Imaging across the spectrum

Synergies between SKA and other future telescopes

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Introduction

Square Kilometer Array (SKA) is the next generation radio interferometry instruments that will consist of a large number of receiving elements arranged into clusters (stations) and spread over a large area. SKA will be operational at the time when all astronomy fields will be covered by next generation instruments, including several new large optical (LBT, CELT, EURO50, OWL) X–ray (CONSTELLATION-X, XEUS, MAXIM) and Gamma–ray (GLAST) telescopes. The main drive for building SKA is a significant improvement of sensitivity that would widen the general scope of the centimeter–wavelength radio science and connect better the radio science with astrophysical studies made in other bands of the electromagnetic spectrum. In the past two decades, radio astronomical instruments have typically featured a superior resolution and adequate imaging performance, compared to the instruments working in other spectral bands. The future optical telescopes like CELT and OWL would both surpass the dynamic ranges offered at present in the radio by the VLA (Very Large Array) and match the resolution of ground–based centimeter wavelength VLBI (Very Long Baseline Interferometry). The X-ray interferometry mission MAXIM would even achieve an order of magnitude better resolution than that of the contemporary VLBI. These advances provide a good possibility for synergies between future facilities in the radio, optical and high-energy domains, provided that the need for complementarity between different facilities is recognized, and dealt with, already at the design stage. A brief discussion of some of the SKA designs is presented here, and their imaging capabilities are compared to those of the major future facilities in other spectral domains.

Imaging performance

Imaging performance of different telescopes can be compared, to the first order, using three basic parameters: resolution ($\theta_{\rm res}$), conventional dynamic range (D) an spatial dynamic dynamic range (SDR) defined as the ratio between the largest and smallest detectable features. All these parameters are estimated readily for filled aperture instruments. Additional constraints must be considered for interferometers in which image performance is affected by such factors as observing bandwidth ($\delta\nu$), integration time (τ) and coverage of the Fourier domain (***Fourier sampling*** or *uv*–coverage). The Fourier sampling can be described by the quantity $\Delta u/u$, where Δu is the size of the gap between the measurements made around the Fourier coordinate u.

In most of the designs proposed for SKA, the bandwidth and integration time may need to be significantly reduced, if one would require to reach dynamic ranges similar to that of the largest optical instruments. These two corrections can be introduced at the stage of observation preparation, and their worst effect is the increased observing time needed to reach the required sensitivity. The Fourier space sampling, described by the $\Delta u/u$ ratio, is however "hard–wired" into the array design, and can only be improved by adding new stations. It is therefore rather imperative to optimize this parameter at the earliest possibles stages of the array design. In addition to that, optimization of $\Delta u/u$ is also required by high–fidelity imaging at low SNR levels. The lowest SNR of "trustable" pixel in an interferometric image is given by

$$\ln({\rm SNR_{low}}) = \left[\frac{\pi}{4}\left(\frac{\Delta {\rm u}}{\rm u}+1\right)\right]^2 \frac{1}{\ln 2}. \qquad (1)$$

Pixels with SNR lower than $\rm SNR_{low}$ cannot be used for extracting information from the image. Integration over a larger area ("blob") consisting of a number of pixels is then required in order to obtain a trustable information about the brightness distribution of the object observed. This is illustrated in Figure 1 which shows the areas in which individual pixels can ("pixel science") and cannot ("blobby science") be used for extracting information from an image. It is obvious that Fourier domain coverages with $\Delta u/u > 0.5$ (for which $\rm SNR_{low} > 10$) may negate effectively most of improvements in instrumental sensitivity and resolution.

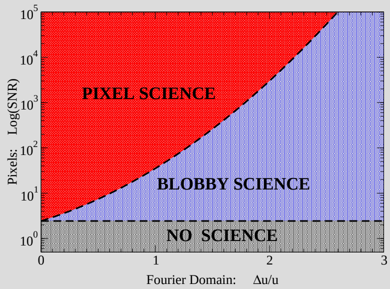

Figure 1. Effect of the Fourier sampling on pixel fidelity. The Fourier sampling is characterized by the fractional gap $\Delta u/u$ in interferometric data. "No science" area shows pixels with SNR ≤ 3. "Blobby science" area shows pixels in which information are corrupted by incomplete Fourier sampling. For these pixels, one has to integrate over a "blob" of several pixels, in order to obtain a verifiable information about the brightness distribution observed. "Pixel science" shows an area in which valid information can be obtained from each pixel.

Spatial dynamic range

Spatial dynamic range of an interferometer depends on a number of conditions. The maximum $\rm SDR_{FOV}$ is simply a ratio between the field of view (FOV) and the synthesized beam (HPBW). For an array composed of parabolic antennas,

$${\rm SDR_{FOV}} \approx 0.80 \frac{B_{\rm long}}{\eta_{\rm a}^{0.5} D_{\rm an}}, \qquad (2)$$

where $\eta_{\rm a}$ is the aperture efficiency. However, $\rm SDR_{FOV}$ can be typically achieved only at the shortest baselines. The SDR is significantly reduced at highest instrumental resolution, due to a finite bandwidth ($\delta\nu$) and integration time (τ) and an incomplete Fourier domain sampling. This reduction is visible in all of the SKA designs in Figure 2. The maximum SDR that can be achieved at a given integration time is

$${\rm SDR}_\tau \approx 1.13 \cdot 10^4 \tau^{-1}. \qquad (3)$$

The finite $\Delta\nu$ yields

$${\rm SDR}_{\Delta\nu} = \frac{1}{\Delta\nu}\left[\left(\frac{I_0}{I}\right)^2 - 1\right]^{0.5}, \qquad (4)$$

where I_0/I is the maximum acceptable peak brightness reduction (assumed to be 30%, in these calculations). Incomplete sampling of the Fourier space results in

$${\rm SDR}_{uv} = 3{\rm SDR_{FOV}}\left\{\exp\left[\frac{\pi^2}{16\ln 2}\left(1+\frac{\Delta u}{u}\right)^2\right]\right\}^{-1}. \qquad (5)$$

For a regular array (i.e. logarithmic spiral) with N stations, $\Delta u/u$ can be roughly estimated by $(B_{\rm max}/B_{\rm min})^{3/N} - 1$.

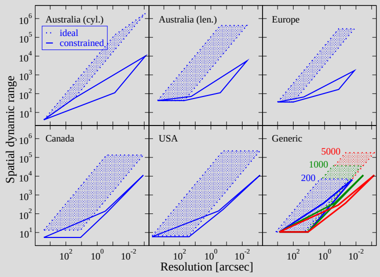

Figure 2. Maximum (shaded areas) and realistic (solid polygons) spatial dynamic ranges of different SKA designs plotted against the resolution (the panel with "generic" designs describes a "typical" SKA with baselines extended up to 200, 1000 and 5000 km, respectively). Bandwidth (BW) of 1 MHz and integration time τ=1 s are assumed in these calculations.

In a real observation, the actual spatial dynamic range is determined by the most conservative limit provided by estimates above (this limit is given by $\rm SDR_m$ for different SKA designs described in Table 1). For most of the SKA designs plotted in Figure 2, this results in a factor of ~100 reduction of the SDR at the highest instrumental resolution (the Canadian design suffers from the SDR reduction at all resolutions, due to a small number of stations and poor $\Delta u/u$ ratio).

Removing the discrepancy between $\rm SDR_{FOV}$ and $\rm SDR_m$ requires reducing Δnu and/or τ. The reductions necessary to achieve SDR_{uv} are given in Table 1 by BW_{uv} and τ_{uv}. This, correspondingly, leads to an increased point source sensitivity and longer observing time required.

The SDR reduction due to the poor Fourier space sampling becomes significant at $\Delta u/u \gtrsim 0.4$ (see Figure 2). At $\Delta u/u \gtrsim 0.25$, the SDR reduction becomes negligible. It should therefore be possible to reach the $\rm SDR_{FOV}$ levels in an array configuration that provides $\Delta u/u = 0.2$ at all baselines. For an inhomogeneous array in which $\Delta u/u$ varies depending on the baseline length, the reduction of spatial and even conventional dynamic range may be substantial (see Figure 4). Therefore, this requirement must be considered as one of the basic requirements for the design of the SKA.

Conclusions

New large astrophysical facilities planned to be built in the coming decades would present scientists with excellent opportunities for cross-disciplinary research, provided that the new instruments are designed such as to achieve similar imaging capabilities and enable direct comparison between images taken in different domains of the electromagnetic spectrum. This would bring new and remarkable possibilities for synergies and complementarity between different fields of astrophysics.

As one of the major future instruments, SKA should be designed to provide image resolution and spatial dynamic range which will be comparable to those of the future optical and high-energy astronomy facilities. To make the SKA a competitive imaging instrument that would match the capabilities of future optical and X-ray telescopes, two basic conditions must be fulfilled:

1. Resolution of $\lesssim 1$ mas at $\nu_{\rm high}$.
2. Fourier plane filling factor $\Delta u/u \lesssim 0.2$ over the entire range of the *uv*–coverage.

Compromising either of these two conditions would reduce the imaging capabilities and effectively narrow the scientific scope of the SKA.

SKA and all others

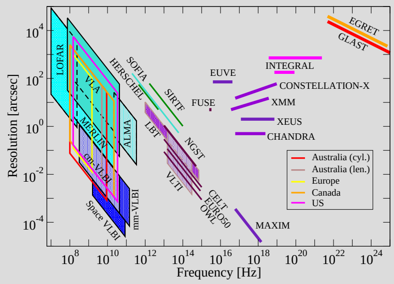

Figure 3. Resolution of the SKA compared with the resolution of several other existing and future astronomical instruments. All of the basic SKA designs provide a ≈ 1 milliarcsecond resolution at the highest observing frequency. This resolution is going to provide and adequate counterpart to the resolution of the largest projected optical telescopes, and may be inferior to the resolution of the proposed X–ray interferometer mission MAXIM. The imaging capability of MAXIM is however rather modest ($D \lesssim 700$), and it should be matched easily by radio observations using millimeter– or space–VLBI.

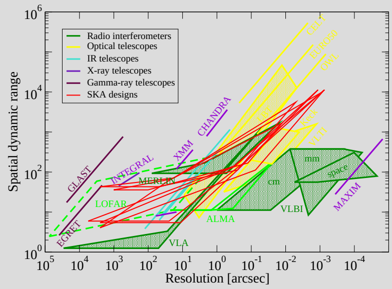

Figure 4. Spatial dynamic range of the SKA designs ($\rm SDR_m$ for observations with $\delta\nu$=1 MHz and τ=1 s) compared to other major instruments. $\rm SDR_m$ of the SKA will be higher than that in most of the existing radio interferometric instruments. Future optical instruments however will be able to achieve much higher SDR levels, comparable with the maximum $\rm SDR_{FOV}$ of the SKA presented in Figure 2. This implies that the SDR reductions described by equations (3)–(5) should be considered carefully at the stage of the instrument design, in order to optimize the imaging performance of the SKA.

SKA imaging capabilities

Imaging performance of the five out of seven basic SKA designs which are currently discussed (see www.skatelescope.org for descriptions of all of the designs).

Table 1. SKA designs: Imaging performance

Parameter	**Australia Cylinders**	**Australia Lenses**	**Europe Tiles**	**Canada LAR**	**USA SAR**
Frequency and baseline coverage					
$\nu_{\rm low}$[GHz]	0.1	0.1	0.15	0.1	0.15
$\nu_{\rm high}$[GHz]	9.0	5.0	1.5	22	34
$B_{\rm short}$[km]	0.3	0.3	0.5	0.5	0.1
$B_{\rm long}$[km]	10000	3000	4000	3000	3000
Characteristics of a single array element					
$D_{\rm an}$[m]	13	7.0	1.0	200	12
$T_{\rm sys}$[K]	50	40	40	40	30
$A/T_{\rm sys}$[m^2/K]	2.0E+4	2.5E+4	2.5E+4	2.5E+4	3.3E+4
SEFD[Jy]	20.3	81.1	27.0	16.2	32.4
Configuration and *uv*–coverage					
$N_{\rm an}$	600	52800	1.0E+6	60	4400
$N_{\rm st}$	60	300	100	60	160
$(\Delta u/u)_{\rm best}$	0.04	0.06	0.10	0.50	0.17
$(\Delta u/u)_{\rm worst}$	0.11	0.14	0.33	0.50	0.24
Spatial dynamic range and image sensitivity					
$\rm SDR_{FOV}$	1.9E+06	4.3E+05	2.9E+05	1.3E+05	2.2E+05
$\Delta I_{\rm m}$[μJy]	5.7	4.5	4.5	4.5	3.4
$\rm SDR_m$	1.1E+04	5.6E+03	1.7E+03	1.1E+04	1.1E+04
SDR_{uv}	1.9E+06	4.1E+05	1.8E+05	5.4E+04	1.7E+05
BW_{uv}[Hz]	830	280	940	2050	980
τ_{uv}[ms]	83	28	63	207	66
ΔI_{uv}[μJy]	197.5	271.7	147.5	100.4	108.2

Parameter designation: ν – observing frequency; B – baseline; $D_{\rm an}$ – equivalent diameter of a single array element; $T_{\rm sys}$ – system temperature at 1.4 GHz; $A/T_{\rm sys}$ – aperture/system temperature ratio; SEFD – system equivalent flux density; $N_{\rm an}$ – total number of array elements; $N_{\rm st}$ – total number of array stations; $\Delta u/u$ – Fourier plane filling factor of the array; $\rm SDR_{FOV}$ – theoretical spatial dynamic range, unconstrained by the array design; $\Delta I_{\rm m}$ – point source sensitivity (with $\Delta t = 1$ hour and BW = 1 MHz); $\rm SDR_m$ – spatial dynamic range of observations reaching $\Delta I_{\rm m}$; SDR_{uv} – spatial dynamic range limited by the *uv*–coverage of the array; BW_{uv} – maximum channel bandwidth required by SDR_{uv}; τ_{uv} – maximum correlator integration time required by SDR_{uv}; ΔI_{uv} – point source sensitivity reached with SDR_{uv}.

Reference: Lobanov, A.P. 2003, SKA Memo 38, "Imaging with the SKA: Comparison to other future telescopes" (see www.skatelescope.org)

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