A Baseband Receiver Architecture for Medium-N SKA

Dick Ferris [0]

Receiver architecture, correlator architecture, digitisation, beamforming, interference mitigation, data transport, cost and complexity are inexorably intertwined. A combination of baseband receiver, digital filterbank correlator and mixed delay and phase digital beamformers, provides a flexible and efficient solution. It supports progressive development in capacity and sophistication as technology costs decrease with time, without compromising the performance of a minimal initial installation.

ADC Operation

Component	Definition	Factor	Level
Quantising Noise	$q^2/12$	=	0.29q
Excess Noise (#1)	1.5 bits	*2.83	0.82q
Minimum SNR	20dB	*10	8.2q
Input Ripple Margin	2dB	*1.26	10.3q
Gain Steps, Hysteresis	2.2dB	*1.29	13.2q

Ie. Operating Point is σ = 10.3q-13.2q

8-bit ADC: Range = +/-128q
Ideal Operating Point (#2): σ = 33.8q
$\Rightarrow$ Nominal Headroom for Interference = 33.8q/13.2q, ie. 8.2dB above Tsys (integrated across 5GHz).

#1 Typical difference between physical and effective number of bits for state of the art fast ADCs [1], [2].
#2 Minimum gain-compression and distortion operating point for Gaussian signals [3], corresponds to clipping at ~4σ level. For 1% compression, 'effective' headroom ~12dB.

Baseband Receiver

The particular spectrum of interest invites the adoption of a 'Baseband Receiver', in which the antenna signal is simply amplified, bandlimited to 100MHz-5GHz and digitised at 10Gsps (real data) or 5Gsps (complex).

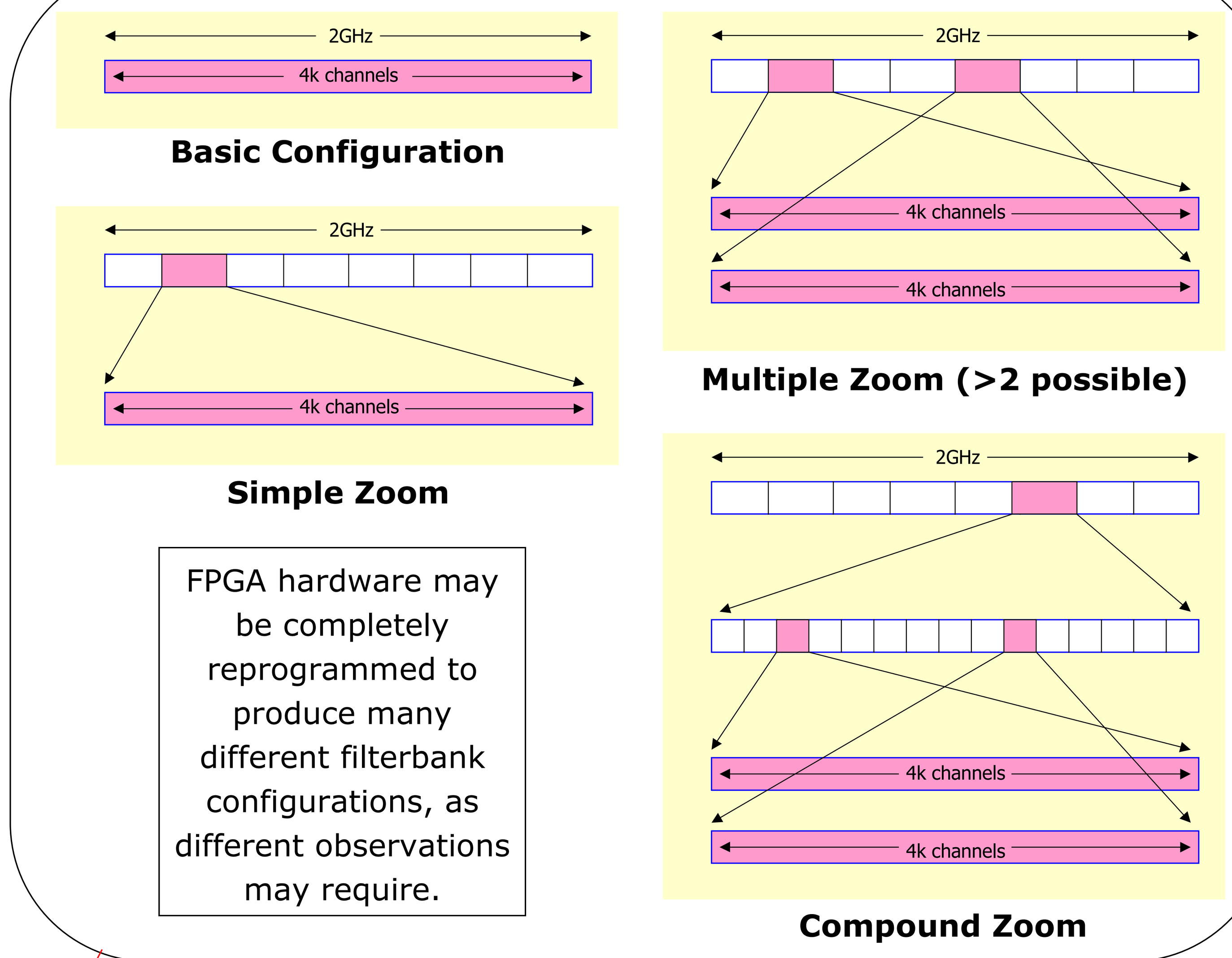
The absence of LOs, mixers, analog bandpass filters and the need to distribute LO phase to the antennas, represents a significant reduction in cost, complexity and maintenance.

Net analog gain = $P_{ADC}/kT_{sys}B$, ~85dB (Tsys=50K, B=5GHz).

Gain $\propto$ 1/B $\Rightarrow$ reduced susceptibility to strong interferers for large B; also 2nd and 3d order intermodulation products decrease as 1/B^2 and 1/B^3 respectively.

Together with the absence of mixer images and high-order products, inverse mixing noise etc., this suggests a very clean receiver. The critical design factor is the open market availability of suitable ADC chips.

The design would also benefit from the availability of high dynamic range analog links with suitable bandwidth. That would allow the ADC to be moved back into the Control Building, and possibly even the implementation of photonic sampling [4].



Filterbank

A digital filterbank correlator is trivially split into its 'filter' and 'correlator' parts, and the filterbank moved in front of the beamformer(s). This has many advantages:

Beamforming computation is only performed for the desired part(s) of the spectrum, which may be different for individual beams;

Self-cal and interference nulling may be applied independently to each channel;

Fine delay tracking is applied to each (relatively narrow) channel as an additional phase component, to easily provide accurate time-delay beamforming;

Strong interference signals are confined to their own channels, thus protecting the rest of the spectrum and allowing significant reductions in word size and data rate.

These features do not detract from the flexible spectral mode capability which the filterbanks bring to the correlator.

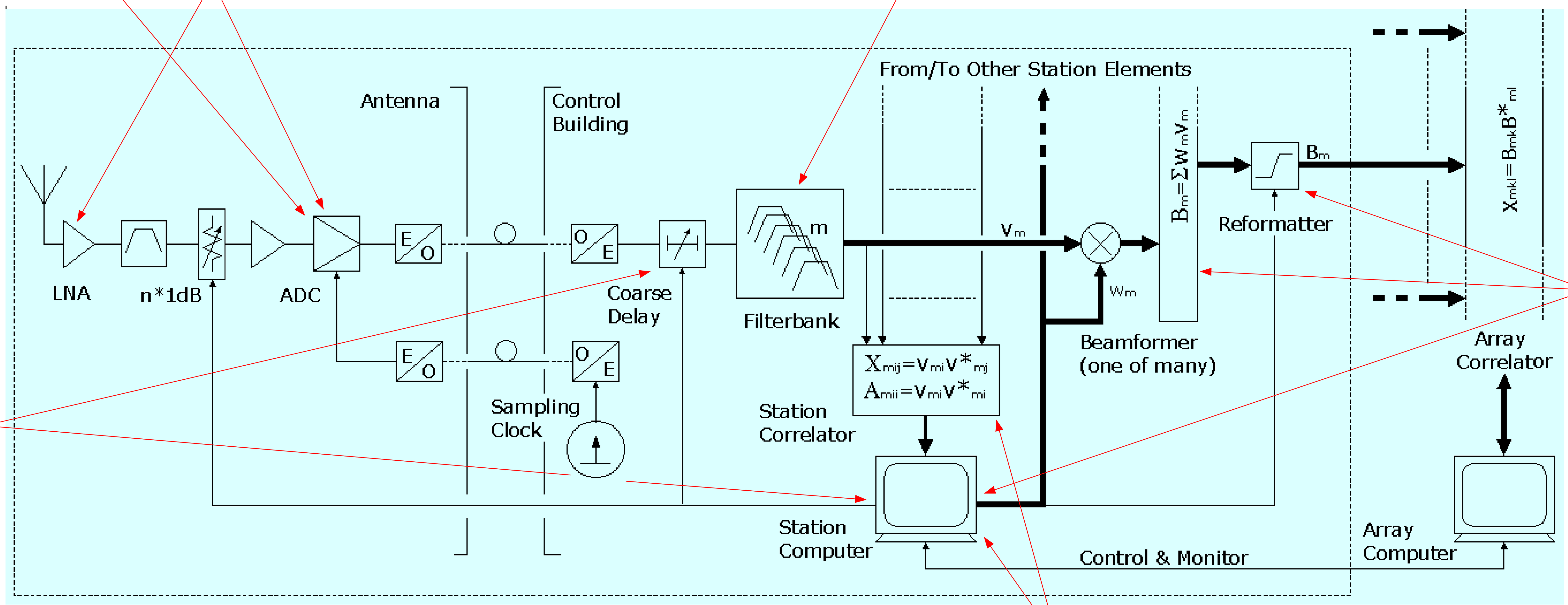
To avoid bandwidth smearing, the number of channels = longest baseline/station diameter. eg. 3000km/250m = 1.2*10^4. To obtain this resolution it may be necessary to reconfigure the filterbank to 'zoom' the upper part of the spectrum.

Beam Steering

Combined n*sample delays at the full bandwidth followed by phase compensation ('fine delay') in each frequency channel after the filterbank.

Minimum element spacing of 2 diameters means delay tracking to the nearest sample (real data at Nyquist rate) corresponds to steps of beamwidth/6. Because the delay is at the sky frequency (rather than at IF) there is no associated phase component.

The remaining time delay is implemented as a phase shift in each channel. The high frequency decimation factor (=no. of channels) ensures the residual phase slope across each channel is negligible (0.1deg for 4k channels).



Data Growth & Compression

In a 4k channel filterbank the word size necessarily grows by 6 bits in order to maintain the input dynamic range. Each zoom factor of 4 adds another bit.

In the beamformer the desired signals add coherently but interferers outside the main beam will add quadratically. Eg. a 176 element array thus provides 22.5dB discrimination.

If active beam nulling adds another 20dB then the required dynamic range is reduced by 7 bits, and the word size may be so reduced by saturation logic. Another bit may be recovered by rounding out the LSB which is mostly ADC excess noise q.v.

Thus in most cases only 8-bit data needs be sent to the correlator. Its now ~18dB headroom allows residual interference to wash out in the correlation and integration stages without damaging the astronomy signal.

In cases of persistent excessive interference individual channels may be scaled by 'fixed' factors of 2 or 4 to retain linearity but at the expense of degraded SNR. In extreme cases where the channels cannot be abandoned,or if interference nulling is not implemented, 16-bit data can be retained and correlated with some loss of processing bandwidth.

Dynamic Range

A linear, stationary signal path with at most occasional, scheduled, gain adjustments, is proposed as necessary to achieve wide dynamic range in the end results, to be inherently robust against interference, and as an ideal platform for post-processing interference mitigation.

Data precision is varied along the signal path to maintain SNR while allowing practical amounts of headroom for interference so it can be removed by linear processes in later stages.

References

[0] Dick.Ferris@CSIRO.au

[1] R.H. Walden, "Analog-to-digital converter survey & analysis", IEEE JSAC, vol. 17, no. 4, pp. 539-550, April 1999.

[2] R.H. Walden, "Analog-to-Digital Converter Survey & Analysis", http://www.hrl.com/TECHLABS/micro/ADC/ADC-Survey-Jul99.ppt.

[3] F.A. Jenet & S.B. Anderson, "The Effects of Digitisation on Non-stationary Stochastic Signals with Applications to Pulsar Signal Baseband Recording", Pub. Astron. Soc. Pacific, 110, pp. 1467-1478, 1998.

[4] T.R. Clark, J.U. Kang, and R.D. Esman, "Performance of a Time- and Wavelength-Interleaved Photonic Sampler for Analog-Digital Conversion," IEEE Phot. Tech. Letters, vol. 11, pp. 1168-1170, September 1999.

Station Calibration

Full correlation of all station elements in a **sparse set** of interference free frequency channels allows self-cal on a calibrator found within the element primary FOV.

All requested channels are monitored for suitable candidates for active interference nulling.

Sets of beamforming weights are generated, including perturbations for propagation delays, interference nulling and fine delay compensation.