SKAO staged delivery, array assemblies and layouts

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1 Introduction

1.1 Purpose of this document

The design baseline of the Low and Mid telescopes of the Square Kilometre Array Observatory (SKAO) consists of 512 stations in Australia and 197 dishes in South Africa. We refer the reader to the SKA Design Baseline Description document for a detailed description of the Low and Mid telescopes [**AD1**].

Interferometers lend themselves to easy expansion as new antennas can be added to existing arrays, provided sufficient compute and network resources are available to accommodate the increased data rates. With this in mind, SKAO has adopted a staged approach to construction where the Low and Mid telescopes are constructed and verified in stages called array assemblies (AA). This ensures that the full functionality of all the software and hardware can be tested and verified at the earliest possible stage during construction.

The purpose of this document is to provide the astronomy community with a single point of reference that describes the array assemblies, and the list of antennas and their coordinates in the array assemblies (AA) that will be available to the scientific community from the start of Science Verification through to the full design baseline. The content presented in this document is complemented by a Python package that allows users to simulate interferometric observations using both the entirety of the dishes or stations available during a particular AA, or a subset of those available (i.e. a "subarray"). Both Low and Mid telescopes are capable of providing up to 16 concurrent subarrays, offering a lot of flexibility to both operations and science observing.

This document and the associated Python package describe the full arrays available through the scientifically available AAs and also provide a means for simulating observations with subarrays in these array assemblies. A few example use cases are demonstrated in Appendix A.

1.2 Scope of this document

This document collates information about the dish/station coordinates, array layout, and timelines of the various AAs from several internal SKAO memos [**AD1-AD8**]. Note that the content presented in this document, including the timelines, reflects the current understanding of rollout plans and is subject to change as construction progresses. This document and the associated software package will be updated and released to reflect any such future changes, as appropriate.

The information presented in this document forms the basis of several memos, such as the definition of subarray templates and commensal observing modes, that the Science Operations team plans to release to the community.

Finally, we encourage feedback from the SKA users community, ideally directly addressed to members of the Science Operations team at sciops@skao.int.

2 Array layout in different array assemblies

SKAO aims to deliver the Low and Mid telescopes that match the design baseline. To test and validate the various functionalities that will be available on the telescopes, the construction phase is split into five stages, each of which is marked by a milestone called an array assembly. The five array assemblies in chronological order are AA0.5, AA1, AA2, AA*, and AA4 (or the design baseline). Table 1 below shows the current timeline of the different array assemblies and key milestones in the development of the SKAO telescopes.

While SKAO is committed to delivering the design baseline, funding to meet this goal has not been fully secured yet. With the funding currently secured[1], SKAO is working towards delivering an intermediate stage called AA*, which will have fewer Mid dishes and Low stations (see Table 1) than available in the design baseline. AA* will support all of the planned observing modes, although some with reduced capacity. As more funding becomes available, the gap between AA* and AA4 (or the design baseline) will be bridged while maintaining a continuously working and expanding facility demonstrating the full performance of the SKA design baseline. Allowing operations to begin at the intermediate AA* stage gives the community access to the SKA to facilitate the delivery of transformational science at the earliest possible stage.

Table 1: Timeline of array assemblies and key milestones [**AD2, AD3, AD4**]. The timeline is based on the Integrated Program Schedule (**AD5**; version Oct 02, 2023).

Milestones	**Mid (end-date)**	**Low (end-date)**
AA0.5 • 4 Mid dishes • 6 Low stations	2025 May	2024 Nov
AA1 • 8 Mid dishes • 18 Low stations	2026 Apr	2025 Nov
AA2 • 64 Mid dishes • 64 Low stations	2027 Mar	2026 Oct
AA* (staged delivery plan) • 144 Mid dishes • 307 Low stations	2027 Dec	2028 Jan
Operations Readiness Review	2028 Apr	2028 Apr
Formal end of construction (including schedule	2029 Mar	

[1]Due to inflationary pressures caused by recent geopolitical events, the funding originally secured to construct AA* is no longer sufficient to achieve this milestone. Following a resolution of the SKAO Council, the representatives of the SKA Member countries, and of countries on the path to membership, are seeking additional funding from their respective governments to enable the Observatory to deliver AA*.

contingency)	
AA4 (design baseline) ● 197 Mid dishes ● 512 Low stations	TBD

An important milestone for the SKA scientific community will be Science Verification (to be fully described in a forthcoming document expected in 2024), which is planned to begin towards the end of AA2 at which stage the SKA telescopes will be scientifically competitive. The community will be invited to submit suggestions for science verification targets, and science verification data will be made publicly available.

Array assemblies AA2, AA* and AA4 will therefore be relevant to science planning within the community and, as such, we include them within this document and the software package. These AAs are described in Sections 2.1 and 2.2 for Mid and Low, respectively. Section 2.3 describes the software package accompanying this memo that allows users to create different array configurations with both the SKA telescopes.`

2.1 SKA Mid

The SKA Mid design baseline (AA4) consists of 197 dishes, of which 133 are 15m SKA Mid dishes, and 64 are 13.5m MeerKAT dishes. The 133 SKA Mid dishes include the 16 dishes that are planned as part of the MeerKAT Extension project design baseline (also called MeerKAT+). The 133 15m dishes are labelled with the prefix SKA (SKA001 to SKA133), and the 13.5m dishes will retain their MeerKAT names (M000 to M063).

Table 2 lists the frequency ranges and maximum observable continuum bandwidths (exclusive of RFI flagging) of the Mid telescope receivers. These ranges do not overlap completely between the SKA Mid and MeerKAT dishes, so users can expect reduced collecting area at the lower ends of bands 1 and 2. We also note that the observable bandwidth of band 5b is limited to two tunable 2500 MHz bands placed within the receiver bandwidth.

Table 2: Frequency range and bandwidth of receivers on the Mid telescope (based on [**AD1, AD6**]).

Receiver band	**Frequency range (and maximum observable continuum bandwidth) of SKA Mid receivers on 15 m dishes**	**Frequency range (and maximum observable continuum bandwidth) of MeerKAT Legacy receivers on 13.5 m dishes**
Band 1	0.35 - 1.05 GHz (700 MHz)	0.58 - 1.015 GHz (515 MHz)
Band 2	0.95 - 1.76 GHz (810 MHz)	0.95 - 1.67 GHz (720 MHz)
Band 5a	4.6 - 8.5 GHz (3900 MHz)	
Band 5b	8.3 - 15.4 GHz (2x2500 MHz)	

Array assembly AA2 will comprise 64 SKA Mid dishes [**AD3**]. By the end of AA* (staged delivery plan), the Mid array will comprise 144 dishes, which includes 80 15m dishes (including 16 MeerKAT+ dishes) and 64 13.5m MeerKAT dishes. All the dishes in AA* will be equipped with band 1 and 2 receivers, but at this stage, only the 80 15m dishes will be equipped with band 5 receivers [**AD4**].

Table 3 lists the dishes that will be part of the array assemblies made available to the scientific community during the science verification phases. The positions of the MID dishes in the three relevant array assemblies are shown in Figure 1.

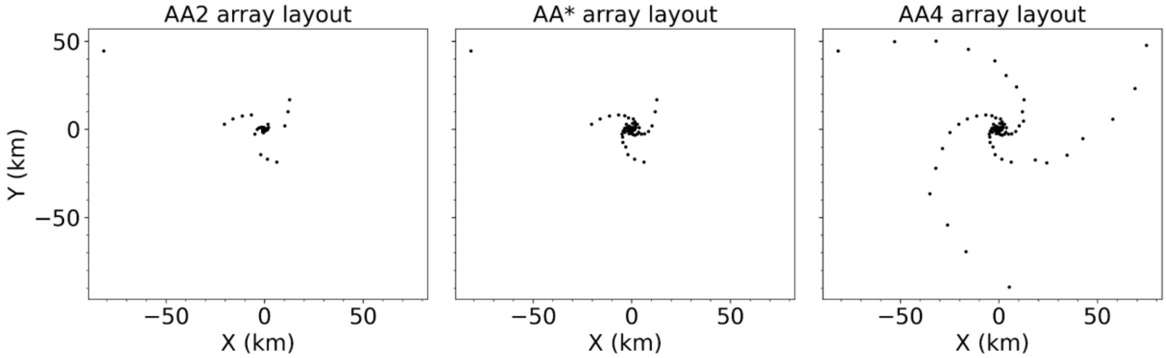


Figure 1: SKA MID array layout in AA2, AA* and AA4. The list of antennas in each array layout is listed in Table 3 below.

Table 3: List of Mid antennas in three array assemblies (based on [**AD3, AD4**]).

Array assembly	**Mid dish names**
AA2 (64 antennas[2])	SKA001, SKA008, SKA013, SKA014, SKA015, SKA016, SKA019, SKA024, SKA025, SKA027, SKA028, SKA030, SKA031, SKA032, SKA033, SKA034, SKA035, SKA036, SKA037, SKA038, SKA039, SKA040, SKA041, SKA042, SKA043, SKA045, SKA046, SKA048, SKA049, SKA050, SKA051[3], SKA055, SKA060, SKA061, SKA063, SKA067, SKA068, SKA070, SKA075, SKA077, SKA079, SKA081, SKA082, SKA083[3], SKA089, SKA091, SKA092, SKA095, SKA096, SKA097[3], SKA098, SKA099, SKA100, SKA101, SKA102, SKA103, SKA104, SKA106, SKA108, SKA109, SKA113, SKA123, SKA125, SKA126,
AA* (144 antennas)	AA2 antenna list + 16 SKA MID dishes from the MeerKAT Extension project: SKA017, SKA018, SKA020, SKA023, SKA026[3], SKA105, SKA107, SKA110, SKA111[3], SKA114[3], SKA115, SKA116, SKA117, SKA118, SKA119, SKA121 + 64 MeerKAT antennas

[2] Note that we expect to integrate 4 MeerKAT dishes into Mid during AA2 for testing purposes but are not expecting them to be available for Science Verification until AA*.
[3] To be confirmed

AA4 (197 antennas)	Design baseline (i.e. SKA001 - SKA133 and M000 - M063)

2.2 SKA Low

The SKA Low design baseline (AA4) consists of 512 Low-Frequency Aperture Array (LFAA) stations spread over an area with a diameter of about 80 km. Each LFAA station consists of 256 log-periodic dipoles. Table 5 below lists the stations that will be part of the AAs that will be made available to the scientific community during the Science Verification phases. The positions of the LOW stations in the three relevant array assemblies are shown in Figure 2.

The LFAA stations are laid out in a three-armed spiral pattern with a dense core. Low stations in the three spiral arms are grouped together in clusters of six stations each. In the AA4 configuration (design baseline), the core consists of 224 stations (C1 to C224), and the remaining 288 stations are grouped into remote clusters, such that each spiral arm contains 16 remote clusters (clusters E1 to E16, N1 to N16, and S1 to S16). The six stations in each remote cluster are then labelled following the naming convention where cluster S8, for example, contains stations S8-1 to S8-6.

Table 4: List of Low stations in three array releases (based on [**AD2**]).

Array assembly	**Low station/cluster names**
AA2 (64 stations)	Remote clusters: S8, S9, S10, S16 + Core stations: C4, C8, C16, C17, C22, C23, C30, C31, C32, C33, C36, C52, C56, C57, C59, C62, C66, C69, C70, C72, C73, C78, C80, C88, C89, C90, C91, C98, C108, C111, C132, C144, C146, C158, C165, C167, C176, C183, C193, C200
AA* (307 stations)	AA2 stations + Remote clusters: N8, N9, N10, N16, E8, E9, E10, E16, E12, E14, N11, N14, S12, S14 + Core stations: C1, C2, C3, C5, C6, C7, C9, C10, C11, C12, C13, C14, C15, C18, C19, C20, C21, C24, C25, C26, C27, C28, C29, C34, C35, C37, C38, C39, C40, C41, C42, C43, C44, C45, C46, C47, C48, C49, C50, C51, C53, C54, C55, C58, C60, C61, C63, C64, C65, C67, C68, C71, C74, C75, C76, C77, C79, C81, C82, C83, C84, C85, C86, C87, C92, C93, C95, C96, C97, C99, C100, C101, C102, C103, C104, C105, C106, C107, C109, C110, C112, C113, C114, C115, C117, C119, C120, C121, C123, C124, C125, C126, C128, C129, C130, C133, C135, C137, C138, C139, C140, C141, C142, C143, C145, C147, C148, C149, C150, C151, C153, C154, C155, C156, C160, C161, C162, C163, C164, C166, C168, C170, C171, C172, C173, C175, C177, C179, C180, C181, C184, C185, C186, C187, C190, C191, C192, C194, C195, C197, C198, C199, C201, C202, C203, C204, C205, C206, C207, C208, C212,

	C213, C214, C216, C217, C219, C222, C223, C224
AA4 (512 stations)	Design baseline (i.e. Core stations C1 - C224, remote clusters E1 - E16, N1 - N16, and S1 - S16)

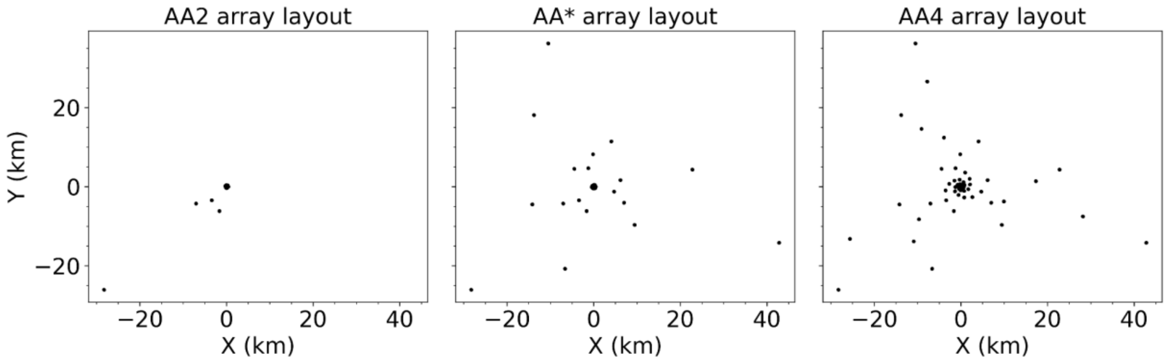


Figure 2: SKA LOW array layout in AA2, AA* and AA4. The list of stations in each array layout is listed in Table 5 above.

2.3 Antenna coordinates and software package

Instead of merely adding the raw antenna coordinates[4] here, the content presented in this memo is complemented with a Python package called ska_ost_array_config (https://gitlab.com/ska-telescope/ost/ska-ost-array-config) which allows users to:

1. query the coordinates of a station/dish,
2. define subarrays,
3. simulate simple observations with the subarrays,
4. plot the array layout and uv coverage, and
5. export the array layout in a format that is compatible with NRAO CASA for more comprehensive simulations using the simutil module.

A few example use cases are described in Appendix A of this document. For a detailed description of all the functionality supported by this package, see the Jupyter Notebook located in the Gitlab repository at ska-ost-array-config/docs/example.ipynb.

For interested users, the raw antenna coordinates of the full Low and Mid arrays can be found in the Gitlab repository at ska-ost-array-config/src/ska_ost_array_config/static/. These coordinates are taken from internal SKAO documents referenced as **AD7** and **AD8**. Note that the antenna coordinates for both Low and Mid are given as latitude and longitude in degrees in the WGS84 coordinate system.

Users interested in adding more functionality to this package are welcome to issue merge requests to the GitLab repository.

[4] Interested users can find the raw antenna coordinates here (LOW) and here (MID).

3 References

3.1 Applicable Documents

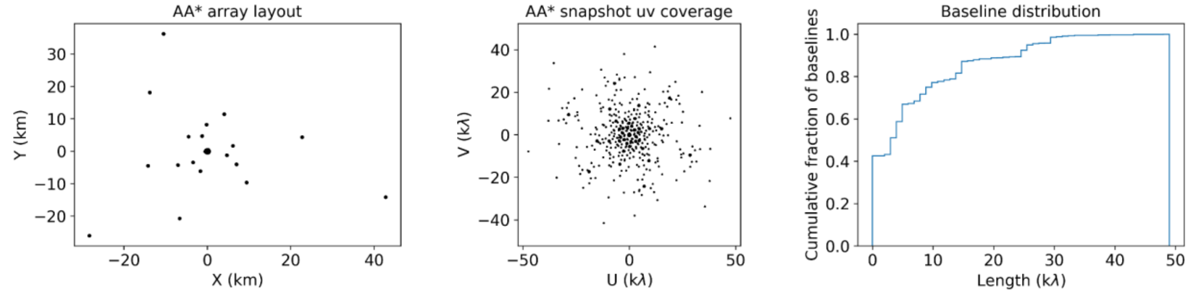
The following documents are applicable to the extent stated herein. In the event of conflict between the contents of the applicable documents and this document, **the applicable documents** shall take precedence.

[AD1] SKA1 Design Baseline Description (SKA-TEL-SKO-0001075 revision 02)
[AD2] Roll-out plan for SKA1 LOW (SKA-TEL-AVIV-4410001 revision 10)
[AD3] Roll-out plan for SKA1 MID (SKA-TEL-AVIV-2410001 revision 10)
[AD4] SKA1-Mid Staged Delivery Plan (SKA-TEL-SKO-0001827 revision 01)
[AD5] Integrated Program Schedule (version October 02, 2023)
[AD6] Jonas et al (2016), Proceedings of MeerKAT Science: On the Pathway to the SKA. 25-27 May, 2016 Stellenbosch, South Africa.
[AD7] SKA1 Low Configuration Coordinates - Complete Set (SKA-TEL-SKO-0000422 revision 04)
[AD8] SKA1 Mid Physical Configuration Coordinates (SKA-TEL-INSA-0000537 revision 10)

A Example simulations with the Python package

A.1 Array layout and snapshot uv coverage of SKA Low in AA* configuration

The figure below shows the subarray layout (left panel), snapshot narrow-band uv coverage (middle panel), and a cumulative histogram of the baseline distribution for the SKA Low array in AA* configuration.



The plots were generated using the following code snippet:

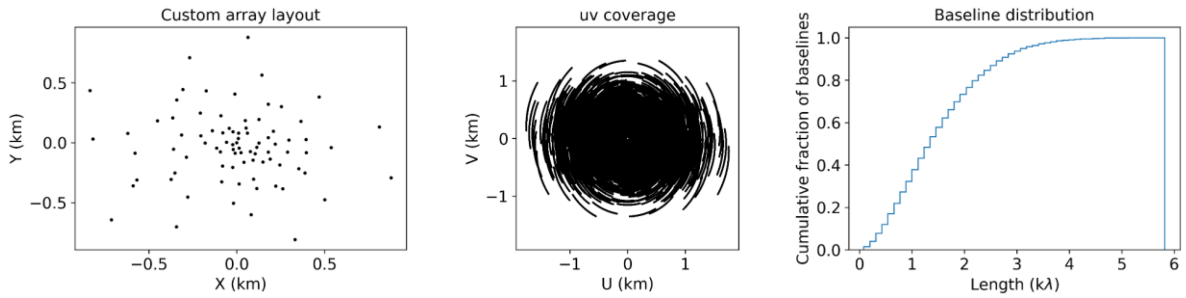
```
from ska_ost_array_config.array_config import LowSubArray
from ska_ost_array_config.UVW import plot_baseline_distribution
import matplotlib.pyplot as plt

# Create a subarray containing all Low stations in
# AA* configuration
low_aastar = LowSubArray(subarray_type="AA*")

fig, axes = plt.subplots(1, 3, figsize=(15,4))

# Plot the array layout
low_aastar.plot_array_layout(
    axes=axes[0],
    scale="kilo",
    s=4,
)
axes[0].set_title("AA* array layout")

# Plot snapshot uv coverage for a fiducial source at zenith
uvw = low_aastar.plot_snapshot_zenith_uvcov(
    axes=axes[1],
    ref_freq=200e6,
    chan_width=5.4e3,
    n_chan=1,
    method="lambda",
    plot_conj=True
)
axes[1].set_title("AA* snapshot uv coverage")

# Make a histogram of the baseline distribution
plot_baseline_distribution(
```

```
    uvw,
    axes=axes[2],
    method="lambda",
    scale="kilo",
    plot_type="uv",
    label="uv distance")
axes[2].set_title("Histogram of baseline distribution")
```

A.2 Array layout and uv coverage for a custom SKA Mid observation

This section showcases a simulated two-hour scan of the Large Magellanic Cloud using a SKA Mid subarray. The subarray is constructed using all Mid dishes (in AA* configuration) within a distance of 1 km from the array centre. The simulated observation is set up to record continuum data in Mid Band 2 (SKA Mid and MeerKAT legacy receivers overlap 0.95 - 1.712 GHz) with time and frequency resolutions of 1s and 13.44 kHz. The scan is centred on transit.

The figure below shows the subarray layout (left panel), uv coverage (middle panel), and a cumulative histogram of the baseline distribution for the SKA Low array in AA* configuration.



The plots were generated using the following code snippet:

```
from ska_ost_array_config.array_config import (
        MidSubArray,
        filter_array_by_distance
)
from ska_ost_array_config.UVW import (
    UVW,
    plot_baseline_distribution,
    plot_uv_coverage
)
from ska_ost_array_config.simulation_utils import (
    find_rise_set_times,
    simulate_observation,
)
from astropy.coordinates import SkyCoord
import matplotlib.pyplot as plt
from astropy import units
from astropy.time import Time, TimeDelta

plt.rcParams["font.size"] = 14
```

```python
# Create a custom MID array using all dishes within 1 km from the array centre
mid_aastar = MidSubArray(subarray_type="AA*")
custom_stations = filter_array_by_distance(mid_aastar, 1000.0)
mid_custom = MidSubArray(
        subarray_type="custom",
        custom_stations=custom_stations
)

# Define the pointing centre
lmc = SkyCoord(
        "05:23:34 -69:45:00",
        unit=(units.hourangle, units.deg)
)

# Find the UTC time when the source transits
_, transit_time, _ = find_rise_set_times(
    location=mid_custom.array_config.location,
    phase_centre=lmc,
    date=Time.now(),
    elevation_limit=20.0,
)

# Simulate the observation and get the uvw values
duration = 7200.0  # in seconds
observation = simulate_observation(
    array_config=mid_custom.array_config,
    phase_centre=lmc,
    start_time=transit_time - TimeDelta(duration, format="sec"),
    duration=duration,
    integration_time=1,
    ref_freq=0.95e6,
    chan_width=13.44e3,
    n_chan=60628,
    horizon=20,
    freq_undersample=200,
    time_undersample=20,
)
uvw = UVW(observation, ignore_autocorr=True)

fig, axes = plt.subplots(1, 3, figsize=(15, 4))

# Plot the array layout
mid_custom.plot_array_layout(
    axes=axes[0],
    scale="kilo",
    s=4,
)
axes[0].set_title("Custom array layout")

# Plot the UV coverage
plot_uv_coverage(
        uvw,
```

```
        axes=axes[1],
        method="lambda",
        scale="kilo",
        plot_conj=True
)
axes[1].set_title("uv coverage")

# Plot the baseline distribution
plot_baseline_distribution(
    uvw,
    axes=axes[2],
    method="lambda",
    scale="kilo",
    plot_type="uv",
    label="uv distance",
)
axes[2].set_title("Baseline distribution")
```

A.3 Exporting array configuration file for simulations with CASA

Continuing with the code snippet from section B.2, the array layout of the custom Mid array can be exported to a format consistent with CASA as

```
mid_custom.generate_casa_antenna_list(file_name='mid_custom.cfg')
```

The exported configuration file can be used to run simulations using CASA simutil module. An example simulation using the CASA simutil module can be found in a Jupyter notebook on the Gitlab repository. For a more detailed description, see CASA documentation.

LIST OF ABBREVIATIONS

AA	Array Assembly
AD	Applicable Document
CASA	Common Astronomy Software Applications
ECP	Engineering Change Proposal
SKA	Square Kilometre Array
SKAO	SKA Observatory

DOCUMENT HISTORY

Revision	Date Of Issue	Engineering Change Number	Comments
01	2023-11-03	N/A	Initial Release

DOCUMENT SOFTWARE

	Package	Version	Filename
Word processor	MS Word	Office 365	SKAO-TEL-0002299_01_SKAO Staged Delivery, Array Assemblies and Layouts
Block diagrams			
Other			

ORGANISATION DETAILS

Name	SKA Observatory
Registered Address	Jodrell Bank Lower Withington Macclesfield Cheshire, SK11 9FT, UK
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