A New Correlator Architecture for the SKA

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The design of the back-end digital signal processing system for the Square Kilometer Array (SKA) is a significant engineering challenge. Recently, a new correlator architecture called WIDAR [1] has been developed in Canada for the Expanded Very Large Array project. This architecture is well suited to an SKA constructed of either a large array of small (reflector) elements or an SKA constructed of a smaller number of Large Adaptive Reflector (LAR) elements. The WIDAR architecture is capable of efficiently correlating data over wide bandwidths with many spectral points per cross-power result. Anti-aliasing and digitally-generated self-interference suppression features allow high spectral dynamic range to be achieved. This should permit savings in electronics when digital beamforming needs be done on a massive scale since fewer bits can be used to represent digital mixer functions. This poster presents a straw-man design of a "patch" phasing and correlation system using the WIDAR technique for both above mentioned SKA configurations for the benchmark case of ~700 MHz of bandwidth up to 1.4 GHz. Cost estimates based on current technology, +5 year technology (based on +5 year industry predictions), and on +10 year technology (extrapolating +5 year predictions) are developed and presented.

Many Small (Reflector) Element SKA

Station Electronics and Patch Beamforming

Each antenna of each "patch" (a patch is a closely packed phased-array of antennas) includes the basic electronics shown in **Figure 1**. The LO in each *patch* is offset in frequency by *fshiftp* as required by the WIDAR technique. The signal is then quantized at 1.5 Gs/s into demux'ed form at 6 x 250 Ms/s. This data undergoes Digital Delay Tracking (that, combined with phase rotation, yields sub-sample delay tracking). The data is FIR-filtered into 6 x 125 MHz sub-bands--these outputs go to the downstream beamformers.

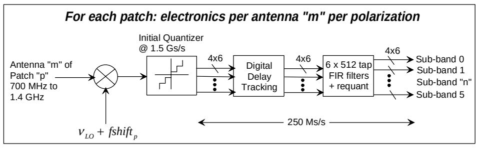

Figure 1

Many phased-array beams must be formed for each sub-band to produce the desired wide field-of-view (FOV). The small sub-bands allow beam delays to be approximated with sub-band phase shifts eliminating **costly** per-beam, per-antenna delay compensation. The band-edge efficiency from this approximation is (*assuming* uniform phase error distribution across the patch):

$$\eta_{bf} \cong \frac{\sin(\phi_{\max}/2)}{(\phi_{\max}/2)} \quad ; \quad \phi_{\max} = \Delta f_{sb} \cdot \frac{D_{patch}}{c} \cdot \left[\cos(EA) - \cos(EA + \delta_{EA})\right] \cdot \pi$$

where: Δf_{sb} -- sub-band bandwidth in Hz.
D_{patch} -- Diameter of patch of antennas.
δ_{EA} -- beam offset from field center.
EA -- Elevation angle.
$\phi_{\max}$ -- maximum band-edge phase excursion (in radians) across the patch.

For a 125 MHz (sub-band) bandwidth, a patch diameter of 200 m, an elevation angle of 30 deg, and a beam that is 0.5 deg off the field center, the band-edge efficiency is 95%.

Phase-rotation in the sub-band patch beamformer is performed with coarse, (15-level?), approximations of sine and cosine functions as shown in **Figure 2**. This allows the beamformer to be highly integrated--key to reducing cost--and should allow a 50 to 100 antenna, single sub-band beamformer chip to be built (limited mostly by pin count). Spurious signals from the coarsely quantized functions will decorrelate once the final frequency shift is removed in the correlator. The 2nd stage complex adder and phase shifter functions can be done in one chip per beam. Thus, only a small number of chips (~5-10 depending on patch size and antenna size) are required to form each beam.

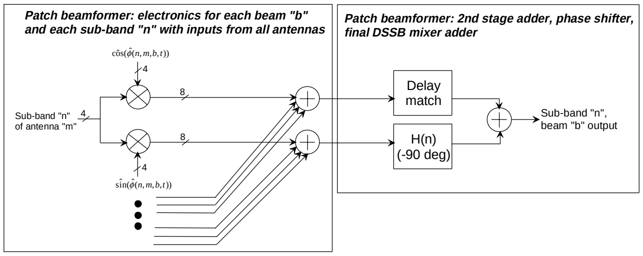

Figure 2

Multi-beam Correlation

Station electronics in the correlator performs "patch-based" interferometer delay compensation and generates the final interferometer phase models used for fringe stopping and patch *fshiftp* removal. Since delay is being performed on sub-band data, baseline delay tracking to (effectively) +/-0.25 samples is performed--resulting in 90% efficiency at the edge of the sub-band. Four-bit correlation and 5-level fringe stopping will yield >50 dB spectral dynamic range even in the presence of powerful narrowband interference sources. Two-bit correlation and 5-level fringe stopping will drop this to <40 dB. The lag-based fringe-stopping architecture shown in **Figure 3** will yield a complex correlator chip with minimum power dissipation--particularly for 4-bit correlation--since there is one multiplier per lag (plus phase rotation which is a sign change and a bit shift) and phase contributes a negligible amount to chip power dissipation.

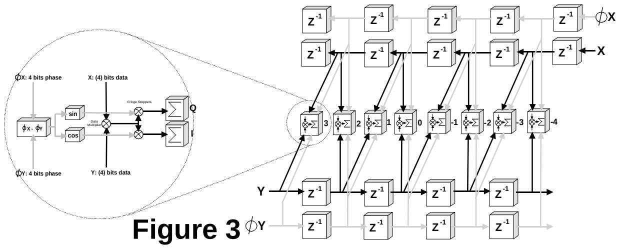

Figure 3

Once the sub-bands are correlated, they are seamlessly concatenated together to yield the wideband spectrum. The WIDAR technique yields the most efficient correlator possible when the original sample rate is greater than can be processed directly with downstream digital hardware. An XF correlator is particularly attractive since it can be argued that it is more efficient than an FX correlator when the cost and complexity of station to baseline cabling in the correlator is considered. Additionally, sub-band generation required by WIDAR nicely dovetails with simplification of patch digital beam forming using phase--even for arbitrarily large analog bandwidths.

Cost Estimate

The following tables estimate the patch beam forming and correlation costs for an SKA with 1000, 200, 100, and 50 patches using 5 m and 10 m antennas. The following equations are used to estimate the number of beams for 1 sq. deg FOV at a 30 deg elevation angle (as it affects antenna spacing) and factor in sufficient beam overlap (factor of ~1.2) for a filled image with a ~700 MHz bandwidth from 700 MHz to 1.4 GHz. The effect of elevation angle on the profile of the patch's phased beam is not considered. Note that the number of beams is independent of the size of the individual antennas and is calculated for a 21 cm wavelength. The estimate does not include antenna to beamformer cable cost or patch to correlator cable cost. All estimates are based on a system clock speed of 250 MHz. The +5 year estimate is based on **industry projections** of 0.08 um feature size by 2004-5 (Ref: Xilinx foundaries) and the +10 year estimate (0.04 um) is based on extrapolation of the +5 year estimate. All estimates are for 8192 spectral channels per baseline per beam.

$$D_{patch} \cong \frac{2000}{\sin(EA)} \cdot \sqrt{\frac{1}{\pi \cdot \eta_{ant} \cdot N_{patches}}} \qquad N_{beams} = 4\pi \cdot \left(\frac{D_{patch}}{\lambda \cdot 180}\right)^2 \cdot 1.2 \qquad N_{ants/patch} \cong \frac{10^6}{\pi \cdot \left(\frac{D_{ant}}{2}\right)^2 \cdot \eta_{ant} \cdot N_{patches}}$$

5 m antennas, 70% efficiency

N_{patch}	$N_{ants/patch}$	$N_{beams/pol}$	0.18 um: Current Pricing (million U.S.$ y2000)			0.08 um: +5yrs Projected (million U.S.$ y2000)			0.04 um: +10 yrs Projected (million U.S.$ y2000)		
			Patch Cost (ea)	Corr. Cost	Total	Patch Cost (ea)	Corr. Cost	Total	Patch Cost (ea)	Corr. Cost	Total
1000	73	77	0.16	19600	**19800**	0.1	3900	**4000**	0.08	990	**1100**
200	364	384	1.6	3900	**4200**	1.1	790	**1010**	0.9	200	**390**
100	727	770	5.7	1970	**2500**	3.9	400	**790**	3.0	110	**410**
50	1455	1536	20	980	**2000**	13	200	**850**	10	60	**560**

10 m antennas, 70% efficiency

N_{patch}	$N_{ants/patch}$	$N_{beams/pol}$	0.18 um: Current Pricing (million U.S.$ y2000)			0.08 um: +5yrs Projected (million U.S.$ y2000)			0.04 um: +10 yrs Projected (million U.S.$ y2000)		
			Patch Cost (ea)	Corr. Cost	Total	Patch Cost (ea)	Corr. Cost	Total	Patch Cost (ea)	Corr. Cost	Total
1000	18	77	0.13	19600	**19700**	0.09	3900	**4000**	0.07	990	**1100**
200	91	384	0.6	3900	**4000**	0.4	790	**870**	0.3	200	**260**
100	182	770	1.9	1970	**2100**	1.3	400	**530**	1	110	**200**
50	364	1536	6	980	**1300**	4.2	200	**410**	3.3	60	**220**

Current year estimate conditions:
("Moore factor" = 1)
MAX I/O per chip: 400.
Beamforming electronics:
-Fixed sampler package cost of $200 per antenna.
-1 Chip for digital delay tracking per ant. ($40 ea).
-6 FIR filter chips per antenna (1024 tap; $40 ea).
-100 antenna, 1 sub-band beamforming chip, 4-bit data ($40 ea).
-Max 80 custom chips (+overhead) per cct. board.
-$2000 fixed cost per beamforming board (includes PCB, synch, PS).
Correlator electronics:
-All custom chip costs $40 ea.
-Station board: 20 beams both pol'n, $2000 fixed + $3000 electronics cost per board (includes PCB, delay chips, control, synch, PS).
-Baseline board: max 80 Corr chips + overhead. $5000 per board (includes PCB, synch, LTA, readout, PS) cost.
-Corr chips: 0.18 um CMOS, 4096 C-lags.
Cabling:
-$2000 per Baseline Board and $500 per Station Board.

+5 year estimate conditions:
("Moore factor" = 5)
MAX I/O per chip: 400
Beamforming electronics:
-Fixed sampler package cost of $200 per antenna.
-1 Chip for digital delay tracking per ant. ($20 ea).
-1.2 FIR filter chips (0.08 um) per antenna (1024 tap; $40 ea).
-100 antenna, 1 sub-band beamforming chip, 4-bit data (this chip is I/O limited and does not increase in density by the "Moore factor") ($20 ea).
-Max 80 custom chips (+overhead) per cct. board.
-$2000 fixed cost per beamforming board (includes PCB, synch, PS).
Correlator electronics:
-All custom chip costs $40 ea.
-Station board: 20 beams both pol'n, $2000 fixed + $600 electronics cost per board (includes PCB, delay chips, control, synch, PS).
-Baseline board: max 80 Corr chips + overhead of $5000 per board (includes PCB, synch, LTA, readout, PS). (The number of boards is a factor of 5 less than the current year estimate.)
-Corr chips: 0.08 um CMOS, 20480 C-lags.
Cabling:
-$2000 per Baseline Board, $500 per Station Board.

+10 year estimate conditions:
("Moore factor" = 20)
MAX I/O per chip: 400
Beamforming electronics:
-Fixed sampler package cost of $200 per antenna.
-1 Chip for digital delay tracking per ant. ($10 ea).
-0.3 FIR filter chips (0.04 um) per antenna (1024 tap; $40 ea).
-100 antenna, 1 sub-band beamforming chip, 4-bit data (this chip is I/O limited and does not increase in density by the "Moore factor") ($10 ea).
-Max 80 custom chips (+overhead) per cct. board.
-$2000 fixed cost per beamforming board (includes PCB, synch, PS).
Correlator electronics:
-All custom chip costs $40 ea.
-Station board: 20 beams both pol'n, $2000 fixed + $150 electronics cost per board (includes PCB, delay chips, control, synch, PS).
-Baseline board: max 80 Corr chips + overhead of $5000 per board (includes PCB, synch, LTA, readout, PS). (The number of boards is a factor of 20 less than the current year estimate.)
-Corr chips: 0.04 um CMOS, 81920 C-lags.
Cabling:
-$2000 per Baseline Board, $500 per Station Board.

Large Adaptive Reflector (LAR) SKA

The number of 200 m diameter LARs required to provide an effective collecting area of 1 sq km is given by the following equation:

$$N_{LARs} = \frac{10^6}{\eta_{ant} \cdot \eta_{foresh} \cdot \pi \cdot \left(\frac{D_{ant}}{2}\right)^2}$$

This equation factors in the antenna efficiency (~70%) and the sky-weighted efficiency due to foreshortening (~75%). Using 200 m diameter LARs with the above efficiencies requires an array of about **60 LARs for the SKA**.

Current estimates require a phased-array feed of ~8 m diameter to achieve 0.5 sq deg FOV. Since it is risky to predict that a feed larger than this can be built and stabilized, **the following cost estimate will only be for 0.5 sq deg FOV**.

An SKA comprised of LAR elements uses the same basic digital back-end as described for the many small element SKA. Since the phased-array feed is steered mechanically, beamforming does not require complex mixers but rather uses amplitude weighting functions. These weighting function beamformers will require digital ICs with similar pin counts but less complexity than that described above. Thus, the cost of the beamformer chips are estimated to be ~75% of the complex mixer chips but this cost savings will probably be used up by additional electronics costs associated with a limited mass budget design. At 21 cm the number of elements that are used to form a low-sidelobe beam is an average of about 500 and does not change with the number of LAR elements used in the SKA. Since the LAR aperture is fixed in size, a constant ~210 beams per polarization is required for 0.5 sq deg FOV. This uses the same beam calculation as for the many small element SKA including beam overlap inefficiences for a filled image.

Based on the above conditions and using the same technology and technology improvements as the many small element SKA, the following cost table for the phased-array beamformers and correlator has been developed*. For cost comparison, the table also includes using fewer than 60 LARs in the SKA--resulting in reduced effective area and cost.

200 m LARs

N_{LARs}	A_{eff} (m^2)	$N_{beams/pol}$	0.18 um: Current Pricing (million U.S.$ y2000)			0.08 um: +5yrs Projected (million U.S.$ y2000)			0.04 um: +10 yrs Projected (million U.S.$ y2000)		
			Station Cost (ea)	Corr. Cost	Total	Station Cost (ea)	Corr. Cost	Total	Station Cost (ea)	Corr. Cost	Total
60	10^6	210	2	190	**310**	1.3	40	**120**	1	11	**70**
50	0.82×10^6	210	2	130	**230**	1.3	30	**90**	1	7.9	**60**
30	0.5×10^6	210	2	60	**120**	1.3	12	**60**	1	4	**40**

Finally, it must also be noted that the LAR will (at least initially) require multiple feeds for multi-frequency operation. To mitigate the cost of the samplers and beamformers, a feed design should be contemplated that is able to share the digital hardware between feeds that operate at different frequencies (i.e. changing feeds swaps receivers--not digital hardware).

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*It is important to note that cost estimates produced for the LAR antenna include all feed components and so the additional cost for the SKA is really only the correlator cost. The above table is useful for comparison purposes, though.

Conclusions

In this paper, a straw-man design for a digital phasing and correlator system for the SKA was developed based on the WIDAR technique and its cost has been estimated for the benchmark case of ~700 MHz of bandwidth up to 1.4 GHz with 8192 spectral channels per baseline per beam. Designs for two configurations were developed. The first design is for an SKA made of many small reflector elements where "patches" of elements are phased together before being correlated. The second design is for an SKA made of Large Adaptive Reflector (LAR) elements. In both cases, the size of the system will be extremely large and expensive if the science requirement of an effective collecting area of 1 square kilometer and a field-of-view of 1 square degree at 21 cm wavelength is strictly adhered to. For an SKA made of many 5 m reflector elements the phasing and correlation costs, according to this paper, will be cost prohibitive even extrapolated (from 5 year industry predictions) 10 years into the future. If the element size is increased to 10 m then the extrapolated cost is about one-half the total desired cost of the SKA of $0.5 billion U.S.--still prohibitive. If the SKA is made of 60 LAR elements--to maintain an effective collecting area of 1 square kilometer-- but with a 0.5 square degree field-of-view, then a not so unreasonable cost of $70 million U.S. is obtained extrapolated 10 years into the future. The many 5 m reflector element SKA with a 0.5 square degree field-of-view is still cost prohibitive since the phasing and correlator costs drop only by a factor of ~2. In this case, the SKA is one-half the efficiency of the full-spec instrument.

If the science requirements are reduced somewhat to an effective collecting area of 0.5 square kilometers, and 0.5 square degree field-of-view, then the cost for a many 5 m reflector element phasing and correlation system (with 100 patches) 10 years into the future becomes not so unreasonable at $80 million U.S. In this case the substantial cost reduction is possible since the number of beams that need to be generated and correlated has dropped by a factor of 4. The cost for the phasing and correlation system using LARs is $40 million under the same conditions. Unfortunately, with this reduced capability, the SKA would be one-eighth the efficiency of the full-spec instrument.

References

[1] Carlson, B.R., Dewdney, P.E., Efficient wideband digital correlation, Electronics Letters, IEE, Vol. 36 No. 11, p987, 25th May, 2000

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