

## Mid Frequency Aperture Array

### Technical Description

Reference : AAMID-TEL.MFAA.SE.MGT-AAMID-PL-002  
Issue - Revision : 1 - 0  
Date : 2013-06-09  
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## Record of Changes

Issue	Rev	Date	Change	Affected Area	Author
0	A	2013-03-26	Initial version	Entire document	Gunst
0	B	2013-05-29			Gunst
0	C	2013-06-05		Entire document	Gunst
0	D	2013-06-06		Entire document	Gunst
0	E	2013-06-07		Entire document	Gunst
0	F	2013-06-08		Entire document	Gunst
1	0	2013-06-09	Formal release	Science section	Gunst

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## Definition and Acronyms

Acronym	Explanation
AAMID	Aperture Array MID frequency
AD-n	nth document in the list of Applicable Documents
AIV	Assembly Integration and Verification
CE	Conformité Européenne
CIDL	Configuration Item and Document List
DRB	Delivery Review Board
EIDP	End Item Data Package
ENG	Engineering
HW	Hardware
ICD	Interface Control Document
MFAA	Mid Frequency Aperture Array
MOM	Minutes of Meeting
PA	Product Assurance
QA	Quality Assurance
RD-n	nth document in the list of Reference Documents
SKA	Square Kilometre Array ( <a href="http://www.skatelescope.org">www.skatelescope.org</a> )
SKAO	Square Kilometre Array Office
SOW	Statement of Work
SW	Software
TBC	To be continued
TBD	To be done
TBS	To be supplied
TRB	Test Review Board
WBS	Work Breakdown Structure
WP	Work Package

# 1 Introduction

## 1.1 Scope

This document is the Technical Description of the Mid Frequency Aperture Array (MFAA) technology for SKA Phase 2. The MFAA technology is part of the Advanced Instrumentation Program (AIP) and needs to prove its maturity during Stage 1 of SKA Phase 1.

The document focuses mainly on the design of MFAA stations. The impact on the surrounding elements (correlator, time and synchronisation, power and post processing) are not considered in this document.

## 1.2 Document Structure

- Section 1 introduces the purpose and scope of this document.
- Section 2 lists the applicable and reference documents.
- Section 3 discusses the scientific motivation.
- Section 4 provides the requirement analysis.
- Section 5 describes the functional system decomposition.
- Section 6 overviews a cost analysis.
- Section 7 provides the functional architecture.
- Section 8 discusses the physical design concepts.
- Section 9 overviews the way forward.
- Section 10 contains the conclusions.

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## 2 Applicable and Reference Documents

### 2.1 Applicable Documents

Id	Title	Code	Issue
AD-1	SKA Request for proposal Proposals	SKA-TEL.OFF.RFP-SKO-RFP-001	1
AD-2	Statement of work for the study, prototyping and design on an SKA element	SKA-TEL.OFF.SOW-SKO-SOW-001	1
AD-3	Statement of Work for the Study, Prototyping and Preliminary Design of an SKA Advanced Instrumentation Programme Technology	SKA-TEL.OFF.AIP-SKO-SOW-001	1
AD-4	SKA Pre construction Top Level WBS	SKA-TEL.OFF.WBS-SKO-WBS-001	1
AD-5	SKA-1 System Baseline design	SKA-TEL-SKO-DD-001	
AD-6	The Square Kilometre Array Design Reference Mission: SKA Phase 1	SCI-020.010.020-DRM-002	3
AD-7	SKA System Engineering Management Plan	SKA.TEL.SE-SKAO-MP-001	1
AD-8	The Square Kilometre Array Intellectual Property Policy	SKA IP Policy	1.3 Draft
AD-9	Draft Consortium Agreement	PD/SKA.26-4	Draft
AD-10	Document Requirements Description	SKA-TEL.SE-SKO-DRD-001	1
AD-11	SKA Document Management Plan	SKA-TEL.OFF.MGT-SKO-MP-001	1
AD-12	SKA Product Assurance and Safety Plan	SKA-OFF.PAQA-SKO-QP-001	1
AD-13	Change Management Procedure	SKA-TEL.SE.CONF-SKO-PR-001	1
AD-14	SKA Interface Management Plan	SKA-TEL.SE.INTERF-SKO-MP-001	1

### 2.2 Reference Documents

Id	Title	Code	Issue
RD-1	The Square Kilometre Array Design reference Mission: SKA-mid and SKA-lo		1.0
RD-2	MFAA Delivered Items and Document List	AAMID-TEL.MFAA.MGT.DMT-AAMID-LI-001	1.0
RD-3	MFAA Management Plan	AAMID-TEL.MFAA.SE.MGT-AAMID-PL-0021	1.0
RD-4	The Aperture Arrays for the SKA: the SKADS whitepaper		

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RD-5	AA-Mid Concept Descriptions	WP2-015.020.010-TN-001	D
RD-6	EMBRACE: A Multi-Beam 20,000-Element Radio Astronomical Phased Array Antenna Demonstrator	IEEE Transactions on Antennas and Propagation, volume: 59, issue: 6	
RD-7	Aperture Array Integrated Receiver	French funding proposal 2011	
RD-8	APERTIF: Phased Array Feeds for the Westerbork Synthesis Radio Telescope	IEEE International Symposium on Phased Array Systems and Technology, October 2010	
RD-9	AA-mid system requirements specification	WP2-015.020.010-SRS-001	D
RD-10	Octagonal Ring Antenna for a Compact Dual-Polarized Aperture Array	IEEE Transactions on Antennas and Propagation, Vol. 59, No. 10, pp. 3927-3932, October 2011	
RD-11	Design of Wide-Band Dual Polarized Aperture Array Antennas	International Journal of Microwave and Wireless Technologies, Vol. 4, Special Issue 3, pp. 373-378, June 2012	
RD-12	Ansari R., et al.	2008, arXiv:0807.3614	
RD-13	Peterson J., et al.	2006, arXiv:astro-ph/0606104	
RD-14	Rawlings S., et al.	2004, New Astr. Review, 48, 1013	
RD-15	Smits R., Kramer M., Stappers B., et al.	2011, SKA Memo Series 105	
RD-16	Torchinsky S.A.	2010, in "Wide Science & Technology for the SKA," pg. 33	
RD-17	Wilkinson, P.N., et al.	2004, New Astr. Review, 48, 1551	



## 4 Scientific motivation

Aperture Arrays are the enabling technology that will lead to the promise of SKA as a transformational survey machine. The Mid Frequency Aperture Array (MFAA) is particularly well suited to perform the billion galaxy survey. This will enormously advance our understanding of galaxy formation and evolution, and help determine the nature of dark energy. In addition, MFAA will accommodate a range of survey related science projects profiting from wide field of view, large bandwidth, and the unique multi beaming capabilities.

### 4.1 Dark Energy

The earliest science driver for the SKA was the measurement of the HI mass distribution at cosmological epochs. By tracing the HI of individual galaxies over the entire sky and at different redshifts, the SKA will be able to detect Baryonic Acoustic Oscillations (BAO) and their evolution as a function of time. This enables a direct measurement of the effects of dark energy [RD-14]. Using the radio 21-cm transition avoids optical bias and confusion of emission lines, making the SKA MFAA the most reliable instrument to perform this experiment.

The optimal redshift range for this study is between  $z=0.5$  and 3, corresponding to a frequency range of 350 to 1000 MHz. A large field-of-view of order 100 square degrees will be critical in accessing large numbers of galaxies in a few years observing time. Sufficient angular resolution is needed to beat the confusion limit, requiring baselines on the order 10km [RD-1].

The resulting catalogue contains a billion galaxies with highly accurate positions and redshifts, a unique source of information with high legacy value. It will give exquisite constraints on the Equation of State of the Universe, and may well indicate that Einstein's theory of General Relativity, together with a Cosmological Constant, is insufficient to explain dark energy.

The method of Intensity Mapping has been proposed to make a statistical detection of the BAO in the HI mass distribution [RD-12], [RD-13]. It is likely to detect the first peak in the power spectrum, and a modest sized MFAA precursor can be the first to achieve this result. However, only the full phase 2 SKA MFAA can make a detailed map of the HI distribution in an unprecedented cosmic volume. It will enable measurements of the higher order features in the power spectrum, which are necessary to properly match the signature found in the Cosmic Microwave Background.

### 4.2 Pulsars and transients

Another high gain science case for the SKA is the test of General Relativity using high precision pulsar timing. Timing experiments require ultra-stable, isolated millisecond pulsars, well distributed on the sky. Currently, only a few suitable candidates are known, and a dedicated pulsar survey is essential to find new candidates. These sources need to be monitored for an extended period to determine which are suitable for high precision timing. The wide field of view, large instantaneous bandwidth, and multi-beaming capabilities make aperture arrays an unrivalled pulsar finding and timing machine.

Excluding a few degrees on either side of the Galactic Plane, pulsar surveys are most effective in the frequency range 600-900MHz [RD-15]. A large field of view makes them time efficient, while the large bandwidth enables an accurate estimate of dispersion measure and scattering. The multi-beaming enables highly efficient monitoring and timing, while eliminating instrumental effects in the calibration by observing multiple pulsars simultaneously.

For transient searches, a large field of view is crucial. Only aperture arrays can meet the 200 square degrees field of view required for the discovery and location of fast transients such as Lorimer bursts [RD-1]. In addition, the proposed MFAA is sensitive to slower transients, as it can perform an all sky survey down to sub-milli Jansky levels

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and at arcsecond resolution (assuming 100km baselines ) on a daily basis. This opens up entirely new parameter space in time domain astronomy.

### 4.3 Additional science

Except for Galactic center pulsar observations, molecular lines and Epoch of Reionization, all science cases defined in the DRM for SKA phase 2 can benefit from the unique capabilities of aperture array technology. The match is improved significantly by tuning the frequency range of the proposed MFAA design to slightly lower values. The loss of the capability to detect neutral hydrogen in the local Universe is well balanced by an increase in science return from other cases and computing efficiency. Even for the BAO detections, the local volume is relatively small, and the optimal results are expected for frequencies between 450 and 750 MHz.

The SKA MFAA will open up a new phase space, leading to new discoveries [RD-17]. In fact, most telescopes have made unexpected discoveries completely outside the domain for which the instrument was designed [RD-16]. The unknown covers not just time-domain science. The combination of multi-beaming along with unprecedented instantaneous field of view enables studies of structures that span tens of degrees in size on the sky. From our own Galaxy out to cosmological distances, the SKA MFAA is to be expected to transform our knowledge of the Universe.

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## 5 Requirement Analysis

In this section the assumptions for the technical description are given. No requirements or references to requirements are given in the RfP material as input for the MFAA system. For the proposed conceptual design the first DRM is assumed which covers both the full SKA (phase 2) [RD-1].

For the technical description of the MFAA the relevant top level requirements are listed in Table 1. These requirements are extracted from [RD-1].

	f_low	f_high	B	SS	Aeff/Tsys	FoV
Science Case						
Resolving AGN (2)	500	8000		1,E+03		
Cosmic Magn. (4)	300	3000	500	6,E+08		
Wide Field Pol. (5)	300	2000	500			
Cosmic Star Form. (6)	300	3000			10000	
Deep HI field (7)	450	1400				
HI absorption (11)	150	1400		1,E+08		
HI BAO (12)	460	1400		1,E+10		
Transient radio sky (14)	500					200 from 500 MHz
Probing AGN (15)	150	1400			10000	
Pulsar surveys (16)	400	3000			5000	
Pulsar timing (17)	400	3000			10000	
Unit	MHz	MHz	MHz	m <sup>4</sup> deg <sup>2</sup> /K <sup>2</sup>	m <sup>2</sup> /K	deg <sup>2</sup>

**Table 1: Science requirements relevant for the MFAA technology (color indicates the driving requirements)**

As a function of frequency the most important requirements are depicted in Figure 1, Figure 2, Figure 3 and Figure 4.

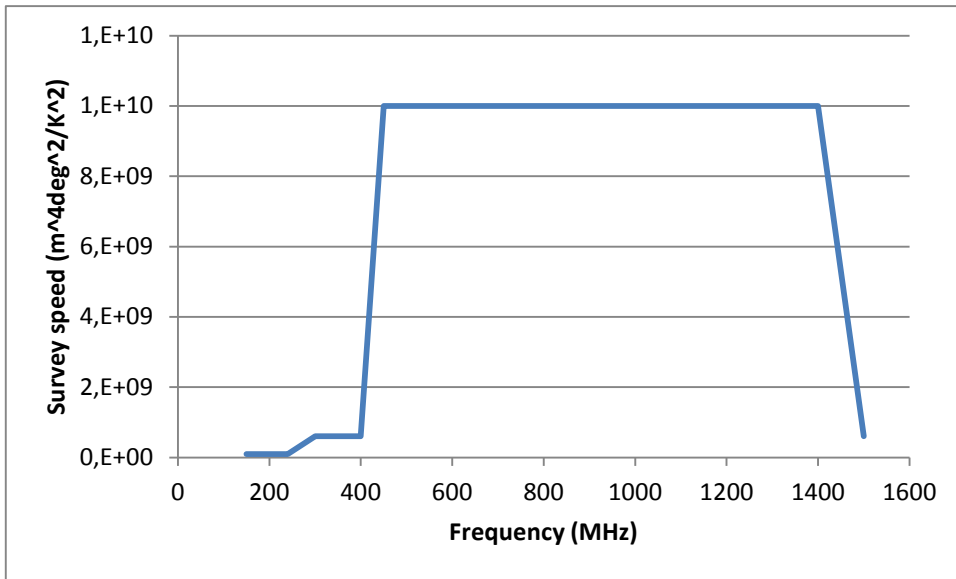


Figure 1: Survey speed requirements as a function of frequency

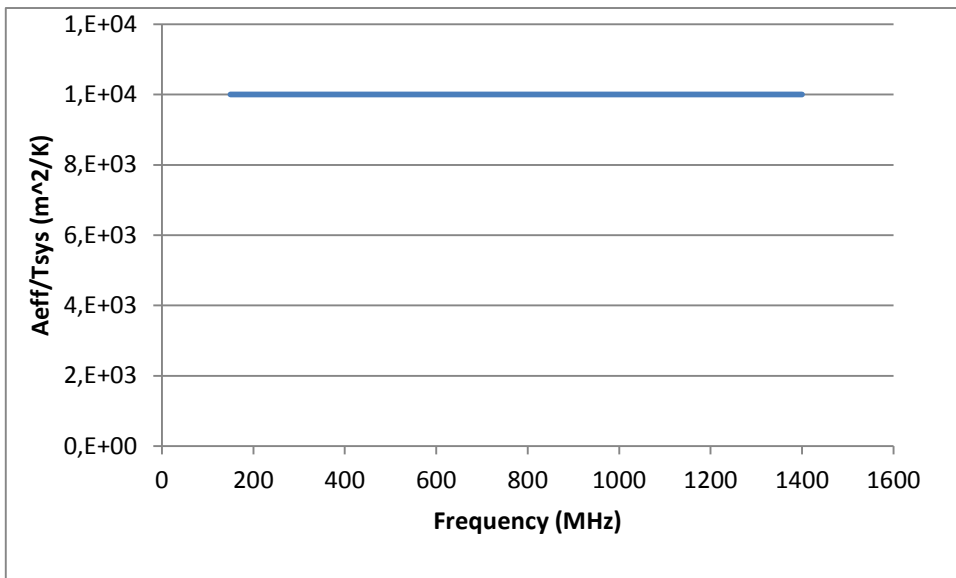
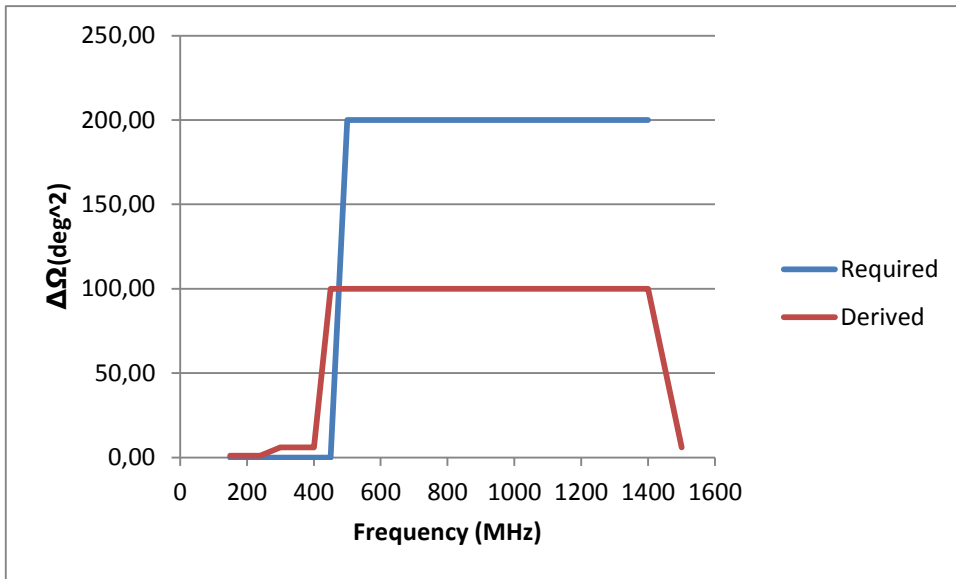
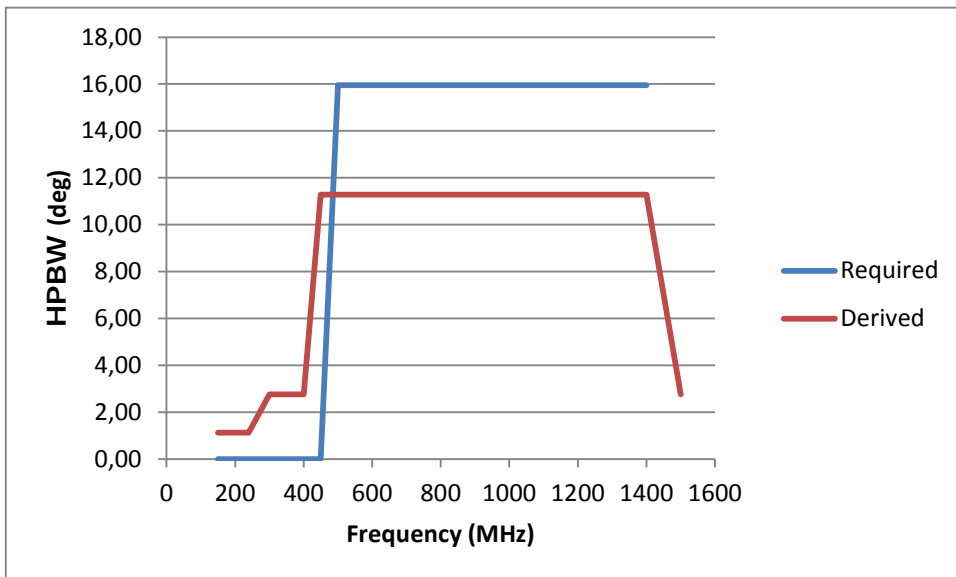


Figure 2: Aeff/Tsys requirements as a function of frequency



**Figure 3: Solid angle requirement as a function of frequency. Blue is the requirement from the transient radio sky, while the red curve is derived from the most stringent survey speed and sensitivity requirements.**



**Figure 4: Field of view requirement as a function of frequency. Blue is the requirement from the transient radio sky, while the red curve is derived from the most stringent survey speed and sensitivity requirements.**

Based on these science requirements, realistic technical requirements have been set. These are listed in **Table 2** and more thoroughly discussed in the next sub-sections.

Parameter	Requirement	Unit
Frequency range	300 - 1000	MHz
$\Delta\Omega$	100 @ 500 MHz	deg <sup>2</sup>
Aeff/Tsys	10000 from 400 - 800 MHz	m <sup>2</sup> /K
Polarisation	2	
RF beams	1	
Electronic scan angle		
Instantaneous bandwidth	250	MHz
Number of stations	250	

**Table 2: Assumed technical requirements**

### 5.1 Frequency Range

The frequency range for MFAA technology at the time of the dCoDR was 400 - 1450 MHz [RD-9]. Although this remains the goal, it seems likely that some compromise will be needed in order to realise MFAA's with the desired performance for an acceptable cost. A preliminary target frequency range has been set to 300-1000 MHz, which matches the baseline's LFAA frequency range which runs from 50- 350 MHz. Discussions with the astronomers will be needed to fine tune the frequency requirements in conjunction with sensitivity, cost etc. This may lead to further adjustments of the target frequency range.

Also the perceived risk and cost for MFAA technology is reduced by lowering the frequency. In principle there is no significant difference in between the LFAA and MFAA except for the number of antennas and their configuration.

### 5.2 Field of View

For the transient radio sky the solid angle requirement is set to 200 square degrees from 500 MHz and upwards. Since in the transient radio sky science case, also known as the exploration of the unknown in [RD-1], the requirements are stated as "to the extent possible" a solid angle requirement is derived from the survey speed required for the HI BAO in combination with the sensitivity requirements of cosmic star formation, AGN probing and pulsar timing (this results in a FoV of 100 square degrees). Since no specific frequency is specified for meeting those requirements, it is assumed that the FoV naturally decreases quadratically as a function of frequency. This is not specific to MFAA technology, but also the case for dishes. Technically there are ways to compensate for this drop by assuming more beams for the higher frequencies. These possible enhancements are not assumed in this document. Furthermore such measures are not efficient.

A frequency of 500 MHz is assumed as a spot frequency to meet the 100 square degrees requirement.

A FoV of 200 square degrees at 500 MHz can be achieved by trading a polarisation for one RF beam as will be clear presented in Section 5.4.

### 5.3 Sensitivity

The sensitivity requirement is derived from cosmic star formation, AGN probing and pulsar timing. This is the sensitivity required in zenith and for both polarisations simultaneously.

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#### 5.4 Polarisation & RF beams

Two polarisations are specified for the HI BAO in [RD-1] and required for cosmic magnetism and wide field polarimetry as well. For science cases not requiring two polarisations FoV can be traded with a second polarisation. Using this possibility also results in meeting the solid angle requirements of the transient radio sky at 500 MHz. In the same way an instantaneous bandwidth of 500 MHz can be achieved for science cases not requiring both polarisations or FoV.

#### 5.5 Instantaneous Bandwidth

In the absence of clear bandwidth requirements, a preliminary target of 250 MHz has been set for the instantaneous bandwidth. A 500 MHz instantaneous bandwidth can be achieved by trading beams for frequency coverage. Currently the science cases that need a high survey speed have not specified a bandwidth requirement. A reduced bandwidth has also been chosen to simplify and lower the cost of the analog beamformer.

#### 5.6 Number of Stations

The number of stations is set to 250 [RD-4]. This number can be backed up later in time by doing configuration studies and using more detailed science requirements. The anticipated MFAA concepts will be scalable.

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## 6 Physical System Decomposition

For the main decomposition of the system in terms of the number of tiles per station and the number of antennas per tile, additional assumptions are necessary. This is still independent on the mapping of the functions to a physical architecture (Chapter 8).

### 6.1 Technical Assumptions

A receiver temperature of 50 Kelvin is assumed at the spot frequency of 500 MHz. With EMBRACE [RD-6] 100 Kelvin is achieved as system temperature. During recent lab measurements a LNA with a noise temperature of 25 K has been measured. Assuming another 25 K in the rest of the signal chain results in a total of 50 Kelvin. This temperature can only be achieved in the centre of the beam at zenith. It should be noted that sensitivity is decreased by a factor of 2 at the half power beam directions. The system temperature is calculated by  $T_{sys}=T_{sky}+T_{rec}$  wherein  $T_{sky}=60.\lambda^{2.55}$ .

For the design a half lambda antenna spacing is assumed at a critical frequency  $f_c$  of 750 MHz. This results in an antenna pitch  $d$  of 0.2 m and a physical area of 0.04 m<sup>2</sup>. The effective area of one antenna element  $A_{el,eff}$  can be approximated as:

$$A_{el,eff} = \left( \min \left( \frac{\lambda}{2}, d \right) \right)^2$$

This results at 500 MHz in an effective area of 0.04 m<sup>2</sup>.

A lower  $f_c$  results in fewer antennas and is a direct cost reduction. Drawbacks are grating lobes above the critical frequency and a reduced sensitivity at higher frequencies. Hence this is a parameter to further optimize in a next iteration of the development cycle “requirements – design – cost”.

### 6.2 Technical Design

According to [RD-5] the design can be optimized for cost when the tile size or base receptor element as is used in [RD-5] is tailored to the required FoV. This minimizes the number of signal paths. FoV, also indicated with  $\Delta\Omega$ , in steradians is defined in this document as

$$\Delta\Omega = \frac{\pi}{4} \cdot \frac{\lambda^2}{D^2}$$

wherein  $\lambda$  is the wavelength and  $D$  the diameter of a tile. This can be converted to square degrees by multiplying by  $(180/\pi)^2$ . Assuming a FoV of 100 degrees<sup>2</sup> at 500 MHz results in a diameter of 3 m. Since it is difficult to analog beamform antenna elements within a diameter of 3 m (long time delays) with an acceptable performance, a tile of  $A_{tile}=2.88$  m<sup>2</sup> is assumed (diameter 2.4 m). This tile can be built with 144 single polarized (72 dual pol.) antenna elements which results in a square array of 12 by 12 elements. Although aperture array technology is assumed in this document, the same performance graphs as presented in Section 6.3 hold for dishes with the same diameter as assumed here.

At 500 MHz the  $T_{sys}=66.3$  Kelvin. Giving a required  $A_{eff}/T_{sys}$  of 10,000 m<sup>2</sup>/K results in a total  $A_{eff}$  of 663,000 m<sup>2</sup>. Dividing this over the tile area  $A_{tile}=2.88$  m<sup>2</sup> and the number of stations (250) results in about 961 tiles per station (rounded up such a square station can be made of 31 by 31 tiles). It is assumed that the sensitivity needs to be achieved for both polarisations.

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As an alternative, a design with less total area ( $6000 \text{ m}^2/\text{K}$  at 500 MHz) is assumed but more FoV (362 square degrees at 500 MHz). In order to make a larger FoV a smaller tile size is assumed for this ( $1.28 \text{ m}^2$ ). This design alternative illustrates the possible exchange between requirements for roughly the same cost and is further referred to as design 2.

### 6.3 Technical Performance

Given the design numbers, the technical performance of the design in relation to the requirements are depicted in Figure 5 to Figure 8. Note that these figures are independent of technology.

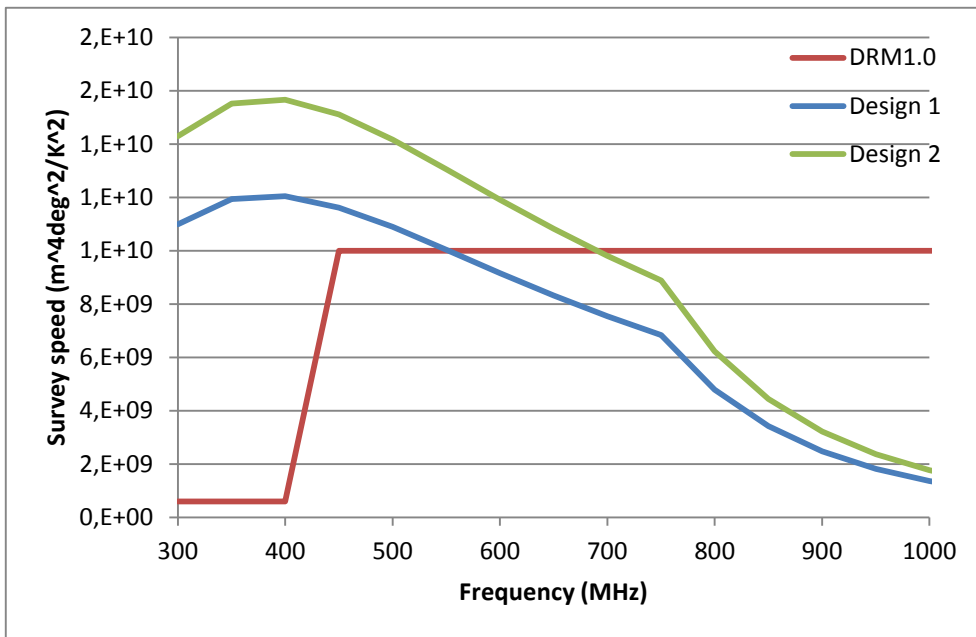


Figure 5: Survey speed performance as a function of frequency at zenith

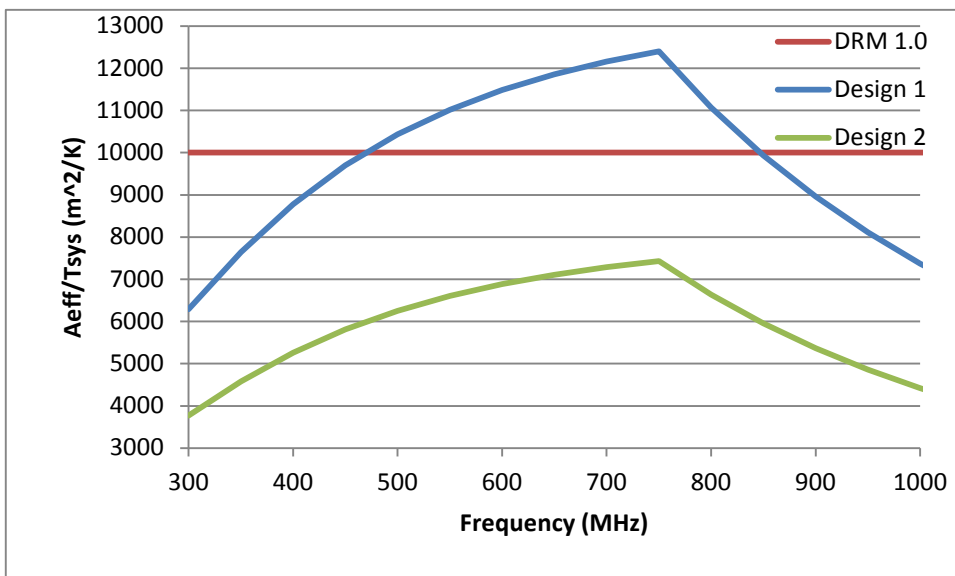


Figure 6: Aeff/Tsys as a function of frequency at zenith

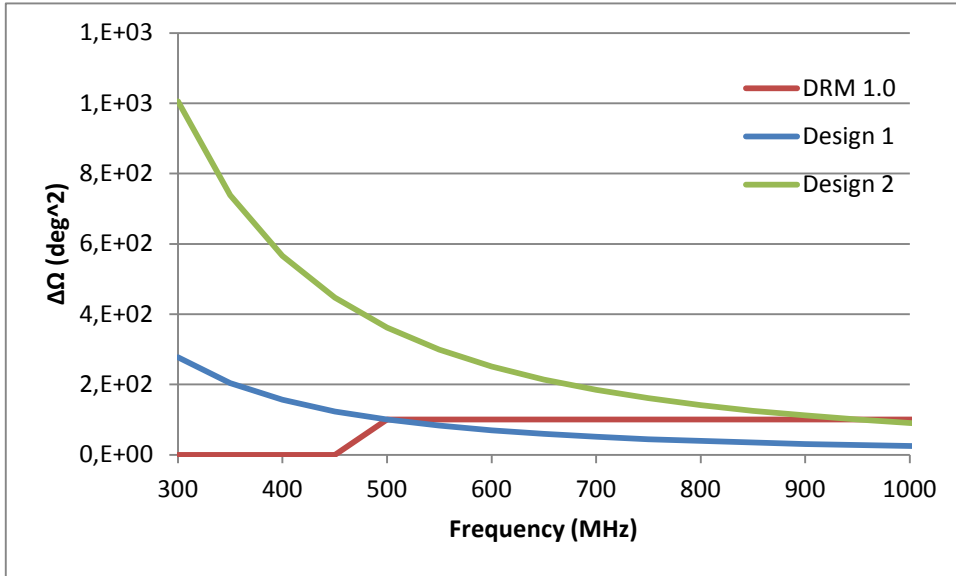


Figure 7: FoV requirement as a function of frequency at zenith

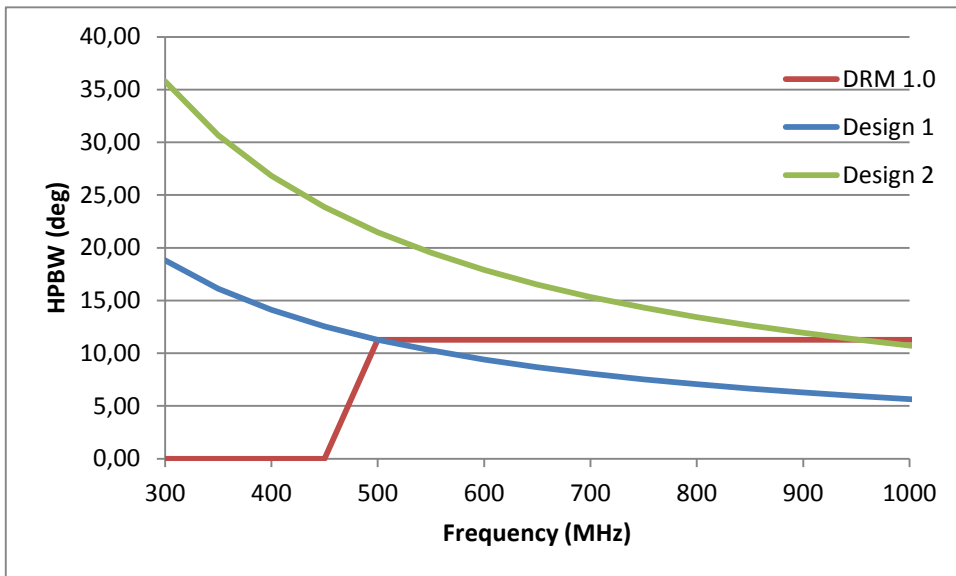


Figure 8: Half Power Beam Width requirement as a function of frequency at zenith

More FoV could be obtained by exchanging bandwidth for FoV. However this is not assumed as a requirement. The maximal FoV obtained by a tile of 2.88 m<sup>2</sup> at 500 MHz is 161 square degrees (diameter of a tile is  $\sqrt{2.88}\sqrt{2} = 2.4$  m). This forms an upper bound of the maximal FoV which can be realised. For the second design, wherein a tile size of 1.28 m<sup>2</sup> is assumed the maximal FoV at 500 MHz is 363 square degrees.

## 6.4 Station Processing

The main goal of the station processing is to do the beamforming over all the tiles in a station. The number of beams necessary are dictated by the FoV requirement and station size. At system level the processing of the beamformer is driven by the total effective area, required FoV and instantaneous bandwidth. There is still a careful trade off required between the processing in the field (at the stations) and centrally. By increasing the number of stations the processing at the stations is reduced, while the processing in the correlator increases (quadratically with the number of stations). However the total data rate at the input of the correlator is fixed and driven by the total effective area, required FoV and instantaneous bandwidth as is motivated in the last equation of Section 3.4.2.1 in [RD-5].

Fixing the number of stations to 250 and given the total effective area, the FoV per beam of a station can be calculated with

$$\Delta\Omega_{station} = \frac{\pi}{4} \cdot \frac{\lambda^2}{D_{station}^2}$$

where  $D_{station}$  is the station diameter and equals the tile diameter (2.4 m) multiplied by the square root of the number of tiles per station (31). At 500 MHz this results in a FoV of 0.17 square degrees. Equating the required FoV of 100 square degrees over the 0.17 square degrees results in 596 beams. Those 596 beams fills the 100 square degrees for one polarisation, assumed that the beams are stitched together at their half power.

The total data rate in samples per second and per station can now be calculated as

$$B_{station} = \frac{\Delta\Omega_{req}}{\Delta\Omega_{station}} \cdot 2 \cdot B \cdot N_p$$

with  $B$  the required instantaneous bandwidth (250 MHz),  $\Delta\Omega_{req}$  the required FoV (100 square degrees) and  $N_p$  the number of polarisations (2). The factor 2 is inserted because the sample frequency is twice the bandwidth. Filling in the numbers for design 1 results in 596 Gsamples/s. Since design 2 delivers much more FoV the bandwidth goes up to 1.3 Tsamples/s.

Note that the number of beams and data rate is fully driven by the requirements and not by the technology.

## 7 Cost Estimation

In this section a cost estimation is given based on analogous costing. The main goal of the estimation is to find it on real hardware with attached to it real costs. The extrapolation to the future is a prediction and will be transparently motivated. The assumptions made are given in Section 7.1, while the underlying cost relations used for the analogous projects are discussed in Section 7.2. Finally the MFAA station costs including an extrapolation are presented in Section 7.3.

### 7.1 Assumptions

The projects used for the costing are EMBRACE [RD-6] and the APERTIF beamformer [RD-8]. For EMBRACE the tile and front-end costs (including frequency conversion and control) are used, while for the receiver (A/D unit) and digital processing the APERTIF beamformer is used for the cost estimation. Both projects use technology from the year 2009.

EMBRACE is a multi-beam phased array antenna demonstrator and built in Nancay and the Netherlands. The antenna system covers a frequency range of 500-1500 MHz. The current system is suitable for one polarization, but delivers two RF beams. Each tile of EMBRACE consists of 144 antenna elements (72 dual pol.) and is connected to an analog beamformer. From each tile two RF beams are transported to a receiver wherein a part of the full band is selected and mixed down to a low IF frequency. The pitch of the Vivaldi antennas within EMBRACE is 12.5 cm. The costs for EMBRACE are split in an area cost and a cost per signal path. The cost per signal path includes the receiver electronics excluding the A/D conversion, while the area cost is basically the cost of the tiles per squared meter. The EMBRACE costs are based on real costs made in the year 2008.

One sub-rack of the APERTIF beamformer currently implemented has 64 analog signal paths as an input and is designed to deliver 42 beams at the output. The instantaneous input bandwidth is 400 MHz, while the output bandwidth is 300 MHz for each beam. The cost and power of the APERTIF beamformer is scaled to a cost per signal path and a cost per signal path times the number of beams to reflect two different cost relations. The APERTIF costs are based on quotations received in January 2013 for about 16 units, while the UniBoard which is used in the APERTIF beamformer was developed with 2009 technology (40 nm).

The assumptions of both designs presented in Section 6 are presented in Table 3.

	Design 1	Design 2	Unit
Number of stations	250	250	
Number of pol.'s	2	2	
Number of elements/tile	72	32	dual pol.
Number of tiles/station	961	1296	
Number of beams/station	596	1294	
Input bandwidth/signal path	250	250	MHz
Output bandwidth/beam	250	250	MHz
Antenna pitch	0,2	0,2	m

**Table 3 Assumptions for the cost estimation**

From these assumptions the parameters of Table 4 are derived.

Number of signal paths	1922	2592	
Number of beams	1192	2588	
Input bandwidth	961	1296	Gsamples/s
Output bandwidth	596	1294	Gsamples/s
Tile size	2,88	1,28	m <sup>2</sup>
Station area	2768	1659	m <sup>2</sup>

**Table 4 Derived parameters from the assumptions**

## 7.2 Cost Relations

From the projects used for the analogous costing a number of cost relations can be derived. These are presented in Table 5 for a pitch of 0.2 m (see Table 3). The original cost data is not provided for confidentiality reasons. However the evidence is available upon request. The tile costs include the antennas, mechanical construction and electronics of each tile and is normalized to square meters. The receiver costs include the down conversion and control and is specified per signal path. For the design presented in this document each tile delivers two signal paths (two RF beams or two polarizations). The antenna processing covers the A/D conversion and digital processing (e.g. filterbank) which is required per signal path. These costs were derived from the APERTIF beamformer project (hence the A/D converter is not included in the receiver for the cost relations). Finally the digital beamforming is related to signal paths and beams because this operations scales with both factors.

	Design 1		Design 2	
	Cost (€)	Power (W)	Cost (€)	Power (W)
Tile/m <sup>2</sup>	1809,0	50,4	1993,5	63,4
Receiver/signal path	700,0	7,0	700,0	7,0
Antenna processing (dig)/signal path	620,2	16,7	620,2	16,7
Beamforming/(signal path*beams)	7,3	0,3	7,3	0,3

**Table 5 Cost relations used for the analogous costing**

Although the costing year is slightly different for both projects it is assumed for the extrapolation that the cost presented in Table 5 are given for ~2009 technology.

Costs for assembly in the field and development are not considered yet. Furthermore it should be noted that from mechanical point of view an important cost driver is tile interconnection and assembly cost. Electrical connections between antennae over a large area (continuous array) has impact on flatness and precisions of the array. Compared with EMBRACE the environmental requirements on protection against water, dust, bugs, etc will be different and should also be taking into consideration for a next costing iteration.

## 7.3 MFAA Station Costs

Giving the number of signal paths, beams and area for a MFAA station the total cost can be calculated. In Table 6 the total MFAA station cost is given for both designs presented in Section 6 when it would be built in 2009.

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	Design 1		Design 2	
	Cost (M€)	Power (kW)	Cost (M€)	Power (kW)
Tiles	5,0	140	3,3	105,2
Receivers	1,3	13,5	1,8	18,1
Antenna processing	1,2	32	1,6	43,3
Beamforming	16,7	597	48,8	1746,9
Total	24,2	782	55,5	1913,6

**Table 6 MFAA station costs with 2009 technology**

From Table 6 can be concluded that the processing is dominant for both designs. Since design 1 is based on larger tiles and less FoV needs to be processed the beamforming costs are not as dominant than for the second design. This accounts as well for the power.

In order to extrapolate these costs and power to the year 2020 the extrapolation factors in Table 7 are assumed. The motivation for these factors is as follows:

- Tiles and receivers: the cost estimates used are based on low volume costs compared of what the SKA requires. For this a factor of two reduction in cost is taken into account. Another factor two in cost and power is expected to come from technology development and improvement. For example from a mechanical perspective alternative production methods can be used for mass production (use of expensive molds is possible for high volumes). From an analog electronics perspective custom integrated chips can be used for the amplifiers and beamformer. Also the assumed frequency range for the technical design presented in this document is lower and narrower than for EMBRACE (300-1000 MHz instead of 500-1500 MHz ).
- Antenna processing and beamforming: most significant part of this processing is realised by FPGA technology (40 nm) for the APERTIF project. For the calculation of the extrapolation factor a weak Moore’s law factor of a doubling in technology for every 2 year is assumed (instead of the traditional 1.5 year). Assuming a time frame of 10 year (till the year 2019) gives a reduction in cost of a factor 25=32. This is also assumed to hold for the power. An extra factor two on the cost is added to this number to reflect the fact that larger volumes are required for the SKA compared with the price paid for the APERTIF beamformer project for only 16 boards.

The reduction in cost and power has to be proven in the course of time. The main challenges and road ahead for the MFAA technology lies exactly in meeting the extrapolation factors over time. If necessary these factors need to be adapted to the reality. A glimpse of this is discussed in Section 10.

	Cost	Power
Tiles	4	2
Receivers	4	2
Antenna processing	64	32
Beamforming	64	32

**Table 7 Assumed extrapolation factors for the cost and power**

Given the extrapolation factors the total cost of a MFAA station in 2020 is presented in Table 8.

	Design 1		Design 2	
	Cost (M€)	Power (kW)	Cost (M€)	Power (kW)
Tiles	1,3	70	0,8	53
Receivers	0,3	6,7	0,5	9,1
Antenna processing	0,0	1	0,0	1
Beamforming	0,3	19	0,8	55
Total	1,9	96	2,1	118

**Table 8 MFAA station hardware costs in 2020**

Multiplying this with the number of stations results in the total hardware budget for the MFAA technology in Table 9.

	Design 1		Design 2	
	Cost (M€)	Power (MW)	Cost (M€)	Power (MW)
Tiles	313	17	207	13
Receivers	84	2	113	2
Antenna processing	5	0	6	0
Beamforming	65	5	191	14
Total	467	24	517	29

**Table 9 SKA2 MFAA hardware costs in 2020**

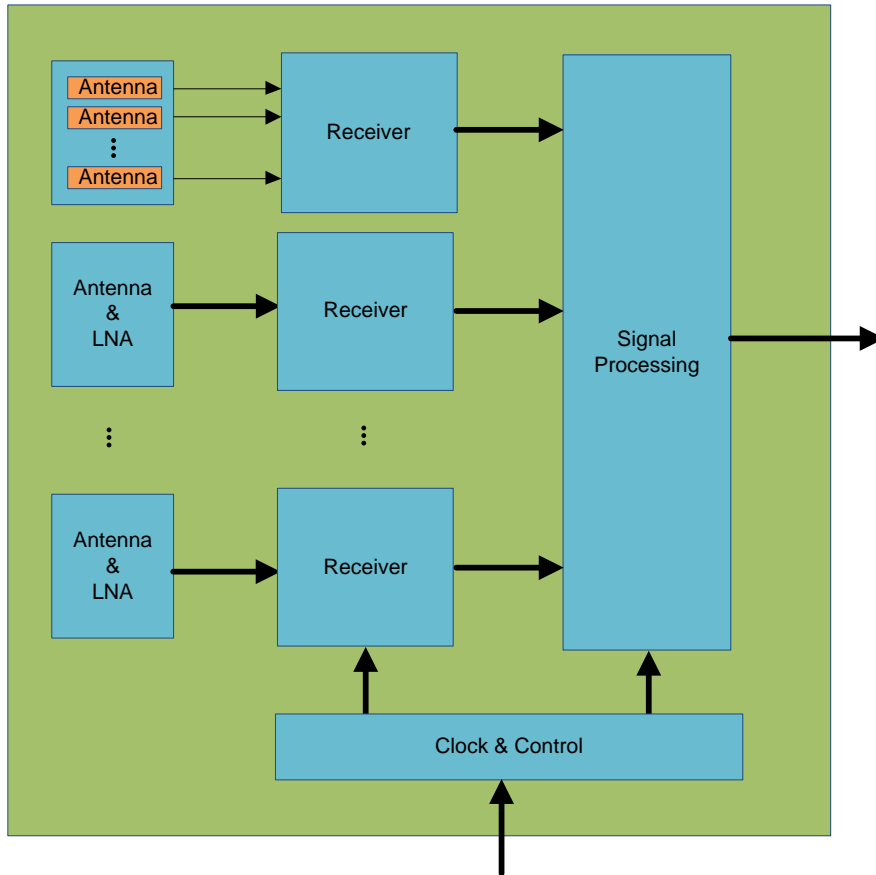
So, given the cost extrapolation involved it can be concluded that for 2009 the processing was dominant while in 2020 it is predicted that the tiles are dominant for design 1. That was one of the reasons to propose an alternative design wherein the balance between the processing and analog electronics including the mechanics is more even. Also from a power perspective design 2 is balanced more than design 1.

The cost estimates presented show exactly the strong case for aperture array technologies. With the same investment in area the FOV and consequently survey speed can be increased by adding more processing power. Since the cost of the latter reduces over time, more processing could be added later to improve the capabilities of the instrument.

The cost per square meter of the aperture array technology is in the same ball park if not lower as alternative technologies. For the aperture array costs per square meter the electronics is included. Hence for similar or lower costs, aperture arrays can deliver on top of the same area an unprecedented FOV.

## 8 Functional Architecture

The functional architecture of one MFAA station is depicted in Figure 9. This resembles the Work Break Down structure of the MFAA at level 4 [AD-7] as well.



**Figure 9: Functional architecture of a MFAA station**

The level 5 [AD-7] architecture is depicted in Figure 10. In the next subsections a brief description of the level 4 and level 5 systems will be given.

### 8.1 Antenna and Low Noise Amplifier

Both are integrated in one subsystem since both need to be designed in close interaction in order to find a global design optimum in terms of mainly (1) noise level and (2) cost. The latter also includes the cost of manufacturing the antennas and to assemble them in the field. So this includes the mechanical aspect of the antennas. For the antenna type currently two concepts have been on the table: a Vivaldi and Octagonal Rings Antenna (ORA). Since the assumed requirements have been changed (frequency range lowered), it might be worth considering other concepts as well. For the mechanical design several concepts for the Vivaldi have been considered as was presented in [RD-5].

Since the environment is of importance for the design currently various mechanical prototypes are designed be put on the RSA SKA site, such that experiences are gained with the environment.

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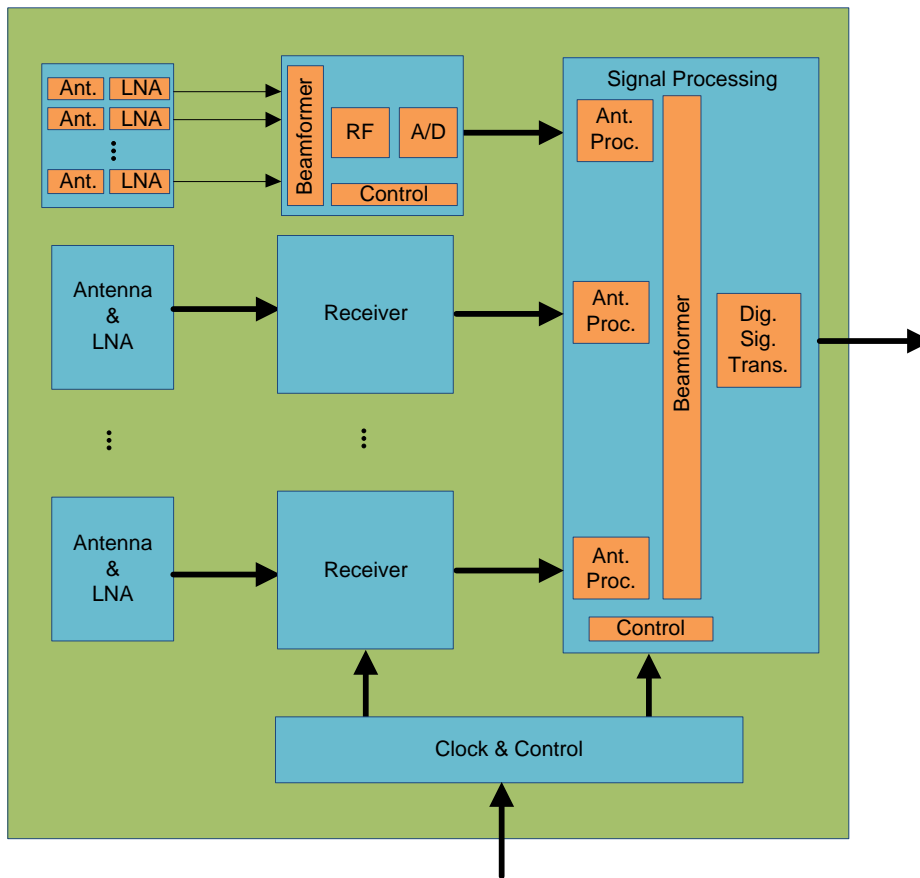


Figure 10: Functional architecture of a MFAA station at level 5 [AD-7]

## 8.2 Receiver

The main function of the receiver is to combine a subset of the antennas, further referred to as tile, amplify and filter the relevant portion of the spectrum (RF) and convert this to the digital domain (A/D). When necessary also a mixer is included to shift the signals in frequency. The necessity of that will depend on the requirements, design and costs and is part of the work to be done.

The main reason to combine a subset of the antennas with an analog beamformer is to reduce cost. Cost in terms of hardware (gain stages, signal conditioning, signal transport, A/D converters and digital processing) and power (each individual antenna has to be amplified to the A/D voltage range). Budget will drive the number of antennas which will be combined.

Receiver control is necessary to select the frequency band, select between two polarisations or two RF beams and set the beamformer phases or time delay steps. Both beamformer concepts are still on the table.

## 8.3 Signal Processing

The main goal of the signal processing is to combine multiple tiles to form the final station beams. The antenna processing presented can consists of time delays or a filter bank dependent on the signal processing architecture

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chosen. In the beamformer the signals of all antennas are combined to form a beam on the sky. The digital signal transport block outputs the beams to the correlator.

Control is necessary to set the weights of the beamformer.

Since the type of signal processing of the LFAA system is similar to what is required for the MFAA system, it is assumed that we can re-use most of the development and hardware from the LFAA signal processing system.

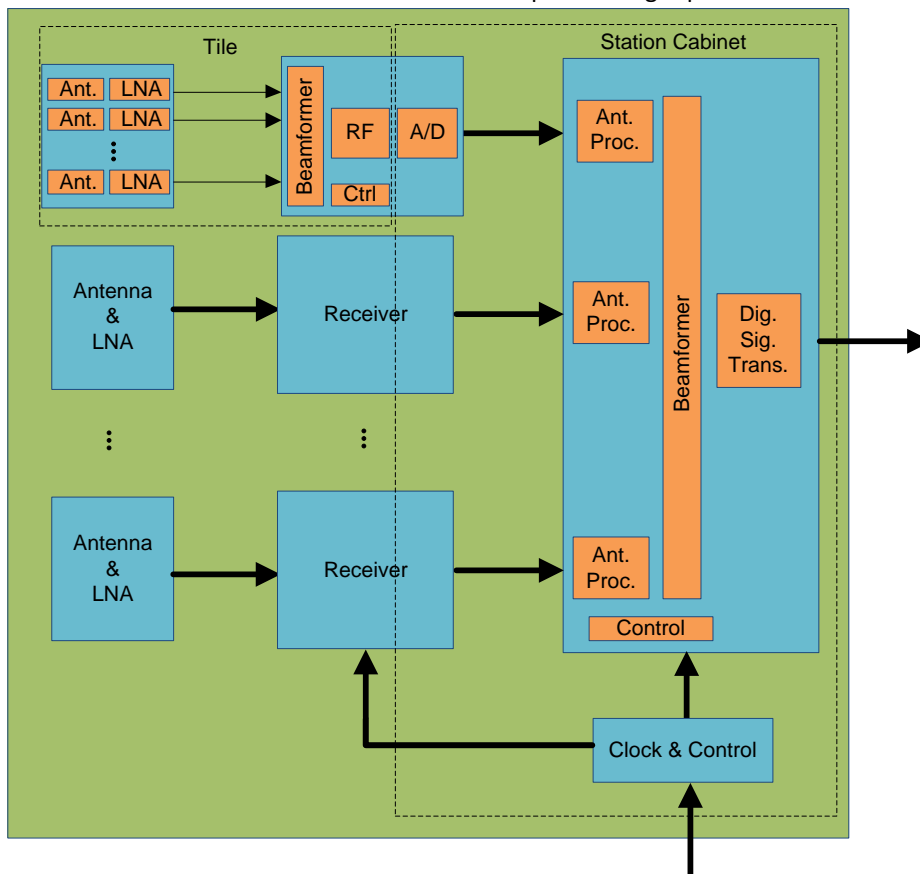
## 9 Physical Design Concepts

Two system design concepts are proposed at the moment. The major difference between both design concepts is the location of the A/D converter. For the first concept a fully analog tile is assumed. The digitisation of the signals takes place in a central station cabinet, while for the second concept the A/D conversion is located near the antennas within the tile.

At technology level also different types of technology are considered, like for example the antennas. This is not discussed further in this document.

### 9.1 Analog Tile

In Figure 11 the functional architecture is redrawn to indicate the physical interfaces. With this concept a subset of the antennas is grouped in tiles. The beamformer reduces the number of signals which have to be transported to a central location in each station. A more detailed partitioning is part of the work to be done in the next two stages.



**Figure 11: Analog tile concept**

The analog tile concept has been proven with EMBRACE [RD-6] for a frequency range of 500-1500 MHz. In Stage 1 more validations with EMBRACE are planned to prove the maturity level of MFAA technology.

## 9.2 Digital Tile

The second concept developed is shown in Figure 12. Within this concept the A/D conversion is located in tiles. This means that the A/D clock has to be transported to each tile. For the digital tile concept direct conversion is assumed. Designs for the subsystems of the digital tile are already in development as part of the Aperture Array Integrated Receiver (AAIR) work [RD-7].

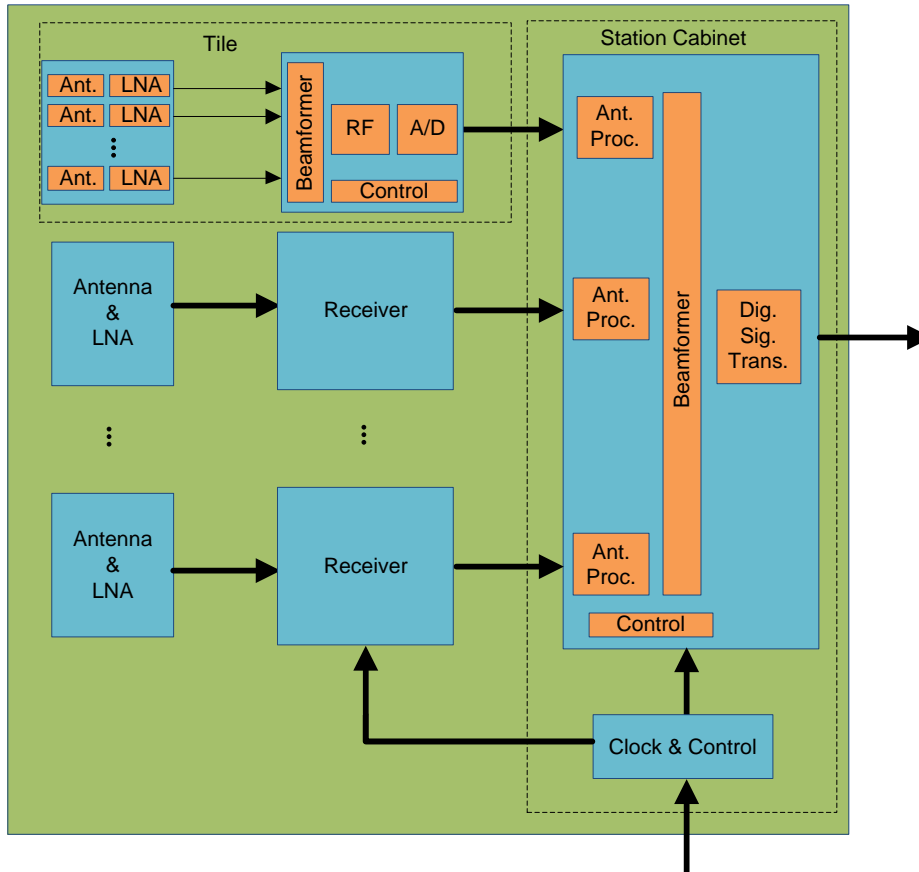


Figure 12: Digital tile concept

## 9.3 Concept Selection

Currently the digital tile concept is at a higher risk since it is not proved yet with a demonstrator. A significant amount of gain is required close to the antennas and also the clock for the A/D conversion needs to be distributed to the tiles in field. However there is still a considerable amount of time before the MFAA technology is constructed on site.

In order to be able to choose one concept a selection process will be defined. The major selection criteria will be performance, power and cost. The latter needs to be refined in Stage 1.

## 10 Way forward

The main areas for the MFAA concept to be developed further for the SKA are:

- An acceptable cost level
- An acceptable power consumption level
- Reduction of the system noise temperature
- Scalability

For the first two bullets the extrapolation factors assumed in Section 7 need to be tracked and proven over time. However the first step would be to establish firm requirements. Based on the design presented in this document another iteration on the science requirements is appropriate. From a technology point of view the work to decrease cost and power consumption will continue.

Although calibration is also an important item to consider for the MFAA technology, this has lots of similarities with the LFAA technology. In fact from a calibration point of view the MFAA is seen as having a lower risk profile because the elements work in the dense regime and are placed in a regular structure. Hence all elements behave identically and the beam pattern as a function of scan angle is more constant. Furthermore due to the regularity, redundancy calibration can be used e.g. in the context of self-calibration and as a consequence more complex sources could be used as a calibration source. For the LFAA technology additional techniques are required to minimize the effect of side lobes and grating lobes.

### 10.1 Cost

The cost reduction strategy is aimed at bringing down the uncertainties in the procurement cost estimates by (1) a targeted technology selection and technology research programme aimed at exploration of lower cost alternatives for those parts of the system that dominate the cost of the MFAA stations, and (2) a carefully defined prototyping programme, that demonstrates performance and compliance with relevant requirements (predominantly in the period after SRR). Alternative technologies already under investigation include the ORA (see Appendix 1) antenna design and the development of a digital tile with an integrated receiver.

Given the vast number of elements in each MFAA station, an important objective of the prototyping plans will be to steadily increase the scale of the system, focussing on efficient and reliable mass production. Each prototype delivery also provides cost information for larger quantities and will be used to check that the extrapolations are on target.

### 10.2 Power

Along the same lines as for the cost, the strategy for the power is also to decrease the uncertainty and total power requirements. The power consumption of the MFAA technology, when compared with EMBRACE, can be brought down because the RFI conditions in which the MFAA stations operate will be much better. It should be stressed that power consumption is highly dependent on the architecture and reality of the various technology roadmaps. Combining analog signals with an analog beamformer prior to digitisation may result in a significant power reduction for a restricted number of FOVs. This will be a crucial parameter for the selection process of the MFAA technology in SKA<sub>2</sub>.

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### 10.3 System Noise Temperature

Given a required sensitivity, the cost of the MFAA system is inversely proportional with the system noise temperature  $T_{sys}$ . Hence optimizing this parameter is very beneficial. In [RD-5] the 15 year history of AA-mid is discussed: in 2000, an important demonstrator THEA was built. For that system the system noise was  $\sim 200$  K. In EMBRACE in 2009  $\sim 100$  K was achieved. At the moment an LNA noise temperature of 50 K has been shown in the lab. Thereafter the next step is to decrease  $T_{sys}$  below 50 K. Compared with EMBRACE that leads to halving the cost of MFAA technology for the SKA advancing toward a sensible receiving system in the low sky noise regime.

### 10.4 Scalability

#### 10.4.1 Towards a Large System

The strategy for building a large MFAA system is to build a 1-5% prototype version before SKA<sub>2</sub> implementation. The steps between the various generations of demonstrators and prototypes will be driven by risk mitigation, performance benchmarking and to anticipate possible showstoppers at an early phase.

#### 10.4.2 System Architecture

Currently and in the immediate future a large number of aspects of the array will remain in flux. Hence, decisions such as station size, for example, will not be taken very soon. The strategy for the MFAA programme is to develop designs that are inherently scalable, in the sense that more antennas or more FOV can be added within reasonable boundaries.

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## 11 Conclusions

In this document a global technical design has been presented based on a number of assumptions for the requirements. Also a cost has been derived. Those costs are founded on real hardware costs and extrapolated to 2020. The derived costs are not driven by the chosen technology but by requirements. The same holds for the data rates involved. Those are a direct consequence of the amount of effective area and FOV required.

From the costing exercise it has become clear that the cost balance between the analog part of the system (including electronics and mechanics) and the digital part changes significantly over time. A much greater FOV can be processed at the same cost later in time. This was and still is the strongest aspect of aperture array technologies. Although the cost of aperture array technology per square meter is similar if not lower than alternative technologies, in terms of FOV it is invincible.

The MFAA technology will be developed in such a way that the design is scalable, i.e. the number of tiles per station and number of stations can be changed over time. The foundation will be a tile which is optimized for the required frequency range. Hence the frequency range needs to be known as soon as possible.

At least two design concepts will be further explored in the next stages: the analogue tile and the digital tile. Besides these two different concepts, also different (lower cost) technologies will be developed further before down selection in time for PDR.

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## Appendix A. Octagonal Rings Antenna (ORA)

### Introduction

The ORA represents a novel and potentially breakthrough technology using a planar, easily fabricated, structure. ORA is expressly designed to be a low cost, low loss, wideband array. The antenna is dual polarised and operates at wide scan angles. The original research work on ORA was undertaken as part of the SKADS project. The results of that work were embodied in a 2.7m × 2.7m prototype array operating over 300MHz to 1GHz. Measurements, in conjunction with SELEX-Galileo (Edinburgh) were extremely encouraging and confirmed the fundamental electromagnetics could be produced in hardware.

The potential of ORA as a low cost array is clear; however SKADS had only demonstrated the principles of ORA. The next stage was to further improve the ORA design and integrate it with the LNAs. This is being undertaken in PrepSKA, with ORA structures being developed to integrate either with a single ended or balanced LNA. Large scale manufacturing techniques of ORA is also being investigated.

### The ORA Array

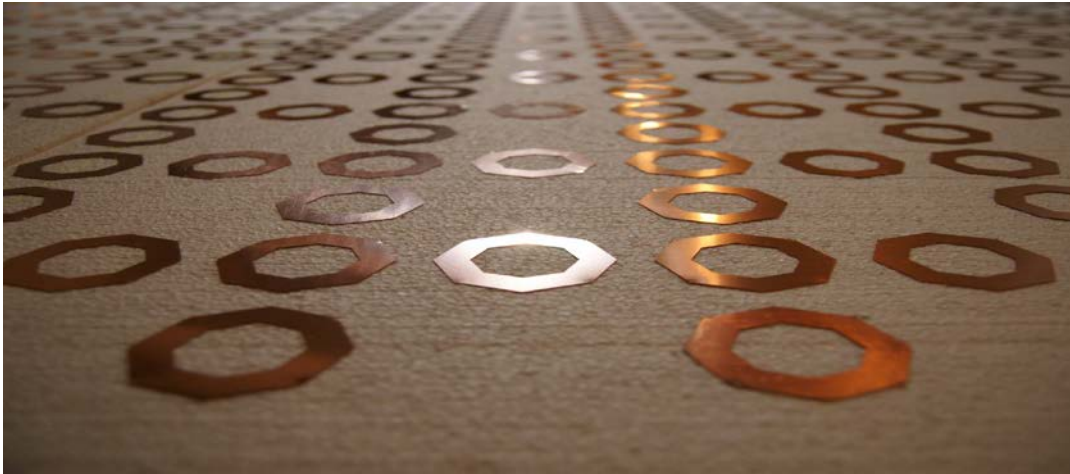
The patented Octagonal Rings Antenna (ORA) for compact aperture arrays has been developed through two phases in SKADS and PrepSKA. The main characteristics of the ORA array have been verified with field measurements. The ORA's properties include:

- A simple planar structure based on low cost manufacturing techniques
- Low and stable cross polarization over broad bandwidth and wide scan angle
- Wide scan angle with a stable scan pattern
- Feed connection flexibility, can be fed with a differential and single-ended LNA

The ORA design has been discussed in [RD-10][RD-11]. The embedded active radiators or receptors are mutual coupled rings with a meta-material superstrate layer above the element rings. The rings are fed in pairs, each pair using a balanced feed. To achieve two polarisations one ring is "shared" between the two polarisations. Hence the basic dual polarised ORA is a triangular structure. A section of the active layer of the ORA array is illustrated in Figure 13.

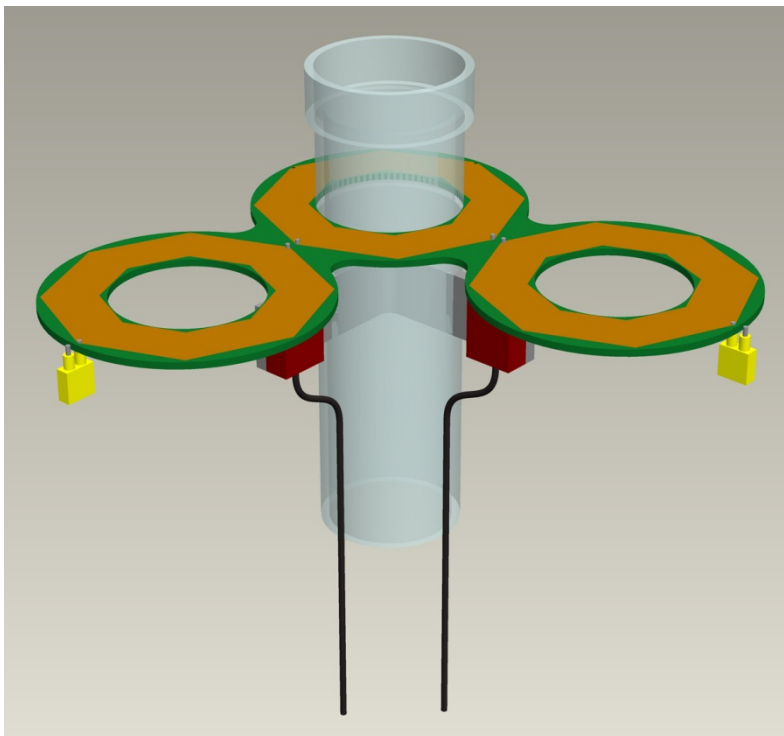
The planar antenna array structure can be fabricated by etching, ink-jet or screen printing, ideal for a large-scale low-cost implementation. The initial finite ORA arrays have been built and measured under the SKADS and UK PrepSKA projects.



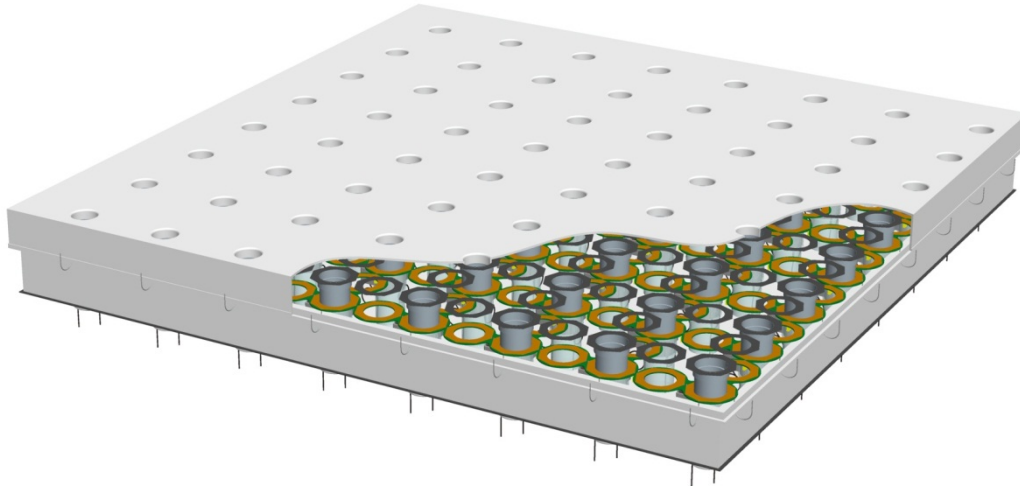


**Figure 13. The active layer of the ORA array.**

The initial production study of ORA array has been investigated including the mechanical and thermal designs. The production design model for one element in the array is shown in Figure 14. This includes the direct LNA integration and thermal management. A production design model for the array environment is shown in Figure 15.



**Figure 14. A single ORA element and the LNA housing box.**



**Figure 15. The production model for ORA elements in an array sub-panel.**

The ORA array can produce a low and uniform cross polarization performance over broad bandwidth and wide scan angle. The impact of ORA technology is potentially highly significant in a number of fields outside of radio astronomy itself, both in the broader imaging community and elsewhere.



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