Technology Drivers, SKA Pathfinders
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Outline

1. What is a Pathfinder?
2. “Solutions” for the mid-freq. SKA.
   • Dishes with “single-pixel feeds”.
   • Dishes with Phased Array Feeds (PAF’s).
   • Aperture Arrays.
3. Critical Technologies and cost drivers.
   • Antennas/Feeds/Receivers, Digital Systems, Computing.
4. Priorities
SKA Technology – Eyes on the Ball

• SKA success
  – Dominated by technology development.
  – Moderated by cost.
  – Dependent on science outcomes.

• $A_{\text{eff}}$ – effective collecting area => antenna innovation.
• FoV – Field-of-View => to be optimized or maximized.
• $T_{\text{sys}}$ – System Noise Temp. => develop better LNA’s (esp. uncooled).
• $f_{\text{max}}$ – maximum frequency => antennas & receivers.
• $f_{\text{min}}$ – minimum frequency => depends on reflector, feed sizes.
• Digital signal processing.
  – PAF beam-formers, correlators.
• Calibration & Imaging forming (algorithms, computing).
What is an SKA Pathfinder?

- **Technology**: Contains new technical elements that have not been tried on the scale of a large telescope.
  - New technical elements must bring new science capabilities to the SKA or reduce cost of a required capability (e.g. FoV expansion technology, extremely deep imaging, new antenna technology, ultra wide-band feeds).

- **Science**: Contains observational tests that challenge new capabilities at the flux and dynamic range levels similar to (or scaled from) the entire SKA.

- **Operations**: science operations that test the methods for scheduling and allocating time similar to what will be needed for the SKA.
  - This may be very different from current practice, esp. campaigns, surveys.
  - e.g. Telescope outfitting might be optimized for a specific large project, such as two separate observing campaigns at different redshift ranges.
  - Simultaneous multi-science surveys (e.g. pulsar + HI survey).
Pathfinders

• Technology + Science Ops
  – Australia SKA Pathfinder (ASKAP)
  – Allan Telescope Array (ATA)
  – Karoo Array Telescope (KAT)
  – [LOFAR, MWA, LWA (low band)]

• Science Ops
  – EVLA (mid, high band)?
  – ALFA – multi-science surveys?

• High Sensitivity Science
  – EVLA
What (ideally) Precedes Construction of SKA Pathfinders?

• Research on specific technologies to improve performance or cost (e.g. antennas, FoV expansion, computing, algorithms).

• Testing at “appropriate scales”
  – Small scale: Can be done without a powerful telescope
    • Lab, “unit”, test-interferometer, etc.
  – Large scale: Tests on existing telescopes (VLA, AT, WSRT)
    • Time-variable, low-level scattering over wide angles (e.g. rotating feed-legs).
    • Incorporation of new equipment into existing telescopes
      – PAF’s, antennas, and other equipment, where the full power of an operational system is required (e.g. efficiency measurements).

• Science operations on existing telescopes that tests potential SKA scenarios.
  – For example, EVLA could do this, but maybe more planning is needed.
  – e.g. How to deal with different detection thresholds for multi-science surveys?
Wide-band Single-Pixel Feed + Dish “Solutions”

- Lowest risk technology of the three technologies (WBSPF, PAF, AA).
- Antenna size – 12-15 m?
  - large enough to cover meter wavelengths (>300 MHz) efficiently.
  - Not too large so as to narrow FoV.
    • Note the FoV \( \propto \lambda^2 \).
- Requires many antennas
  - to attain survey speed while still covering lower frequencies.
  - could be high cost, leading to compromises, such as “stations”.
  - Emphasis should be on antenna technology development.
    • Could result in much higher frequency coverage than 3 GHz.
- Wide-band feeds are key technology – several candidates to choose from.
  - May need two frequency ranges.
  - Probably require cryo-cooling
    • Low frequency versions will be fairly large for cooling.
    • Higher operational cost
Wide-Band Feeds

- Chalmers Kildal Feed
- Quadridge Feed
- Quasi Self-Complementary Feed
- ATA Log Periodic
Areas of R&D for WB Feed + Dish

- **Antenna Cost Reduction**
  - reflector manufacture, feed legs, drive systems, and optics.

- **Wideband Feed Design**
  - Assess the ATA feed to see if further refinements could reduce cost and solve the frequency-dependent phase-center issue.
  - Make & test low-freq. versions of Kildal, QSC, etc. with integrated LNA (uncooled).
  - Study optimum subreflector optics for wideband feeds.
  - Assess best frequency split for feeds.

- **Wideband Receivers**
  - Integrate with feeds as much as possible.
  - Work on wide-band noise matching.

- **Cryogenic Receiver Cooling**
  - Cost of cooling entire feed – innovations possible?
Phased Array Feed + Dish Solutions

- Provides mechanism for science-based optimization of $A_e/T_{sys}$ & SS independently.
- A risk mitigator for expensive antennas?
  - Substitutes FoV for $A_e/T_{sys}$ in survey speed equation $(A_e/T_{sys})^2 \Omega_{FOV}$.
  - Success depends on cost of PAF’s versus antenna cost.
  - Moore’s Law cost component to beamformer $\Rightarrow$ reduces over time.
- In the long run may be the only way to get high survey speed.
  - Development time could be an issue.
  - Possibly need to “future-proof” antennas and other things to permit substitution, especially if Pathfinders develop directly into SKA.
- More control over feed pattern
  - potentially be able to reduce polarization systematics and increase efficiency $\Rightarrow$ lower system costs.
- $T_{sys}$ potentially dominant technical problem.
  - Cyro-cooling expensive (capital & operating).
  - At $<1.4$ GHz promising uncooled solutions are being developed.
## Challenges for PAF’s

<table>
<thead>
<tr>
<th>Challenge</th>
<th>Consequences</th>
<th>Mitigation</th>
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<tr>
<td>Efficiency.</td>
<td>+ better dish illumination.</td>
<td>Low-loss element design.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cooling?</td>
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<td>Frequency Coverage.</td>
<td>Reduced z coverage.</td>
<td>Improved elements.</td>
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<tr>
<td></td>
<td>Reduced cont. sensitivity.</td>
<td>Trade against A&lt;sub&gt;e&lt;/sub&gt;/T&lt;sub&gt;sys&lt;/sub&gt;.</td>
</tr>
<tr>
<td>Polarization Purity.</td>
<td>+ beam-former correction.</td>
<td>Dual pol’n input beam former.</td>
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<tr>
<td></td>
<td>- starts with poor quality.</td>
<td></td>
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<tr>
<td>Calibration/stability.</td>
<td>Reduced image quality.</td>
<td>Many solutions possible.</td>
</tr>
<tr>
<td>Power, weight, RFI.</td>
<td>High capital, operating cost, feasibility.</td>
<td>Minimize electronics at focus. Use secondary focus.</td>
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<td>Use ASIC’s.</td>
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Wideband Room-temperature CMOS LNA

14 K Noise Temperature

- LNA designed in 90 nm CMOS.
- Frequency: 800MHz-1400MHz
- DC Power: 43mW
- Noise Figure: 0.2dB (14 K) at 85 Ω source impedance.
- Gain (S21): 17dB
- Return Loss: > 11dB

Next Steps:
- Verify on an antenna system.
- Integrate with PAF elements.

Fig. 11. Measured $F_{\text{min,LNA}}$ noise figure with $R_s = 85 \Omega$ for two different LNAs. $F_{\text{min,LNA}}$ represents the minimum noise figure the LNA can achieve.
Cables from receivers

RF section

- 192 receivers
- Four banks of 12 modules
- 4 (COTS) Receivers per module
- Outputs: RJ-45 and Cat-7 Cable

Antennas

- 192 Vivaldi’s
- 2 polarizations

COTS Digital Back End

- 192 Channels, 16 boards
- 100 MS/s ADCs (14-bit)
- Xilinx FPGA, 128 MB RAM per board
- Programmed using Simulink-System Generator

DRAO PAF Prototype
MeqTree Simulations: PAF beams
(Veidt & Willis)

- Assume or measure element patterns,
  - including leakage terms, pol’n response, etc.
- Use reflector code (GRASP) to transform to “sky patterns”.
- Calculate weights using “algorithm under test”.
  - Linear combination of element beams on sky.
- Form beams from weighted sums.
Off-axis Simulated Synthesized Beam

Conjugate Weighting

Iterative weight generation

I-map

Q-map
Aperture Array (AA) Solutions (0.3 – 1 GHz)

• Extremely high degree of flexibility in principle; greatest risk in mid-band.
• Large FoV’s possible.
• Mixed Close-Packed & Sparse arrays proposed.
  – Breakpoints at 300 & 700 MHz.
• Sparse arrays (naked telescope approach)
  – No “anti-aliasing filters”
    • Individual elements see the whole sky and some ground.
  – Heavy reliance on signal processing.
  – Beam patterns strong function of frequency.
    • Require careful modelling & calibration over frequency.
• Element patterns change in transition from close-packed to sparse.
• This solution may be very reliant on pre-observed sky models (database).
• Computing costs need quantification.
Antenna R&D and Prototyping

• Antennas were initially considered an area where little substantial progress on cost/performance could be made, especially in comparison with “silicon”, software, etc.
  – Correcting antenna inadequacies with “silicon” not as cheap and easy as it sounds.
  – But regardless of progress in other areas, antennas will attract much of the SKA budget: thus R&D is warranted.

• R&D areas:
  – Materials: composites.
  – Production techniques: mold-based forming, production planning.
  – “Sky-mount” antenna designs: Mitigate SKA high dynamic range imaging issues.
Mold-Based Fabrication (metal & composite):

- Now being used in four different antenna designs:
  - ATA, DRAO, KAT (entire surface), Patriot (panels and some sheet-metal parts).
- Repeatable process.
- Cost-Frequency curve flatter
  - up to mold surface-accuracy limit, ~30 GHz.
  - Additional structural/mount cost to actually increase freq. performance.
- Mold cost (NRE) can be amortized over large numbers.
- Other antenna components may also be molded in production:
  - Feed legs, structures.
Reflector Mold

- Delivered in Three Sections
- Joined and aligned in place.

Internal Construction

Surface Measurement

Final Mold Alignment
Critical Antenna Issues

• **Production engineering: cost ($/m^2)**
  – No current mass market for large antennas
    • Even the SKA numbers do not qualify for “mass” production.
    – Production techniques need to be imported into the world of large antenna design.
    – Patriot antennas may be close to this capability for current 12-m model.

• **Deciding on antenna optics.**
  – folded vs prime focus, f/D, off-set designs.

• **Deciding on antenna diameter.**

• **Composite antennas require further development:**
  – Must apply the “1, 10, 100” concept.
  – Requires Pathfinder effort to justify.


Critical Antenna Issues (cont’d)

- **Mount designs must be refined:**
  - Need optimized, parameterized Alt-Az designs to act as a cost baseline:
    - Is the 1:3 mount/reflectors cost ratio correct (rule of thumb)?
    - A series of designs for available reflector weights, diameters.
    - Important to get a realizable design using commercially available components.
    - May need to incur NRE for castings, etc.
  - What is the cost premium for “sky mount” (most likely equatorial)?
    - Balance against computing costs.
  - Off-set designs pay a premium in mount design. Can this be remedied?

- **Importance of “future-proofing” the antenna design??**
  - Especially high frequency capability.
  - May be more important for Pathfinders, where experimentation is required.
  - Pathfinders may provide high-freq. capability in Southern Hemisphere.
Digital Data

• For all digital systems
  – Must optimize technology at a strategically important time.
  – ASIC’s will play a key role – possibly astronomy-specific “FPGA’s”.
  – Moore’s Law is not the whole story.

• Correlators
  – Historically a small part of total system cost.
  – But the SKA digital systems could be huge
    • PAF beamformers/digital filters (cost \(\propto N_{\text{ant}}, N_{\text{beam}}\)).
    • Wide-band Single-pixel systems may require very large numbers of antennas.
      – Hence digital system cost will be high (cost \(\propto N_{\text{ant}}^2\)).
      – Probably will limit antenna diameter for this design.
  – Expandable architectures rarely have worked in the past.

• Data Transport
  – More data to transport from PAF-equipped antennas.
  – Large FoV not needed on long baselines.
Imaging & Data Reduction Software

• Cannot afford to view software as a big “job jar” that gets stuffed with upstream performance issues to be fixed in the software.
  – e.g. Far-out, rotating antenna scattering patterns can be fixed in S/W in principle, but at what cost?
  – Software is just as expensive as hardware (maybe more so).
    • Radio astronomy has a mixed record in delivering usable software.
  – For very large systems, the actual computing hardware and power consumption become real cost factors (especially if $N_{\text{ant}}$ is large).
  – Scale of the SKA changes everything – cannot rely on software as much as for smaller telescopes.

• On the other hand
  – Software is flexible, if specialized systems are not required to run it.
  – Algorithm development has historically been a powerful factor in the success of radio telescopes.
  – Moore’s Law over time enables more complex algorithms to be deployed.

• Strong arguments for specialized hardware assist (NRAO working on this?).
Key Priorities

- **Overall Coordination**
  - Checking for “holes” in development programs.
  - Efficient use of regional R&D efforts.

- **Cost model**
  - Realism, accuracy, completeness.
  - Folding information from Pathfinders, industry (where possible).

- **Production scenarios**
  - Cost savings

- **Development of key technologies**
  - PAF’s, Wide-band feeds.

- **Operations Planning**
  - Capital/operating cost tradeoffs.
  - Strawman observing scenarios.
  - Ensure current technical thinking is in synch with science.
Summary

- The SKA is feasible in the mid-band.
- Range of technical solutions available will depend on construction timing.
  - Lowest risk solution will still be a major advance.
- Pathfinders, utilized in the right way, will greatly enhance science potential of SKA.
- Challenges can be met if agency support is sufficient and work is well coordinated.