A Road Map for the United States' Development Efforts on the Square Kilometer Array

PREPARED BY THE US SKA CONSORTIUM

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Draft: March 15, 2001

Contents

Questions and Comments for US SKA Consortium Members

1. The draft white paper is about twice as long as once talked about! However, we felt that more detail is needed than 6-10 pages would allow. Please comment.
2. Would a better ordering of §3,4,5,6 be 6, 3, 5, 4?
3. Do we need any details on who will do what during the development phase? (Probably not).
4. Do we need more discussion or links to NVO type enterprises, data storage, and backend processing?
5. We would like to comments by one week from today, i.e. on Thursday 22 March. It is best for us if you send us email or fax us your marked pages. Please send comments to all three of us.
6. The idea is to incorporate your comments and send a revised version of the white paper to you in the week before the 2 April Cambridge meeting.

Thanks!

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1 Executive Summary

The Square Kilometer Array (SKA) will be the largest radio telescope ever built and will serve as the Great Observatory for meter and centimeter wavelengths. The radio sky will be probed at levels of less than 100 nano-Janskys for both time domain and imaging applications. Along with sensitivity, the resolution and coverage of observational phase space will unveil the universe — from the solar system to the high-redshift universe — in radical new ways.

New developments in all fields of astronomy have brought the current generation of astronomers to the threshold of probing the origin and evolution of the Universe as a whole. The scientific forefront demands a revolutionary new instrument at radio wavelengths, with two orders of magnitude more sensitivity than any existing or planned instrument. The recent U.S. decadal review[1] of astronomy concluded that such a Square Kilometer Array (SKA) should be pursued by the U.S., with a $22M technology development program being initiated by the NSF. This document has been prepared for the NSF by the U.S. SKA Consortium, which represents a broad spectrum of the U.S. radio astronomy community, and presents a possible "roadmap" for SKA technology development.

The radio telescopes of past decades have achieved a striking series of discoveries such as pulsars, quasars, gravitational lenses, radio galaxies, and the cosmic microwave background. These discoveries have illuminated not only our understanding of the universe, but also of fundamental physics, and have proven to be fruitful sources of knowledge about gravitation, nuclear matter, the interstellar medium, high energy phenomena, and cosmology. The SKA, with an extraordinary leap in sensitivity, is certain to produce many new discoveries. Key goals include probing the early universe (formation of structure at $z < 20$ and the epochs of galaxy and star formation), unveiling the transient universe at radio wavelengths, surveying the Milky Way to provide a deep census of its constituents, and identifying the population of asteroids that might collide with the Earth, as well as a plethora of other new discoveries in all fields of astronomy. The SKA will be the only means for providing centimeter wavelength data that will complement with sufficient sensitivity astronomical instruments planned in other wavelength domains (e.g., NGST, ALMA, GLAST, VLT, VLT1).

The concept of the SKA has excited astronomers around the world, who envision the development of the SKA as an inherently international endeavor. Scientific review committees have already recognized the SKA as one of the most important future astronomical instruments in a number of other countries (e.g., Australia, Canada, China, European Union). The global SKA effort is being coordinated through the International SKA Steering Committee (ISSC), which includes U.S. membership. This group has adopted a five-year development plan that will allow convergence to a single design for the SKA by mid-2005.

[1] *Astronomy and Astrophysics in the New Millenium*, National Research Council, 2001

At present several possible designs for the SKA are being explored around the world. The U.S. SKA Consortium has concluded the the preferred implementation of the SKA would be an array of a very large number of small antenna elements, concentrated into a large number N of separated stations ("the Large-N Array"), which would provide extraordinary image fidelity and dynamic range. However, the Large-N Array poses very significant technical challenges because of the large number of required receivers and electronic packages, the complexity of the interconnections, the massive correlations that must be performed, and the need to develop new signal processing algorithms that optimize the science return.

This roadmap highlights the scientific return possible from a Large-N SKA implementation, and identifies the areas of required technology development. The technology development plan is broken down into five major areas: improving sensitivity per dollar, achieving high dynamic range and resolution over large fields-of-view, signal processing improvements, interference management strategies, and operational challenges. The timescale for this development is critical if the US is to become a full partner in the international SKA and influence the 2005 choice of its implementation.

The initial development of the SKA is envisioned to be university and institute based. However, the roadmap is not entirely independent of existing or planned U.S. observatories and facilities, as it indicates where leveraging off and synergy with other funded activities would be particularly beneficial to development of the SKA, even though the capabilities of the SKA would far transcend other planned instruments. The suggested NSF funding profile from 2002-2005 for SKA technology development is as follows:

2002	2003	2004	2005
$2M?	$2M?	$4M?	$4M?

Although we recommend an FY'02 start for the SKA development effort, we recognize that some advance funding in FY'01 would be very beneficial if the NSF had that flexibility.

It is envisioned that a prototype array would be built between 2006-2009, with $15M coming from the NSF and $30M being supplied by international partners. The full SKA would be built from 2010-2014 with $200M coming from NSF and $400M being supplied by international partners.

2 What is the SKA?

The SKA will be an instrument of the digital age. Its design will necessarily exploit Moore's law increases in digital capability to obtain the giant leap forward in collecting area, imaging capability, and coverage of observational phase space (time, frequency and location). A set of design goals has emerged from a series of meetings and workshops that have taken place internationally over the last 5 years. The baseline specifications (Table 1) are driven by science requirements which we summarize in §4.

The SKA as a Great Observatory for Radio Astronomy. The SKA will provide at least 100 times the continuum sensitivity of existing imaging instruments in radio astronomy. The SKA will allow radio science to be conducted on par with innovations expected across the entire electromagnetic spectrum in the next two decades. With its specified sensitivity, angular resolution, and frequency coverage, the SKA concept is the only means for providing centimeter wavelength complementarity to telescopes such as ALMA at mm wavelengths, the NGST in the optical and infrared (IR), the VLT and VLTI and GSMT follow-ons operating in the optical/IR, and GLAST in the gamma-ray range.

The extraordinary range of astronomical targets and topics enabled by the SKA — from the solar system to early cosmological epochs — is well documented in *Science with The Square Kilometer Array: A Next Generation World Radio Observatory.*[2] The broad science goals include:

- probing the pregalactic universe;
- charting the formation, evolution and distribution of galaxies and the roles of dark matter and magnetic fields;
- detecting low frequency gravitational waves using an ensemble of millisecond pulsars as wave detectors;
- detecting the ionized intergalactic medium;
- tracing star birth and death through deep Galactic censuses of protostars, main sequence stars, neutron stars, black holes and supernova remnants;
- identifying protoplanetary systems and relating their properties to those of our solar system; and
- searching for signals from other civilizations.

In addition, we fully recognize that the value of the SKA may ultimately comprise serendipitous discoveries, much as those that have occurred in the past[3] and which are expected to emerge when new parts of observational phase space are explored[4].

The SKA will be configurable in a variety of modes that allow exploration of the radio universe to a level of completeness that is unprecedented. For example, observing modes include those required for (1) spectroscopy of the high-redshift universe; (2) searches for pulsed and transient sources with variable time-frequency complexity while mitigating against radio frequency interference (RFI); (3) high dynamic range imaging on a variety of angular resolutions; and (4) radar surveying and monitoring of solar system objects (with the SKA used to receive only).

The SKA as Radio Science Infrastructure. The SKA, when included in VLBI arrays, enables great strides in detectability and imaging capability, particularly through the ability to use weak but plentiful sources for phase referencing. The SKA's specifications also allow it to be used, when the need arises, as part of the nation's infrastructure for spacecraft telemetry. It can also be used as the receiving element of bistatic radar measurements of solar system objects. We expect that synergies with NASA will be significant.

Why is the SKA Challenging Technologically? The collecting area (1 km^2), frequency range (0.15 to 20 GHz), and imaging dynamic range ($10^6 : 1$) of the SKA are required for high redshift science. The higher frequencies are also demanded by solar system science (surveys of Kuiper-belt objects) and detection of thermal radiation from nearby stars. To achieve the requisite sensitivity, entirely new approaches to achieving collecting area per dollar and for RFI mitigation are mandatory. These most likely require different approaches at low and high-frequencies.

As discussed below, the US SKA is considering "large-N" designs that exploit the economy-of-scales of replicated antennas and digital electronics. The performance of critical elements —

[2] A. R. Taylor and R. Braun, editors. (`http://www.skatelescope.org/ska_science.shtml`)
[3] *Serendipitous Discoveries in Radio Astronomy*, NRAO Proceedings, Eds. K. Kellerman & B. Sheets., 1983
[4] M. O. Harwit, *Cosmic Discovery*, Basic Books, 1981.

antennas, receivers, digital samplers, fiber optic interconnects, beamformers and correlators, and postprocessing — all 'push the envelope' in their requirements.

In the following sections, we discuss in more detail the science goals and drivers of the SKA's specifications; we describe the technological milestones that we wish to achieve over the time frame from now until 2005; and we discuss the plan for achieving those milestones.

Table 1: SKA Baseline Specifications

Parameter	Design Goal	Comparison
Sensitivity	$A_{\mathrm{eff}}/T_{\mathrm{sys}} = 2 \times 10^4$ m^2/K	20× Arecibo
Surface brightness sensitivity	1K at 0.1 arcsec (continuum)	
Frequency range	0.15-22 GHz	
Redshift coverage	$z < 8.5$ HI, $z > 4.2$ CO(1→ 0)	
Detectability of L_* Galaxy in HI (CO)	$z_{\mathrm{max}} \sim 2$ (20)	
Imaging field of view	1-10 square degrees at 1.4 GHz	$\frac{1}{2}$ deg (VLA)
Multibeam capability	$N_{\mathrm{beams}} > 100$	
Angular resolution	0.04 arcsec at 1.4 GHz	4 mas with SKA in VLBI array (1.4 GHz)
Number of spatial pixels	10^8	
Instantaneous bandwidth	0.5 GHz + frequency / 5	
Number of spectral channels	10^4	
Image dynamic range	10^6 at 1.4 GHz	
Polarization purity	−40 dB	

3 The U.S. Large-N Design Concept

The US Square Kilometer Array Consortium currently consists of ten universities and research organizations that have self-organized to find technical solutions to some of the implementation challenges inherent in the design and construction of the SKA. The Consortium is concerned with promoting SKA implementations that best serve the research interests of the US science community, while using the SKA to revitalize the cm-wavelength community. Towards these ends, the Consortium has concluded that the preferred implementation of the SKA would be an array of a very large number of one or more types of small elements, concentrated into a large number N of separated stations; denoted as a Large-N Array. The Large-N Array provides extremely dense u-v coverage and a large primary field of view, yielding unprecedented imaging fidelity, excellent dynamic range, and phase-stable operations because calibration sources are always available within the large primary field of view, extraordinary flexibility for multiple subarrays and multibeaming for multiplexing simultaneous projects. This implementation of the array maximizes the number of strategies available for RFI suppression and for surveys. For all its benefits, the Large-N Array also poses very significant technical challenges because of the large number of required receivers and electronic packages, the complexity of interconnections, the massive correlations that must be performed, and the need to develop new signal processing algorithms that optimize the science return by exploiting the extraordinary amount of redundant information inherent to this design choice.

This roadmap is intended to highlight the scientific returns possible from a Large-N SKA implementation, and to identify the areas of required technology development. The timescale for that development is critical, if the US is to become a full partner in the international SKA and influence the 2005 choice of its implementation. The roadmap is independent of existing or planned US observatories and facilities, but it does indicate where leveraging of and synergies with other funded activities would be particularly beneficial.

4 Key Science Areas that Drive SKA Technology

The pre-eminent reason for building the SKA is the revolutionary advance it will allow in several areas of cutting-edge science. Here we discuss a few key areas that address current fundamental questions in astrophysics and space science and that make the SKA's construction a compelling endeavor. These areas also drive the baseline specifications summarized in Table 1.

I. The High-Redshift Universe.

WHAT: Science enabled by the SKA includes the following:

- **Probing epochs of structure formation both before and after galaxy formation.** The key questions are (a) when did reionization begin and (b) when and through what mechansims did stars and galaxies form and evolve? Sensitive imaging of the redshifted 21 cm line of neutral hydrogen from clouds and galaxies will sample redshifts $z \lesssim 8.5$. Pregalactic HI structure will be probed at the highest redshifts by mapping emission and absorption lines. Galaxies with the same gas content as the Milky Way can be detected in HI to $z \sim 2$ and galaxies with greater gas contents to redshifts as large as 5. The yield is $\gtrsim 10^{4.5}$ galaxies *per square degree* in a survey of a few hundred hours. Depending on field of view, a sample of up to $10^{7.5}$ galaxies can be obtained, more than an order of magnitude larger than the Sloan Digital Sky Survey (SDSS). Rotation curves of a large subset of these can be measured. Redshifted CO ($1 \rightarrow 0$ transition) can be detected in the SKA frequency band for $z > 4.2$ with sensitivity that could reach $z = 20$ for a Milky Way type galaxy. CO observations with the SKA can therefore reach the earliest phases of star formation at $10 \lesssim z \lesssim 20$. The redshift coverage of the SKA for CO complements that of ALMA.
- **Strong synergy with deep IR surveys with the NGST that image $z \lesssim 5$ galaxies**. As with low-z galaxies, HI and IR studies together yield a detailed picture of galaxies' content, morphology and star-formation rate. Similar complementarity exists between SKA continuum measurements and IR and millimeter wavelength studies with ALMA through exploitation of the correlation between nonthermal radio emission and dust and molecular radiation, both driven by star formation. A detailed picture of star formation and galaxy merger activity will emerge as a function of z from the large galaxy samples.
- Correlations between bulge velocity dispersions and galactic nuclear ("black hole") masses can be explored as a function of z.
- Evolution of large-scale structure in galaxy distributions and the structure and evolution of dark matter as probed through the distribution of galaxies, measurement of HI rotation curves, and gravitational lensing will be routinely made on large samples.

- AGNs can be mapped over a wide range of central-engine powers, thus allowing tests of the unified model. Polarization mapping on large samples can be accomplished on angular scales of mas to arcsec.
- AGN jets can be used as standard rods in cosmological tests. Through sampling of the broad luminosity function of pc-scale jets, the SKA will yield large samples from which biases can be minimized.
- Megamaser surveys will reach OH out to z$\sim$ 2 and H_2O to z$\sim$ 0.15, yielding samples over a wide range of redshifts. Merger activity that drives OH masers can be mapped vs. z. Circumnuclear H_2O masers can be used to constrain black hole masses.
- The HI content of Lyman α forest clouds can be measured down to column densities $\approx 10^{17}$ cm^{-2}.
- Weak gravitational lensing is measureable in large fields with a point-spread function that is narrow < 0.1 arc sec and with high dynamic range.

Need a few more details about comparison with other instruments, NGST etc.

HOW: Detecting pregalactic structure, protogalaxies and galaxy disks requires 1 km^2 collecting area, an imaging array with sub-arcsecond resolution and high dynamic range, and wide frequency coverage down to 0.15 GHz for red-shifted HI. Redshifted CO ($z \gtrsim 4.2$ for $1 \rightarrow 0$ transition) requires frequencies from 22 GHz downward. Use of the SKA in a VLBI network enables phase referencing observations on a large number of object types, but necessitates the collecting area. Imaging a wide range of structure sizes with a static array configuration requires both a compact subarray and widely separated stations. The correlator must handle the enormous number of antennas and is one of the most technically challenging digital components of the SKA. The number of stations is not tightly constrained by extragalactic science though it must be large, $N > 1000$. RFI mitigation is mandatory at most frequencies but especially for those < 1.5 GHz that probe the $z > 0.4$ universe using HI. Beam formation with dynamic RFI nulling is required to combat satellite RFI.

The ability to remove RFI at low frequencies must be demonstrated during the development phase. One approach is to measure redshifted HI from individual galaxies using antennas with large separations (e.g. the Allen Telescope Array [ATA] in combination with Arecibo or the Green Bank Telescope [GBT]). RFI excision techniques can exploit the differences in RFI at the two sites.

II. The Transient Universe

WHAT: The radio sky is poorly known with respect to transient sources. By comparison, the high-energy sky has been surveyed with great success, identifying dynamic source populations using instruments such as the All Sky Monitor on the Rossi X-ray Timing Explorer and the BATSE instrument on the Compton Gamma-Ray Observatory. SKA surveys can target known classes of transient sources, such as gamma-ray burst afterglows, counterparts to other high-energy sources, Galactic flare stars, the recently identified flaring brown dwarfs, and bursting pulsars. The temporal and sky coverage and depth (maximum distance of detection) will be unprecedented. Entirely new classes of sources can be expected once sky surveys are repeated on a variety of time scales. Also included in this class are signals from ETI. The synoptic capabilities of the SKA will complement those planned at optical wavelengths using the LSST (Large-aperture Synoptic Survey Telescope).

Expected highlights include the following detections:

- Analogs to the giant pulses of the Crab pulsar out to about 5 Mpc.
- Flares from brown dwarfs out to at least 100 pc.
- Gamma-ray burst afterglows down to 800 nano-Jy (10σ) in one hour of observation, a factor of 125 smaller than currently detected afterglows.

HOW: The challenge of transient detection is to discriminate between RFI and celestial signals with a high degree of time-frequency complexity. Blind searches require a large instantaneous field of view and usage of coincidence tests from sites with large spatial separation. The SKA must therefore be configurable so that large instantaneous fields of view with high gain may be achieved by mosaicing the sky using subarrays of antennas at each station and making coincidence tests between stations at large separations. Synoptic surveys demand a high degree of configurational agility for the SKA. For example, wide-field surveying might be interrupted for high-resolution imaging response to a threshold trigger. Also, the tradeoff between instantaneous gain and field of view suggests a range of different kinds of surveys that could be conducted with the array. Coincidence tests and RFI mitigation must be explored carefully to determine optimal baselines between stations, considering transmission footprints of relevant satellites, etc. Backend signal processing and data mining algorithms need to be explored along with data storage and dissemination. Lessons from observations using prototypes of the ATA and the Low Frequency Array (LOFAR) are crucial during the development phase with the SKA.

III. A Milky Way Census

WHAT: The SKA can detect many classes of objects across the entire Milky Way Galaxy. Galactic surveys will provide information about populations of objects and their evolutionary relationships at a high level of completeness. Molecules in star-forming regions and jets in young stellar objects will provide a detailed spatial and temporal picture of the star-forming process. Nonthermal emission from main sequence stars, microquasars and soft-gamma repeaters can be surveyed. The relationship to supernovae of all star classes — young and old — will be delineated with unprecedented completeness. Pulsar surveys with the SKA will yield up to 10,000 new objects, allowing a full inventory to be made of canonical pulsars, and rare objects with sub-millisecond spin rates and hypermagnetic objects, binaries with orbital periods of hours and less, and companion objects ranging from planets to black holes. Large numbers of neutron stars in the Galactic center will be found by detecting pulsations at frequencies between 10 and 20 GHz. Exploiting radio propagation effects, the large pulsar sample can be used to map in detail the Galactic electron density and its fluctuations and the large scale magnetic field and turbulence therein.

Additional galactic work will include:

- A completely new capability of the SKA is the ability to image thermal emission of main sequence stars out to tens of parsecs and to 10 kpc for giants. Coronal activity can be identified as a function of class and age through SKA studies that complement high resolution optical and IR interferometric observations that will emerge on the time scale of the SKA.
- Surveys for atomic and molecular spectral lines can thoroughly map the density-temperature regimes of most of the interstellar medium, especially those in star-forming regions.
- Surveys for narrowband signals from other civilizations, can be made routinely and with minimal assumptions about frequency-time signatures.

- Astrometry (proper motion and parallax) of galactic objects to at least 10 kpc can be performed with the SKA used in a VLBI array. Phase referencing mitigates against the ionosphere at low frequencies and the troposphere at high frequencies. Distances and space velocities of significant samples of neutron stars and black holes can be studied, yielding insight on core collapse processes in supernovae.

HOW: As with transient studies, the correlator, RFI excision techniques, and data-mining algorithms are important elements for Galactic science. High gain, wide field, and programmable spectro-temporal responses are needed to explore the full range of anticipated objects. Beam formation is required for pulsar searching and followup timing observations. Imaging capability is needed for detection of individual stars. RFI excision is mandatory. Large collecting area at high frequencies is needed to detect large numbers of pulsars in the Galactic center.

Detecting, resolving and localizing (astrometrically) stellar disks, require the collecting area of the SKA distributed out to 1000 km or more.

IV. Inventory of Kuiper-belt Objects and Orbit Determinations of Near Earth Asteroids

WHAT: Kuiper belt objects are thought to be undifferentiated icy remnants of the formation of the solar system. So far, the known population comprises several-hundred objects from which a population of 160,000 is inferred. Exact numbers, their size distribution, and composition and morphology are important input to models for the formation of the solar system and for dynamical processes that shaped the final configuration of planets and which continue today.

The SKA will be able to detect thermal radiation of KBOs larger than 350 km out to 100 AU and objects out to 50 AU larger than 100 km. Detection of thermal radiation drives the requirement that the SKA operate at or near 20 GHz. Deep surveys require the field of view to be as large as possible at this frequency.

Near-Earth astroids pose a threat to life on Earth as well as being objects of scientific interest, especially in the area of chaotic dynamics. The SKA, when operated bistatically with a transmitting station, provides the means for detecting Near-Earth asteroids larger than 0.2 km and establishing their orbital elements to sufficient precision for indefinite recovery. These potentially hazardous objects may also be diagnosed for composition, of interest for future space-mining efforts.

HOW: the collecting area of the SKA is required at high frequencies for KBO studies. For radar studies, flexible beam formation and backend data processing are needed for reception of radar signals transmitted elsewhere.

5 Possible NASA Interest in the SKA

Although the SKA is currently being developed as an astronomical observatory, it might also be a powerful tracking instrument for NASA spacecraft. If NASA requirements could be integrated into the SKA design, the SKA would provide an opportunity for powerful synergistic cooperation between the NSF and NASA.

Compared to the existing Deep Space Network, the SKA would provide a two-order-of-magnitude increase in sensitivity (equivalent to 200 70-meter tracking antennas!). This would allow not only much higher data rates, and hence much greater science returns from future NASA science missions, but also new types of missions to be flown. The SKA could enable such revolutionary new concepts as streaming video from Mars or miniturized planetary probes. Reduced requirements for the mass, power, and pointing accuracy of spacecraft telecommunications hardware could result in very large savings to NASA when applied to many future missions. Additional benefits include the ability to simultaneously track multiple spacecraft, the flexibility of a wide range of available sensitivity, reduced mission risk through greater link margins and high array reliability (due to fault-tolerance of the array as individual elements fail), real-time angular spacecraft navigation, and the ability to detect many solar system targets (asteroids, comets, moons, Kuiper belt objects, terrestrial planets, etc.) in the same reference frame as spacecraft angular position measurements.

6 The SKA as an International Project

The concept of the SKA has excited astronomers around the world, who envision the development of the SKA as an inherently international endeavor. This observatory will be so revolutionary in scale and technology, that it will require the best minds the international community can offer. However, the science return will be so extraordinary that there will be plenty to share. Scientific review committees have already recognized the SKA as one of the most important future astronomical instruments in a number of countries (e.g., U.S., Netherlands, European Union, Canada, Australia, China).

How the SKA will be built is not clear at this point, and exploration of key technology areas is needed before a final choice can be made. Several countries and organizations have instituted SKA technology development efforts. Competing concepts for the design of the SKA individual telescope elements over various portions of the desired frequency range include small parabolic antennas (U.S.), planar phased-arrays (Netherlands), spherical radio lenses (Australia), flat reflectors with balloon suspended receivers (Canada), and large Arecibo-like dishes (China). Various technologies important to all of these designs are also being investigated around the world including imaging simulations, signal processing, interference reduction, and operations.

The global SKA effort is being coordinated through an International SKA Steering Committee (ISSC), which includes 6 U.S. members. This group has adopted a five-year plan that will allow convergence to a single design for the SKA. This design may not be any of the designs currently being pursued, but could be an amalgamation of more than one concept. It is expected that whatever the final design, all the participating countries would retain key roles in the final implementation of the SKA, and that scientific access would be open to any scientist around the world through international peer review.

Figure 1 shows the draft ISSC timeline of milestones for the development of the SKA. The timeline has two separate horizontal paths, one for the design choice and one for the choice of a site location. The horizontal axis is an approximate (but not linear) measure of time. Items in rectangles indicate major milestones while items in ovals indicate input needed to achieve those milestones. The timeline is driven by a desire to choose an SKA design and site within 5 years (i.e., by mid-2005). The justification for selecting 5 years for SKA development is that this would allow some time for technologies to mature as well as match the anticipated beginning of possible funding wedges around the world. However, the choice of 5 years is somewhat arbitrary, and the timeline could prove overoptimistic.

The ISSC has also developed a draft international management structure for the development of the SKA, as shown in Figure 2. The ISSC is the ultimate authority in setting the goals and monitoring the progress of the SKA project. A Project Director, who reports to the ISSC, would have overall responsibility for every aspect of the project, but is dependent on both a Project Engineer and Project Scientist for dealing with the myriad of technical and scientific details needed to accomplish the project. These three positions, including other staff activities, would be funded by the ISSC members (including the U.S.). The organization chart also contains several groups whose salaries would be covered by their institutions around the world. These groups are the source of detailed information and studies that allow the SKA paid staff to direct the project through the 5-year plan. However, the SKA staff will also require funding for studies that can not be accomplished in this manner. Primary responsibility for carrying out the 5-year plan resides with the SKA international management team, but some of the critical choices would be relegated to independent review committees.

The U.S. plan for SKA technology development must be chosen in the context of this global effort. The technological challenges to be pursued in the U.S. over the next 5 years are in some cases unique, and in some cases complementary to other international efforts. It is clear that the U.S. contributions are critical to the successful completion of the SKA.

This roadmap makes the following assumptions:

1. The US desires to be a full partner in the international SKA development plan from 2001 to 2005, and the implementation of the SKA thereafter.
2. To enable full US participation, minimum financial obligations must be covered.

    a. The travel expenses for approximately six US delegates to international SKA meetings will continue to be borne by the US SKA Consortium.

    b. The proportional US share of funding for the SKA Secretariat will continue to be borne by the US SKA Consortium.

    c. As part of the US SKA development effort addressed by this roadmap, the NSF will assume the US share of the fiscal responsibility for supporting an international SKA project office consisting of a Project Manager, Project Scientist and Project Engineer as shown in Figure 2.

3. The US has a preferred concept for implementation of the SKA as a Large-N array of small elements. To cover the entire frequency range for the SKA, more than one type of element may be required.
4. The US would like to consider construction of the SKA on the North American continent if suitable sites can be identified.
5. The US intends to conduct its SKA technology development activities in a timely manner so that they may have the greatest impact on the international SKA development effort. To that end, the US accepts the timeline developed by the ISSC as shown in Figure 1.

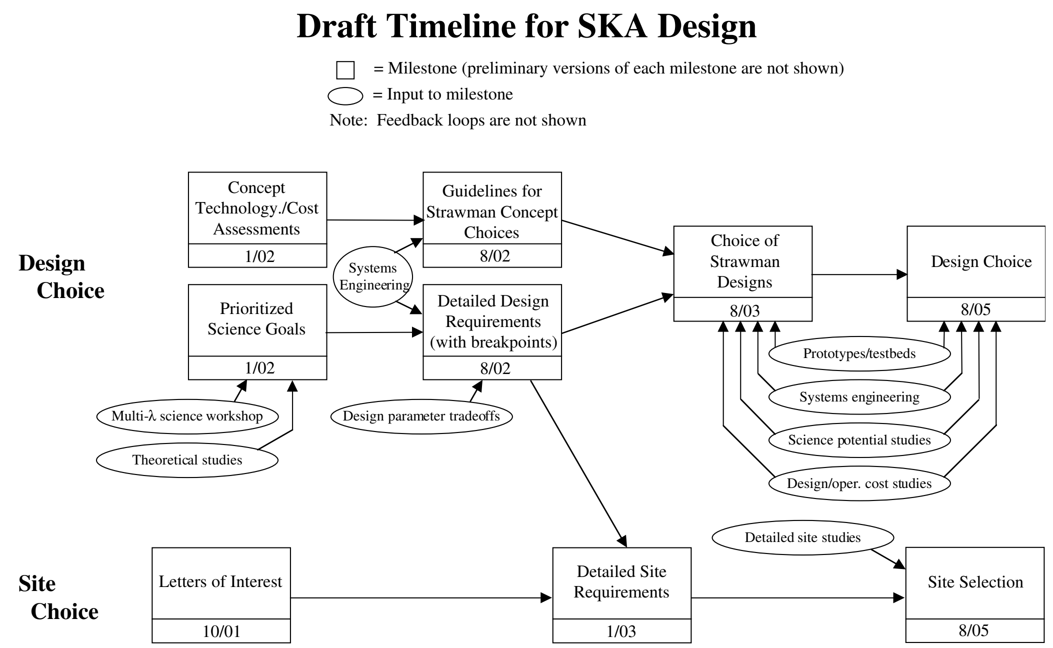

Figure 1: Time line.

7 The Technical Challenges: U.S. Development Efforts and Payoffs

In principle, the Square Kilometer Array could be built tomorrow, but it would be unaffordable. The cost per square meter of collecting area must be reduced by a factor $\sim 5-10$ to make it affordable. The key to achieving an acceptable price/performance ratio lies in breaking the historical pattern of brilliant, but single-purpose, invention of necessary technologies by radio astronomers and focusing instead on modifying or adopting the new and more affordable technologies being developed for the consumer market. Where this has been done in the recent past (e.g. VLBI recording) it has proven very successful. Repeated and creative application of "hammer" technology (i.e. reshaping what is available to do what is needed) is what will make a Large-N implementation of the SKA affordable.

This is an ideal decade in which to develop the SKA; telecommunications markets are driving down the costs of data transportation and processing, while commercial applications for the kinds or wideband data streams commonplace to radio astronomy are developing explosively. Since the signal-to-noise ratios (S/N) in the mass communication market are so much higher than those of radio astronomy, the biggest technological challenge is to drive down the cost of A_e/T_{sys} and maintain phase stability. Continued operation of Moore's law, and consumer pressure, will likely provide affordable components and subsystems to solve most other requirements, given sufficient cleverness on the part of the radio astronomical community. Even the SKA software development may be able to borrow effectively from modern operating systems and solutions for dynamically monitoring huge traffic networks and databases. Postponing implementation of the SKA only

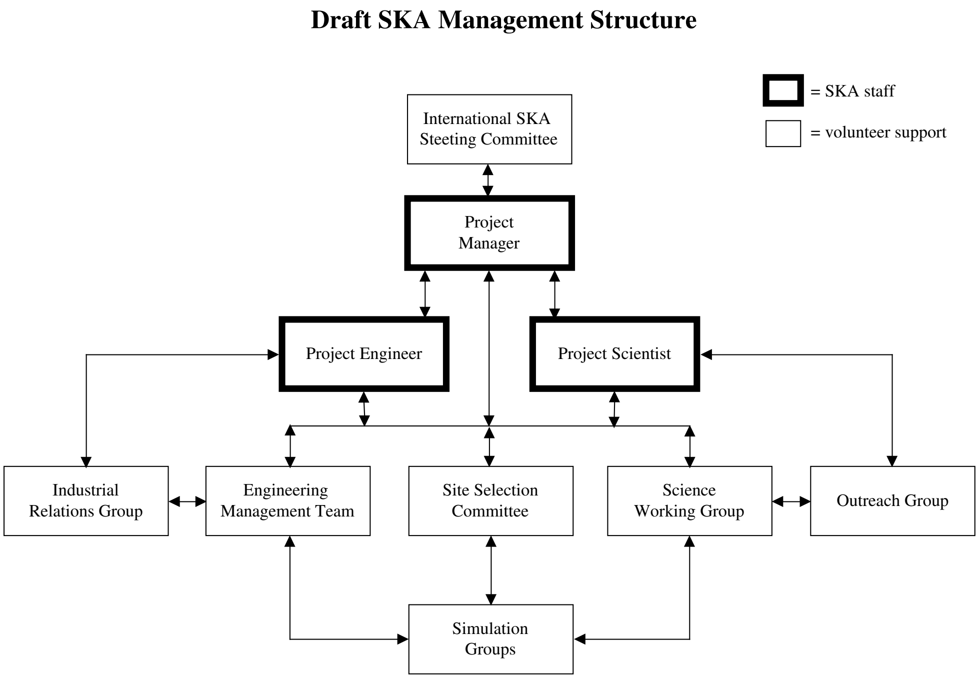

Figure 2: Management plan.

increases the complexity of the processing needed to deal with increasing RFI.

What follows are some abbreviated descriptions of required development efforts. These areas have been highlighted because they address one or more of the ambitious science goals presented in §4. The various high priority science areas described in Section §4 require different performance specifications to be successful. Not all technological challenges need to be met in order to do any one of these science programs. However, the full suite of science of interest to US astronomers does require solutions. Therefore, in parallel with the technology development there must be an iterative process of prioritization arriving at a minimum set (as well as a desirable set) of requirements to be met by the final Large-N design.

Early and wise investment in the development activities below should lead to an affordable design for the Large-N version of the SKA by the 2005 international decision deadline.

Whatever implementation decision is taken, the US community will continue to participate in the international effort of creating second generation prototypes of the selected components. This is the best way to ensure that projected price/performance goals can be met when construction of the SKA begins near the end of this decade.

The items below appear in rough order of their urgency.

Improving Sensitivity per Dollar:

Collecting areas and mounts. Several technologies routinely produce large quantities of television (receive only) antennas for little more than the cost of the raw material. These manufacturing techniques (particularly hydroforming of solid aluminum reflectors) can be harnessed to produce optimally shaped, minimal cost, antennas for the stations of Large-N Array. At the lowest frequencies specified for the SKA, shaped reflectors will need to be replaced by dipoles or other optimal elements. The challenge is to cover the entire frequency range with the fewest (ideally only two) different types of antenna elements. Suggested development efforts:

1. Simulate and compare various optical designs for antenna elements in order to optimize the antenna performance per dollar over as much of the SKA frequency range as possible.
2. Design, or adapt, a fully steerable mount, having adequate accuracy and reliability, that is suitable for mass production and depends to the greatest possible extent on consumer, off the shelf components
3. Manufacture and test one or more prototype antenna systems.
4. Devise the most cost effective manufacturing plan, comparing on-site plants with creative delivery systems from distant (including foreign national) plants, while factoring in all on-site assembly costs.

Feeds and Optics. Very low-cost wideband feeds are required to match the anticipated performance of a new generation of LNAs. The illumination pattern, gain, and polarization properties of the feed must optimally match the optical design of the antenna, and to the input impedance of the LNA. Suggested development efforts:

1. Design, or adapt, dual-polarization wideband feeds that are a good match to the other components of the antenna system, and are inexpensive to manufacture and reliable to operate.
2. Simulate feed performance including spillover, and ohmic losses for various optical antenna designs.
3. Manufacture and verify the simulations of one or more prototype feeds.

Receivers. Today, state-of-the-art low noise amplifiers consist of multiple transistors of limited (20%) bandwidth and very large, cold cryogenic refrigerators, with price tags of order $1M for wideband coverage. MMICs operating at relatively high temperatures using miniaturized cryocoolers offer good performance over bandwidths in excess of 20:1. The expected price is two or three orders of magnitude lower than current technologies and should make an array of tens of thousands of antennas affordable. Suggested development efforts:

1. Design and test MMIC LNAs covering the entire SKA frequency range, with emphasis on higher operating temperatures.
2. Investigate miniature refrigeration and packaging methods with emphasis on the 50-200 K range.
3. Integrate LNAs, refrigeration system, and wideband feed with suitable antenna elements to verify price/performance.

Improving signal processing

HARDWARE. The mega-baselines of a Large-N array and the large bandwidth of the SKA pose processing challenges for a large-field-of-view imager that are orders of magnitude beyond the ALMA or EVLA correlators now under design. [DEFENSIBLE NUMBERS NEED TO GO HERE] This area is ripe for exploitation of the new technologies emerging in the telecommunications industry, and is key to making a Large-N array affordable. Suggested development efforts:

1. Study processing architectures to determine the most cost effective and scalable approach to producing astronomical images with required dynamic range and stability.
2. Determine the most cost effective technologies for processing, connectivity, and data transport at the projected time of construction.
3. Experiment with wideband data transportation schemes to determine whether public resources (if available) could in principle provide the required reliability and phase stability over the maximum likely extent of the SKA, or whether dedicated resources must be used.
4. Construct prototype SKA imagers that can be tested on existing arrays or augment the design of planned array imagers to test SKA concepts.

SOFTWARE. The SKA will be a multipurpose facility. The task of managing the real-time monitor and control of a multi-beam, multi-user array, while dynamically mitigating against RFI, routing high-speed data streams, and efficiently building large multidimensional databases is quantitatively so much more complex than current practices as to make it qualitatively different. [DEFENSIBLE NUMBERS NEED TO GO HERE] While we should not ignore our hard-won knowledge base, it will be important to seek out and adapt innovative solutions to analogous tasks in other disciplines, and test them on existing arrays.

Achieving high dynamic range and resolution over large primary field of view:

CONFIGURATIONS. The elements and stations of a static array must be placed to achieve excellent instantaneous u-v coverage, low-surface brightness sensitivity, and point source sensitivity. The enormous number of baselines in a Large-N array have the potential to accommodate all three requirements with little compromise. Suggested development efforts:

1. Model the hierarchical beam forming process to determine the appropriate distribution of elements within stations, the extent and placement of the central concentration of stations, the maximum extent of the array and the pattern of outlying stations, taking into account the potential for re-using existing infrastructures within some of the national sites being proposed.
2. Augment existing arrays to test the configuration modeling.

SIMULATIONS. The radio sky at the nanoJansky sensitivity of the SKA is unknown, but can be guessed at on the basis of our current understanding. To assist the configuration studies, and define the spatial resolution required for utilization of the million-to-one clean beam dynamic range in the face of the expected source confusion and complexity, detailed simulations of the sky and the Large-N array response must be performed. Suggested development efforts:

1. Evolve existing modeling tools, or adapt appropriate tools from other disciplines to simulate the crowded fields and complex source structures inherent to the high priority science areas highlighted in this roadmap.

2. Iterate the simulations and configuration studies.

New Algorithms. Large-N arrays yield huge amounts of redundant data. In theory, this redundancy can be exploited to achieve the desired dynamic range, excise RFI, assist in calibration, and enable new classes of source and signal detection schemes. Exploration of redundancy-based algorithms and testing on existing arrays should be supported.

Calibration. It is more difficult to use astrophysical self-cal techniques on the small antennas of a Large-N array. Beam shaping becomes critical for achieving the desired dynamic range. Suggested development efforts:

1. Explore hierarchical methods for self-calibration that first calibrate the array at the station level before phasing calibrating individual antennas.
2. Investigate the relative performance and costs of using constellations of LEOs or rented transponders on geosynchronous satellites for LO distribution and calibration.
3. Use existing arrays to test proposed solutions.

Managing interference:

Man-made interference (RFI) poses one of the major technical challenges to achieving the superior sensitivity and dynamic range goals of the SKA across two decades of the spectrum. Aggressive, innovative, and continuous countermeasures will be the price of doing business with the SKA. A Large-N array offers many advantages. No single line of defense is likely to work, and multiple techniques will necessarily be cascaded to permit successful operations.

Characterization. It is necessary to understand in detail the level of current and projected interference from all sources, as a function of location, in order to design the hardware and software of the SKA to be robust and resilient, yet affordable. It is also necessary to categorize the science of primary interest to the US community, to know where performance will be limited, compromised, or unaffected by RFI, and thus prioritize the development work needed to enable the most important research. Suggested development efforts:

1. Support ongoing RFI measurement efforts at existing sites.

2. Develop RFI measurement capability and implement it at potential SKA sites within North America.

3. Derive RFI-suppression performance metrics for each science area of interest.

On-line RFI mitigation. Recent successes with adaptive filtering, stochastic blanking, null-forming, and parametric signal processing indicate that many problems are tractable, given sufficient interference-signal to noise ratios, and processing power. These techniques need to be extended to wider frequency ranges and complex, multiple interferers. Suggested development efforts:

1. Support ongoing RFI mitigation experiments on single dishes, focal plane arrays and existing telescopes.

2. Demonstrate the achievement of specific RFI-suppression performance metrics by application of multiple techniques using existing telescopes.

3. Design real-time hardware and software RFI mitigation systems that are scalable and that can be integrated into the SKA signal processing systems without introducing undesirable distortions. The cost for designs that enable important science areas that otherwise would be inaccessible should be considered a secondary optimization.

4. Test the designs on existing arrays.

Post-processing. Cross-spectral post-correlation processing is effective at removing certain classes of satellite RFI, as are other algorithms developed over years of operational experience with short- and long-baseline cm wavelength interferometers. Continued development of post-processing algorithms on archival datasets should be supported.

Negotiations. It may be possible to site at least the central concentration of SKA stations in an uninhabited (or nearly so) location. This might afford an opportunity for the creation of an international radio quiet zone, including agreements with satellite service providers to switch off transmitters when flying over the site. US participation in such international negotiations should be supported.

Operating a Large-N array:

Siting and logistics. The current strawman SKA concept (pending the outcome of configuration studies) consists of a central concentration of stations within 100 km and a sparser distribution of stations over 1000 km. The most important characteristics for a site are the RFI environment, weather, sky coverage, access, power and water sources. Suggested development efforts:

1. Establish a set of metrics for uniform evaluation of sites in conjunction with the international SKA ISSC.

2. Conduct site surveys at likely sites within North America

3. Prepare and submit the case for the preferred sites (central and dispersed stations) to meet the schedule for a 2005 decision date

4. Cooperate with cognizant authorities to facilitate discussions on establishment of an international radio quiet zone at the central site.

Scheduling and multiplexing multiple projects. The scheduling system for the SKA must be largely automated and capable of balancing the requirements of multiple users and synergetically combining compatible observations. Elements of such software exist already, although the level of complexity far exceeds the experience of the radio astronomy community. Suggested development efforts:

1. Develop or adapt (from other astronomical disciplines or industry) prototype software for real-time automated schedule and control of the SKA.

2. Test on existing arrays.

Data product storage and data mining. The cost of data storage is not likely to be the limiting factor for the SKA. No affordable media/mechanisms exist today, but industry projections are robust and promising. The challenge presented by the SKA is in the organization, cross-referencing, and accessibility of the data. Suggested development efforts:

1. Collaborate in efforts to establish a National Virtual Observatory.

2. Develop data mining algorithms and test them with existing telescopes.

3. Develop algorithms for transient source detection and test them on existing telescopes to determine the required storage duration for different types of data from raw to finished image or spectrum.

System analysis. A detailed and interrelated tradeoff study of the SKA construction encompassing the central facility (monolithic or distributed), the stations of the array, and the site infrastructure, needs to be made in order to minimize the cost and maximize the reliability of the facility.

Annual operating costs. Operational costs have historically dominated the life-cycle costs of large observing facilities. For a twenty-year lifetime, annual operating funds including personnel, maintenance, continuous upgrading of capabilities, RFI-mitigation efforts, power, and security must be kept below 5% of the initial investment in order to counter historical experience. If this could be done, then continuing expansion of the initial facility might be enabled at an accepted level of expenditure. Designing the SKA to be remotely operated by a minimal number of staff offers the greatest opportunity for operational savings. The system analysis for SKA construction should be extended into a life-cycle analysis to include these long-term trades.

8 The U.S. plan

What follows is an opportunistic technology development plan and timeline for the US participation in design of the SKA. The end product will be a design for the SKA implemented as a Large-N array including price/performance estimates for individual components and the system infrastructure. The timescales are set by the ISSC decision date in 2005, and the pace of other technological developments within the US.

8.1 An Implementation Plan that Leverages Ongoing Activities

The US preference for a Large-N implementation of the SKA is based on design studies conducted by several US institutions involved in the implementation of Large-N arrays: the ATA (the Allen Telescope Array being implemented by the SETI Institute and UC Berkeley Radio Astronomy Lab with private funding) and LOFAR (the Low Frequency Array being implemented by the NFRA, the NRL, and MIT/Haystack with funding from NFRA and NRL). These two approaches span much of the strawman frequency range of the SKA, leaving only 150-500 MHz and 11-22 GHz uncovered. SKA development activities aimed at minimizing the cost of Ae/Tsys could profitably experiment with performance extensions of of these two array concepts to achieve complete frequency coverage.

The benefits of multibeaming with focal plane arrays on single dishes (demonstrated so clearly by the 13-beam feed on the Parkes antenna) have been appreciated in the US and design studies are underway to incorporate them at Arecibo and the GBT. These focal plane arrays will provide innovative testbeds for RFI excision schemes.

Phase I of the EVLA will address challenges of wideband correlation, data transport, RFI excision, high dynamic range imaging, pipeline processing, and archival retrieval, while the Phase II project will move the EVLA closer towards a Large-N array covering territorial dimensions that approximate some of those of the SKA.

To the extent that any or all of these projects can be modified or augmented to directly test technology concepts for the SKA, the NSF will be able to strongly leverage its funds.

Both the ATA and LOFAR must devise solutions for wideband, large-field-of-view imaging. Given the intrinsic complexity of Large-N connectivity, neither solution is likely to resemble a traditional lag correlator. Both development efforts will be essential for demonstrating the feasibility of correlation techniques for a Large-N array SKA and for establishing a reliable costing curve.

Both these arrays will also require aggressive interference mitigation strategies. They can incorporate all the successful strategies developed on focal plane and synthesis arrays. They will provide powerful evidence that it will be possible for a Large-N array SKA to operate over much of its desired frequency range outside of the protected radio astronomy bands. This is essential for the eventual funding of the SKA, and it will illuminate the limitations of what can and cannot be done by the passive services to protect themselves. Thus the efforts will provide guidelines for what still needs to be done through negotiations with the active service providers. The ATA and LOFAR represent an important interim step that will impact (in fact, swing) the 2005 international implementation decision.

If LOFAR is sited in the US, and the Large-N array implementation for SKA is selected in 2005, then LOFAR, the ATA, and early components of the EVLA Phase II, can be augmented and expanded into an international testbed hybrid-array. A small number of SKA prototype-paraboloids and other optimized elements can be placed at the ATA, at each of the LOFAR stations, at EVLA sites, and perhaps at the VLA itself. Second generation beam-forming and imaging hardware and software can then be developed. The problems of RFI mitigation, signal processing, and data transport can be explored across all the distance scales pertinent to the SKA. If a North American SKA site is chosen in 2005, then the geographic details of that site would also be factored into this hybrid-array.

By taking advantage of the opportunity to augment arrays already in progress, and then combining them into a second-generation hybrid-array as an international venture, the orders of magnitude gap between current facilities and the capability of the SKA can be bridged with minimal risk, and SKA development funding can be maximally leveraged.

8.2 Suggested Timeline for SKA Technical Development

Table 2 represents the current best estimate for the major milestones of the ATA, LOFAR, and EVLA arrays.

Table 2: MILESTONES FOR THE ATA, LOFAR & EVLA

Milestone	ATA	LOFAR	EVLA Phase I	EVLA Phase II
Start project	1999		2000	2003
Requirements	1999	2000		
Funding	2000		2001	
Site	1999			
Critical Design Review	2002	2004	2003	
Start construction	2003	2005	2003	
First Operations	2004	2006	2005	
Project complete	2005	2007	2008 - 2010	2010

Over the next decade, a multi-faceted SKA technology development plan should unfold as diagrammed in Figure 3.

8.3 Suggested Funding Profile For SKA Technology Development

The appropriate level of funding for SKA technology development will be determined by the availability of individuals and institutions prepared to execute the tasks outlined in the development plan of §7. However, if the timeline in Figure 3 represents the desired development pace, an estimate of the annual funding needed to match that pace is given in Table 3.

9 Outreach

The SKA development effort of the next 5 years will provide numerous opportunities for outreach. These will include:

1. Projects associated with the development efforts themselves posed to undergraduate and graduate students in science and engineering.
2. Leveraging the mass production of small radio telescopes by using them in laboratory courses on radio astronomy techniques. Especially good applications are the detection of the 21 cm line from Galactic hydrogen and galactic OH masers. The same telescopes can be used in SKA development efforts on RFI excision through simultaneous multisite observations.
3. Usage of results of simulations for SKA science feasibility in publications and presentations to the general public. The impact of the SKA in essentially all astrophysical domains provides an excellent opportunity to convey developments at the scientific forefront to a wide audience.

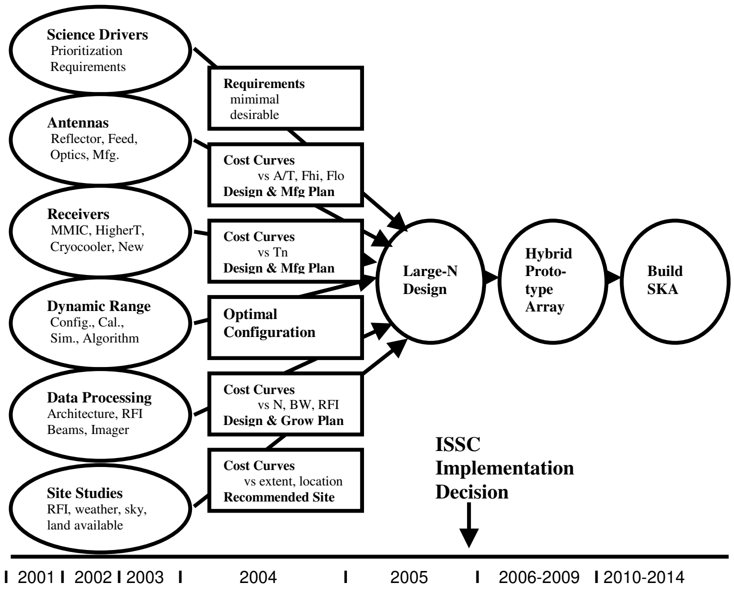

Figure 3: Timeline for the US SKA technology development plan. **(need a new version of postscript file to get better sizing and fidelity)**

Table 3: FUNDING PROFILE

2002	2003	2004	2005	2006-2009	2010-2014
				$30M from other international partners	$400M from other international partners
US FUNDING					
$2M?	$2M?	$4M?	$4M?	$15M?	$200M?

10 Requested Actions from the NSF

We request the NSF to:

1. provide funding and a review structure for a coherent set of development proposals tied together as a single large proposal from a lead institution.

2. also accept auxiliary proposals on related topics that are of direct interest to the US SKA development plan.

3. expedite synergies between NSF initiatives in computer science and astronomy that are relevant to the SKA effort.
