30th Annual INCOSE international symposium

Virtual Event
July 20 - 22, 2020

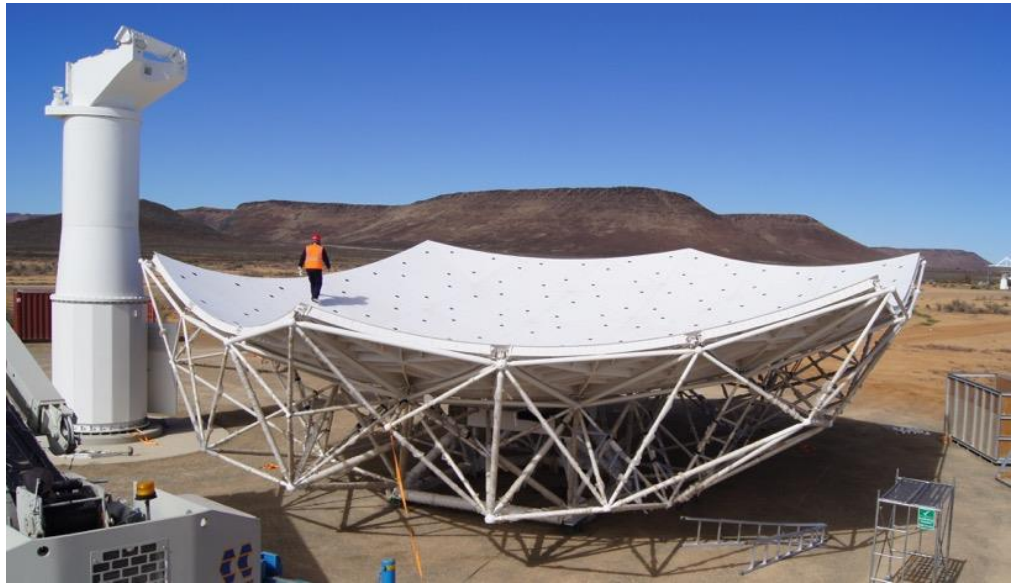
Managing Integration and Verification Risks of the SKA Radio Telescope

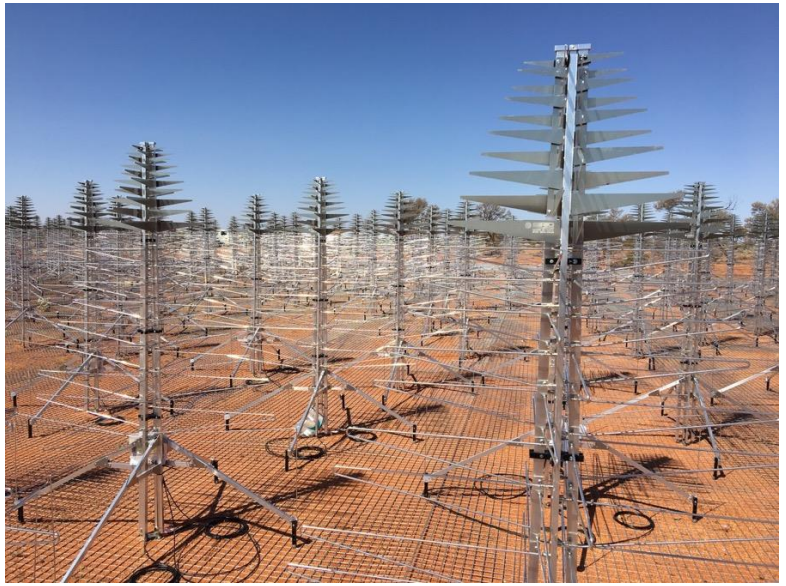
Richard T. Lord

www.incose.org/symp2020

Overview

- Introduction to the SKA
- Integration & Verification Planning
  - Managing risks an underlying theme
- MeerKAT Precursor Integration



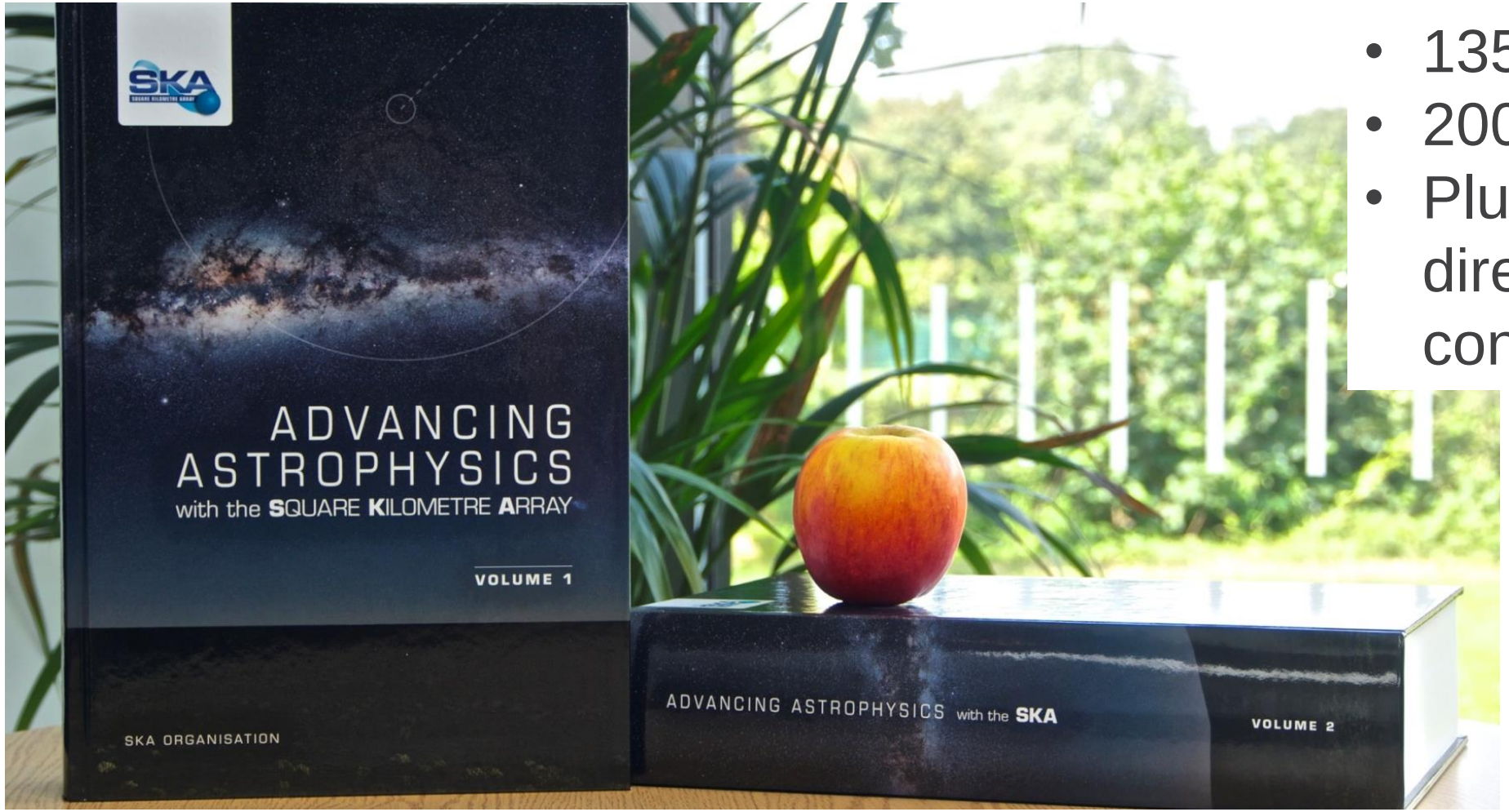


What is the SKA?

An international effort,
to build the world's largest Radio Telescope.

One of the largest scientific endeavours in history!

SKA Science Book 2015

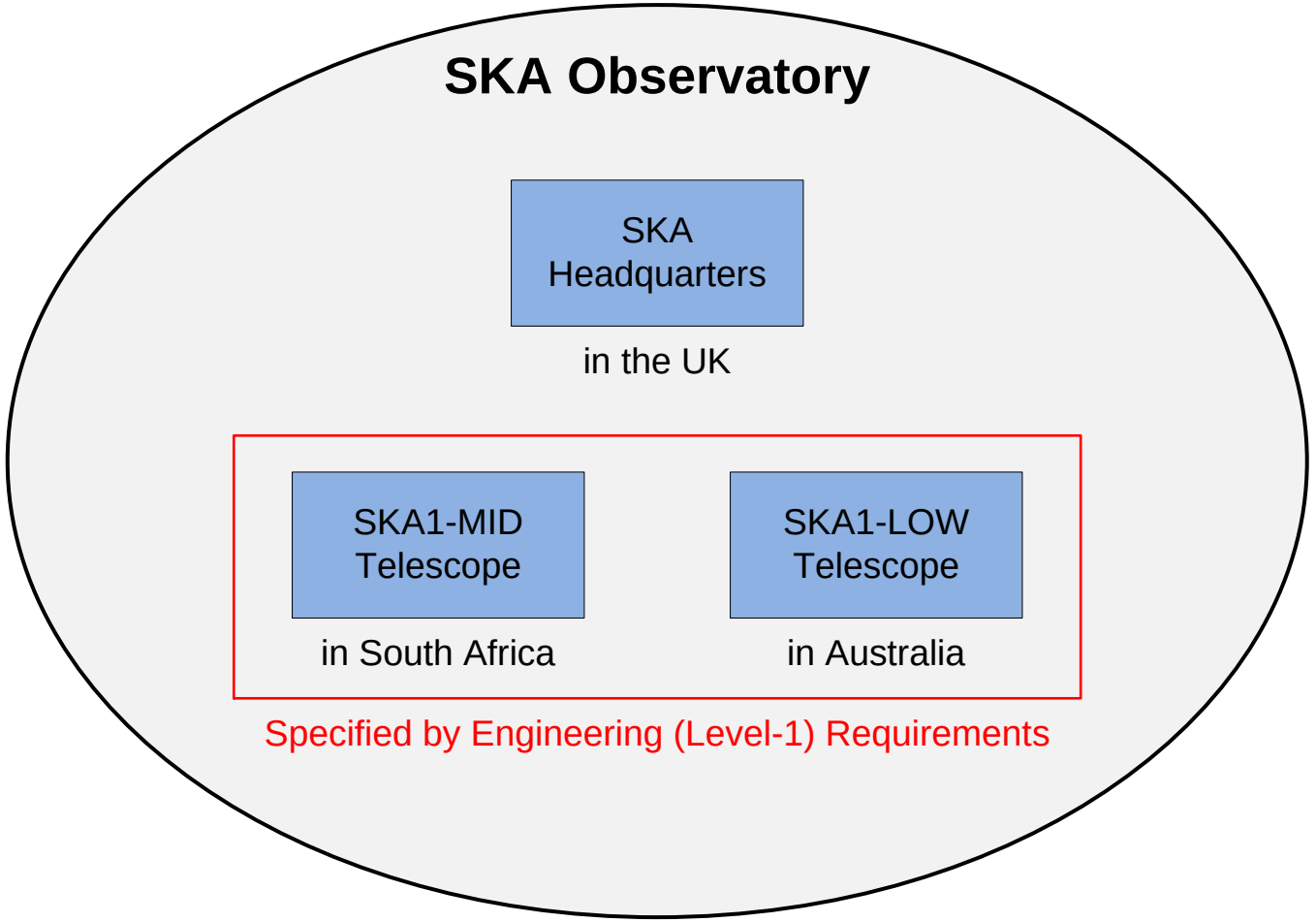


- 135 Chapters
- 2000 pages, 8.8 kg
- Plus new science directions that continue to emerge!

15 Participating Countries

1) Australia
2) Canada
3) China
4) France
5) Germany
6) India
7) Italy
8) The Netherlands
9) New Zealand
10) Portugal
11) South Africa
12) Spain
13) Sweden
14) Switzerland
15) UK

1 Observatory
3 Sites, 2 Telescopes, 1 HQ



SKA Headquarters

Sites in Australia and SA

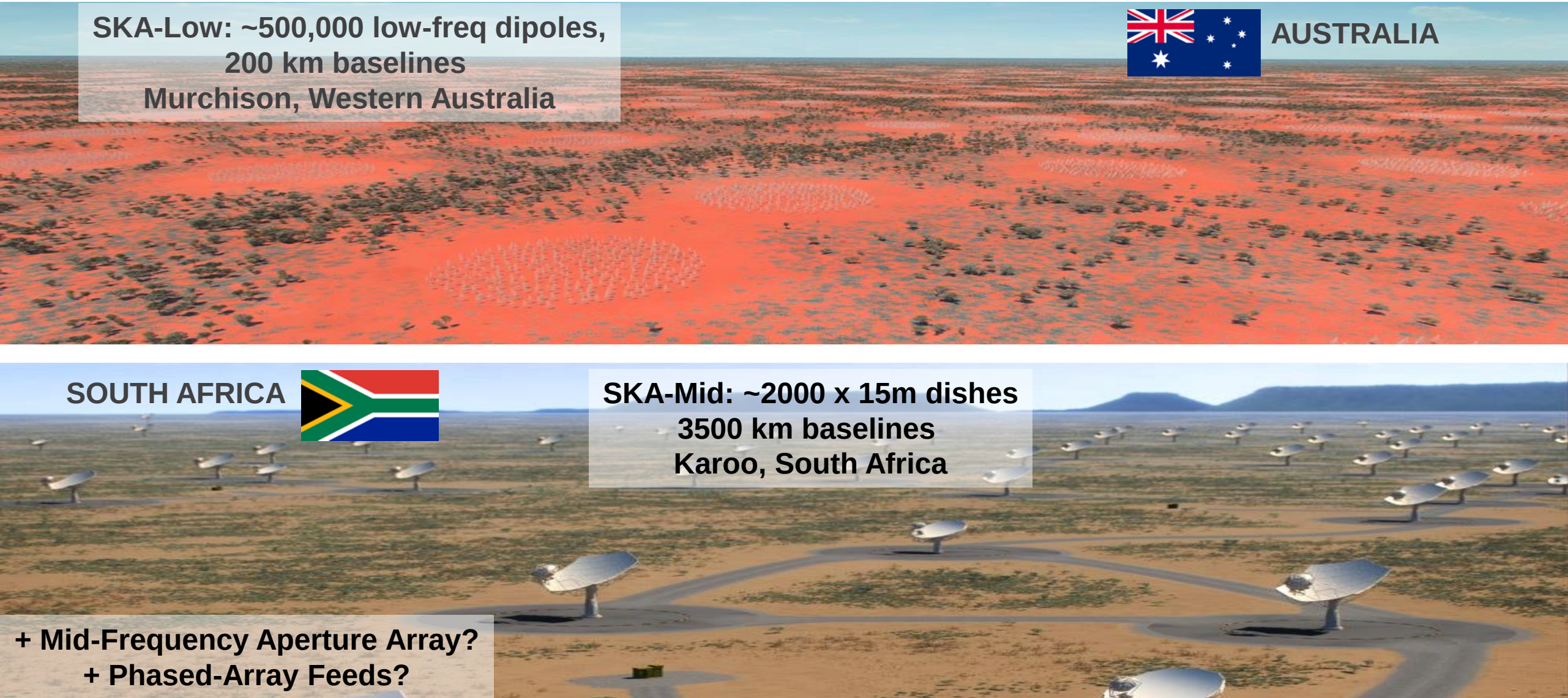
- SKA1-LOW: 50 – 350 MHz
- Phase 1: ~130,000 Antennas
- Across 65km

- SKA1-MID: 350 MHz – 24 GHz
- Phase 1: ~200 15m Dishes
- Across 150 km

SKA – Phase 1

- Currently at the end of the Design Phase
- 9 Design Consortia
- > €200M, >500 engineers and scientists
- Construction: 2021 – 2028
- Cost of Construction + 10 Years Operation: ~ €1.7 Billion
- MeerKAT will be integrated into SKA1-MID

SKA – Phase 2 (2030s?)



SKA-Low: ~500,000 low-freq dipoles,
200 km baselines
Murchison, Western Australia

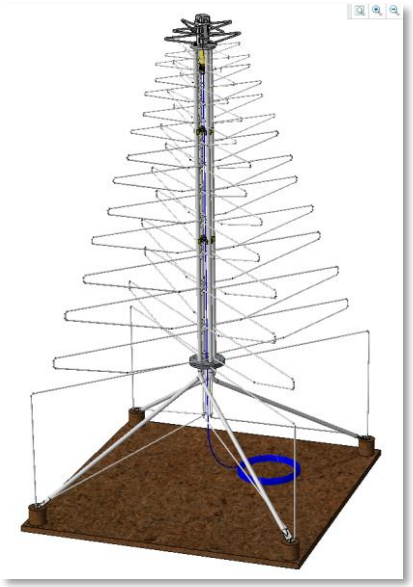
AUSTRALIA

SOUTH AFRICA

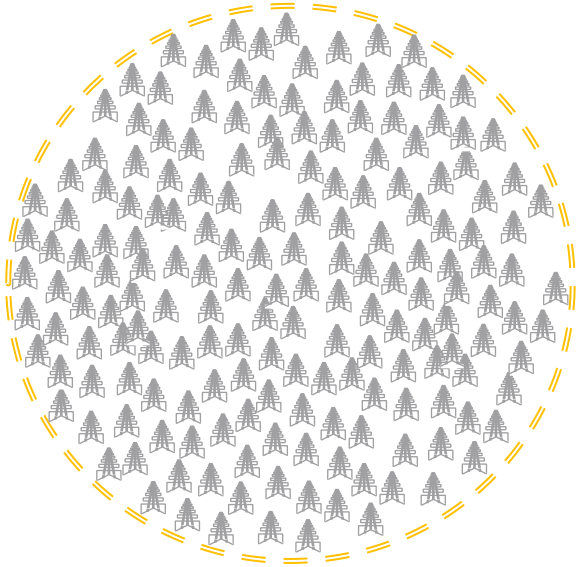
SKA-Mid: ~2000 x 15m dishes
3500 km baselines
Karoo, South Africa

+ Mid-Frequency Aperture Array?
+ Phased-Array Feeds?

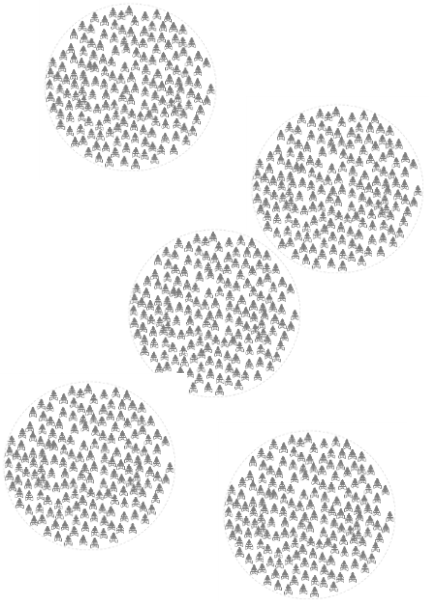
SKA1-Low: Array of Arrays



256



512



SKA1-Low
Antenna/Receptor

Antenna Beam

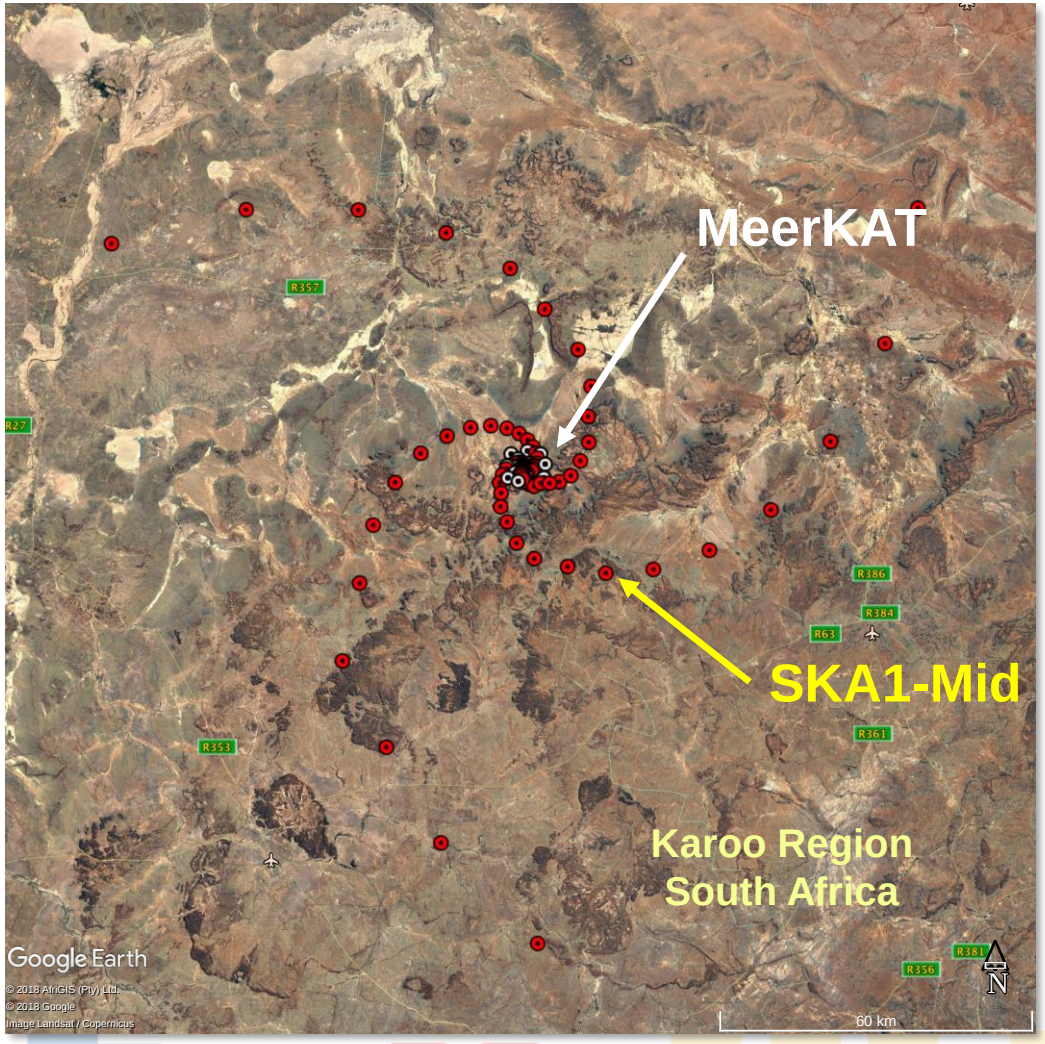
SKA1-Low
"Station"

Station Beam

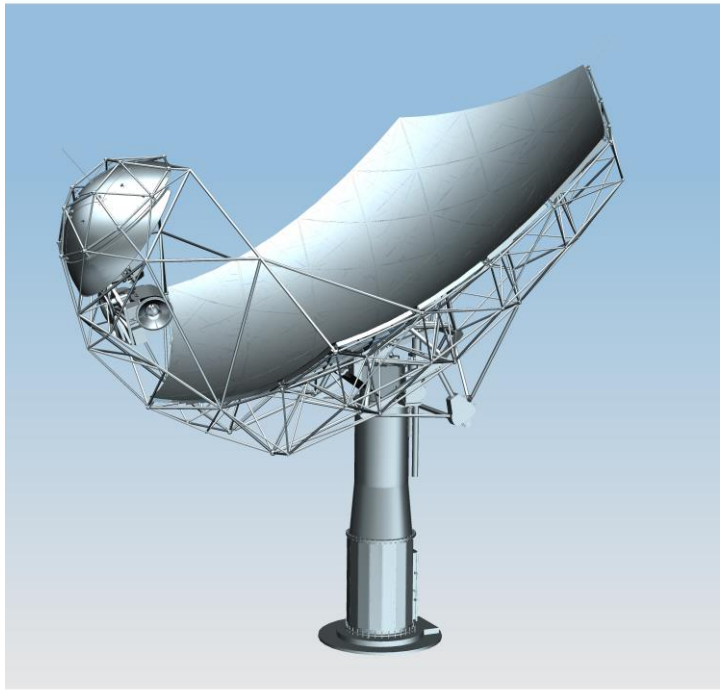
SKA1-Low
"Array"

Correlation and
Tied-array Beams

SKA1-Mid: Layout



- 133 SKA 15m Dishes
- 64 MeerKAT 13.5m Dishes
- Maximum baseline 150 km
- 3 logarithmic spiral arms
- ~ 50% within ~2 km

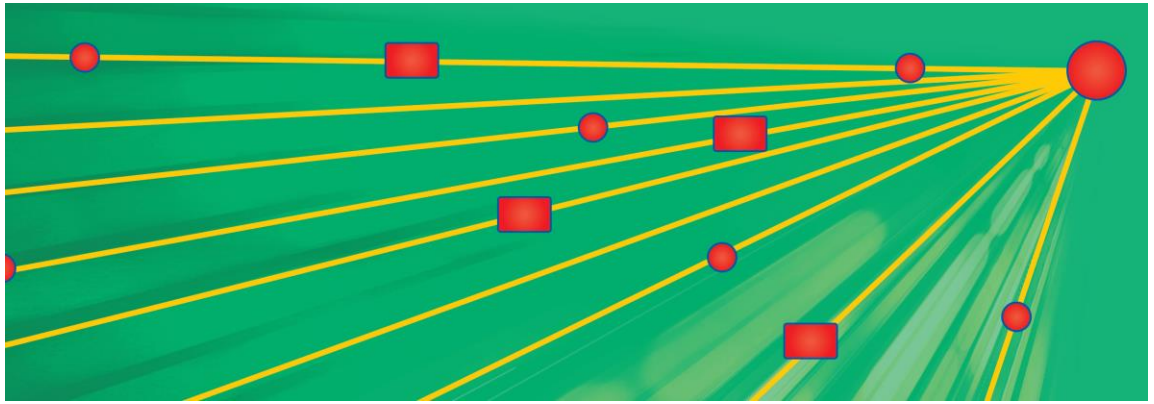


SKA Organisation ➔ SKA Observatory

- SKA Member governments are negotiating the establishment of an **Inter Governmental Organisation (IGO)**, similar to ESO/CERN/ITER/ESA.
- Will provide:
  - Long-term government commitment and funding stability
  - Availability of Privileges and Immunities for members
  - ‘Freedom to operate’, specifically through procurement process
- Critical step to allow SKA Observatory to operate as an international scientific facility

Seven members signed IGO Convention in Rome, 12 March 2019

The Netherlands, Italy and South Africa already ratified the SKA Convention



Integration & Verification Planning

It’s all about Managing Risk

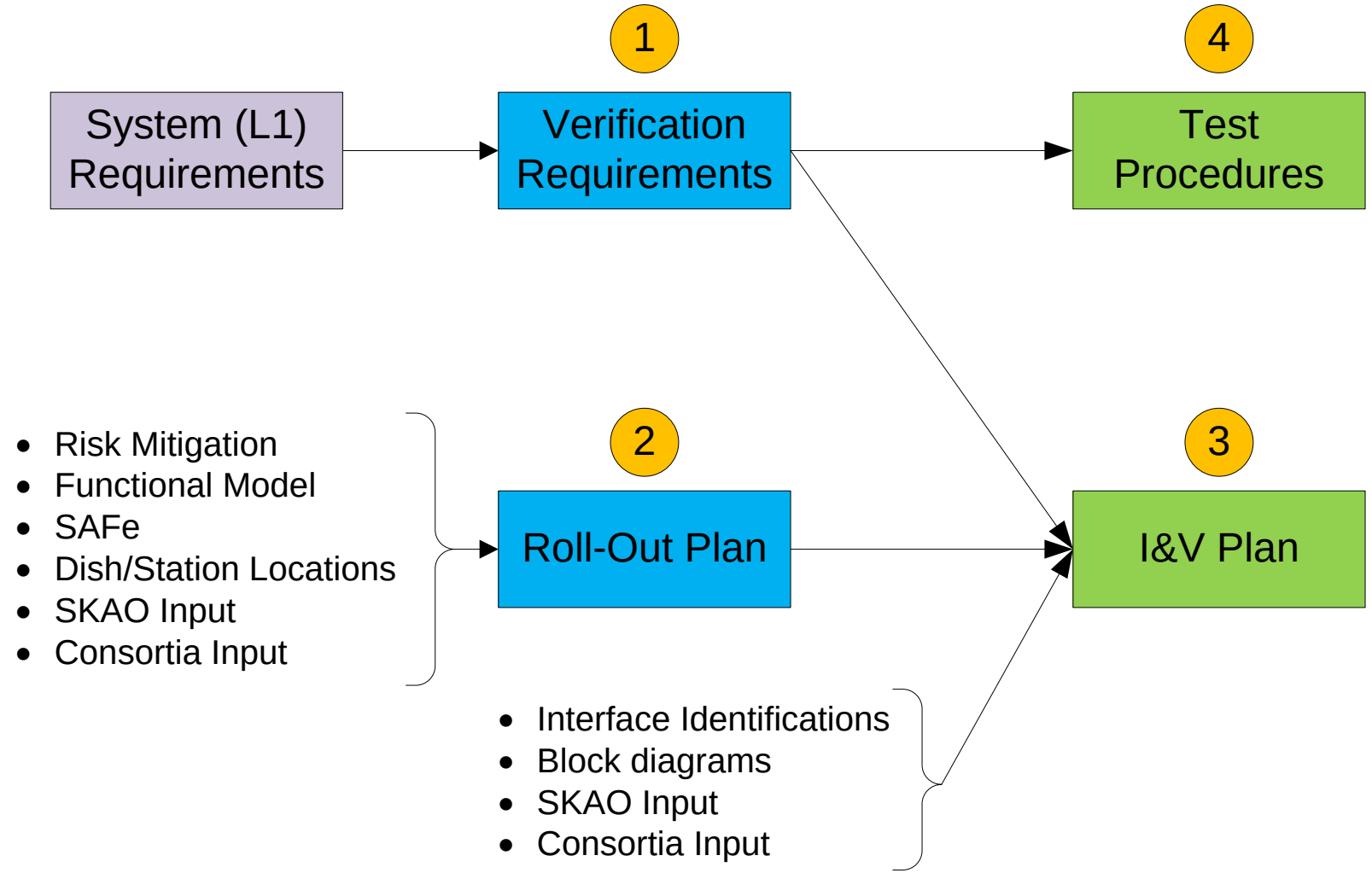
- Are we building the right thing?
  - Validation of the Design

- Are we building it correctly?
  - Verification of Requirements

AIV Consortium

SARAO led the AIV Consortium

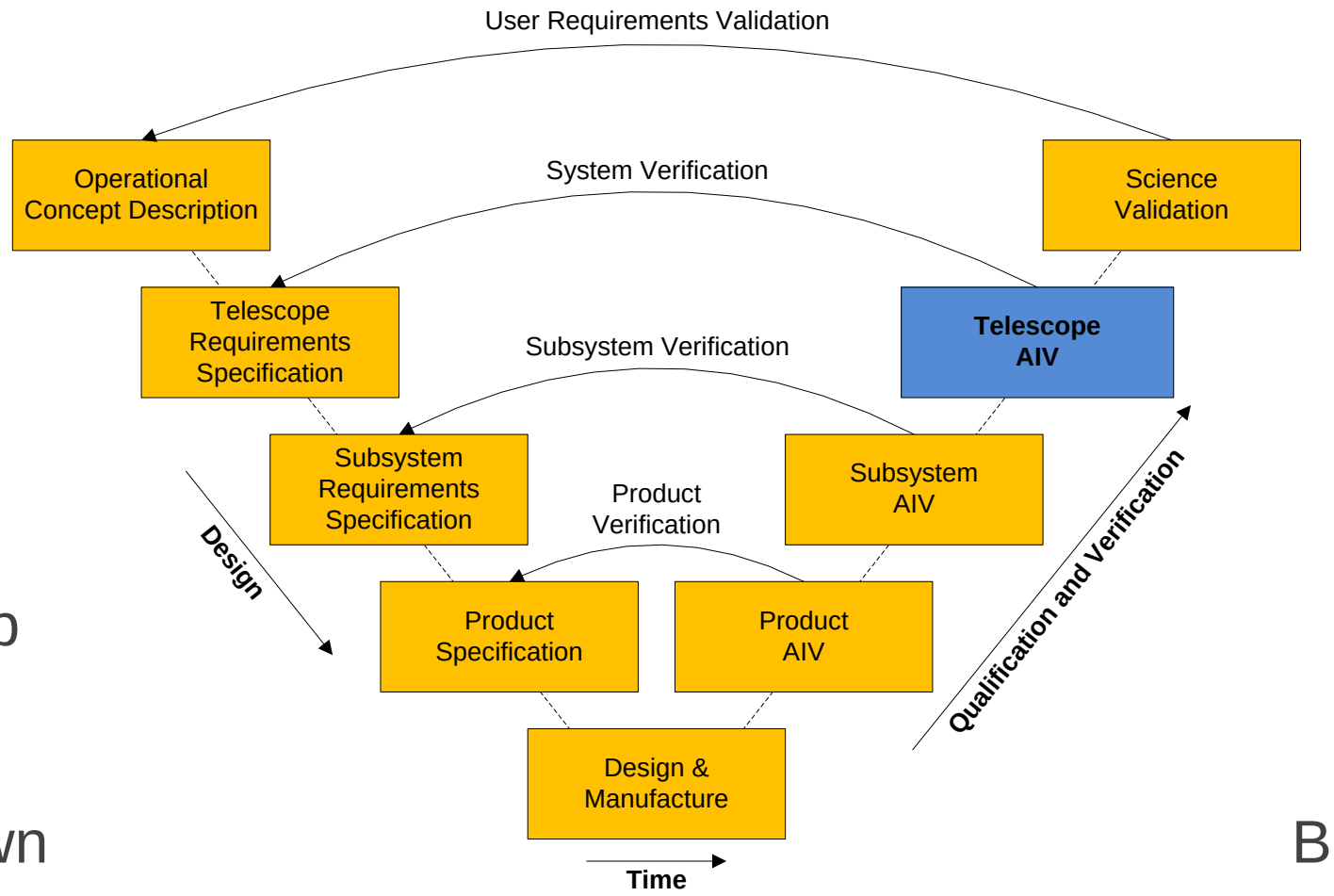
I&V Planning – Key Outputs



SKA Challenges

- Unprecedented Scale
  - Distance of 150 km between two SKA1-MID Dishes
  - Enormous amount of data traffic
  - Fastest supercomputer
- Co-Hosting
  - SKA1-MID in South Africa's Karoo
  - SKA1-LOW in Western Australia's Murchison Shire
- A global effort
  - Fifteen participating countries
  - 500 engineers and scientists
  - from around 100 organisations
  - in 20 countries

The V-Diagram



Top

↓

Down

Up

↑

Bottom

Product hand-over process is important

Product Hand-Over Process

- Important quality gate
- Well-tested products -> less system I&V issues
- Factory Acceptance Testing
- On-Site Acceptance Testing
- Product can be supported and maintained after hand-over

Subsystem CDRs

- Should provide evidence that design requirements have been met
- Heavy reliance on analysis
- Interfacing products do not exist
- Simulators/Emulators might mask problems
- Prototype hardware used
- Different levels of rigor applied

⇒ System-level risks remain, even after product-level designs have been qualified

⇒ Qualify aspects of the design at system level early during construction

System Integration Test Facility (ITF)

- Line-up of products to (partially) qualify the system-level design
- Convenient environment to
  - install products
  - integrate with other products
  - test product-to-product interfaces
  - troubleshoot issues, etc
- Verify new releases of software/firmware (and hardware), before installing on-site
- Knowledge transfer between contractors, engineers, AIV Team, Science Commissioning Team, etc

Roll-Out Plan

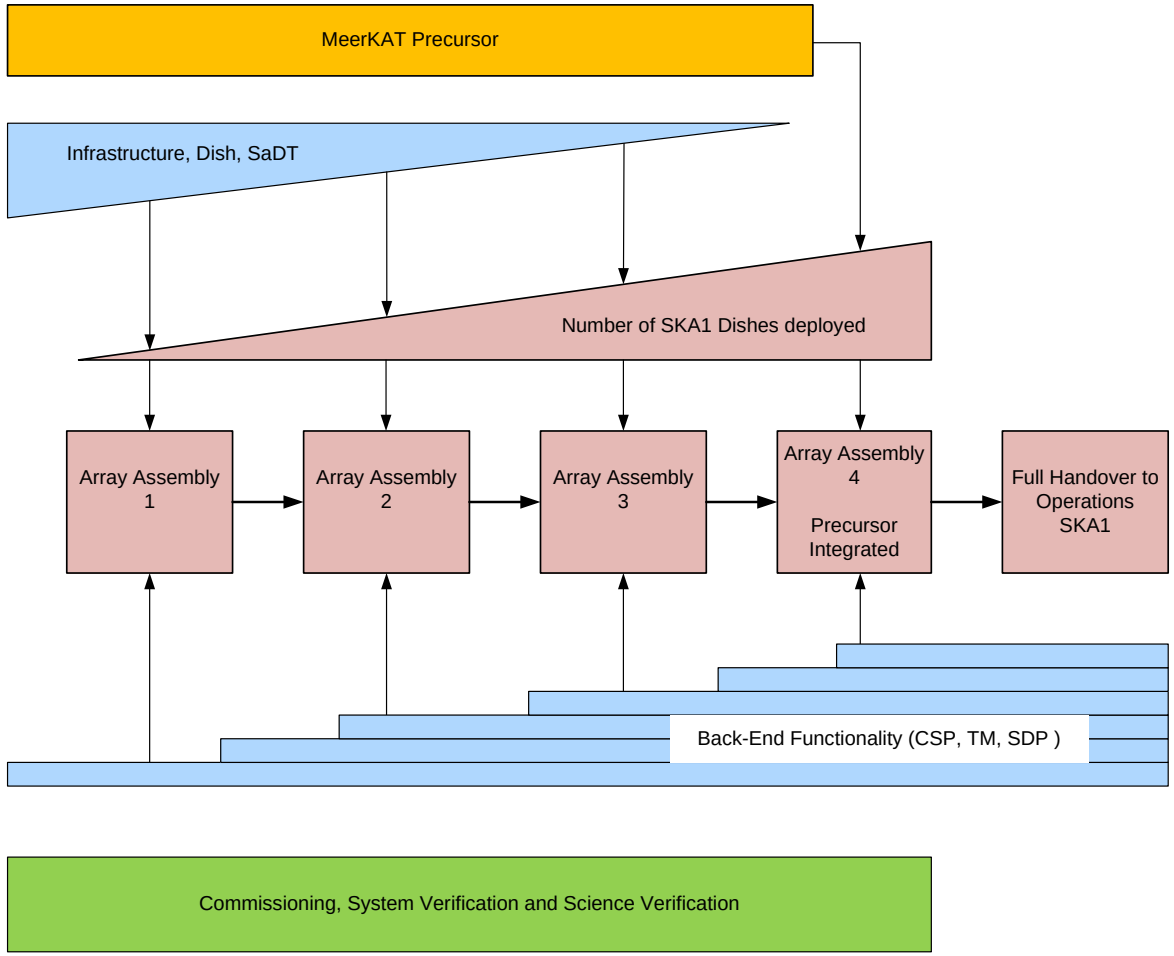
- Forms the basis for the delivery of products and planning of integration & verification activities
- Considers:
  - Sequencing of implemented functionality
  - Scale: How many Dishes / Stations deployed and when
  - Integration of MeerKAT Precursor into SKA1-MID

- Sequential process – early retirement of risks
- Achieved by specifying “Array Assemblies”

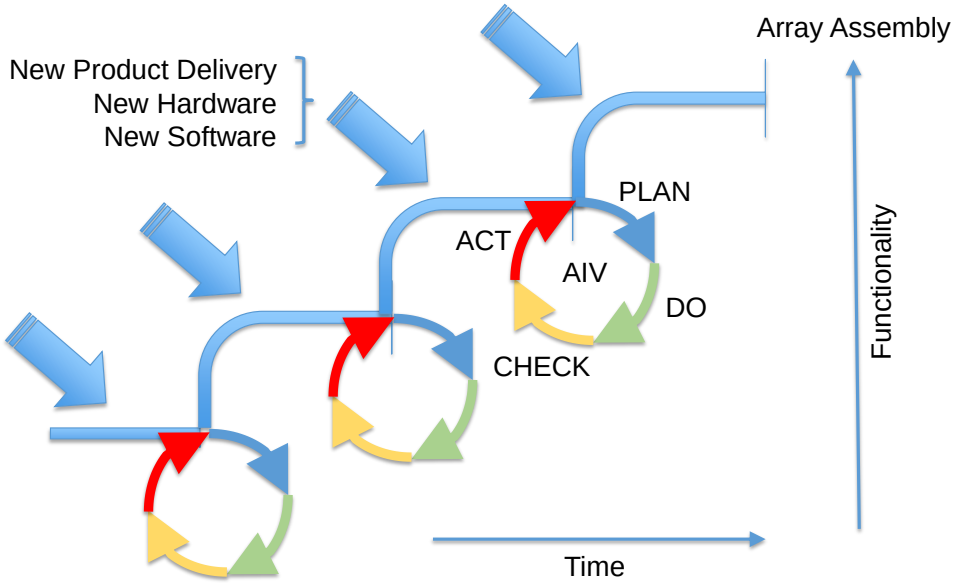
Array Assemblies

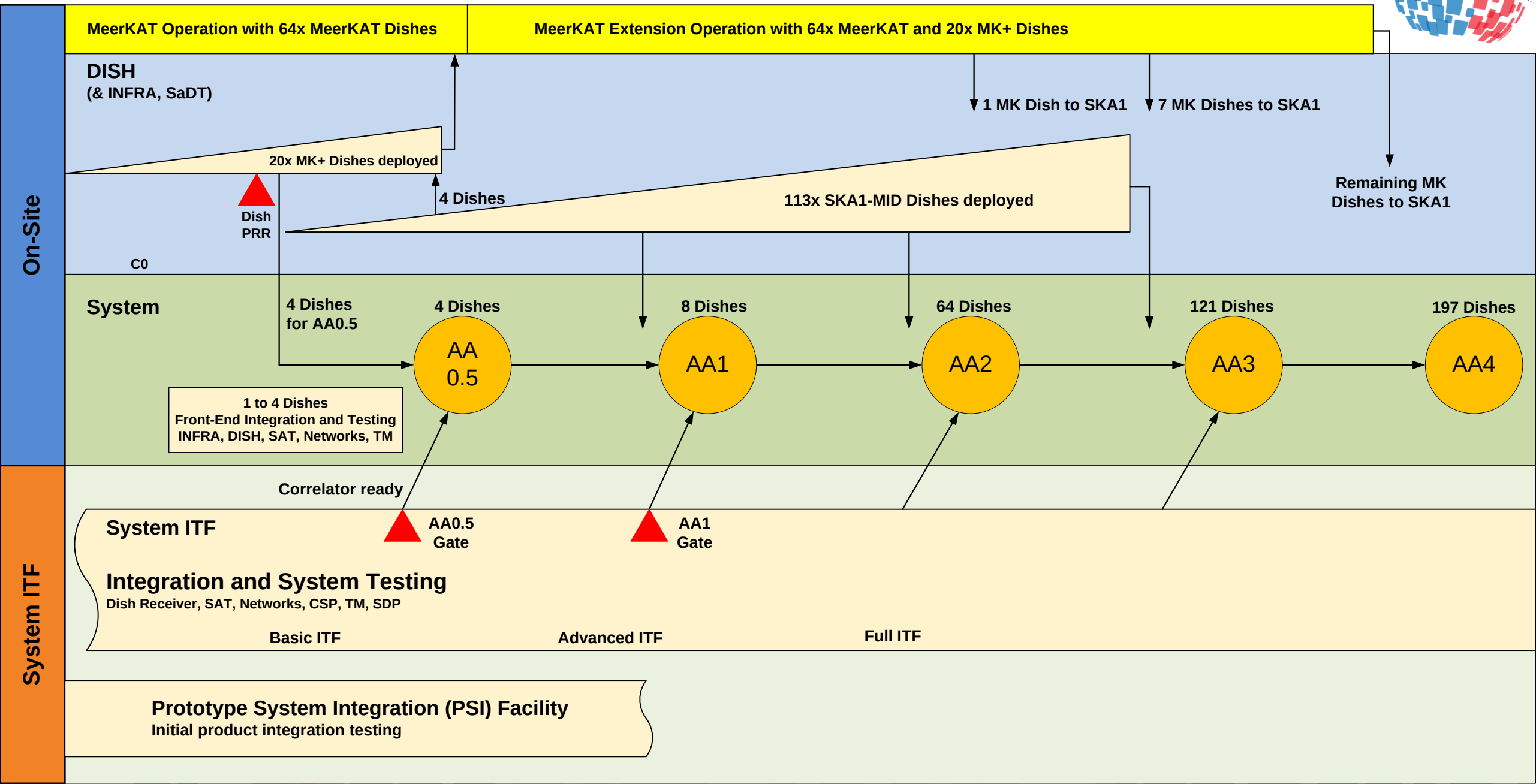
- Fixed number of Dishes / Stations
  - Determined by Correlator size
  - But: Flexibility regarding *which* Dishes / Stations
- Defined Capability / Functionality
  - Basis for the delivery of products and planning of I&V activities
  - Informed by the risks that need to be mitigated
- Start Date
  - When all AA components are available
  - But: Maintain I&V flexibility regarding exact product delivery date

Sequential Roll-Out



- Verify the system in stages
- Detect problems early
- Apply design changes early

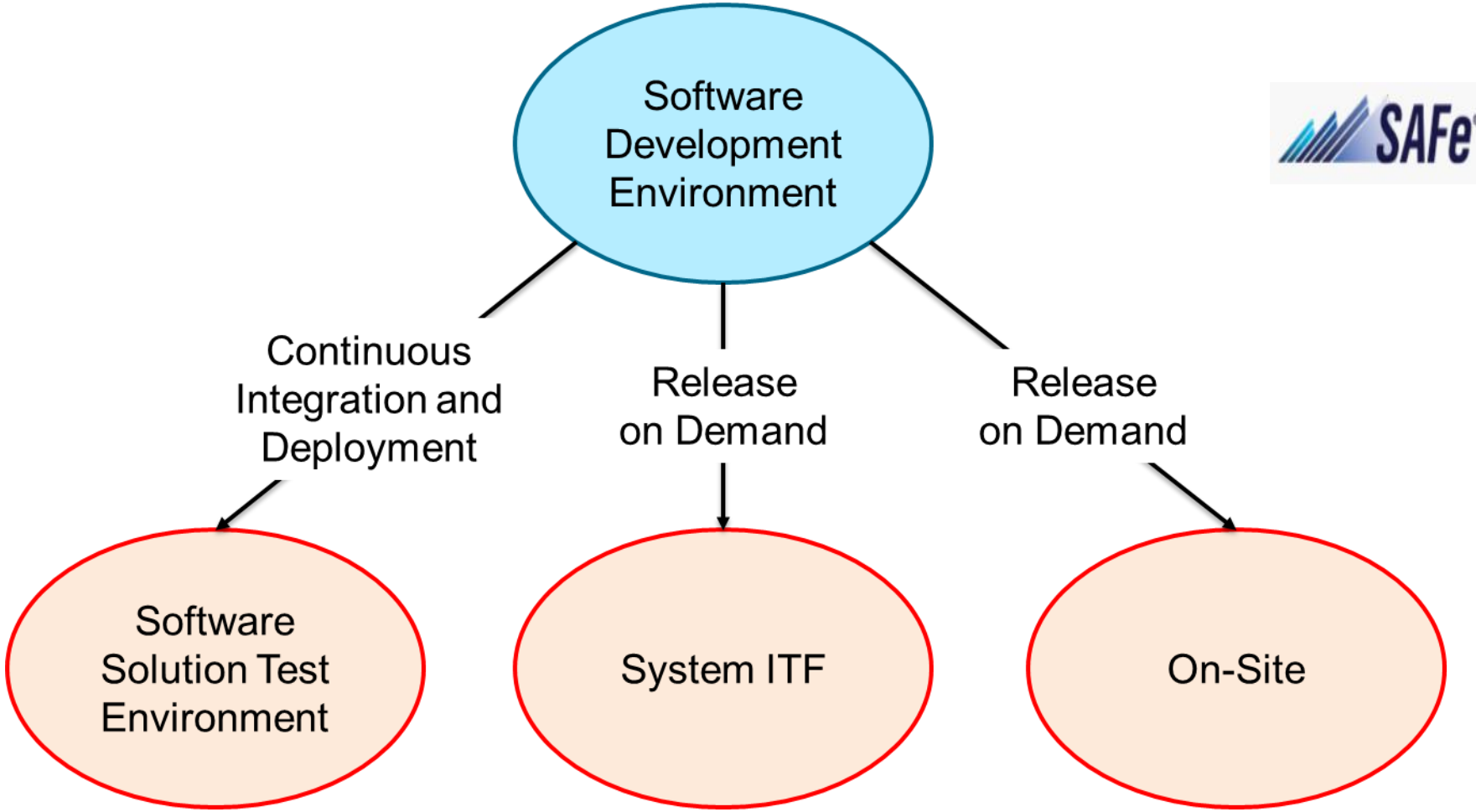



On-Site
System ITF
MeerKAT Operation with 64x MeerKAT Dishes
MeerKAT Extension Operation with 64x MeerKAT and 20x MK+ Dishes
DISH
(& INFRA, SaDT)
1 MK Dish to SKA1
7 MK Dishes to SKA1
20x MK+ Dishes deployed
4 Dishes
113x SKA1-MID Dishes deployed
Remaining MK
Dishes to SKA1
Dish
PRR
C0
System
4 Dishes
for AA0.5
4 Dishes
8 Dishes
64 Dishes
121 Dishes
197 Dishes
AA
0.5
AA1
AA2
AA3
AA4
1 to 4 Dishes
Front-End Integration and Testing
INFRA, DISH, SAT, Networks, TM
Correlator ready
System ITF
AA0.5
Gate
AA1
Gate
Integration and System Testing
Dish Receiver, SAT, Networks, CSP, TM, SDP
Basic ITF
Advanced ITF
Full ITF
Prototype System Integration (PSI) Facility
Initial product integration testing

Rolling out Software

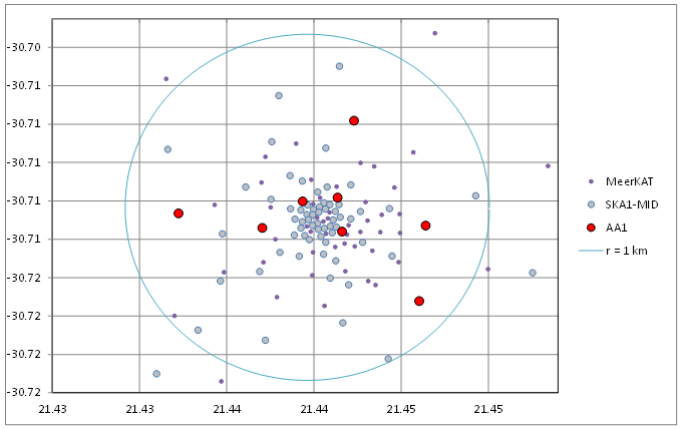
- Scaled Agile Framework (SAFe ®)
- An agile process that allows scalability of overall team size by having “teams of teams”
- 3-month “cadence” called Program Increment
- Release on demand, develop on cadence
- Continuously builds value and reduces risk
- Has an evolving architectural runway
- Working product demonstrated frequently
- Regular stakeholder engagement

Rolling out Software

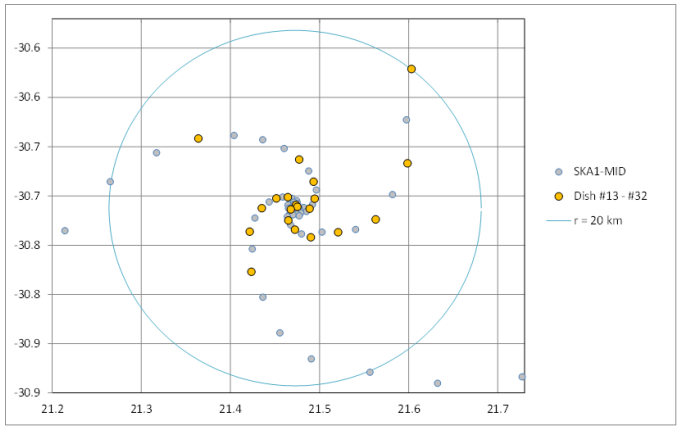


Roll-Out of MID Configuration

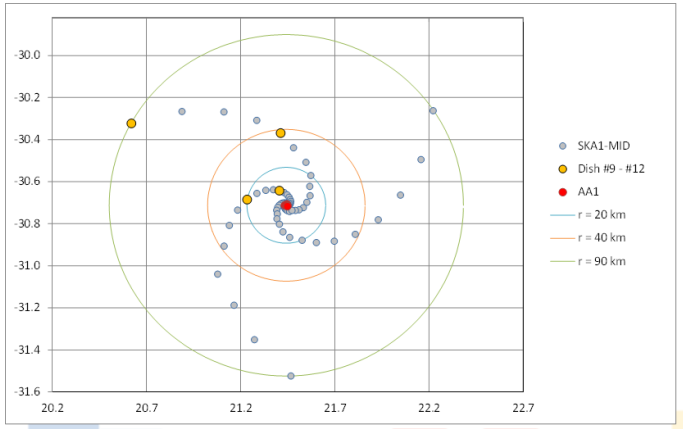
Batch #1 (8 Dishes = AA1)



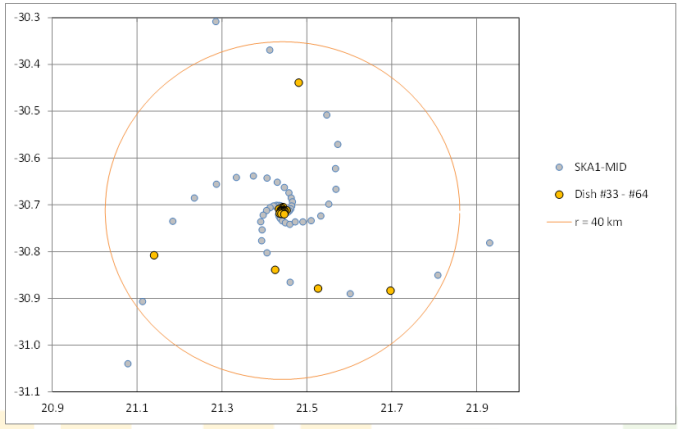
Batch #3 (+20 Dishes)



Batch #2 (+4 Dishes)



Batch #4 (+32 Dishes)



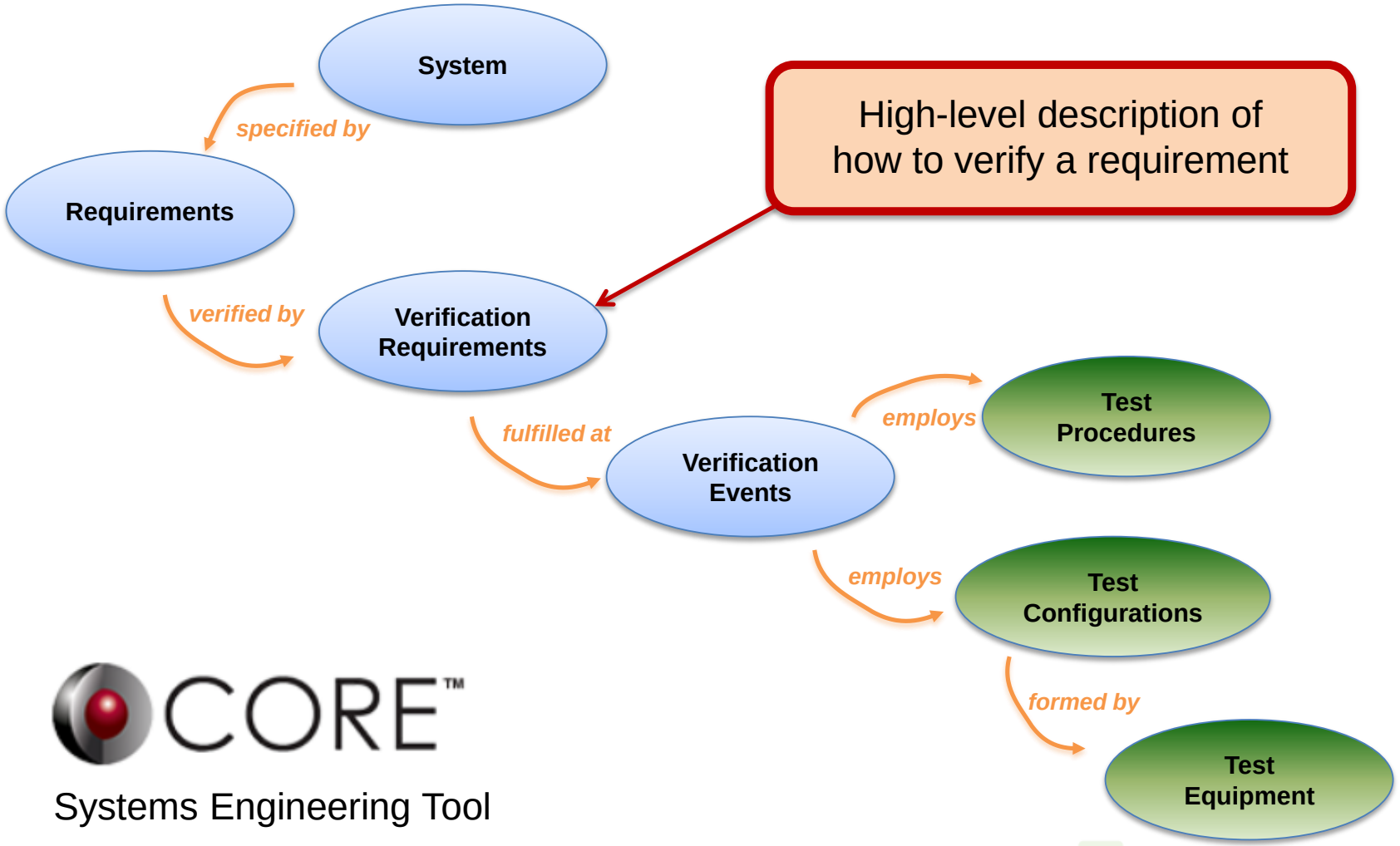
Considerations:

- Verification and commissioning requirements
- Minimisation of costs
- Infrastructure constraints, including the roll-out of PV stations

Verification Requirements

- High-level description of how each requirement will be verified
- At what level of system integration the verification will be performed
  - System ITF, AA0.5, AA1, AA2, AA3, AA4
- Who is responsible for executing the verification
  - AIV Team, Science Commissioning Team, etc

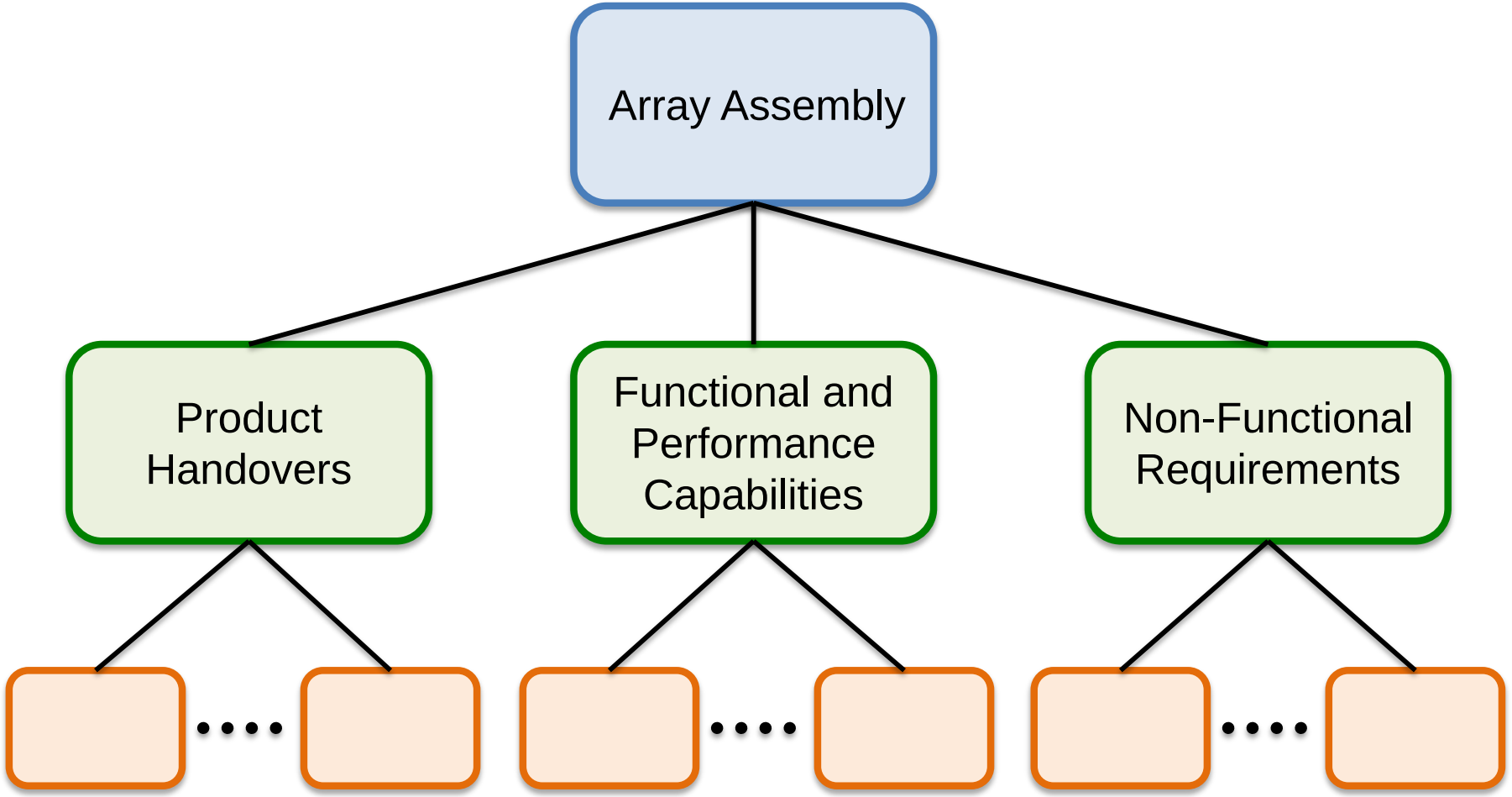
Verification Model



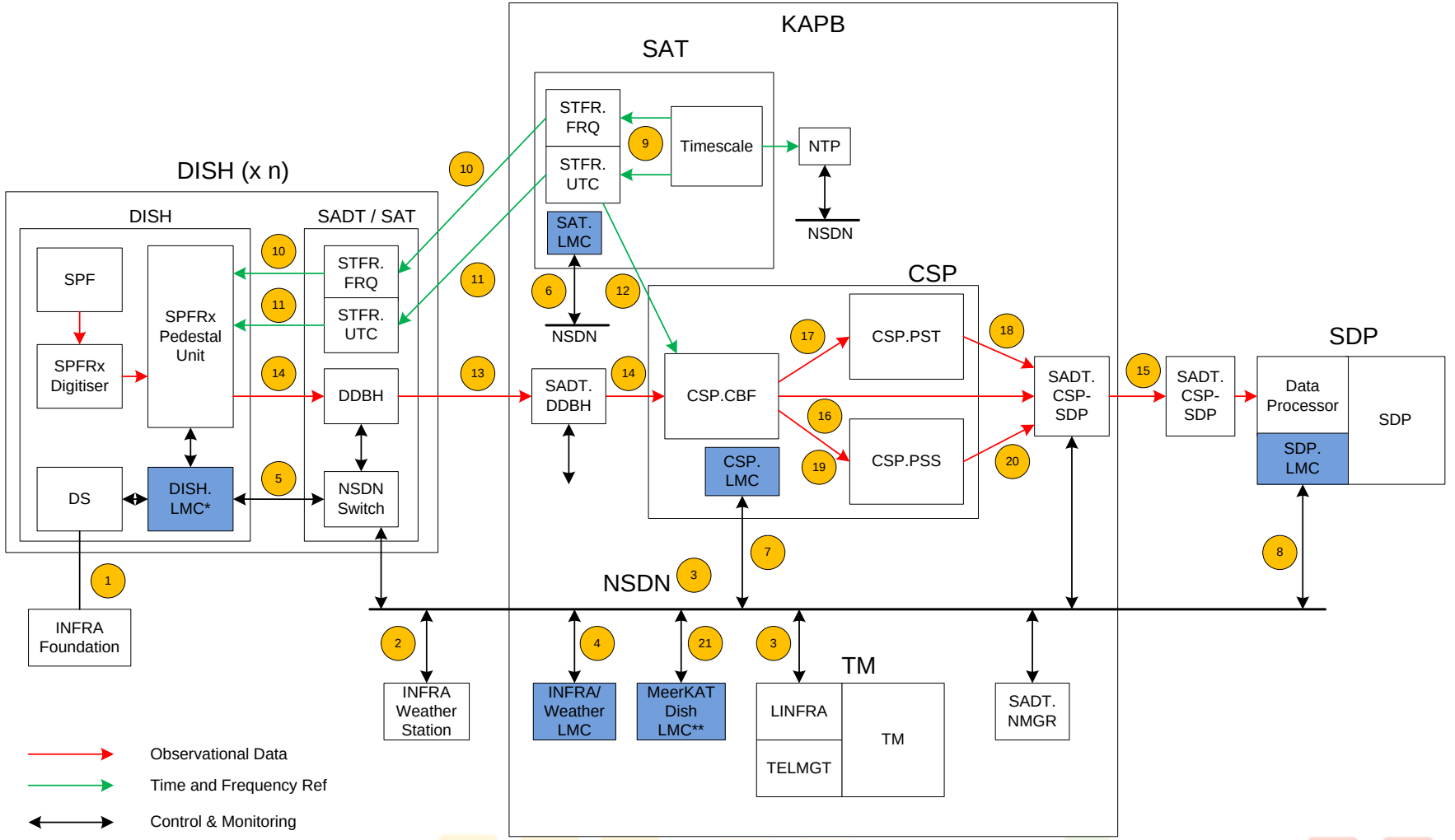
CORE™

Systems Engineering Tool

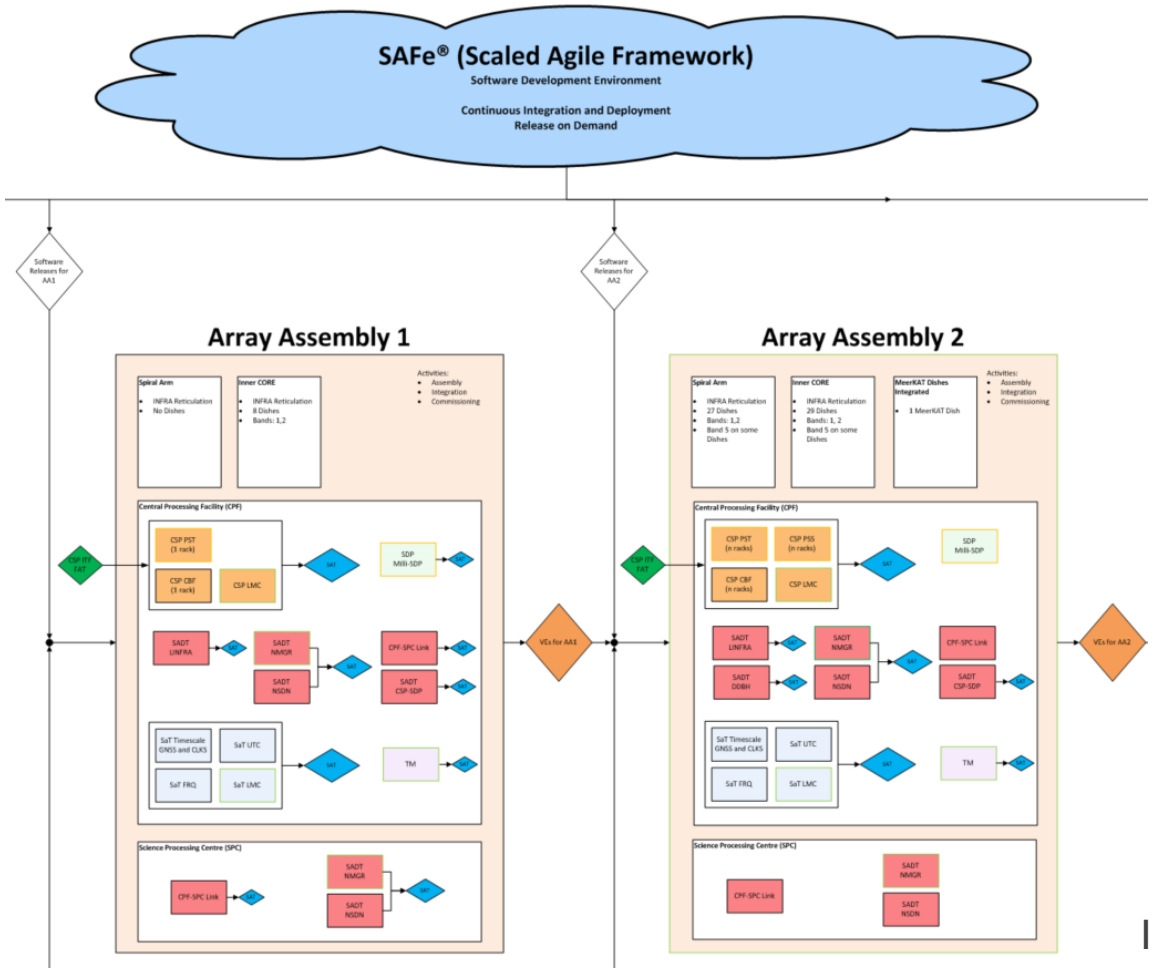
Verification Events



Integration Events



Verification Flow



- Sequencing of milestones and dependencies
- Factory Acceptance Tests
- Delivery of hardware or software to site
- Site Acceptance Tests
- Major Verification Events
- Hand-over of responsibility from product contractor to SKAO

Useful to ensure that there are no gaps in the verification planning

Initiated by L. Stringhetti

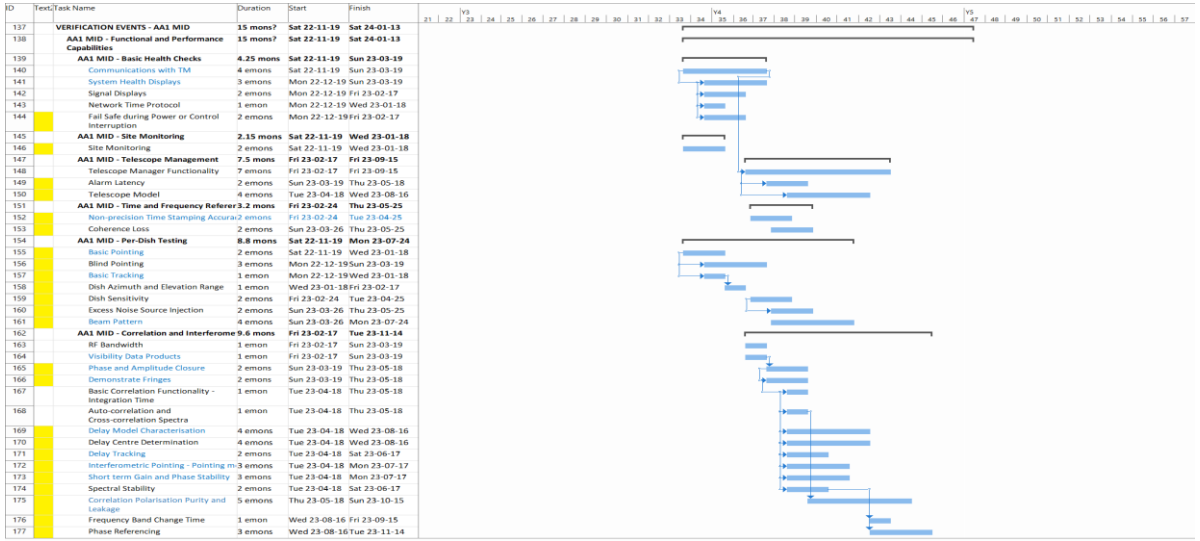
Test Procedures

- Exported directly from CORE
- Full traceability is given with regard to:
  - The originating System (Level-1) Requirement
  - The derived Verification Requirement
  - The Test Procedure executing the Verification Requirement
- Commissioning Tests
  - No traceability to System (Level-1) Requirements
  - But needed to commission the system
- Most tests are repeated at future Array Assemblies

Integration & Verification Plan

- Provides a structured framework, in which all integration and verification activities will be carried out in a coordinated manner
- Identifies:
  - Integration Events
  - Verification Events
- Each event has:
  - Start date
  - Duration
  - Resources
  - Prerequisites

Gantt Chart showing Verification Events



ID	Text	Task Name	Duration	Start	Finish
137		**VERIFICATION EVENTS - AA1 MID**	**15 mons?**	**Sat 22-11-19**	**Sat 24-01-13**
138		**AA1 MID - Functional and Performance Capabilities**	**15 mons?**	**Sat 22-11-19**	**Sat 24-01-13**
139		**AA1 MID - Basic Health Checks**	**4.25 mons**	**Sat 22-11-19**	**Sun 23-03-19**
140		Communications with TM	4 emons	Sat 22-11-19	Sun 23-03-19
141		System Health Displays	3 emons	Mon 22-12-19	Sun 23-03-19
142		Signal Displays	2 emons	Mon 22-12-19	Fri 23-02-17
143		Network Time Protocol	1 emon	Mon 22-12-19	Wed 23-01-18
144		Fail Safe during Power or Control Interruption	2 emons	Mon 22-12-19	Fri 23-02-17
145		**AA1 MID - Site Monitoring**	**2.15 mons**	**Sat 22-11-19**	**Wed 23-01-18**
146		Site Monitoring	2 emons	Sat 22-11-19	Wed 23-01-18
147		**AA1 MID - Telescope Management**	**7.5 mons**	**Fri 23-02-17**	**Fri 23-09-15**
148		Telescope Manager Functionality	7 emons	Fri 23-02-17	Fri 23-09-15
149		Alarm Latency	2 emons	Sun 23-03-19	Thu 23-05-18
150		Telescope Model	4 emons	Tue 23-04-18	Wed 23-08-16
151		**AA1 MID - Time and Frequency Referer**	**3.2 mons**	**Fri 23-02-24**	**Thu 23-05-25**
152		Non-precision Time Stamping Accura	2 emons	Fri 23-02-24	Tue 23-04-25
153		Coherence Loss	2 emons	Sun 23-03-26	Thu 23-05-25
154		**AA1 MID - Per-Dish Testing**	**8.8 mons**	**Sat 22-11-19**	**Mon 23-07-24**
155		Basic Pointing	2 emons	Sat 22-11-19	Wed 23-01-18
156		Blind Pointing	3 emons	Mon 22-12-19	Sun 23-03-19
157		Basic Tracking	1 emon	Mon 22-12-19	Wed 23-01-18
158		Dish Azimuth and Elevation Range	1 emon	Wed 23-01-18	Fri 23-02-17
159		Dish Sensitivity	2 emons	Fri 23-02-24	Tue 23-04-25
160		Excess Noise Source Injection	2 emons	Sun 23-03-26	Thu 23-05-25
161		Beam Pattern	4 emons	Sun 23-03-26	Mon 23-07-24
162		**AA1 MID - Correlation and Interferome**	**9.6 mons**	**Fri 23-02-17**	**Tue 23-11-14**
163		RF Bandwidth	1 emon	Fri 23-02-17	Sun 23-03-19
164		Visibility Data Products	1 emon	Fri 23-02-17	Sun 23-03-19
165		Phase and Amplitude Closure	2 emons	Sun 23-03-19	Thu 23-05-18
166		Demonstrate Fringes	2 emons	Sun 23-03-19	Thu 23-05-18
167		Basic Correlation Functionality - Integration Time	1 emon	Tue 23-04-18	Thu 23-05-18
168		Auto-correlation and Cross-correlation Spectra	1 emon	Tue 23-04-18	Thu 23-05-18
169		Delay Model Characterisation	4 emons	Tue 23-04-18	Wed 23-08-16
170		Delay Centre Determination	4 emons	Tue 23-04-18	Wed 23-08-16
171		Delay Tracking	2 emons	Tue 23-04-18	Sat 23-06-17
172		Interferometric Pointing - Pointing m	3 emons	Tue 23-04-18	Mon 23-07-17
173		Short term Gain and Phase Stability	3 emons	Tue 23-04-18	Mon 23-07-17
174		Spectral Stability	2 emons	Tue 23-04-18	Sat 23-06-17
175		Correlation Polarisation Purity and Leakage	5 emons	Thu 23-05-18	Sun 23-10-15
176		Frequency Band Change Time	1 emon	Wed 23-08-16	Fri 23-09-15
177		Phase Referencing	3 emons	Wed 23-08-16	Tue 23-11-14

Configuration Management

- Critical to the I&V effort
- Hardware / Firmware / Software configuration status of the Telescope has to be recorded with test results

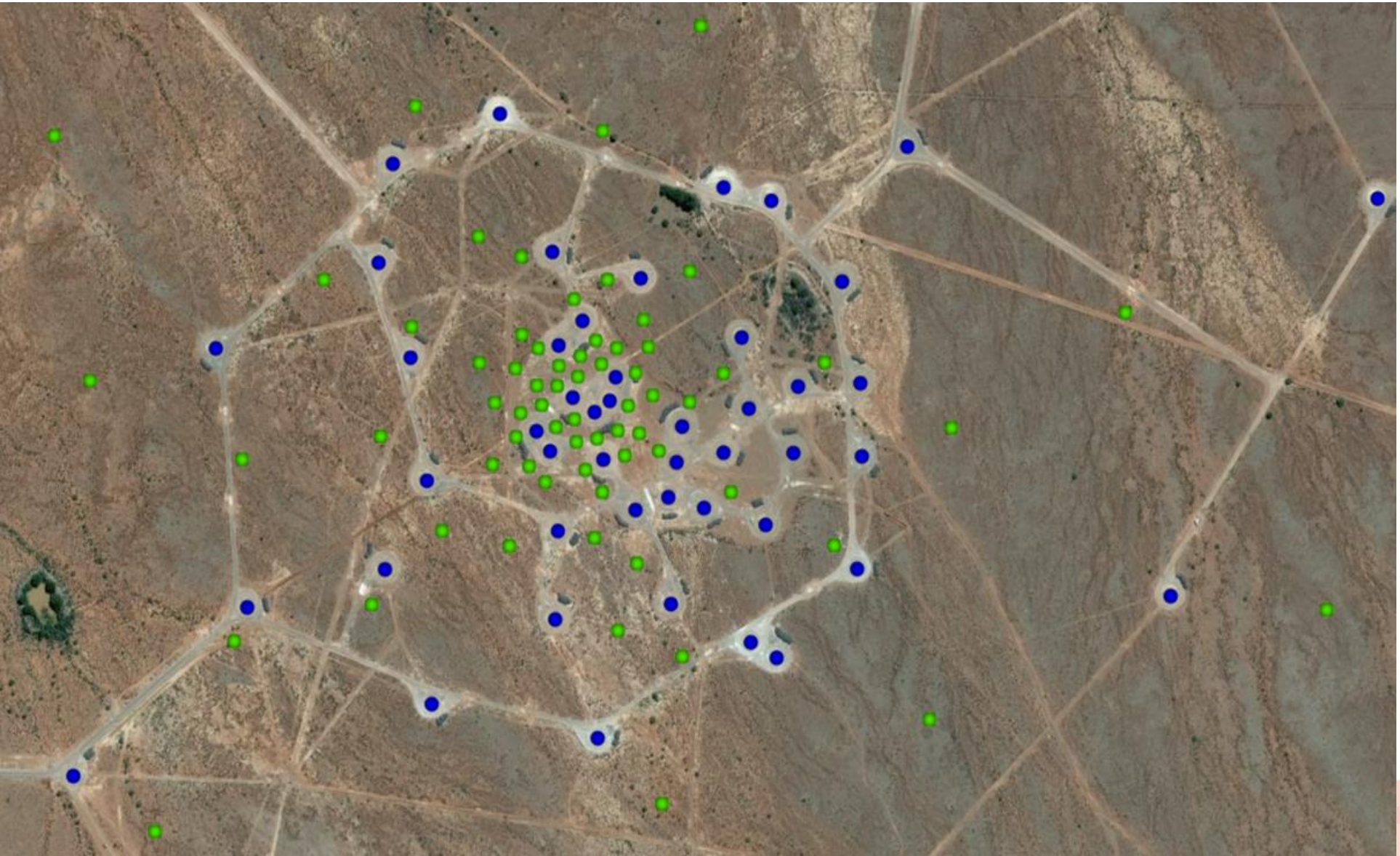
MeerKAT Precursor Integration

MeerKAT Precursor Integration

- Significant activity which carries schedule, technical and budgetary risks
- Requires careful roll-out planning
- Ensure that interfaces between MeerKAT components and SKA1-MID components are fully described

MeerKAT Precursor Telescope Dishes

SKA1-MID Core Area



Blue Dots = MeerKAT Dishes

Green Dots = SKA1-MID Dishes

Integration Timeline

AA1	AA2	AA3	AA4

Preliminary Testing

- LMC integration in ITF
- Feed to Digitiser interface
- SDC Cooling verification
- EMI verification
- LMC installation

Retro-fit and Integrate 1st MeerKAT Dish

1st Dish Handover

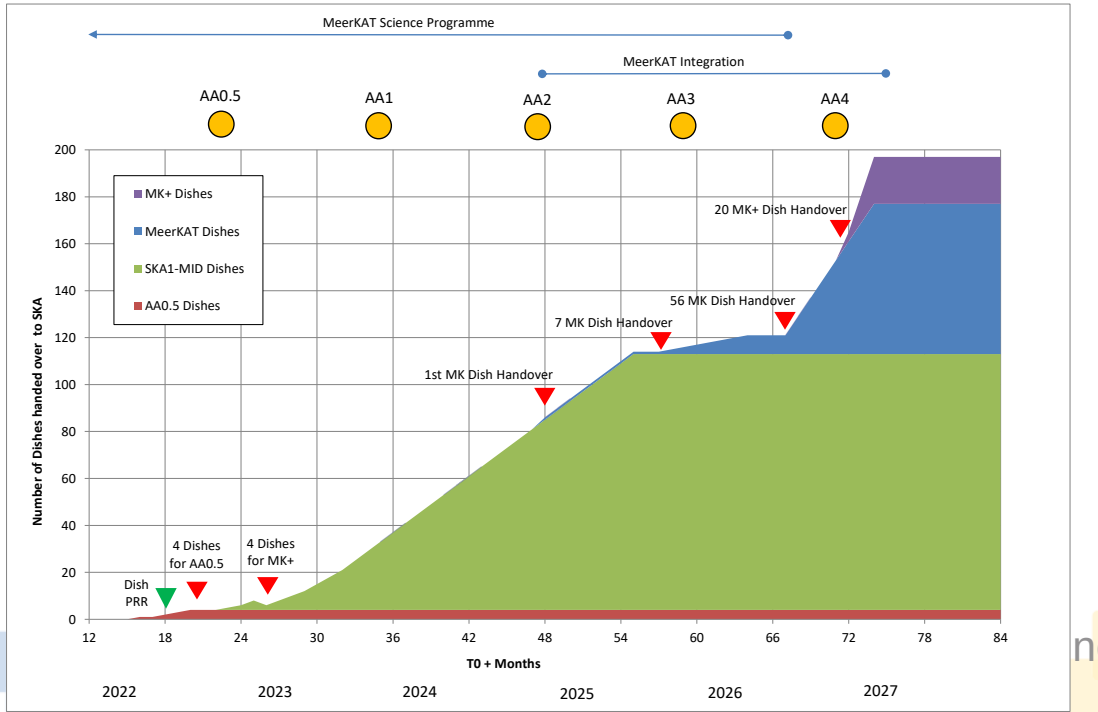
Retro-fit and Integrate 7 MeerKAT Dishes

7 Dish Handover

Retro-fit and Integrate 76 MeerKAT Dishes

76 Dish Handover

End of MeerKAT Science Program



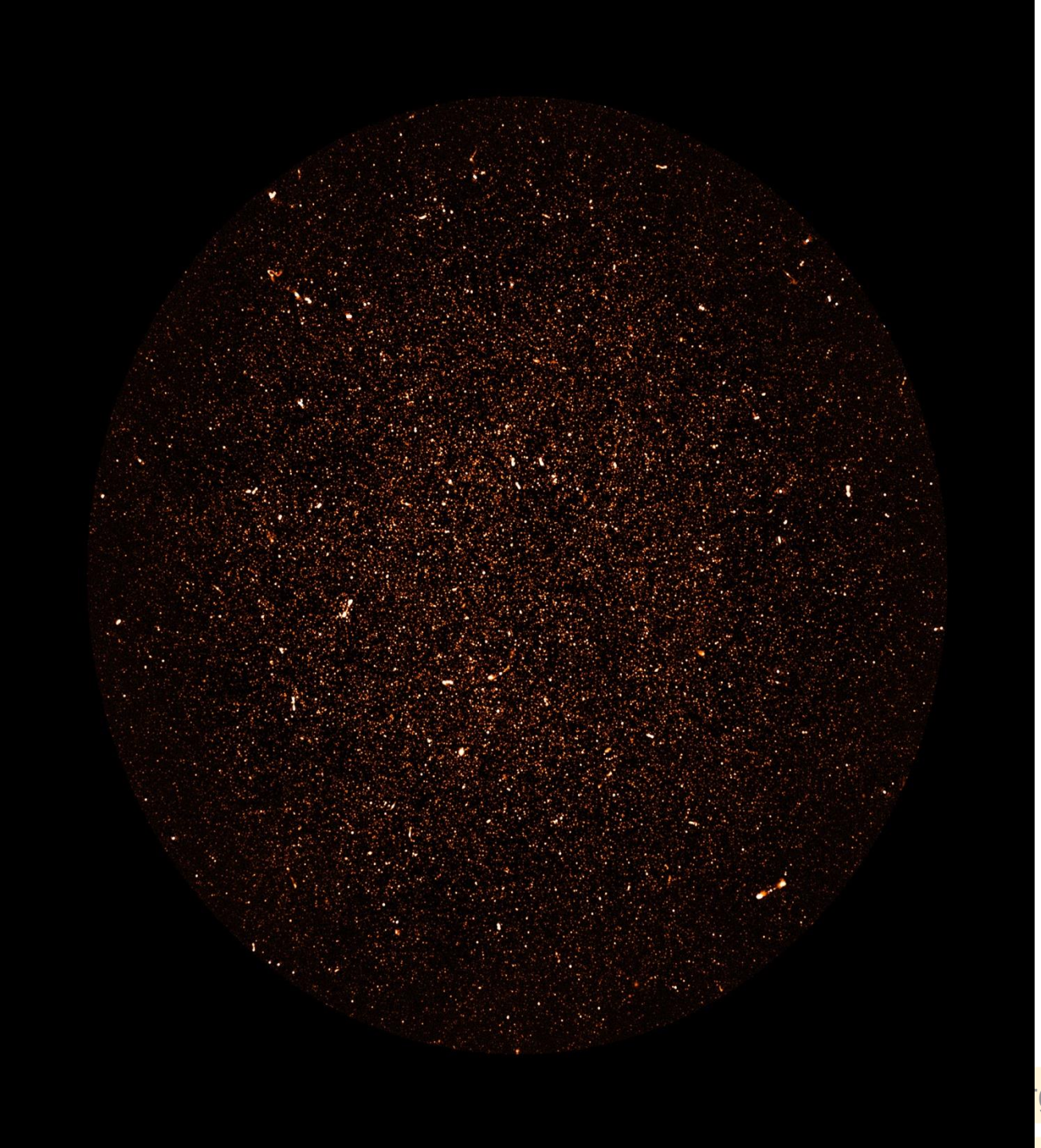
Ramp-up of Dishes over time

The view with an Optical Telescope

Optical image of the famous *Fornax A* galaxy with the MeerLICHT telescope in Sutherland

The view with a Radio Telescope

MeerKAT image of the same field of view as in previous slide



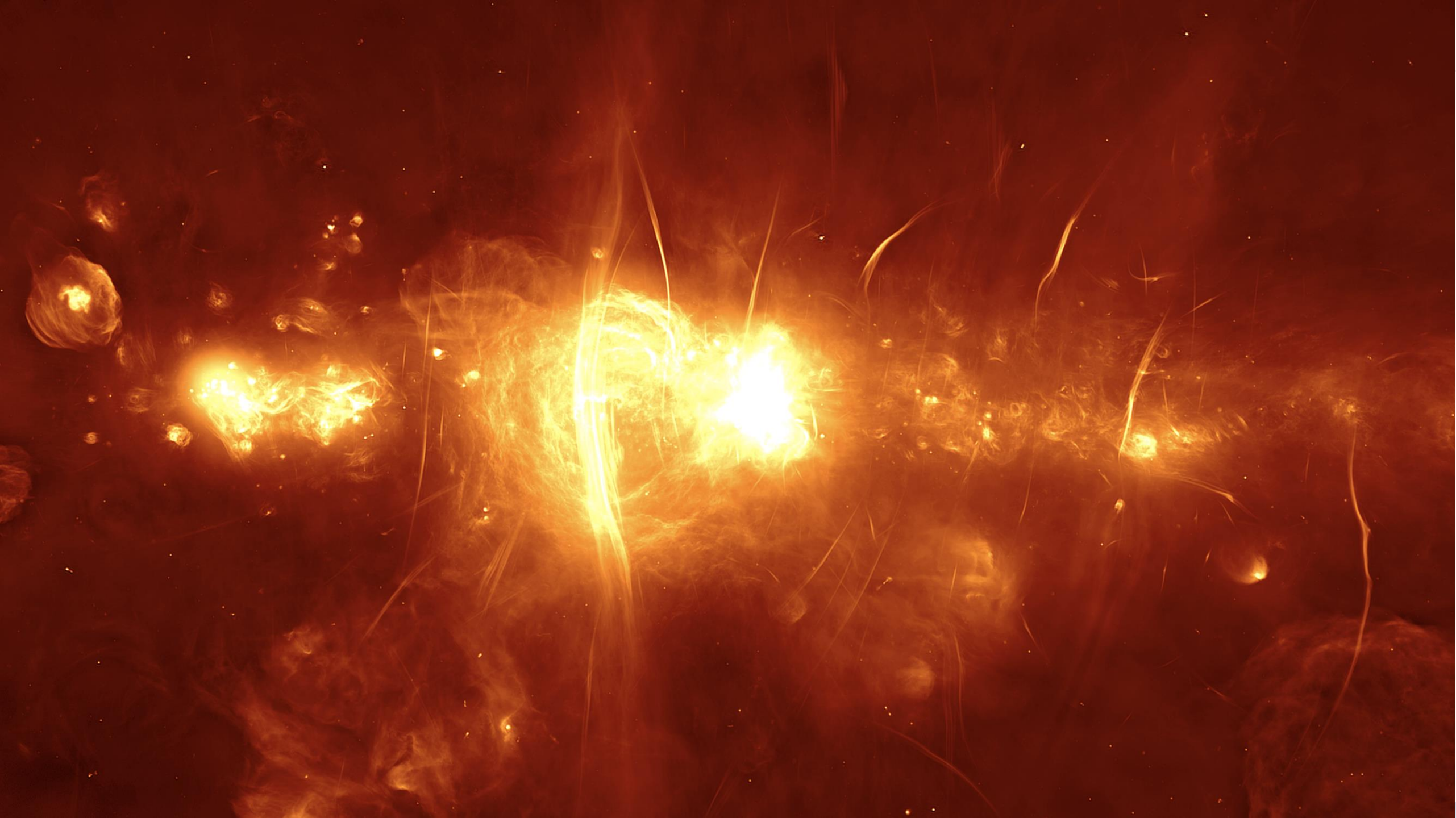
MeerKAT peers deep into the Universe

First radio image of distant Milky Way-like galaxies reveals star formation history of the Universe

Thousands of galaxies are visible in this radio image covering a square degree of sky

t_i = 130 hours

https://www.sarao.ac.za/media-releases/south-africas-meerkat-peers-deep-into-the-universe/



Lessons Learned

- Integrate early and often!
- Roll-out activities and AIV work scope is often under-estimated, even at product level
- Separate R&D from construction
- The value of a qualified solution is immense (much more valuable than another unproven solution that looks good)
- Learn from prototypes
- Accurate and complete requirements (that are traceable to science goals) are very important, especially when placing contracts
- Properly qualify subsystems
- Get timely and effective support and maintenance

Conclusions

- The SKA project is one of the largest scientific endeavours in history
- It needs mature processes and thorough planning in order to succeed
- The Product Hand-Over Process is important
- Develop a staged Roll-Out Plan
- Develop an Integration & Verification Plan
- Maintain Traceability
- Keep looking at Lessons Learned

30th Annual INCOSE international symposium

Virtual Event

July 20 - 22, 2020

www.incose.org/symp2020