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MID-Radio Telescope, Single Pixel Feed Packages for the Square Kilometer Array: An Overview

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(Invited Paper)

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ABSTRACT The Square Kilometre Array (SKA) project is an international effort to build the world's largest radio telescope, enabling science with unprecedented detail and survey speed. The project spans over a decade and is now at a mature stage, ready to enter the construction and integration phase. In the fully deployed state, the MID-Telescope consists of a 150-km diameter array of offset Gregorian antennas installed in the radio quiet zone of the Karoo desert (South Africa). Each antenna is equipped with three feed packages, that are precision positioned in the sub-reflector focus by a feed indexer platform. The total observational bandwidth (0.35–15.4 GHz) is segmented into seven bands. Band 1 (0.35 – 1.05 GHz) and Band 2 (0.95 – 1.76 GHz) are implemented as individual feed packages. The remaining five bands (Bands 3, 4, 5a, 5b, and 6) are combined in a single feed package. Initially only Band 5a (4.6 – 8.5 GHz) and Band 5b (8.3 – 15.4 GHz) will be installed. This paper provides an overview of recent progress on design, test and integration of each feed package as well as project and science goals, timeline and path to construction.

INDEX TERMS Dish, MID-telescope, radio astronomy, radio telescope, single pixel feed, SKA.

I. INTRODUCTION

The Square Kilometre Array is an ambitious international project to build the world's largest radio astronomy telescope that will enable breakthrough science and discoveries not achievable with the current facilities.

The SKA technology has been demonstrated by precursor telescopes: MeerKAT [1], [2], built in the Karoo desert (South Africa) and operational since 2018, currently the world's most sensitive telescope array in L-band. ASKAP [3], able to achieve extremely high survey speed, and MWA [4], a low frequency telescope for large surveys of the southern hemisphere, are both commissioned at the Murchison Radio-astronomy Observatory (MRO) in Western Australia. LOFAR

[5], commissioned by ASTRON and deployed in The Netherlands with extensions to other European countries, operates at the lowest frequencies observable from Earth.

After more than a decade of groundwork, the pre-construction phase started in 2012 and concluded in December 2019 with a successful System Critical Design Review (SCDR) that established the foundation for the Design Baseline. The baseline design describes one observatory placed in three host countries: the Headquarters (HQ) in UK, the MID telescope in South Africa and the LOW telescope in western Australia [6], [7]. The combined sensitivity of the two telescopes covers a potentially continuous frequency band that spans from 50 MHz up to 15.4 GHz with provision to extend

TABLE 1. Frequency Range and Fractional Bandwidth of the SKA1-MID Telescope

Band	Frequency (GHz)	Fractional Bandwidth
1	0.35 – 1.05	3.00:1
2	0.95 – 1.76	1.85:1
3	1.65 – 3.05	1.85:1
4	2.80 – 5.18	1.85:1
5a	4.60 – 8.50	1.85:1
5b	8.30 – 15.40	1.85:1
6	15.00 – 24.00	1.60:1

it up to 26 GHz. The SKA1-LOW [8] consists of an array of $\sim 130,000$ dual-polarised, log-periodic antenna elements deployed in the Murchison Shire of Western Australia. The SKA1-MID [9] consists of a total of 197 Gregorian antennas deployed in the Karoo region of the Northern Cape Province of South Africa. The SKA1-MID telescope will be able to achieve high sensitivity over a wide frequency range. To this end, the Single Pixel Feed (SPF) – so called as it creates a single beam per antenna, in one frequency band at a time – sub-element has been divided in the seven bands shown in Table 1. Each feed is precision positioned in the secondary focus by a feed indexer platform. The two lower bands (Band 1 and Band 2) are contained in separate feed packages. They have both successfully passed the Critical Design Review (CDR) and the qualification tests and are currently installed on the antenna prototype for the on-dish testing activities. The five high frequency bands share a single feed package which can be populated in stages. The cryostat and the two initial bands (SPF Band 5a and 5b) are completing the development and test phase and expected to pass CDR in 2021.

Further details on the technology developments for the Single Pixel Feed are provided in this paper along with the status of the project, the timeline and the roadmap to construction.

II. PROJECT DRIVERS AND EVOLUTION

The proposal for the SKA arose from the demand of the scientific community for new capabilities to address fundamental questions in astronomy.

A. SCIENCE GOALS

Beginning 2012 eight Science Working Groups (SWGs) developed the science analysis and goals [10], [11] for the SKA and set the High Priority Science Objectives (HPSO). These were later reviewed in an open process to reassess and refine the key areas of science and eventually define science requirements. Fig. 1 shows the high and medium priority SKA1 observational categories over the available observing frequency bands of the LOW and MID telescopes.

Band 1, Band 2 and Band 5 are the highest priorities for the initial deployment of the MID telescope. Band 3, Band 4 and Band 6 will not be treated in this paper. Nevertheless, the mechanical interfaces and the thermal and electronics infrastructure needed to support them forms part of the present

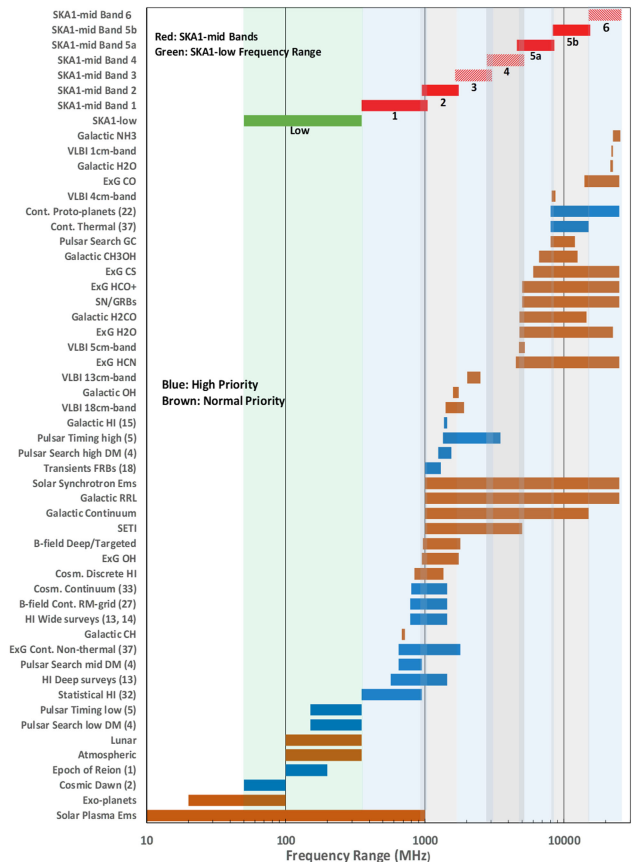


FIGURE 1. SKA1 Observational Categories, science priorities and allocation to the electromagnetic spectrum.

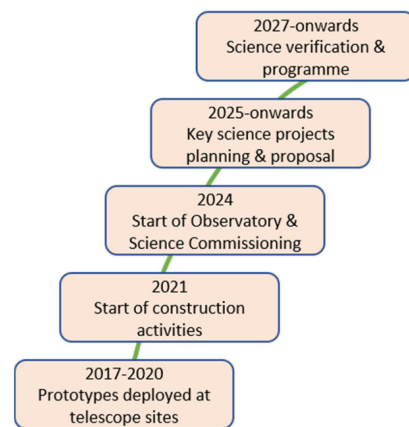


FIGURE 2. SKA Project key dates.

design. A summary of the frequency range covered by the SKA1-MID feeds is shown in Table 1.

B. TIMELINE

The key dates of the project are shown in Fig. 2. Prototypes of SKA1-MID and -LOW telescopes have been deployed at

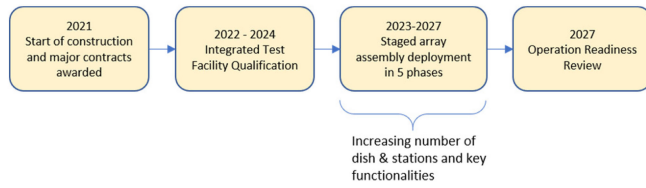


FIGURE 3. High level of SKA1 roll-out-plan for construction.

the host sites and the construction phase is expected to start in 2021, further details are provided in Section C.

It is worth mentioning that in 2019 the SKA Observatory Convention was signed by funding member countries; the SKA Observatory will become an Intergovernmental Organisation (IGO) in full force in early 2021.

C. ROADMAP TO CONSTRUCTION

The central HQ, located in the iconic site of Jodrell Bank, is leading the construction of the observatory. The roll-out-plan for the construction of the SKA1-MID and -LOW telescopes is shown in Fig. 3.

At the time of writing, project management and engineering teams in the SKA Organisation (SKAO) are preparing the contractual data package to start construction in mid-2021.

Following the start of the contract tendering process and construction activities, a sequential assembly of hardware, software and firmware is rolled out in five phases. The Integration Test Facility (ITF) tests as much as possible of the system in a laboratory environment. The system integration and verification on site is staged in five phases known as Array Assemblies (AA). Each Array Assembly is characterized by a number of dishes (SKA1-MID) or stations (SKA1-LOW), the key functionalities of the array and the resulting scientific capability. The activities end with a demonstration of operational readiness. Science verification and commissioning are tied to the roll-out plans, as they depend on these capabilities.

III. SKA1-MID TELESCOPE

The MID telescope project is a global endeavour that sees the collaboration of more than 11 countries spread in 9 time zones. Once fully deployed, the SKA1-MID telescope will consist of a combination of 133 15 m shaped Gregorian offset reflector antennas and 64 13.5 m similar, but unshaped dishes from the MeerKAT telescope. The antennas will be located in a 3-arm spiral configuration departing from an inner dense core of 1 km diameter towards the outer part of the array and will extend over a 150 km diameter (Fig. 4) with a total collecting area of $\sim 32600 \text{ m}^2$.

The sensitivity (A_e/T_{sys}) and the efficiency as well as the feed and receiver noise of the single SKA dish are shown in Table 2. For Band 1 and Band 2 the data have been obtained around the mid-band frequency at an elevation of 45° . The data for Band 5 are instead averaged across the band with the dish pointing at zenith.

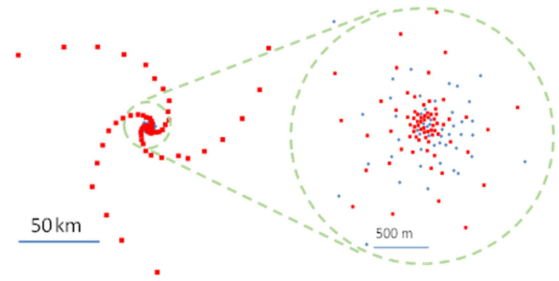


FIGURE 4. SKA1-MID array configuration and internal core.

TABLE 2. Single SKA Dish Sensitivity, Efficiency and Noise Contributions

Parameter	Band 1	Band 2	Band 5a	Band 5b
Frequency (GHz)	0.7	1.4	Average	Average
Cosmic Background (K)	2.73	2.73	2.73	2.73
Galactic (K)	4.53	0.67	0.01	0.002
Atmosphere (K)	2.2	2.6	2.0 ^a	4.3 ^a
Spillover (K)	3	0.9	0.8 ^a	0.2 ^a
Total T_{antenna} (K)	12.5	6.9	5.5 ^a	7.2 ^a
T_{receiver} (K) ^b	13.5	5.6	7.4	9.2
$T_{\text{structure and backend}}$ (K)	1	1	1.6	1.6
T_{system} (K)	27	13.5	14.5 ^a	18.0 ^a
Aperture Efficiency, η ^c	0.81	0.90	0.84	0.83
Effective area, A_e , (m^2)	143.1	159	148.4	146.7
A_e/T_{sys} (m^2/K)	5.3	11.8	10.2 ^a	8.1 ^a

^a Referred to zenith

^b Includes the feed and vacuum window contributions

^c Assuming perfect optics, i.e., excluding mechanical tolerance of the structure

TABLE 3. SKA1-MID Array Performance

Frequency band	SEFD (Jy)	Equivalent A_e/T_{sys} (m^2/K)
Band 1 + UHF Band	2.85	967
Band 2 + L-band	1.55	1784
Band 5a	2.38	1161 (2.5 GHz max. sampled band)
Band 5b	2.77	998 (2.5 GHz max. sampled band)

The sensitivity and the System Equivalent Flux Density (SEFD) of the whole SKA1-MID array (combination of SKA and MeerKAT dishes) are shown in Table 3 for the four high priority bands.

IV. SINGLE PIXEL FEEDS: OVERVIEW

High antenna efficiency and low total noise are the key drivers of the SPFs design in the individual bands to achieve maximum on-dish sensitivity. While the dish has been designed to accommodate up to seven feeds, at the time this paper is released, four of them are at a mature stage of prototyping and will be discussed in the next sections.

A. SPF BAND 1

The Band 1 SPF package (shown in Fig. 5), developed at Onsala Space Observatory (OSO) is a room temperature system that operates over the frequency from 0.35 to 1.05 GHz [12].



FIGURE 5. SPF Band 1 feed package shown without cover shield.

The SPF is based on a dual linear polarized Quad Ridged Feed Horn (QRFH) of 1.3 m diameter and overall feed package length of 1.5 m.

The QRFH assembly is comprised of three main parts: four ‘ridges’, an outer flare split into four ‘quarter sections’ and a back-short section. The feed is mounted on a support that also acts as an interface to the indexer on the antenna. The aperture of the horn is protected by a polycarbonate radome, the feed is made moisture proof by sealing all mechanical parts while a desiccator absorbs any moisture leakage. An environmental shield protects the feed package from rain and direct sunlight. The two room temperature low-noise amplifiers (LNA) [13], manufactured by Low Noise Factory (LNF), are integrated in the ridges close to the feed pins of the two orthogonal polarisations, minimizing the losses in front of the LNA. The noise-injection coupler is combined with the LNA in a single assembly with the calibration signal injected prior to the first amplification stage. The rest of the feed electronics (i.e., 2nd stage LNAs, calibration noise diode, monitor and control electronics, etc.) are located in the feed-controller enclosure mounted on the rear of the feed horn. The block diagram of the Band 1 Feed Package is shown in Fig. 6.

The QRFH spline-defined horn and ridge profiles, together with the back short design, are optimized to provide maximum sensitivity over the wide fractional bandwidth (3.0:1) [12]. The phase centre is accurately determined to maximize the phase efficiency and determine the mounting position on the dish feed indexer to achieve maximum sensitivity.

A prototype has been fully qualified to demonstrate compliance with the SKA requirements. Due to the size of the feed package, customized equipment has been developed to carry out some of the qualification tests (e.g., RFI and environment tests). The dish system sensitivity, presented in Fig. 7, has been estimated by combining measurements performed in the laboratory and simulations of the feed on the SKA dish.

The measured receiver noise temperature is below 18 K for both polarisations while the receiver gain is compliant with the SKA requirements as shown in Fig. 8.

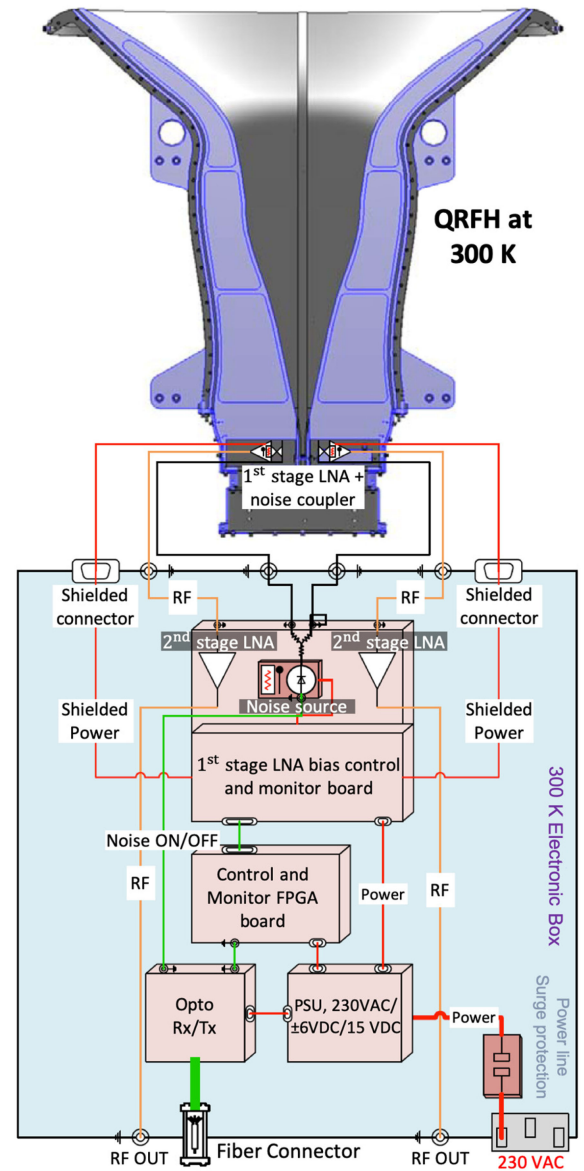


FIGURE 6. SPF Band 1 system block diagram.

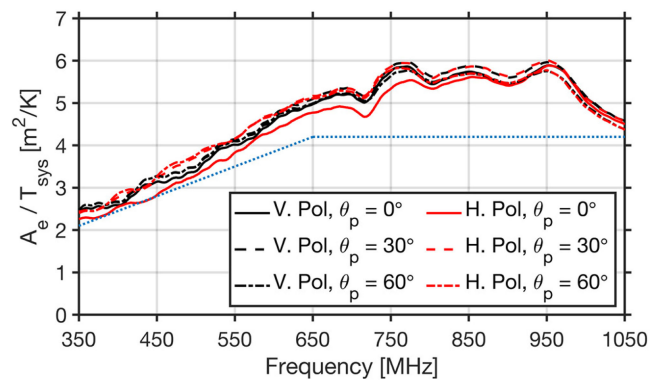


FIGURE 7. Sensitivity derived for the H/V polarisations across the Band 1 frequency range for three zenith angles.

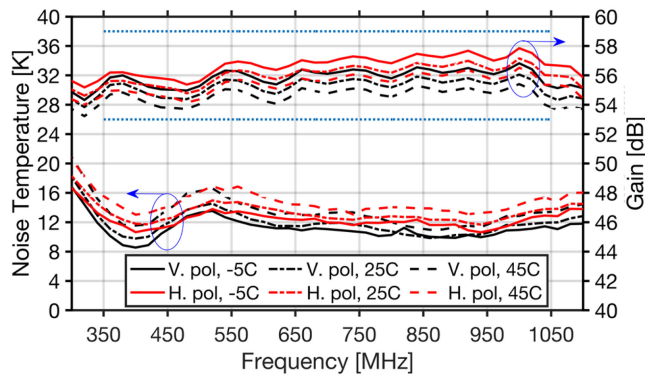


FIGURE 8. Receiver gain and noise temperature for the H/V polarisations across the Band 1 frequency range at different temperatures.

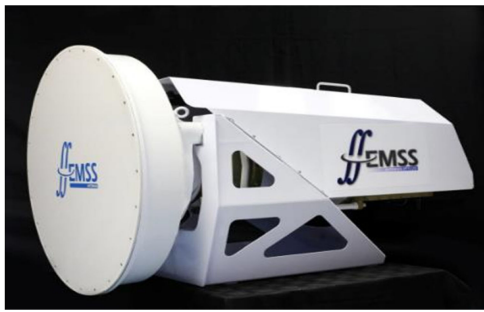


FIGURE 9. SPF Band 2 package.

Successful tests have been performed with the Band 1 SPF installed on a MeerKAT antenna [14] and on the Dish Verification Antenna 1 (DVA-I) [15], an offset Gregorian SKA telescope precursor, located at the Dominion Radio Astrophysical Observatory (DRAO) in Canada. Although a direct comparison may be not possible, the results of these tests confirmed the simulated system performance of the SKA dish. Installation, integration and verification of the Band 1 SPF on the SKA-MPG dish (funded by the Max Plank Society) is ongoing at the time this paper is released and expected to conclude in 2021.

B. SPF BAND 2

The Band 2 SPF (shown in Fig. 9) developed by EMSS Antennas operates over the frequency band 0.95 GHz to 1.76 GHz.

The Band 2 SPF block diagram is shown in Fig. 10; the feed package consists of an ambient temperature wide flare angle axially corrugated conical horn [16], a cryogenic Orthogonal Mode Transducer (OMT) realised as a pair of orthogonal dipoles [17], LNAs cooled to below 20 K and a final room temperature amplification and matching stage. Cooling is achieved with a Gifford McMahon (GM) cryogenic-cooler that requires high pressure helium. The cryogenic components inside the cryostat are thermally insulated by a high vacuum. The SPF vacuum service supplies the initial vacuum during

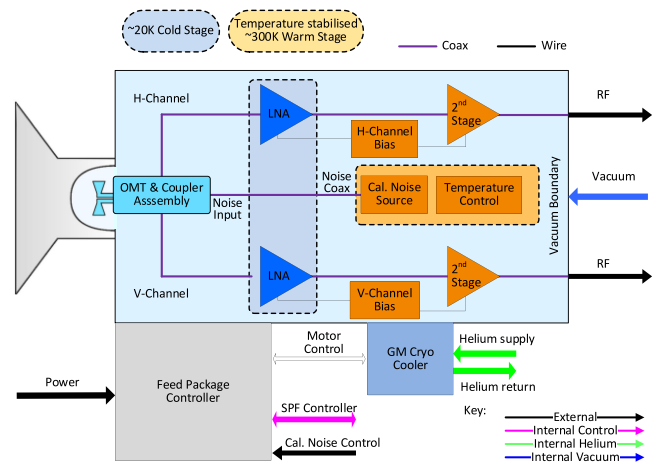


FIGURE 10. SPF Band 2 system block diagram.

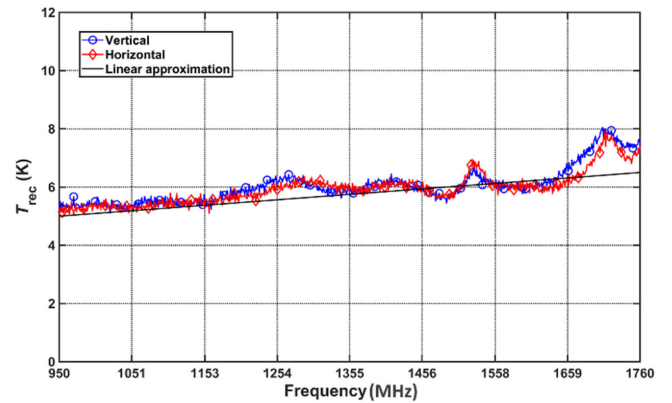


FIGURE 11. Measured Band 2 receiver noise temperature for both polarisations.

start-up, while the cryo-pump maintains vacuum during operations. The waveguide is at ambient temperature with a High Density Poly Ethylene (HDPE) dome over the cryogenic dipoles creating the vacuum window. The calibration noise source is thermally stabilized at ambient temperature inside the cryostat to minimize amplitude variations on the signal path. The feed package is covered with a sun shield to reduce solar heating and provide protection against direct rain. Moisture collection is limited by protecting the horn aperture with a hydrophobic radome membrane and desiccator breather.

Extensive simulation work has been carried out on the performance analysis of the Band 2 feed on the SKA 1 dish geometry. In [18]–[20] the authors present a method to estimate and maximise the telescope sensitivity over the frequency range allocated to Band 1 and Band 2.

Qualification tests have been performed on the Band 2 SPF prototype and have successfully demonstrated compliance with the SKA requirements. The receiver temperature has been evaluated by using the Y-factor method [21] and the results are shown for both polarisations in Fig. 11. A linear increase from 5 K at the lowest frequency end to 6.5 K

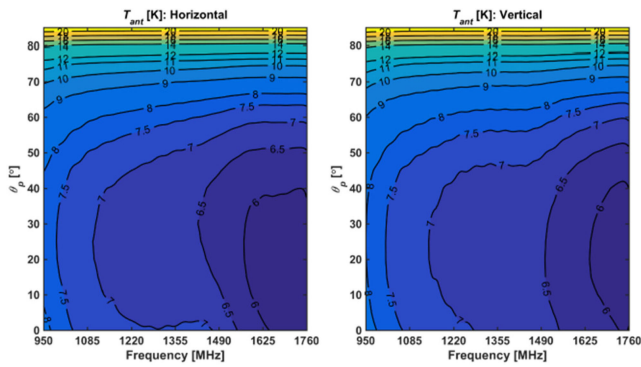


FIGURE 12. Antenna temperature as function of frequency and zenith angles for both polarisations.

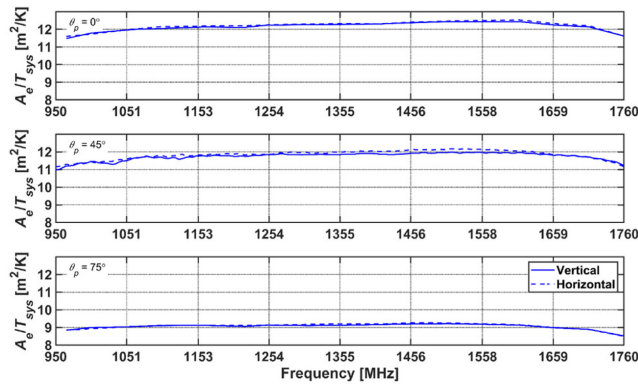


FIGURE 13. Sensitivity derived for the H/V polarisations across Band 2 frequency range for three zenith angles.

at 1760 MHz has been used to evaluate the sensitivity. The system temperature has been calculated as the sum of the receiver temperature, a 1 K contribution allocated to all other effects (i.e., surface, loss, digitizing noise, unexpected effects, etc.) and the antenna temperature.

The latter (shown in Fig. 12) has been calculated using the brightness temperature from [22] with the following parameters:

- $T_{\text{gnd}} = 300$, Ground Temperature
- $\epsilon_{\text{r}} = 3.5$, relative permittivity of ground
- $H_a = 100$, Height of atmosphere
- $T_{\text{go}} = 20$, base temperature
- $f_0 = 0.408$, base frequency
- $T_{\text{cmb}} = 2.73$, Cosmic microwave background emission
- $R_e = 6370.95$ earth radius [km]

The dish system sensitivity is shown in Fig. 13 for several zenith angles.

C. SPF BAND 345(6)

The SPF Band 345(6) feed package has been developed at the University of Oxford, Department of Physics. It is designed to house up to five feed horns for Bands 3, 4, 5a, 5b and 6 in a single, modular cryostat cooled by a single Gifford McMahon (GM) coldhead. This design was adopted because

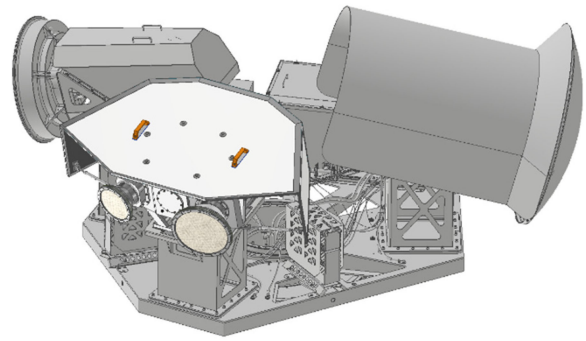


FIGURE 14. The Band 345(6) feed package with bands 5a and 5b feed fitted (centre) mounted on the feed indexer. Also visible is SPF Band 1 (right) and SPF Band 2 (left).

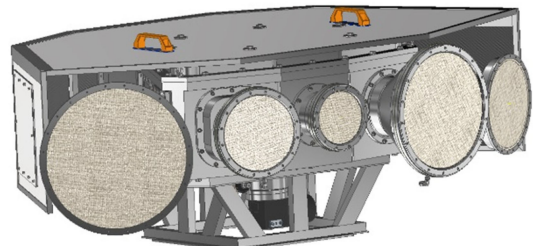
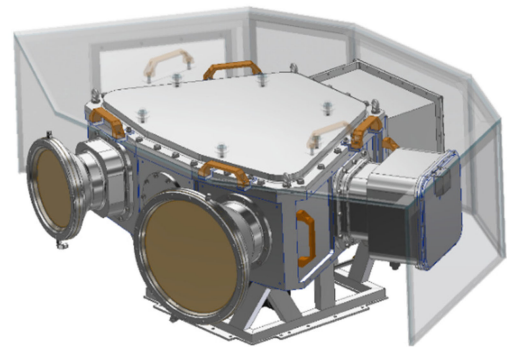


FIGURE 15. (Top) The Band 345(6) feed package with bands 5a and 5b cryostat windows and feeds fitted. (Bottom) The Band 345(6) feed package showing the addition of side mounting modules to accommodate the band 3 and 4 feed horns. The band 6 feed horn and window can be seen between mounted centrally between the 5a and 5b feeds.

constraints on the electrical power available for cryogenics at each antenna (5 kW) made running each band from a separate coldhead impractical. By careful cryogenic design, a single Oxford Cryosystems Coolstar 6/30 coldhead which has 30 W of first stage cooling (@ 80K) and 6 W of second stage cooling (@ 10 K) is expected to provide sufficient cooling for up to 5 bands. In the first instance, the higher science priority band 5a and 5b feed horns, OMTs and RF chains will be populated, with the intention of adding bands 3, 4 and possibly 6 at a later date. Fig. 14 shows the Band 345(6) feed package, with bands 5a and 5b populated, mounted on the feed indexer (centre) alongside the separate Band 1 and Band 2 feed packages.

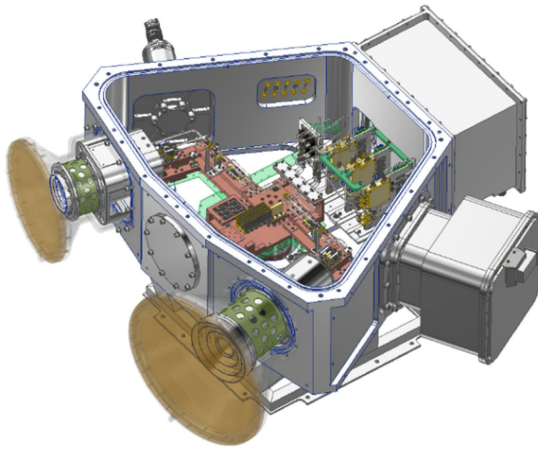


FIGURE 16. The Band 345(6) feed package, showing the cryostat interior. Visible is the copper thermal plumbing (with radiation shielding and multilayer insulation removed) and the mounting plates for the warm RF electronics towards the rear of the cryostat. The cryostat windows are shown in transparent brown and the apertures of the corrugated feed horns are visible behind them.

Fig. 15 shows the Band 345(6) feed package. Visible at the front are the cryostat windows for the band 5a and 5b feed horns. At the rear of the cryostat is an RFI-tight enclosure for the Feed Package Controller (FPC), which houses the unit's power supplies and monitoring and control electronics. Mounted on the right is an RFI-tight enclosure for a turbomolecular vacuum pump. The unit is protected by a lightweight weather/sun shield and is mounted on a welded steel support frame. The feed package with the full complement of receiver bands is also illustrated.

The cooling power from the GM coldhead (mounted vertically towards the centre of the cryostat) is directed to the feed horns, OMTs and LNAs via copper “thermal plumbing” (Fig. 16). The feedhorns are cooled to the coldhead's first stage temperature of ~ 80 K, whereas the OMTs and LNAs are cooled to the second stage temperature of ~ 12 K. The feed horns for each of the two bands are 1:1.85 bandwidth wide flare-angle corrugated horns. Each horn is positioned behind a vacuum window consisting of a Mylar sheet mechanically supported by a closed-cell polyethylene foam (Zotefoam) sheet, which also acts as an infrared block. The horns (cooled to 80K) couple the incoming radiation, via a narrow thermal waveguide break, to the OMTs (at 12K) which couple the two vertical and horizontally polarized TE_{11} waveguide modes into standard semi-rigid cable. The Band 5a OMT is a quad-ridged finline design, whereas the higher frequency Band 5b OMT is a waveguide turnstile type. The horns and OMTs were designed and manufactured by JLRAT/CETC54, China [23]–[25].

The block diagram of the Bands 345(6) electronics is shown in Fig. 17.

The orthogonally polarized signals propagating along coaxial cables from each OMT are first amplified by commercial LNAs manufactured by Low Noise Factory. The signals

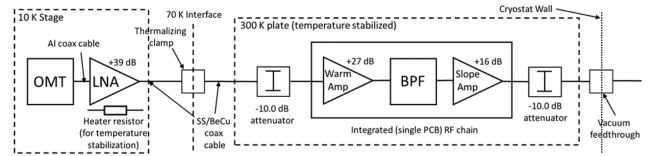


FIGURE 17. Block diagram for the Band 5a RF chain. The Low Noise Factory LNA is temperature stabilized by a heater resistor under PI loop control by the Feed Package Controller (FPC). The warm (300K) RF components (warm amplifier, bandpass filter and slope compensating amplifier) are fabricated on a single Duroid substrate housed in a machined aluminium enclosure and temperature stabilised using an analogue PI control circuit.

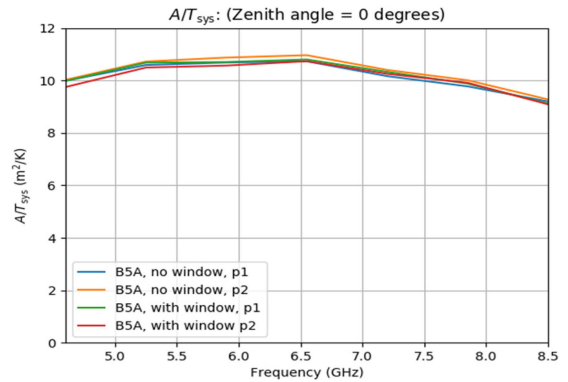


FIGURE 18. Sensitivity estimates (for two polarizations $p1$ = horizontal and $p2$ = vertical, with and without cryostat windows) for a single antenna pointing at zenith as a function of frequency for Band 5a (4.6 – 8.5 GHz).

are then directed, via thermally isolating stainless steel/BeCu semi-rigid coaxial cables to a warm RF chain which consists of two additional stages of amplification either side of a band-defining bandpass filter. For each band these components are integrated onto a single planar substrate within a machined aluminium enclosure. These warm RF units are mounted on a 310 K temperature controlled mounting plate inside the cryostat to the rear of the coldhead and thermal plumbing structure. Here we also find a temperature controlled broadband RF noise source for calibration purposes. This noise calibration signal can be RF switched to the band in use and is injected into the throat of each feed horn via a weakly coupled waveguide probe.

The noise performance of the 5a and 5b RF chains have been modelled to obtain estimates for the likely T_{rec} receiver noise performance. The system noise temperatures are expected to be between 8.2 and 9.5 K for band 5a and 9.4 and 13.2 K for band 5b. Electromagnetic modelling of the diffraction between the horn aperture and cryostat window has been performed using CST Microwave Studio. The window has a significant effect on the feed beam pattern compared to an isolated horn, but by careful design of the window aperture and position it is possible to maintain the overall A/T of the antenna (Fig. 18). The full beam patterns for each feed and window on the SKA-MID dish have been calculated using Ticra's GRASP physical optical modelling package. The beam patterns were then used with atmospheric and ground

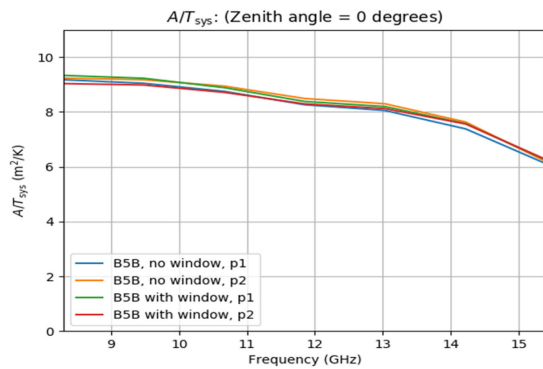


FIGURE 19. Sensitivity estimates (for two polarizations p_1 = horizontal and p_2 = vertical, with and without cryostat windows) for a single antenna pointing at zenith as a function of frequency for Band 5b (8.3 – 15.4 GHz).

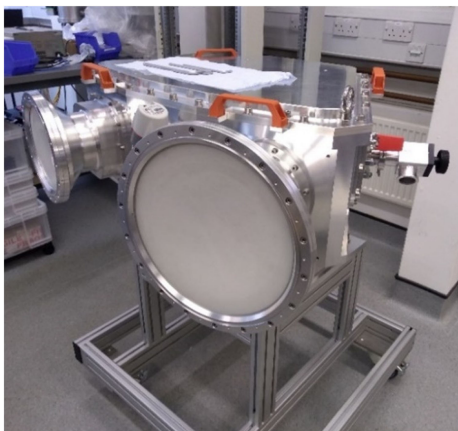


FIGURE 20. Band 345(6) prototype cryostat ready for assembly and integration at the University of Oxford.

emission models [22] to calculate the expected T_{spill} spillover contribution to the system noise temperature ($T_{sys} = T_{rec} + T_{spill}$). Finally, these system temperature estimates were used to calculate the expected single antenna point source sensitivity (A_e / T_{sys}) (Fig. 18 and Fig. 19).

The SPF Band 345(6) prototype cryostat, horns, OMTs and RF components have now been manufactured (Fig. 20) and are currently undergoing assembly, integration and testing at the University of Oxford. Completion of the Critical Design Review and beginning of on-dish testing are expected in 2021.

IV. CONCLUSION

An overview of the goal, science and road to construction of the Square Kilometre Array radio-telescope has been provided in this paper.

The latest technology developments on the design and prototyping of the Single Pixel Feeds for the SKA1-MID telescope have been discussed. Extensive qualification tests are being carried out at the time this paper is released and will be subject of future publications.

The consolidated effort from all the teams involved demonstrates that the SKA project is mature to enter the construction phase and is certainly on the path to success.

ACKNOWLEDGMENT

The work detailed in this paper would not have been possible without the collaborative efforts of the international SKA Dish consortium, one of 12 engineering consortia responsible for designing the look and functionality of the SKA's different elements and ensuring they all work together. The consortia brought together hundreds of experts from research institutions and industry around the world, whose talents and inputs were invaluable throughout the SKA's design phase and in preparations for SKA construction.

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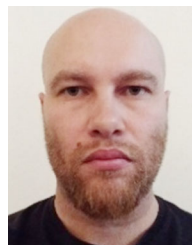
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