr>
<td>2500</td>
<td>1200</td>
<td>2</td>
</tr>
<tr>
<td>5000</td>
<td>2000</td>
<td>4</td>
</tr>
</tbody>
</table>
Receiver gain calibration subassembly

• Uses noise radiated from the dish surface or rim
  • to measure and track the relative complex gains of the individual receiver channels from the low-noise amplifier through to the digitiser.
  • A sample of the radiated noise is also digitised using a spare channel of the receiver.
  • The sample of the radiated noise is correlated with the output of each of the RF channels to measure and track the relative complex gains of the individual receiver channels.
  • The relative complex gains of the individual receiver channels are used to adjust the weights fed to the beamformer and thus compensate for channel gain and phase variations.
Other Sub-Assemblies

• Digital Filterbank and data formatter subassembly
  • After the analogue data is digitised it is processed by Digital Filterbank and data formatter subassembly. The Digital Filterbank and Data formatter for the output optical signal will be in the same FPGA. Each Digital Filterbank is ultimately connected to each of the beamformer boards and for N beamformer boards the data on each connection carries data for 1/N of the frequency channels being processed

• Digital transmission over optical fibre
  • For distances up to 10 km – to the central site for antennas in the “core” and “inner” regions (for SKA Phase 1) and signals from antennas in one or more “clusters”
  • SFP+ transceiver modules are available at 10 Gbps.
  • MSA SFP+ modules 1310nm 10GBASE-LR are currently ~AUD 200 each in volume.
Other Sub-Assemblies

• Digital Beamformer subassembly
  • For the Phase 1 SKA beamformer, multiple processing boards are needed for the beamformer and a cross connected beamformer is used.

• Digital transmission within the Beamformer
  • Digital data would be transported within the Filterbank/Beamformer shielded enclosure on optical fibre.
  • Currently the cheapest method of transporting digital data over short spans, ie very short reach (VSR) on fibres is with the use of 12 fibre optical cables illuminated by 12 element optical transmitters such as the industry standard SNAP12 modules.
Risks

• See Neil Roddis’ draft
Thank you