SKA Hybrid

Cylindrical Reflectors + Small Dishes

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1 Introduction

We consider a design for the Square Kilometre Array in which it is composed of high- and low-frequency sub-arrays. A two-component parabolic cylindrical reflector (cylindrical reflector, CR) concept forms the low-frequency sub-array while the Large-Number/Small-Dish (small dish, SD) concept forms the high-frequency sub-array.

The low-frequency sub-array is composed of two sets of 600 cylindrical reflector stations, one operating below approximately 2 GHz and the other below 0.7 GHz while the high-frequency sub-array is 2500 12-meter parabolic dishes operating between 0.47 and 24 GHz. The frequency overlap encompasses H I emission at redshifts $z < 2$ as well as providing coverage of the OH line. Extension of the cylinders to 5 GHz may be possible and would provide improved timing accuracy of pulsars. The maximum frequency of 0.7 GHz for the low frequency cylinders is chosen so as to satisfy the science requirements for high survey speeds at a redshift of 1.

We now discuss the 15 items requested by the International Project Office in the 2004 March 12 communication. As our hybrid concept is based on two of the original design concepts, much of this material is drawn from the original design concept whitepapers and their revisions.

2 Hybrid Concept

2.1 Frequency Range

The total frequency range covered by the hybrid, with the design range for each component specified explicitly.

Total frequency range: 0.10–24 GHz with

- Small dishes covering 0.47 to 24 GHz;
- Low frequency cylindrical reflectors covering 0.1 to 0.7 GHz; and
- High frequency cylindrical reflectors covering 0.1 GHz to an upper frequency in the range 2–5 GHz.

Henceforth, we shall assume that the upper frequency limit for the high frequency cylindrical reflectors is 2 GHz, but we shall note ways to extend it to 5 GHz. We also note that reduced performance is available from the components at frequencies about 50% higher than the nominal maximum. In all cases pointing and surface accuracy becomes a problem. Pointing problems can be ameliorated by under illuminating the surface. This together with surface errors will lead to an approximate halving of performance. At this reduced performance level the small dishes would operate as high as 36 GHz and the cylinders 3 to 7.5 GHz.

2.2 Station Configuration

A sketch of the arrangement of component collecting areas within stations and central arrays.

2.2.1 Core Configuration

The SKA Science Requirements specify that 20% of the collecting area should be within a diameter of 1 km and 50% within a diameter of 5 km. We take the 5-km diameter region to specify the "core." Within the central 1 km, the elements are packed so closely that separate regions are needed for the various elements.

For the small dishes, the core consists of 1250 antennas, 500 of which are in the central 1-km region and 750 of which are grouped into fifty-eight (58) 13-antenna stations. For the cylindrical reflectors, the core consists of 300 low frequency and 300 high frequency cylinders. Within the central 1 km region are 220 of the high frequency cylinders, which are then surrounded by an annulus of 220 low frequency cylinders. The compactness of this core enhances both surface brightness sensitivity and pulsar search speed. Below 0.7 GHz, the two cylinder components augment each other.

We envision an "interlocking" distribution in which the cores of the various sub-arrays overlap, but the central regions of the dishes and cylinders do not. Figure 1 illustrates how this might be accomplished.

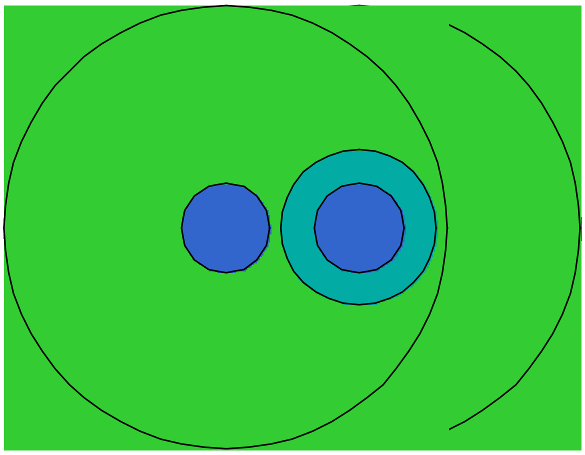

Figure 1. The cores of the SKA sub-arrays. Shown are the overlapping cores for the small dishes and cylindrical reflectors. The lightly shaded green regions are 5 km in diameter. The heavily blue shaded region is 1 km in diameter with the small dishes on the left and the high-frequency cylinders on the left. Surrounding the high-frequency cylinders is an annulus of low frequency cylinders.

The various 1-km central regions will block some possible placements of longer baseline antennas. One of the strengths of a large-N design, such as this concept, is that modest changes in antenna placements are handled easily. In addition, the ratio of 1 km to 5 km baseline antennas is easily modified to accommodate any changes that might be indicated by a full simulation of the configuration.

2.2.2 Antenna Stations

At baselines between 1 and 5 km, the small dishes will be grouped into 13-antenna stations. Beyond 5 km, all antennas will be grouped into stations.

On baselines longer than 5 km, an antenna station consists of 13 small dishes, 3 high frequency cylindrical reflectors, and 3 low frequency cylindrical reflectors. Figure 2 shows a possible arrangement of the antennas. For small-dish stations within 5 km, the arrangement of the antennas would be the same as what is shown for the small-dish portion of the station in Figure 2.

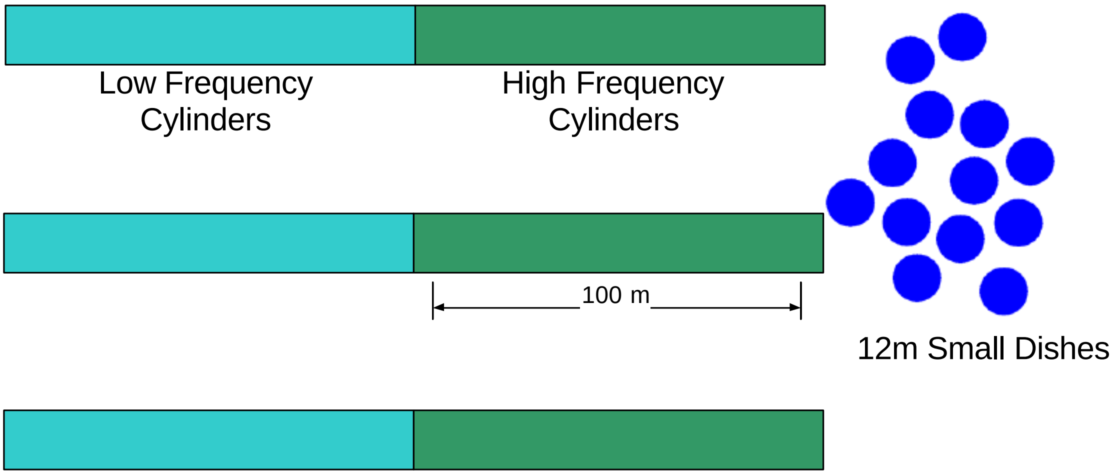

Figure 2. Possible arrangement of antennas in an antenna station outside of the core.

The Science Requirements specify that 75% of the collecting area be within 150 km, with the remainder spread over approximately 3000 km baselines. Thus, there would be 48 stations between 5 and 75 km and an additional 48 stations beyond 150 km.

2.3 Costing

Any updated costing information on the hybrid concept.

Table 1 summarizes our current cost estimate. Our initial, though highly uncertain, estimate is $1273M.

The estimated cost of the 2500 small dishes outfitted with receivers and including the cost of making a foundation for the antennas is $493M, which incorporates an approximate $50M savings resulting from changing the small dish concept from its current offset feed design to a symmetric antenna. The estimated cost of the 600 low frequency cylindrical reflectors is $140M, including the reflector and foundations as well as the line feed, the digitizer, and the beamformer.

As the low frequency cylinders and small dishes combined cover the full SKA frequency range, the total area and maximum frequency of the high frequency cylinders is a parameter that can be adjust to optimise the science. For 600 cylindrical reflectors operating between 0.1 and 2 GHz, the additional cost is $226M, for a total cylindrical reflector cost of $366M.

The cost of a station is clearly highly site dependent. We use cost estimates based on the U.S. white paper. These are based on an SKA sited in the United States, where land acquisition and other costs are likely to be higher than the other potential SKA sites, so we consider them to be conservative estimates. The U.S. white paper estimates that the infrastructure associated with a 13-antenna station costs $0.5M. This infrastructure includes such items as power lines, fiber optics connections from a main “trunk,” land acquisition, roads, and environmental impact statements. For the purpose of this estimate, we shall assume that the stations described here (small dishes and cylindrical reflectors) cost approximately the same. There are 96 stations outside of the core, for a station infrastructure cost of $48M.

In the core, there should be some cost savings because the road, power, and fiber optic networks can be optimised based on the distribution of antennas. Clearly, though, in the proposed “interlocking cores” configuration, the cost of the two cores will be larger than the cost of a single core. The small dishes are still grouped into stations, with a total of 58 stations, except in the central 1 km where there are 500 antennas (equivalent to approximately thirty-eight 13-antenna stations). We adopt a cost of $0.4M per station, to take into account potential cost savings. The infrastructure cost for the small dish core is $38M. We assume that the cylindrical reflector core would be comparable in cost. We also include $20M for a central office/processing facility building.

The remaining costs include the cost of the correlator, signal transmission, computing (both hardware and software), system engineering, and non-recurring engineering costs. For these we adopt the estimates in the U.S. white paper. Namely, signal processing we fix at $80M, computing costs we estimate to be $130M ($50M for software engineering and $80M for hardware), and $60M for system engineering and non-recurring costs.

Table 1. SKA Costing

2500 small dishes	493M
600 low frequency cylindrical reflectors	140M
600 high frequency cylindrical reflectors	226M
Small dish core infrastructure	38M
Cylindrical reflector core infrastructure	38M
Central office/processing facility building	20M
Infrastructure for 96 stations	48M
Signal processing	80M
Computing	130M
System engineering/NRE	60M
TOTAL	**$1273M**

As expansion options, possibilities include increasing the upper frequency range of the high-frequency cylinders or increasing the number of small dishes. A 50% increase in the number of small dishes would add $246M. For high frequency cylinders with a 5 GHz maximum frequency the increase is $113M.

As cost savings options, it is not obvious that there is a scientific driver for a long-baseline (> 150 km) operating capability at frequencies below 0.7 GHz. A cost savings of $35M could be achieved by eliminating the low-frequency cylindrical reflectors in the long-baseline stations. Other cost saving are reduction of the number of high-frequency cylinders to 400 or 500. With 400 high-frequency cylinders the saving is $75M for a 2 GHz maximum frequency and $160M for a 5GHz maximum frequency

2.4 A_{eff}/T_{sys}

A_{eff}/T_{sys} for each component of the hybrid at band edges (also specify explicitly component and total SKA sensitivities at 1.4 GHz).

Figure 3 shows the sensitivity of the hybrid components. In the frequency range 0.1 to 0.7 GHz the performance of the two cylindrical reflector components are identical and the net effect is a doubling of A_{eff} below 0.7 GHz.

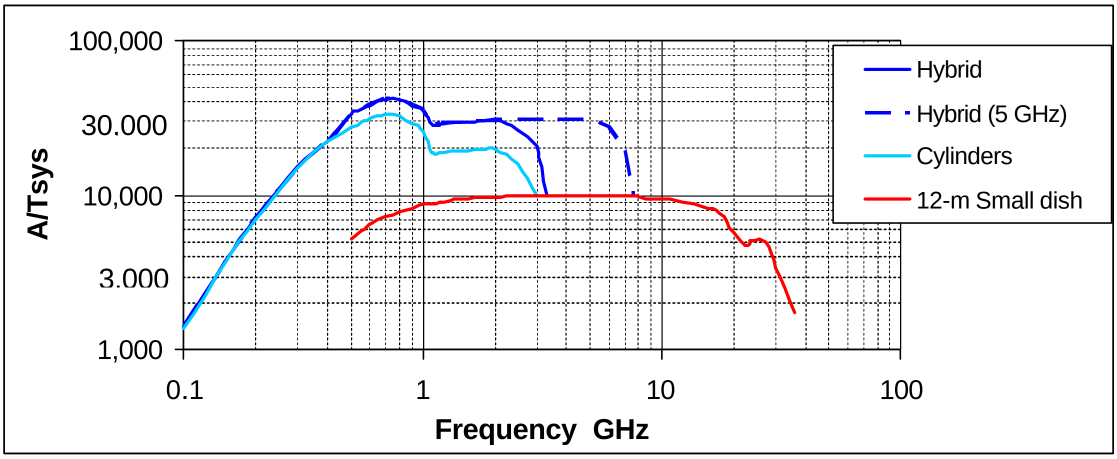

Figure 3: Sensitivity of Components and Hybrid inregion of overlap 0.5 to 2-5 GHz.

Above 1 GHz the small dishes and cylinders when combined give a sensitivity of 30,000 m^2/K which falls to 10,000 m^2/K when the small dishes must operate on their own the values are also tabulated below.

Table 2. Sensitivity of the Hybrid Components

Frequency (GHz)	A_{eff}/T_{sys} (10^4 $m^2 K^{-1}$)	Component	T_{sky}
0.10	1 400	CR-high + CR-low	1000
0.15	3 600	CR-high + CR-low	350
0.3	14 700	CR-high + CR-low	63
0.5	27 000	CR-high + CR-low	19
0.7	33 000	CR-high + CR-low	10
1	18 500	CR-high	5.5
Above 1.5	20 000	CR-high	3
0.5	5 700	SMALL DISH	19
0.7	8 000	SMALL DISH	10
1.0	9 500	SMALL DISH	5.5
1.5	10 400	SMALL DISH	3.7
5	11 000	SMALL DISH	2.7
10	10 400	SMALL DISH	3.7
20	6 300	SMALL DISH	16
22.5	5 200	SMALL DISH	23
24	6 300	SMALL DISH	16
36	1 800	SMALL DISH	11

2.5 Antenna Elements

The type of antenna elements used in each component, and the dimensions of any concentrators.

A cylindrical reflector is a 111 m × 15 m reflector with a wide-band linear feed. An offset feed design is used to reduce baseline ripple and provide a large focal plane area for multiple feed structures.

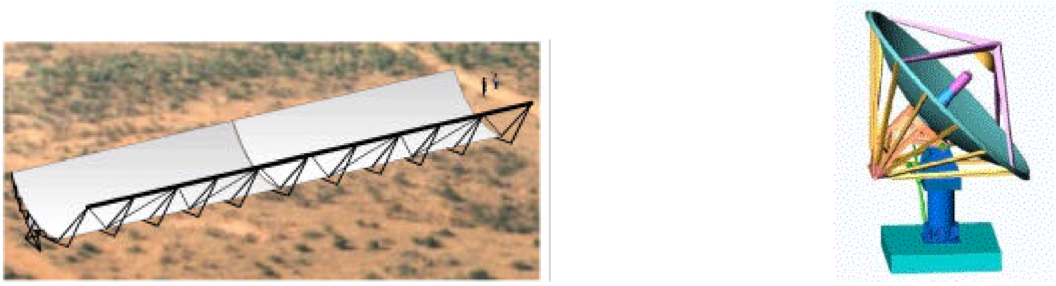

Figure 4. Illustrations of the proposed cylindrical reflector and 12-m symmetric parabolic dish.

A small dish is a 12-m shaped parabola with a wide-band feed and low-noise receiver. This antenna would be similar to those being contemplated for future use in the NASA Deep Space Network and similar to, though larger than, the antennas being used in the Allen Telescope Array (ATA).

2.6 Fields of View

The number of fields-of-view provided by each component of the hybrid array.

For the small dishes, only one (1) field of view with the full array sensitivity could be obtained. At 1.4 GHz this field of view has an area of 1.5 deg^2. Splitting the array into sub-arrays would enable multiple fields of view with less than the full array sensitivity.

Below 0.7 GHz the field of view of cylindrical reflectors is $1.4^\circ/f \times 120^\circ$, and, with a 200 MHz bandwidth, it is possible to simultaneously image this full field of view with full sensitivity. In order to achieve this capability at 0.5 GHz, each antenna needs to generate 340 beams. This is possible on the 1200 cylindrical reflectors of the high and low frequency arrays if the bandwidth is reduced to 200 MHz.

From 0.7 to 2 GHz the beams generated by the cylindrical reflectors will usually be less than that needed to cover the full 120º electronic scan range of the line feed. As an example at 1.4 GHz, 192 beams each with a bandwidth of 800 MHz can be generated and processed. This gives a total field of view of 24 deg^2 without impacting on the separate operation of the small dish. This 24 deg^2 can be placed anywhere within the 1º by 120º field of view of the antennas

Above 2 GHz, it is proposed that RF beamforming in the cylindrical reflectors be used to reduce cost. Doing so will reduce the antenna field of view to 10 deg^2 at 5 GHz.

2.7 High- and Low-Frequency Sub-Arrays

Parameters for each component, including: equivalent number of stations, station FOV, number of antennas per station, physical area per station, effective area per station, station dimensions and antenna shadowing limits (if applicable).

The small dish sub-array consists of 154 13-antenna stations with an additional 500 antennas in the central 1-km region. For stations within 150 km, the full signal from each antenna would be transmitted to the central processing facility, while beamforming on the outer stations would be used to reduce the transmitted bandwidth. For the small dishes the physical area is 113 m^2, and it has an effective area of 79 m^2 with an aperture efficiency of 0.7. A station would have a total area of 1469 m^2 and an effective aperture of 1030 m^2.

The minimum proposed antenna separation within a station is 20 m, which will lead to some shadowing. The issues surrounding shadowing are somewhat different for the antennas within the core and for those in remote stations. In the U.S. design concept, within the core, the minimum antenna separation approaches only 25 m, corresponding to a minimum unshadowed elevation of 26º. Even this shadowing will occur for only a very small fraction of the antennas at any given azimuth. Shadowing is more significant within the inner 1 km. Nearly or partially shadowed antennas are a necessary consequence of observations seeking sensitivity to extended structures and where foreshortening of baselines is exploited to achieve the needed sensitivity. In the remote stations, the antennas are spaced as closely as possible in order to maximize the field-of-view (FOV) of the station beam. The proposed minimum spacing provides an FOV of approximately 10 arcminutes at 21 cm. These outer station antennas are important only for high-resolution studies, so a small degree of shadowing does not degrade the performance significantly. In general, further study will be needed to optimize the station configuration and the antenna placement/shadowing tradeoffs.

Below 0.7 GHz the cylindrical parabolic reflector high and low frequency components act cooperatively so the basic antenna station unit is one high frequency cylindrical reflector and one low frequency cylindrical reflector placed end to end. Each antenna is 110 m × 15 m making the basic antenna station 220 m × 15 m. The total area below 0.7 GHz is 3300 m^2; above 0.7 GHz, this reduces to 1650 m^2. The estimated aperture efficiency is 69% for the high frequency cylindrical reflectors between 0.7 and 2 GHz giving an effective aperture of 1140 m^2; we believe that this aperture efficiency would remain unchanged for operations up to 5 GHz. For operation below 0.7 GHz the aperture efficiency increases to 72% due to reduced end losses. The resulting effective aperture is 2380 m^2.

Associated with each station are three low-high frequency cylindrical reflector pairs having a total area of 9900 m^2 below 0.7 GHz, giving an effective aperture of 7100 m^2. Above 0.7 GHz the total aperture is 4950 m^2 and the effective aperture is 3400 m^2. Of the three cylindrical reflector pairs one will be co-located with the 13 small dishes. The disposition of the other two will depend on baseline. At less than 1000 km the two cylinders will be placed up to 10 km from the core of the station. Beyond this all three will be co-located with the three EW pairs separated by 58 m in a NS direction. With this separation there is no shadowing down to elevations of 15 degrees. In both arrangements of the cylindrical reflectors it is planned to bring back beams from individual antennas so the FOV at 1.4 GHz is 1° × 0.125° for a single beam. If the three high-frequency cylindrical reflector antennas area arrayed together, the beam size is 7 arcminutes.

2.8 Configuration

A broad indication of the array configuration, the total bandwidth transmitted in representative distance regimes, and the total entity (station or antenna) FOV at chosen spot frequencies (including 1.4 GHz).

We adopt the SKA Science Requirements distribution. One of the strengths of a large-N design is that the placement of individual antennas is quite flexible, so this baseline configuration can be changed easily.

Table 3 Specification for small dishes

SKA Diameter Regime	***% of Area***	***Bandwidth (GHz)***	***Total FOV @ 1.4GHz (square degrees)***
0–5 km	*50*	*4*	*1*
5–150 km	*25*	*4*	*1*
150–3000 km	*25*	*4*	*0.1*

The cylindrical reflectors generate 64 full bandwidth beams so the total bandwidth is 2.4 × 64 = 154 GHz. As there are many more small dishes than cylinders, the total data rate is 4.6 times that of the small dishes. Over 150 km the rate reduces to 1.5 times greater.

Table 4 Specification for high frequency cylindrical reflectors

SKA Diameter Regime	***% of Area***	***Bandwidth (GHz)***	***Total FOV @ 1.4GHz (square degrees)***
0–5 km	*50*	*2.4 ´ 64*	*8*
5–150 km	*25*	*2.4 ´ 64*	*8*
150–3000 km	*25*	*2.4 ´ 6* *(for 3 pairs)*	*0.25*

Specifications for the low-frequency cylindrical-reflectors are given at 0.7 GHz, its highest operating frequency. It is not obvious that there is a scientific driver for a long-baseline (> 150 km) operating capability at frequencies below 0.7 GHz. A cost savings could be achieved by eliminating the low-frequency cylindrical reflectors in the long-baseline stations.

Table 5 Specification for low frequency cylindrical reflectors

SKA Diameter Regime	***% of Area***	***Bandwidth (GHz)***	***Total FOV @ 0.7 GHz (square degrees)***
0–5 km	*50*	*0.2 ´ 64*	*32*
5–150 km	*33*	*0.2 ´ 64*	*32*
150–3000 km	*25*	*0.2 ´ 6* *(for 3 pairs)*	*1*

2.9 Feeds

The nature of the feeds employed (single or multi-channel), focal plane array dimensions (if applicable), the level of RF beamforming employed (if applicable), and patch dimensions (for aperture arrays).

For the small dishes, there are presently 3 candidate wideband feeds being investigated, all with a decade or more bandwidth.

ATA-like feed: The ATA has led the way in introducing wideband feeds to radio astronomy with the log-periodic design. This feed will be extensively tested on the ATA in 2004 and a system noise temperature of 42 K is expected; a lower system temperature goal, 18 K, has been set for the SKA small dish concept (see below). A potential issue with the log-periodic feed is the movement of the phase center with frequency, which causes of the order of 1 dB of effective area loss at band edges unless the feed is mechanically moved to focus for the desired frequency. However, there are two frequency bands where this feed may be appropriate: 1) 11 to 24 GHz where the feed would be less than 2 cm wide at the base and could be housed close to a window in a cryogenic dewar, and 2) 0.5 to 1.7 GHz where feed losses are lower and a cryogenic dewar could fit between the feed terminals.

Ingersen feed: The construction of the feed has not been revealed but extensive test data have been purchased by JPL. In summary, the data show reasonably good power patterns but unacceptable impedance variation with frequency. Work is in progress to improve the impedance variation.

Kildal feed: This feed has been invented recently, and only numerical electromagnetic analysis is available. It also has good patterns but does not have acceptable impedance variation. Rapid progress on the optimization of the feed is being made.

For the cylindrical reflector a number of options are available for implementing the line feed including:

- Crossed bowties,
- Four square,
- Vivaldi, and
- Sinuous feeds

Work is already underway to investigate the last to options for phased arrays. These efforts would directly translate to a focal plane array implementations of the linefeed. As an alternative the four square feed structure is currently under theoretical and practical investigation at the University of Sydney and CSIRO.

2.10 Receivers

The physical temperature of receivers used in each component (15K, 80K and 300K might be standard choices).

For the small dishes, the objective is to produce decade bandwidth receivers with acceptable noise temperatures. The focus within the U.S. community is on cryogenically cooled HEMT receivers. Table 6 shows goals for the receiver and resulting system performance. Specific technologies being investigated include both SiGe and InP HEMT MMIC-based amplifiers. The associated cryogenics are key to achieving these goals as they must have low power consumption and long mean time between failures (MTBFs). Coolers with (claimed) MTBFs of order 5×10^4 hr either exist or should be possible based on pulse-tube coolers, gas-bearing piston compressors, and flexure bearings to hold pistons.

Table 6 Receiver temperatures for small dishes

Frequency	Physical Temperature	System Temperature
(GHz)	(K)	(K)
0.5–1.5	200	32
1.2–11	15	18
11–25	15	45

For the cylindrical reflectors uncooled LNAs are to be used as the cost of cooling is too great. The target system temperature at 1.4 GHz is 36 K using SiGe based amplifiers.

2.11 Receiver Output

The quantization accuracy at the receiver output (1/2/4/8 bits might be standard choices).

The ATA has decided upon analog optical transport of the wideband antenna signals back to the correlator, as being most cost effective and the easiest way to accommodate future performance enhancements. This matter is under active investigation, but we suggest that out to some as yet to be determined radius (~ 150 km), optical transport of the receiver output will be used. The signal is then digitised with an accuracy of 8-bits before being processed in a filter bank.

The cylindrical reflector intends to use an integrated RF-CMOS receiver, digitiser and optical fibre driver with a digitiser accuracy of 8-bits.

2.12 Correlator Input

The accuracy at the correlator input (1/2/4/8 bit choices).

Quantisation accuracy into the cylindrical reflector correlator is (4,4) bits (real, imaginary). Quantization is to (4,4) bits (real, imaginary) for small dish component.

2.13 Correlator Sharing

The fraction of available information (see (7) above) able to be processed by the correlator

Using technology that is certain to be available by 2005, we believe that five 800-MHz wide spectral windows (3.2 GHz total bandwidth) can be processed to 200 kHz spectral resolution for 2500 small dish antennas. By the time of the SKA a bandwidth of 8 GHz will be practical as well as a 64-beam 2.4-GHz correlator for the 600 high frequency cylindrical reflectors. The correlator has an estimated cost of $50M soon after 2010 with the cost evenly distributed between the two components.

When the 600 high frequency cylindrical reflectors and 600 low frequency cylindrical reflector antennas are operated together below 0.7 GHz, the bandwidth will be reduced to 200 MHz, and without affecting small dish operation, a total of 192 beams can be processed with full sensitivity for the 1200 cylindrical reflectors. The resulting sensitivity is 27,000 m^2/K at 0.5 GHz. The resources could also be distributed between the high and low cylindrical reflector range 64 full-sensitivity 200-MHz-bandwidth low-frequency beams and 128 800-MHz-bandwidth high-frequency beams.

When the cylindrical reflectors and small dishes are used together (0.5 to 2–5 GHz) each cylindrical reflector could be subdivided into eight subsections to generate beams with approximately the same dimensions as the small dishes. Thus the correlator will have 2500 small dish inputs and 4800 cylindrical reflector inputs for a total of 7300 inputs. This requires almost nine times more correlator than small dish correlator alone. Using all correlator resources the sensitivity is 31,000 m^2/K and the bandwidth is 2 GHz. At a maximum frequency of 5 GHz this bandwidth matches the SKA science requirements for two separate 25% fractional bandwidth bands.

2.14 Shared Infrastructure

Comments on the amount of station and central infrastructure (civil, signal processing and distribution, computing) likely to be shareable between components, and an estimate of the amount of new infrastructure needed to support the hybrid SKA.

An important additional cost borne by both hybrids is the need for separate “core” arrays. Various Key Science Projects—the Dark Energy project, the Strong-Field Test of Gravity project, and the cradle of Life project—all require a portion of the array to have a high filling factor. In order to avoid physical collisions between the different kinds of receptors or shadowing, the two cores would have to be separate, resulting in little savings for engineering, data transmission and processing, and civil costs for each core. As a rough indication of this separation, we take it to be comparable to the size of the most compact central portion of the SKA—specified currently to be approximately 1 km. Estimates for the cost of the infrastructure for the core differ in various white papers. But in this case the estimated cost of adding a half size small dish core is \$15M and another \$15M for the low frequency cylindrical reflector core.

Outside the core cost of roads, power distribution, cable trenching and other infrastructure cost will be shared. There will be a small increase in cost due to extra fibres in cable but the major extra cost is increase in power requirements. The low frequency cylindrical reflectors add about 10% to the high frequency cylindrical reflectors and the small dishes add extra 50%.

2.15 New Operational Modes

Comments on non-imaging or new operational modes (e.g. simultaneous observing at widely separated frequency bands) supported by the hybrid SKA

2.15.1 Widely separated frequency bands in a common field of view

The low frequency cylindrical reflectors and small dish do not have any significant frequency overlap and will operate independently. However, both can be used to access the same field of view providing widely separated frequency bands. The high frequency cylindrical reflectors could be used to augment the low frequency cylindrical reflectors or they could be used to add a third set of frequencies in the band 0.7 to 2–5 GHz. As an example the same field could be simultaneously observed at 0.5, 2, and 8 GHz with close to the SKA specification sensitivity on all bands.

2.15.2 Full sensitivity high and low frequency surveying

When surveying the fields of view of different frequency bands do not need to overlap. Thus while the high frequency cylindrical reflectors are being used for survey in the frequency bands 0.7 to 2–5 GHz, they can also survey within the 0.1–0.7 GHz band. As the bandwidth needed for the low frequency survey is low, this will not have a significant impact on the high frequency survey in terms of beamforming and signal transport. Adding the high and low frequency cylindrical reflectors doubles the sensitivity of the low frequency survey.

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