Overview of the SKA

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Outline*

SPDO

1. SKA Science Drivers.
2. The SKA System.
3. SKA technologies.
4. Trade-off space.
5. Scaling.
6. Data Rates & Data Processing
7. Dynamic range & Calibration.
8. Computing and Software Development.

* See also "The Square Kilometre Array", Proceedings IEEE, Vol 97, No 8, Aug 2009.

What is the SKA?

- A large radio telescope with 5 key science drivers & a very wide range of science impact.
- It comprises
  - a number of sensor types spread over 1000s of km,
  - connected to a signal processor and HPC system via optical fibre network
    - *SKA-low : 70-300 MHz*
    - *SKA-mid: 300 MHz-10 GHz*
    - *SKA-high: 10-25+ GHz*

SKA-low and SKA-mid: Being planned for completion 2022.

SKA-mid and SKA-high: Planned for completion later.

- It is a global program involving more than 50 institutes in 19 countries.

SKA Key Science Drivers

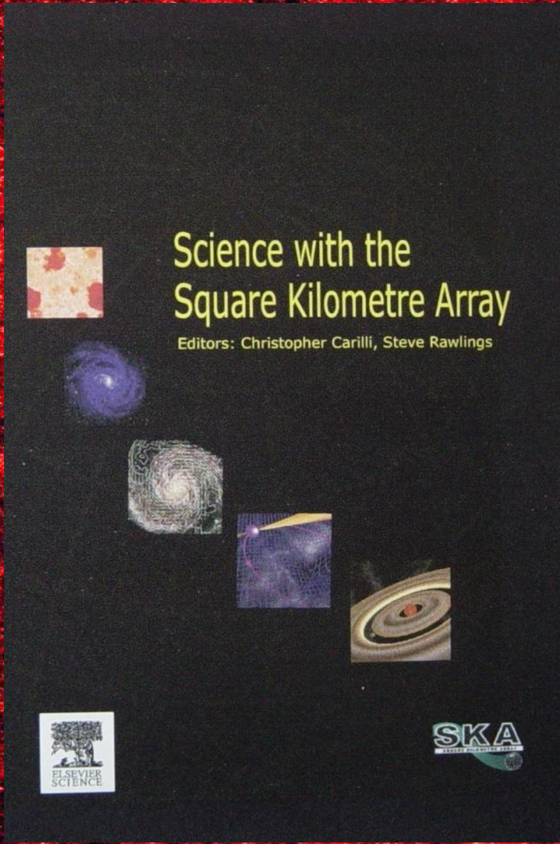
ORIGINS

- Probing the Dark Ages
  - When & how were the first stars formed?
- Cosmology and Galaxy Evolution
  - Galaxies, Dark Energy and Dark Matter
- Astrobiology
  - What are the conditions for life and where can it be
  - found?

FUNDAMENTAL FORCES

- Strong-field tests of General Relativity
  - Was Einstein correct?
- Origin & Evolution of Cosmic Magnetism
  - Where does magnetism come from?

plus The Exploration of the Unknown

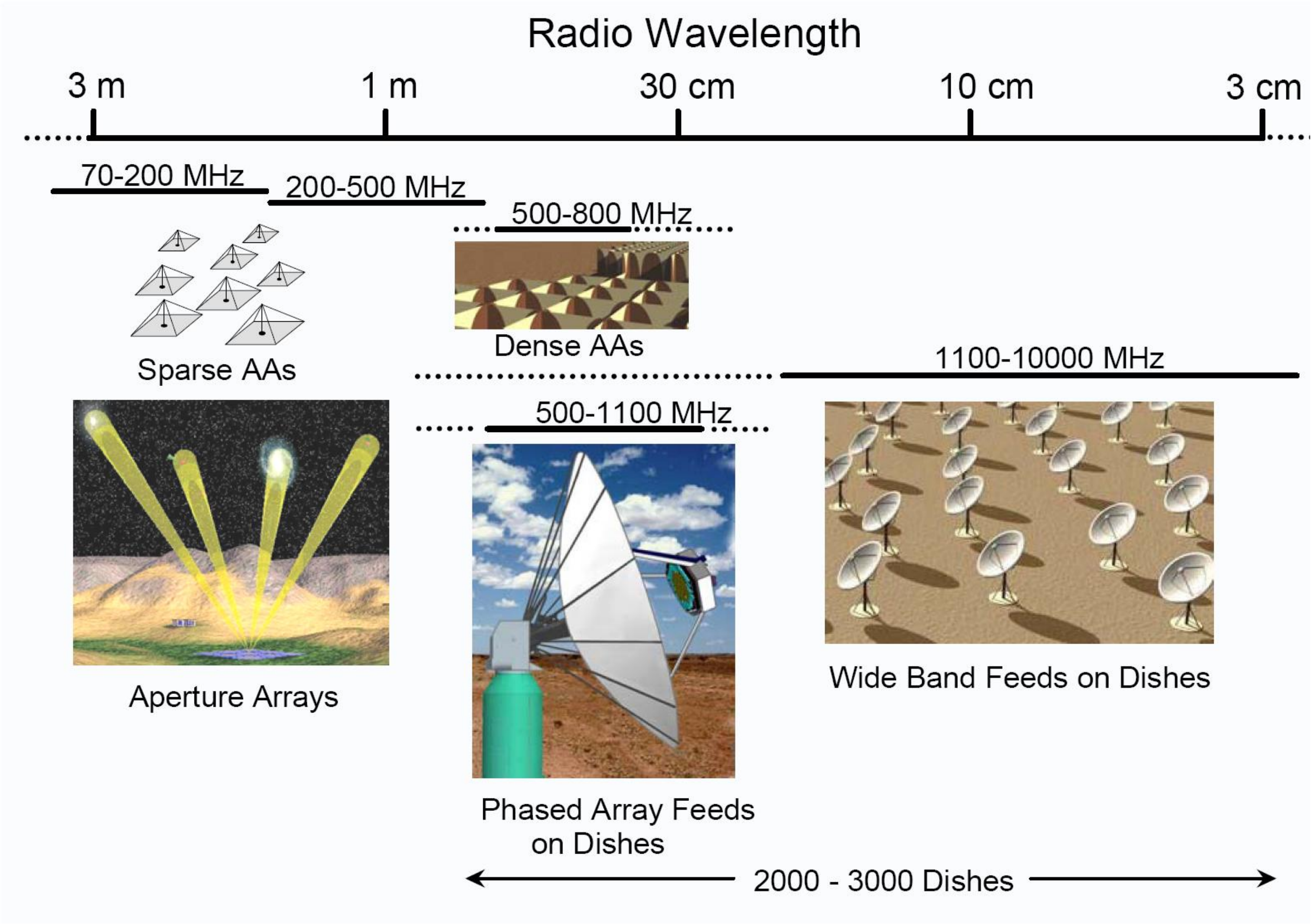


Science with the Square Kilometre Array

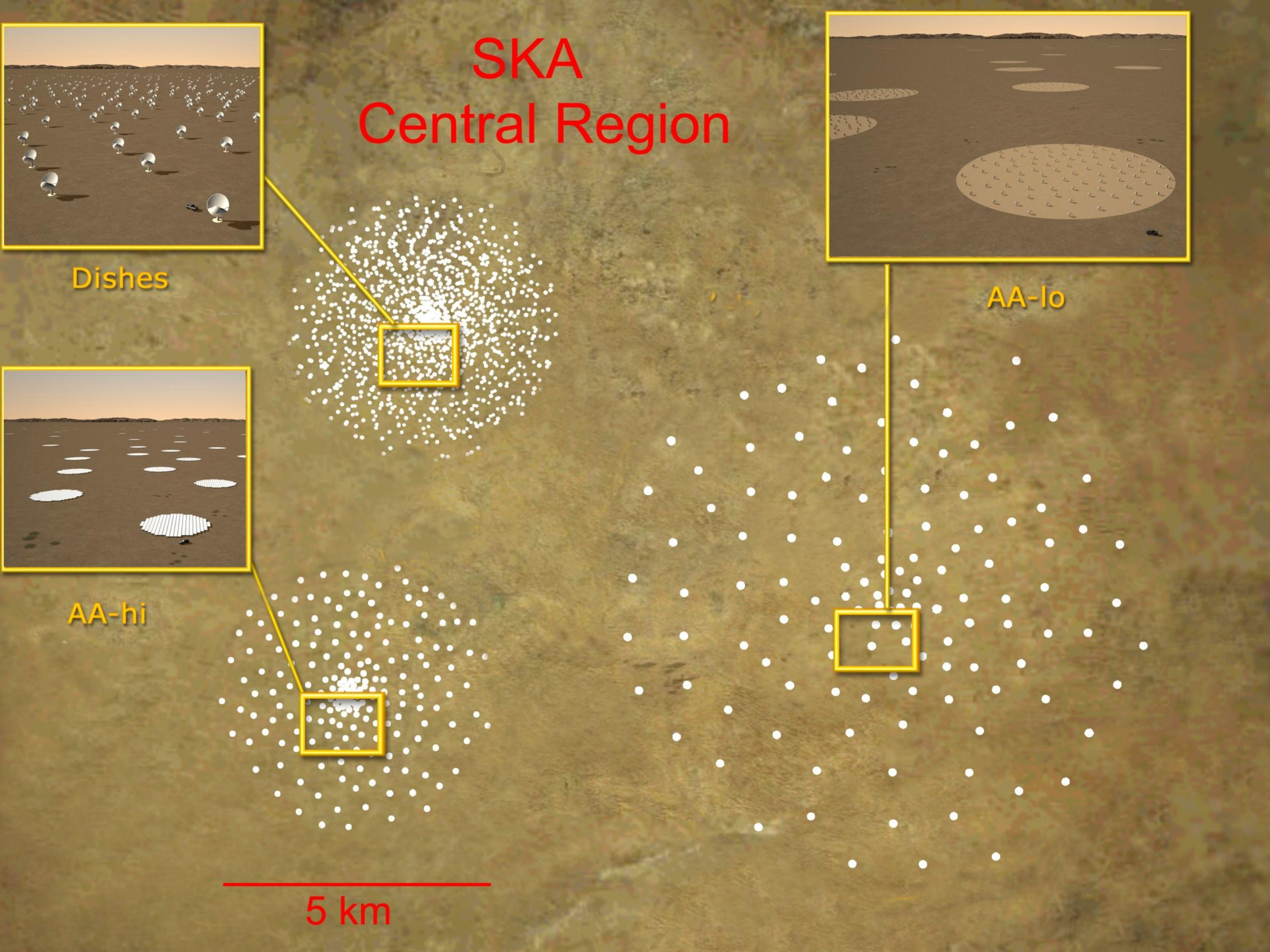
(2004, eds. C. Carilli & S. Rawlings, *New Astron. Rev.*, **48**)

Concise Picture of Technology Options

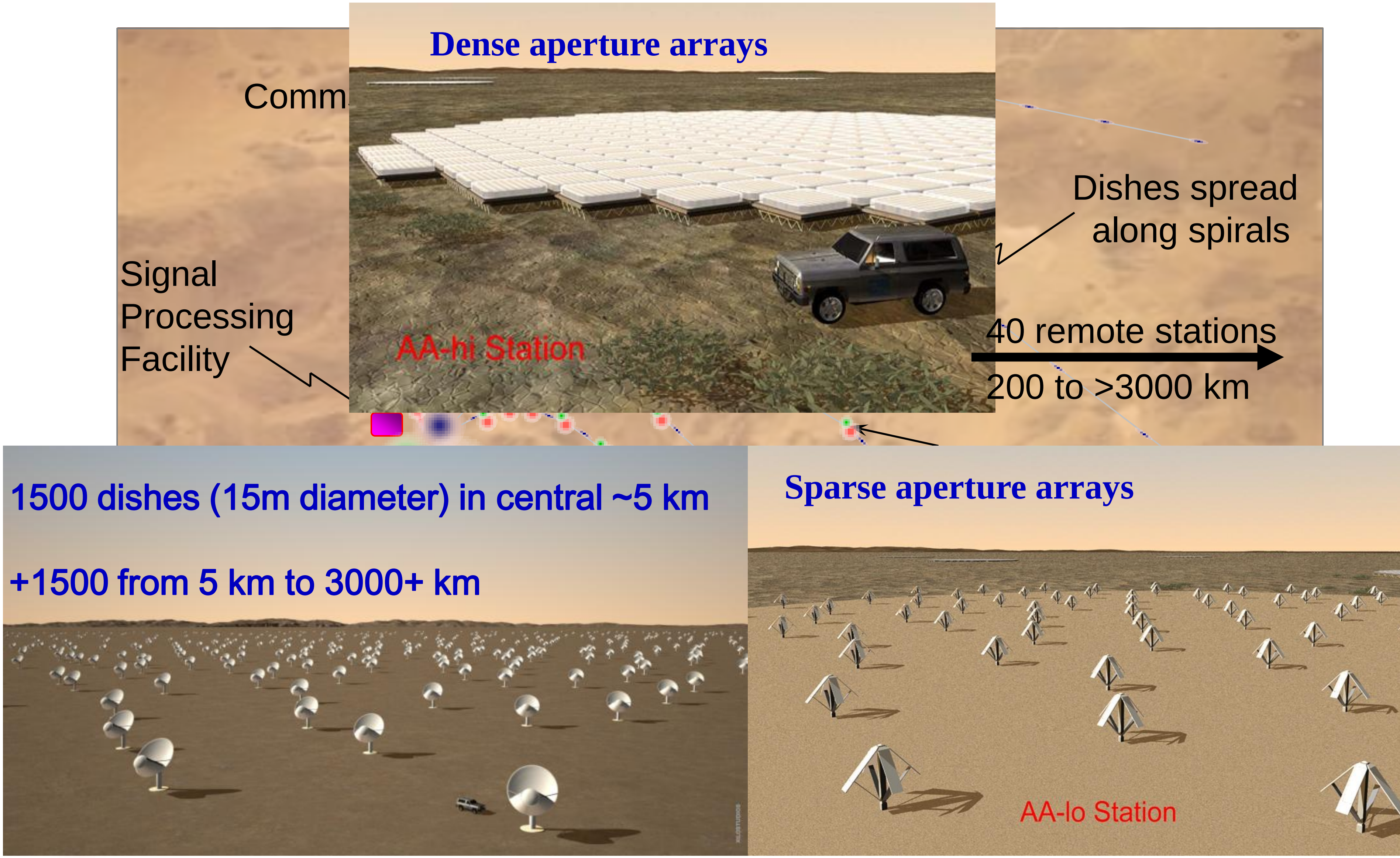
SPDO

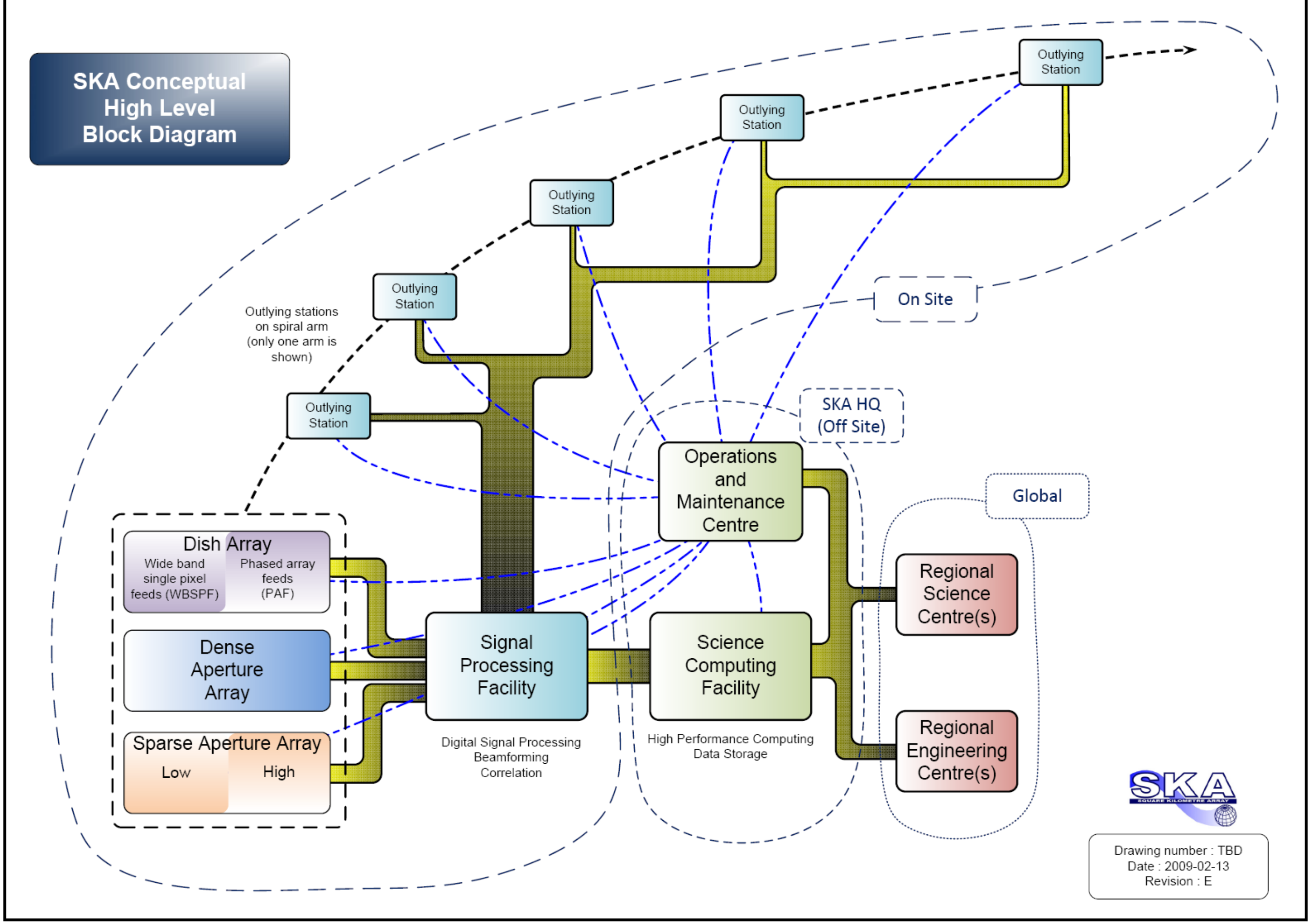


- Numbers of dishes (2000-3000) depends on whether Phased Array Feeds and/or Aperture Arrays are used in the SKA.
- Each technology is characterized by a frequency range and field of view.


SKA
Central Region
Dishes
AA-lo
AA-hi
5 km

Site Configuration Schematic

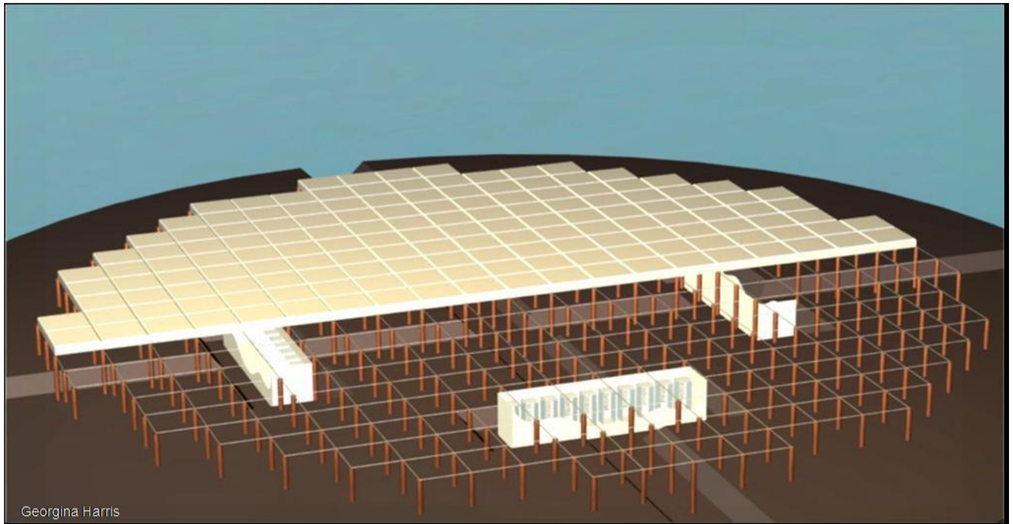




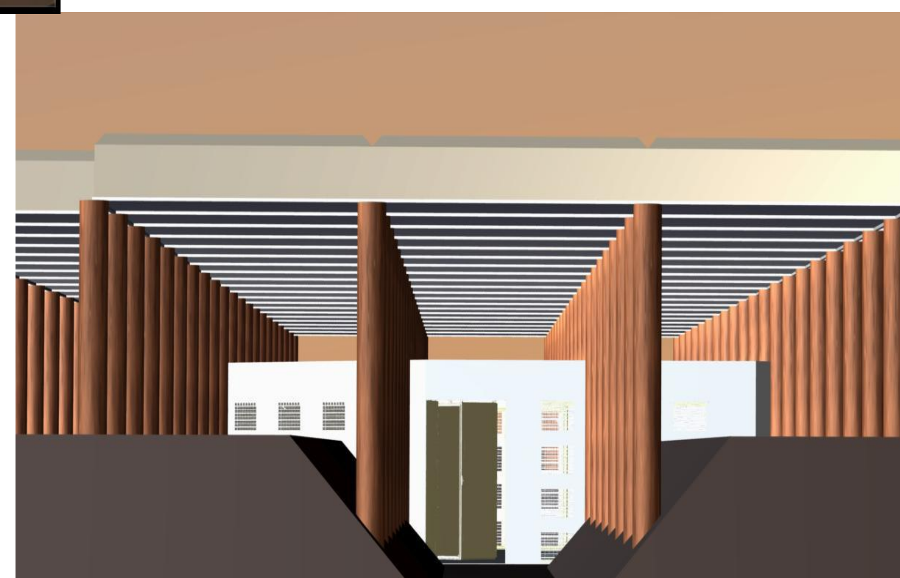
<u>Potential Maximum System Size (i.e. if we do everything)</u>

15m Dishes with Single Pixel Feeds	3000
Sparse AAs	~10^6 m^2
Dense AAs	700,000 m^2 (250 x 60m dia. stations)
15m Dishes with Phased Array Feeds	2000

Dense Aperture Array Station



- ~256 tiles x 256 elements per tile
- 2 polarisations per element
- Sample rate ~ 2.5 Gsamp/s
- 4 bits/ sample
- 56 m diameter
- 250 stations
- Tsys Target 35K

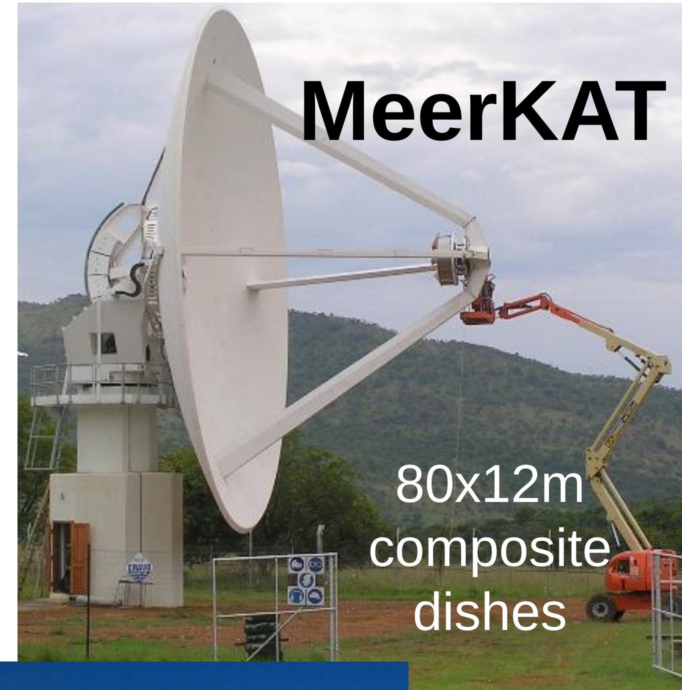


Processing Bunker

- 56m diameter array => 2463 m^2
- 44.4 x 2-pol elements m^{-2} (λ30cm)
- Need 250 stations for 10,000 $m^2\,K^{-1}$ sensitivity (for antenna efficiency 75%, Tsys = 35K)
- 300MHz to 1GHz (700MHz bandwidth)

Dishes

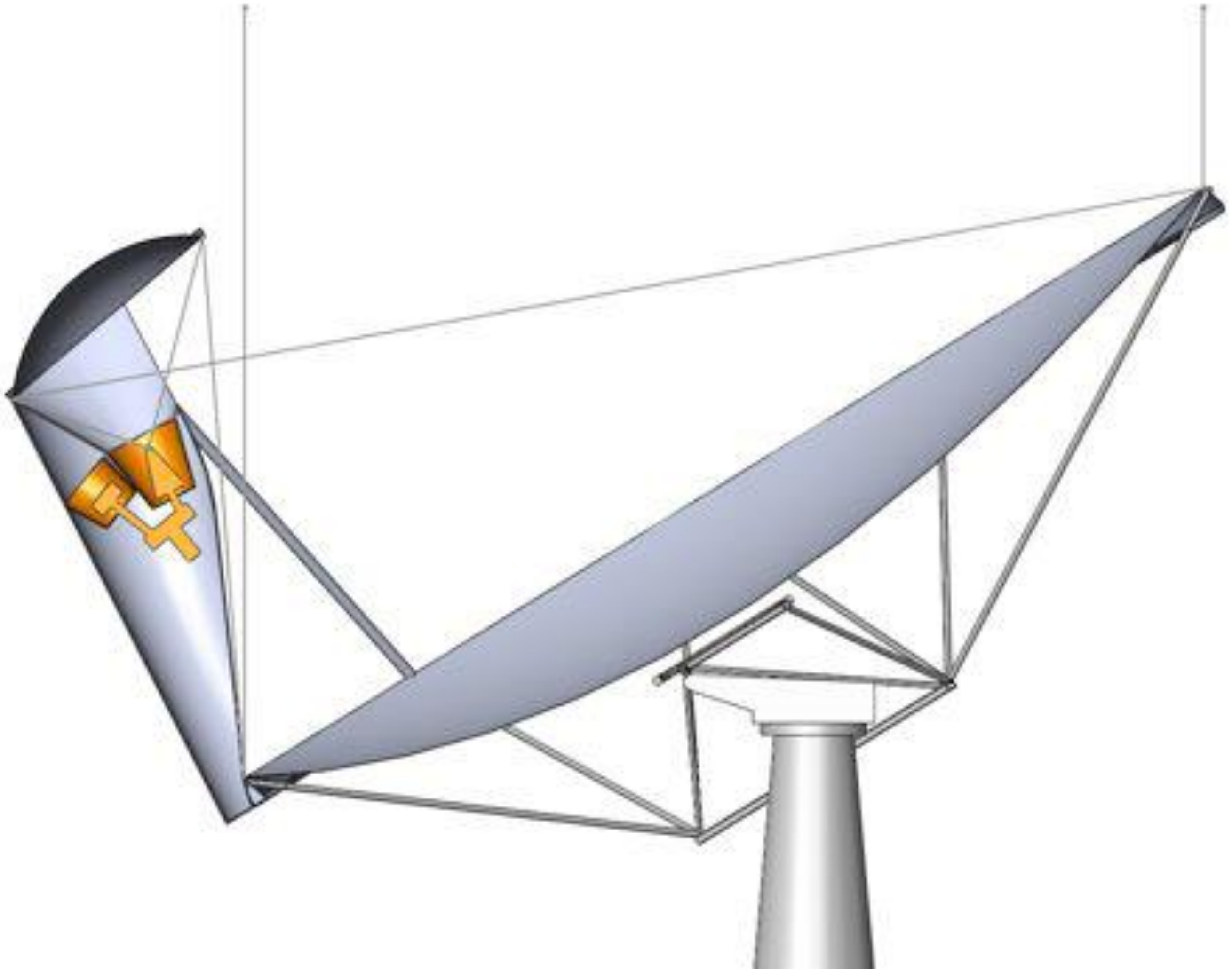

ATA
42x6m
hydroformed
dishes


MeerKAT
80x12m
composite
dishes


ASKAP
36x12m
panel
dishes

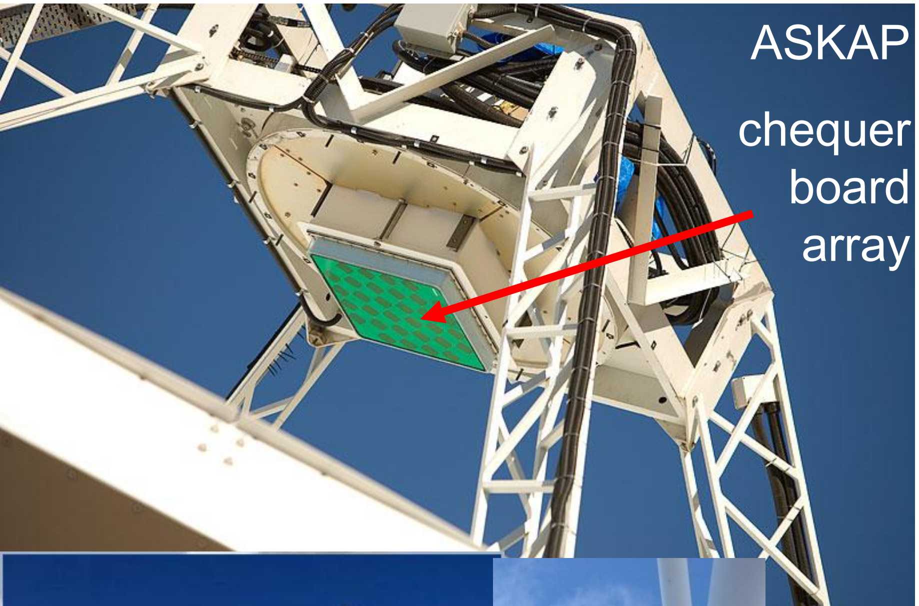

CART
10 m composite prototype
10/05/2007 15:18

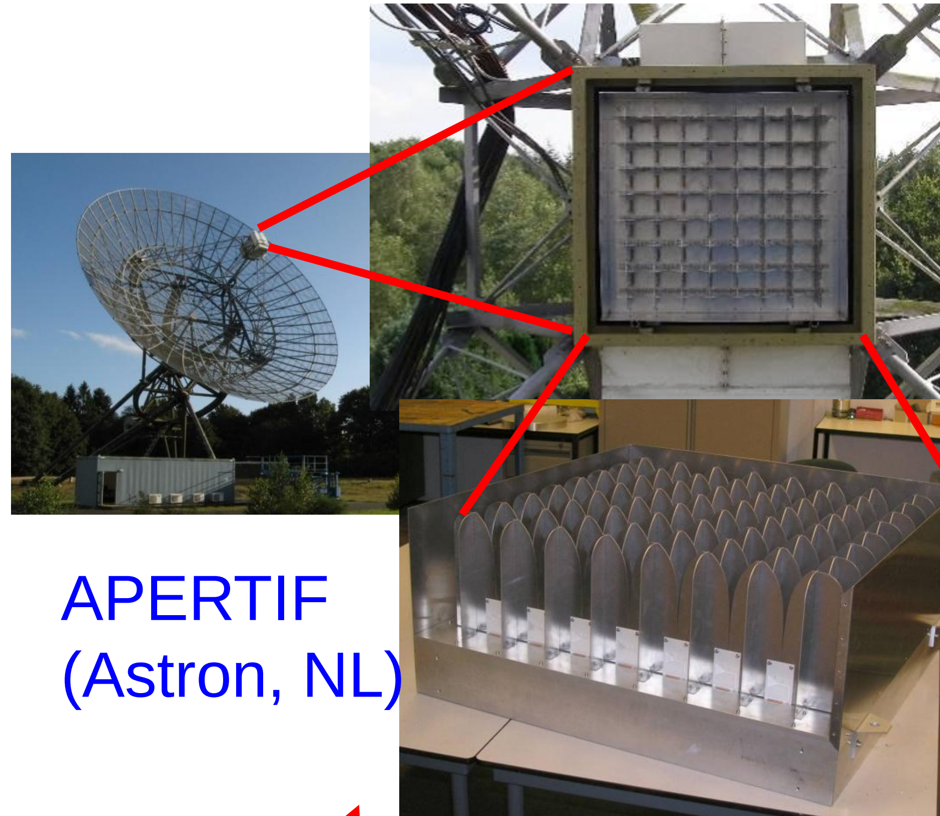
Offset design



Multi-pixels at mid frequencies with dishes + phased-array-feeds

SPDO



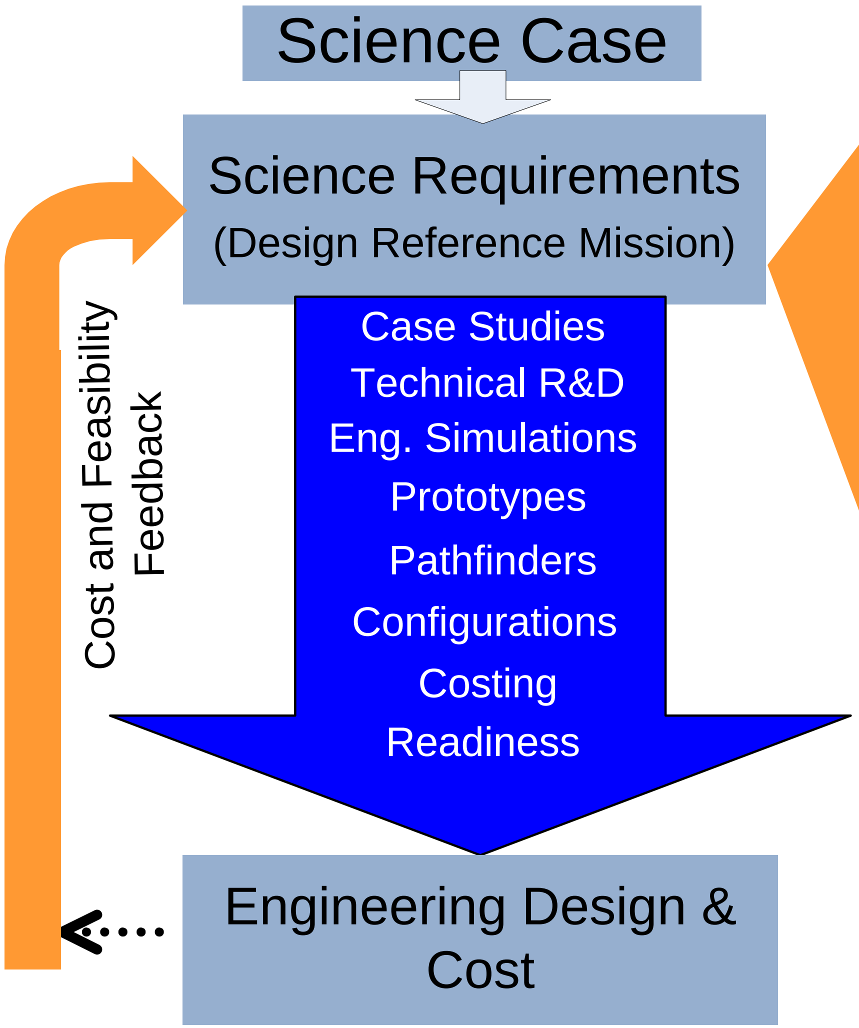


APERTIF (Astron, NL)

DRAO Canada

Vivaldi arrays

Design Cycle



- Design Reference Mission
- Assembly of science case studies that can be used to define the upper envelope of technical requirements of the telescope.
- Not another science case.
- Does not include all science.
  - Includes all key science as a minimum.

Implementation of this flow requires a series of analyses, measurements and tests, and a means of making science choices, trades and technical decisions.

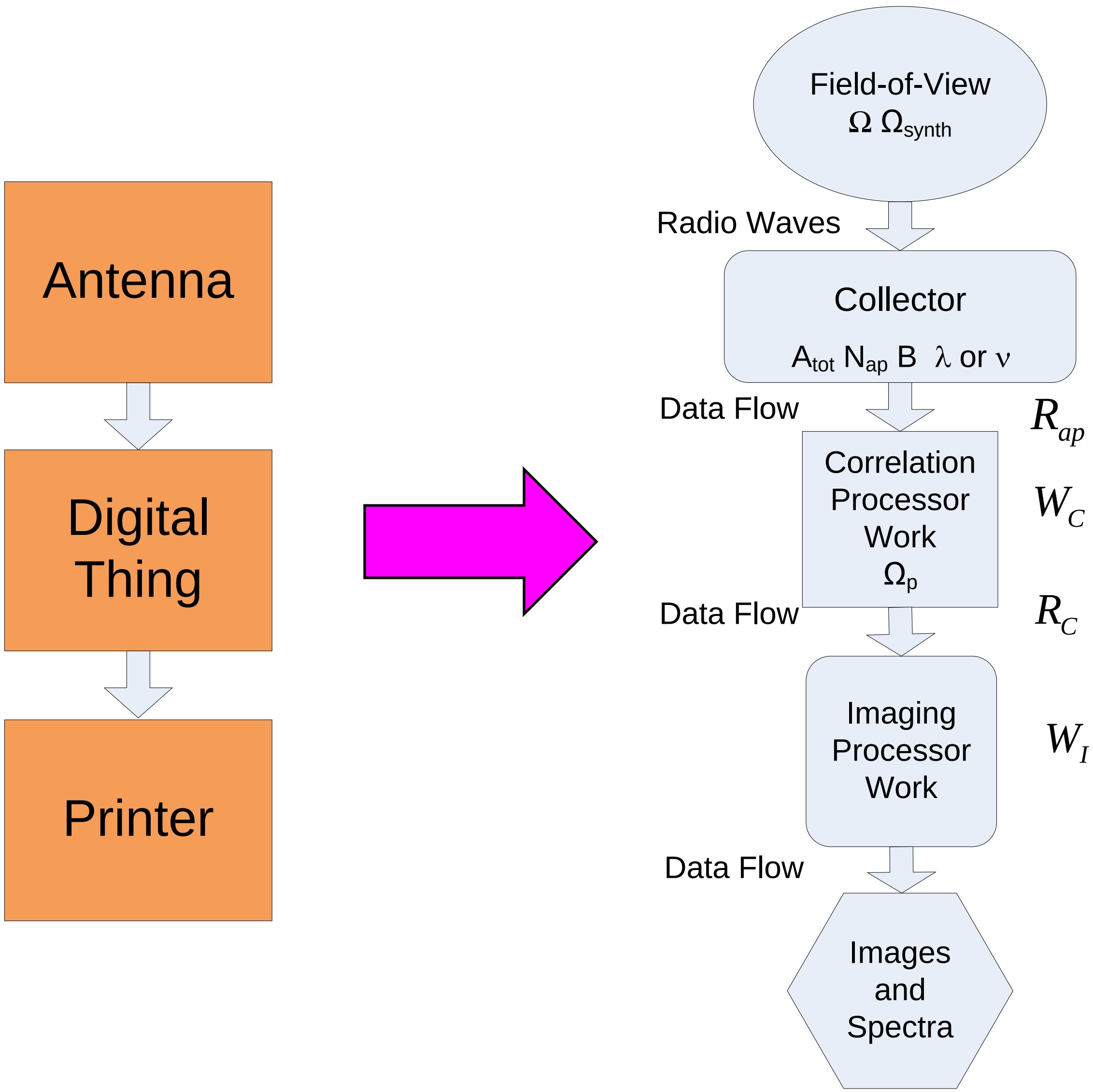
*Design Reference Mission

Scaling & Cost

SPDO

- SKA scale is much larger than current radio telescopes.
  - Many of the techniques used in current radio telescopes do not scale efficiently.
    - Need highly integrated sub-systems, power efficient.
    - Production engineering (DFM) very important.
    - Countries with low-cost production may be needed for some aspects.
- Industrial involvement
  - SKA is large enough to attract industry involvement.

Generalized Synthesis Radio Telescope Model



$$W_B \propto n_{chan} N_{elements} \Delta \nu$$

$$R_{ap} \propto B A_{tot} \Omega / \lambda^2$$

$$W_C \propto N_{ap} \Omega (A_{tot} / \lambda^2) B$$

$$R_C \propto \Omega \left(\frac{B}{\nu} \right) \left(\frac{A_{tot}}{\lambda^2} \right) \left(\frac{\Omega_p}{\Omega_{synth}} \right) N_{ap}$$

$$W_I \propto R_c$$

"Technology-Independent" Proportionalities*

SPDO

$$R_{ap} \propto B A_{tot} \Omega / \lambda^2$$

Total Data Rate to Central Processor

$$W_C \propto N_{ap}{}^2 B$$

Correlator Size for SPFs

$$W_C \propto N_{ap} \Omega (A_{tot} / \lambda^2) B$$

Correlator Size for PAFs or AAs.

$$R_C \propto \Omega \left(\frac{B}{\nu} \right) \left(\frac{A_{tot}}{\lambda^2} \right) \left(\frac{\Omega_p}{\Omega_{synth}} \right) N_{ap}$$

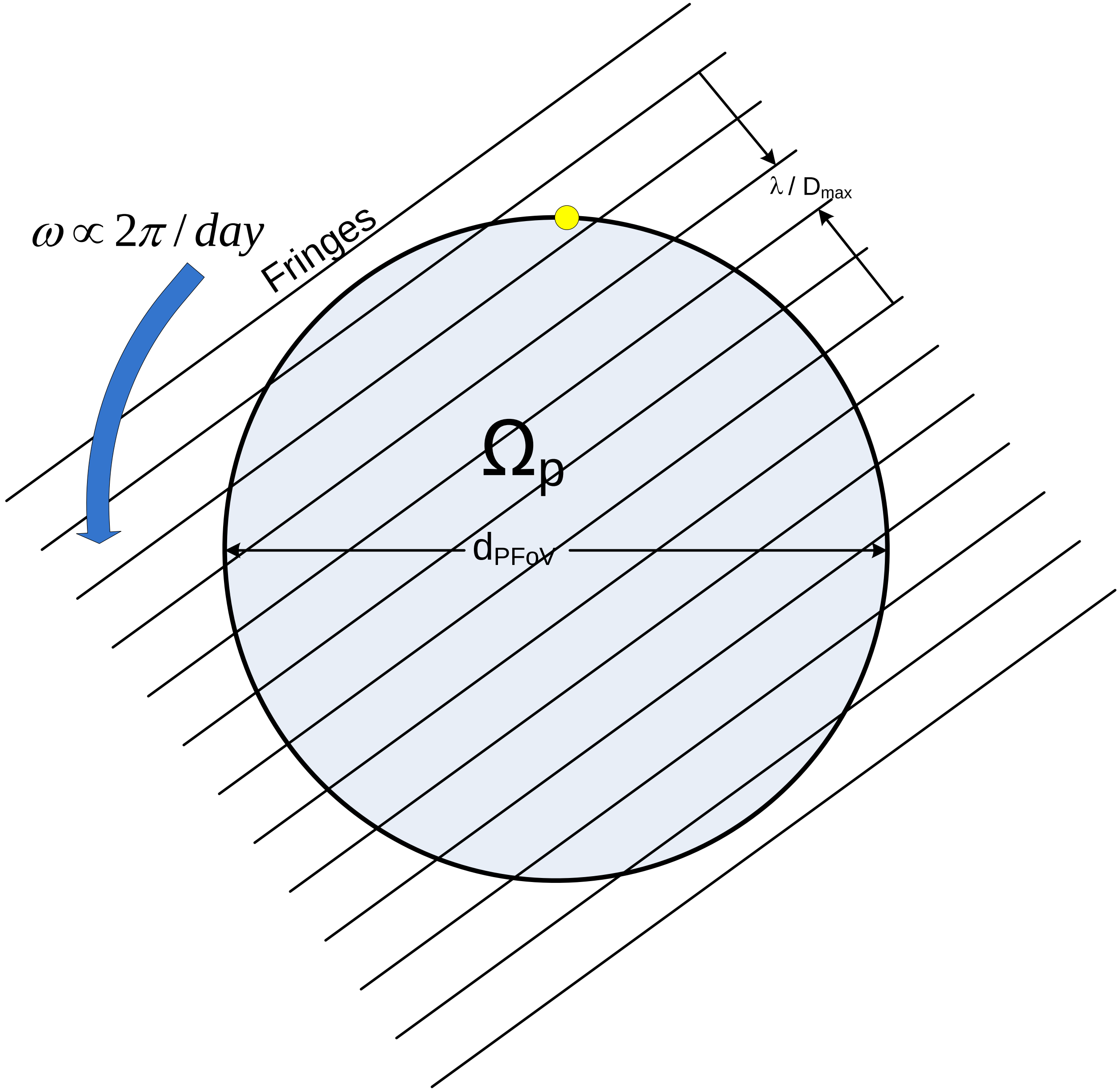
Output Data Rate from Central Processor

N_{ap} = number of beamforming apertures
λ = wavelength
ν = center frequency
B = total bandwidth

A_{tot} = total collecting area
Ω = Total FoV
Ω_p = processed FoV
Ω_{Synth} = synthesized beamwidth

*Approximate relations.

Single Beam with Fringe Pattern



Data Rate from Antennas

$$R_{ap} \propto B N_{ap} N_{beam}$$

From this equation, substituting the following:

$$N_{ap} \propto \frac{A_{tot}}{A_{ap}} \qquad N_{beam} \propto \frac{\Omega}{\Omega_{beam}} \qquad \Omega_{beam} \propto \frac{\lambda^2}{A_{ap}}$$

$$N_{beam} \propto \frac{\Omega}{\lambda^2} A_{ap}$$

Yields:

$$R_{ap} \propto B A_{tot} \Omega / \lambda^2$$

Note: For the single-pixel feed case, N_{beam} = 1 and Ω_{beam} = Ω.

Correlation Work

$$W_C \propto N_{ap}^2 N_{beam} n_{chan} \Delta\nu$$

From this equation, substituting the following:

$$N_{ap} \propto \frac{A_{tot}}{A_{ap}} \qquad N_{beam} \propto \frac{\Omega}{\lambda^2} A_{ap} \qquad B \propto n_{chan} \Delta\nu$$

Yields:

$$W_C \propto N_{ap} \Omega (A_{tot} / \lambda^2) B$$

Note: For the single-pixel feed case, $N_{beam} = 1$, and $W_C \propto N_{ap}B$.

Correlator Output Data Rate

$$R_C \propto N_{baselines} n_{chan} (1/\Delta t) N_{beam}$$

From this equation, substituting the following:

$$N_{baselines} \cong N_{ap}^2$$

$$n_{chan} \propto B/\Delta\nu$$

$$\Delta\nu << 1/\Delta\tau$$

$$\Delta\tau \propto (D_{\max}/c)\Delta\theta_p$$

$$\Delta\theta_p \propto \Omega_p^{1/2}$$

$$\Rightarrow \quad n_{chan} \propto \frac{B}{\nu}\frac{D_{\max}}{\lambda}\Omega_p^{1/2}$$

$$N_{beam} \cong \frac{\Omega}{\lambda^2}\frac{A_{tot}}{N_{ap}}$$

$$\Delta t << \frac{\lambda}{D_{\max}}\frac{1}{\Delta\theta_p}$$

$$\Rightarrow \quad 1/\Delta t \propto \frac{D_{\max}}{\lambda}\Omega_p^{1/2}$$

Yields:

$$R_C \propto \Omega\left(\frac{B}{\nu}\right)\left(\frac{A_{tot}}{\lambda^2}\right)\left(\frac{\Omega_p}{\Omega_{synth}}\right)N_{ap}$$

Imaging Dynamic Range

- Imaging Dynamic Range
  - Ratio of brightest object in image field to weakest detectable object.
  - Ideally limited by natural noise, not systematics.
- Don’t want to build a supersensitive (high A/T_{sys}) telescope:
  - then find that it hits a limit after 50-hrs integration, which is then irreducible because of systematic errors.
  - i.e. Systematics not fully understood, or rapidly time variable.
- High DR is a system issue.
  - need to consider the whole signal chain, signal processing and imaging as a system.

e.g. Reflector Pointing

- High DR imaging will require very accurate antenna pointing
  - Strong sources near ½ power point very sensitive to pointing ($\Delta P \approx 0.72\ [\Delta\theta/FWHM]$ for Gaussian).
  - For $\Delta P < 10^{-6}$, $\Delta\theta \approx 1.4 \times 10^{-6}$ FWHM.
  - Clearly this antenna "spec" cannot be met by mechanical means alone.
  - Self-calibration, mosaicing and other "solving" techniques will be necessary to effectively recover pointing errors.
  - Simulations and testing with existing telescopes will be needed to verify and delineate limitations.
- "Recovered pointing" could meet the original spec.

Modelling/Calibration

1. Cannot model and calibrate systematic effects (errors) that are not fully understood.

- Sounds obvious … but years of work on specific telescopes have typically been required to understand the subtle systematic effects needed to achieve high DR imaging.
- The lessons learned from this work must be applied to the SKA from the beginning.
- Unprecedented level of collaboration needed for the SKA between design engineers and astronomers (also cross-training).

Modelling/Calibration (cont'd)

2. Degrees of Freedom

- Cannot solve for more parameters than there is information to support.
  - Information theory provides a fundamental basis for evaluating combinations of measurements, assumptions, and a-priori information.
    - Theory originally arose from studies of the amount of information that can be transmitted over a "noisy channel".
  - Recent work on LOFAR by van der Tol, Jeffs, and van der Veen is an example of a formal information theory approach to this problem.
  - Information theory provides guidance on optimum use of information, but does not provide guidance on actually understanding sources of errors.
- Errors with direction-dependency, frequency-dependency or time-dependency add greatly to the number of parameters to be solved for.
  - e.g. beam-errors, ionospheric propagation effects, etc.

Modelling/Calibration (cont'd)

3. Time Variability

- Strictly speaking time-variability is a subset of previous slide.
- All analog systems "drift".
  - e.g. Gains of amplifiers are functions of temperature.
  - e.g. Switching levels and sample intervals in A/D converters vary in complex, non-random ways.
- Characteristic drift times cannot be too short.
  - signal-to-noise will limit the frequency of calibrations, especially those based on celestial sources.
  - e.g. bandpass cals require high signal-to-noise.
- Digital systems do not drift.
  - Much better than analog systems.
  - Cost of digital systems is high compared with analog, especially including power.
  - Subject to bit errors at a low level.

Key Instrumental Issues

- Stability
- Linearity
- "Calibratibility"

All Contribute to Dynamic Range

- System Temperature
- Cost
  - Capital
  - Operations

Software Development

- Hardware production and scaling relationships do not seem to apply to software.
- Survey speed, time-variable astronomy implies very high data flows and possibly number crunching.
- Scale of SKA implies the use of supercomputer architectures (1000's of cores) for which there is no current body of code.

Types of SKA S/W

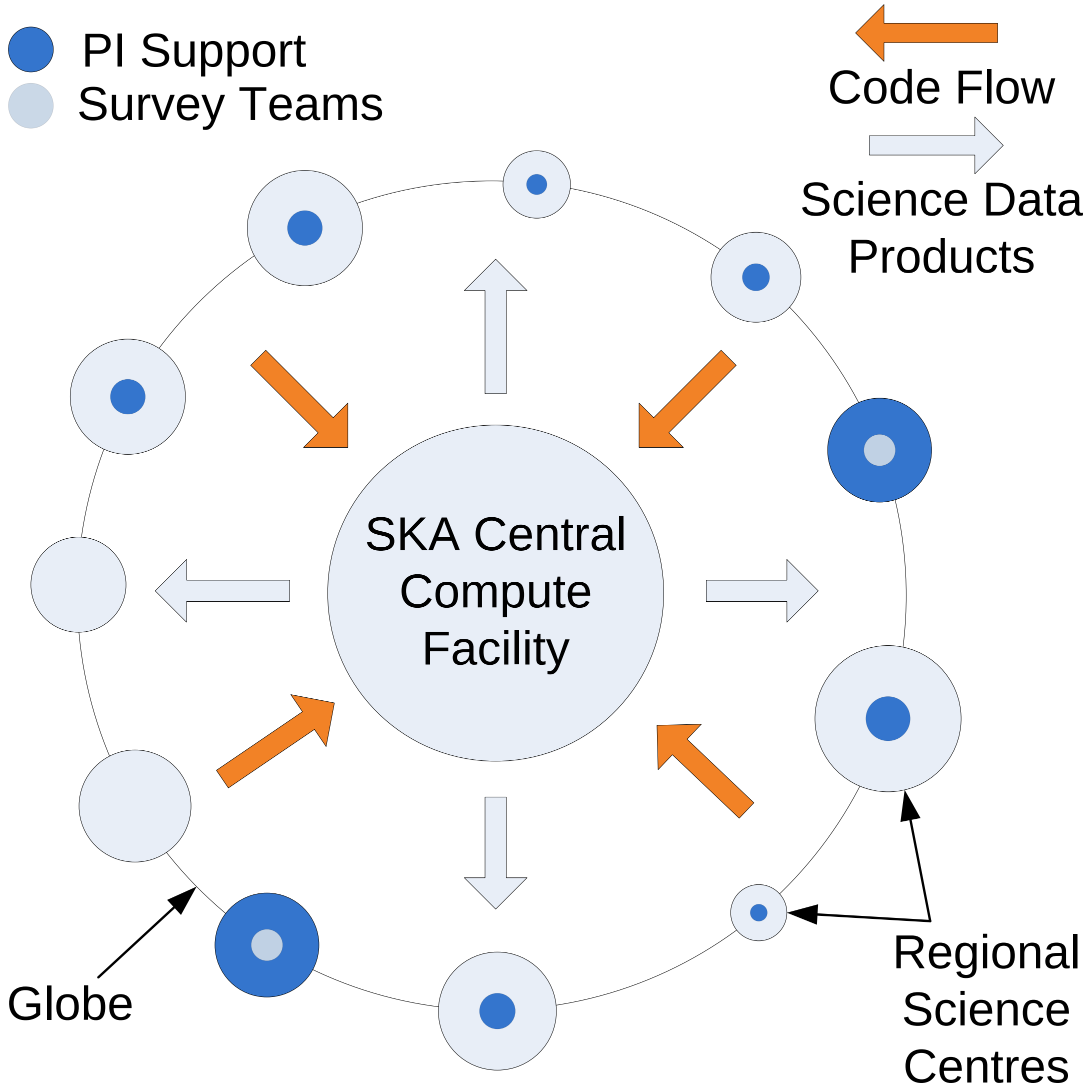
- Development Stage
  - Simulation
    - Some aspects of design.
    - Needed to plan surveys and other
  - Engineering Design S/W
    - Available for $/€: very expensive.
  - S/W Development Tools
- Operations Stage
  - Observation preparation.
  - Telescope operations
  - Monitor & Control
  - Visualization & Display
  - Calibration & Imaging
  - Special Data Processing (e.g. Pulsars)
  - Data management and distribution
    - Middleware
    - Data bases
    - Storage management: speed of access.
    - Data paths to outside world.
  - Science data processing.

Compute Requirements for Dish-based Version of SKA

Central Computing Facility (Example)			Based on
Input data rate*		44 x 10^{12}	Byte s^{-1} av'ge from correlator (4-Byte real's)
Imaging Processor		110 Pflops	@ 10^4 flops / input number (EVLA Memo 24)
Archive		0.1 to 1 ExaByte	

* From correlator with 10^5 chans out, ~14000 input data streams, dumped every 200 ms.

A Potential Code-development Operational Model



Code Integration and test at CPC.

End