Science Commissioning

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Outline

- Overview of SKA-MID and LOW roll-out
- The first arrays: AA0.5
- Engineering, Commissioning and Science Verification
- Commissioning Tests in more detail
- Milestones
- Commissioning scientists:
  - What do they do?
  - How are they organised?

Construction Strategy

- Target: the SKA Baseline Design (197 Mid dishes; 512 Low stations: AA4)
- Not all funding yet secured, therefore follow Staged Delivery Plan (AA*)
- First Milestone: Develop the earliest possible working demonstration of the architecture and supply chain (AA0.5).
- Then maintain a continuously working and expanding facility until achieve the baseline design.

Milestone Event	SKA-Mid (date)	SKA-Low (date)
AA0.5	2024 Jul	2024 May
AA1	2025 Sep	2025 May
AA2	2026 Jul	2026 Jul
AA*	2027 Jun	2027 Aug
Operations Readiness Review	2027 Aug	2027 Oct
End of Construction	2028 Jul	2028 Jul

Dates are earliest possible for test phase and assume prior delivery and integration of sub-systems

Operations Readiness Review
= Milestone for handover to Operations

Design Baseline and Staged Delivery

- Aim is still to deliver the full functionality of the SKA Design Baseline
  - Documented in Design Baseline Description
  - 197 dishes (MID) and 512 stations (LOW)
  - Original roll-out divided into 4 Array Assemblies (AA) 1-4 of roughly equal duration
  - AA0.5 added later, recognising the need for a faster, minimal deployment
- Staged Delivery (AA*) is a financial and schedule break point set by committed member contributions, roughly equivalent in scope to the former AA3
  - MID 144 (80x15m+64x13.5m) dishes; baseline infrastructure to 150km (but see later); Bands 1, 2, 5.
  - LOW 307 stations; baseline infrastructure to 74km; 50-350MHz
  - Both: subset of data-processing hardware and pulsar search/timing capability
  - Roll-out AA0.5, 1, 2, *, 4

	# Dishes	Frequency Bands	Imaging	Pulsar Timing	Dynamic Spectrum	Pulsar Search	Transient Capture	VLBI
AA0.5	4	Band 1 Band 2 Band 5: goal on 4 Dishes, but may not be supported by correlator	✓ Basic Continuum and Spectral Line imaging Using CASA 16k channels 800 MHz bandwidth	? • Goal, single beam				
AA1	8	Band 1 Band 2 Band 5: on 2 Dishes, goal on 4	✓ Basic Continuum and Spectral Line imaging Using CASA 16k channels 800 MHz bandwidth	✓ Basic 1 boresight nonsteerable beam 400 MHz bandwidth				
AA2	64	Band 1 Band 2 Band 5: on 32 Dishes	✓ Basic Continuum and Spectral Line imaging Using CASA 16k channels 800 MHz bandwidth	✓ 6 steerable beams With de-dispersion 800 MHz bandwidth		✓ • 16 steerable beams • Not fully pipelined • Non-real time operation • Full bandwidth		
AA*	144	Band 1 Band 2 Band 5: on 80 Dishes	✓ Continuum and Spectral Line imaging pipelines 64k channels Zoom mode 5200 MHz bandwidth	✓ 16 steerable beams With de-dispersion Full bandwidth	? Maybe	✓ • 128 steerable beams • Not fully pipelined • Non-real time operation • Full bandwidth	? Maybe	
AA4	197 Includes all MeerKAT Dishes	Band 1 Band 2 Band 5	✓ • Full Continuum and Spectral Line imaging pipelines • 64k channels • Zoom mode • Full bandwidth	✓ • 16 steerable beams • With de-dispersion • Full bandwidth	✓ • Supported by PST	✓ • 1500 steerable beams • Fully pipelined • Real time operation • Full bandwidth	✓	✓ • 4 beams

✓ Functionality is partially implemented

✓ Functionality is fully implemented

? Not sure if functionality will be implemented

AIV Plan MID Roll-out

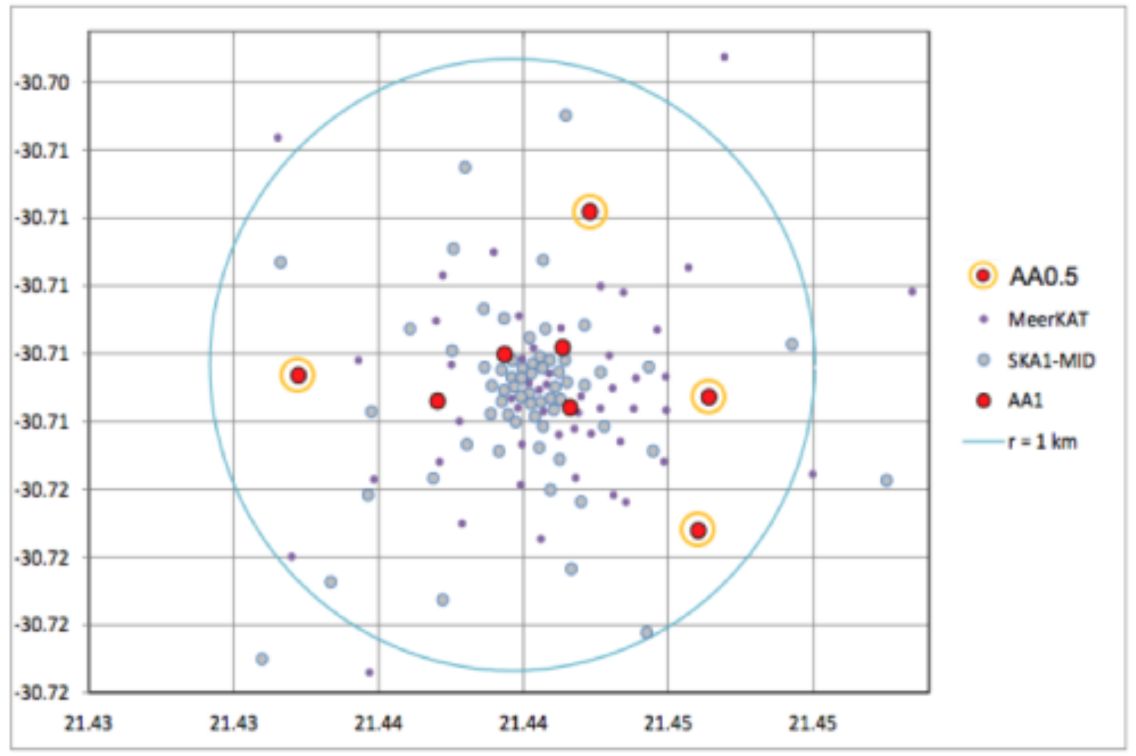
Assembly Integration Verification

	# Stations	Imaging	Pulsar Timing	Pulsar Search	Dynamic Spectrum	Transient Capture	VLBI
AA0.5	6	• Basic Continuum and Spectral Line imaging • Standard Channelization • 1 Station beam • 75 MHz bandwidth	• 1 beam				
AA1	18	• Basic Continuum and Spectral Line imaging • Standard Channelization 75 MHz bandwidth • 8 station beams • Substations mode up to 512-substations	• 4 beams	• 30 beams			
AA2	64	• Basic Continuum and Spectral Line imaging • Standard Channelization • 16 zoom windows, zoom of 1808Hz • 150 MHz bandwidth • 8 station beams • Substation mode up to 720-substations	• 4 beams	• 30 beams	• Supported by PST		
AA*	307	• Basic Continuum and Spectral Line imaging • Standard Channelization • 32 zoom windows, zooms down to 226Hz • 300 MHz bandwidth • 8 station beams • Substation mode up to 1440-substations	• 8 beams	• 250 beams • Pulsar de-dispersion and acceleration processing	• Supported by PST	• Transient response and commensal observing	• Full capabilities
AA4	512	• Basic Continuum and Spectral Line imaging • Standard Channelization • 64 zoom windows, zooms down to 14Hz • 300 MHz bandwidth • 8 station beams • Substation mode up to 2880-substations	• 16 beams	• 500 beams • Pulsar de-dispersion and acceleration processing	• Supported by PST	• Transient response and commensal observing	• Full capabilities

AIV Plan

LOW Roll-out

Path to interferometry: AA0.5
What *are* we trying to do?



- Deployment of minimal arrays on-site as early as possible
- Primary goal: end-to-end test of interferometry
  - Tied-array beamforming is secondary goal
- (Almost) **all** sub-systems (including initial control and data processing software)
  - Includes Dish/Station (not tested at the Integration Test Facility)
- Verify fundamentals of system performance
  - realistic operating environment (e.g. RFI, wind, temperature, ...)
- Interfaces
- Develop AIV, Commissioning teams and procedures
- Identify failures to meet requirements, lack of reliability
- Reduce risk by fixing problems as soon as possible, ideally before mass production; verify the supply chain

What are we *not* trying to do at AA0.5?

- Implement an all-singing-and-dancing system: we want essentials only
  - No fancy widgets for their own sake
- ”Do Science"
  - The arrays are not remotely competitive with existing instruments
  - At this stage, it is all about measurement and calibration
- Make nice images, search for lots of pulsars, ...
  - Does not work with 4-6 dishes/stations and one oddly-shaped tied-array beam
- Verify every system requirement
  - Some performance requirements do not depend on number of stations, or scale in simple ways (sensitivity) ...
  - ... others (e.g. dynamic range) depend on array configuration, field, conditions in complicated ways and are not fully testable until the end of construction
  - ... but we do need to compare AA0.5 results with predictions to make sure we are on track

Brief Definitions

- **Observing Mode:** *A distinct type of observation applicable to a range of astronomical targets.*
- **Assembly (A):** *The activities required to physically establish a product of the SKA Telescope System on-site.*
- **Integration (I):** *The activities required to incorporate a product into the SKA Telescope System*
- **Commissioning (C):** *All activities necessary to arrive at a working end-to-end system that can be used to perform system verification*
- **Science Commissioning (SC):** *The subset of commissioning which requires specification, execution and analysis of astronomical observations.*
- **Verification (V):** *All activities that are executed to formally verify the Telescope system against its Level-1 Requirements.*
- **Science Verification (SV):** *All activities that are executed to verify the Telescope system against its Level-0 Requirements, i.e. to ensure that the Telescope system meets the needs of the science and operational user [Shari's talk]*

Science Commissioning

- **Commissioning**
  - *All activities necessary to arrive at a working end-to-end system that can be used to perform system verification.* These include:
    - setting-to-work
    - integration testing
    - system testing
    - execution and analysis of test science observations, with the aim of debugging the system.
  - Commissioning is a collaborative, interdisciplinary activity, requiring skills in astronomy / interferometry, signal processing, control and data-analysis software, as well as hardware engineering. It is a highly iterative process, usually involving several repetitions of each test.
  - Boundaries between AIV (hardware and software) and Commissioning are fundamentally blurred
- **Science Commissioning**
  - *The subset of commissioning which requires specification, execution and analysis of astronomical observations.*
  - This is separated out, since it will be primarily performed by a different group from that responsible for engineering commissioning.

Integrated Team

- **Integrated Product Teams** for LOW and MID (located in the respective host countries) include:
  - Engineering (hardware and software)
  - Verification coordination
  - Science Commissioning
  - Operations
  - Assurance
- **Division of responsibility** between Engineering and Science Commissioning is (and should be) fuzzy: debugging and verification are collaborative activities. Lead roles and responsibilities:
  - **Engineering Lead** is the authority for product readiness, installation, integration and engineering commissioning/verification, co-leads science commissioning and supports science verification.
  - **Science Commissioning Lead** supports product readiness and installation; co-leads engineering commissioning; is the authority for science commissioning and co-leads science verification.
  - **Science Operations Lead** supports product readiness, installation, integration, engineering commissioning/verification and science commissioning and is the authority for science verification.

Commissioning and Science Verification Roles

Commissioning Scientist	Operations Scientist
Lead integration testing	Support astronomical observations
Lead system testing	Review and edit operational documentation
Execute and analyse test science observations with the aim of debugging the system	
Optimise the system efficiency	
Develop initial documentation	
Train Operations Scientists	

Science Commissioning

Commissioning Scientist	Operations Scientist
Identify and resolve faults	Develop and pre-select SV projects for defined observing models with the aid of an outside advisory group
Optimise observing modes	Prepare, verify and execute scheduling blocks
	Maintain SV documentation (e.g. web pages) which describe all plans and activities including availability of observations
	Reduce (or monitor pipeline reduction of) data and perform quality checks
	Deliver the data to Science Data Centres (and individual users)
	Provide information about and assist users in exploitation of the data

Science Verification

How do the parts fit together?

For a given observing mode:

- AI → C → fix problems → C → V → SV → additional IV, C, SV → Operations
  - with iteration until the performance is good enough to meet user expectations.
  - Overall balance of activities tends to change between AIV and science commissioning as the array develops, with the latter increasing in importance as the system matures.
  - Not the classical “V diagram”
- **Planning Cadence**
  - Longer-term planning on a three-monthly cycle, synchronised with SAFe programme increments.
  - Group leaders meet weekly (chaired by the Engineering Lead) to coordinate work on site
  - Daily planning/fault triage meetings with delegated responsibilities.

Support Assumptions

- Science Commissioning and Verification Teams are based primarily at Perth and Cape Town
  - Very limited travel to array sites: requires good communications with site staff
  - Co-located with AIV, computing, correlator
- Access to the Array
  - LOW: Assume contractors working 0700-1700, 7 days/week
  - MID: Assume contractors working 0700-1900, weekdays
  - Cannot guarantee RFI levels during these times
  - Primary science commissioning/verification periods at night
    - What fraction of night-time will be available in practice? Current assumption is 50%
    - Will need daytime access for some tests: live with RFI or negotiate access
- Operator and on-call technical support consistent with this assumption
  - Array Operator executes observations
  - Science Commissioning Team plans observations; reduces data (again, some special cases)

Commissioning Test Groups

- Basic functionality (AA0.5)
- Dish (MID) and Station (LOW) Calibration
- Array Calibration
- Interferometric Imaging
- Beamforming and non-imaging modes
- Regression and integration tests
- Calibrator and Global Sky models

Basic Functionality (AA0.5)

- Repeat single-dish/station tests
- Single-baseline interferometry ("first fringes")
- Basic multi-element interferometry using point-source calibrators/simple fields
  - Calibrate flux, complex gain, bandpass, delay, leakage, ….
  - Array calibration and stability (dish/station locations, cable delays, ..)
- Rudimentary imaging
- Dish/station characterisation with interferometry/holography
- Single tied-array beam for pulsar timing

MID Commissioning Groups:
Dish Calibration

- Pointing
  - Blind
  - Reference (band-to-band offsets)
- Holography
  - Surface accuracy, alignment, voltage beams
- Dish location and cable delay
- Gain-elevation model

Array Calibration

- Bandpass
- Delay (parallel and cross-hand)
- Polarization leakage and X-Y phase difference
- Flux scale and transfer accuracy
- Complex gain stability
- Beamforming weights
- RFI characterisation and excision methods

Interferometric Imaging

- Range of parameters:
  - Frequency band
  - Spectral resolution
  - Field complexity
  - Snapshot/full track
  - Observing conditions (wind, troposphere, ionosphere)
- Self-calibration
  - Direction-independent
  - Direction-dependent

Beamforming and Non-imaging modes

- Calibrate beamforming coefficients
  - Includes off-axis Jones matrices
- Verify tied-array beamforming
  - Beamshape, phasing efficiency, polarization purity, …
- Pulsar timing
  - Verify by comparison with other telescopes (particularly MeerKAT)
- Pulsar and transient search
- VLBI

Regression and Integration Tests

- Monitor the performance of the system as a function of time.
- Final verification of newly integrated dishes or stations
- Check the effect of system changes
  - e.g. correlator upgrades
- Early warning of failures

Calibrator/Global Sky Model Survey

- Models for flux density, bandpass, polarization standards
- Grid of phase-reference calibrators (higher frequencies)
- Global sky model for initial calibration and imaging (lower frequencies)

IPS Science Milestones (MID AA*/ORR)

*/ORR	144-dish array including MeerKAT dishes and longer baselines Demonstrate imaging with full MID array including MeerKAT dishes in Bands 1 and 2 and with all SKA1 dishes in Band 5 (full bandwidth). At least one zoom modes; full polarization. Demonstrate pulsar search, pulsar timing and dynamic spectrum with multiple beams. Demonstrate simultaneous use of three subarrays (2 commensal for science + 1 for engineering) Demonstrate commensal imaging and transient search Complete initial calibrator survey. Data reduction by SDP operational system pipeline. Demonstrate consistency with earlier off-line reduction and ability to operate at AA* scale. Demonstrate full end-to-end operation, including proposal submission, scheduling block generation, scheduling array and data processing, data processing at full scale, data delivery to Regional Centres

IPS Science Milestones (LOW AA*/ORR)

*/ORR	307-station array including long baselines Demonstrate imaging with up to 307-station array, including long baselines and with optimised direction-dependent calibration. Range of targets, spectral resolutions, including at least one zoom mode. Full polarization. Demonstrate simultaneous use of three subarrays (2 commensal for science + 1 for engineering) Deliver initial Global Sky Model. Data reduction by SDP operational system pipeline. Demonstrate consistency with earlier off-line reduction and ability to operate at AA* scale. Demonstrate pulsar search, pulsar timing and dynamic spectrum with multiple beams.

Commissioning Scientist Skills

- Understand the system as a whole and be able to diagnose (possibly complex) faults in collaboration with hardware and software engineers
- Collectively be able to cover all of the key test group areas
- Have experience with technically similar projects
- Have data reduction and scripting skills
- Collaborate effectively with other disciplines
- Know what the science users expect

Intend to enable transition from commissioning to operations at the end of construction, both to provide a career path and to ensure knowledge transfer

What sort of problems does a commissioning scientist have to solve?

- Example: a careful comparison of an SKA-MID image of a well-known field reveals that there are astrometric errors of up to a few arcsec, varying with time (over ~weeks) and position in the field.
- What might be wrong?

Some possible solutions

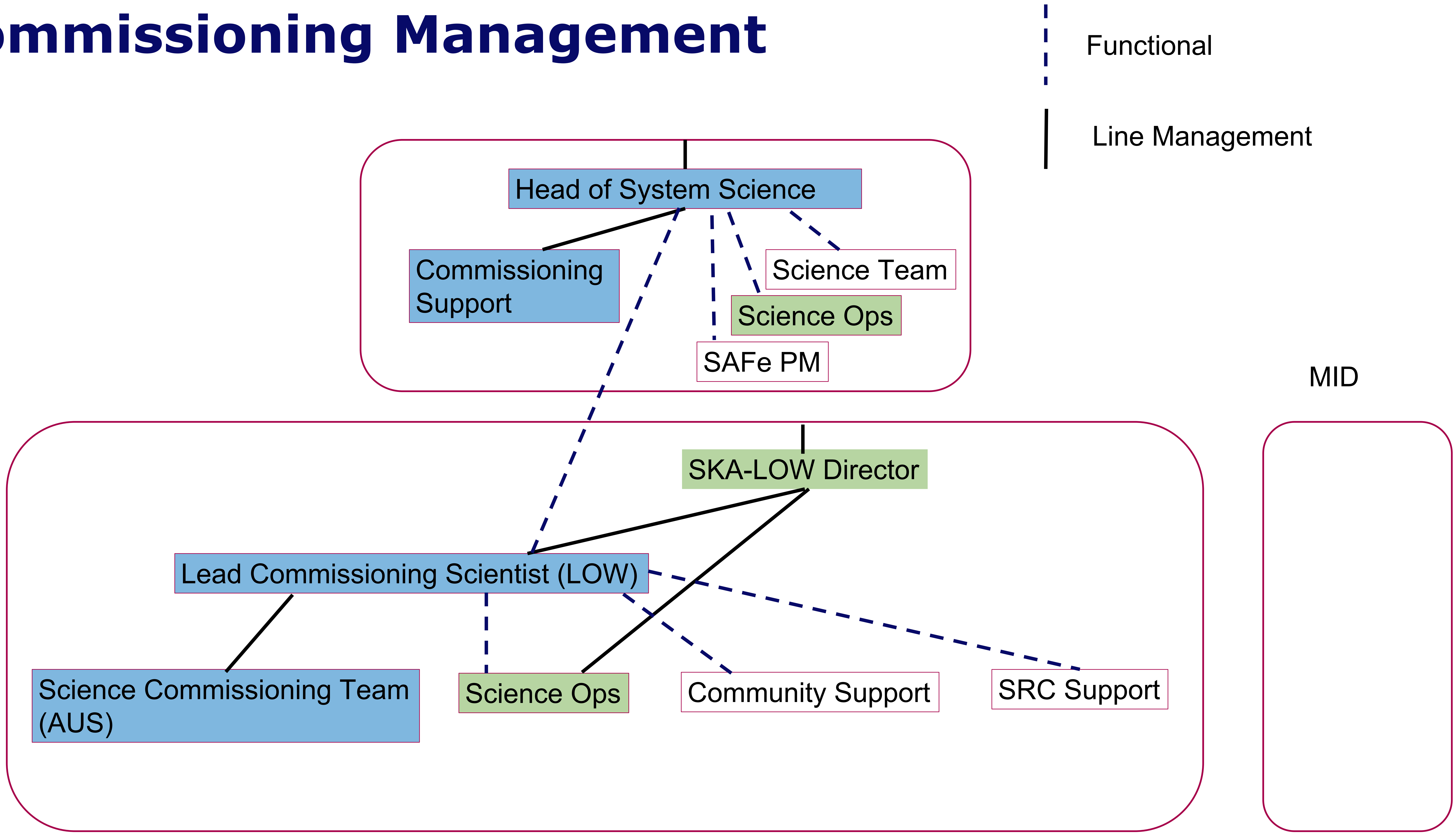
All of these have actually happened, either to me or to the MeerKAT team

- Offset time-stamp, so that uvw coordinates are incorrect.
  - Field appears rotated
- Wrong frequency value (uvw wrong again)
  - Field appears expanded
- Wrong Earth orientation parameters (UT1-UTC, polar motion) e.g. because of failed connection to IERS
  - Absolute RA is wrong, varying slowly over the year + rotation again
- Faulty weather station leading to incorrect refraction calculation/poor model for tropospheric or ionospheric refraction
  - Errors in elevation
- Errors in dish positions
- Errors in assumed positions for phase-reference calibrators
- Software for coordinate conversions is not accurate enough

Science Commissioning Staff

- GHQ
  - Head of System Science has overall responsibility for commissioning
  - Supported by a small System Science Group (in post now)
- Host Countries
  - Majority of Science Commissioning effort located in Cape Town and Perth
  - Lead Commissioning Scientist + Team (ramping up ~6 months before AA0.5)
  - Commissioning test group functions given earlier.
  - Directly employed by SKAO
- Additionally:
  - Science Operations
  - GHQ Science Group
  - SRCs
  - Wider Community

Commissioning Management



Community Involvement in Commissioning

- Experienced commissioning astronomers from the community contribute a huge amount, but are very rare.
  - SKA needs to attract them
- Degree of involvement in hands-on commissioning varies a lot between sub-fields
- Not usually effective to offer observing time in exchange for commissioning effort, but motivating/rewarding commissioning scientists with access to the array is beneficial.
- Substantial commitments of time are needed (usually >3 months) with at least some f2f contact with the core commissioning team initially.
- Structured training and management of community effort is essential.

Any questions?