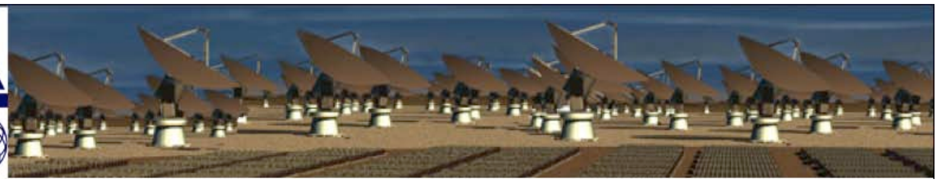

The Square Kilometre Array

Project Description for Astro2010
Response to Program Prioritization Panels
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Summary

The Square Kilometre Array (SKA) is a revolutionary telescope program that will address a broad range of key science areas in galaxy evolution and cosmology, fundamental physics, and astrobiology. It will also be a superb discovery instrument. The key science goals of the SKA are in place and a well-structured, global technology development program is under way. While construction is not funding-ready in 2010, the significant work done to date on technology development and cost estimates will lead to technology choices and definitive costings early in the decade and proposals for phased deployment. Phase 1 comprising low-and-mid frequency arrays will be funding-ready early next decade and Phase 2, defined as the completion of these arrays, is planned to begin in the second half of the decade. A Phase 3 high-frequency array will be funding-ready soon after 2020 upon the completion of technology development and an engineering design phase. The SKA is presented to Astro2010 as warranting high priority in 2010 on the basis of the science case, the level of global interest and commitment at both the scientific and governmental levels, and the comprehensive international technology development program now in place. It is recognized that funding decisions will depend on the delivery of technology-ready, risk-mitigated proposals along with successful completion of milestones. The submission here includes indicative technologies, costs, and timescales. These will be refined using input from both the international scientific community (via the SKA Science and Engineering Committee) and funding agencies (via the Agencies SKA Group) as the SKA program progresses.

The SKA presently involves 55 institutions in 19 countries, with the U.S. as a one-third partner. Activities within the U.S. are organized through the U.S. SKA Consortium that includes 11 organizations, including universities, laboratories, and the two national radio observatories (NAIC and NRAO). The Consortium is conducting an SKA Technology Development Project, funded by the National Science Foundation in accordance with the last decadal-survey recommendation for the SKA, that contributes key expertise and technology to the global design effort.

The primary emphasis of the activity proposed here is on the mid-frequency array (SKA-mid) because the science goals are timely and the world-wide community is working toward bringing the technical readiness level to that needed for construction by the middle of next decade. The baseline design for SKA-mid comprises 3000 15-m reflectors separated by up to a few thousand kilometers. Signal analysis will provide the unprecedented sensitivity, survey speed, and resolution needed for the key science. Two viable sites for the SKA core array have been identified (Western Australia and South Africa), on which precursor arrays will further develop some of the technologies needed for the SKA.

Project milestones over the next few years include site selection targeted for 2012, technology selection, and critical design reviews that will lead to the first phase of construction in ~2015. The anticipated 1/3 contribution of the U.S. is (2009 dollars) ~$725M for construction, $65M/yr for operations, and $10M/yr for programmatic support of U.S. scientists, including a U.S. based SKA Science Center. The draft spending profile for the US starts at about $5M/yr in 2012 and 2013, reaches about $100M/yr during peak construction starting late in the decade and continues near this level for full SKA operations starting in the following decade.

Key Science Goals for the SKA

The international physics and astronomy community has identified a set of Key Science Programs (KSPs) to address fundamental issues in modern astronomy, physics, and astrobiology and for which SKA observations will provide unique and essential information complementary to multi-wavelength and multi-messenger campaigns in astronomy. Given page constraints, we first summarize a few of the primary KSPs and then focus several for which construction beginning in the next decade will yield significant scientific returns. Like all major science facilities, the SKA will conduct a far broader range of observations than described here, as may be seen in *Science with the SKA* (Carilli and Rawlings, eds., New Astronomy Reviews, 2004).

Probing the Dark Ages and the Epoch of Reionization: The most direct probe of the transition of the intergalactic medium from a neutral to ionized state and of the formation of large-scale structure will be obtained by imaging neutral hydrogen. Moreover, as the first galaxies and AGN form, the SKA will provide an unobscured view of their gas content and dynamics via observations of highly redshifted, low-order molecular transitions (e.g., CO).

The Origin and Evolution of Cosmic Magnetism: By measuring Faraday rotation toward large numbers of background sources, the SKA will track the evolution of magnetic fields in galaxies and clusters of galaxies over a large fraction of cosmic time. SKA observations also will address whether magnetic fields are primordial or are generated much later by dynamo activity.

The Cradle of Life/Astrobiology: The SKA will observe the centimeter-wavelength thermal radiation from pebbles in the inner regions of nearby proto-planetary disks and monitor changes as planets form, thereby probing a key regime in the planetary formation process. On larger scales in molecular clouds, the SKA will search for complex prebiotic molecules, and the SKA will provide sufficient sensitivity to enable deep searches for “leakage” radio emissions from nearby extraterrestrial civilizations.

Galaxy Evolution, Cosmology, and Dark Energy: Relevant Science white papers: “How Do Galaxies Accrete Gas and Form Stars?” (Putman et al.) and “The Billion Galaxy Cosmological HI Large Deep Survey” (Myers et al.).

Hydrogen is the fundamental baryonic component of the Universe. Studies of the 21-cm hyperfine transition of HI over cosmological distances were the original driver toward a collecting area of ~1 km^2, and such observations remain an important SKA design requirement. The ultimate goal is a “billion galaxy” spectroscopic survey, which would be a transformational resource for astronomy and cosmology, analogous to that of the current generation of optical surveys (e.g., SDSS) but unaffected by dust obscuration. It will provide a deep sample for comprehensive inferences on dark energy and galaxy evolution.

Galaxy Evolution: HI gas is the fuel of star formation and galaxy evolution; imaging it is key to following the process whereby galaxies collect gas and subsequently form stars. Maximum science will be derived from the combination of studies of atomic hydrogen (SKA), molecular lines (e.g., ALMA), and tracers of star formation and stellar populations (JWST, ground-based optical telescopes).

Observations of HI reveal on-going accretion of cold gas in galaxies, and galaxies with surrounding HI complexes may signal minor mergers or infall of intergalactic gas. Deep HI observations of nearby spirals have revealed cold extraplanar gas, some of which is infalling intergalactic gas.

Further, gas infall may explain extended, sometimes lopsided, HI disks and warps. The sensitivity of the SKA is required to probe cold accreting gas to $z > 0.5$ and in a range of environments.

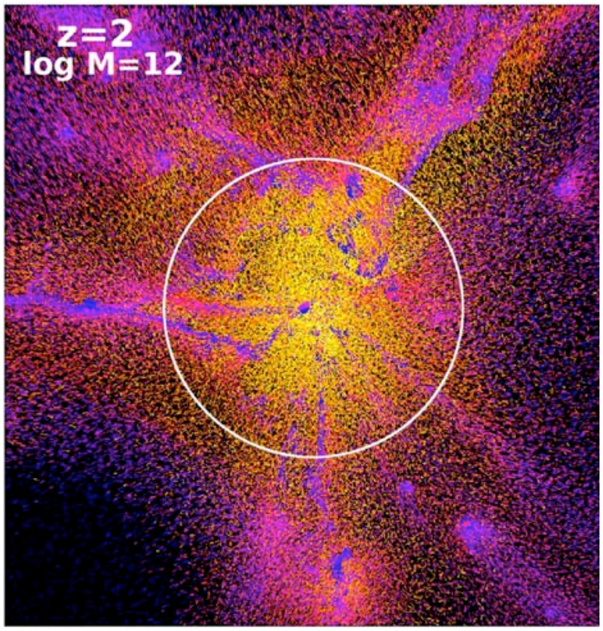

Figure 1—Simulation of a Milky Way-size halo at $z = 2$ being fed by cold streams of gas ("cold mode accretion," Keres et al. 2009, arXiv: 0809.1430). Gas temperature is color coded from blue (~ 10^4 K) to yellow (~ 10^6 K). The circle indicates the virial radius of the halo. SKA HI observations are required to understand the role of cold accretion in galaxy formation.

While the star formation rate evolves significantly from $z \sim 1$, the HI mass density remains effectively constant. Ongoing gas accretion and conversion to molecular form must be important, but the processes are not yet understood in any detail. Absorption-line studies currently measure the HI mass density beyond $z = 0.24$, but they do not reveal how gas is distributed relative to galaxies' star formation nor do they reveal the sequence of accretion and consumption. Only the SKA will have the sensitivity to extend our view to $z \sim 1$ and beyond.

The HI line in absorption will also be a powerful tool for tracing the HI content of galaxies to much higher redshifts ($z > 4$) and along with circumnuclear environments.

AGN and Star Formation: Both star formation (SF) and AGN evolve strongly with time, reaching a peak near $z \sim 2$, but it is unclear what the relation is between SF and AGN. Did the first massive black holes (MBHs) form before or after the first galactic-scale assemblies of stars? What is the role of jet feedback? Tracking the inter-relation between SF and MBH growth will require observations across the entire spectrum, via observations with the SKA, ALMA, JWST, ground-based optical telescopes, and IXO. The SKA can observe the radio synchrotron emission generated by both supernovae and MBH accretion and which penetrates the gas and dust that often obscures SF and AGN at shorter wavelengths.

Recent deep VLA observations indicate a new population of radio-quiet micro-Jansky AGN. High-resolution observations of radio morphology, spectra, and polarization are required to distinguish between SF galaxies and AGN. The SKA, with its unique combination of sensitivity and resolution, will for the first time allow study of "normal" galaxies and radio-quiet AGN at cosmological redshifts. It will provide the means for discriminating between radio emission from SF and AGN and for investigating the co-evolution of galaxies and their MBHs.

Cosmology and Dark Energy: The first decade of the 21st century has seen a cohesive "concordance model" cosmology built upon the successes of the pioneering CMB and galaxy surveys. In this model, dark energy and dark matter are the primary constituents of the Universe, and their densities and properties govern the evolution of the expansion (Hubble constant) and the growth of structure.

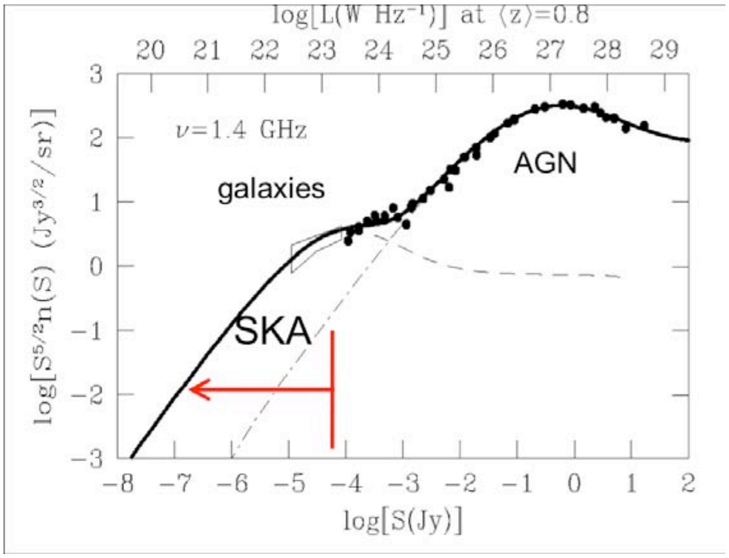

Figure 2 —Source counts vs. flux density S weighted by $S^{5/2}$ at 1.4 GHz. The upper axis shows equivalent luminosity at z=0.8. SKA surveys will probe to sub-micro-Jy levels, as shown, in large scale surveys. Figure adapted from Condon, ASPC, 380, 189.

The emerging focus is on probing the physics of these constituents: Is dark energy a quintessence fluid or a failure of general relativity? Is inflation responsible for the initial conditions? What is the mass of the neutrino? Current data are insufficient to answer these fundamental questions, but cosmological surveys across the spectrum are necessary next steps, as recognized in *Connecting Quarks to the Cosmos* and the Dark Energy Task Force (DETF) report.

For the SKA, a particularly promising approach to dark energy studies is the baryon acoustic oscillation (BAO) signature in the 3D galaxy power spectrum. The objective is to conduct a HI 21-cm line galaxy survey that would provide redshifts, HI masses, and velocity profiles for a large sample of galaxies probing a large volume of the Universe (~ 100 Gpc^3). Exploiting this HI survey for precision cosmological measurements was described as a Stage IV project in the DETF report. An HI BAO survey offers three significant advantages in comparison to surveys at other wavelengths: (1) The detection of a galaxy in the 21-cm line immediately provides its redshift; (2) The HI line of a galaxy is optically thin and is not subject to dust obscuration; (3) Galaxy rotation curves from the HI line provide input for understanding galaxy biasing.

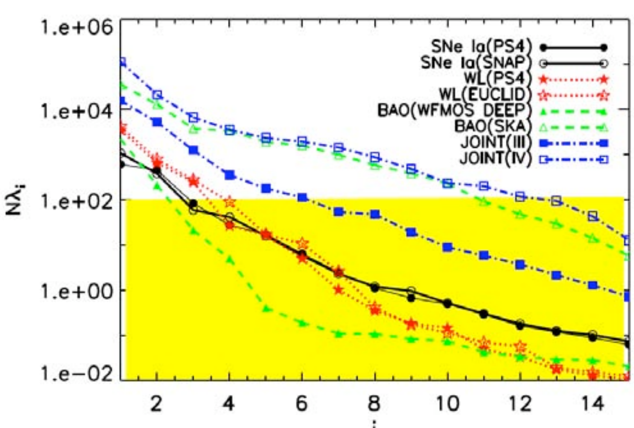

Figure 3—Dark Energy survey capabilities (Tang et al. 2008, arXiv:0807.3140). Shown are the eigenvalues of the Fisher matrix as a proxy for signal-to-noise ratio on dark energy parameterizations; only eigenvalues in the white region are significant. The SKA survey (top green curve) provides superior sensitivity by having a much larger sample of galaxy redshifts than other Stage III or IV experiments, allowing more complex Dark Energy parameterizations and equations of state to be explored.

In addition to BAOs, the SKA cosmological HI survey is rich in astrophysical and cosmological information: (1) Redshift-space distortions and higher-order clustering statistics measure the growth rate of structure, which can be combined with the cosmic expansion history to constrain models of dark energy; (2) Cosmological parameters can be extracted from weak lensing distortions of galaxy shapes in the continuum; (3) Higher-order clustering and topological measures are tests of Gaussianity of the seeds of large-scale structure and the predictions of inflation-inspired models; (4) The shape of the galaxy power spectrum contains information on physics such as the neutrino mass; and (5) Spectroscopic velocities and widths can be used to determine Tully-Fisher distances and to measure peculiar and bulk motions that are inaccessible to purely photometric surveys.

Strong Field Tests of Gravity Using Pulsars and Black Holes: Relevant Science white papers: "Tests of Gravity and Neutron Star Properties from Precision Pulsar Timing and Interferometry," (Cordes et al.), "Gravitational Wave Astronomy Using Pulsars," (Demorest et al.), and "Extreme Astrophysics with Neutron Stars" (Lai et al.).

Pulsars have demonstrated themselves to be impressive laboratories for fundamental physics—two Nobel Prizes have been awarded for pulsar science. The SKA will conduct a two-pronged program that first discovers new pulsars and then does high-precision timing to probe fundamental physics. The first part is a *Galactic Census*. Many of the current tests of theories of gravity and attempts at detecting gravitational wave emission rely on just a few known pulsars. The SKA will survey the Galaxy with the objective of increasing by an order of magnitude the number of millisecond pulsars and neutron star binary systems suitable for further timing.

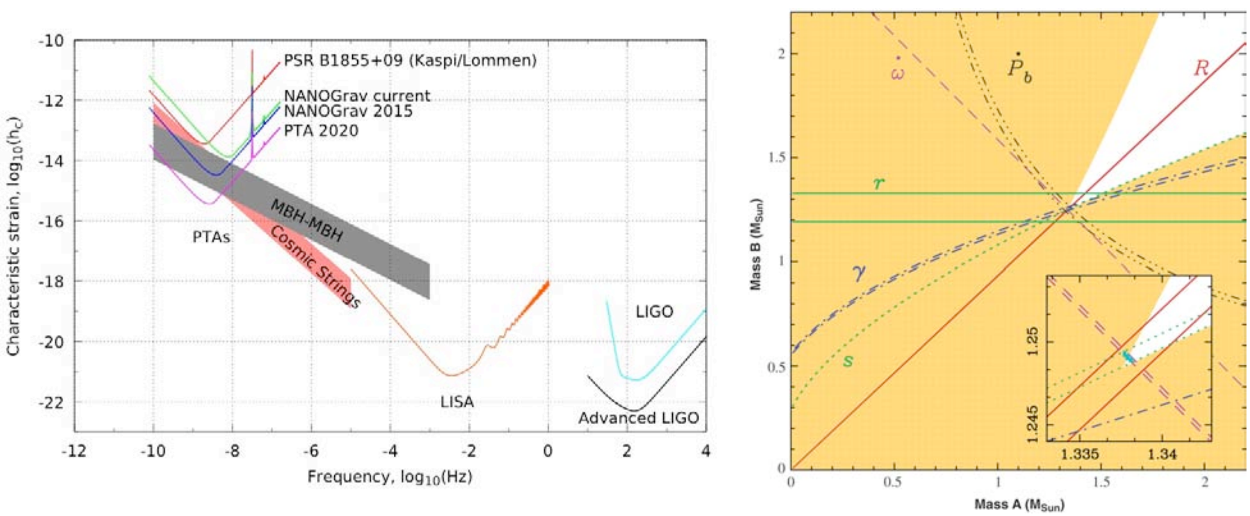

Figure 4 — (*Left*) The gravitational wave spectrum with expected signal levels from various sources and limits set by existing and future pulsar timing arrays (PTAs), including the SKA tagged as "PTA 2020". Sensitivities for LIGO, Advanced LIGO, and LISA are also shown. (*Right*) Testing General Relativity (GR) with the double pulsar PSR J0737–3039. The axes show the possible mass range for the two pulsars in the system. Curves indicate constraints from measured post-Keplerian parameters. The white area is the GR prediction; the inset shows the area around the intersection of the various curves.

The second part of the program exploits the census yield of millisecond and binary pulsars :

Gravitational Wave Astronomy Using Pulsars: Mergers of large galaxies are expected to result in binary massive black holes (MBHs, $M > 10^6\ M_\odot$). The ensemble of MBH binaries in the Universe should produce a gravitational wave (GW) background over a large range of frequencies. By timing an array of millisecond pulsars widely distributed on the sky, the SKA will be a GW observatory sensitive to nanohertz GW frequencies. Changes in the spacetime metric around the Earth, due to the GW background, will be detected by correlated shifts in the pulse times of arrival from millisecond pulsars in different directions. Timing precision of 100 ns is needed on a few tens of millisecond pulsars over a span of 5 to 10 years.

Ultra-relativistic Binaries: Timing of relativistic binaries yields the orbital elements to high precision and, depending on the system, selected post-Keplerian parameters. Studies of the double neutron star system PSR B1913+16 and the double pulsar J0737−3039 have already demonstrated the promise of high-precision timing of double neutron star systems. Post-Keplerian parameters allow determination of the individual stellar masses to high precision (<0.1%) and can also constrain theories of gravity in the strong-field regime to similar precision. Particularly important constraints are made on the maximum mass of neutron stars, the Strong Equivalence Principle, any preferred-frame existence of dipolar gravitational radiation, and secular changes in the gravitational constant.

Exploration of the Unknown: The Dynamic Radio Sky: Relevant Science white papers: “The Dynamic Radio Sky” (Lazio et al.), “Coordinated Science in the Gravitational and Electromagnetic Skies,” (Bloom et al.), and “Exploration of the Unknown” (Kellermann et al.).

Observations at radio wavelengths have a lengthy history of revealing new and unanticipated types of objects and phenomena. Here we focus on the time domain, which is ripe for exploration, as observations over the past decade have revealed new phenomena from known types of sources and have discovered entirely new source classes. Radio observations triggered by high-energy observations (e.g., GRB afterglows), monitoring programs of known high-energy transients (e.g., X-ray binaries), giant pulses from the Crab pulsar, a small number of dedicated radio transient surveys, and the serendipitous discovery of transient radio sources (e.g., near the Galactic center, brown dwarfs) all suggest that the sky is active on timescales from nanoseconds to years. In addition to the known classes of radio transients, the SKA will explore the sky for objects such as orphan GRB afterglows, radio supernovae, tidally disrupted stars, flare stars, exoplanets, magnetars, and transmissions from extraterrestrial civilizations. The surveys undertaken by the SKA will complement surveys at other wavelengths (e.g., PanSTARRS, LSST, and Fermi) and potentially non-photonic observations (LIGO and LISA).

The promise of the SKA for exploring the dynamic radio sky is threefold: (1) The high sensitivity, large field of view, and multiplexing capabilities of an array will enable complete surveys over a significant fraction of the sky; (2) Surveys (both line and continuum) offer a natural platform for synoptic operation to cover the sky repeatedly; and (3) Computational and algorithmic advances will enable commensal observations to achieve multiple science goals.

Technical Description

Table 1 summarizes the broad requirements of the key science projects (KSPs) including frequency range, sensitivity expressed in terms of the system equivalent flux density (SEFD), field of view, and survey speed (defined below). Details of the science requirements are contained in SKA Memo 100, "Preliminary Specifications for the Square Kilometre Array."[1] The required >350:1 frequency range (0.07 to >25 GHz), along with field-of-view, angular resolution, and technical considerations, imply that the SKA is best realized using three different receptor types and configurations:

Low-frequency Array ("SKA-low"): The primary driver —Epoch of Reionization science targeting redshifts of 6 to >15 or < 90 to 200 MHz — is realizable using a dipole array that provides stable, wide-field imaging capabilities for three dimensional mapping of the cosmic web. Detection and mapping of the HI EoR signal is contingent on important studies now being done with experimental low-frequency arrays (MWA, PAPER, LOFAR), which will inform the design of SKA-low with regard to imaging algorithms, collecting area, and the configuration needed for mapping HI structure. SKA-low in turn can benefit from preparations for SKA-mid that include establishment of radio-quiet zones at the two candidate SKA sites and because there is considerable potential for joint use of required civil and digital infrastructure. Specific plans may be found in the Astro2010 submission by Backer et al. for HERA (Hydrogen Epoch of Reionization Arrays).

Mid-frequency Array ("SKA-mid") *(The focus of this Astro2010 paper)*: Galaxy evolution and cosmology, pulsars and gravity, cosmic magnetism, transients, extrasolar planets, and SETI require fast-survey capabilities from 0.3 to 10 GHz. A realizable system can be based on a large-N array of dish reflectors outfitted with single-pixel feeds and receivers, possibly enhanced by field-of-view expansion systems to increase survey speed. Further discussion is given below.

High-frequency Array ("SKA-high"): Studies of protoplanetary disks (and other thermal sources) and the high-redshift universe, including the first stars and black holes, and organic molecules require a dish array operating to 25 GHz and preferably to 50 GHz on a site that minimizes tropospheric effects. SKA-high science is highly complementary to some of the primary goals for the EVLA and ALMA, both of which will come to fruition in the first half of the next decade. The SKA can sample debris disks that are optically thick at ALMA wavelengths and too weak to detect with the EVLA. An SKA-high implementation plan for the frequency range, configuration and other specifications must be informed by science and technical results from EVLA and ALMA on disks, CO from high-z galaxies, and pulsars in the Galactic center. Consequently, construction of SKA-high can await these results and be funded in accord with the fulfillment of other priorities in the next decade. Technology development for SKA-high is needed in the 2010-2020 decade that will build upon SKA-developed antenna technology under the current U.S. SKA TDP and extrapolated to higher frequencies. An implementation plan is given in the Astro2010 submission for the North American Array (Myers et al.).

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[1] Available at http://www.skatelescope.org/pages/page_astronom.htm; click on SKA Memo Series

Table 1: Technical Specifications for Key Science Programs (KSPs)

KSP	KSP Description	Frequency Range			SEFD (Jy)	Survey Speed	b_{max}	Other Requirements
		Low	Mid	High	Jy	(Deg /Jy)^2	km	
1	**The Dark Ages**							
	EoR				0.1 - 3		1	dynamic range, pol
	First Metals				0.2		125	
	First Galaxies & BHs				0.14		3000+	dynamic range, pol
2	**Galaxy Evolution, Cosmology & Dark Energy**							
	Dark Energy					800	10	
	Galaxy Evolution				0.14		>100	
	Local Cosmic Web					3	1	
3	**Cosmic Magnetism**							
	Rotation Measure Sky					25	Tens	polarization
	Cosmic Web					13	5	polarization
4	**Gravity, Pulsars & Black Holes**							
	Galactic Survey				0.2 - 2	13	~1	
	Gravitational Waves				0.2 - 2		Any	polarization
	BH Spin				0.2 - 2		Any	polarization
	Theories of Gravity				0.2 - 2		Any	polarization
5	**Cradle of Life**							
	Protoplanetary Disks				0.4		3000+	
	Prebiotic Molecules				0.4		Tens	
	SETI				0.2 - 2		Any	
6	**Exploration of the Unknown**							
	(e.g. Transients)				Small	Large	Any	Large Field of View

Notes: FoV = field of view defined by beam solid angle of single dish + single-pixel feed
SEFD = System Equivalent Flux Density = system temperature / gain $\propto T_{sys} / A_e$ (smaller SEFD is better)
Survey speed = FoV/SEFD^2 $\propto$ FoV$(A_e/T_{sys})^2$
b_{max} = maximum baseline needed to achieve required angular resolution

Performance Parameters for SKA-mid Science: KSPs are heavily oriented toward surveys but also require sustained follow-up observations, such as pulsar timing over several to many years. Not to be forgotten are new discoveries from across the entire electromagnetic spectrum and from non-photonic messengers (neutrinos, other cosmic rays, and gravitational waves) that will undoubtedly spawn the need for targeted observations with the SKA in both small and large programs. The broad requirements for key SKA-mid science are:

1. **High sensitivity**: detection of galaxies with 5×10^9 $M_\odot$ of HI at a redshift z=1 requires 100 hr of integration for sensitivity A_e/T_{sys}=1.2×10^4 m^2 K^{-1} equivalent to SEFD=0.23 Jy. The sensitivity corresponds to ~1/3 square kilometer of effective collecting area with a 30 K system noise temperature (early discussions of a full square kilometer were based on higher system noise). A full Galactic census of pulsars and timing precision for detecting nano-Hertz gravitational waves requires 10 to 100 times greater sensitivity than currently available in the southern hemisphere. The sensitivity requirements translate into a large-N

array of small diameter antennas (LNSD); e.g. ~3000 15-m antennas, the exact number depending on system temperature and tradeoffs associated with desired survey speed field-of-view enhancements. Small-N arrays of large reflectors do not satisfy imaging requirements.

2. **High Survey Speed and Field of View:** Extragalactic source surveys for Galaxy Evolution and Cosmology, the Dark Ages (the first AGNs), and for Cosmic Magnetism require full sampling of available sky over reasonable survey durations of, say, five years. Pulsar surveys also must be done efficiently. For steady, broadband sources, the survey speed is $SS = FoV \times B/SEFD^2 \propto FoV \times B(A/T)^2$, where $FoV \sim \lambda/D$ is the field of view provided by a reflector of diameter D with a single-pixel feed and B is the bandwidth. (For simplicity in Tables 1 and 2 we do not include the B factor.) Tradeoffs between the various factors are now being explored in research and development of low-cost collecting area (A_e), low-noise receivers (T_{sys}), wide-bandwidth systems (B) and maximal field of view. Larger FoV can be achieved by using smaller-diameter antennas or by using phased-array feeds to provide multiple pixels, but at the cost of much greater digital processing. Significant R&D now concerns the development of such systems along with planar aperture arrays and the required real-time and post processing.

   Surveys for transient radio sources alter the tradeoffs, particularly for fast transients with durations less than 10 s, because the net integration time is the event duration rather than the telescope dwell time. Transient surveys therefore place a greater emphasis on FoV alone in order to sample the sky with a high completeness factor.

3. **High-performance Algorithms and Processing:** The SKA has processing requirements that greatly exceed those of existing arrays because of the large number of antennas. Signal transport from antennas to a central real-time processing site is at a rate of 160 gigabit s^{-1} for an 8 GHz bandwidth. The rate, distance and cost are highly dependent on the schedule of antenna deployment next decade (e.g. compact array first, long baselines later) and on how distant antennas are "stationized" by combining signals from antenna clusters before long-haul transport. The ATA and EVLA have already paved the way for use of dedicated optical fiber and eVLBI in Europe has demonstrated the use of commercial fiber networks for real-time imaging.

   SKA correlator feasibility has been demonstrated in paper studies that take into account expected Moore's-law advances and real-world developments in ASIC designs and specialized processors from IBM and other vendors (e.g. GPUs). A detailed design will be done as part of the engineering-design activity leading to Phase 1 construction.

   New aperture synthesis algorithms are being developed to provide the dynamic range needed for deep continuum surveys (10^6-10^7) that will reach sub-micro-Jy levels. Dynamic range issues also drive reflector choices toward designs that provide small and stable sidelobes in the beam pattern.

   Spectroscopic and time-domain surveys place less stringent requirements on dynamic range but need many spectral channels and high time resolution that also increase the throughput requirements on the digital processing.

Baseline SKA-mid Project: The baseline project is an LNSD array outfitted with single pixel feeds in a configuration that enables both low-surface brightness science, high-throughput time-domain and spectroscopic surveys, and high-angular resolution imaging. Table 2 summarizes the salient features. The antenna diameter for fixed total sensitivity is tentatively identified to be in the 12 to 15 m range, as demonstrated in Figure 6, which is an optimization example from SKA Memo 100.

Table 2 Baseline Specifications for SKA-mid LNSD Design

Attribute	Nominal Values
Frequency Range	0.3 – 10 GHz
Sensitivity (SEFD, A_e/T_{sys})	0.23 Jy or 1.2×10^4 m^2 K^{-1} at 1.4 GHz
Survey Speed	6×10^7 deg^2 m^4 K^{-2} or 8 $(deg/Jy)^2$ at 1.4 GHz
Antenna diameter	15 m (possible range: 9 to 15 m)
Number of antennas	3000 (subject to antenna diameter at fixed total sensitivity)
System temperature	30 K
Processing bandwidth	Full frequency range
Configuration	20, 50, 75, 100% of dishes within 1, 5, 200, 3000 km of core-array center
Signal Transmission	160 Gbps per antenna for antennas nearer to core than 200 km 160 Gbps per station for distances >200 km (40 stations)
Signal Processing	Direct correlation of antennas out to 200 km (2280 antennas) Correlation of station signals for distances > 200km (40 stations)
Feed antennas	Broadband single-pixel feeds (0.3 – 10 GHz)
Innovation Paths for Survey-speed Enhancement	Radio Cameras (Phased-array feeds), Aperture Arrays

Operating Modes: The surveys comprising SKA key science, though diverse in their sampling and processing requirements, can share the most precious commodity: telescope time and sky coverage. Conducting surveys simultaneously is highly desirable but challenging. Precedents for *commensal observing* are now being made at Arecibo and the ATA and are planned for low-frequency and mid-frequency SKA pathfinders (LOFAR, MWA and ASKAP). They will be an integral part of the SKA design, placing strong demands on the correlator, beam formers, and science-specific backend processors. Tradeoffs in the SKA design must also factor in the total time available to conduct a survey. SKA surveys will be highly synergistic with those across the entire electromagnetic spectrum and with gravitational wave and cosmic-ray telescopes, including real-time reports of transient events. The SKA and its data products will be accessible through an open-skies policy.

Signal Detection and Computing: The real-time data rates require that substantial processing occur in near real-time, both for visibility data used for imaging and for summed- or phased-beam data used for commensal observations (e.g. transient detection). In this operational mode, a global sky model will be accumulated for real-time calibration, along with array image products, but without long-term archiving of raw visibility data. Signal conditioning including mitigation of radio-frequency interference is anticipated before and during correlation. The data and associated processing rates require high-performance computing at Petascale to Exascale levels, likely including hardware acceleration. This level of peak computing power will be available on the construction time scale of SKA-mid through geometric growth predicted by Moore's Law and by industry, but investment in algorithm scalability on anticipated high-end computing architectures is required. SKA-mid poses important requirements on data management, long-term curation, and

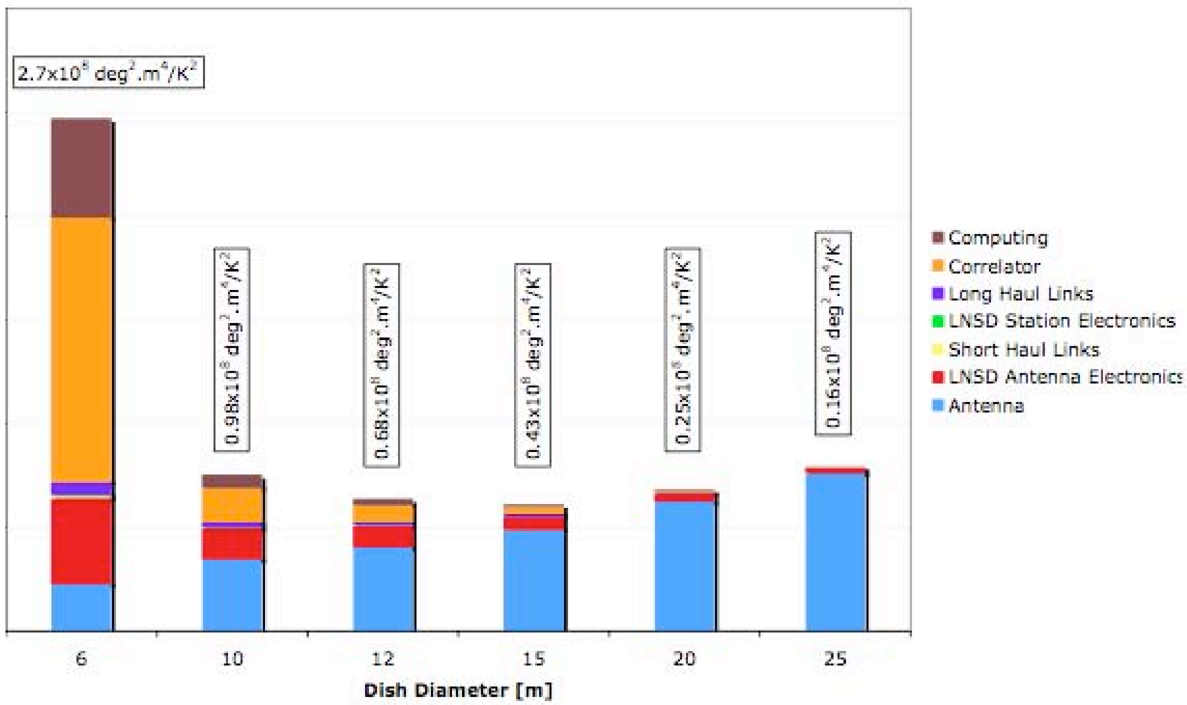

Figure 6 — Example of cost optimization showing relative array costs versus dish diameter for an SKA mid-band array with a fixed sensitivity of $A_e/T_{sys}=10^4$ m^2 K^{-1}. The survey speed varies and is given above each bar. Antenna costs dominate at large diameters while electronics and processing costs dominate at small diameters. This and other cases are given in SKA Memo 100.

community access to SKA science products. A set of regional data and science centers is anticipated, including a North American Science Center, linked by high-bandwidth networks. Secondary analysis of archived data by the community will be supported by these science and data centers. At all levels, SKA-mid computing requirements pose large data challenges, an order of magnitude greater than contemporary large-data projects such as LSST, for example. The data and computation problems are at a scale, and incorporating sufficient leading-edge technical innovation, to be of substantial interest to industry and academic partners in computational science and engineering. Leveraging this inter-disciplinary and industrial expertise is an integral element in SKA-mid development planning.

Siting, Infrastructure and Construction: A site-identification process in 2005-2006 considered radio frequency interference, atmospheric and ionospheric conditions, and local programmatic issues, leading to two acceptable sites for the SKA core: the Karoo desert in South Africa and the Murchison region in Western Australia. Outlier antennas may reside in other countries to provide requisite long baselines. Infrastructure (roads, power, optical fiber and operations buildings) are now being emplaced on both sites for the precursor arrays that will be constructed over the next few years (ASKAP = Australia SKA Pathfinder and MeerKAT = Meer Karoo Array Telescope). The SKA project, via the SKA Science and Engineering Committee, will make a site recommendation in mid-2011 that will be considered by international stakeholders, leading to a final selection targeted for 2012. Additional infrastructure for the SKA will be installed as needed over the pre-construction phase of ~2012-2015.

Technology Drivers

Background: Radio astronomy has always been fundamentally dependent on the rapid development of technology, both in hardware and processing techniques, producing continual advances in sensitivity and spatial, temporal, and spectral resolution. The sheer scale of the SKA with its enormous collecting area and data rate presents an unprecedented challenge, demanding new approaches to designing radio telescopes and a need to build on the tradition of technological innovation.

The two principal technological challenges of the mid-frequency range SKA are:

1) Achieving science-demanded sensitivity at minimum cost, with sufficiently wide fields-of-view to achieve key survey science, and
2) Identifying signal/data processing methods that will reach needed sensitivities in imaging, spectroscopic and time-domain observations.

Technological requirements for the SKA have been intensely investigated over the last decade using the combined expertise of a multinational collaboration, including the NSF-funded U.S. SKA Technology Development Project (TDP) to address the two key challenges. Initial institute-level efforts have led to a coordinated, global effort under the leadership of the SKA Program Development Office that targets reaching sufficient technological maturity to begin detailed design of the SKA by 2012.

Technology Driver 1: Maximizing Sensitivity and Survey Speed at Minimum Cost

Attaining low-cost sensitivity implies a technology development program aimed at investigating possible antenna types and wide-bandwidth amplifier/feed designs, keeping in mind the requirements of the large key science surveys. This is one of the primary areas of the TDP.

For the baseline design in Table 2, obtaining the high dynamic range needed to fully exploit the sensitivity of the SKA, pointing precision better than 1% of the primary beamwidth at 2 GHz and surface accuracy better than 1 mm rms are needed. Many factors need to be considered, including performance and cost as a function of dish/mount design and dish diameter, manufacturing methods and suitability for mass production, durability, maintenance requirements, thermal and gravitational deformations, pointing accuracy, and field-of-view capability. The TDP is leading an international effort, along with industry partners, to identify the best options for the parabolic dishes. Several antenna prototypes using both monolithic (hydroformed) and composite designs are being built and tested, some in conjunction with new SKA prototype arrays (e.g., ATA, ASKAP, MeerKAT). A new Chinese antenna design, destined for installation and testing in the ASKAP array, serves as an existence proof for meeting SKA performance and cost specifications, but even better solutions are expected.

The SKA baseline design goals include broad-band single-pixel feeds and low-noise receivers capable of up to 10:1 frequency coverage with system temperatures of ~30K. Feed designs under consideration fall into two general classes: log-periodic dipole-like structures (development at UC Berkeley and Cornell) and ridged-horned structures (Caltech/JPL). Both are being investigated as part of the TDP. Decade bandwidth LNAs (Caltech) will utilize either MMIC or CMOS processes, with much of the receiver chain integrated on one device. If adequate performance of such wideband feed/receiver modules is not achieved, multiple narrower bandwidth devices could still meet the design goals.

The nominal-diameter parabolic dishes of the SKA will produce quite broad antenna beams (~1 deg^2), but even broader fields-of-view are desirable for some of the key science surveys. Extensive international SKA technology development is aimed at producing mutually-coupled, phased-array feeds (PAFs), which could provide a large number of simultaneous antenna beams on the sky and dramatically improve the field-of-view for the band of interest for redshifted HI (<1.4 GHz). Significant progress is being made on PAFs by groups in Australia, Canada, the Netherlands, and in the U.S. at NRAO and BYU. The major challenges for PAFs are to provide stable, calibrated beams in real time and to reach system temperatures competitive with those of single-pixel feeds. Another innovation path, being pursued in the Netherlands and the U.K., would be to cover the lower portion of the frequency range (0.3 GHz to perhaps as high as 1 GHz) with a large array of planar phased-array tiles (aperture array) independent of the parabolic dishes. Figure 7 illustrates two of these efforts.

Figure 7— (*Left*) Example "checkerboard" phased array feed (PAF) for the Australian SKA Pathfinder project (Photo credit: David McClenaghan, CSIRO). PAFs will greatly increase the survey speed of the SKA. (*Right*) An alternative approach is to use phased arrays to sample the sky directly, as in European efforts to develop aperture array tiles (courtesy SKADS project).

Technology Driver 2: Identifying Signal/Data Processing Methods

The processing challenges for the mid-frequency range SKA are driven by three key factors: (i) the raw post-correlation data rates, (ii) the computational cost of calibration and processing for imaging and non-imaging science, and (iii) the level of calibration required for routine high dynamic-range imaging required by the science goals.

The large post-correlation data rates are a direct result of the large number of antennas. Cross correlation of all stations with complete polarization information, wide fields of view, and up to 32k frequency channels can lead to data rates of 90 to 900 GB s^{-1} at the correlator output for a *single* beam. Multiple simultaneous beams increase the data rate proportionately. Fortunately, several promising techniques to mitigate the data processing load could be deployed in a staged manner over the early lifetime of SKA, while exploiting the exponential increases in computing power that will become available by virtue of Moore's Law. It is also believed that part of the solution will involve special purpose hardware to perform the initial stages of post-correlation processing to relieve the general-purpose computers of the burden of extreme data rates.

Calibration and Processing: The computation cost of calibration and image formation increases as the product of the post-correlation data rate and the processing required per byte of correlated data to form a calibrated, deconvolved (where necessary), wide-field image. The predicted computational rates are in the petaflop to exaflop regime, depending on the angular image extent and number of spectral channels, but again, these requirements can be judiciously staged to exploit the exponential increases in peak supercomputer performance that will be available in the 2010–2020 decade.

Calibration and imaging techniques will need to achieve a dynamic range of 10^6:1 in routine continuum imaging and possibly greater in targeted fields. For wide-field survey imaging, the calibration issues are focused on adequate characterization and correction of direction-dependent calibration effects and a host of other calibration effects that become significant in this dynamic range regime.

Non-imaging science, such as pulsar and transient searches, also places strong requirements on post-processing. The non-imaging post-processing is anticipated to routinely operate simultaneously during other survey observing programs and will rely on summed-output signals at high time sampling, generally aggregated from the inner core array (the inner 5 km). As with imaging post-processing, it will not be possible to record raw summed-voltage output data over long periods for subsequent off-line data analysis. However, it is possible that detected transient events could trigger higher, temporary rates of burst-mode data capture. Non-imaging post-processing overlaps with requirements for mitigation/excision of radio-frequency interference, and these techniques will need to be developed jointly.

Archiving and Curation: The mid-frequency range SKA will operate in an era of large survey telescopes planned across a wide range of observing wavelengths, all pursuing complementary goals in modern astrophysics and cosmology. Hence, it is essential that SKA science data products, including large Peta- to Exabyte archives, be broadly available to the full astronomy community so that they can be independently analyzed and combined with data from surveys at other wavelengths. This will require an investment in data management infrastructure that is tightly integrated with community data archive standards (e.g., the Virtual Observatory), a data distribution network from the telescope site to multiple primary archive sites, and subsidiary regional data centers to support community astronomers.

The signal/data processing challenge of the SKA poses significant operational differences from current radio interferometer arrays, but not necessarily issues of concern. The current set of global technology research programs, including a part of the TDP led by UIUC, and experience with prototype SKA arrays will provide key insights into these issues.

Activity Organization, Partnerships, and Current Status

From the start, over ten years ago, the SKA has been a global effort. Some 55 institutions in 19 countries currently participate in the SKA design and activities. Top level governance is via an International Collaborative Agreement (ICA) to establish the SKA Science and Engineering Committee (SSEC) and a Memorandum of Agreement (MoA) to establish the SKA Program Development Office (SPDO) at the University of Manchester, U.K. The SSEC provides scientific and technical oversight of the SPDO. It has eight representatives each from the United States, from Europe, and from the "rest of the world" (Australia, Canada, China, India and South Africa). Observers from Japan, New Zealand, Russia and South Korea attend SSEC meetings and are expected to join the project in coming years. Fiscal oversight of the SPDO is the responsibility of the SSEC Executive Committee, whose current Chair is from the U.S. (K. Kellermann).

The SPDO is staffed by a Director, a Project Engineer, and a U.S. Project Scientist (J. Lazio, NRL), an Executive Officer, a half-time Outreach Officer, and an Office Manager, all supported by funds made available through the MoA by the participating parties. The U.S. pays 1/3 of these costs (€ 232K for the calendar year 2009). The technical staff of 8 senior engineers and software personnel is supported through a contract with the European Commission for the Preparatory Phase of the SKA (PrepSKA). The work of the SPDO is also supported by several international Working Groups and Task Forces as well as by the extensive development work in Europe, Australia, South Africa, Canada, and the U.S. Three policy work packages dealing with SKA governance, procurement, and financing are supported by PrepSKA. External advisory committees report to the SSEC.

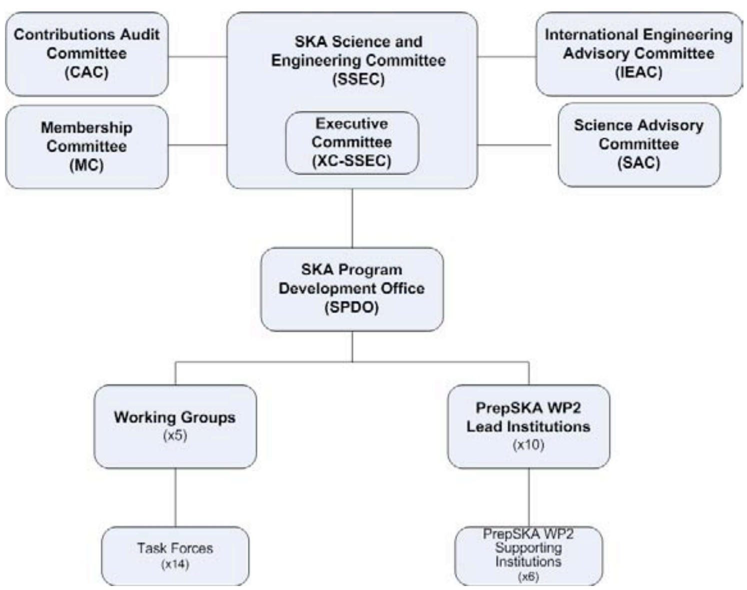

Figure 8 — Organizational chart for the SKA Project.

U.S representatives on the SSEC are elected by the U.S. SKA Consortium, which consists of two representatives from each of 11 dues paying institutions (research universities, research centers, and national observatories). Technical design and development work in the US and the SPDO are supported by a NSF funded Technology Development Program (TDP) administered by Cornell University.

The international funding agencies have formed an Agencies SKA Group (ASG) to consult and interact with the SKA project on scientific and technical matters and to deliver a non-binding joint agreement on the implementation of the SKA in the 2011/2012 timeframe. Representatives from Australia, Europe, India, Japan, New Zealand, and South Africa, as well as the U.S. (NSF), participate in the ASG.

SKA Activity Schedule

The SKA development and construction program is a multi-decade activity that began in the 1990s and will extend past 2020. The next decade, 2010-2020, is the time for bringing to fruition current work on new technologies, design of the SKA, and a governance model into a construction project and an operations phase. Starting with the present decade, the broad activity schedule includes:

1997-2007	Evolution of the science case, science requirements, concept design, preliminary technology development programs, establishment of International SKA Steering Committee (ISSC), International SKA Project Office (ISPO), U.S. SKA Consortium, and development of preliminary specifications (SKA Memo 100). Acceptable sites for SKA-low and SKA-mid identified in 2006.
2005-2008	Start of formal SKA-oriented design efforts (SKADS, U.S. TDP, and PrepSKA) (SKADS=SKA Design Studies concentrating on aperture arrays)
2008	Initiation of new governance structure, replacing the ISSC with the SSEC and the ISPO by the SPDO
2009-2013	Technology development continues with design reviews and technology down-selects. The U.S. TDP and PrepSKA will finish in 2011-2012. Continued assessment of SKA sites. Construction of precursor arrays on the two candidate sites (ASKAP, MeerKAT) with first science results expected 2012-2013.
2010	Completed Reference Science Plan
2011	Technical Selection for Baseline System
2012	Site Selection and Completed Deployment Plan for Telescope
2012-2013	Costed System Design from PrepSKA complete, initiation of detailed engineering design
2013	Initial Infrastructure Emplacement on SKA Site
2013-2018	Technology Development Project for SKA-high
2015	Production Readiness Review for SKA-mid and SKA-low
2018	Phase 1 Construction Complete
2018-2020	Full construction ramp up of Phase 2; identification of site for SKA-high in Phase 3 construction
2022	Completion of Phase 2, begin construction of SKA-high.

An imminent action is to make a final decision to select the SKA location. A short list of two acceptable sites – Australia and Southern Africa – was provided to the funding agencies in 2006 by the International SKA Steering Committee (predecessor of SSEC) following proposals from four countries and a site testing campaign. Additional tests are being performed on these two sites and a recommendation will be made to the ASG by the SSEC in mid 2011. The ASG will develop a process to make the final decision, with 2012 as a target date.

Current activities on design and development (TDP, PrepSKA) and identification of a governance model will conclude in 2012. The subsequent engineering-design phase will bring the project to construction readiness in 2015. A vigorous construction program will require the remainder of the decade and part of the next.

Phased construction: While construction of the SKA can be viewed as a continuous process extending over a ~10 yr period, it is also useful to consider several phases that better match programmatic and funding cycles, as discussed in SKA Memo 100, which refers to three phases of deployment:

Phase 1: Initial deployment of the SKA-mid array will lead to the first phase of observations. The scale of Phase 1 is approximately the geometric mean of the full SKA-mid (3000 antennas) and the largest current instrument (VLA, 27 antennas) weighted by effective area, or a few hundred antennas. Key milestones for science capabilities along the way are to reach the sensitivity of the EVLA and then Arecibo (respectively, four and twelve times that of the current largest telescope in the southern hemisphere: Parkes, 64m) combined with orders of magnitude better survey speeds and imaging capabilities. As appropriate, a follow-on SKA-low array consistent with developments in EoR (and other) science will be initiated.

Phase 2: Completion of the SKA-mid array with the nominal 3000 antennas and an SKA-low array with full science capabilities.

Phase 3: Implementation of SKA-high in accord with technology development and pathfinder observations in the 2010-2020 time frame, with construction primarily taking place after 2020. The siting of SKA-high is yet to be determined.

Cost Estimates for SKA-mid

We discuss costs in terms of 2009 Euros, the working currency of the SKA. The capital construction cost is estimated to be €1670M, and the operations costs €150M/yr. It is expected that the US will contribute 1/3 of these amounts ($724M, $65M/yr at a 1.3:1 exchange rate) and $10M/yr to support U.S. scientists and a U.S. based Science Center with the remaining construction and operations costs to be equally shared by Europe and the Rest of the World.

Construction Costs: While the SKA design is still being developed with a goal of delivering a costed proposal in 2013, we give here the cost of the baseline design for SKA-mid given in Table 2 based on our ideas of how to design and build the SKA using current technology (SKA Memo 100), and taking into account implementations in various SKA pathfinding activities, savings from mass production, and projections based on expected advances in digital signal processing. The baseline design consists of 15m parabolic antennas, each equipped with a single pixel wideband feed/receiver combination extending up to 10 GHz. Additional functionality providing significantly increased survey speed, achieved from multi-element phased array feeds and/or aperture arrays, will be adopted with a corresponding reduction in other areas, if the technology proves cost effective after further development and testing. The cost for the phased array feeds and aperture arrays is currently less well understood than the parabolic dish array. The SKA project also includes a low frequency component, covering 70 – 450 MHz, at a cost of ~250 M€, but this is not discussed here in view of other complementary White Papers which cover the low frequency band.

Civil Works: The civil costs include land acquisition, grading, antenna foundations, power supply to central and remote stations, backup power, power reticulation, security, roads, water provision, small buildings at each station and the main buildings. An initial estimate is €90M for the central site including power access, buildings and antenna foundations. The estimate for the remote sites including power, buildings and antenna foundations is €25M, and €55M has been budgeted for land acquisition, roads, security, stores, offices, laboratories and water provisioning. The total for civil works is thus €170M.

Antennas & RF Systems: We adopt a unit cost of €160K for the antennas and €40K for the receiver systems. The antenna cost is the same as that for the 12m dishes being constructed for the Australian SKA Pathfinder by the CETC54 company in China. Mass production in large numbers and the use of other fabrication techniques now being investigated is expected to reduce the unit cost for 15m dishes to the current cost of the 12m examples.

Signal Transmission: Signal transmission cost estimates assume 2280 dishes with data rates of 160 Gbps per dish for distances less than 200 km from the core-array center. At distances greater than 200 km, there will be 720 dishes in 40 stations, with a 160 Gbps data rate per station. Leased dark fibers, already in place, will be used wherever possible to reduce the capital costs of the fiber infrastructure. The costs include budgets for an estimated 1500 km of trenching within the inner 200 km array and a further 1000 km of trench to connect stations, at long baselines, to a network of 20,000 km of leased dark fiber lines. Signal transmission costs also include allocations for monitor and control, and clock distribution networks. The total capital cost is estimated to be €90M.

Signal Processing: In most previous radio astronomy instruments the cost of the correlator system has been less than 5% of the total cost, excluding infrastructure. The SKA correlator will be more complex due to: 1) The Phase 1/Phase 2 construction model, which implies a correlator for Phase 1 at an early stage; and 2) During the 5-7 yr construction timeframe for the full SKA, substantial gains in performance/cost ratio can be achieved. We devote a fixed cost for signal processing, €100M, split between initial and final correlators, but heavily overlapped in development time, with the first generation correlator costing much less than half of the €100M.

Software Development and Computing Hardware: SKA software includes 1) observation preparation 2) telescope operations 3) monitor and control 4) data handling, storage and distribution 5) calibration and imaging, and 6) special data processing (e.g. pulsar data). Additional effort is required for algorithms developed in parallel with the previous items. Items 1 and 2 can be adapted from existing large telescopes and will consume only a small fraction of the total software effort. Item 3 will be based on industrial standards, and use commercially available hardware and software sub-systems wherever possible, at a cost of €30M. Items 4-6 will draw in part on existing code and methods (e.g. CASA, AIPS). Studies of similarly large software projects indicate that about 1000 Person-Years (PY) is required to produce a robust code base of ~10^6 lines of code. Some fraction of items 5 and 6 is expected to be developed by the survey project teams. The total software effort over a 7-10 year period at the central organization is expected to be ~1000PY (100-150 people). An exaflop scale computer costing ~€100M will be needed. A rough estimate for data storage and distribution hardware is ~€20M. The total capital cost will be €150M for hardware and ~1000PY (€100M) for software.

Design, Integration, and Testing: We extrapolate upon experience with the EVLA, ALMA, LOFAR, and ATA projects, although the SKA is larger and more complex. An initial estimate suggests a staff of 100 people, working 7 years, for a total of €70M. Many of these people will be later absorbed into the operations staff.

Project Management and *Contingency:* We have included an additional 10% of the direct costs for project management, and we have allowed for a contingency equivalent to 20% of the estimated direct costs reflecting the uncertainties of extrapolating signal processing and other costs 5-10 years from now and cost savings due to mass production. An alternative approach to contingency is to build to a cost cap by reducing the number of antennas (sensitivity), the frequency range, the number of long baselines (resolution), or the number of phased array beams.

Operating Costs: As for other major facilities, the full life cycle costs of the SKA will be dominated by operations, and not construction. We base our estimates of operating cost on experience gained from the VLA and the VLBA and from current plans for ALMA operations. For SKA there are four theatres of operation: a) the "headquarters" activities located within a few hundred km of the center of the array which includes scientific, engineering, computing, operations, and administrative staff; b) the central technical support center located near the array center with technical, electronics, and facility maintenance staff to support the operation of the "core" site (e.g., those antennas accessible within a working day); c) distributed activities at a number of remote support centers located beyond a few hundred km from the center; and d) a network of global regional science centers supporting the "local" user community.

SKA telescope operations will be conducted from the headquarters site. The central antennas and the central processing facility can be operated and maintained by a staff which provides administrative services, buildings & grounds maintenance, antenna, cryogenic, electronic, and computer maintenance. We estimate that this will take about 200 engineers and technicians, 50

PhD scientists, 20 individuals to support computing hardware, 40 for systems work and communications, 20 to support monitor and control systems, and 30 for data management. We assume an additional two FTEs per remote site or 80 individuals located at the regional service centers to provide support for the antennas located beyond a few hundred km from the central facility. Administrative personnel probably will number 10% of the total personnel, and will include a fiscal/business division, management, human resources, and secretarial support bringing the total to 500 people. This complement of staff will ramp up over the period of detailed design, testing, construction and commissioning,

The extensive signal and data processing facilities are estimated to require an average power consumption of ~50 MW costing ~€50M/yr. A Power Investigation Task Force has been created by the project office to investigate green and other alternative power sources and to consider designs that minimize power consumption. Personnel costs of €50M/yr, and other materials and services including leasing dark fiber lines (€20M) bring the direct operating cost to about €120M/yr.

Recurring investment in the renewal of instrumentation and computing will be essential in maintaining optimum scientific returns from the SKA. €30M/yr, about 2% of the construction budget, would allow a complete turnover of instrumentation and computers on an average time scale of 20 years, although items such as computers will need to be renewed more frequently. This brings the annual SKA operating cost to about €150M/yr with a 1/3 U.S. share of $65M/yr.

No scientific facility can be productive without a skilled scientific user community. It will be desirable to operate a US or North American SKA Operations Center to handle observing and data archive support, to train students and post doctoral researchers, and to provide scientific and technical support to external users. A further $10M/yr, provides for the operation of the U.S. Science Center and for user grant support.

Implementation of financing: Two additional years of post PrepSKA funding (€5M) will be needed to complete a fully costed proposal, followed by two years of engineering design, development, and prototyping (€60M, including staff costs). With funding for both SKA construction and operations shared equally among the U.S., Europe, and the Rest of the World, the projected US costs are about $725M for construction and about $175M/yr for operations (at current exchange rates). Phase 1, which is planned to start in the first half of the next decade, will cost €320M. The long lead time to obtain NSF MREFC funds probably precludes full participation by the United States assuming Phase 1 construction begins 5 years from now. The European AstroNet Roadmap - adopted as a working model by the PrepSKA Work Package-6 on Finance - proposes a model by which Europe pays for 60 percent of the cost of Phase 1 or €190M. It is expected that the host country will support the ~€65M of initial Phase 1 infrastructure costs leaving ~€65M to be found for Phase 1 construction, of which $20-25M over 4 years might be needed from non MREFC NSF funding for the U.S. to maintain influence in the direction of the SKA program.

The draft spending profile for the US starts at about $5M/yr in 2012 and 2013, reaches about $100M/yr during Phase 2 construction starting late in the decade and continues near this level for full SKA operations starting in the following decade.