SKA Concept Designs (whitepapers)
ISAC Comments, November 1, 2002

Executive Summary

We summarize the scientific review of the SKA white paper design concepts presented in Groningen, 2002. The detailed review as a function of SKA design and level 1 science program can be found in matrix form at:

http://www-astro.physics.ox.ac.uk/~sr/ska/ska_matrix.html

The scientific working groups are in the process of refining this matrix, and we have invited the proposers of the SKA designs to participate in the process.

The ISAC has identified four issues that appear paramount to the review process at this time: high and low frequency limits, multibeaming and response times, configuration, and field of view. There was general agreement within the scientific working groups that reasonable compromises can be reached on the issues of configuration and field of view. The ISAC (like the EMT) recognized that full-sky multibeaming must come at the expense of the high frequencies. If it came to a trade between the two, the majority of the ISAC feels that high frequencies would take priority over multibeaming, although the novelty and practicality of multibeaming remains very attractive. Again like the EMT, the ISAC recommends the designers consider hybrid solutions which include multibeaming capabilities at low frequencies.

1 Introduction

Whitepaper design concepts for the Square Kilometer Array (SKA) were submitted to the International SKA Steering Committee (ISSC) for review in June 2002. The review process entailed detailed consideration of the designs by the Engineering Management Team (EMT) and the International Science Advisory Committee (ISAC). These reviews are preparatory to the design down-selection process, and eventual final design selection, by the ISSC. This document is the final report of the ISAC to the ISSC concerning our review of the white paper designs.

We would like to emphasize at the start that the science case, and the compliance matrix, are under active revision. The opinions expressed in this review are based primarily on ISAC discussions in Berkeley (July 2001), Bologna (Jan 2002), and Groningen (Aug 2002), plus a review of previous documentation (Taylor & Braun 1998 and Amsterdam SKA meeting 1999), and some intensive efforts via email and telecon in July 2002. There is a consensus within the ISAC that a number of scientific areas (eg. solar system science) are clearly incomplete, and that for such a large project, input from a wider community (ie. non-radio astronomers) is fundamental to determining the optimum SKA design requirements. Also, we need to clarify what is meant by level-1 science, with some attempt at overall prioritization. We are in the process of revising the science case along these lines, and hope to have a more complete and current document by August 2004.

The contents of this document are as follows:
Section II summarizes the review process prior to the Groningen meeting, then presents the review matrix in more detail.
Section III describes the four primary questions that arose from the review process, and the discussion of these questions in Groningen.
Section IV gives some general remarks, and an outline for proposed future ISAC activities.
Sections V-IX The appendices present some of the material from the preliminary review process.

2 The Matrix

2.1 Generating the compliance matrix

The time between the appointment of Carilli (CC) and Rawlings (SR) as chair and vice-chair of the ISAC and the Groningen meeting was limited. Also, more than half the science working groups were without chairs. The first order of business was to fill these positions. The current list of ISAC membership, working groups, and working group chairs is given in Appendix 3.

The ISAC then reviewed all the available material relevant to the science case for the SKA. Although the existing case is compelling, it was clear that potential level-1 science areas were missing from the reports produced by the Working Groups at the SKA Bologna meeting. Given the limited time, it was decided that our initial evaluation of the White-Paper designs would be limited to the level-1 science areas identified at the Bologna meeting.

The nine working groups were given the task of determining the requirements on SKA design demanded by the level-1 science topics in their area, and then matching these against the capabilities of the seven White-Paper design concepts. In a few cases, the Working Groups promoted topics designated level-2 at Groningen to level-1. To guide the process, a generic form which summarized the capabilities of each concept was developed. CC and SR made an independent check of the matches between science requirements and concept capabilities across the full range of level-1 science topics.

The material was collated to produce a web-based 'Compliance Matrix'. This matrix should be treated as the primary documentation in the ISAC white paper design review process as of August

2002. The matrix and supporting material can be found at:

http://www-astro.physics.ox.ac.uk/~sr/ska/ska_matrix.html

The eight columns of this matrix represent the straw-man SKA plus the seven existing design concepts. The eighteen rows of this matrix represent the current level-1 science topics. The entry in the matrix is either 'YES', meaning the concept can clearly deliver the required capabilities, 'NO', meaning it clearly cannot, or 'MAYBE', meaning that it is feasible that the concept can be suitably modified. The reasoning behind each decision can be deduced from eighteen web-based forms showing the detailed match between science requirement and concept capability (linked from the Compliance Matrix web page). An example of one of these forms is reproduced as Fig. 2.

It should be noted that the posting of this material on the web instigated various useful email exchanges between us, other members of the ISAC, and engineers working on the design concepts. As a result various entries in the web-based tables were modified. We are continuing to refine this matrix, through input from the design teams and a detailed review by the science working groups.

2.2 Evaluation of SKA Design Concepts at Groningen

SR made a presentation at Groningen based on the initial evaluation of the design concepts, and featured a discussion of the Compliance Matrix and its associated tables. He emphasized that this was only a rough first stab at the exercise of comparing science requirements and concept capabilities, and thus that the current Compliance Matrix should be treated with extreme caution. He also cautioned against mis-use of any Compliance Matrix, which can only ever be an imperfect way of summarizing a large body of complex information in a simple way.

He suggested some action items for the ISAC. First, as it seems likely that potential level-I science is currently missing, a reanalysis of the key science drivers for the SKA is an obvious priority. CC and SR have begun to compile a list of topics which might fall into the level-1 category, but all members of the ISAC have been encouraged to attempt similar analyzes. Second, he suggested that efforts should be made to ensure uniformity across the Working Groups regarding what is meant by level-1 science. Third, he opened up the question of whether the strawman proposal should ultimately be revisited and revised.

An ISAC closed session at Groningen considered these issues. The question of determining what is meant by level-1 science is clearly of utmost importance. We are working toward constructing a written definition of level-1 science against which all scientific applications for the SKA can be judged. Once this is done, we must ensure, as best we can, that all potential level-1 science applications for the SKA are assessed. We expected that a revised, probably shorter, list of key science topics will result from this process. We also recognize the importance of maintaining the interest of the widest possibly community of potential SKA users. We will therefore construct a much longer list of level-2 science topics in which the SKA is likely to make a fundamental contribution.

3 Four issues

During the white paper review process, four major issues were identified as critical to the SKA design and open to scientific debate.

- High and low frequency limits (Dougherty/van der Hulst)
- Multibeaming and response times (Cordes/Taylor)
- Configuration (Gaensler/Garrett)

- Field of View (Bunton/Carilli)

Appendix 4 gives some introductory material for the four questions. In all cases the question of sensitivity was considered in the context of potential trade-offs with a given capability, eg. is a full SKA needed at high frequency? can sub-arraying substitute for multi-beaming? The working groups were asked to look for clear break-points in the science return with respect to sensitivity.

In Groningen it was decided to first consider these issues in detail within the science working groups, then discuss them in a plenary session. The people listed above were the facilitators of the plenary discussions. The working groups communicated their opinions to the facilitators. These opinions were presented during the plenary session, and subsequent discussion was captured in notes by the facilitators (and other members of the ISAC). The sections that follow are comprised of the WG opinions and the plenary discussions, as summarized by (primarily) the facilitators.

3.1 High and low frequency limits (van der Hulst & Dougherty)

Here is a summary list of the high and low frequency desires of each of the SWG's, with an indication of the Level-1 science that is addressed.

WG 1 - Galactic and nearby galaxies

Low – 480 MHz essential for C+ line
High – 8 GHz essential for polarimetry – 10-12 GHz highly desired

WG 2 - Transients, SETI

High – 10-15 GHz defeat scattering toward the Galactic Centre

WG 3 - Cosmology & Large Scale Structure

Low – 110 MHz HI at z$\sim$ 10 corresponds to 130 MHz
High – $\sim$ 10 GHz S-Z effect

WG 4 - Galaxy Evolution

Low – 200 MHz HI emission at z$\sim$ 6
High – 20 GHz CO at z$>$ 4.5

WG 5 - AGN & Super-massive Black Holes

Low – $\sim$ 100 MHz First generation radio galaxies at high z
High – 22 GHz Water megamasers
34 GHz desirable for higher resolution and a better atmospheric window than 22 GHz.

WG 6 - Life cycle of stars

Low – no science driver for the low-frequency limit.
High – $\geq$ 22 GHz Sub-AU imaging of thermal envelopes, notably particularly proto-planetary systems, within 200pc. Assumes baselines of order 1000-3000km.

WG 7 - Solar-system

Low – ~ 200 to 1 GHz (simultaneous) for dynamic spectra of non-thermal processes.
High - 20 GHz for thermal emission from asteroids, KPOs, NEO's, also for extra-solar detection of thermal emission from proto-Jupiters out to reasonably large distances.

WG 8 - Inter-Galactic Medium

Low – 300 MHz
High – ≥ 10 GHz Spectral studies of halo relics. S-Z effect

WG 9 - Spacecraft Tracking

High – 32 (and 8) GHz Needed for telemetry reception and angular tracking (32 GHz is highest priority (Ka-band coverage), 8 GHz has some value)

3.1.1 Opening thoughts

The high frequency limit is mostly driven by thermal science and the mas resolution provided. It is useful to find a general criterion for thermal science which expresses the power of the instrument as a function of frequency and make a comparison with other instruments such as ALMA and the E-VLA possible. For optically thick thermal sources ($S_\nu \propto \nu^{+2}$), it is appropriate to consider a signal-to-noise ratio figure of merit (FOM) given by ν^2/σ_ν. Taking the rms thermal noise figures from the SKA science case (Taylor & Braun 1999 - Table 1.2) for 2 polarizations, each with a bandwidth of $\nu/5 + 0.5$ and 8 hours of observation, gives the FOM's listed in table 1. A similar argument holds for thermally excited spectral lines.

Table 1: SKA SNR figures of merit for various observing bands

ν (GHz)	σ_ν (nJy)	FOM
1.3	16	0.1
5	11	2.3
10	8	13.1
21	12	35.0
30	$\sim 10^*$	~ 100
40	$\sim 8^*$	~ 200

* Calculated assuming a bandwidth of $\nu/5 + 0.5$

It is readily seen that the FOM increases with frequency, demonstrating that at least for thermal continuum science, going to the highest feasible frequency improves the detectability of a signal for a given integration time. Certainly not a new concept - but important to keep in mind! Interestingly, if one was to calculate similar numbers for ALMA at 35 and 345 GHz, the FOMs are 1.3 and 21.7 respectively (for optically thick thermal emission only).

In arguing the high frequency limits, the merits of a 30 GHz limit over a 10 GHz limit from the point-of-view of continuum science alone may not be readily apparent, other than perhaps via resolution requirements (obvious trade-offs here between frequency and baseline length). More compelling arguments undoubtedly arise from science drivers based around fundamental frequency limits, most particularly spectral lines – Water masers at 22 GHz, Ammonia at 24 GHz, CCS at 11 GHz, Methanol at 12 GHz, high-redshift CO 20-30 GHz (dependent primarily on redshift) etc. We should not forget other "fundamental" limits – spacecraft tracking at Ka-band setting a frequency limit of 32 GHz.

The low frequency limit is mostly driven by the highest redshift one needs to go to for measuring the first epoch of reionisation, currently estimated to be somewhere in the range of z $\sim$ 6 to 10, or 200 to 130 MHz. Other science driving the low frequency limit is the quest for finding the oldest radio galaxies at high redshift harboring the first black holes.

Most designs cover the lowest frequencies (except the Karst design which cuts off at 300 MHz), so the discussion really focuses on what the high frequency limit ought to be. It is important to identify the level 1 science which drives the high frequency limit.

3.1.2 Plenary discussion summary

Low frequency limit

The Epoch of Re-ionization (EOR) is **the** key science driver for both the SKA and LOFAR at frequencies $\sim$ 100 MHz. This science requires the ability to observe fluctuations $\sim$ 20 mK over angular scales as large as 1 arcminute. Clearly, a compact configured SKA with a low frequency capability around 100 MHz would be an ideal instrument for such science. LOFAR should be able to detect the overall (statistical) signal of HI reonisation over large spatial scales in long integrations. A sensitivity improvement by a factor of 10 or more is needed to be able to map out the detailed structure of the HI signal from the EOR.

High frequency limit

This is one of the more difficult specifications to decide upon since it could preclude some of the SKA-designs.

The major science questions that need to be addressed to pin down the limit:

1. the scientific capabilities of ALMA relative to the SKA, since much of the SKA science at 20-30 GHz will/can be addressed in some manner by ALMA.
2. what are the fundamental frequency points that we should consider? 22 or 34 GHz, or something lower, for example 12 GHz? The precise limits probably will be set by line transitions still to be included in the frequency range (e.g. Water at 22 GHz, Ammonia at 24 GHz, CCS at 11 GHz, Methanol at 12 GHz etc.).

One thing that is certain is that the large field-of-view of the SKA makes it a premier survey instrument - much more efficient than ALMA. Further, if the SKA has baselines of a few $\times$1000 km, then the resolution of the SKA at $\sim$ 20 GHz will be $\sim$ 10$\times$ that of ALMA at 345 GHz. These parameters need to be kept in mind when comparing the two instruments. Basically it means that for surveys of any kind, SKA will be much more efficient than ALMA due to the large FOV and collecting area, even for thermal sources (see Table 1).

Here are a few of the arguments that were discussed (in random order) which are relevant for the different high frequency limits considered.

- 34 GHz
  - Clearly opens up more redshift space for CO observations than 22 GHz. It means having access to CO 1-0 beyond z=2.4 instead of z=4.2 and CO 2-1 beyond z=5.9 instead of z=9.5.

  - Would incorporate a Ka-band (32 GHz) spacecraft-tracking capability. This opens up potential synergies with NASA for technology development.
  - A better atmospheric window. However, the large primary beam of the SKA will incorporate many potential phase-reference sources within an isoplanatic patch so it is not clear how imperative this is (needs to be examined further).

- Redshifted water (mega-)maser science - primarily motivated by the dynamics of AGN (cf. NGC4258). This is not sensitivity limited, the SKA will easily detect such systems, but resolution limited. Earth-based baselines will resolve maser disks of the type seen in NGC 4258 out to redshifts of 0.05, ie. well into the Hubble flow.

- For a SKA that operates up to around 22 GHz redshifted CO would be a key science driver - the large FOV makes SKA an efficient survey instrument.

- Star-forming galaxies - resolution is important to distinguish AGN from star forming disks. So for a given baseline, the higher the frequency the better. Here maximum baseline and resolution are coupled. If hierarchical formation scenarios are correct one expects progressively smaller objects at higher redshifts, so the resolution is even more important.

- Star formation - the high resolution potential of the SKA combined with its sensitivity make it the premier instrument for imaging of high-mass star formation and proto-planetary disks around low-mass stars in the well-known complexes (e.g. Taurus-Auriga) between 100-200pc. Frequencies of $\sim$ 20 GHz or higher will give sub-AU imaging at these distances (assuming 1000+ km baselines), a capability unique to the SKA in comparison to any instrument being planned for the near future. Also, going to the high frequencies allows study of critical molecular tracers, such as ammonia (23 and 25 GHz) and water (22 GHz).

3.2 Multibeaming and response time (Jim Cordes & Russ Taylor)

The discussion centered on the the following questions:

(a) What is meant by multibeaming in the context of the SKA?

(b) What science areas need multibeaming to achieve the Level 1 science goals? Here we distinguish between multibeaming as an enabling feature and multibeaming as a capability that increases the efficiency of observations.

(c) If multibeaming is required, is the full SKA needed for each beam? and

(c) What response time(s) are needed in beam forming to respond to a trigger from (e.g.) another instrument?

3.2.1 Basic Definitions:

To discuss multibeaming as clearly as possible, we first define some basic terms.

Primary Beam = response of an individual element at a single focal point.

At L band we have for the various designs the following primary beam diameters:

$\ll 1$ deg	KARST, LAR
~ 1 deg	Australia, India, USA
$\gg 1$ deg	Europe

In the KARST and LAR designs, feeds at multiple focal points are used to produce multiple primary beams on the sky and thus could potentially meet the specification of 1 deg FOV at 1.4 GHz. All other designs meet the specification with single feeds, though they too could utilize multiple feeds.

We also need to define several beams associated with arrays of primary elements:

Station Beam = the synthesized beam of a *station* built up from primary elements. (For single-dish stations such as the KARST and LAR this is identical to the Primary Beam.)

Core-Array Beam = the synthesized beam from elements within a central core array.

Science areas that need a core-array beam include those requiring high surface brightness sensitivity at intermediate angular resolution (EoR studies, HI detection of galaxies, molecular line studies), and blind surveys for pulsars, transients and SETI.

It is useful to define the core-array beam because elements within the core-array can be phased together or correlated individually. In this sense, the core-array is simply a large station. Additionally, and perhaps most importantly, it may be possible to sample the *entire* FOV of ~ 1 deg at 1.4 GHz only for the core array. The size of the core array is TBD and is dependent on details of the science case. However, it should be noted that if the SKA FOV specification ~ 1 deg (see below) is to be sampled completely, the requisite number of core-array beams $\propto b_{\mathrm{core}}^2$, where b_{core} is the diameter of the core array. For time-domain science and spectroscopy, the number of operations scales with the number of core-array beams. For these areas of science, the core array should be as small as possible (e.g. ≤ 1 km). However, imaging of low-surface brightness structures (EoR and Galactic non-thermal radiation, for example) might push the core-array to larger sizes, e.g. up to 10 km.

SKA Beam = synthesized beam of the entire SKA.

Finally, we define the field of view (FOV) in terms of previous definitions and relate it to the current SKA specification:

Single-focus FOV = the primary beam $\times$ delay beam (or equivalent), where the relevant delay beam is for a station composed of multiple elements. For the KARST and LAR designs, the single-focus FOV is identical to the primary beam. For the European tile design, the delay beam is presumably much smaller than the primary beam.

FOV = the *aggregate* FOV including any multiple focal-plane sampling (KARST and LAR).

The SKA specification is for FOV ~ 1 deg at 1 GHz. For the European tile design, the FOV specification is much smaller than the intrinsic beam width of the tiles. Multibeaming is therefore much more flexible in this design and it is possible to simultaneously sample regions of the sky separated by $\gg 1$ deg and using the entire collecting area of the SKA. The Australian cylindrical design allows such sampling in one dimension, while all the remaining designs require a sacrifice in collecting area if $\gg 1$ degree sampling is used.

3.2.2 What is Multibeaming?

Two definitions are used in discussions about the SKA:

Definition 1: Multibeaming = multiple beams formed within the FOV. If formed in real time these would result from a beam-forming system; if formed off-line, we would call these synthesized beams. [1] We prefer this definition of multibeaming.

Definition 2: Multibeaming = multiple, simultaneous fields of view (FOV) spaced widely on the sky. This kind of multibeaming requires a sacrifice in sensitivity in the KARST, LAR, US and Indian designs. For the European tile design and the Australian cylinder and lens designs, multiple FOV can be achieved through multiple feeds (or equivalent focal-plane sampling).

The strawman specifications indicate a requirement of 100 beams that conform to Definition 1. Some science discussions, however, imply the need for multibeaming according to Definition 2. *We recommend that Definition 1 be used for 'multibeaming' while Definition 2 can be referred to as 'multiple fields of view.'*

3.2.3 What are the scientific needs for multibeaming? And with what gain and response time?

Comments from the scientific Working Groups of ISAC are as follows:

WG1 *Galactic HI, Nonthermal Emission and Magnetic Fields:*

Multibeaming is not critical but maximizing FOV is important.

WG2 *Transients, Stellar end products, and SETI:*

Multiple beaming (Definition 1) is needed to the extreme where the entire FOV is 'accessible' in the time-domain and spectral-line studies that comprise the science of this WG.

Blind surveys for natural or artificial signals require construction of time series from all beams needed to cover the FOV. Such time series need to have time resolutions $\leq 100\,\mu s$ and with spectral resolution ~ 0.1 MHz for pulsar and transient surveys, ~ 10 kHz for spectral line surveys (natural sources), and ≤ 1 Hz for SETI. (These data sets might more naturally be referred to as dynamic spectra.)

The data rate associated with this requirement scales with the square of the maximum baseline on which full-FOV beam forming is done. Realistically,

[1] In the following we will refer to array beams as synthesized beams, for simplicity, independent of how or at what time they are implemented.

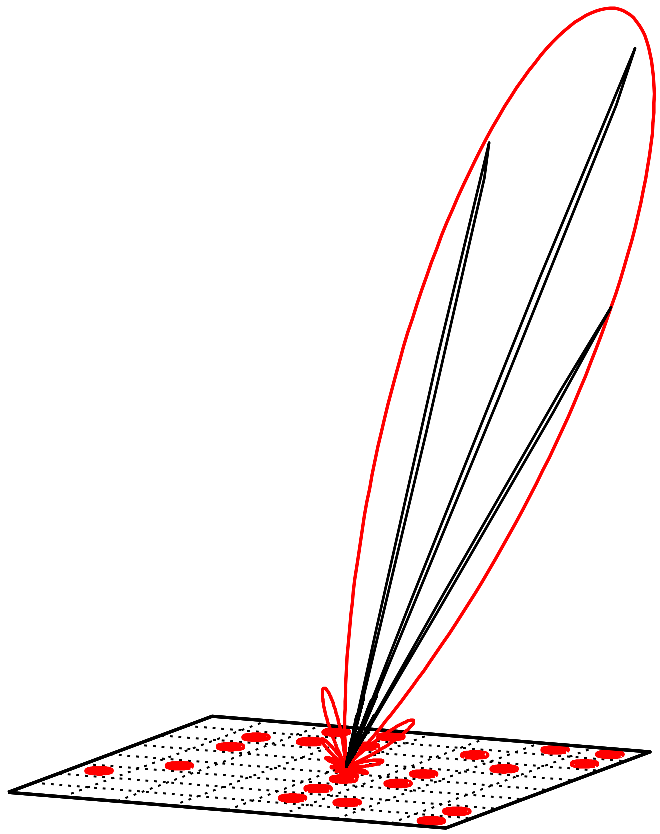

Figure 1: **Multibeaming Definition 1:** Depiction of a station, the primary beam of an array element (red), and multiple array beams (black) within the primary beam. These array beams are called *synthesized beams* in off-line analysis and would be the outputs of a real-time *beam former* if formed in real time. For the European tile design, the primary beam $\gg 1$ deg while for the KARST and LAR designs, the primary beam $\ll 1$ deg. The remaining (Australian, Indian, and US) designs all have primary beams ~ 1 deg, at least in one dimension.

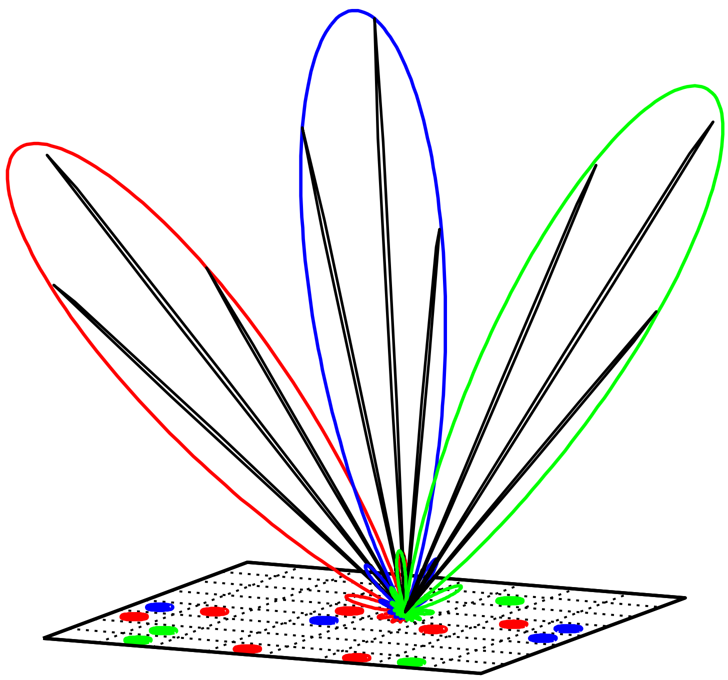

Figure 2: **Multibeaming Definition 2:** Here multiple primary beams (red, blue, and green) are shown that correspond to usage of subarrays of station elements. Within each primary beam, multiple array beams are formed (black).

full-FOV analysis can be done only on the core-array. If the maximum baseline is $b_{\rm core}$, then the number of beams needed is $N_{\rm beams} \sim \Omega_{FOV} b_{\rm core}^2/\lambda^2$. Unless the core-array is smaller than a few km, the implied data rate ($\sim N_{\rm channels} N_{\rm beams}/\Delta t$, where $N_{\rm channels}$ = number of spectral channels and Δt = sample interval) is most likely unachievable.

The size of the core-array needed for WG 2 science needs to be considered in more detail, especially in relation to data rates and to other areas of science that require a core array. This also raises the question, "What fraction of A_e should be in a core array?" We note that WG 2 also requires the SKA to have collecting area on long ('VLBI') baselines for astrometric purposes and for studies of interstellar scattering.

Caveat and Comment: For blind surveys that require sky coverage much larger than the specification FOV $\sim$ 1 deg (at 1.4 GHz), sensitivity ($\rm A_e/T_{sys}$) may be sacrificed. That is, we can use multiple fields of view (Definition 2) by sub-arraying the SKA. This follows because, except for pulsar surveys, we do not know the sensitivity requirements for the transient sky nor for ETI sources. Additionally, for much of this WG's science, the collecting area can be used in a mode where widely-spaced stations or collections of stations are used for anticoincidence tests of RFI.

Targeted Searches and Observations , e.g., SETI on individual stars, pulsar timing, radio studies of X-ray selected objects, need "many" multiple beams within the FOV. This yields a large increase in efficiency that implies a qualitative change in how the science is conducted. The technical requirements (number of beams, data rates) are less stringent than for blind surveys.

Response Times: Triggers may be expected from the SKA itself or from other telescopes throughout the electromagnetic spectrum (and perhaps from non-electromagnetic facilities: gravitational wave and neutrino detectors). For gamma-ray bursts, for example, response times of seconds are needed to determine whether there is a prompt radio burst in addition to the well-known afterglows. Dispersion delays ($\propto$ frequency^{-2}) in interstellar and intergalactic media can aid in lengthening the response time needed, especially at low frequencies, at the expense of sensitivity (see Appendix 5). The rate of radio bursts is not known so we cannot specify what FOV is needed to yield SKA self-triggers at a rate, say, of one per day. If we use the detected GRB rate ~ 1 day^{-1} in a hemisphere, then the nominal FOV $\sim$ 1 deg will yield a very small rate $\sim 10^{-4.3}$ day^{-1}.
Triggers from other instruments, such as gamma-ray satellites, are likely to require tens of seconds (see Appendix 5).
Two related issues are:

1. Requirements on phasing of the SKA using celestial sources. How often will this be needed and over what solid angle will the phasing solution be valid?
2. What are the requirements on a 'delay buffer' that would allow transients to be identified after the fact. Is it feasible to use such a buffer only with the core array? Or with a few stations? What are the costs as a function of sampled solid angle?

WG3 *Cosmology and Large-scale Structure:*

Multibeaming is not critical but maximizing FOV enhances the science

WG4 *Galaxy Evolution:*

Multibeaming not essential.

WG5 *AGNs:*

Astrometry (phase referencing) and calibration greatly benefit from having four beams (sufficient to solve for a plane-slab atmosphere).

Source slewing times need to be small to allow monitoring of many sources, including Intra-Day Variable (IDV) sources which sample the changing interstellar medium. What is small? During the Groningen discussion "10 sec or less" was stated. However, it is not clear that such fast response results from Level 1 science requirements. For example, with the great sensitivity of the SKA, fainter and more compact sources can be detected that will show IDV. The density on the sky of IDV sources will be sufficiently large that an IDV source can be found relatively near to any arbitrary position. IDV time scales are typically an hour or more, so slewing to a particular source does not seem to require a very rapid slew rate.

WG6 *Life Cycles of Stars:*

Multibeaming not essential.

WG7 *Solar System:*

No comments.

WG8 *Intergalactic Medium:*

No comments.

WG9 *Spacecraft Tracking and Geodesy:*

Wide-angle multiple FOVs (c.f. Definition 2) are useful for spacecraft tracking but not a fundamental requirement. The full gain of the SKA may not be needed for this; sub-arraying may be sufficient.

Time multiplexing is not useful for telemetry reception.

3.2.4 Questions for Further Study

1. What is the maximum data rate that can be achieved in 10 to 15 years, taking into account the beam-forming process, large numbers of channels, and high time resolution needed for WG 2 science? What parts of the required processing are real-time and which off-line?

2. What fraction of the SKA's collecting area should be in a core array and how large should this core array be? This is equivalent to the question, "Over what subarray size can we instantaneously sample the entire FOV ~ 1 deg for time-domain studies and spectroscopy?"

3. What are the specific needs for fast response times?

3.3 Configuration (Gaensler & Garrett)

3.3.1 Introduction

Many of the key science drivers that are unique to the Square Kilometre Array (SKA) seem to have very different, often conflicting, array configuration requirements. Studies in which high brightness sensitivity is an important issue, e.g. EOR experiments, IGM studies and H I surveys, require a centrally condensed array, distributed over scales of $\leq$10 km. Other science drivers, e.g. AGN, stars, deep continuum surveys, astrometry programmes and spacecraft tracking, require sparse arrays with baseline lengths on scales of $\geq$1000 km. The final decision on the SKA's array configuration has various implications. These include the demands on the correlator, data transmission, computing facilities and naturally the total cost of the instrument.

The trend seen in next-generation space and ground based instrumentation toward much higher angular resolution (e.g. ALMA, VLTI, NGST) should also be borne in mind. By the time SKA construction begins, the EVLA and eMERLIN will already be operational, routinely providing μJy sensitivity with up to 40 mas resolution. Although the SKA will be $\sim$ 50 times more sensitive than these upgraded instruments, it will nevertheless be essential to address the final configuration of the SKA on the basis of the EVLA and eMERLIN experience.

In the meantime, a "fair" distribution of the total collecting area of the SKA is sought. In this section we attempt to summarise the SKA configuration required for each of the key science drivers, as specified in Groningen through the input of the ISAC working groups and then through subsequent open discussion. While we should be aware of prematurely over-optimising the array, it is essential to make a start now. For example, some idea of the likely SKA configuration is required in order to guide the EMT and those involved in developing the various SKA concepts. In addition to the requirements demanded by the various science drivers, other limitations must also be taken into account. In particular, there are legitimate concerns regarding the calibration and dynamic range performance required of the SKA. Such limitations must also be taken into account and *realistic* simulations are desperately needed in order to investigate (for example) the various merits of "Large-N / Small-D" vs "Small-N / Large-D" concepts. Some progress has been made in this area but not nearly enough.

3.3.2 Shortest Baseline

The issue of $u - v$ coverage at the shortest baselines is a key one for all science which involves imaging large-scale and diffuse structure. Such requirements are particularly crucial for imaging of Galactic continuum emission, polarization and H I, as well as for studying relics and halos associated with galaxy clusters. The general specification which emerges from these science drivers is the need to be able to image scales $> 30'$ at $\lambda = 20$ cm, corresponding to a shortest baseline ≤ 20 m.

If we broadly group the existing SKA strawman concepts into "Small-D" (i.e. the Indian, European, USA and two Australian designs) and "Large-D" (i.e. Canadian and Chinese) concepts, some broad general design constraints emerge which need to be addressed given the above criteria.

The "Small-D" concepts can generally meet the requirement of closely spaced antennas without difficulty. However, shadowing is inevitable at low elevations in such designs. These configurations must therefore ensure good snapshot $u-v$ coverage, so that survey work can be carried out without aperture blockage. It is worth noting that some of the "Small-D" designs include the concept of stations, in which the signals from many individual elements are combined to reduce bandwidth. The need for short spacings requires that at least some of the elements are not grouped into stations but are correlated individually. (In some concepts, this requirement has already been met by using individual elements within the most closely-packed central region of the array, and switching to the station concept at longer baselines.) We note that regardless of how closely packed one designs the array, an important set of applications, particularly those which involve wide-field imaging within the Milky Way or which involve studies of entire external galaxies, will require measurement and addition of the zero spacing component. In such cases, these measurements can presumably be carried out with a single dish and added to the data-set after processing.

In "Large-D" concepts, the shortest interferometric spacing is typically hundreds of meters. However, each element of the array acts as a single-dish, covering a large range of compact $u-v$ spacings. Since any project in which angular scales of $\geq 2'$ (at $\lambda = 20$ cm) are of interest will need access to the spatial scales measured by these individual elements, single-dish mapping and combination will need to be applied by a wide range of users (far more so than for the "Small-D" case), and it is crucial that this process be routine and straightforward. It is also essential that the single-dish calibration be accurate and well-understood, particularly for polarimetry experiments.

3.3.3 The Central Core

A common theme which has emerged from the science cases of several ISAC working groups is that *a very dense core is essential for unique, low surface brightness science.* Two key questions thus emerge: what should be the spatial extent of this core, and what fraction of the total SKA collecting area should it encompass?

As an example of how these questions can be answered, we consider the need to map Galactic H I at high sensitivity and high angular resolution (this is a SKA "Level 1" science goal of the "Milky Way and Nearby Galaxies" working group). The criteria for studying Galactic H I is that one should be able to survey the Galaxy at a brightness temperature sensitivity of 1 K, at a velocity resolution of 1 km s^{-1}, and at a mapping speed of ≥ 1 deg^2 hr^{-1}. We require an angular resolution for such surveys of at least $5'' - 10''$, representing an order of magnitude improvement over existing surveys. Such requirements can be reached by a core which contains 50% of 1 km^2 contained within a diameter of 7 km. For fast surveying at maximal brightness sensitivity, one would want the innermost region of the array to be even more concentrated, with perhaps 30% of the total collecting area within the central 1–2 km.

Consideration of other science requirements produces comparable requirements on the central core:

- Epoch of reionisation studies require 40% of the array within 7 km.
- Mapping of structures within the intergalactic medium requires 50% of the collecting area within 5 km.
- Studies of transients and pulsars require a substantial fraction of the collecting area within 1 km, in order to carry out all-sky surveys with sufficient sensitivity.

While it appears clear that a multitude of science goals are crucially dependent on the existence of a central core containing a significant component of the collecting area, it is important to note that the mapping speed of the core is proportional to D^{-4} (where D is the diameter of the central core). Thus the moderate dispersion in D among the above examples will have a very large impact on array performance. Whether a distribution of collecting area which adequately meets all requirements may exist can only be established once all of the scientific working groups calculate and justify their required distribution of collecting area. An alternative solution is that the central core have movable elements, as for the VLA and ATCA.

Many of the experiments which utilize the central core of the array will involve imaging surveys of large regions of the sky. It is thus important that the core have a very dense $u-v$ coverage in snapshot mode. An important contribution to this requirement can be made through mosaicing, and also through multi-frequency synthesis for continuum observations.

For the "Large-D" SKA concepts, there is potentially a physical limitation on the minimum spacing between elements. In these designs, there may be difficulty creating a central core which is as densely packed as required by the specifications outlined above. In such cases a hybrid array might be needed, in which a closely-packed array of smaller elements provides the collecting area needed for the central core, and the larger elements operate over longer baselines.

3.3.4 Baseline Distribution

Beyond consideration of the central core, the overall distribution of collecting area is a difficult requirement to specify without detailed simulations of each science goal; the wide variety of scientific projects endorsed by the ISAC represent a similarly wide range of specifications for the overall array configuration. To briefly summarise the broad requirements of the working groups as specified in Groningen:

- Studies of nearby galaxies require $\sim 75\%$ of the SKA collecting area to be contained within ~ 100 km.
- Studies of stars and of galaxy evolution both require $\sim 50\%$ of the area within ~ 50 km, and $\sim 75\%$ within ~ 350 km.
- Studies of AGN need matched $u - v$ coverage between widely spaced observing frequencies.
- Studies of low frequency emission from solar system objects require simultaneous imaging at multiple frequencies (eg. 300 and 600 MHz) with similar $u - v$ coverage at each frequency in order to make dynamic spectra.

Thus the only common theme is that *good sensitivity is needed on a very wide range of spatial scales.* Specifically, the current set of "Level 1" science goals collectively require very good $u - v$ coverage on scales from 0 to 1000 km after an 8 hour track. There is general agreement among the ISAC that the quality of the $u - v$ coverage required should be specified in terms of the largest gaps in coverage which are acceptable within a given range of baselines. Considerable further work will be needed to quantify just how big these gaps can be. Given the wide range of scientific specifications, it seems desirable that the final array configuration be comparatively scale-free, the enclosed area increasing smoothly with increasing baseline. By the same token, it is not clear whether the central core need be a distinct component, at least as far as the distribution of the collecting area is concerned (the topic of individual elements vs stations is a separate issue).

Overall, we emphasize that the distribution of collecting area and ensuing $u-v$ coverage required to meet the science goals will ultimately provide strong constraints on the minimum number of stations needed. The ISAC working groups need to quantify their configuration needs through detailed simulations in order to provide these constraints to the engineering teams.

3.3.5 Longest Baseline

The specification for the array's longest baseline is set simply by the desired angular resolution at a given wavelength. This is the one category in which the requirements of the different scientific working groups diverge considerably. A summary of the requirements of each group is given in table 1, ranked in order of increasing angular resolution needed. It is important to realize that the working groups are yet to specify what fraction of the total collecting area needs to be situated on the longest baselines; the specific requirements in this regard need to be quantified by the ISAC.

Table 2: Maximum baseline needed for each SKA science working group, sorted by increasing baseline.

Group	Topic	Max Baseline (km)	Comments
8	IGM	4	
1	Nearby galaxies	100	Resolution of 2 pc at 5 GHz in M 82
7	Solar system	300	Thermal studies at 20 GHz
3	Extragalactic surveys	>300	Galaxies in H I at $z = 3$
4	Galaxy evolution	500–1000	Confusion limit
9	Spacecraft tracking	>1000	
6	Stars	1000	Sub-AU at 22 GHz out to 200 pc
2	Pulsars & Transients	3000	5 mas at 5 GHz for astrometry
5	AGN	8000	astrometry; mas imaging of cores

3.3.6 Other Issues

Some of the science working groups in Groningen offered additional specifications for array configuration, which we briefly review here.

An important recurring theme was that of dynamic range. Several groups emphasized the need for a dynamic range of 10^6 (over a 1-deg^2 field of view), and some of the deepest surveys require 10^7. Some projects also need a reasonably high dynamic range even in short snapshot observations. Simulations will be needed to determine the minimum number of stations in the array which can achieve the required dynamic range at a given angular resolution.

The AGN working group emphasized the need for a stable phase center for precision astrometry experiments. The spacecraft tracking group requires continuous monitoring capability, at least for sub-arrays.

3.3.7 Summary: configurations

The wide range of topics encompassed by "Level 1" science demands baselines ranging from 0 up to >1000 km. Within this broad specification, it is surprising to find that a reasonably consistent picture has emerged from the configuration requirements specified by the nine science working groups. In summary, the array should be configured so as to achieve the following goals:

- Recovery of the zero spacing is essential for many projects. The measurement and addition of the zero spacing both need to be straightforward processes.
- Many projects require a dense central core. This core should be ~ 5 km across, and contain $\sim 50\%$ of the total collecting area.
- The majority of the specified science can be accomplished provided that $\sim 75\%$ of the collecting area is encompassed within an extent of 100–250 km.
- Good $u-v$ coverage is needed out to 1000 km, with some applications requiring some stations on even longer baselines.

As emphasized above, detailed simulations of both scientific experiments and SKA concepts will be needed in order to develop a more quantitative set of specifications, and to develop array configurations which can meet these demanding requirements.

3.4 Field of View (Bunton/Carilli)

The issue of Field of View was not discussed in Groningen. This was partially due to time constraints, partially due to the fact that the issue was raised under other topics (see multibeaming section), but mostly because there was broad agreement among the working groups that the current SKA spec of a 1 square degree FoV at 1.4 GHz is fundamental to the SKA design. Much less makes the instrument less interesting. Much more appears unrealistic. Some of the designs currently don't meet this spec (eg. the KARST design), but possibly could be made to do so with large focal plane arrays.

The general impression of the ISAC is that it is preferred to make this FoV contiguous (eg. for studying large scale structure), although this question needs to be considered in more detail. Another issue that should be addressed with simulations is which type of array (small D vs. large D + focal plane arrays) will lead to better imaging characteristics, both in terms of dynamic range and imaging large structures.

4 Summary

4.1 Four questions

Considering the configuration, the ISAC was pleasantly surprised by the broad general agreement. Many details need to be worked out to reach an optimal balance between low surface brightness science and high resolution science, but these can be considered at a later date, and somewhat independently of the fundamental SKA design choice. The main issue we see that does affect the design choice is whether large D/small N arrays will be able to perform the high dynamic range imaging, especially considering sparse UV coverage on longer baselines. The simulations group should make this issue a high priority.

Considering the high and low frequency issues, it is clear that most of the proposed designs meet the requirements of the 'classical' centimeter science with large collecting area, and that the gain in sensitivity over facilities such as the EVLA and eMERLIN is compelling, in particular for spectral line observations.

The situation at low and high frequencies is less clear. For instance, at the lowest frequencies the gain in sensitivity over LOFAR is marginal for some of the proposed SKA designs, and some designs do not cover frequencies below 300 MHz, at least as proposed. Likewise, for thermal science at the higher frequencies one needs to consider ALMA and ask whether the gain in collecting area offsets the increase in signal with increasing frequency for thermal sources (see Table 1). The ISAC recognizes that the science case must be very explicit as to the unique contribution of the SKA over other facilities.

4.2 Multiple fields of view vs. high frequencies

The most difficult issue for the ISAC was that of 'multiple fields of view' (definition 2 of multibeaming; section 3.2) and very fast response. It is clear that it will be difficult for the SKA to do both full-sky multiple fields of view and fast response, and also go to high frequency ($\geq$ 20GHz), the former being the main advantage of the European design, the latter being a major advantage of the US design. The ISAC identified many areas in which going to high frequency provided compelling science. Multiple fields of view is attractive since it facilitates long exposures and surveys that would otherwise occupy the telescope for large periods of time. However, we were hard pressed to come up with any quantifiable science topic that was fundamentally enabled by multiple fields of view.

Considering very fast response ($\leq$ seconds) the ISAC sympathizes with the idea of opening new parameter space. However, we have not identified any science issues that will be addressed by opening this parameter space. Also, when considering new parameter space it is important to consider whether physics precludes such space, either intrinsically or due to propagation effects (see appendix 5). Nor was it clear whether even the European design can do full sky, very fast response. The design still requires some mechanical movement to off-set geometric area losses, and the phase calibration requirements have not been discussed, ie. does the telescope need to re-phase using a celestial calibrator when responding to an event at some arbitrary position on the sky?.

At this stage, if it came to a trade between the multiple fields of view and high frequencies, the majority of the ISAC feels that high frequencies would take priority over multibeaming, although the novelty and practicality of multibeaming remains very attractive.

The ISAC recommends that the designers consider hybrid solutions which include multibeaming capabilities at low frequencies. The ISAC and the EMT independently reached the conclusion that a science demonstrator project was required to investigate the new parameter space afforded by multiple fields of view and very fast response. The EMT recommends a 100m class telescope, but given the totally unknown parameter space, the ISAC suggests that even a 10 to 25m class telescope should provide some insight into this new area.

In this context, one might consider the LOFAR telescope to be the science demonstrator telescope for multiple fields of view and very fast response. Based on this idea, one member of the ISAC (CC) proposed a possible hybrid-solution to this problem: incorporate a 'LOFAR-upgrade' into the SKA project. This solves a number of outstanding issues. First, multiple fields of view and very fast response can be done at low frequencies, where it is perhaps most compelling scientifically (Appendix 5). Second, the low frequency configuration can be weighted to short spacings for EOR studies without sacrificing the longer spacings at cm-wavelengths. And third, there are clearing scientifically compelling arguments at both ends of the spectrum (eg. EOR and redshifted CO). By incorporating a LOFAR-upgrade into the SKA project we avoid having to shoe-horn low and high frequencies into the same telescope design, such that each device can be optimized in their respective frequency ranges. We note that a similar recommendation has been made by the EMT.[2]

[2] "With the likely split between high and low frequency and multiple fields of view SKAs, it is important to examine options such as shared infrastructure (eg. data transmission and signal processing) for telescopes operating in the two regimes." Section II EMT, SKA concept designs – EMT comments, Oct. 2002, P. Hall.

5 Appendix 1: General Comments

Signal processing, and post-processing, needs to be presented in more detail for most of the designs.

Following are some general comments that arose from the discussions in Groningen.

The ISAC emphasized that the data rates for the SKA will be unprecedented (eg. the single HI survey project will generate data at the level of 100x the Sloan survey). These data rates require a new operational model, and like the EMT we recommend more effort be placed on determining the SKA operational model.

The ISAC supports the idea of an SKA simulations/calculations team. Some particularly relevant problems are: dynamic range and small N arrays, HI surveys over large cosmic volumes, and protoplanetary disk imaging at 20 GHz.

The ISAC and ISSC agreed that some 'level 0' science topics are required to show-case SKA science eg. up-front on the web page.

6 Appendix 2: ISAC Timeline

We have drawn up the following timeline for progress on the science case for the SKA over the next two years.

- Early 2003: ISAC has a preliminary list of level-0 science topics, plus a first-pass at prioritization of existing level-1 and level-2 science goals. CC/SR to ensure this happen in consultation with the full ISAC.
- Mid 2003: SKA meeting at Geraldton. ISAC has identified groups and individuals willing to carry out simulations and other work required to support a revised SKA science case. Work on these simulations will preferably have begun, with perhaps some preliminary results available.
- Early 2004: ISAC has agreed, detailed plan for who is to write what in the revised SKA science case. Progress on this work to be closely monitored by CC/SR.
- Mid 2004: Completion of a revised science case for the SKA which will demand support from a wide scientific community.

We note that during the current period of rapid progress in astrophysical research, and the availability over the next decade of a variety of new astronomical facilities, that the science case for the SKA will necessarily be a dynamic document.

7 Appendix 3: ISAC membership and working groups

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Science Working Groups and Chairs

1. The Milky Way and Local Galaxies – John Dickey
2. SETI, Stellar End Products and Transient Sources – Joseph Lazio
3. Cosmology and Large Scale Structure – Frank Briggs
4. Galaxy Evolution – Thijs van der Hulst
5. Active Galactic Nuclei and Super Massive Black Holes – Heino Falcke
6. The Life Cycle of Stars – Sean Dougherty
7. The Solar System and Planetary Science – None
8. The Intergalactic Medium – Luigina Feretti
9. Spacecraft Tracking – Dayton Jones

8 Appendix 4: Introductory material for the 'four questions' (Memo to ISAC from Carilli, August 7, 2002)

from: Carilli (ccarilli@nrao.edu)
to: ISAC
re: preparation for the break-out sessions in Groningen
cc: LOC, Peter Hall, Steve Rawlings, R. Ekers, J. Bunton

This note is a final summary of the Wednesday afternoon ISAC-defined breakout sessions. Given time constraints and other issues, we've decided to go with the four topics listed below. The 'sensitivity issue' can be incorporated into the discussions of the other topics as a possible 'trade-off' issue. Throughout the process we should highlight truly new parameter space being explored, as oppose to issues of convenience, or simply increased observing time (within reason).

The clear consensus within the ISAC was to hold the discussions in series. Holding such discussions in a large group requires that we be well prepared, and that the facilitators be active. There will be a session Wednesday morning for the individual working groups to consider these 4 issues, and consolidate their opinions. These opinions should be communicated to the facilitators prior to the afternoon session (on a viewgraph or other). The facilitators will introduce the topics via these viewgraphs, but they may also ask the WGs to defend or clarify their positions in the open forum. The subsequent discussion should be captured by the scribe, to be incorporated into a final report to the ISSC.

Attached below (again) are some notes related to each topic. It is not expected that we settle all these issues in Groningen. The purpose is to start the prioritization process, inform the ISSC of the scientific ramifications of given design choices, look for areas of compromise, and identify areas that need real work (calculations, simulations).

Looking forward to seeing you all next week,
Chris Carilli

1. Low and High frequency limits

- Currently, the only designs that go above 9 GHz are the US and CA. Can others designs be pushed to higher freq? at what cost? Are such high frequencies compelling scientifically?
- For a given level 1 science goal, is the express high frequency limit fundamental or just preferred? (ie. would 10 GHz get at least some of the science, or is 22 or 32 GHz fundamental?)
- Can adequate sensitivity be maintained at low frequency (A/T = 20000 at $\geq$ 300 MHz) with the same antennas that go to $\geq$ 20 GHz? Note that the background temperature at $\leq$ 200 MHz is $\geq$ 100 K, and this increases roughly quadratically with decreasing frequency, such that A needs to increase to maintain constant A/T.
- If two instruments are required (low and high frequency), where is the break-point wrt. cost and science, eg. 300 MHz? 1.4 GHz?
- If two instruments are built, what aspects can be shared (eg. software, IF, infrastructure, correlator, operations/maintenance)?

2. Multibeaming.

It appears wide field multibeaming ($\geq$ 10's of degrees) may limit the high frequency capabilities. Some issues that could be considered:

- Will subarrays suffice? or time 'multiplexing'?
- One of the drivers for wide field multibeaming is fast response times (of order a sec). Is this possible with any of the current designs over the full sky (all the current designs require some mechanical movement to reach the full sky)?
- Are any proposed future triggers fast enough?
- Is there any proto-type physics which points toward this regime being interesting?
- Will phase calibration be needed for beam-forming after large 'slews', thereby precluding very rapid response times, regardless of design?
- Which single-beam designs provide the fastest response times, and can any be optimized in this way?
- Can any of the multibeam designs be pushed to higher frequency? At what cost?
- What is the cost of adding an extra beam to eg. the Luneberg lens design?

3. Configuration

- What DNR is required for: i. VLBI continuum sources, ii. the nano-Jy sky at $0.1''$ res, iii. deep HI 21cm images at $1''$ res. Simulations are clearly in order here, eg. can VLBI be done with a few outlying stations + large inner collecting area?
- Malleability of given design to compact vs. large configuration, eg. KARST has max. baseline of 300 km, and in general large D means sparse VLBI UV coverage, although much simpler signal transmission/processing etc...
- Other issues: continuous monitoring/continuous visibility (eg. DSN)

4. 1 square deg FoV: large N/small D vs. [small N/large D + focal plane arrays]. Some issues:

- Number of cross correlations required
- Imaging DNR: limited uv coverage vs errors in beam-forming (simulations)
- Operations, maintenance

5. Trade-off in Sensitivity:

Deliberations thus far have assumed an SKA, and asked: what could we do with it? At some point, someone (presumably a funding agency) will ask: why an SKA? why not a half-SKA? This is a difficult topic to address, since many of the science goals do not have clear break-points wrt sensitivity, but the issue cannot be ignored. Some issues that could be considered in Groningen:

- Are there any clear break points near A/T=20,000 in your area, ie. without this the science suffers catastrophically? [in general, the working groups should be very clear on what an SKA provides over existing facilities, and how that addresses fundamental issues that cannot be addressed otherwise.]
- Would you trade collecting area for some other property of the array, eg. frequency range, multibeaming, FoV, long or short baselines?

- Is A/T=20,000 required over the entire frequency range, or can compromises be made at high or low frequency?
- What increase in collecting area over existing or planned instruments (eg. GMRT, EVLA, LOFAR) is sufficient to push mankind into qualitatively new territory?

9 Appendix 5: Fast response times

The fastest proposed satellite triggering system is SWIFT, for which the trigger timescale to ground-based telescopes, set by on-board processing and telemetry, is of order 10's of seconds. Many of the SKA designs, suitably modified and operated, could probably respond on these timescale. Triggering on shorter timescales (seconds or less) will require using the SKA itself as a trigger, or a dedicated link to another ground-based telescope (eg. LIGO or optical).

For cosmologically distance sources there is also the requirement that the emission mechanism be a coherent process in order to detect very short timescale variability. The argument is simply that incoherent emission processes (eg. normal synchrotron radiation) have maximum intrinsic brightness temperatures of order 10^{12} K. Let us consider GRBs, with typical peak flux densities of 0.2 mJy at 5 GHz, and at typical redshifts of $z \sim 1$. At 10^{12} K such a source would be 4.4×10^{-6} arcsecs in size, or about 40 light days across. Interestingly, the typical 1/e lifetime of a GRB radio after-glow is comparable (about 100 days).

Plasma collective, or coherent, emission processes are typically steep spectrum (eg. pulsars) and/or low frequency phenomena (eg. solar and jupiter bursts). Hence, fast triggers are most likely needed at the low radio frequencies ($<$ 1GHz). However, flat-spectrum pulsars are known to exist and, as a population, have been selected against in pulsar surveys that are traditionally at 1.5 GHz and below.

A compounding effect is frequency dependent temporal dispersion and scattering due to propagation through the ionosphere, IPM, ISM, and IGM. Detecting short timescale phenomena requires de-dispersion either by introducing frequency-dependent time delays into time series or by unwrapping phases of complex sampled data. The dispersion timescale is of order 8 μs/DM/MHz $\times \nu_{\rm GHz}^{-3}$. For known pulsars, DM ranges between 1 and 1200 pc cm^{-3} but most likely extends to 2000 pc cm^{-3} for lines of sight through the inner Galaxy. The IGM is expected to yield DM $\sim$ few $\times$ 100 pc cm^{-3} for z = 1. Assuming a 500 MHz bandwidth, a typical impulse will be dispersed over 2 seconds.

The good news is that dispersion provides a probe of the intervening ionized medium. The bad news is that the added degree of freedom will increase the processing requirements for detecting short, coherent pulses. Further bad news results from temporal broadening from scattering, which is not recoverable from data processing and introduces another, unknown time scale in matched-filter detection schemes. At 1.4 GHz, the most heavily scattered pulsar is smeared by about 0.2 sec from scattering. Lines of sight through the Galactic center are scattered by $>$ 200 sec at 1.4 GHz. Such temporal broadening scales as ν^{-4}, so the SKA will allow detection of narrow pulses at high frequencies. There are obvious optimizations that trade spectral steepness of source flux densities against the strong dependence of propagation effects.