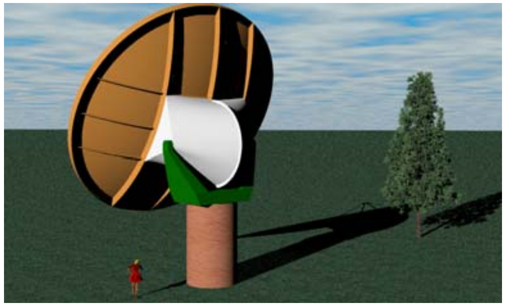

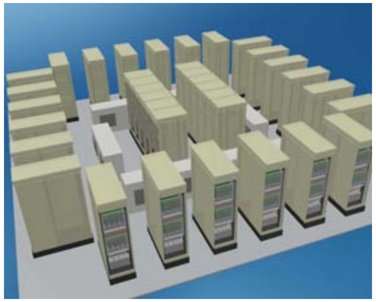

Technology Drivers, SKA Pathfinders

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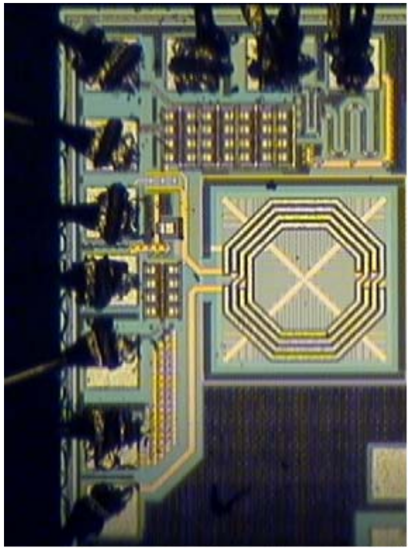

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Outline

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_{eff} – effective collecting area => antenna innovation.
- FoV – Field-of-View => to be optimized or maximized.
- T_{sys} – System Noise Temp. => develop better LNA's (esp. uncooled).
- f_{max} – maximum frequency => antennas & receivers.
- f_{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

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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?

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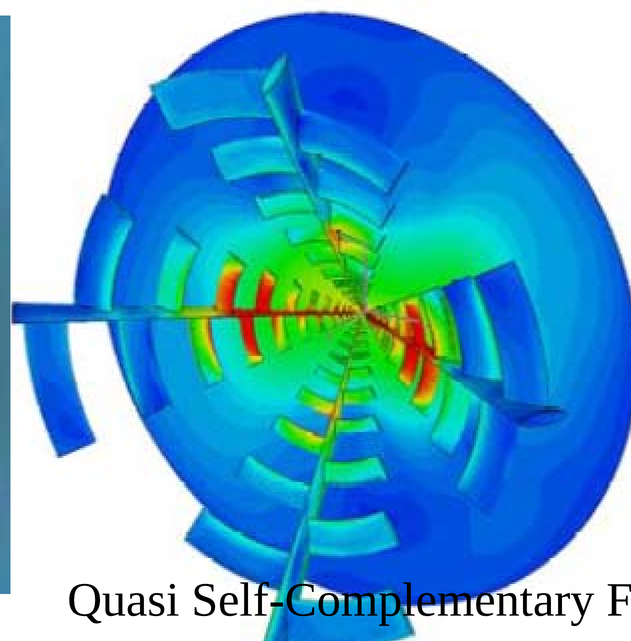
Wide-band Single-Pixel Feed + Dish "Solutions"

- 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

Quad-ridge 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?

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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 => 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 => 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

Challenge	Consequences	Mitigation
Long R&D Lead Time.	May not be adopted.	Coordinated R&D Effort.
Efficiency.	+ better dish illumination. - element loss.	Low-loss element design. More elements.
High T_{sys}.	Telescope Sensitivity Loss.	Element LNA integration. Cooling?
Frequency Coverage.	Reduced z coverage. Reduced cont. sensitivity.	Improved elements. Trade against A_e/T_{sys}.
Polarization Purity.	+ beam-former correction. - starts with poor quality.	Dual pol'n input beam former.
Calibration/stability.	Reduced image quality.	Many solutions possible.
Power, weight, RFI.	High capital, operating cost, feasibility.	Minimize electronics at focus. Use secondary focus.
Cost.	Impacts overall design.	Adopt DFM techniques. Use ASIC's.

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.

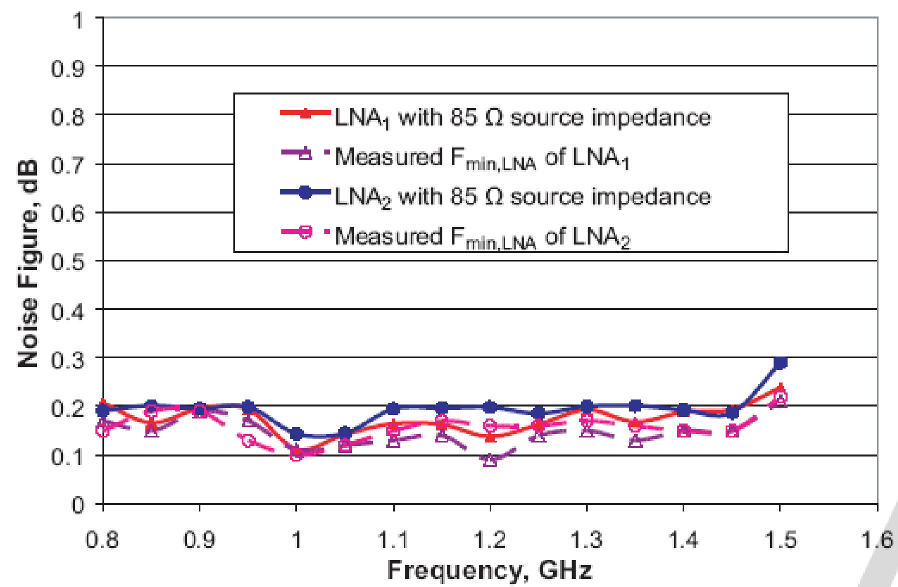
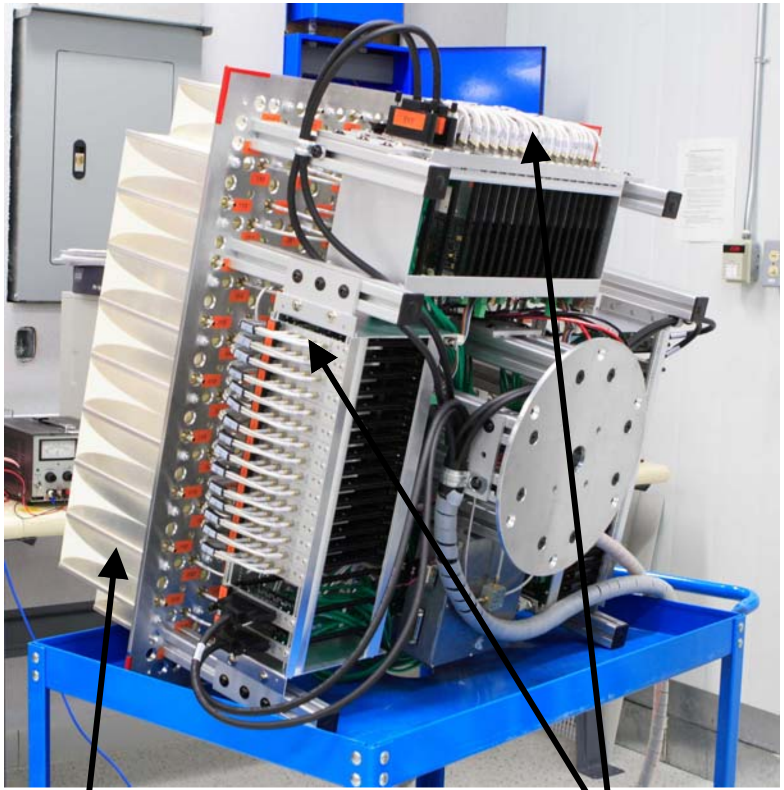


Fig. 11. Measured $F_{min,LNA}$, noise figure with $R_s = 85\,\Omega$ for two different LNAs. $F_{min,LNA}$ represents the minimum noise figure the LNA can achieve.

DRAO PAF Prototype



Cables from receivers

Antennas

- 192 Vivaldi's
- 2 polarizations

RF section

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

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

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.

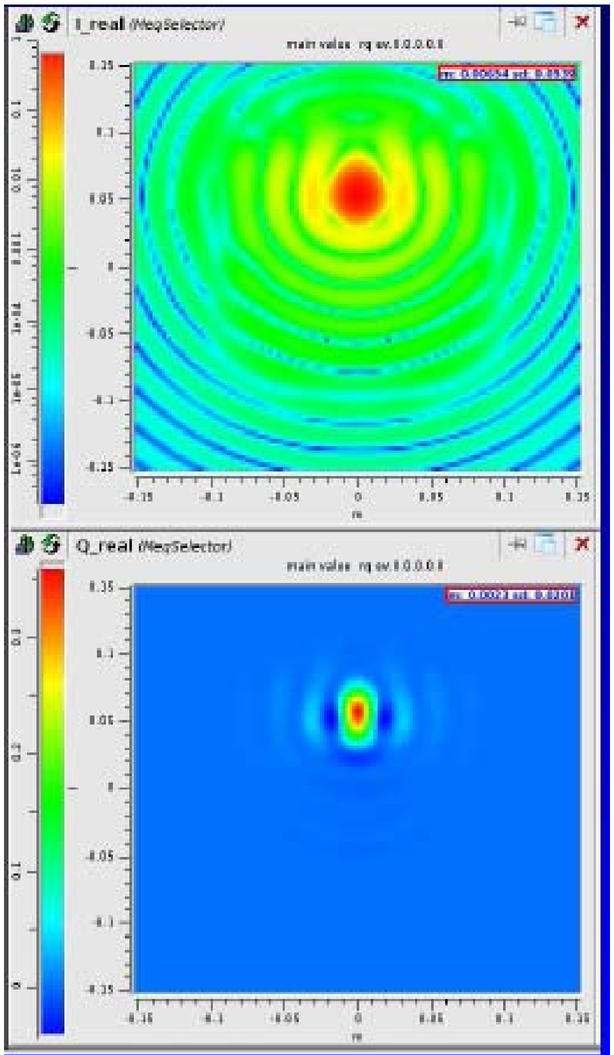
Off-axis Simulated Synthesized Beam

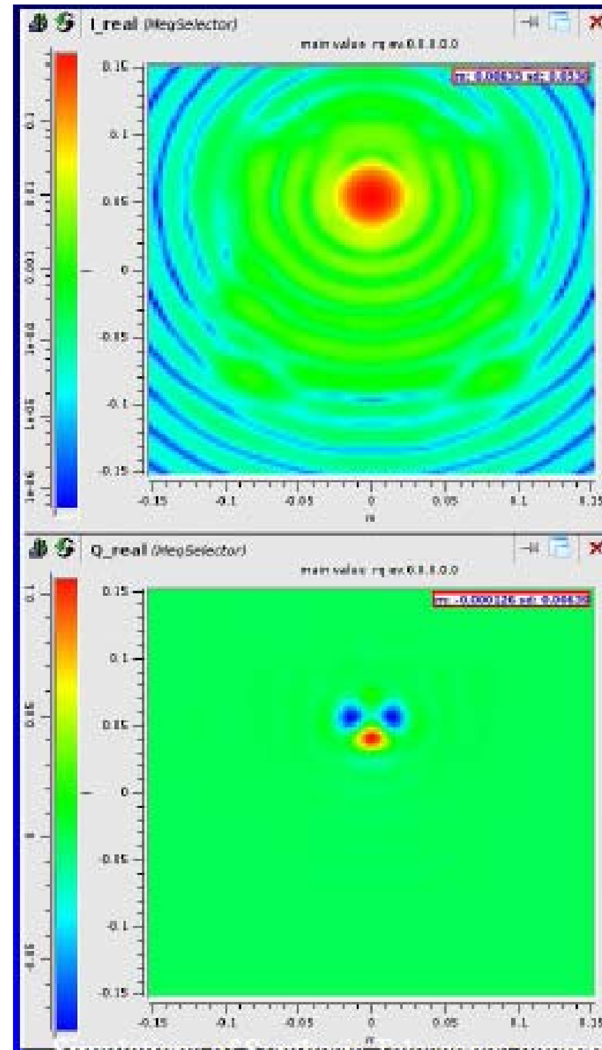
Conjugate Weighting

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.

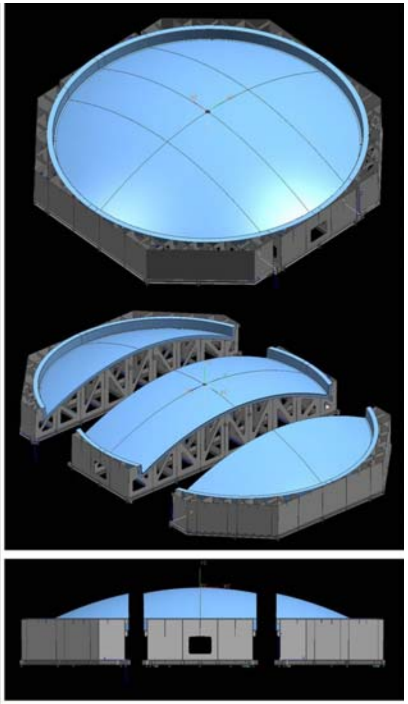
Antenna R&D and Prototyping

- 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

ATA Antenna (6 m)

KAT Antenna (15 m)

Patriot Antenna (12 m)

DRAO Antenna (10 m)

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/reflector 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 $\propto N_{ant}, N_{beam}$).
    - Wide-band Single-pixel systems may require very large numbers of antennas.
      - Hence digital system cost will be high (cost $\propto Nant^2$).
      - 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_{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.