WP 1 Investigate and report on design approaches for cryogenically cooling receiver front ends for the SKA Dish Array

Report

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1. INTRODUCTION

1.1 Purpose

It is anticipated that the Square Kilometre Array (SKA) radio observatory will grow from 250 dishes in Phase 1 to a final size of a few thousand dish antennas, each equipped with multiple feeds and associated low noise amplifiers (LNAs). In order to maximise the sensitivity per unit cost of the SKA Dish Array it has bee anticipated that it will be necessary to enhance the individual sensitivities of the dish subsystems by using cryogenically cooled front ends [RD3, RD4].

Use of cryogenically cooled front ends will lower the system noise temperature, and hence reduce the number of dishes needed for a given overall sensitivity target, thus reducing the cost of the dishes themselves as well as the corresponding signal transport, signal processing, computing, infrastructure and the operating and maintenance costs.

However, cryogenic systems have a significant cost implication themselves, and for the success of the SKA project this presents itself as one of the key technological challenges. Benefits that would result from the use of various cryogenic options must be balanced against their implications for the full lifetime costs of the Dish Array system.

The key factors impacting cost and overall performance are as follows.

1. Weight and volume of receiver packages: This is important for reducing the impacts on antenna structure and mechanisms. It also affects handling of receiver packages during installation and maintenance. The overall multi-feed-receiver package must ultimately be designed as a systemic whole, rather than as an assembly of individual parts “bolted” together. For example, cryo-pumps, power supplies, external cooling devices may be shared among several feed-receiver combinations. The mechanical arrangement for switching receivers must be optimized for weight and volume (as well as easy of maintenance, reliability, etc. – see below).

2. Reliability and scheduled maintenance: An array of 250-3000 dishes, each with 4-5 receiver packages presents an overwhelmingly expensive maintenance cost. In addition, reliability issues will certainly be important for these numbers.

3. Power consumption: Cryo-coolers will use significant amounts of power, which adds to both capital (infrastructure) and operational (usage) costs.

4. Cost reduction: Reduction of total cost of ownership is main goal. However, this can only be achieved with a balance of capital cost, cost of maintenance/repair, and power cost.

1.2 Applicable & Reference Documents

This section lists other documents which are referred to in the main body of this document. In cases when the document cited is listed without an issue number, revision number or date, then the reader should refer to the latest available issue.
1.2.1 Applicable Documents


AD2  PRP/685/2734 Issue 1.1, Callisto Proposal for a Study into the Options for the Square Kilometre Array Cryogenics, 19 Dec 2011.

AD3  REP/1304/2779, Callisto report for Work Package 2.

1.2.2 Reference Documents

RD1  SKA PHASE 1 SYSTEM REQUIREMENTS SPECIFICATION, Document number WP2-005.030.000-SRS-002, SKA Program Development Office.

RD2  REQUIREMENTS DOCUMENT FOR SKA DISH ARRAY, Document number WP2-020.030.020-RS-001 Revision B, SKA Program Development Office, Date 2011-06-16


2. SKA LOW NOISE FRONT ENDS: DESIGN ASSUMPTIONS

2.1 Hardware assumptions

The initial assumption is that there will be two types of Dewar: one with circular waveguide input (the Dewar mounts directly on the flange of the feed horn) and one with coax (or possibly open line feeder) input to connect to a broad band feed. If we assume the latter version is used for the lower frequencies, say 450 MHz to 1 GHz, then the biggest cryogenic challenge will be the cryostat with the largest waveguide input: here we are assuming 900 MHz to 1700 MHz. We also assume that the Morgan OMT scheme [RD6] will be adopted with four probes and four LNAs, with a small fifth probe for cal injection.

For the purposes of this study we therefore initially consider a design for the 900 – 1700 MHz, 4 probe front-end for the purposes of our analysis, on the basis that it will be the most difficult to cool. For higher frequencies, with smaller input waveguides, the heat load will be significantly lower, as a result of which it will be possible to reach lower temperatures for the OMT probes and LNAs for a given cooling capacity. In practice this will be an advantage, since the intrinsic noise performance of low noise transistors increases with increasing frequency; hence the lower temperatures that can be reached for a given cooling power should counterbalance this trend, and facilitate the attainment of low noise temperatures over the full range of SKA frequencies.

Specific LNA designs for the SKA do not yet exist, so some assumptions have to be made about the likely power consumption and heat load that they will produce, as well as the likely variation in sensitivity with cryogenic temperature that is discussed in 2.2 below. Power consumption is assumed to be 30 mW per LNA: this is a specified value for a commercially available cryogenic LNA supplied by Low Noise Factory in Sweden.

SKA dishes are assumed to have an effective diameter of 15 metres. Overall frequency coverage of 450 MHz to 10 GHz may need 5 feeds, each covering a little less than one octave. It may be possible to develop wide band feeds that cover greater than one octave, but at the time of compilation of this report the performance of such feeds has not reached the levels that would be acceptable for use in the SKA Dish Array. So for the purposes of this study it is assumed that 5 feeds will be employed.

2.2 Performance assumptions

Sensitivity requirements for the SKA Dish Array are as follows.

- Phase 1: 1000 m²K⁻¹ [RD1]
- Phase 2: 10,000 m²K⁻¹

In order to meet these requirements in each the SKA Dish Array System will need to comprise a sufficient number of dishes to produce the required ratio of effective collecting area to system noise temperature. The lower the system noise temperature, the smaller the number of dishes required.

The implications for the cost of the SKA go far beyond the cost of the dishes themselves. Associated with the dishes are signal transport networks, signal processing, computing and infrastructure. All of these represent a large cost per dish, for both capital expenditure and operation and maintenance.
Hence, there is potentially a strong financial incentive to minimise system noise temperature, and therefore the number of dishes in the SKA Dish Array.

Cryogenic cooling of low noise front ends is a well established practice in radio astronomy; it brings about substantial improvements in system noise temperature at frequencies from a few hundred MHz upwards. Cryogenic cooling of the front ends is clearly desirable for the SKA, as it would reduce the number of dishes required, and could thus potentially reduce the system cost substantially. However, the cost, particularly the operation and maintenance cost, of cryogenic systems can be very high. Hence there needs to be a careful assessment of the costs and benefits of the various cryogenic options.

Measurements of low noise amplifiers at cryogenic temperatures reveal that the variation of noise temperature with physical temperature is approximately parabolic at temperatures below 100 K. For the purposes of this study we adopt the following model for temperatures below 100 K, which closely follows the noise performance of some of the better low noise amplifiers currently available.

\[ T_{LNA} = 3 + \left( \frac{T-15}{1430} \right)^2, \quad 15 < T < 100 \text{ K} \]  

(1)

However, the noise temperature at the Dewar flange will be a little higher than this, owing to losses in the input waveguide and OMT probe assembly. Waveguide losses will depend on the size of waveguide chosen, the plating on the guide inside surface, and the temperature of the guide. It is assumed that the OMT assembly will be maintained at the same temperature as the LNAs; in fact one option would be to build the LNAs inside the probe assembly.

Above 100 K physical temperature the LNA noise temperature tends to rise linearly. We adopt the general rule of thumb is that the LNA noise temperature at 300 K is approximately 10 times the noise temperature at 15 K. This leads to estimates of 30 K for the LNA noise temperature and 50 K for the system noise temperature if no cooling is employed. If we assume that the mean temperature of the waveguide is mid-way between 300 K and the LNA temperature, T, then the noise temperature at the Dewar input flange is related to the losses and temperatures as follows.

\[ T_{Dewar} = \frac{(300-T)}{2} \left( \frac{L_{WG}}{L_{WG}} \right) + TL_{WG} \left( \frac{L_{probe}}{L_{probe}} \right) + L_{WG}L_{probe}T_{LNA} \]  

(2)

Overall system noise temperature will depend further on the noise temperature associated with the antenna, including Cosmic Microwave Background, atmospheric losses, spillover and feed loss. Here we assume an optimistic value of 15 K, leading to a minimum system noise temperature of 20 K.

\[ T_{sys} = 15 + T_{Dewar} \]  

(3)

Aperture efficiency of the SKA dishes is expected to be around 70 %, which leads to an effective collecting area of approximately 124 m² for a 15 metre dish. Hence the number of 15 metre dishes required, \( N_D \), is given by the following expression.

\[ N_D = \frac{10,000 \times T_{sys}}{124} \]  

(4)
3. DESIGN APPROACHES USING EXISTING TECHNOLOGY

3.1 GM coolers

Cryocoolers are machines « producing » cold i.e. removing heat from a system.

Various thermodynamic principles and technical principles can be used in these machines: Reverse Stirling (Stirling), Gifford-McMahon (GM), Pulse Tubes (PT), Thermo acoustic, Thermoelectric, Joule-Thompson, Magnetic Refrigeration… Figure 3-1 presents the temperature operation range of these various principles:

![Cryocoolers Technologies Performance](image)

Figure 3-1: Cryocoolers Technologies Performance

The following section focuses on the GM principle which is the most used for cooling LNAs down to 15K.

3.1.1 Principles of operation

Compared to other gas refrigerators the Gifford-McMahon (GM) principle allows compressor unit and cold head (expansion unit) being separated by several meters distance. This provides installation flexibility as well as the fact that cold head is relatively low mass and can be operated in any mounting position whereas the compressor must remain horizontal.

They follow the Ericsson thermodynamic cycle (Isobaric-Isothermal):

![GM-Ericsson Thermodynamic Cycle](image)

Figure 3-2 : GM-Ericsson Thermodynamic Cycle

The theoretical value of the amount of heat transferred during one cycle corresponds to the rectangular area in the PV diagram.

The GM cryocooler systems present the following helium pressure range:
High Pressure = 1.5 – 2.5 MPa (15-25 bar)

Low Pressure = 0.4-0.7 Mpa (4-7 bar)

They use normal oil-lubricated refrigeration compressors modified to remove the higher heat of compression by the monatomic helium gas as working fluid.

GM success comes from minimal maintenance (generally every 10,000 to 30,000 hours) of compressors and cold heads.

How does GM work?

A simplified description of the GM cycle is illustrated in Figure 3-3. The GM cooler represented here has a piston volume and a regenerator physically separated; common designs have combined regenerator and pistons. This principle is shown for a single stage cooler; the cold stage (where the sample to be cooled is thermally linked) is located on the top of the working volume, on the left side of the following figure.

![Figure 3-3: Description of the Gifford-McMahon closed cycle](image)

GM coolers can be designed commonly as single stage or two-stage machines. Single stage coolers reach temperature as low as 60K; two-stage coolers can reach temperatures as low as 4K.

Commercialisation of GM cycle cryocoolers was first established during the 1950’s and today they are used in a wide range of applications (cryo pumps, IR detectors, LNAs, nuclear physics, medical equipment…). Some of these applications need to run continuously for years with only periodic maintenance and GM cryocoolers technology fits well with this requirement. GM technology can be considered as mature cryocooler technology.

The Figure 3-4 presents a detailed description of a GM-based two-stage cold head such as the units used for deep space telecommunications. It also points out the main system failure sources.
The role of the regenerator item is to store heat during a cycle: when pressure decreases inside the cold head, the helium passes through the regenerator lattice and extracts heat from it; when high pressure helium enters the system through the regenerator lattice at the beginning of a cycle, it is pre-cooled by releasing heat into the regenerator.

First stage regenerators/pistons are made of metallic wires mesh; this structure increases the surface contact area between helium and regenerator and the material improves the heat exchange.

Second stage regenerators/pistons can be made of lead shots (which have large volumetric heat capacity compared to helium). This allows better heat exchanges at very low temperatures. Modern cryocoolers can use a combination of rare-earth for the regenerator materials.

Single stage coolers cooling power performance is up to 200W at 80K. For two-stage coolers it is up to 20W at 20K along with 80W at 80K.

Cooling power mainly depends on: compressor input power, external heat loads, Helium purity, valve and joints wear, compressor heat rejection efficiency, regenerator quality.

Figure 3-4: Detailed description of a GM cold head

The system main failures could come from a contamination of the helium gas: high purity helium gas is required as working fluid. High purity means at least 99.995% purity helium gas. Contamination can...
come from system leaks, oil contamination due to saturation of compressor absorber, dust particles from mechanical wear inside the cold head…. Failure in reaching and/or keeping base temperature could also come from wear inside the cold head: regenerator/pistons are circled by 'o'-rings and gaskets that wear due to mechanical work. Finally failure could also be due to the high/low pressure valve (a rotative valve): the rotation of the valve at each cycle produces mechanical wear of this component.

3.1.2 Performance capabilities

Two stage GM coolers are in common use in radio astronomy, satellite ground stations and deep space networks. They are used to cool instrumentation down to temperatures in the range 4 to 25 kelvins, with second stage cooling powers typically ranging between 0.1 and 100 watts. First stage cooling is generally available in the range 30 to 100 K , with cooling capacity up to 600 W.

3.1.3 Hardware needed and typical capital cost

A typical GM cooling system is illustrated in Figure 3-5. It comprises the following major elements.
Figure 3-5 GM cooling system hardware

1. Helium gas compressor, power cords and water cooling lines
2. Two sets of helium pipes (low and high pressure between 3-20m long): often a combination of rigid and flexible
3. GM refrigerator (cold head)
4. Chiller or other heat rejection system
5. Helium gas: for initial charge of the system and to replace losses due to leaks and maintenance

In principle it would be possible to use a single GM refrigerator to cool two or more front ends for the SKA Dish Array, in which case there is a potential saving in capital cost, maintenance cost and possibly the cost of electricity to run the coolers (there would be fewer coolers, but higher cooling power is likely to be needed to cool multiple front-ends). The most efficient (from a cryogenic point of view) way to do this would be to use a dual or triple band feed connected to low noise amplifiers located in a single Dewar. However, the complexity of the interface (including OMTs) between the feeds and the LNAs, and the losses that would result, may rule out this option.
Typical costs for the hardware are as follows

Cold head and compressor (possibly 1 compressor per 2 cold heads): 13 to 31 k€ depending on cooling power needed.

Vacuum pump: 5 – 15 k€, depending on vacuum level needed and volume of Dewar.

Helium pipes: 2 k€

Chiller: 5 k€, this may not be needed on a low power system if the compressor can reject the heat.

Typically the mass of a GM cold head is 10 kg, and the associated compressor is approximately 100 kg.

Total capital hardware cost is thus expected to in the range from 20 k€ to 53 k€ per Dewar. For the purpose of comparison with other cooling systems we assume two versions of GM cooled front ends (5 per dish), both of which cool the LNAs to 15 K, as follows.

1. Low cost 15 K GM: 17 k€ capital cost (assuming 1 chiller and 1 low cost vac pump per dish)
2. High cost 15 K GM: 37 k€ capital cost (assuming 1 chiller and 1 high cost vac pump per dish)

### 3.1.4 Power consumption and efficiency

Power consumption for GM systems is relatively high: most of the power is needed to drive the compressor. Typically compressors consume between 1.5 and 20 kW. Power to drive the cold head is negligible in comparison to the power consumed by the compressor. Overall efficiency of the cooling system in terms watts of cooling per watt of power consumption is in the range $7 \times 10^{-5}$ to $5 \times 10^{-2}$.

### 3.1.5 Maintenance

With its multiple mechanical moving parts the GM cooling system requires regular maintenance. The most frequent maintenance requirement is cold-head replacement, typically every 14 months. Recent developments for the satellite communications industry have drastically reduced the complexity and time required for this operation by removing the need to open the Dewar when exchanging a cold head. However, it will still be necessary to provide a constant supply of new or refurbished cold heads for exchange. Replacement periods for other major items of hardware are as follows.

- Compressor: 10 years (with regular maintenance typically every 20,000 hours)
- Helium pipes: 15 years
- Vacuum pump: 10 years
- Chiller: 10 years (this may not be reached in the SKA environment without significant development effort owing to the elevated ambient temperatures and dust)

In addition to end-of-life replacement there may be other minor routine maintenance activities that need to be done, depending on the final design that is chosen. These have not been assessed in this report, so would represent costs in addition to those estimated below.
All of the main items described are liable to random failure, either because they use moving mechanical parts or, in the case of the helium pipes, because they are subject to regular mechanical stress (flexing as the dish moves). The harsh environment in which the SKA is expected to be situated will add to the challenge of making a GM cooling system reliable.

3.1.6 GM coolers in radio astronomy

GM coolers are very widely used in radio astronomy around the world. Some examples of existing arrays where they are used is given below.

- EVLA in New Mexico
- eMERLIN in UK
- ATCA in Australia
- Westerbork in The Netherlands (soon to be decommissioned)
- ALMA in Chile

All of these cryogenic systems were built, and are maintained, by experts. None is optimized from the point of view of power consumption or other running costs; hence their designs cannot be adopted directly for the SKA. However, the experience gained in operating some of these systems in remote areas with harsh environments could be of value to the SKA.

3.2 Stirling coolers

3.2.1 Principles of operation

The Stirling cycle cryocooler is based on an isothermal-isochoric (constant temperature-constant volume) cycle, which is illustrated in Figure 3-6.

![Figure 3-6 the isothermal-isochoric cycle](image)

Figure 3-6 the isothermal-isochoric cycle

Figure 3-7 illustrates the beta type Stirling engine. The cryogenic version is basically the reverse.
The main advantages of the Stirling thermodynamic cycle over the GM for our application are the higher efficiency (cooling power/input power), the reduced size and compactness of compressor and cold head, and the oil free compressor.

### 3.2.2 Performance capabilities

Stirling cycle refrigerators are potentially attractive for the SKA Dish Array for two major reasons:

i. they can have a very long maintenance free lifetime (many years) with high reliability, and

ii. they are significantly more power-efficient than GM coolers.

For example, the STI Sapphire Stirling cooler (see Annex 7.3.1) can provide 8.5 W of cooling at 100 K, with 100 W of input power, with field demonstrated MTBF\(^1\) of in excess of 1 million hours. It has been used in large numbers (thousands) in cell-phone base station applications.

Many other Stirling coolers are commercially available, offering a range of cooling capacities and base temperatures potentially to 30 K. None of these is currently optimal for the SKA, and there are undoubtedly several design challenges to be met before an optimum solution can be found for the SKA

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\(^1\) This is a calculated value based more than 5000 units in the field. This is not the value for one single unit.
Dish Array. One critical design challenge is the need to reject heat at the maximum SKA ambient temperature of +50°C with robust, reliable, compact and efficient heat rejection systems.

### 3.2.3 Hardware needed and typical capital cost

An additional advantage of the Stirling cooler approach is the relative simplicity of the hardware, as compared to the GM approach. All of the components of the cooling system are contained in a single assembly, which just requires a separate power supply to drive it. No gas supply is needed, and there is no routine maintenance required.

The mass of a Stirling cooler is typically 10 kg, substantially less than a typical GM system, which can amount to 100 kg. This is an advantage for the SKA Dish Array, since it potentially reduces the mass (and volume) to be mounted on the dish, including the mass of the front end payloads to be mounted at the secondary focus of the dish. Although the compressor can be mounted remote from the Dewar, on another part of the dish or even on the ground, the long helium lines that will be needed will also contribute to the mechanical loading of the dish.

As mentioned above, heat rejection is one aspect of the use of Stirling coolers that needs significant development for the SKA. All of the primary input power is turned into heat, in addition to the heat removed from the Dewar: all of this must be removed for the cooler to function. The efficiency of the heat removal directly affects cooler performance, the ultimate base temperature achievable and also the cooler reliability over a long period of operations. In the SKA environment the maximum ambient air temperature is specified to be +50°C: this presents a serious design challenge in respect of heat disposal from the Stirling cooler. It will be essential to develop a cooling system that is reliable, has the necessary long maintenance-free lifetime in the SKA environment and consumes the minimum power. (Note that the challenge will be no less for the GM cooler option, where the amount of heat to be removed is far greater).

Estimated capital costs for Stirling coolers are as follows:

- 100 W (producing 100 K base temperature): 10 k€
- 200 W (producing 80 K base temperature): 15 k€
- 500 W (producing 50 K base temperature): 20 k€

### 3.2.4 Power consumption and efficiency

Cooling power is typically a few percent of the primary input power to the cooler, and diminishes as the base temperature decreases. Efficiency also decreases as the heat rejection temperature increases. Nevertheless, the overall efficiency of a properly designed Stirling cycle cryo cooler system is generally far greater than that of a GM system, so the operating costs will be substantially lower.

In addition to the example mentioned in 3.1.2 above, we also consider example Stirling coolers that cool the LNAs to 80 K, with 200 W input power, and to 50 K, with 500 W input power. Whilst there are existing commercially available Stirling coolers that theoretically meet these limited requirements they are not suitable for the SKA in their current form, and there needs to be significant research and development to produce an optimum solution for the SKA.
A potentially useful feature of the Stirling cooler is the ability to vary the input power, and hence the base temperature. This opens up several possibilities:

i. the temperature of the LNAs and OMT could be maintained constant as the ambient temperature varies (this would save power when the ambient temperature dropped, for example at night), or
ii. the input power could be increased over time to maintain the base temperature as the Stirling cooler ages, or
iii. the input power could be reduced (to save power) when maximum sensitivity is not required.

3.2.5 Maintenance requirements

Routine maintenance is not required for the type of Stirling coolers that are seen as potentially useable for the SKA Dish Array. It is envisaged that worn-out coolers would be replaced by new ones. At the dish level this would involve exchanging a complete Dewar; owing to the small size and low mass of the cooler this could be a simple task that could be performed in a few tens of minutes. If a low vacuum design were used (see 3.4.2 below) then there would be no need for further action once the new Dewar was connected: it would cool down automatically.

3.2.6 Examples of applications of Stirling cycle coolers

Stirling cycle coolers are widely used in such applications as infra red detectors, medical electronics, HTS wire, and liquid nitrogen production. However, the most relevant example for the SKA Dish Array is probably that illustrated in Figure 3-8; here Stirling coolers are used to cool high temperature superconducting filters in cell-phone base stations. This application, like the SKA Dish Array, requires long lifetime and high maintenance-free reliability. Many thousands of such coolers have been deployed in the field. Military infra red detectors have been using Stirling cycle coolers since the 1970s, with cooling powers ranging from 0.3 to 1.75 W; to date more than 160,000 coolers have been produced.
3.3 Pulse tube coolers

Pulse tube coolers have the potential attraction of relatively high energy efficiency, although this is usually inferior to that of Stirling coolers. They are also valuable in applications where vibration must be minimised. However, they suffer from a significant disadvantage so far as the SKA Dish Array is concerned: they need to be maintained in a constant orientation except in zero gravity (they have been used successfully in space applications). Although some pulse tube coolers can operate at any angle, their cooling power varies with tip angle. Hence, they are not considered further in this study report.

3.4 Vacuum

3.4.1 High vacuum systems

Existing radio astronomy cryogenic front ends, discussed in section 3.1.6, rely on maintaining relatively high vacuum within the Dewar. Typically a turbomolecular pump is used to reduce the pressure inside the Dewar to around $10^4$ mbar before and during the cool down. Once the cold surfaces inside the Dewar fall below about 40 K cryo-pumping starts to dominate, so the Dewar can be sealed and the external vacuum pump removed.
A high level of vacuum is used to insulate the cold parts of the Dewar from the warm parts (the outer container and waveguide window. It also avoids any possibility of condensation forming on the cold surfaces. However, it has no effect on the heat radiated from the warm surfaces onto the cold surfaces (waveguide, LNAs and OMT housing in this case); this is a significant source of heat input and in vacuum only systems with larger waveguides, such as may be used for the lower frequency SKA Dish Array front ends, it is common practice to use an infra red heat shield, often cooled by the first stage of a GM cooler, to reduce this effect.

Maintenance of the vacuum is essential for the continued operation of the Dewar. If the vacuum starts to fail there is a conduction/convection path from the warm outer surfaces of the Dewar onto the cold parts. Thus the temperature will rise, causing molecules trapped on the cold surfaces to out-gas, thus compromising the vacuum further and creating a vicious circle of increasing temperature and declining vacuum. Loss of vacuum can be caused by a number of different processes.

- Permeability of the polymer ‘o’-rings and waveguide window
- Leaks
- Out-gassing from components inside the Dewar
- Power failure to the cryo cooler
- Degradation of the cooler, leading to excess temperature and out-gassing from the cold surfaces

One of the design goals for a waveguide window is to make it vacuum tight, but even the best waveguide windows will admit some gas molecules, and over a long time these may become sufficient in number to start the vacuum degradation process described above, particularly if there are other sources of unwanted molecules.

Leaks can be minimized by good design and careful assembly and maintenance, but it is impossible to completely seal the Dewar, and there will inevitably be a finite leak rate that will eventually compromise the vacuum.

Out-gassing from components is another source of unwanted gas molecules, and can be thought of as a ‘virtual leak’. This effect can be kept to a minimum by careful choice of components, avoiding materials that can out-gas in a vacuum, by cleaning and polishing components to eradicated places where gas molecules can be temporarily trapped (e.g. in the rough outer surface of a waveguide), and by using a powerful vacuum pump to evacuate the Dewar before cooling (if this is done at an elevated temperature it is more effective). It can further be ameliorated by including some sort of absorber material, such as molecular sieve or charcoal, in the Dewar to absorb the gas molecules.

Power failure to the cryo cooler will result in a fairly rapid rise in the temperature of the cold surfaces, giving rise to out-gassing and the vicious cycle of vacuum degradation and temperature rise described above. Unless the power to the cryo cooler is restored within a given time (typically a few hours), dependent on the current state of the vacuum, the thermal mass of the cold parts and the power of the cooler, then it will not be possible to re-cool the Dewar without using a vacuum pump.

If the best design is adopted, the best assembly and maintenance practices are carried out, and the Dewar is thoroughly evacuated before cooling, then the Dewar should maintain its vacuum sufficiently to remain at the design temperature for the lifetime of a GM cold head, typically 18 months.

High vacuum operation at higher temperatures, such as those typically reached by Stirling coolers, are feasible only in systems that can be extremely well sealed and thoroughly evacuated before cooling: this implies the use of welded seams and flanges, rather than o ring seals. If a waveguide window were
used it would need to be extremely vacuum tight. One possible solution would be to equip each Dewar with a vacuum pump that automatically operated whenever the vacuum deteriorates to a pre-set threshold. This adds to the complexity of the design and would also increase the mass and volume of the hardware. A thorough design study would be necessary to verify that such a system could be developed for the SKA.

In order to operate high vacuum cryogenic systems for the SKA it will be necessary to provide for Dewar evacuation at the dishes. Dewar evacuation will be required in the following circumstances.

i. On installation of a cryogenic front end, prior to and during initial cool-down.
ii. In the event of a Dewar warming up due to power failure to the cryo cooler.
iii. If the vacuum deteriorates for any reason (see above) before the end of life or routine maintenance of the cryo cooler.

Evacuation of a Dewar will require that a vacuum pump is connected to the Dewar’s vacuum port; once the vacuum pump is operational a valve is opened to allow the pump to evacuate the Dewar. Once the temperature falls sufficiently to allow cryo-pumping the valve can be closed and the pump removed. These operations can be carried out manually, with trained staff attaching carrying out these activities, or it could be automated such that the pump and valve are controlled remotely. One complication with the automated version is that many vacuum pumps need to be operated on a level or near level, surface and cannot therefore be mounted on a moving radio telescope structure.

An example of a set of vacuum equipment is given below. It is based on the use of a turbomolecular pumping system with dry scroll backing pump.

Figure 3-9 example of a turbomolecular vacuum pump
EXT75DX Turbomolecular Pump

Ambient Operating Temperature: 5°C to 40°C

Maximum Operating Humidity: 10% - 90% non-condensing

XDS10 Dry Pump (backing pump)

Typical Ultimate Vacuum : 7×10⁻² mbar

Maximum Pumping Speed : 9.3 cubic metres per hour

Maximum Permitted Inlet Pressure : 0.5 bar gauge

Maximum Permitted Outlet Pressure : 1 bar gauge

Ambient Temperature Operating Range : 10°C to 40°C.

Storage Temperature Range : -30°C to + 70°C

Maximum Humidity (Operation): 90% RH

Altitude: up to 2000m
Turbo Instrument Controller TIC

Ambient Temperature Operating Range : 0°C to 40°C.

Storage Temperature Range : -30°C to + 70°C

Maximum Humidity (Operation): 90% RH non condensing at 40°C

Maximum operating altitude: 3000m

Wide Range Gauge WRG

Pressure range : 100 to 10^-9 mbar (indicates pressures up to 1000 mbar at reduced accuracy)

Output signal : 2 - 10 V d.c.

Maximum over pressure: 6 bar absolute (5 bar gauge)

Maximum operating altitude: 2000m

Vacuum fitting: NW25KF

Ambient Temperature Operating Range : 5°C to 60°C.

Storage Temperature Range : 0°C to + 70°C

Maximum Humidity: 90% RH non condensing up to 31°C

70% RH non condensing above 31°C

Purchase cost of a vacuum pump system suitable for this application is typically 15 k€, and they have a lifetime of approximately 10 years. Regular maintenance is also required: an example of the maintenance specified by a pump manufacturer (Edwards) is shown in Table 3-1, which is taken from their documentation.

Power consumption is typically 1 kW, although this is not expected to contribute significantly to the SKA power budget as the vacuum pumps will only be used intermittently for relatively short periods.
### Table 3-1 Example vacuum pump maintenance schedule

<table>
<thead>
<tr>
<th>Time</th>
<th>Task</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yearly</td>
<td>Inspect and clean inlet strainer.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Inspect and clean gas ballast control.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Clean the external fan cover.</td>
<td></td>
</tr>
<tr>
<td>9,000 hours</td>
<td>Replace the tip seal</td>
<td>See Section 4.4, Edwards Manual for XDS Dry Pumps, paragraph 5</td>
</tr>
<tr>
<td>15,000 hours</td>
<td>Test condition of pump motor.</td>
<td></td>
</tr>
<tr>
<td>35,000 hours</td>
<td>Replace bearings</td>
<td></td>
</tr>
</tbody>
</table>

#### 3.4.2 Low vacuum solid insulation systems

As discussed in the previous section even if the best design is adopted, the best assembly and maintenance practices are carried out, and the Dewar is thoroughly evacuated before cooling, the high vacuum cryogenic systems have only limited lifetimes. Furthermore, the high vacuum approach is difficult to apply in the case of cryogenic coolers operating above 30 K as a slight increase in temperature will lead to reduction in cryo pumping. An alternative approach, developed in response to satellite ground station operators’ desire for higher reliability and reduction in maintenance costs, is to use solid insulation in the Dewar with a much lower vacuum.

Certain solid materials, silica aerogels, provide very good thermal insulation properties, and have been demonstrated to work very effectively in cryogenic applications. Use of the aerogel material to fill all the available space inside the Dewar removes the need for a high vacuum in the Dewar as the aerogel material is an excellent thermal insulator and its presence prevents convection. In addition the aerogel acts as an infra red filter between the warm outer parts of the Dewar and the cold parts. Partial evacuation of the Dewar is still the usual practise, in order to eliminate water vapour (which would otherwise condense on the cold parts) and to augment the thermal insulation. Alternatively, it may be desirable to replace the air in the aerogel with an inert gas, with very low thermal conductivity, at atmospheric pressure; this possible approach is discussed further in Work Package 2.

The key advantage of the solid insulation approach for the SKA Dish Array is that it does not rely on cryo-pumping. The consequences are as follows.

i. It is straightforward to use cryo coolers with base temperatures above 30 K
ii. Recovery from power failure to a cryo cooler does not necessitate the use of a vacuum pump
iii. Failed Dewars can be replaced in the field without the need for a vacuum pump
iv. Dewars can be switched off an on as required without the need for a vacuum pump

All of these have the potential to lower the cost of the SKA Dish Array. Use of Stirling coolers, which currently typically cool to 50 to 100 K, could save a great deal of cost owing to their higher efficiency, longer lifetime and greater reliability, when compared to GM coolers. These savings have to be
balanced against the need for larger dish numbers to compensate for the higher system noise temperature that will result from operation at higher temperature (see section 2.2).

Unfortunately, the advantages of solid insulation come at some cost in insulation performance, as compared to the high vacuum approach. This can be ameliorated by increasing the dimensions of the Dewar (and hence its mass) to allow for a greater volume of insulating material around the cold parts, and/or by increasing the power of the cryocooler. Clearly these are additional design trade-offs that need to be taken into consideration in the choice of the optimum design for the SKA Dish Array. Potential enhancements to the solid insulation performance are discussed in the Work Package 2 report.

As mentioned above, a key feature of the solid insulation approach is the avoidance of the need for vacuum equipment at the dish. Each Dewar would be prepared before shipment to the dish, either by evacuation and sealing, or by filling with inert gas (see Work Package 2); once installed the cooling process could be started immediately with no need for personnel to remain on site. In the case of a Stirling cycle Dewar the mechanical and electrical interfaces are potentially very simple: perhaps 6 screws to fasten the Dewar to the antenna feed plus single cable connections to the Dewar.

Although we have mostly concentrated here on the advantages of solid insulation where Stirling cryocoolers are deployed, there are also potentially great benefits to adopting a solid insulation/low vacuum approach if 15 K GM coolers are chosen for the SKA Dish Array. This approach potentially simplifies the option to operate Dewars on each dish one at a time, i.e. cooling them only when they are required for observations and allowing them to warm up when not needed. It may not be feasible to cool all Dewars all of the time because of the high cost of electrical power. Solid insulation could allow the Dewars to be cooled on demand without the need to use vacuum pumps between regular cold head services, thus greatly reducing the complexity and cost of the cryogenics system.

Callisto has implemented solid insulation on Dewars operating at 15K and at 70K. These designs have been validated by prototypes and by long term performance tests (12 months). Operational systems of the 15K Dewar have been built and delivered to ESA and are currently being installed in an operation Deep Space antenna. ESA has recently taken the decision to upgrade all the cryo LNAs in its Deep Space network to use solid state insulation and replace all the existing vacuum insulated Dewars. Orders have already been placed with Callisto to implement this plan which will be rolled out over the next 3 to 4 years.
4. TECHNICAL ANALYSIS

4.1 Thermal modelling

The simplest cooling scheme uses a single stage cryogenic cooler, such as the Stirling cycle refrigerator described above. Figure 4-1 shows a schematic of a single stage cryostat to illustrate the heat loads; the contributions are as follows.

i. *Conduction along the waveguide.* This is minimised by using thin-walled waveguide fabricated from a material with low thermal conductivity, such as stainless steel or invar. A very thin layer of electrically conductive metal, typically gold or silver, is usually plated on the inside surface of the waveguide in order to reduce its RF loss. This is further discussed in section 4.3. A short gap may also be left in the waveguide to reduce thermal conduction without significantly affecting the RF loss: this technique is not used in conjunction with solid insulation, but can be used in vacuum only systems.

ii. *Infra red radiation.* There are potentially two sources of infra red (IR) heat load: the waveguide window and the internal surfaces of the Dewar. The former can be limited by the inclusion of an IR filter in the waveguide: this would ideally reflect the incoming IR radiation, whilst not affecting the radio frequency radiation from the dish. IR radiation from the inside walls of the Dewar can be limited by polishing the surfaces, thereby reducing their emissivity, and if solid insulation is used this acts as an effective radiation shield. For the case of a 2-stage refrigerator it is also possible to include a low emissivity metallic heat shield cooled to an intermediate temperature.

iii. *LNA dissipation.* DC input power to the LNAs contributes directly to the heat load. This can be minimized by use of good quality LNAs; typically the DC power per LNA is around 30 mW.

iv. *Coaxial cables.* Coaxial cables used for the RF outputs and calibration input connect directly between the wall of the Dewar, at ambient temperature, and the LNA/probe assembly. The heat load depends on the number and length of the cables, but also on the materials used for their manufacture. This is further discussed in section 4.3.

v. *Conduction and convection.* Traditionally radio astronomy cryostats have avoided these by operating at a high level of vacuum, typically <10^-4 mbar. As discussed above this leads to operation and maintenance costs that are potentially too high for the SKA. The alternative approach, using solid insulation and a soft vacuum, is an effective alternative method to reduce conduction and convection, whilst permitting much lower operation and maintenance costs.
In section 2.1 there is a description of the assumed cryostat design for the purpose of this study. This has been analysed to determine the level of cooling power required in order to maintain the OMT probes and LNAs at 100 K, see section 4.4.

4.2 Vacuum

*High-vacuum option:* dry air thermal conductivity is negligible for pressure below 5e-4mbar. This is the upper limit for operations. Above this limit the system temperature rapidly degrades (from few days to few hours). Frequency of vacuum pump down depends on vacuum design (gas loads) of the system; basic design require vacuum recycling every 10,000 hours of continuous operation.
Low-Vacuum option: pressure between 1mbar and 100 mbar are typically acceptable values. System can operate with degraded but stable performance at higher temperatures. Frequency of vacuum recycle also depends on vacuum design (gas loads). Basic design is typically once a year. On-going studies show this can be extended to several years, between 5 and 10.

4.3 Input/output connections: thermal, RF and DC aspects

4.3.1 RF input

As described in section 2.1 three possible types of RF input are envisaged, as follows.

i. Circular waveguide
ii. Coax
iii. Balanced feeder (4 wire open line)

In each case the input connection will cause a heat load on the Dewar’s cooling system, and will introduce losses (and hence noise) into the system. Hence, the design goal for the RF input connection is simple: minimum thermal conduction, with minimum RF loss. Unfortunately these conditions are essentially contradictory, since low thermal conductivity is usually associated with low electrical conductivity, and hence high RF loss. Thermal conduction can be reduced by increasing the length of the input connection; this may make a significant difference to the loss of a coax or open line feeder. In the case of the waveguide approach the RF losses may be sufficiently small that the additional length is not significant, but additional length implies larger Dewar size and greater mass, and the benefits of lower thermal conduction along the length of the waveguide have to be balanced against the greater heat loads onto the outside of the waveguide walls due to infra red and conduction.

It is common practice in centimetre wavelength radio astronomy Dewars to use a thermal gap in the input waveguide to provide thermal isolation between the input guide, at ambient temperature, and the waveguide components that are cooled (usually some sort of ortho-mode transition). If the gap size and location are chosen carefully it is possible to get substantial thermal isolation without significant RF loss. This technique should be considered for the SKA Dish Array, but is not compatible with existing application of solid insulation schemes.

An alternative approach, that is applicable to all three types of RF input, is to exploit the skin effect. In this case the bulk material used for the waveguide, coax or open wire feeder construction is chosen to be a material with low thermal conductivity, such as stainless steel or invar. RF losses are reduced by applying a very thin layer of plating of a high conductivity material such as gold or silver, amounting to perhaps five skin depths at the frequency of operation. Although the plating adds to the heat load its effect is vastly less that would be the case if the bulk material were made from the good conductor.

Dielectric losses can also degrade the loss of a coax input connection, and hence add to the noise temperature of the system, so if coax lines are to be used for the SKA Dish Array, these will need to be vacuum dielectric lines.

4.3.2 RF output and calibration input

There are potentially four RF outputs per feed (assuming a 4-probe OMT) plus a calibration input. Each of these is a source of heat load, although for these connections the RF losses are less critical. Various commercially available solutions exist, all relying on the principle described above: high
conductivity plating onto low thermal conductivity bulk material. Since RF loss is less critical here it is possible to use relatively long connections to reduce the thermal transmission.

### 4.3.3 DC wiring

Wiring for the LNA power supplies and Monitor and Control will provide a thermal path between the outside of the Dewar and the cold parts. Well established techniques exist to provide good DC connections with little heat load.

### 4.4 Modelled performance example

Based on the hardware assumptions in section 2.1 we can calculate the various contributions to the heat load. This example was chosen as being potentially the most challenging cooling problem for the SKA Dish Array, covering possibly the lowest frequency band that will have a waveguide input.

Design assumptions are summarized in Table 4-1. The cryocooler is a model used expensively in industry, with a well-proven performance record.

<table>
<thead>
<tr>
<th>Description</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input waveguide dimensions</td>
<td>L<del>200mm ; ϕ</del>200mm</td>
</tr>
<tr>
<td>not plated</td>
<td></td>
</tr>
<tr>
<td>Cryocooler temperature</td>
<td>100K</td>
</tr>
<tr>
<td>Cryocooler heat removal capacity @100K</td>
<td>8.5W</td>
</tr>
<tr>
<td>for 100W input power</td>
<td></td>
</tr>
<tr>
<td>Cryocooler input power</td>
<td>100 W</td>
</tr>
<tr>
<td>Main Thermal Insulation</td>
<td>Solid state</td>
</tr>
</tbody>
</table>

Table 4-1 Thermal modelling assumptions: 200 mm waveguide

Table 4-2 presents the various contributions to the thermal load on the cryocooler according to the design assumptions presented above and in section 2.1.

The solid state thermal insulation is the most important heat source. However, the solid insulation is absolutely necessary to remove the high-vacuum retention constraints and significantly reduce the maintenance effort on the cryo system and provide the operational benefits described in section 3.4.2. It is anticipated that the solid state insulation performance can be significantly improved but this requires further development work.
The Infra-red (IR) radiation thermal load inside the RF input waveguide is also substantial, but this can be significantly reduced using IR filter transparent to RF signals. Various designs already exist, but further developments are needed specific to the SKA Dish Array application. The most challenging point is the reduction of the heat loads through the input waveguide bulk and plating if any.

At early development stages the thermal insulation design efforts must focus on the above points in order to reduce the required cooling power and so to reduce the electrical power requirements. In the example above there is a large gap between the available cooling power and the thermal load at 100 K, so even if most of the IR inside the waveguide were removed by filtering the target temperature would not be reached. At higher frequencies, where the component sizes are much smaller, the heat loads would be substantially lower, as shown in Table 4-4.

<table>
<thead>
<tr>
<th>Description</th>
<th>Thermal Load [W]</th>
<th>% of total thermal load</th>
</tr>
</thead>
<tbody>
<tr>
<td>RF Input Waveguide</td>
<td>4</td>
<td>23</td>
</tr>
<tr>
<td>LNAs and bias wires</td>
<td>0.5</td>
<td>3</td>
</tr>
<tr>
<td>RF Coax Output, Test Input</td>
<td>0.3</td>
<td>2</td>
</tr>
<tr>
<td>Solid state thermal insulation on I/P waveguide</td>
<td>1.5</td>
<td>9</td>
</tr>
<tr>
<td>Solid state thermal insulation on cold parts</td>
<td>5</td>
<td>30</td>
</tr>
<tr>
<td>IR radiation inside I/P Waveguide</td>
<td>5.7</td>
<td>33</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>17</strong></td>
<td><strong>100</strong></td>
</tr>
</tbody>
</table>

Table 4-2 Thermal load contributions: 200 mm waveguide

<table>
<thead>
<tr>
<th>Description</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input waveguide dimensions not plated</td>
<td>L<del>200mm ; ϕ</del>100mm</td>
</tr>
<tr>
<td>Cryocooler temperature</td>
<td>100K</td>
</tr>
<tr>
<td>Cryocooler heat removal capacity @100K for 100W input power</td>
<td>8.5W</td>
</tr>
<tr>
<td>Cryocooler input power</td>
<td>100 W</td>
</tr>
<tr>
<td>Main Thermal Insulation</td>
<td>Solid state</td>
</tr>
</tbody>
</table>

Table 4-3 Thermal modelling assumptions: 100 mm waveguide
<table>
<thead>
<tr>
<th>Description</th>
<th>Thermal Load [W]</th>
<th>% of total thermal load</th>
</tr>
</thead>
<tbody>
<tr>
<td>RF Input Waveguide</td>
<td>2</td>
<td>20</td>
</tr>
<tr>
<td>LNAs and bias wires</td>
<td>0.5</td>
<td>5</td>
</tr>
<tr>
<td>RF Coax Output, Test Input</td>
<td>0.3</td>
<td>3</td>
</tr>
<tr>
<td>Solid state thermal insulation on I/P waveguide</td>
<td>0.8</td>
<td>8</td>
</tr>
<tr>
<td>Solid state thermal insulation on cold parts</td>
<td>5</td>
<td>50</td>
</tr>
<tr>
<td>IR radiation inside I/P Waveguide</td>
<td>1.4</td>
<td>14</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>10</strong></td>
<td><strong>100</strong></td>
</tr>
</tbody>
</table>

Table 4-4 Thermal load contributions: 100 mm waveguide

To meet the 100 K target temperature for the 200 mm waveguide case, using existing technology, it would be necessary to use a higher power cryocooler. However, new technology described in Work Package 2, particularly the use of Xenon gas to replace air in the aerogel insulation, should make the 100K/100W goal attainable.

For the 100 mm diameter waveguide example the goal is almost achievable with current technology, and the addition of an IR filter in the waveguide plus a slight reduction in thermal conductivity of the waveguide itself, would be sufficient to meet it.

In these examples the solid state thermal insulation is a major source of heat load. However, its use may be highly desirable for the SKA Dish Array to remove the high-vacuum retention constraints and significantly reduce the maintenance effort on the cryogenics system. Therefore the further development of the solid insulation technique, described in Work Package 2, is considered to be very important for the SKA Dish Array.

SKA Dish Array cryogenics development needs to devote significant effort to the thermal insulation design in order to reduce the required cooling power and so to reduce the electrical power requirements. Following such development it is quite possible that the goal of 100 K base temperature with 100 W cooling power will be reached even for the 200 mm diameter input waveguide case.

### 4.5 Cryo cooler heat rejection

Whichever cryogenic cooling system is adopted for the SKA Dish Array it will be a challenge to dispose of the waste heat: heat removed from the Dewars plus heat generated in the cooling process. To date there has been little SKA specific development work carried out on this subject.

Essentially two types of heat rejection are available: liquid cooling and air cooling. Liquid cooling requires water pumped in a closed circuit, with the heat being removed to some sort of reservoir. Often the reservoir is the surrounding atmosphere into which hot air is blown by fans. An alternative method of removal of water heat can be done using ground pipes (typically down to 10m deep); this type of cooling arrangement has already been investigated as part of the SKA Pathfinder/Precursor programme. This avoids problems that can arise with fan cooling, such as long term reliability and failure due to dust contamination.
Air cooling can be passive or active. Passive (no fan) requires radiators with extremely large surface area to exchange heat with the atmosphere. This is very sensitive to ambient temperature but there are no moving parts so it is intrinsically reliable. Even so, dust build-up can reduce efficiency over time. Given the high upper ambient temperature specification for the SKA Dish Array (+50 °C) it may prove very difficult to achieve the required heat rejection with this method. Active air cooling, which can incorporate heat pumps, requires smaller radiators but uses fans to blow hot air into the atmosphere. Fans are sensitive to dust and typical MTBF is between 8,000 and 80,000 hours depending on model and environment.

Given the remote location and likely high cost of maintenance manpower for the SKA Dish Array the lifetime and reliability aspects of the heat rejection system are of paramount importance, so this aspect of the cryogenics system design needs to be investigated very thoroughly.

An example of a large scale heat rejection system is that used by the European Space Agency in their Deep Space Antenna systems. One such system provides 315 kW of cooling for a capital cost of approximately 200 k€, and annual maintenance cost of 10 k€. It might be possible to share such a system between several SKA dishes. ESA are also very concerned about reliability, so this approach is probably worthy of further study.

Figure 4-2  315 kW Water Chiller Plant at the ESA Deep Space Antenna located at Cebreros, Spain
5. COST ANALYSIS

5.1 SKA System Cost

Full costing of the SKA System is a long and difficult process, which is still being undertaken by the international SKA office. For the purposes of this report some simple assumptions will be adopted. The simple Excel cost model supplied with the report allows the user to vary some of these and other input assumptions and view the modelled consequences for the SKA system cost. The basic assumptions are as follows.

- Total system capital cost for the SKA Dish Array will be 1000 M€
- Annual running cost will be 100 M€
- Electricity cost will be 0.25 €/kWHR
- The Dish Array will operate for 30 years

Note that these cost assumptions are used in order to make comparisons between the various cryogenic cooling options that could be employed in the SKA Dish Array; they are not meant to be accurate cost estimates for budgeting purposes.

5.2 Number of dishes in the SKA Dish Array

For the purposes of this study the overall sensitivity of the SKA Dish Array is assumed to be 10,000 m²K⁻¹. Using the expressions in section 2.2 we can calculate the required number of dishes for any given level of cryogenic cooling. Some examples are shown in Table 5-1, assuming 70% aperture efficiency.

<table>
<thead>
<tr>
<th>Cryogenic Temperature K</th>
<th>System Noise Temp K</th>
<th>No. of Dishes N_D</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>20</td>
<td>1623</td>
</tr>
<tr>
<td>50</td>
<td>22</td>
<td>1746</td>
</tr>
<tr>
<td>80</td>
<td>24</td>
<td>1967</td>
</tr>
<tr>
<td>100</td>
<td>27</td>
<td>2174</td>
</tr>
<tr>
<td>(300)</td>
<td>53</td>
<td>4281</td>
</tr>
</tbody>
</table>

Table 5-1 Estimated number of SKA dishes for various cooling options
5.3 Cryogenics hardware cost

Five options will be considered as follows.

1. Cooling to 15 K using Low cost GM coolers at the minimum possible cost.
2. Cooling to 15 K using High cost GM coolers (similar to existing systems)
3. Cooling to 50 K using a high power Stirling cooler
4. Cooling to 80 K using a medium power Stirling cooler
5. Cooling to 100 K using a low power Stirling cooler

Significant R & D would also be required to produce Stirling coolers with performance optimized for SKA requirements. For the purposes of this study it has been assumed that this development would be funded separately.

Approximate estimates of hardware costs in each case are given in Table 5-2.

<table>
<thead>
<tr>
<th>System</th>
<th>Hardware needed</th>
<th>Cost estimate (per front end assuming 5 front ends per dish) k€</th>
<th>Basis of estimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>15 K GM</td>
<td>Cold head, compressor (0.5 per cold head), helium pipes, vacuum pump (1 per dish), heat rejection equipment (e.g. chiller)</td>
<td>13 to 31</td>
<td>Previous purchase</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 (solid) to 3 (vac)</td>
<td>Previous purchase</td>
</tr>
<tr>
<td>50 K Stirling</td>
<td>500 W Stirling cooler, power supply, heat rejection system</td>
<td>20</td>
<td>Estimate</td>
</tr>
<tr>
<td>80 K Stirling</td>
<td>200 W Stirling cooler, power supply, heat rejection system</td>
<td>15</td>
<td>Estimate</td>
</tr>
<tr>
<td>100 K Stirling</td>
<td>100 W Stirling cooler, power supply, heat rejection system</td>
<td>10</td>
<td>Previous purchase</td>
</tr>
</tbody>
</table>

Table 5-2 Estimates of cryogenic hardware costs for the SKA

5.4 Cryogenic maintenance

Maintenance assumptions are shown in Table 5-3 and estimates of 30 year maintenance costs are in Table 5-4.
<table>
<thead>
<tr>
<th>System</th>
<th>Replacement parts over 30 yrs</th>
<th>Maintenance manpower over 30 years</th>
<th>Estimated cost per front end (assuming 5 front ends per dish)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15 K GM</td>
<td>20 cold head replacements, replacement helium pipes, 2 replacement vacuum pumps, heat rejection system?</td>
<td>80 man days cold heads, 6 man days helium pipes, 2 man days vacuum pumps</td>
<td>Cold head repair (service) between 2 and 4k€, He pipes pair ~1.5k€, man day (eng)~750 €, heat rejection system (depends on cooler) if harsh environment, might need replacement every 5-10 years, + yearly maintenance</td>
</tr>
<tr>
<td>50 K Stirling</td>
<td>2 cooler replacements, 2 power supply replacements, heat rejection system?</td>
<td>4 man days coolers, 2 man days power supplies</td>
<td>cost is new cooler, no service</td>
</tr>
<tr>
<td>80 K Stirling</td>
<td>2 cooler replacements, 2 power supply replacements, heat rejection system?</td>
<td>4 man days coolers, 2 man days power supplies</td>
<td>cost is new cooler, no service</td>
</tr>
<tr>
<td>100 K Stirling</td>
<td>2 cooler replacements, 2 power supply replacements, heat rejection system?</td>
<td>4 man days coolers, 2 man days power supplies</td>
<td>cost is new cooler, no service</td>
</tr>
</tbody>
</table>

Table 5-3 SKA cryogenic maintenance estimates

<table>
<thead>
<tr>
<th>System</th>
<th>30 yr manpower per operational Dewar k€</th>
<th>30 yr parts per operational Dewar k€</th>
<th>30 yr maintenance per Dewar k€</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low cost 15 K GM</td>
<td>44</td>
<td>72</td>
<td>116</td>
</tr>
<tr>
<td>High cost 15 K GM</td>
<td>44</td>
<td>122</td>
<td>166</td>
</tr>
<tr>
<td>50 K Stirling</td>
<td>3</td>
<td>80</td>
<td>83</td>
</tr>
<tr>
<td>80 K Stirling</td>
<td>3</td>
<td>40</td>
<td>43</td>
</tr>
<tr>
<td>100 K Stirling</td>
<td>3</td>
<td>20</td>
<td>23</td>
</tr>
</tbody>
</table>

Table 5-4 Estimates of 30 yr maintenance costs per Dewar
5.5 Electricity cost for cryogenics

Estimates of 30 year electricity consumption and costs per Dewar for various cooling options are in Table 5-5. This assumes an electricity cost of 0.25 €/kWh and continuous operation for 30 years. There is no allowance for inflation: an annual rate of 2 % would add about a third to the overall cost, 3 % would add about a half, and 5 % would more than double the overall cost.

The full cost of electricity for the Dish Array cryogenics will depend very much on the operating regime that is chosen. As discussed in section 3.4 the use of solid insulation together with a soft vacuum, or low thermal conductivity gas, will allow for the intermittent cooling of SKA Dish Array front ends without the need for vacuum pumps. This opens up the possibility that SKA Dish Array front ends could be cooled on demand, so that only the Dewar needed for the current observation frequency need be powered at a given time. Given that there may be as many as 5 Dewars per dish this could reduce the electricity cost by up to 80 % as compare to the cost of continuously running all Dewars, as is common practice on existing radio telescopes. In practice the saving will probably be somewhat less than this because of the need to cool a second Dewar in readiness for a frequency change.

<table>
<thead>
<tr>
<th>System</th>
<th>Power consumption per front end</th>
<th>30 yr cost per Dewar k€</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low cost 15 K GM</td>
<td>3.5 kW (compressor + cold head + heat rejection)</td>
<td>230</td>
</tr>
<tr>
<td>High cost 15 K GM</td>
<td>5 kW (compressor + cold head + heat rejection)</td>
<td>329</td>
</tr>
<tr>
<td>50 K Stirling</td>
<td>500 W Stirling cooler, power supply, heat rejection system</td>
<td>33</td>
</tr>
<tr>
<td>80 K Stirling</td>
<td>200 W Stirling cooler, power supply, heat rejection system</td>
<td>13</td>
</tr>
<tr>
<td>100 K Stirling</td>
<td>100 W Stirling cooler, power supply, heat rejection system</td>
<td>7</td>
</tr>
</tbody>
</table>

Table 5-5 Estimates of 30 yr electricity costs for SKA Dish Array Dewars

Total system costs can be estimated on the basis of the performance assumptions described in section 2.2. These are summarised in Table 5-6.
5.6 Logistical Engineering

Operation of an array of thousands of radio astronomy dishes will inevitably be complex and will require a great deal of planning and organisation. As far as the cryogenics are concerned there will need to be a well thought out system to procure, store and transport all the necessary spare parts. Failed or worn-out parts will also need to be disposed of or refurbished. Staff will need to be recruited and trained to carry out repairs and routine maintenance (if required), and possibly refurbishment of equipment. Recruitment and training will be an ongoing process, as staff turnover is likely to be significant for the remote location of the SKA Dish Array. For the purposes of this study, which aims mainly to compare the costs and benefits of different cryogenic cooling options and suggest the best options to be pursued further, a simplistic approach has been taken to costing manpower to maintain the cryogenics systems.

5.7 Total cost of ownership

Total cost of ownership of the cryogenics for the SKA Dish Array depends on the sum of the capital cost together with the operation and maintenance costs over the lifetime of the array, here assumed to be 30 years. Accurate estimates of cost are not possible at this stage of the project as detailed designs do not exist and there are many unknowns, such as manpower costs and especially the cost of electrical power. However, it is possible to make meaningful comparisons between the various technological options that we have considered in this report, and the cost estimates should give a reasonable indication of the order of costs involved.

As stated above it is important to remember that the cost of the cryogenics system, though undoubtedly very significant, is only a part of the overall cost of the Dish Array. Costs of infrastructure, signal transport, signal processing and computing all depend heavily on the number of dishes in the array. These costs are not analysed in this report, but their effect will be to push the chosen design for the Dish Array towards a solution involving a minimum number of dishes.
Figure 5-1 shows a comparison of estimated costs per Dewar for four of the example cooling options considered above. The high cost GM option (based on the traditional radio astronomy approach) is omitted since it is sufficiently impractical for the SKA to be ruled out even at this preliminary stage.

![30 year costs per operational Dewar](image)

**Figure 5-1 Comparison of 30 year cost per Dewar**

Figure 5-1 immediately highlights an important feature of the difference between GM and Stirling coolers, namely power efficiency. Use of GM coolers will require vastly more electrical power than the use of Stirling coolers, albeit providing lower LNA temperatures. Over the lifetime of the system the cost of electricity would dominate the cost of a cryogenics system based on GM coolers, whereas for Stirling coolers most of the cost is likely to be in hardware as illustrated in Figure 5-2. These charts have been produced using an assumed cost of 0.25 € per kWHr of electricity; this is thought to be towards the minimum that will have to be paid by the SKA, and at the time of preparing this report there is a great deal of uncertainty as to the cost of electricity for the SKA over its lifetime. Thus the choice of technology whose cost is dominated by electricity use would carry significant financial risk. The sensitivity of system cost to electricity cost variation is illustrated in Annex 7.2.

![Low cost 15 K GM and 80 K Stirling](image)

**Figure 5-2: 30 year cost breakdown per Dewar for GM and 80 K Stirling**

Overall cryogenic system cost of ownership for the SKA Dish Array will depend significantly on the operating strategy employed. On existing radio astronomy arrays it is normal practise to operate all
Dewars continuously. This allows the array operator to switch rapidly between feeds operating in different frequency bands. The alternative would be to cool a Dewar only when it was required for observations; for a traditional GM high vacuum scheme this would require some sort of automated vacuum pumping arrangement to allow the Dewar to be cooled in preparation for use ahead of the time when it was needed. Typically a Dewar might take 12 to 24 hours to cool to its operating temperature. Whilst such a system is feasible, it would be relatively complex, requiring a vacuum system that could cope with the full range of motion of the dish and equipped with multiple remotely controlled valves.

As described in section 3.4 the advent of low vacuum Dewars with solid insulation opens up the possibility to cool a Dewar ‘on demand’ without the need for a vacuum pump. Callisto has obtained cool down times of two hours or less with Stirling coolers operating in this way. Hence, this opens up the possibility of a relatively simple scheme where only one Dewar at a time is cooled on a dish: the result could be a huge saving in electricity cost.

For the purpose of this report we assume two extreme cases: one where 5 Dewars are continuously cooled for 30 years, and the other where only one Dewar is cooled at a time. It is recognized that both of these cases are artificial, since the former case does not account for inevitable ‘down-time’, and the latter does not allow for times when a second Dewar is being cooled in readiness for a frequency band change. However, these extreme cases will serve to estimate the range of possible costs of ownership.

Section 5.1 sets out the SKA full system costs for the Dish Array as 1,000 M€ capital, and 100 M€ operating cost per annum. Thus the total funding available for 30 years is assumed to be 4,000 M€. Estimated cost of ownership, based on 5 Dewars per dish operating continuously, is shown in Table 5-7. There is no allowance for inflation in these estimates, and it is worth re-iterating that over a 30 year lifetime an annual rate of 2 % would add about a third to the overall cost, 3 % would add about a half, and 5 % would more than double the overall cost. The high cost GM option is not considered in the following analyses.
Table 5-7: 30 years estimated cryogenics cost in M€: 5 operational Dewars per dish

An equivalent estimate based on operating only one Dewar at a time on each dish is shown in Table 5-8. Here the capital cost is unchanged, since the assumption is that 5 Dewars will still be needed to cover the frequency range, but maintenance and electricity costs are assumed to be one fifth. This is an over simplification: maintenance costs are likely to be higher than this, as some degradation will occur even in Dewars that are not operating and the on-off cycling will also reduce reliability to some extent. Hence, this estimate is included to set a lower bound to the expected range of ownership costs.
<table>
<thead>
<tr>
<th></th>
<th>Low cost 15 K GM</th>
<th>50 K Stirling</th>
<th>80 K Stirling</th>
<th>100 K Stirling</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Tsys</strong></td>
<td>20</td>
<td>22</td>
<td>24</td>
<td>27</td>
</tr>
<tr>
<td><strong>N_o</strong></td>
<td>1620</td>
<td>1741</td>
<td>1962</td>
<td>2169</td>
</tr>
<tr>
<td><strong>capital cost</strong></td>
<td>162</td>
<td>348</td>
<td>196</td>
<td>108</td>
</tr>
<tr>
<td><strong>manpower</strong></td>
<td>71</td>
<td>5</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td><strong>parts</strong></td>
<td>117</td>
<td>139</td>
<td>78</td>
<td>43</td>
</tr>
<tr>
<td><strong>electricity</strong></td>
<td>532</td>
<td>57</td>
<td>26</td>
<td>14</td>
</tr>
<tr>
<td><strong>total</strong></td>
<td>882</td>
<td>550</td>
<td>306</td>
<td>173</td>
</tr>
</tbody>
</table>

Table 5-8: 30 years estimated cryogenics cost in M€: 1 operational Dewar per dish

Taking the value of 4,000 M€ for the 30 year budget for the SKA Dish Array, we can now see the proportion of this sum that is estimated to be needed for the cryogenics. Table 5-9 shows the percentage of the overall Dish array 30 year cost of ownership that is estimated to be needed for the cryogenics systems. This table shows that the proportion of the Dish Array budget that could be spent on the cryogenics system could range very widely, from a massively impractical 94 % (i.e. leaving 6 % of the budget to buy dishes, signal transport, signal processing, computers, software and infrastructure) to a very modest 4 %.
Table 5-9: Percentage of 30 years Dish Array cost spent on cryogenics

Of more interest to this study is some indication of the technology choice that would lead to the minimization of the Dish Array cost of ownership. In other words: what is the cryogenics technology choice that will maximize the ‘bang per buck’? This is impossible to determine accurately without knowing the cost of all of the other parts of the Dish Array system (dishes, signal transport, signal processing, computers, software and infrastructure), and these are not available at the time of this study. However, we can make some comparisons of systems, assuming a variety of costs for the system excluding the cryogenics. These are illustrated in Figure 5-3 and Figure 5-4.

Figure 5-3: Overall system cost vs cryo temp: 1 operational Dewar per dish
Various conclusions can be drawn from these simple plots.

1. GM coolers are unlikely to be worthwhile unless they can be operated in the one operational Dewar per dish regime.
2. Operation at temperatures above 100 K is unlikely to be worthwhile unless all five Dewars are required to operate continuously and the cost of 30 year ownership of the Dish Array, excluding cryogenics, is around 1 M€ per dish or lower.
3. For the system costs illustrated (1 to 2 M€ per dish excluding cryogenics) the optimum cryogenic temperature lies somewhere between about 40 K and 100 K for all but the 1 M€/dish 5 operational Dewars case.
4. An increase in the system cost, excluding cryogenics, pushes the design towards lower cryogenic temperature.

5.8 Strategies to minimize system cost

Here we are concerned with minimizing the cost of ownership the complete Dish Array system, including infrastructure, signal transport, signal processing, computing, maintenance, and operating costs including power. It will not be possible to definitively choose the optimum cryogenics technology to minimize the system cost until the costs of the other major components of the system are better known. However, it is possible to suggest strategies that could be used to minimize cost, and to consider various possible scenarios to illustrate these.

5.8.1 Choice of cooling system

Estimated 30 year costs of ownership have been discussed in section 5.7 for four potential cooling options:
There is an underlying assumption that in each case the technology is already well-proven ('new technology' is the subject of Work Package 2) but that significant development work will be carried out over the next few years to optimize performance for the SKA. The options considered are not all-inclusive, but serve as examples that can be used to examine trends. Once the full system costs are more accurately known the chosen solution may well lie at some intermediate temperature.

We suggest that the choice of cooler type lies between Stirling and GM: these are both well-established commercially available technologies, and there is considerable experience of using them in the field. GM has predominantly been the technology of choice for radio astronomy because of its capability to cool front ends to 15 K or lower, whereas Stirling coolers have been used in large numbers in telecommunications. Existing Stirling coolers do not reach as low as 15 K, although there are industry proposals to develop new Stirling coolers to reach lower temperatures, potentially down to 15 K; these are discussed in Work Package 2. In this study we retain the GM option as it would provide the lowest system noise temperature of all the options we have considered, although the operating and maintenance costs of GM hardware are substantially higher than those of the Stirling machines.

It is generally the case that the cost of ownership of the cryogenics will increase with decreasing base temperature, due to an increase in the cost of hardware, higher demand for electricity, and for the GM case higher maintenance manpower cost. Hence, the choice of cryogenic temperature for the SKA Dish Array will negatively correlated with the cost of ownership of the rest of the Dish Array System. If these costs are relatively low then the optimum solution will be a larger number of dishes with higher temperature front ends, conversely if the other system costs are relatively high then the best solution will be fewer dishes with colder front ends. This is illustrated in Figure 5-3 and Figure 5-4.

5.8.2 Choice of vacuum system

The choice of vacuum technology is also crucial to the cost of ownership of the Dish Array system, and also to the choice of cryogenic cooler. Figure 5-4 illustrates the high cost of operating five GM coolers continuously; not only is the estimated cost very high, but it is also very uncertain owing to the unpredictability of future electricity costs (a 5 % inflation rate would more than double this cost). It appears that the only way GM coolers could be affordable for the SKA would be to adopt one or a combination of the following solutions.

- Reduce the number of feeds on each dish.
- Provide an automated vacuum system on each dish such that Dewars can be cooled on demand.
- Use solid insulation/low vacuum in each Dewar such that Dewars can be cooled on demand.

It may be possible to reduce the number of feeds on each dish, if sufficient progress is made in the development of wide band feeds. At the time of this study that is not yet the case; aperture efficiencies obtainable with existing wide band feed designs would be significantly lower than those obtainable with corrugated conical horn type feeds: this would lead to the need for more dishes in the array, and hence higher cost. There are other, potentially even more serious, difficulties in using wide band feeds, as their beam patterns are less well controlled than corrugated conical horns and this could make the SKA’s imaging dynamic range goal harder to achieve.
An automated vacuum system is certainly technically feasible with existing technology. It would however, add significantly to the complexity and cost of the cryogenics system, and would degrade the system reliability to some extent. This option has not been investigated as part of this study, but if it were to be considered as a serious option for the SKA there would be a need for a very thorough investigation, particular of the reliability and maintenance issues.

Solid insulation is probably the best option for multiple GM coolers on an SKA dish as this would remove the need for a complex vacuum system, and still allow the coolers to be operated one at a time.

Solid insulation/low vacuum is also the best existing technology in the event that Stirling coolers are chosen for the SKA; a new alternative using an inert gas at atmospheric pressure is discussed in Work Package 2. The solid insulation/low vacuum approach would allow front ends to be cooled on demand, thus reducing the consumption of electricity and preserving the operational life of the coolers not in use. This approach also simplifies the procedure to replace failed Dewars, since no vacuum pump would be required at the dish.

5.8.3 Design and manufacture for low cost of ownership

Possibly as many as ten to fifteen thousand Dewars will be required for the SKA Dish Array; production on this scale is without precedent in radio astronomy. Design of these Dewars cannot be undertaken in isolation, but must be undertaken with the view to meet the SKA System Requirements in a manner that minimizes system cost of ownership. Money spent on developing the optimum design for the SKA Dish Array could potentially result in enormous savings in overall cost of ownership. Some of the more significant cost-related design features are as follows.

- manufacturing cost
- reliability
- maintainability
- operational lifetime
- power consumption

Manufacturing cost is clearly extremely important, particularly in the case of the Stirling cooler options, where it would have a large impact on the overall cost of ownership, see Figure 5-2 ‘parts’ and ‘capital cost’. However, it would be folly to pursue a low manufacturing cost without paying due attention to all of the other aspects in the list above.

Reliability has a large impact on cost, as well as affecting the usefulness of the Dish Array as a scientific instrument. Dewar failures will require manual intervention, using manpower that may be scarce and will certainly be expensive to employ and train. Maintainability is a related aspect: the SKA Dish Array cryogenics system must be designed to be maintained as easily as possible, using a minimum of manpower and tools. This applies both to routine maintenance tasks and repair of failed equipment. Modular hardware, small in size and low in mass, with simple interfaces should be the design goal.

Operational lifetime will impact the cost of manpower to carry out replacement of worn-out hardware in addition to the cost of the replacement hardware itself. One aspect of this will be to decide how much, if any, refurbishment will be carried out on equipment that has reached the end of its life. Related to this is the cost of disposal, which must also be taken into account at the design stage; disposal of hazardous materials used in manufacture could be expensive.
Power consumption would be the major cost driver if a GM cooling system were adopted, so there would need to be considerable R & D investment to produce a design that was highly optimised from the power consumption point of view. In the case of the Stirling coolers power is not such a big issue, but the uncertainty of future power costs still make the power efficiency an important design feature.

**Figure 5-5 Example Dewar design (not to scale)**

For the purposes of discussing some aspects of the SKA Dish Array cryogenics design Figure 5-5 illustrates a hypothetical example of Dewar that would be mounted at the secondary focus of an SKA dish.

1. **Dewar body**: this should have the smallest volume and mass possible, consistent with meeting other requirements such as reliability, lifetime and cryogenic base temperature. One low-cost manufacturing method would be to turn a cylinder from commercially available aluminium alloy tube and fit end plates with vacuum seals. A drawback of this approach is difficulty of assembly. Rectangular section tube is also available as a standard commercial product, although off the shelf sizes are limited to around 200 x 100 mm; use of rectangular section tube, with flat plate access panels, alleviates the assembly problems associated with the circular cross-section tubing. An alternative could be to make a square-section Dewar from aluminium alloy sheets that are bonded or welded together, with one side accessible for assembly purposes via a vacuum sealed screwed panel. All of these techniques have previously been used on existing radio astronomy and/or satellite ground station Dewars that have been in long-term use.
ii. **Ruggedized waveguide flange:** this would provide the simplest mechanical interface, allowing for rapid installation and removal of the Dewar. Again this approach has been used successfully on existing radio astronomy systems.

iii. **RF, power and monitor connections on Dewar end-plate:** these are the RF outputs (up to 4 per Dewar), calibration input, and LNA bias input and monitor/control interface. Quick release connector options should be investigated to facilitate installation and removal. However, the chosen approach must be consistent with the requirements for reliability and lifetime.

iv. **Controller:** this is the power supply to the cryo cooler. For a GM cooler it would be a simple 2-phase AC supply, which would simply be turned on and off as required. In the case of a Stirling cooler a more sophisticated approach would likely be used, whereby the input power was varied to control the Dewar temperature. This could be used to enhance stability of the OMT and LNAs, and also be used to compensate for cooler long-term deterioration. Unfortunately existing Stirling cryo cooler controllers are a potential source of RFI, so development work is needed to produce a design that is compatible with the SKA.

v. **Cryo cooler inside heat rejecter:** the diagram shows the Stirling cooler arrangement, where the only connection to the cooler is the drive from the controller. Here the main problem, yet to be addressed, is removal of heat from the cooler heat sink. This will be challenging in the SKA environment, particularly when the ambient temperature reaches 50°C. Investigation work is needed. Another potential problem with Stirling coolers is vibration. There has been some work on this, but it too needs to be investigated from the point of view of the SKA Dish Array, where stability will be so important. For the GM cooler case the heat rejection will take place at or near the compressor, which will almost certainly not be mounted at the secondary focus owing to its high mass. Two helium gas lines will connect the Dewar to the compressor; it may be possible to run multiple coolers from one compressor in which the number of long helium lines may be reduced by using gas manifolds. The ultimate heat rejection from the GM system, whilst potentially easier than for the Stirling cooler, nevertheless needs careful design to ensure that reliability and lifetime requirements are met.
6. CONCLUSIONS AND RECOMMENDATIONS

6.1 Choice of technology

It is not yet possible to decide which set of technological options will be the best for the SKA Dish Array. This is because the costs of the full Dish Array system are not yet known to sufficient accuracy. Cost modelling carried out for this study suggests that the optimum solution is likely to be use of Stirling cycle coolers with solid insulation and low vacuum. However, if the other major components of the Dish Array turn out to be much more expensive than was assumed in the modelling, and the cost of electricity is expected to be relatively low, then the optimum solution might turn out to be GM, probably again with solid insulation and low vacuum. If a dish size greater than 15 metres were adopted this would also favour the use of GM coolers. However, given the likely high cost of electrical power it is unlikely that the SKA will ever be able to afford to operate multiple GM coolers simultaneously on dishes.

The SKA Dish Array Concept Design Review Panel made the following recommendation [RD3].

'Recommendation 7: Institute a concerted engineering program to address the challenges related to use of cryogenic receiver systems in the SKA'

They went on to say that, ‘This program could work in concert with the development of prototype receivers…’.

We consider that Stirling cycle systems should be a prominent part of this work, but that GM options should also be addressed unless and until it can be conclusively determined that they will not be needed for the SKA Dish Array.

6.2 Programmes of investigation

It is clear that the design of the cryogenics for the SKA Dish Array will have a major impact on the cost of ownership of the full system. Therefore it is vital for the success of the SKA that sufficient high quality resources are brought to bear on the necessary development activities. Failure to invest sufficiently in the design and development of cryogenics will result in excessive cost and technical under-performance later in the project. As suggested in RD3 there will be need to co-ordinate some of the cryogenic development activities with development work on other aspects of the Dish Array front ends, for example the OMTs and LNAs.
<table>
<thead>
<tr>
<th>No.</th>
<th>Development area</th>
<th>Goals</th>
<th>Organization</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Optimization of Stirling cryocoolers for the SKA</td>
<td>Reduction of base temperatures</td>
<td>These tasks should be undertaken by existing cryocooler manufacturers in consultation with SKA Dewar designers.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Maximum power efficiency</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Maximum lifetime</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Maximum reliability</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>RFI quiet controllers</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Low vibration</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Stirling cooler heat rejection</td>
<td>Efficient cooling of Stirling cryocoolers in the SKA environment</td>
<td>This work should be carried out in consultation with cryocooler manufacturers, as well as SKA Dewar and dish designers.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(leading to lowest possible base temperatures and highest reliability)</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Solid insulation/low vacuum Dewars</td>
<td>Long, maintenance-free, lifetime.</td>
<td>This task should be carried out in consultation with SKA Dewar designers, taking account of the RF design parameters of the SKA front ends (e.g. waveguide and OMT dimensions).</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Multiple warm up and cool down cycles over the lifetime of the cryocooler without the need for a vacuum pump.</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Infra red filters for input waveguides</td>
<td>Maximum reduction of IR heat load on the cryocooler</td>
<td>Initial investigations can be carried out independently. Successful solutions will be inputs to SKA Dish Array Dewar designs.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Minimum RF attenuation</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Optimization of GM cryocoolers for the SKA</td>
<td>Maximum power efficiency</td>
<td>These tasks should be undertaken by existing cryocooler manufacturers in consultation with SKA Dewar designers.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Maximum lifetime</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Maximum reliability</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Lowest maintenance cost</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>GM cooler heat rejection</td>
<td>Efficient, long life and reliable heat rejection from GM cryocoolers in the SKA environment (leading to lowest possible operating</td>
<td>This work should be carried out in consultation with GM cryocooler manufacturers, as well as SKA dish designers.</td>
</tr>
<tr>
<td></td>
<td>Dewar design investigations including electrical and mechanical interfaces.</td>
<td>Low cost of manufacture</td>
<td>This task needs to be co-ordinated with the work of various other contributors to the SKA Dish Array design concerned with the dish, cryocoolers, feeds, low noise front ends, and solid insulation.</td>
</tr>
<tr>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>7</td>
<td></td>
<td>Maximum lifetime</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Maximum reliability</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Low maintenance cost</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Low mass and volume</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Low loss RF input</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Efficient thermal design</td>
<td></td>
</tr>
</tbody>
</table>
7. ANNEXES

7.1 Cost model

A simple Excel Spreadsheet cost model has been produced as part of this study with the aim of informing decisions on the choice of cryogenics technology. It is not intended to be used to make accurate cost estimates relating to the SKA Dish Array. The model estimates a 30 year lifetime cost of the cryogenics, including capital cost, maintenance parts, maintenance manpower, and electrical power. There is no specific estimate of the infrastructure needed for maintenance (stores, transport etc.), but an allowance for these costs can be included in the estimates for the spare parts. Estimates of system noise temperatures associated with various cryogenic base temperatures are made using the principles discussed in section 2.2, and the user can vary the input assumptions. Other inputs are as follows.

- Overall system sensitivity
- Dish diameter
- Aperture efficiency
- System 30 year cost per dish (excluding cryogenics)
- Number of Dewars per dish
- Mean cost of electricity per kWhr over the 30 year life
- Capital cost per Dewar
- 30 year maintenance parts cost per operational Dewar
- 30 year maintenance manpower per operational Dewar
- Power consumption per Dewar
- Manpower cost per annum
- Manpower days worked per annum

The cost model allows the user to estimate the 30 year cost of the cryogenics system and the cost of the overall SKA Dish Array for the case where only one Dewar per dish is operational at any given time and for the case where all Dewars on all dishes are operated continuously.

Sensitivity plots are included that show the variation of the modelled 30 year system cost when the following parameters are individually varied with all other input parameters held constant.

- Electricity cost
- Aperture efficiency of the dish
- Non cryogenic system cost per dish (i.e. the cost of everything except the cryogenics)
- Antenna noise temperature

In practise the antenna noise temperature sensitivity plot shows the effect of noise temperature change on system cost, whatever the source of that noise temperature change, e.g. an improved LNA.
7.2 Sensitivity plots derived from the simple cost model

The following example sensitivity plots were obtained with the inputs to the cost model set as follows.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall system sensitivity:</td>
<td>10000 sq m per K</td>
</tr>
<tr>
<td>Dish diameter:</td>
<td>15 m</td>
</tr>
<tr>
<td>Aperture efficiency:</td>
<td>70 %</td>
</tr>
<tr>
<td>System 30 yr cost per dish (excl. cryo):</td>
<td>1.5 M€</td>
</tr>
<tr>
<td>Dewars per dish</td>
<td>5</td>
</tr>
<tr>
<td>Mean electricity cost per kWHr</td>
<td>0.25 €</td>
</tr>
<tr>
<td>$T_{\text{LNA}}$ at 15 K:</td>
<td>5 K</td>
</tr>
<tr>
<td>scaling:</td>
<td>1400 dB</td>
</tr>
<tr>
<td>WG loss:</td>
<td>0.05 dB</td>
</tr>
<tr>
<td>OMT loss:</td>
<td>0.2 dB</td>
</tr>
<tr>
<td>Antenna noise:</td>
<td>15 K</td>
</tr>
</tbody>
</table>
System 30 yr cost sensitivity to electricity cost (1 Dewar per dish)

System 30 yr cost sensitivity to electricity cost
(all Dewars operational)
System 30 yr cost sensitivity to aperture efficiency
(1 Dewar per dish)

System 30 yr cost sensitivity to aperture efficiency
(all Dewars operational)
Note: ‘non cryo cost’ refers to all costs associated with the dish array except the cryogenics.
System 30 yr cost sensitivity to antenna noise temp
(1 Dewar per dish)

System 30 yr cost sensitivity to antenna noise temp
(all Dewars operational)
7.3 Manufacturers’ data

A vast array of manufacturers’ data is available on the internet; a few selected examples of existing cryocooler technology are shown below.

7.3.1 Superconducting Technologies Inc.: Sapphire Stirling Cryocooler

7.3.2 Thales Cryogenics: Stirling coolers

Linear Stirling Flexure bearing Cryocoolers

The result of many years of fundamental and experimental research have been condensed into state of the art design of a very reliable miniature Stirling cooler, combining two technical breakthroughs, flexure bearings and moving magnets.

These two breakthroughs have resulted in an extremely reliable cryocooler, without sacrificing other important aspects such as affordability, compactness and weight. Flexure bearings allow for movement of the compressor pistons in axial direction, yet it features very high stiffness in the radial direction thus avoiding contact between piston and cylinder wall. This results in extremely long lifetimes, proven by lifetime tests. In these tests almost all coolers are still running well within specification after at least 20,000 operational hours.

The design of the correct flexure geometry is critical. Dedicated Finite Element Modeling techniques have been used to optimize the design and to ensure that the fatigue stress levels of the material are never exceeded. Mounting of the flexure is performed using a patented assembly procedure. The use of stationary coils and moving magnets has removed several common cryocooler failures. As the coils are placed outside the helium working gas, there is no contamination of the working gas due to potential outgassing and there is no need to use vulnerable hermetic head throughs. On top of that, the use of moving magnets implies that there are no flying leads between the coil and the stationary world.

Thales Cryogenics LSF-range of coolers has proven to provide excellent performance under extreme conditions, combining a long life operation with affordability. This provides the perfect cooling solution for highly demanding applications such as constant surveillance, space and aircraft. As in the UF-LS series, the LSF coolers can be combined with several tree displacer cold fingers, in both closed cold finger design and in dedicated DCA design, offering the user the ability to choose the right finger in terms of cooling power and mechanical requirements.
<table>
<thead>
<tr>
<th>Type number</th>
<th>LSF 99XX</th>
<th>LSF 95XX</th>
<th>LSF 91XX</th>
<th>LSF 93XX</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 mm</td>
<td></td>
<td></td>
<td></td>
<td>LSF 9580</td>
</tr>
<tr>
<td></td>
<td></td>
<td>40 W</td>
<td>800 mW</td>
<td>40 W</td>
</tr>
<tr>
<td>7 mm</td>
<td></td>
<td></td>
<td></td>
<td>LSF 9180</td>
</tr>
<tr>
<td></td>
<td>LSF 9587</td>
<td>40 W</td>
<td>1100 mW</td>
<td>40 W</td>
</tr>
<tr>
<td>10 mm</td>
<td></td>
<td>LSF 9588</td>
<td></td>
<td>LSF 9188</td>
</tr>
<tr>
<td></td>
<td></td>
<td>60 W</td>
<td>1850 mW</td>
<td>60 W</td>
</tr>
<tr>
<td>13 mm</td>
<td></td>
<td>LSF 9589</td>
<td></td>
<td>LSF 9189</td>
</tr>
<tr>
<td></td>
<td></td>
<td>80 W</td>
<td>2300 mW</td>
<td>90 W</td>
</tr>
<tr>
<td>20 mm</td>
<td></td>
<td></td>
<td></td>
<td>LSF 9320</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>150 W</td>
</tr>
<tr>
<td>20 mm</td>
<td></td>
<td></td>
<td></td>
<td>LSF 9340</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>170 W</td>
</tr>
<tr>
<td>1/4&quot;</td>
<td>LSF 9997</td>
<td>LSF 9597</td>
<td>LSF 9197</td>
<td></td>
</tr>
<tr>
<td></td>
<td>16 W</td>
<td>45 W</td>
<td>45 W</td>
<td></td>
</tr>
<tr>
<td>8 mm</td>
<td></td>
<td>LSF 9508</td>
<td></td>
<td>LSF 9108</td>
</tr>
<tr>
<td></td>
<td></td>
<td>50 W</td>
<td>1500 mW</td>
<td>50 W</td>
</tr>
<tr>
<td>9 mm</td>
<td></td>
<td>LSF 9548</td>
<td></td>
<td>LSF 9148</td>
</tr>
<tr>
<td></td>
<td></td>
<td>55 W</td>
<td>1800 mW</td>
<td>55 W</td>
</tr>
<tr>
<td>1/2&quot;</td>
<td></td>
<td>LSF 9599</td>
<td></td>
<td>LSF 9199</td>
</tr>
<tr>
<td></td>
<td></td>
<td>80 W</td>
<td>2300 mW</td>
<td>90 W</td>
</tr>
</tbody>
</table>

7.3.3 Sunpower: Stirling coolers

Today, Sunpower sells the CryoTel® family of cryocoolers with a variety of configurations at a low price for diverse array of applications. A number of customer-specific models have also been developed.

<table>
<thead>
<tr>
<th>CryoTel® Model</th>
<th>MT</th>
<th>CT</th>
<th>GT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ambient Operation</td>
<td>-40°C to 60°C</td>
<td>-40°C to 60°C</td>
<td>-40°C to 60°C</td>
</tr>
<tr>
<td>Orientation</td>
<td>any</td>
<td>any</td>
<td>any</td>
</tr>
<tr>
<td>Nominal Cooler Input Power</td>
<td>80 Watts</td>
<td>160 Watts</td>
<td>240 Watts</td>
</tr>
<tr>
<td>Power Supply</td>
<td>DC 24 V/DC48V</td>
<td>DC 24 V</td>
<td>DC 48V</td>
</tr>
<tr>
<td>Performance</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nominal Lift at 77 K (35°C reject)</td>
<td>5 Watts</td>
<td>10 Watts</td>
<td>15 Watts</td>
</tr>
<tr>
<td>No Load Temperature (35°C reject)</td>
<td>40K</td>
<td>35 K</td>
<td>35K</td>
</tr>
<tr>
<td>Cooler Mass</td>
<td>2.1 kg</td>
<td>3.1 kg</td>
<td>3.1 kg</td>
</tr>
<tr>
<td>Operating Frequency</td>
<td>60 Hz</td>
<td>60 Hz</td>
<td>60 Hz</td>
</tr>
<tr>
<td>Temperature Stability</td>
<td>± 0.1K</td>
<td>± 0.1K</td>
<td>± 0.1K</td>
</tr>
<tr>
<td>Skin Drawing</td>
<td>pdf</td>
<td>pdf</td>
<td>pdf</td>
</tr>
<tr>
<td>Performance Curve</td>
<td>pdf</td>
<td>pdf</td>
<td>pdf</td>
</tr>
</tbody>
</table>

7.3.4 QDrive: Stirling cooler

Cryocoolers - 2S132K-FAR

Product Description

We are proud to introduce the new coaxial-head 2S132K - our workhorse miniature model cryocooler. It is driven by our 2S132W TwinSTAR PWG, and is provides over 20 Watts cooling at 77 Kelvin. The 2S132K uses an improved acoustic-Stirling ("pulse-tube") coldhead, with lower mass and smaller diameter. We offer the anodized aluminum motor body shown or optional welded stainless steel. The remote head is also an option (see 'Options' link for full list, build your ideal configuration).

The 2S132K is ideal for laboratory, table-top, and other space-limited, cost-sensitive cryogenic cooling applications, as it can operate in any orientation. Such uses include:

- Instrument and Detector Cooling
- Superconducting Circuit Cooling
- Biological Sample Freezing & Preservation
- Microscopy and Materials Research

General Specifications

- Height: 458 mm
- Length: 312 mm
- Width: 146 mm
- Weight: 21.7 kg
- Cooling Capacity (@77K): 22 W
- Voltage @ Rated Conditions: 90 V 10
- Input Power @ Rated Conditions: 550 W
- Voltage Maximum: 95 V 10
- Input Power Maximum: 600 W
- AC Frequency: 60 Hz
- Ambient Operating Temperature: 0°C - 40°C
- Internal Operating Pressure: 27 bar

For Enquiries, Contact us at:
CFIC-QDRIVE
302 Tenth St, Troy, N.Y. 12180
Ph: 518-272-3565, Fax: 518-272-3582
Email: info@qdrive.com
http://www.qdrive.com
7.3.5 Sumitomo Heavy Industries: GM Cryocoolers

The 10K cryocooler technology powers our product range of shield coolers, laboratory cryostats and cryopumps. The entire series of bare, 2-stage, 10K refrigerators are also available for user interface into a wider range of applications, such as radio astronomy and unique custom design.

The first generation of 10K cryocoolers was developed by Dr. Ralph Longsworth and his team over 40 years ago for the original Displex laboratory cryostats and the APD-range of cryopumps.

In the 1980's both SHI and APD launched higher capacity 10K coolers for the cryopump market in Japan and for diagnostic imaging systems in Europe. In 1983, the engineering team at APD developed the Metric series of cryocoolers, which are employed in the Marathon Cryopump range, offering higher capacities in demanding applications.

Today, to satisfy customer's demands of 1st stage cooling capacity in the MRI industry, Longsworth and Bruce Sloan have developed the latest 10K cooler, the CH-210, boasting 110W @ 77K.

### 10K Cryocooler Specification Chart

<table>
<thead>
<tr>
<th>Watts @ 50 Hz</th>
<th>Watts @ 60 Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st Stage Capacity</td>
<td>2nd Stage Capacity</td>
</tr>
<tr>
<td>CH-200-M (6.5K)</td>
<td>N/A</td>
</tr>
<tr>
<td>RDH-400S (5.5K)</td>
<td>30 W @ 45 K</td>
</tr>
<tr>
<td>CH-202</td>
<td>7.2 W @ 77 K</td>
</tr>
<tr>
<td>CH-204</td>
<td>12.5 W @ 90 K</td>
</tr>
<tr>
<td>CH-208R</td>
<td>95 W @ 77 K</td>
</tr>
<tr>
<td>CH-208L</td>
<td>20 W @ 77 K</td>
</tr>
<tr>
<td>CH-210</td>
<td>110 W @ 77 K</td>
</tr>
<tr>
<td>RDH-400E</td>
<td>54 W @ 40 K</td>
</tr>
<tr>
<td>CH-104</td>
<td>34 W @ 77 K</td>
</tr>
<tr>
<td>CH-110</td>
<td>175 W @ 77 K</td>
</tr>
</tbody>
</table>

Specifications subject to change without notice.

# LIST OF ABBREVIATIONS

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>AD</td>
<td>Applicable Document</td>
</tr>
<tr>
<td>AIL</td>
<td>Action Item List</td>
</tr>
<tr>
<td>AM</td>
<td>Amplitude Modulation</td>
</tr>
<tr>
<td>AZ</td>
<td>Azimuth</td>
</tr>
<tr>
<td>CDR</td>
<td>Critical Design Review</td>
</tr>
<tr>
<td>DC</td>
<td>Direct Current</td>
</tr>
<tr>
<td>ESA</td>
<td>European Space Agency</td>
</tr>
<tr>
<td>ICD</td>
<td>Interface Control Document</td>
</tr>
<tr>
<td>IF</td>
<td>Intermediate Frequency</td>
</tr>
<tr>
<td>k</td>
<td>Boltzman’s Constant</td>
</tr>
<tr>
<td>K</td>
<td>Kelvin</td>
</tr>
<tr>
<td>LNA</td>
<td>Low Noise Amplifier</td>
</tr>
<tr>
<td>MTBF</td>
<td>Mean Time Between Failure</td>
</tr>
<tr>
<td>NF</td>
<td>Noise Figure</td>
</tr>
<tr>
<td>PC</td>
<td>Personal Computer</td>
</tr>
<tr>
<td>QoS</td>
<td>Quality of Service</td>
</tr>
<tr>
<td>RD</td>
<td>Reference Document</td>
</tr>
<tr>
<td>RF</td>
<td>Radio Frequency</td>
</tr>
<tr>
<td>SKA</td>
<td>Square Kilometre Array</td>
</tr>
<tr>
<td>SoW</td>
<td>Statement of Work</td>
</tr>
<tr>
<td>TBC</td>
<td>To Be Confirmed</td>
</tr>
<tr>
<td>TBD</td>
<td>To Be Defined</td>
</tr>
<tr>
<td>WO</td>
<td>Work Order</td>
</tr>
<tr>
<td>WP</td>
<td>Work Package</td>
</tr>
</tbody>
</table>