AUT UNIVERSITY
TE WĀNANGA ARONUI O TAMAKI MAKAU RAU

From Science Aims to building a telescope

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Plan

- Introduction
- From Science Aims to Telescope Design
- From Telescope Design to Computing Needs
- From Computing Needs to Computing Design

Introduction

- Try to tell a story
- A story about Science
- A story about how we can answer some very important questions
- A story about how we can build an instrument to answer those questions
- A story about how SKA will be this instrument
- A story about how important is our work

FROM SCIENCE AIMS
TO TELESCOPE DESIGN

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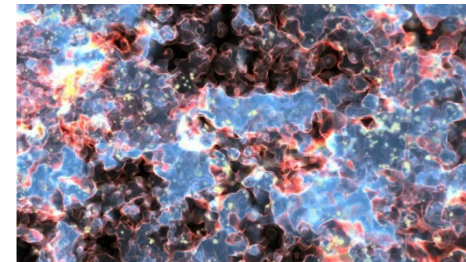
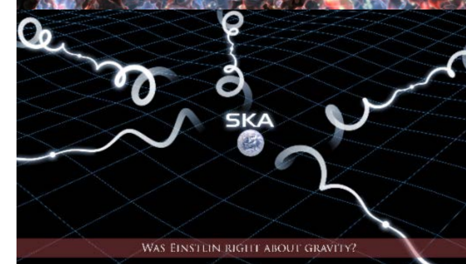
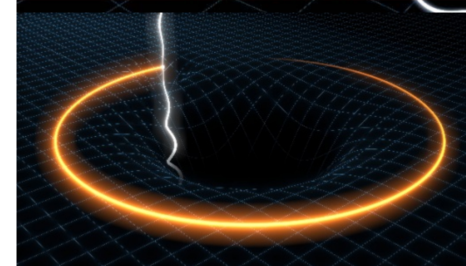
From Science Aims to Telescope Design

- Science cases:
  - Probing the Dark Ages and the Epoch of Reionization (tracking changes in Universe as first stars and galaxies formed)
  - Strong Field Tests of Gravity using Pulsars and Black Holes (high precision pulsar timing observations to test General Relativity)
  - Galaxy Evolution, Cosmology, and Dark Energy (track how galaxies accumulate gas and test properties of dark energy)
  - The Origin and Evolution of Cosmic Magnetism (track how cosmic magnetism has been generated)
  - The Cradle of Life (search for orbiting disks around stellar nurseries, prebiotic molecules)




From Science Aims to Telescope Design

- No instrument requirement so far
- How do we study these Science Aims?
  - Epoch of Reionization (EoR): HI at $z<25$ and very high SNR
  - Strong gravity field test (pulsar): NS-BH and BH-BH
  - Galaxy evolution: HI at $z<6$ or thermal at $z>1$
  - Cosmology and Dark Matter: >5º FoV deep spectral statistics, nHz gravitational waves
  - Cosmic Magnetism: Faraday screen at galactic scale
  - Cradle of Life: SETI + "earth" finding

From Science Aims to Telescope Design

- How to we observe all of this?
- Each field has a vector that can be observed, or a specific technic to analyse this vector
  - Epoch of Reionization (EoR): very high sensitivity of radio signals at ~100 MHz
  - Strong gravity field test (pulsar): precise time pulse profile
  - Galaxy evolution: high resolution imaging at 0.7—10GHz radio signals
  - Cosmology and Dark Matter: Wide-field imaging with very high sensitivity (μJy level)
  - Cosmic Magnetism: Full polarisation for radio signals at 0.7—10 GHz
  - Cradle of Life: Transient detection, <60 MHz planet emission, amino acid emission line

From Science Aims to Telescope Design

- So, what do we have so far?
- Obviously, it is a radio-telescope
- Band of observations is covering 50 MHz to ~10GHz
  - Too spread for a single receiver technology
- High angular resolution imaging means interferometer
  - But wide field means small elements
- Small antennae and very high sensitivity imply
  - A lot of receiver elements
  - Either cooled receivers (cm-λ) or a LOT of them (m-λ)
  - High bandwidth
- Accurate pulse profile imply high spectral/time resolution

From Science Aims to Telescope Design

- What is the telescope design we got from Science Cases?
- One, in fact at least two, radio-interferometers
  - One for cm wavelengths
  - One for m wavelengths
- Large number of quite small antennae
  - Very large number of baselines
- Large bandwidth with lot of spectral channels
  - Very large data rate
  - State-of-art ADC and data links

FROM TELESCOPE DESIGN TO COMPUTING NEEDS

From Telescope Design to Computing Needs

- So we have a lot of antennae, that produce a lot of data each
- What do we do with them?
  1. As astronomical signals are well below the ambient noise, we need to extract the sky signal

  2. Once the sky signal is isolated, we need to built data that can be analysed
     - Spectrum
     - Pulse profile
     - Imaging
     - …

From Telescope Design to Computing Needs

- So we have a lot of antennae, that produce a lot of data each
- What do we do with them?

CSP

1. As astronomical signals are well below the ambient noise, we need to extract the sky signal

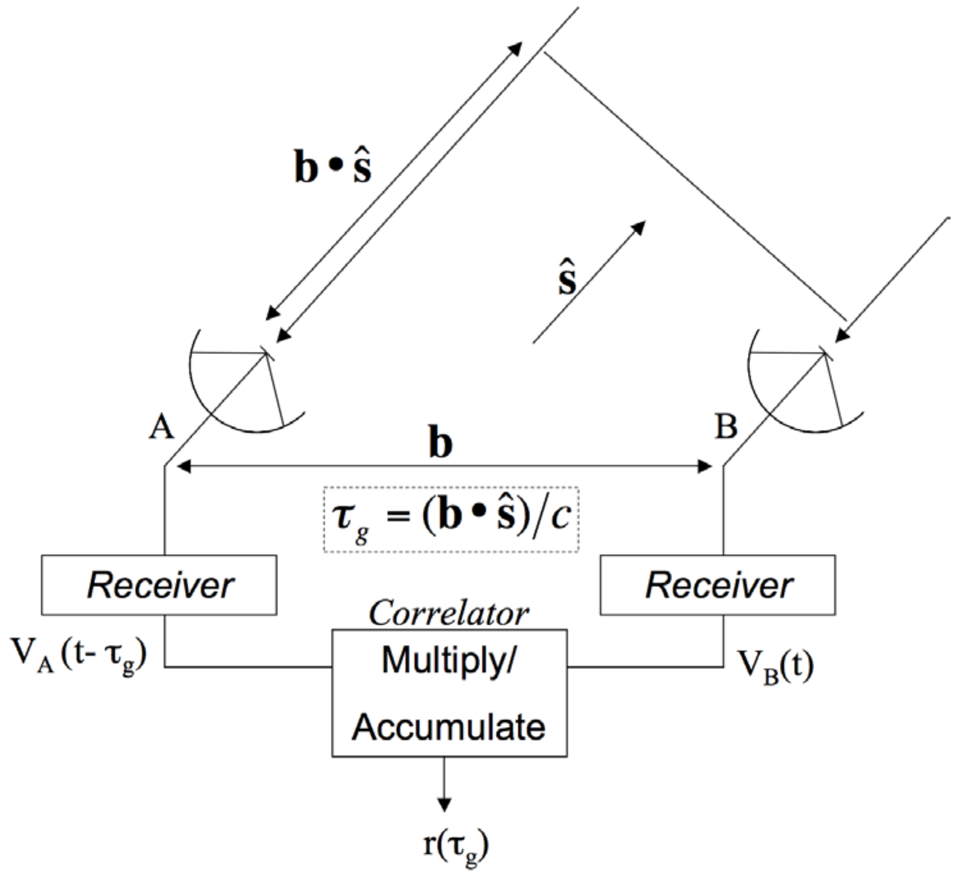
2. Once the sky signal is isolated, we need to built data that can be analysed

SDP

    - Spectrum
    - Pulse profile
    - Imaging
    - …

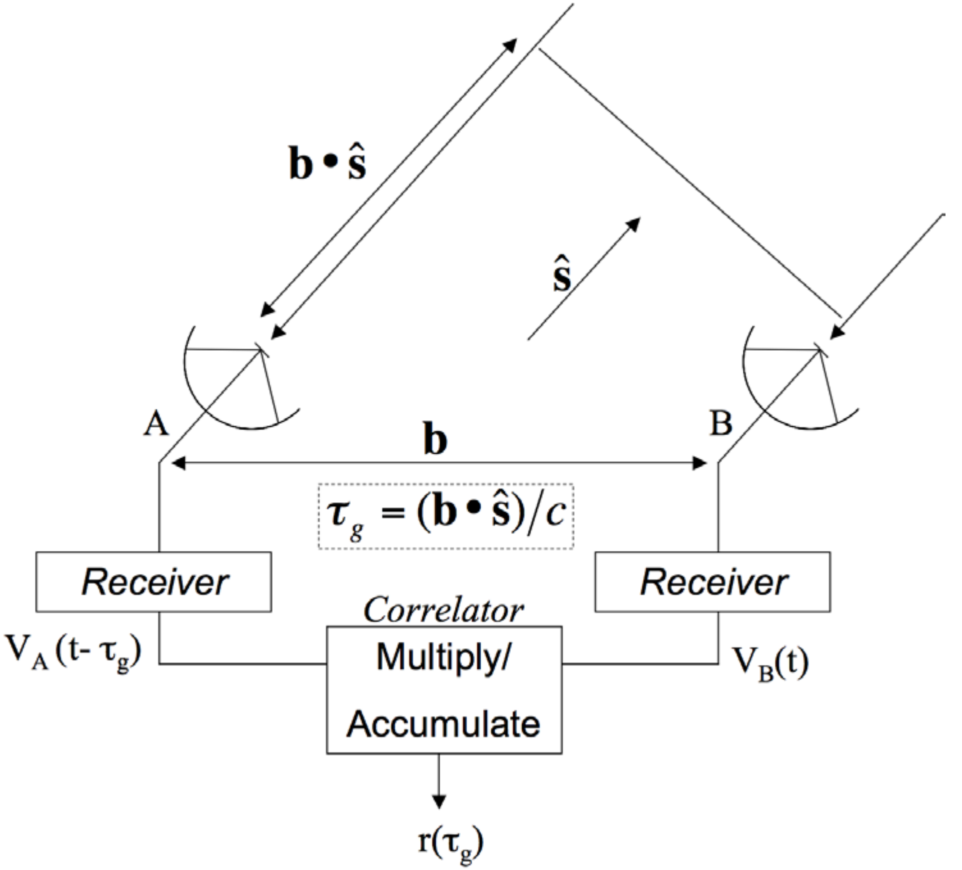
From Telescope Design to Computing Needs

- All interferometers need a correlator (Central Signal Processing consortium for SKA)
  - Gather all the signals (voltages) from all the stations
  - Use geometric time delay model to synchronise the signal for a given target direction
  - Multiply the signal by pair of stations
  - Accumulate this multiplication
  - Do this in the frequency domain
  - The result for imaging is a visibility (complex function)



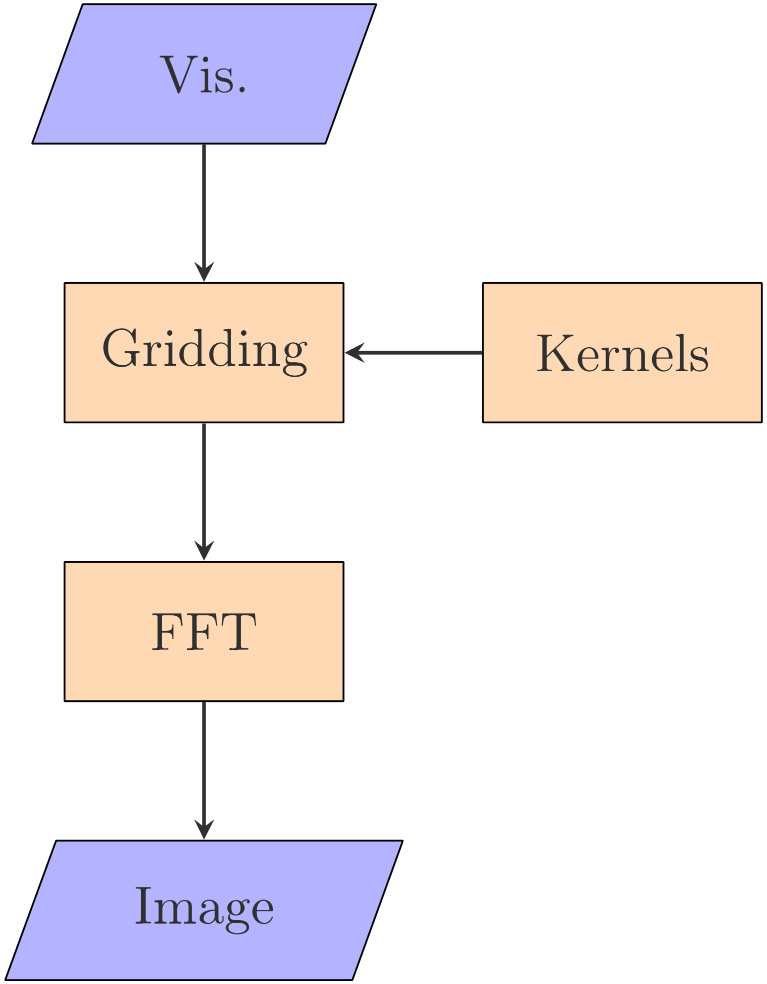
From Telescope Design to Computing Needs

- How does this translate in term of Computing?
  - 160 GB/s per station (hundreds of them)
  - FFT all of them (N.log(N))
  - Auto and Cross multiply ((number of stations)^2)
  - In real time
  - Produce 80 Tb/s output data
  - +“details” (RIF mitigation, flag data, polarisation,...)



From Telescope Design to Computing Needs

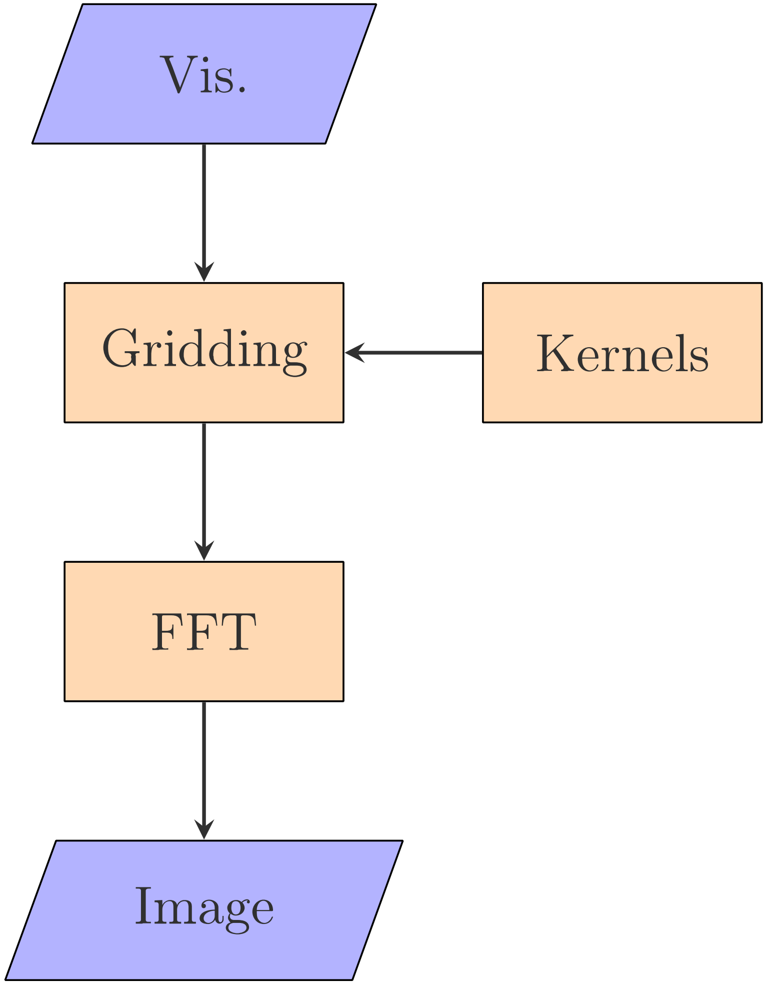
From visibilities, Signal Data Processor build astronomical data (images)



- Visibilities are complex sine waves sampled at one point
- Must use Fourier Transform to obtain image (FFT)
- Need regular spacing > Gridding
- Kernel functions smooth the visibility over the grid
- Need several ”major” cycles that include deconvolution and inverse FT

From Telescope Design to Computing Needs

From visibilities, Signal Data Processor build astronomical data (images)



- Kernel updates scale as N_{kern}^2
- Gridding scale as $N_{vis}.N_{kern}^2$
- FFT scale as $N_{pix}.\log(N_{pix})$
- Need several major cycles with iFFT (scale as $N_{pix}.\log(N_{pix})$)
- Additional calibration tasks increase this by similar factors

FROM COMPUTING NEEDS
TO COMPUTING DESIGN

From Computing Needs to Computing Design

- For both CSP and SDP, base algorithms are well known and the needed operations are documented
- However, brute force applications of these algorithm break other SKA constraints:
  - Power
  - Budget
- Need to optimise the way these operations are done
- Need to circumvent, parallelize and distribute wherever it is possible to do so
- Need to search for computing saving possibilities

From Computing Needs to Computing Design

- At almost every step within the data flow, possibilities exist
  - Efficient parallelization of FFT and cross-multiplication in the correlator
  - Possible bit precision limitation after CSP
  - Distribution of reduced grid kernels (faceting, snapshots, baseline binning,…)
  - “Smart” calibration strategies
  - Possible bit precision limitation in imaging tasks
  - …

From Computing Needs to Computing Design

- As SKA budget (in € and in W) is limited, these possibilities must be studied
- Impacts of various computing strategies must be evaluated and compared
- Need of tools to evaluate these impacts to provide answer to SKA Computing design questions
- We need to be able to model, from end to end, the data flow and the computing operations of SKA

Summary

- SKA science cases are unique in their requirements
- They translate into huge technical and building requirements for the telescope
- The number of stations, the size of the data produced and the accuracy of the data processing infer huge computing power
- Various data processing algorithms and/or computing strategies must be studied
- Need of end-to-end signal path model for SKA