

ADVANCED INSTRUMENTATION PROGRAM WIDE BAND SINGLE PIXEL FEEDS TECHNICAL SOLUTION

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Glossary (definition of terms)

AIP

Advanced Instrumentation Program

SKA Baseline

The SKA specification (baseline) as issued with the RfP and as set out by the SKAO

SKA-WBSPFC

Square Kilometer Array Wide Band Single Pixel Feed Consortia

SKADC

The SKA Dish Consortium comprising institutes, industry and other stakeholders.

Feeds & LNAs

Feed system and LNA

Receiver

Everything post-LNA including A/D, gain, RF and (any supporting) digital systems ahead of the correlator.

SKA Element

Level 3 item in the WBS e.g. Aperture Array, Dishes, Science Data Processing.

QRFH

Quad-ridged Feed Horn

Applicable Documents

Doc #	Title	Official SKAO DMS reference
[AD01]	SKA-1 System Baseline Design	SKA-TEL.SKO-DD-001
[AD02]	Statement of Work for the Study, Prototyping and	SKA-TEL.OFF.AIP-SKO-SOW-001
	Preliminary Design of an SKA Advanced Instrumentation	
	Programme Technology	
[AD03]	SKA Request for Proposals ('header' document)	SKA-TEL.OFF.RFP-SKO-RFP-001

Reference Documents

Doc #	Title	
	The references are listed at the end of the document	

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1 Introduction

This document describes the technical approach to be taken from the SKA-WBSPFC consortium in developing wide-band single pixel technology for the SKA within the AIP area. The baseline plan for SKA1 includes feeds with 3:1 frequency ratio, a range which is already wideband compared to conventional octave feed horns. Technology covering this fractional frequency range will be developed within the SKA Dish Consortium [AD01]. Wider frequency range feed solutions (3:1 to 10:1) are instead included within this AIP [AD02], [AD03].

There are, as outlined below, many science/operational advantages to such ultra-wideband feeds which make them a highly interesting for SKA use. However while there has been much development in recent years in feed/LNA systems covering very large fractional frequency ranges, their performance needs further development for SKA use. This AIP will address the remaining WBSPF challenges described below so that very wideband single pixel feeds become a competitive choice for the SKA.

Advantages of WBSPF

Science advantages --- Ultra wide band WBSPF have many scientific advantages. These include; (1) Wide z space for blind HI and OH surveys increasing survey speed. (2) Simultaneous observations of multiple spectral lines, including multiple molecular rotational lines in the 1-10GHz range important for the 'Cradle of Life' science case. These lines include large sequences of atomic recombination lines or closely spaced lines from large organic molecules which can be co-added for higher sensitivity. (3) Higher bandwidth giving higher sensitivity for continuum observations. The additional sensitivity is both in total intensity and polarization, including a larger fractional Faraday depth resolution. (4) Advantages for observing fast continuum transients (see Thornton et al 2013, Science in press, for the recent discovery of a population of millisecond duration 'Lorimer' bursts). Higher bandwidth gives both a lower threshold for detection of such transients and even larger SNR improvements on dispersion and delay estimates; the latter being of particular importance for the spatial location of weak transients. (5) Although observations toward pulsars on given lines of sight through the galaxy have optimum frequency ranges of only a few hundreds of MHz (see SKA1 baseline design) a WBSPF can search (or time) simultaneously pulsars at a very wide range of galactic dispersion measures along some lines of sight, especially those toward the inner galaxy. (6) Ultrawide WBSPF allow a higher probability of serendipitous discoveries including SETI signals.

System and Operational advantages – The large number of dishes within SKA (in particular for SKA2 where as many as 2500 dishes will be required) puts a premium on minimizing the number of feed bands. By reducing the number of bands savings are possible in three main areas. (1) Capital costs-for any reasonable budget dish costs for SKA2 must be pressed down which increases the marginal importance of the cost of the receiver band suite; costs which can in turn be reduced by having fewer bands, (2) Power costs – studies [1] suggest that for SKA2 it may not be economically feasible to cool multiple bands down to 20K physical temperature using GM coolers, having fewer feed packages increases the practicality of aggressively cooling the bands for good sensitivity performance. (3) Maintenance costs- manpower in remote locations is expensive and reducing failure rates is therefore extremely important to limit operations costs.

Comment on Sampled and Processed Bandwidth – Most of the scientific advantages described above come from a larger sampled bandwidth - which in turn has implications for the dimensioning of downstream SKA data processing (both for interferometry and non-interferometric processing). Some advantages persist if only a part (either a contiguous band or many smaller spread spectrum bands -geodetic style) is transmitted and processed, In contrast the system and operational advantages (reducing the number of feed packages) are independent of whether the full bandwidth is processed or not.

Challenges of WBSPF

The principal challenge of WBSPF solutions is that the feeds themselves have lower sensitivity than octave feed horns and that LNAs have some degradation in performance if they are made very wide band. The gap in feed performance is however narrowing and is now as low as 5% - 10% ([2] Fig. 22),

likewise LNAs increasingly approach octave band performance over ever larger fractional bandwidths. Although WBSPF solutions will always be lower sensitivity than octave horns we believe the gap in performance can be narrowed given further R&D. A full 'cost of ownership' analysis including operations costs for an array with fixed Aeff/Tsys should be done at SKA system level to determine the relative merits of octave horns versus WBSPF, particularly for SKA2. The SKA-WBSPF consortium will work to improve the efficiency of WBSPF designs (carefully talking into account all system loses in practical designs) and supply data to the SKA office to allow system trade studies to be made comparing conventional feed and WBSPF solutions.

2 SKA-WBSPF delivery of SKA pre-construction – overview and approach

The SKA1 baseline design identifies continuous frequency coverage as a high priority goal for the SKA. The full frequency range of the dishes is 350MHz – 20GHz a range of 57:1, this means that in principle two ultra-wideband feeds each covering a factor of 7.5 in frequency could cover the full frequency range. The frequency range of these two feeds would be 0.35 - 2.6GHz and 2.6 - 20GHz. The lower band (Band A) would encompass all red-shifted *HI*, *OH* and non-galactic centre pulsar work. The upper band (Band B) would cover most molecules of the Cradle of Life science goal and detection and timing of pulsars toward the galactic centre.

Despite the simplicity of the above argument the choice of dividing frequency between lower and upper bands must be tempered by practical considerations. A low band feed covering 350MHz – 2.6GHz would be too large to cool and while the feed would give an acceptably low contribution to Tsys at 350MHz this would not be the case at 2.6GHz. Feed cooling would only possible with the higher frequency feed and if the lower edge of this were at 2.6GHz this would give an overall system of feed packages with an unacceptably high Tsys region below 2.6GHz. Because most radio sources increase in brightness to low frequency sensitivity considerations argue that the lowest frequency end of the high band WBSPF feed should be set by the maximum size of feed that it would be possible to fully cool(this argument depends though on what other technologies, for instance dense-AA and PSFs, and their frequency ranges are adopted for the full SKA system). The question of the lowest frequency feasible cooled WBSPF system will be examined as part of the proposed consortium work, but at present we estimate that while going down to 1.6GHz to cover the **OH** lines might be feasible going as low as 1.4GHz may be very difficult. We therefore adopt 1.6GHz as the lowest end of Band B.

The upper end of this B feed assuming a 7.5:1 ratio would be 12GHz. An additional octave (1.8:1) feed (Band C) could be added covering 12GHz to 22GHz, i.e.up to the highest frequency to which the dish operates and including the galactic water line at 22GHz. Such a configuration would have similar sampled bandwidth (10GHz) for both bands B and C and hence use the same data transmission and correlation infrastructure (about twice the bandwidth as in the SKA1 baseline design).

An alternative that might be considered is making bands B and C both 4:1 range feeds (1.6- 6GHz and 6GHz -23GHz). The tradeoff between WBSPF fractional bandwidth and sensitivity is not clearly understood and such an option might be preferable if our studies showed significant sensitivity advantages to lower fractional bandwidths.

A programmatic advantages of 1.6GHz lowest frequency for Band B Is that is very close to the lowest frequency (1.6GHz) of Band 3 in the SKA1 baseline design. This means that either in the first instance or as part of a retrofit (perhaps an expansion in frequency capability of SKA1 to SKA1.5 before the collecting area in increased) Band 3 could be replaced by Band B. The scientific arguments for SKA1 achieving the highest possible sensitivity in Band 3 (1.7GHz – 3GHz) at the expense of having no capability at higher frequencies than 3GHz do not seem to us to be compelling. The broad astronomical community might prefer as part of SKA1 an option such as Band B which although having slightly lower sensitivity between 1.7–3GHz would allow observations up to 6GHz or 12GHz, including for the latter option high priority observations of pulsars in the galactic centre.

Turning to Band A the SKA1 baseline design ([AD01] Table 5) specifies the lowest frequency of operation of the dishes as 350MHz. but the main text of the same document mentions that the

dishes could have some performance down to 300 MHz; we therefore take this smaller as the low end of Band A. Some overlap with Band B is desirable but it should not be too large, an upper limit of 2GHz seems reasonable, this would allow most pulsar observations within one band and fits the 7:1 range possible with the QRFH. The previous designs of Eleven feeds for low frequencies show that the ports of the petals constituting one polarization can be connected with transmission lines at the center of the feed if there are no dipoles for frequencies higher than 2GHz, so from the perspective of the 11-feed, this upper frequency is also a good choice. Cryogenic integration of the feed for either of the available WBSPF technologies is not easily realizable for Band A, therefore keeping the highest operational frequency relatively low, will relax the requirements on the transmission lines connecting the Feed and the Cryostat. This is especially valid for the Eleven feed if it will require amplitude and phase matched pairs of cables.

Given the arguments above in the rest of this Technical solution we will consider solutions for the following bands:

A) 0.30 -2GHz,

B) 1.6 – 12 GHz

we note however that within our R&D study we will also look at other options such as two 4:1 frequency range feeds covering frequencies above 1.6GHz.

3 CURRENT STATUS OF THE WIDE-BAND FEED AND LNA TECHNOLOGIES

The development of WBSPF with fractional bandwidth of 7:1 and higher has rapidly advanced during the recent years, driven mainly by the Geodetic-VLBI community who are aiming for simultaneous observations spanning the 2.2-14GHz band (VLBI2O10 standard). The extensive development work from this community has produced two feed types that are considered as mature enough by our WBSPF consortium for further research and development toward SKA applications: namely the Eleven feed [2], [3], [10]-[17] and Quad-ridged Feed Horn (QRFH) [18]-[25]. Both feeds have been used in various telescopes (including a high performance 0.6 – 3GHz QRH deployed at the Bonn 100m telescope) and good software tools for feed design are available to model and predict the Electro-Magnetic (EM) performance. Although there are other concepts for WBSPF (including the Logperiodic antenna at the Allen Telescope Array) the 11-feed and QRFH feed solutions have been identified as having the best Aeff/Tsys performance in multiple recent reviews of wideband single pixel feeds (i.e Penticton Dish CoDR, 2011 and Dewdney, Manchester PRESKA meeting October 2011). Given our limited resources the SKA-WBSPF consortia has decided to concentrate on further developing only the two most promising WBSPF concepts.

Our consortium work plan will consider Eleven feed and QRFH horn solutions for both bands A and B, in this section we give a general overview of the two feed alternatives while in the dedicated sections 5 and 6 for bands A and Band B respectively we give more extensive discussions on their application for these bands.

3.1 Eleven Feed

The Eleven feed has the following unique characteristics: (1) almost constant beam width, which leads to that a reflector antenna with the Eleven feed has high aperture efficiency and high spillover efficiency (resulting in low noise temperature due to the low spillover to the earth ground); (2) fix phase center, which is always located at the center of the ground plane of the feed; (3) very compact size, which is a critical factor for low frequency feed.

- The Eleven feed (Figure 1) has been developed for many years and we are carrying new developments on improving its performance [2], [3], [10]-[17]. In the following chapters discussing implementation of Band A and Band B we present more detailed information about Eleven feed.



Figure 1: Prototype Elven feed for 0.4-1.5GHz band (left) and 3D CAD model for the 0.3-0.9GHz (right).

3.2 QRFH

The quadruple-ridged flared horn (QRFH) is a flexible reflector antenna feed developed at Caltech generally for radio astronomical applications and specifically for SKA [18]-[25]. Since the first manufactured QRFH, it has proven to be a flexible feed with two unique features among other wideband feeds currently available:

1.It can be designed to have a near-constant beamwidth over 5:1 to 7:1 frequency ranges for nominal 10 dB beamwidths of 50 to 150 degrees; and

2. It requires one single-ended 50 Ohm LNA per polarization.

Figure 2 presents photographs of two built QRFH feeds.



Figure 2: Photographs of circular and square QRFH feeds developed at Caltech.

Particular details of possible QRFH designs for the two bands are given in Sections 5 and 6, it is worthwhile to note that having an optimum design for one of the SKA frequency band necessarily

implies an optimum (or near optimum) design for the other band, because the feed can easily be scaled to work in the other band. However, manufacturability may result in slightly (or considerably) different designs. This will be part of the technical study within this proposal.

4 OUTLINE OF WORK

Feed Work - Given that the WBSPF is an AIP requiring Research and Development technical solutions for the two bands as outlined in sections 5 and 6 are still only provisional and are based on the best analogues of existing designs and [AD02]. Additionally a vital issue that will influence final designs and the choice between the two feed options is the final chosen optics of the SKA dish, in particular its effective F/D. This choice will be made by an Optics CoDR organised by the Dish consortium approximately but involving the SKA Org some 5 months after the start of the project. An important requirement for the SKA is that flexibility is retained for future feed packages to be installed it follows that the implications of the optics choice for future WBSPF is an important input the WBSPF-AIP consortium can give to the SKA Org which in turn can be inputted into the optics CoDR. Work in the early months of the WBSPF-AIP will focus on computer modelling of WBSPF designs for aperture efficiency and noise modelling (see Section 6) as input to the CoDR process. After the optics CoDR decision the WBSPF will conduct its own CoDR to decide which of the two feed options to carry forward for each band., the decision will partly depend on the effecive F7D chosen, viz

(i) If effective f/D > 0.5 is chosen, then it is quite likely, that the efficiency of the Eleven feed will be not so good as QRFH and the WBSPF Consortia will work on the optimization of the QRFH, making selections on exact illumination angle to work on etc.

(ii)) If effective f/D < 0.5 is chosen for SKA dish optics, the WBSPF consortia in its CoDR will consider the pros and cons of the 11-feed and QRH designs and make a decision at each band on which option will be chosen for future work

LNA Work - Obviously a WBSPF also needs high performance very wideband LNAs. For Band A good quality wideband SiGe LNAs already exist. For Band B further development is needed to achieve excellent performance over the very wide frequency ranges required for WBSPF ideally co-designed to match the feed requirements, This proposal therefore includes work in further developing existing technologies for ultra-wide band LNAs both at Frauhoffer IAF in Germany and at Chalmers for the frequency range above 1.6GHz.

Wideband Digital Receiver - The consortium proposal does not contain work on the wideband digital electronics which is needed to capture the full spanned bandwidth for the upper proposed frequency band, we believe such a system can be readily designed around a variety of production samplers as used for instance for ALMA.

5 BAND A

The feed-LNA package for Band A (0.3-2GHz) is very challenging due to number of practical and technological reasons: the sub-reflector is in the near field of the feed and full EM analysis should be applied for the feed optimization. There are no so many projects related to wide band LNAs for the frequency range below 1GHz. The size of the horn for this band is large and cryogenic operation is not possible at reasonable price.

5.1 Eleven Feed

In China JLRAT has developed a dual Circular Polarized feed with frequency coverage (0.4-2GHz) and has successfully provided 40 sets of such feed and receiver for Phase I of the CSRH project (Figure 3). This design is close to that required for SKA Band A. However, the feed and receiver are not cooled.

Thus further research will focus on the design of eleven feed with the integrated balun, expending the low frequency end to 350MHz and optimizing the feed design to accommodate a cryostat. If the 11-feed is chosen for Band A, JLRAT will lead the design and manufacturing of a prototype feed for this band, with input on EM design from Sweden (see below). Experience with the CSRH project has already established Chinese experience in the mass production of low frequency 11-feeds.



Figure 3: Photograph of the 0.4-2GHz UWB feed for CSRH. The dimensions of the feed are 465mm (I) ×465mm (w) ×185mm (h), including 20mm feed radome and bridge height.

Recent models of 11-feeds for low frequency spanning approximately band A have been developed at Chalmers which can give an estimate of the properties of a final Band A SKA 11-feed solution. A feed for 0.4 – 1.5GHz has been constructed for a customer in the US and is presently under measurement test (a photo of the hardware is shown in Figure 1). A second 11-feed is presently being designed for a customer in Europe covering the band 0.3-0.9GHz. Figure 4 shows the recent development on improvement of reflection coefficient of the Eleven feed at low frequency as simulated by CST simulation, showing that the reflection coefficient is below -12 dB for both polarizations. The sizes of the new generation of circular Eleven feeds for low frequency are very compact the 0.3-0.9GHz has a size of $\mathscr{O}750 \times 250 \text{ mm}^2$. The simulated radiation efficiency is about -0.05 dB and the maximum cross-polar level is about -15 dB below the maximum co-polar value. It has been shown by simulation that Eleven feed can function well when it is located close to subreflector (down to one wavelength of the lowest operating frequency away from sub-reflector) [16]-The new low frequency Eleven feed designs have an interface of 4 coaxial connector for dual polarization, which can be connected with either two differential LNAs or four single-ended LNAs (see results in Figure 4). A new wideband balun is under development which will allow an alternative for SKA band A that uses only one single-ended LNA per polarization.

Based on the above two active low frequency projects Chalmers has already started designing an Eleven feed covering SKA band 1 (i.e. 0.35 - 1.05 GHz). Assuming constraints on the feed size of *1mx1m* the Eleven antenna feed satisfies the efficiency requirements over the entire frequency band, while the QRH has a rapid efficiency drop below around 350 MHz due to the low-frequency cut-off occurring around this frequency. Hence, the dimensional constraints have more stringent implication on the performance of the QRFH feed, as compared to the Eleven antenna. On the other hand, the Eleven feed suffers from a slightly higher spillover noise temperature contribution due to its relatively broad pattern for the considered sub-reflector opening angle; this noise contribution was found to vary between 14 and 18 K from 600 to 1050 MHz in contrast to 8-10K for the QRFH feed.

Based on our band 1 11-feed design, if the 11-feed is chosen for band A we have a good starting point for an EM design for an 11-feed design covering 0.3-2.0 GHz. Whichever feed is chosen China

will lead the prototyping work on band A including manufacturing studies prototyping and test. If the 11-feed is chosen Chalmers will contribute its 11-feed feed design for band 1 as a starting point.





5.2 QRFH

The main challenge for Band A which is true for any feed in general is the size of the feed antenna due to its implications on manufacturability and cryogenic cooling. Straight scaling of the QRFH for Band B (see later) suggests dimensions on the order of 135cm at the aperture, and 115cm length, which are reasonable estimates at this time. As above, the horn length will likely change (longer for larger f/Ds) once the final dish optics is chosen.

Manufacturing such a large horn on a numerically-controlled milling machine is expensive. In order to alleviate this issue, the baseline QRFH design for this band will be square. Thus, the horn surface only has curvature in one plane and could be made out of sheet metal.

Given the aforementioned dimensions, it is very difficult to cool it in its entirety. Some brief studies were done at Caltech to evaluate possibility of cooling a portion of the feed; however, these were inconclusive. Thus, the baseline plan is that the QRFH will be warm and there will be short coaxial cables running from the feed to the dewar. These will most likely be APC7 or TypeN connectors to reduce loss and impact on system noise temperature. It is noted that the loss in the QRFH feed is very small because current flows on wide surfaces.

The performance of this feed is expected to be similar to its Band 2 counterpart since both are at secondary focus. Whether it is limited at the bottom end of the frequency range due to sub-reflector size remains to be seen. A final note is needed with regards to the desired frequency band. For a QRFH designed to work well at 0.3 GHz and designed for the abovementioned f/D numbers, it is possible that its performance begins to degrade beyond 1.8 GHz. Therefore, the lowest operating frequency of the QRFH will be studied given the SKA project preferences regarding the lowest telescope frequency including optimization on the illumination pattern of the QRFH feed to achieve the best possible Aeff/Tsys on the F/D chosen for the SKA dishes.



Figure 5: Quadridge Flared Horn Feed, preliminary design for (F/D = 0.461) for 0.27 to 1.62 GHz. Aperture is 1.3m x 1.3m and length is 1.08m. A scaled design for SKA would cover 0.35 to 2.1 GHz with size 1m x 1m x 0.83m.

5.3 LNAs For Band A

Cryogenically cooled LNAs with the best possible noise performance and dynamic range are preferred for Band A. One option is to adopt the existing CITLF2 (see Figure 6) developed by Caltech. This SiGe LNA utilizes resistive feedback to achieve good input match and high gain stability, and it is optimized for the frequency range 0.01 to 2GHz. Further work will be carried out by the consortium to improve the performance of this LNA especially the noise and gain performance at the highest frequency.



Figure 6: Photograph and measured data for Caltech CITLF2 SiGe low noise amplifier. The noise and gain data is is measured at 22K with DC bias of 2.5V and 22mA. Input and output return loss are better than 10 dB. The design will be further optimized for FAST and SKA frequency bands.

5.4 Cryostat integration and performance

A 0.3 to 2 GHz feed will be too large, of the order of 1m aperture, to cool the entire feed in a costeffective cryostat. Methods of partially cooling the feed have been investigated but a thermal and vacuum transition with low loss over the wide frequency range has not been found. The most realistic approach appears to be a small cryostat housing the LNA's with very short, low loss connections to the feed at ambient temperature. Samples of 1.5cm diameter x 30cm long coaxial cable and type N hermetic vacuum seal connectors have been measured to give a total of 0.06dB loss at 1 GHz. A photograph of the interior of a 60K cryostat designed at Caltech for a similar frequency range as SKA WBSPF LO is shown in Figure 7. The Cryostat has dimensions, 24x13x7.5 cm utilizing a Sunpower cooler to the 50K range. Multi-layer foil insulation is used to reduce thermal radiation from the 300K surfaces and the charcoal absorber is to enhance the cryopumping of the vacuum. Integration of a non-directional calibration coupler with the LNA will be considered in the design. This is a dual-polarization system with the other polarization in a layer below the visible components (Figure 7). A dewar for a 20K cooler would be of similar size and designed to allow close connections to the feed.



Figure 7: 60K cryostat designed at Caltech.

An important tradeoff is in the choice of cryostat temperature. Temperatures in the 60K range can be achieved with Stirling type coolers which do not require an external compressor and consume much less power than Gifford-McMann cooler which cool to 20K but require a large external helium compressor, require more maintenance, and consume more primary power. To guide in this choice the following system noise temperature budget, based upon present component measurements, can be made:

Cryostat Temp, <i>Tphy</i>	LNA Noise	Loss at <i>Tphy,</i> dB	Noise Added by Lphy	Transition Loss, <i>dB</i>	Noise Added by Transition	Cable Loss, dB	Noise Added by Cables	Total Noise at Feed Connector	Ant Temp	Tsys, K
60	10	0.4	6.2	0.1	4.5	0.1	7.3	28.0	15	43.0
20	4	0.4	2.1	0.1	3.8	0.1	7.1	17.0	15	32.0

Table 1: System Noise Budget for 0.3 to 2 GHz WBSPF Receiver

Keeping in mind the SKA Tsys goal of 30K, the 20K cryostat will be our baseline approach. There is much experience in radio astronomy observatories with the Gifford-McMann coolers and the 25% difference in Tsys compared to 60K coolers is worth very much in terms of overall system tradeoffs of number and size of antennas. However we will continue to consider other coolers and investigate the assumptions made in Table 1.

6 BAND B

Because of work done for the VLBI2010 geodetic observing system both feed options have good starting designs for the frequency range required for Band B. Figure 8 compares the performance of the two feeds as they would perform in a 12m shaped reflector system like the one manufactured by Intertronics Solutions. It should be noted that this antenna optics design is non-optimum for the 11-

feed, for a lower effective F/D the 11-feed should give higher aperture efficiency compared to QRFH. Further work will be done to optimise the selected feed in the chosen SKA optics but the demonstrated performance of both feed technologies is promising for achieving the SKA specification.



Figure 8: Comparison of the aperture efficiencies of the Eleven feed and the QRFH in a 12m Cassegrain shaped reflector antenna system. The result for the Eleven feed, red curve, is calculated with GRASP software while the result for the QRFH, green curve, is calculated with Physical Optics software. In both cases measure far field patterns were used as input. Real-world complications such as feed leg scattering have not been taken into account.

6.1 Eleven feed for Band B

So far several different versions of Eleven feeds over 1-10 GHz or 2-14 GHz have been developed. The most recently one is the 1.6-14 GHz Eleven feed, see Figure 9 (left). The measured radiation patterns and aperture efficiency are shown in Figure 9 (right) and, Figure 10 (right) respectively. From the figures, we can see that the performance of the feed is very good. The feeding scheme of this model uses eight coaxial connectors, and the reflection coefficient is shown in Figure 10 (left), below -8 dB. This Eleven feed has gone through cryogenic tests, such as reflection coefficient performance (no significant changes see [3]). More cryogenic tests are needed to verify the radiation pattern. The

significant changes, see [3]). More cryogenic tests are needed to verify the radiation pattern. The measured radiation efficiency is about -0.2 dB [17], which contributes a noise temperature increase of 1.4 K when the feed is cryogenically cooled down to 30 K. An important possible advantage of the 11-feed is its very small diameter for a given lowest frequency which may make possible for a given cryostat window size going to a slightly lower frequency than the QRFH.

The further developments of the feed for band B include: (1) reducing port number from 8 ports down to 4 ports or 2 ports for dual polarization, and (2) improving the reflection coefficient, down to -12 dB. (3) Research to reduce the effect of surface along the supporting dielectric surface to improve high frequency performance.



Figure 9: Photo of the 1.6-14GHz circular Eleven feed (left) and measured radiation patterns in 45° plane of 1.6-14GHz Eleven feed. Red line: co-polar; Blue line: cross-polar.



Figure 10: Reflection coefficient of 1.6—14GHz Eleven feed (left) and aperture efficiency based on measured radiation patterns of the 1.6-14GHz Eleven feed (right).

6.2 QRFH for Band B

Of the nine QRFH feeds built and delivered to telescopes around the world thus far, six were designed to cover one of the following bands: 2-12, 2.3-14, 3-18, and 1-6 GHz with nominal 10 dB beamwidths between 85 to 120 degrees. As such, these existing designs provide excellent starting points to build upon in the quest for an optimal Band B feed for SKA.

The expected performance depends much on the final dish optics, especially the shaped reflectors. Nonetheless, it is reasonable to expect aperture efficiency of 65-70% averaged over the entire band and ~70% for most of the target frequency range. These numbers are based on the measured/simulated performance of a comparable QRFH (the first circular one covering 2-12 GHz) installed on a somewhat similar shaped-optics telescope (12m Patriot antenna). It should be noted that these efficiency numbers are with the feed position fixed. Therefore, any phase center movement (and it is small) is accounted for. Aperture efficiencies will be calculated using physical optics either at Chalmers or at Ozyegin University (possibly both) during the design phase to ensure the best possible design is obtained.

A rough estimate for the horn size for Band 2 is as follows: 24cm x 24cm aperture, 20cm long. The dimensions (especially horn length) depend considerably on the desired beamwidth; thus, will be finalized once dish optics is finalized. Nonetheless, the horn is small enough to be cooled entirely. Since it requires single-ended 50 Ohm LNAs, integration with calibration couplers and LNAs is straightforward. More information about QRFH similar to the requirement of Band B for SKA can be found in [18], [19], [21], [25].

6.3 LNAs

Within the frame of the LNA work for Band B, we have involved two partners working on two alternative LNA technologies: IAF with their 50nm mHEMT process and Chalmers/MC2 with their InP process.

6.3.1 mHEMT LNAs for Band B

A low noise amplifier MMIC will be designed and fabricated by Fraunhofer IAF. This MMIC will be based on Fraunhofer IAF metamorphic high-electron-mobility transistor (mHEMT) technology grown on GaAs substrates. This technology combines the advantages of InP-like performance and the cheaper, less brittle GaAs substrates – predestined for large scale production. The Fraunhofer IAF mHEMT technology offers best noise performance (e.g. [27]) and has been validated in several national and international projects in close cooperation with Max Planck Institute for Radio Astronomy (MPIfR). By reducing the gate length to 50 nm, higher cut-off frequencies can be achieved - f_T and f_{max} of 375 GHz and 670 GHz, respectively [27]. Thus LNAs can be realized with even lower noise figures and higher gain. Figure 11 shows a cross section of a Fraunhofer IAF 50 nm transistor finger.



Figure 11: Cross section of a Fraunhofer IAF 50 nm mHEMT finger.



Figure 12: Differential LNA MMIC with on-wafer input matching performing for 1 to 16 GHz.

Figure 12 shows the chip photograph of a first demonstrator MMIC of a three stage differential LNA fabricated on the mentioned Fraunhofer IAF 50 nm mHEMT technology. This prototype MMIC has on-wafer input matching to ease LNA packaging and the LNA input impedance is 100 Ohm differential. At room temperature the MMIC demonstrated more than 30 dB of gain and a noise temperature of less than 120 K over the entire frequency band and around 3 GHz operation frequency a noise temperature of 35 K (Figure 13, right). The common-mode rejection ratio (CMRR) achieved more than 28 dB (Figure 13, left) from 1 to 16 GHz and up to 36 dB at 1 GHz. A redesign of this LNA will provide an input impedance matched to the exact antenna impedance, which will be higher than 100 Ohm differential. By doing so, noise performance can be improved.



Figure 13: Measured S-parameters and CMRR left and measured differential noise figure (right) at room temperature of the differential LNA.

For the second option of feed antenna (QRFH) an LNA will be provided equally covering 1.6 - 12GHz but with both input and output impedances of 50 Ohm single ended.

Based on the demonstrated results and further improvements the main design goal and challenge is simultaneously improving the noise performance and input return loss of the LNAs.

6.3.2 InP LNAs for Band B

Chalmers University Microelectronics Laboratory (MEL) will as part of this AIP project continue to develop very high performance LNA based on the Chalmers clean room InP process. Although already giving good performance further work is required to adapt them to the very wide peformance needed for WBSPF applications. The LNAs need to be designed to be flexible and adaptable to the feed properties such as input interface and feed impedance. In the WP for InP LNAs

We will design at least one single-ended LNA and one so called active balun which is an LNA with balanced input and unbalanced output. The single-ended LNA can be connected to an antenna which has unbalanced coaxial connectors and the active balun can be connected directly to an antenna with balanced ports without the need for a passive balun. Both LNAs will have external input matching networks which allow us to adapt the input impedance in the range of approximately 50-100 ohms for the single-ended LNA and 100-200 ohms for the active balun, after the MMIC has been processed. The single-ended LNA will be based on Low Noise Factories LNF's commercial model (developed with Vhalmers MEL), LNF-LNC1_12A depicted in fig 1 and with test data in fig 2. The LNF-LNC1_12A is designed for 1-12 GHz operation. It will be investigated if the there is any benefit in modifying the design for the slightly narrower frequency range required in this project. The goal would be to improve S11 for the low end of the band. It is not expected that S11 can be improved significantly at the low end without sacrificing some noise performance. A co-simulation of the antenna and LNA will be done and the best compromise of S11 and noise will be determined. The active balun is basically two single-ended LNAs on the same die and its performance is the same as the single-ended LNA.

The LNAs will be processed in Chalmers/MC2's 130 nm InP HEMT MMIC process in at least one wafer run on 3 or 4 inch wafers. At least one wafer will have a new epi structure with a thinner barrier which is expected to give even lower noise in the band and temperature of interest.

The LNF-LNC1_12A is already optimized for volume production, but further investigations will be made with a goal of minimizing the cost for production. Pick and place is already used for part of the LNA. We will investigate if all components can be installed with pick and place. The possibility of using automatic wire bonding will also be investigated. Photo of the LNA is shown in Figure 14 and measured typical performance in Figure 15.



Figure 14: Photo of LNF-LNC1_12A.



References about the Chalmers InP process and reported test results can be found in [28]-[31].

6.4 Cryogenics

The Baseline for cryogenic integration of either Eleven Feed or QRFH is to use CTI-350 cryocooler. The goal is to achieve operational physical temperatures of 15K for the LNAs and 20K for the feed. The heat load from the vacuum window will be analyzed with FEM software. The analysis will also include a study the implication of the Infrared Filter and vacuum window on the RF losses. The current experience with crysotats for the VLBI2010 feeds shows that CTI-350 has enough cooling power. If due to the higher head load because of the larger feed diameter (lowest frequency that is smaller than VLBI2010) higher cooling power will be needed we will investigate CTI-1020 cryocooler or alternative models from Sumithomo.



Figure 16: VLBI2010 cryostat with Eleven feed.

6.5 Performance

The sensitivity of existing Eleven Feed and QRFH high frequency designs have been verified via Y-factor measurements and both feeds show receiver noise of about 20K over 3-8GHz range. Figure 17 shows the measured receiver noise for VLBI2010 receiver with Eleven Feed together with prediction of the noise model and the noise of the LNAs (for this particular tests, wide band LNAs from Caltech were used).



Figure 17: Comparison of measured and modelled noise temperature of Eleven feed receiver with 50ohm Caltech LNAs.

7 Design validation in SKA dish optics

Validation of the feed designs at the SKA dish optics will be carried out through numerical simulations and modeling of the key performance parameters of the radio telescope for a set of test scenarios for observations (scientific cases). To develop the set of these standard test scenarios, w.r.t which the different design options should be compared, we will use inputs from the scientists involved in the SKA. The key performance parameters to be considered will include:

(i) <u>'Engineering performance measures'</u> — such as receiving sensitivity (Aeff/Tsys) of the overall system, side-lobe levels and polarimetric figures of merit (e.g. cross-polarization levels, conditioning of the Jones matrix or IXR), — all over the frequency band and field of view coverage. To determine these measures, we will use dedicated electromagnetic-microwave software tools that can model the signal and noise performance of the integrated optics-feed-receiver system in their entirety. To assure a uniform methodology for the analysis of the receiving sensitivity for all feed designs (including both single- and multi-port antenna feeds), we will adopt 'standard' definitions of generalized signal-noise terms for active receiving (array) antennas that have been recently approved by the IEEE Antenna Standards Working Group for their inclusion in the next update of the IEEE standard for antenna terms (see [6]). Analysis of the sensitivity ripple over frequency (that occurs due to electromagnetic interaction between the primary reflector and sub-reflector) will require a dedicated effort in terms of numerical modeling and computation time, especially for the low frequency feeds.

<u>Top-level performance measures, as used by astronomers</u> — such as dynamic range, image fidelity, survey speed — all over the frequency band and field of view coverage. These measures will be derived from simulations in dedicated radio astronomic calibration-imaging software tools (e.g. MecTrees) that can model the image maps for different observation scenarios (including the important calibration effects), based on the given antenna beams (obtained with the electromagnetic tools), and models of the sky & interferometer configuration to be considered for the SKA. In addition to the numerical simulations of the maps, we will assess the quality of the beam shapes with <u>the low-level performance measures of the antenna calibratability</u> — such as the beam roundness and the number of the beam model calibration parameters. For this analysis, we will adopt analytic and physics-based beam calibration models [7]-[9]. These indirect measures of the imaging quality will allow for the fast analysis of the feed design options and their co-optimization with the optics.

8 References

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