The road to the Radio Synoptic SKA (RSSKA)

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Abstract. The next generation of radio arrays are being designed under the umbrella of the "Square Kilometer Array" (SKA) project. The leading concept for a "mid-frequency" (0.3–10 GHz) array is a large wide-field Radio Synoptic SKA (RSSKA), which is being developed for presentation to the upcoming Astronomy and Astrophysics Decadal Survey. The RSSKA is targeted at obtaining HI observations of a billion galaxies to redshift $z > 1.5$ over 10000 square degrees, and synoptic mapping of the radio sky for transient detection and monitoring. In this talk I discuss the motivation for and the design challenges facing the RSSKA. Also suggested is a path forward from our current generation of facilities, such as the VLA and Arecibo, towards construction and operation of the RSSKA.

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A RADIO SYNOPTIC SQUARE KILOMETER ARRAY

Disclaimer: The following musings are my own and do not pretend to be representative of the opinions of the SKA project. They are primarily intended to spur discussion at this meeting of the "HI-centric" benefits and requirements of a RSSKA.

Over the past 25 years, we as radio astronomers have been enjoying the boons granted us by the construction of the first and second generation of large radio facilities: the Very Large Array (VLA) and Arecibo Observatory. These have been among the most productive research instruments [1], and they continue to produce first-rate science. With these telescopes we have surveyed the local Universe and probed phenomena at the dawn of structure formation. We now are in the process of designing and developing the next generation of radio facilities, which will usher in a grand future of Great Surveys of the Universe.

In the past, the restricted field of view of our telescopes from the radio to the optical has allowed only narrow-field "pencil beam" probes at large distances and very shallow all-sky surveys. However, recent advances in optical/infra-red camera technologies have led to the dawn of large moderate-depth surveys such as the Sloan Digital Sky Survey (SDSS), which is the gold standard for modern cosmological surveys. Our colleagues are planning an ambitious suite of future survey telescopes such as the Large Synoptic Telescope (LST), and powerful follow-up spectroscopic facilities such as the 20m–30m class Giant Segmented Mirror Telescope (GSMT). These will bring large-area survey capability to the high-redshift Universe.

The case for the LST is of particular interest to the radio community. The LST concepts, the Panoramic Survey Telescope & Rapid Response System (Pan-STARRS)[1] and the Large Synoptic Survey Telescope (LSST)[2], are not only aimed at doing nearly all-sky surveys, but also at opening up the temporal domain. The next generation of radio arrays have similar goals, and thus the concept has been proposed for a Radio Synoptic Survey Telescope (RSST) [3]. A RSST would be designed to survey over 10^4 square degrees to cosmological distances in the 21-cm HI line and in the GHz continuum, with regular and repeated time sampling for the discovery and monitoring of transient and periodic phenomena.

The Square Kilometer Array (SKA)[4] (see also Lazio, this conference) is an international program to build the next generation of radio astronomical telescopes and arrays. One of the original drivers for the SKA was the need to carry out a cosmological HI survey, so it is no surprise that a RSST for the detection of high-redshift galaxies in the 21-cm line turns out to be a SKA-sized project. We call this the Radio Synoptic SKA (RSSKA)[5].

Key Science and Drivers: There are a large number of science projects that have been proposed for the SKA program in the Square Kilometer Array Science Book[2]. These encompass a variety of radio survey and targeted science from 10 MHz up to above 50 GHz. Of these, we highlight a smaller number of key science bullets that the RSSKA would address:

- The evolution of neutral hydrogen in galaxies through cosmic time (detection and spatial structure of redshifted 21-cm HI line in emission and absorption from the local Universe to $z > 3$);
- The precision measurement of cosmological parameters through a "billion-galaxy" HI survey (detection of redshifted 21-cm HI line in emission to $z > 1.5$);
- The discovery and timing of a vast network of fast-spinning pulsars suitable as a probe of long-wavelength gravitational waves (high time-resolution pulsar monitoring);
- The exploration of the time domain at sub-milli-Jansky flux densities to search for giant pulses, flares, flashes, periodic or quasi-periodic signals, and ETI (transient detection and monitoring survey);
- The imaging of the non-thermal radio continuum from galaxies, clusters of galaxies, and active galactic nuclei (deep continuum survey, gravitational lens survey);
- The mapping of the large and small-scale magnetic field structure of the galaxy and of the Universe (rotation measure mapping survey).

Of this key science, a few of these are *Key Science Drivers* that compel us to realize the RSST as a RSSKA. For example, the observation of pulsars in high-dispersion environments (lines of sight with high electron content) require the ability to observe

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[1] `http://pan-starrs.ifa.hawaii.edu`
[2] `http://www.lsst.org`
[3] See my RSST website: `http://www.aoc.nrao.edu/~smyers/rsst`.
[4] `http://www.skatelescope.org`
[5] Say "risqué".

at frequencies above 2 GHz (e.g. to 10 GHz for our Galactic Center). In the rest of this paper, as is appropriate for this conference, we will focus on the Key Science Driver of *Cosmological HI* — the detection of redshifted 21-cm emission from galaxies at cosmological ($z > 1$) distances. This is perhaps the most stringent driver, as we will see, and requires a significantly larger radio telescope or array than any currently available.

The SKA: The preliminary specifications for the SKA ("SKA-prelim") were drafted in December 2007 [3]. Several options for the realization of the mid-frequency SKA were outlined. To summarize, these were: (a) 3000 telescopes of 15-m diameter, with single-pixel feeds; (b) 2000 telescopes of 15-m diameter, with focal-plane array receivers; and (c) a dense aperture array from 500-800 MHz plus an array of 2400 telescopes of 15-m diameter (single-pixel feeds) operating above 800 MHz. We call option (a) our "baseline array" given that this is the least risky option presented in the SKA-prelim. All of these would cover the total frequency range from 500 MHz to 10 GHz. The construction cost for these options, including a 10% "Phase 1" stage, was projected to be 920M Euros, or somewhat greater than the total capital cost of ALMA.

To evaluate the suitability of proposed designs for the science, a number of "figures of merit" (FoM) were devised. We will use two of these. First, the *Noise-weighted Area*: $\mathrm{ATFoM} = A_{eff}/T_{sys}$, and the *Survey Speed*: $\mathrm{SSFoM} = \Omega_{FOV}\,(A_{eff}/T_{sys})^2$. The ATFoM (in $\mathrm{m^2K^{-1}}$) sets the sensitivity level for a given integration time on a single field of view (FOV). The SSFoM (in $\mathrm{deg^2m^4K^{-2}}$) sets the amount of time needed to survey a given area of sky down to a given sensitivity level. The primary beam field of view of a single-pixel feed on a 15-m diameter antenna is $\Omega_{FOV} = 4.54\,\mathrm{deg}^2$ observing HI at $\lambda = 0.525\mathrm{m}$ ($z = 1.5$).

One must also include the effects of the antenna configuration of the array. For example, using the SKA-prelim "composite array" configuration for options (a) and (b) with 20% of the antennas in a 1-km core and 50% within 5-km, it is estimated that about 50% of the total HI flux is lost at these redshifts (see Figure 2 of [4]). A dense aperture array (c) could be made more compact but would not have the spatial resolution of the composite array. The longer baselines are also important so that continuum observations are not confusion limited before reaching desired sensitivity levels.

THE RSSKA AND COSMOLOGICAL HI

The prime case for the use of a SKA for cosmological HI is presented in [5, 6, 4]. The goal is to measure redshifts and masses for a significant number of HI galaxies at $z > 1$. As shown in [4], a survey with a "full SKA" leads to a survey that detects more than 10^9 galaxies, reaching a surface density peaking at nearly $10^5\,\mathrm{deg}^{-2}$ at $z \sim 0.5$. They further argue that in order to carry out a cosmological survey that will be competitive with other optical/infrared Dark Energy Task Force "Stage IV" probes [7], the SKA will require a $\mathrm{SSFoM} > 4\times10^9\,\mathrm{deg^2\,m^4\,K^{-2}}$ with $\Omega_{FOV} > 10\,\mathrm{deg}^2$ and $\mathrm{ATFoM} = 2\times10^4\,\mathrm{m^2\,K^{-1}}$ at 1.4 GHz. This is a tall order, and the SKA-prelim options (a) and (b) above fall short of this by a significant factor. Deriving an affordable design that meets the cosmological specifications is a priority for the RSSKA concept.

Another science case for HI at high redshifts is that of tracking Galaxy Evolution and structure formation, e.g. [8]. This has less stringent requirements on sensitivity than the precision cosmology, because smaller galaxy samples from smaller volumes can be used. For example, a comoving survey volume of only $1\,\mathrm{Gpc}^3$ can provide useful evolution constraints, while $> 50\,\mathrm{Gpc}^3$ is needed for cosmology. Thus, we need to survey $178\,\mathrm{deg}^2$ to cover a comoving volume of $1\,\mathrm{Gpc}^3$, and $\sim 10^4\,\mathrm{deg}^2$ for $56\,\mathrm{Gpc}^3$, assuming a "standard" LCDM cosmology [6].

The counts of galaxies detected in a HI galaxy survey are set by the HI mass function (HIMF), which is usually characterized by a exponential times a power law [7] with a mass M^*_{HI} characteristic of the turn-over into the exponential. For example, [4] used the Parkes multi-beam HIMF of [9] to normalize the counts at $z = 0$, and then explored several evolution models. There is a wide variation in the counts for $z > 1$ between the models due to differences between the M^*_{HI} at high redshift.

Even for a SKA, a wide area survey will have rms HI mass detection thresholds at or above M^*_{HI} and thus the expected counts are exponentially sensitive to the cutoff. Thus, an important goal for RSSKA precursor projects should be a more accurate measurement of the local ($z < 0.2$) HIMF , and the detection of HI galaxies out to $z \sim 0.5$ to place limits on HIMF evolution. The ALFALFA survey (see talk by Giovanelli, this conference, and [10]) should deliver the first of these within the next year. The EVLA and a lower-frequency extension of ALFA would allow targeted HI observations of galaxies to $z = 0.5$.

USING THE RSSKA

The RSSKA will be a powerful astronomical facility, with a SSFoM of at least 3000 times that of current instruments (EVLA, ALFA) and a ATFoM of around 10 times that of Arecibo. There are a number of possible modes for operation depending on the science target, from wide to deep surveys, including targets of opportunity and the follow-up on specific objects.

The RSSKA is primarily intended for large *surveys*. In particular, the key science driver of a cosmological HI survey will require years to carry out even if it uses a majority of the observing time available. Furthermore, the RSSKA will be confusion limited at the widest continuum bandwidths ($\Delta\nu > 0.3$ GHz) in a few hours of total integration time. To enable the most key science, one of the fundamental strategies is to carry out *commensal* surveys — with different science targets observing off of the same (or forked) data stream(s) at the same time. The science data products of these surveys will enable breadth of astronomical research.

As an example, we propose the following "strawperson" surveys:

- **CHILDS:** The *Cosmological HI Large Deep Survey*, a nested series of 21-cm line surveys of the sky to various depths;
- **DeCoIS:** A *Deep Continuum Imaging Survey*, obtaining continuum polarimetric images of the sky for cosmology, magnetic field mapping, and other imaging

[6] See `http://www.astro.ucla.edu/~wright/CosmoCalc.html` (Ned Wright's cosmology calculator) using $H_0 = 71$ km/s/Mpc, $\Omega_M = 0.27$, $\Omega_\Lambda = 0.73$.
[7] The Schechter mass function is $dN/dz = \phi^*_{HI}\,(M_{HI}/M^*_{HI})^\alpha\,\exp(-M_{HI}/M^*_{HI})$

science, fully commensal with the CHILDS;

- **TrAMP:** The *Transient Acquisition and Monitoring Program*, commensal with all other observations that are done in synoptic mode (the ultimate freeloader).

These will have both wide and deep galactic and extragalactic components. For the area coverage in a surveys, we use the "single-pixel" FOV of a 15-m diameter antenna, $\Omega_{FOV} = 0.73\,\mathrm{deg}^2$ at 1.4 GHz ($z = 0$), scaling as $(1+z)^2$. Increasing survey speed through multi-beaming, or using smaller dishes keeping same total collecting area, can be used to increase either the integration time per FOV or the survey area accordingly. Conversely, a slower array (ie. with less collecting area, larger dishes, worse system temperatures, or a combination of these) will take proportionally longer to cover a given area to a given level.

Another consideration in scheduling the RSSKA is establishment of a *synoptic cycle* that is capable of carrying out the time-domain science for pulsars and transients (e.g. the TrAMP survey). Characterization of the dynamic radio sky [11] is challenging but rewarding, and is perhaps the most likely key science target to yield truly unexpected results. The difficulty will be in creating hierarchical surveys that are compatible with the HI surveys outlined above. [12] presents the case for the SKA-as-RSST as a time-domain probe and outlines a synoptic cycle that can be used to carry this out. Careful design of the wide and deep HI and continuum surveys, plus Galactic plane and center surveys, will have to be carried out as part of the development of the RSSKA proposal.

The SKA required for the cosmological observations by [4] is 40 times faster than the baseline SKA-prelim array. Thus, the projected counts given in Appendix A and Figure A1 of that paper for 4 hours of integration are what the baseline array would see in 160 hours per 1.4 GHz FOV (or a RSSKA survey of 200 deg^2 over 5 years), with the 1 hour curve corresponding to a 5-year 800 deg^2 RSSKA survey. If we use the fitting formulae given there in Table A1, which assumes the HIMF evolution model "C" favored by the authors, then the RSSKA yield of the 200 deg^2 survey is 3 million $z > 1$ galaxies and that of the 800 deg^2 is only 1 million. Thus, galaxy evolution studies would have extensive samples to work with, and there would be 30–50 million $z < 1$ galaxies as well. However, these are five year projects or longer, rather than the one year survey duration proposed by [4]. And as pointed out in the preliminary SKA specifications and in [4], such an array is too slow to set cosmology and dark energy constraints at the precision required for the 2020 time-frame. It will be critical to plan an upgrade path during the first decade of operations to enable this key science driver.

Because of the sheer amount of integration time needed to carry out the cosmological HI survey(s), the RSSKA would be primarily used in survey mode. However, even a modest amount of time (25%) made available from the start for target of opportunity (TOO) and proposal-driven general observer (GO) projects would enable a even broader science program. This would also accommodate follow-up observations for discoveries made in the main HI, continuum and transient surveys. This time would be folded in to the synoptic cycle schedule, so as not to compromise the key projects. These TOO and GO observations would ideally be carried out in standard survey modes, as then they could use the post-processing techniques developed for the surveys.

The RSSKA will be operating for decades, so we can consider its use over this long time period. For example, we can sketch a 20-year program consisting of (1) a *Wide* *survey* (10^4 deg^2, 5 years total, 4.38 hours per square degree, or 19.9 hours per FOV at $z = 1.5$); (2) a *Deep survey* (200 deg^2, 5 years total, 219 hours per square degree, or 994 hours per FOV at $z = 1.5$); (3) a medium-deep *Galactic Plane Survey* (750 deg^2, 3 years total, 35 hours per square degree, or 25 hours per FOV at $z = 0$); (4) possibly one or more *Ultra-Deep fields* (4.5 deg^2, 1 year each, 1931 hours per single FOV at $z = 1.5$), including the Galactic center; and (5) five years for TOO, GO, follow-up, and other projects.

A ROADMAP TO THE RSSKA

A large next-generation facility like the RSSKA is a major endeavor, with capital and operating costs comparable to and likely greater than that of ALMA. Therefore, a comprehensive build-up and build-out plan that is plausible, affordable, and above all scientifically compelling must be developed. This plan must involve a large cross-section of the astronomical (not just radio) community.

First and foremost, a large ground-based instrument such as the RSSKA will not just appear one day, fully operational and at ultimate science capability. We cannot afford to build and run this like a space mission. Furthermore, the community does not just stop what they are doing and wait for the RSSKA to appear. There is important science that must be done on the way to the RSSKA and this will be done using current and near-future instruments. Support for these *Science Precursors* must be made an integral part of the RSSKA plan. Note that Science Precursors are independent of any technology demonstrators or pathfinders, though some pathfinders (for example, ATA) would also be used as precursors if built out fully.

Science Precursors: It is important to the health of astronomy that our current and upcoming instruments be fully exploited to reach their science goals, as well as to lay the groundwork for future facilities such as the RSSKA. For example, it is of critical importance for the final RSSKA design (and cost) for HI studies to measure the HIMF accurately to and place useful limits on its evolution. The ALFALFA survey is nearing an improved measurement of the local HIMF. Dedicated use of the EVLA, a low-end enhanced ALFA, and a full ATA with optimal performance below 1 GHz would allow us to characterize the HIMF beyond $z = 0.1$ in the coming decade. This program, in conjunction with the pathfinders (see below), would lead to the HI equivalent of the SDSS.

Carrying out such a comprehensive set of large programs will also require the HI radio community to marshal our resources and expertise. It would be in our interests to have a dedicated workshop on this topic in the next year or so.

Demonstrators, Pathfinders, and Technical Issues: There are mid-frequency SKA pathfinders and demonstrators underway in various locales (e.g. ASKAP, APERTIF, ATA, MeerKAT). There is also a US-SKA Technical Development Program (TDP) funded by the NSF. All of these are important to prove technology and gain experience running RSSKA-like instruments. The one that is accessible to the US community and is most like a RSSKA is the ATA. I would like to see its promotion and use as a RSSKA pathfinder and precursor, particularly for wide-area surveys in the time domain, explored in more detail.

Discussion Points: Formulating the mid-frequency SKA as a RSSKA that is affordable and yet capable of both HI cosmology and time-domain science presents a number of challenges.

Some of issues to be discussed and explored include:

- Costing — can we build a capable and compelling RSSKA for a reasonable cost (1-2x ALMA)? Given some of the risky technologies, how do we get a reasonable costing for the Decadal Review? Note that there is at least one costing model, which gave a reasonable cost for the SKA-prelim "baseline array" as mentioned above.
- Design — can we do the RSSKA science with an array of dishes, (which is a generally capable astronomy facility), or do we need to consider an aperture array (more like a cosmology experiment)? If the latter, then the low-frequency SKA Epoch of Reionization aperture arrays become the pathfinders.
- Speed vs. Steel — survey speed is the prime requirement for "static" observations such as the HI, but the collecting area sets the instantaneous sensitivity for time-domain science. Should we follow past experience and put maximum collecting area on the ground during construction, and upgrade the FOV later?
- Science — are we willing to drop HI precision cosmology (Dark Energy) from the RSSKA science case, as would be the case if the baseline array were adopted? Or do we need to ensure this science, either by a cost increase, cuts in other areas, or though aggressive upgrades?
- Frequencies — the SKA-prelim specifications use an upper frequency of 10 GHz. This must have some cost impact on antennas. Would dropping this to 3 GHz allow for substantially more sensitivity for high-redshift HI (below 800 MHz) but retain sufficient capability for the other science (pulsars, continuum, time-domain, other lines)?
- Technique — we have been assuming that precision cosmology is done by a galaxy survey, but [13] suggest that this be done through a power spectrum measurement (like is done for the CMB) where only the Fourier modes in the large-scale HI emission are detected, not individual galaxies. Will this enable the key science with the baseline array (perhaps with only a modest FOV upgrade)?
- Upgrades — it is crazy to think that the RSSKA will be constructed in its final ultimate form, and an upgrade path should be built into the operations model. Is there an affordable upgrade path that can be built in to the RSSKA operations and that will enhance the science capabilities accordingly (e.g. multi-pixel feed arrays)?
- Data Blizzard — the computing requirements for a RSSKA range from the terrifying (Peta-scale for the dish-based designs) to beyond-the-pale (for aperture arrays). How much do we budget for at the end of construction, and how much do we bring along as an operational upgrade? How do we assess the risk, and do the costing?
- Use — can a model for the scheduling and use of the RSSKA be devised that satisfies the commensal use by the HI, continuum, and temporal surveys? What about the allocation of resources between the primary surveys and general observers?

PARTING REMARKS

To use an overused term, the RSSKA would be a truly "transformational" instrument enabling a wide range of key science projects, from precision cosmology to fundamental physics and gravity probes, to bread and butter galaxy evolution and structure studies, to a wide-open exploration of the time domain. Surveys are the primary use for the facility, but general observer programs would also be accommodated. Combined with the future survey telescopes in other wavebands as part of a series of Great Surveys, the RSSKA would complete a comprehensive picture of the Universe.

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