Baseline Design
Non-Imaging Processing
Numbers 16 July 2013

DRM 3.0a Science: Pulsar Search

- The SKA Phase 1 shall be able to complete a survey in no more than 2 years of “on-sky” observation time
- *The SKA Phase 1 shall be capable of detecting pulsars with periods at least in the range 0.5 ms to 10 s, for a nominal duty cycle of 5%, <u>for at least a subset of the specified range in dispersion measure (DM).</u>*
- *The SKA Phase 1 shall be capable of detecting pulsars with dispersion measures (DM) of at least 1500 pc cm^{-3}, <u>for at least a fraction of the pulsars in the specified range in pulse period</u>.*
- *The SKA Phase 1 shall provide access to the entire sky visible from its latitude on the Earth, above a notional elevation limit of 10 deg (TBC).*
- *The SKA Phase 1 shall provide the capability to search for pulsars in binary systems with orbital periods as short as 30 minutes.*

DRM 3.0a Science: Pulsar Timing

- *The SKA Phase 1 shall be capable of timing pulsars with (pseudo)-luminosities as low as 0.1 mJy kpc^2 at 1400 MHz within 10 kpc.*
- *The SKA Phase 1 shall provide access to the entire sky visible from the site with no more than a 10% (TBC) loss in sensitivity in any direction.*
- *The SKA Phase 1 shall be able to provide measurements that will enable the detection of gravitational waves with strain amplitudes of 10^{-16}.*
- *The SKA Phase 1 shall provide data that enable the measurements of average pulse profiles to a precision of at least 100 ns.*

Pulsar Search Array

Pulsar Search Array

Sensitivity, Ae/Tsys ~ 820 $m^2 K^{-1}$

SEFD, S_{min}^* = 13 x 10^{-6} Jy

For D ~ 10 kpc

Pseudo flux density, SD^2 ~ 1.2 mJy kpc^2

cf DRM requirement 0.1 mJy kpc^2

Pulsar Timing Array

Ae/Tsys ~ 1600 $m^2 K^{-1}$ Band 2

Ae/Tsys ~ 1200 $m^2 K^{-1}$ Band 3

SEFD, S_{min} = 1.7 Jy Band 2

SEFD, S_{min} = 2.1 Jy Band 3

Note: no Meerkat in Band 3

$$S_{min} = \frac{2k_b S/N\beta T_{sys}\sqrt{\frac{\delta}{1-\delta}}}{A_e\sqrt{n_p t_{obs}\Delta f}}$$

*Assumed:

δ = 5%

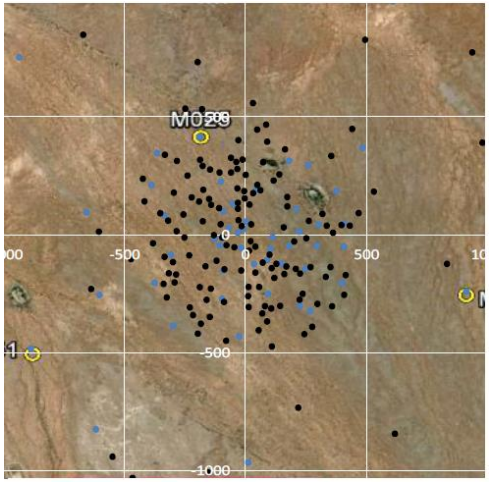
S/Nβ = 10

K_b = Boltzman's constant

N_p = 2

Tobs = 600 s

Δf = 300 MHz



Pulsar Search Array:

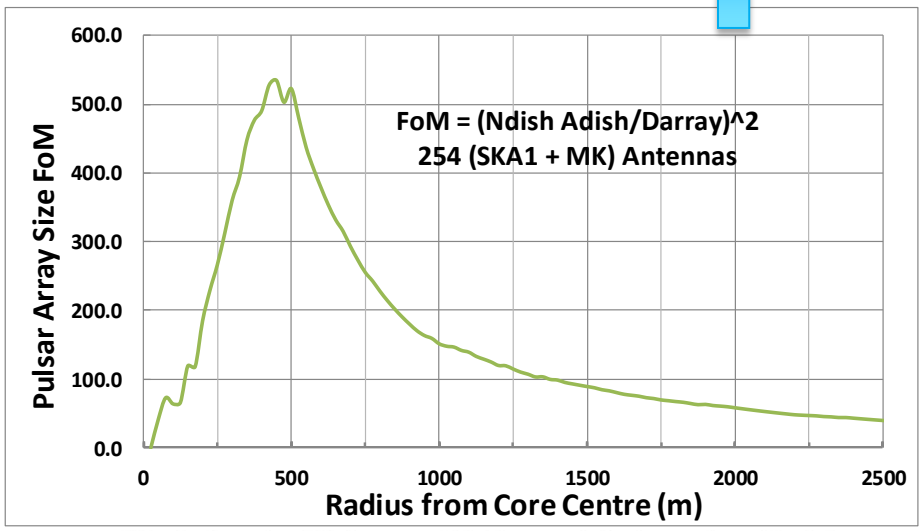
~130 Dishes

39 Meerkat Dishes

91 SKA1 Dishes

Radius~475 m

141 dishes for 500m



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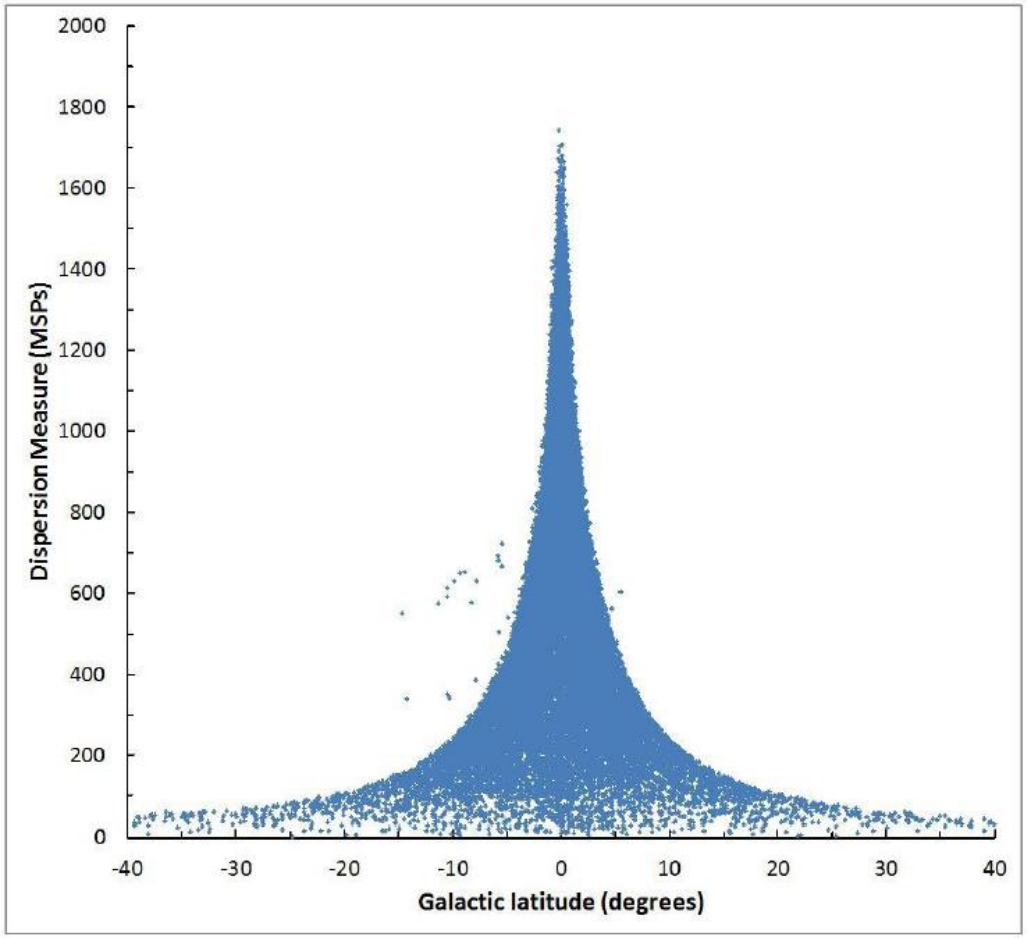
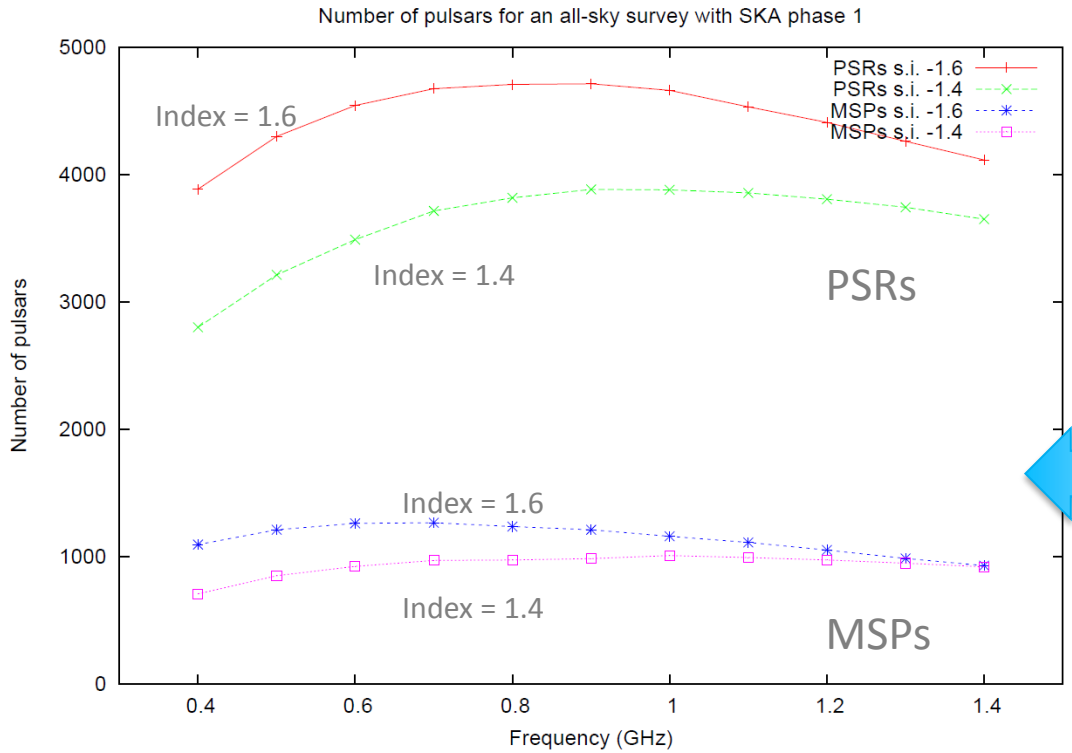
Dispersion Measure, DM.

- Used NE2001 electron density model to estimate DM wrt Galactic Latitude.
- Sky considered in different regions:

Galactic Latitude |b| deg	DM cm^{-3} pc^{-1}	Approx. Sky Area deg2
< 1	3000	720
1 to 5	1000	2875
5 to 15	500	7082
15 to 30	100	9,950
> 30	60	39,847



Survey Centre Frequency



Plot courtesy of Roy Smits: July 2013
(Uses sensitivity of dishes)

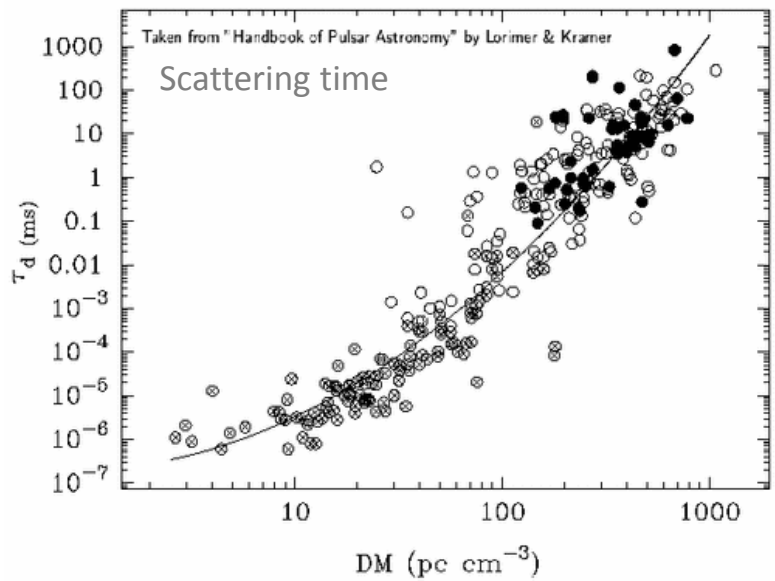
Note: recent publication[3] suggests spectral index of -1.4.

- Pulsars become brighter towards lower frequencies by a power law with an index around –1.6
- At low frequencies the profile from pulsars are smeared due to scattering, leading to a lower sensitivity
- The sky temperature increases towards lower frequencies by a power law with an index of –2.6.
- The beam-width increases towards lower frequencies. The FoV of one beam therefore scales with f^{-2}
- The effects of dispersion smearing due to the propagation of the radio waves through the interstellar medium becomes greater towards lower frequencies.

Dedispersion

$$DM_{max} = \frac{t_{samp}\,(\mu s) f_c\,(GHz)^3}{8300\,\Delta f\,(GHz)}$$ [8]

- $\Delta f > 1/t_{samp}$, DM_{max} max at min Δf
- Estimate tscat ~ tsamp for DM = 250 @ f =1.25 GHz & 170 @ f = 0.75 GHz ?
- Baseline design too optimistic over achievable DM at 50us time resolution?
- Could increase channel width which reduces processing load.
- Use DM diagonal to achieve higher DMs at lower time resolution.
- Could increase observation frequency



Baseline Design Parameters

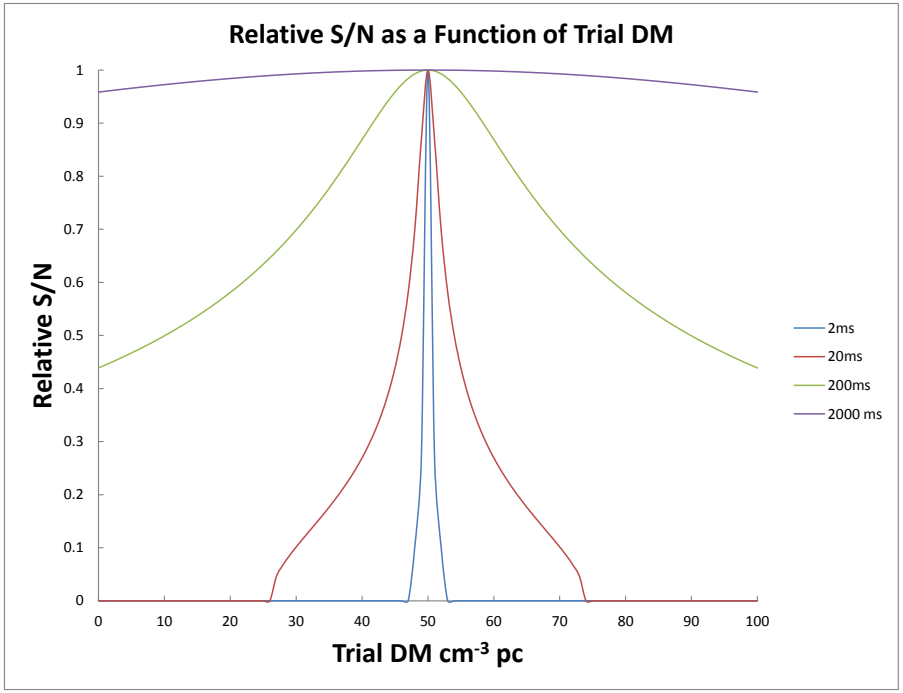
$$t_{scat} = \left(\frac{DM}{1000}\right)^{3.5}\left(\frac{400}{f\ MHz}\right)^{4}$$ [7]

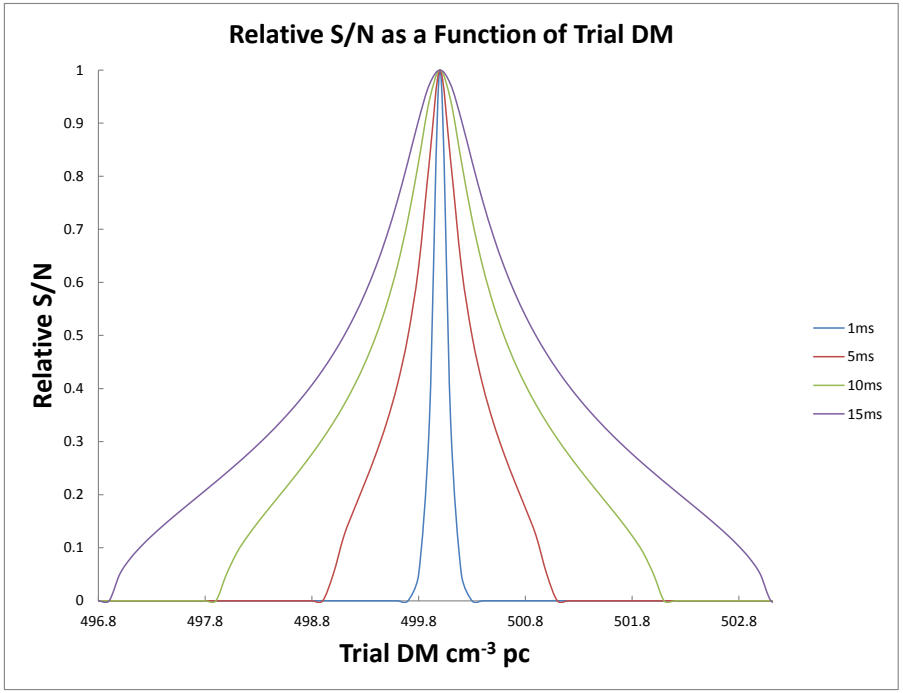
Sky region	DM cm^{-3} pc	NDm(1st diag)	Nchan	time ms		Tscat us	DM_{max}	No. in diag	Δf Hz
0 to 1	3000	15350	15000	2722		5382	827	2	20000
1 to 5	1000	15350	15000	907		5382	827	1	20000
5 to 15	500	16113	15000	454		207	154	2	20000
15 to 30	100	10448	9727	91		45	100	1	30843
the rest	60	6269	5836	54		8	60	1	51406

$$t_{res} = \sqrt{{t_{samp}}^2 + {t_{scat}}^2 + \cdots}\ ,$$

$$t_{scat} \sim -6.46 + 0.154\log(DM) + 1.07(\log(DM))^2 - 3.86\log(f)$$ [9]

S/N wrt. Trial DM & Period

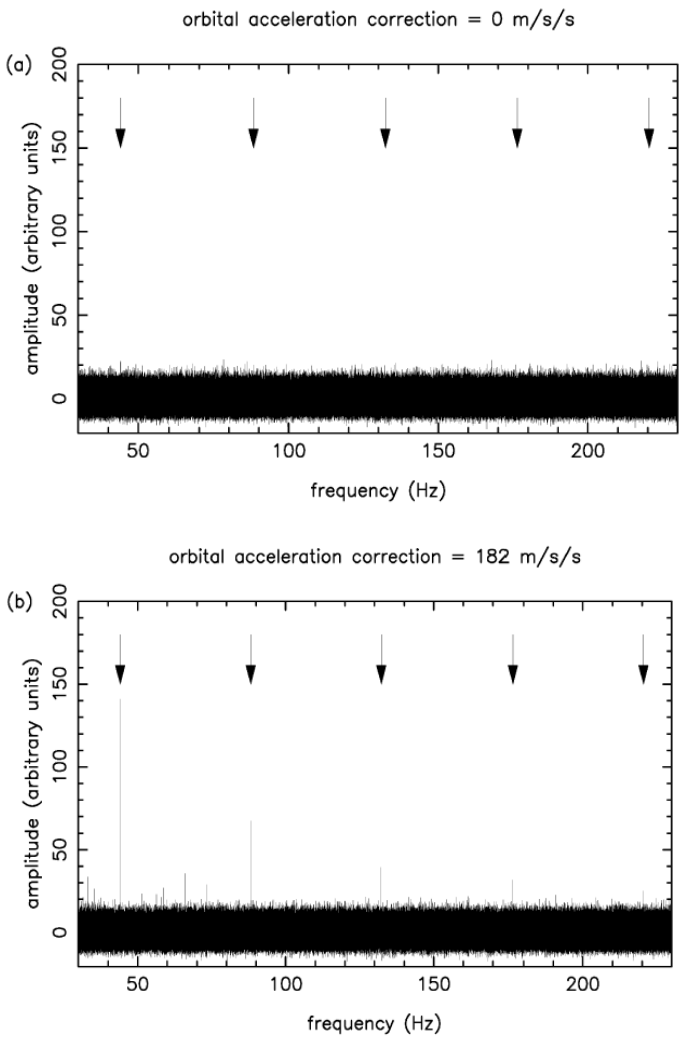


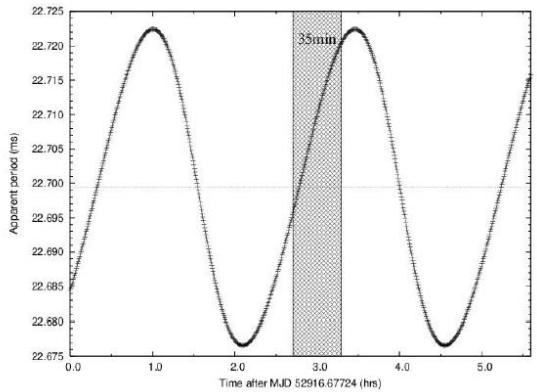


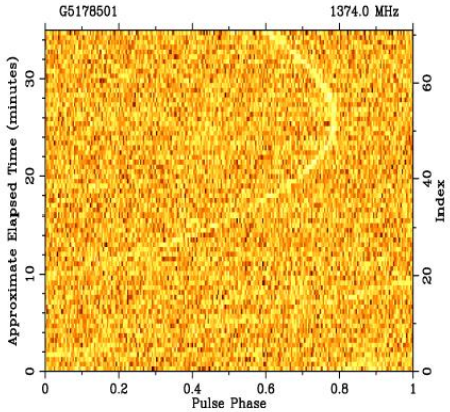
The achievable S/N for De dispersion is dependent on the Pulsar's period and the granularity of the trial Dispersion Measures.
Model does not include pulse broadening due to scattering

Acceleration Search

Example Acceleration Search







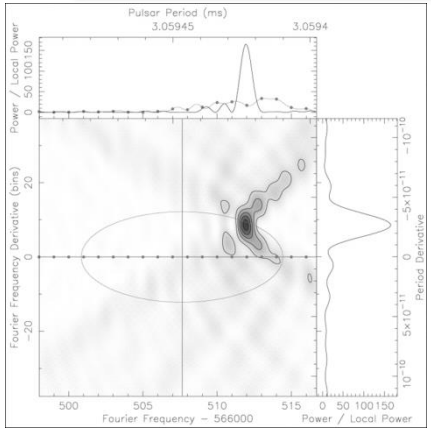
Acceleration Search

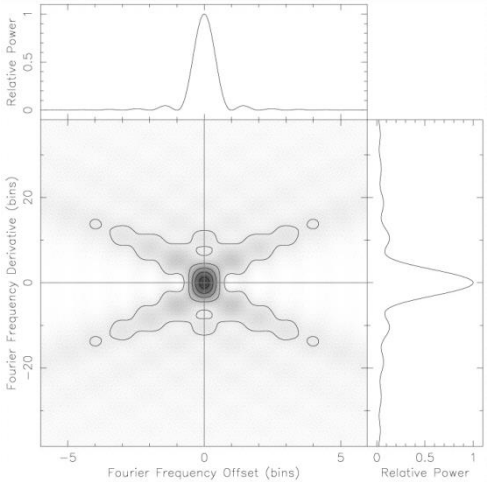
- Pulsars in highly relativistic binary systems show periodic changes in their pulse frequency due to the Doppler effect.
- Standard Fourier based periodicity searches are not sensitive to varying frequency signals.
- Need to compensate using trial accelerations
  Baseline design assumes 120 trial values

Acceleration Search (for Binary Pulsar Systems)

- Beyond linear searches too expensive ?
- Assume linear acceleration search
  - N_{acc} not stated explicitly in Baseline design
  - Acceleration step $\delta a = 0.33 ms^{-2}$ for $t_{samp} = 50us$
  - 120 trials covers accelerations in range ~ $\pm$ 20ms^{-2}**
  - Is this sufficient?
- Potential Algorithms:
  - Matched Filter
  - Hough Transform
  - Stack Search
  - Phase Search
  - Coherence Recovery
  - Time Domain Resampling
- Probably require some additional processing beyond 2D-FFT. For example Scott Ransom's Matched Filter requires:

$$C_{matched} = 2N(5Mlog_2(M) + NM$$

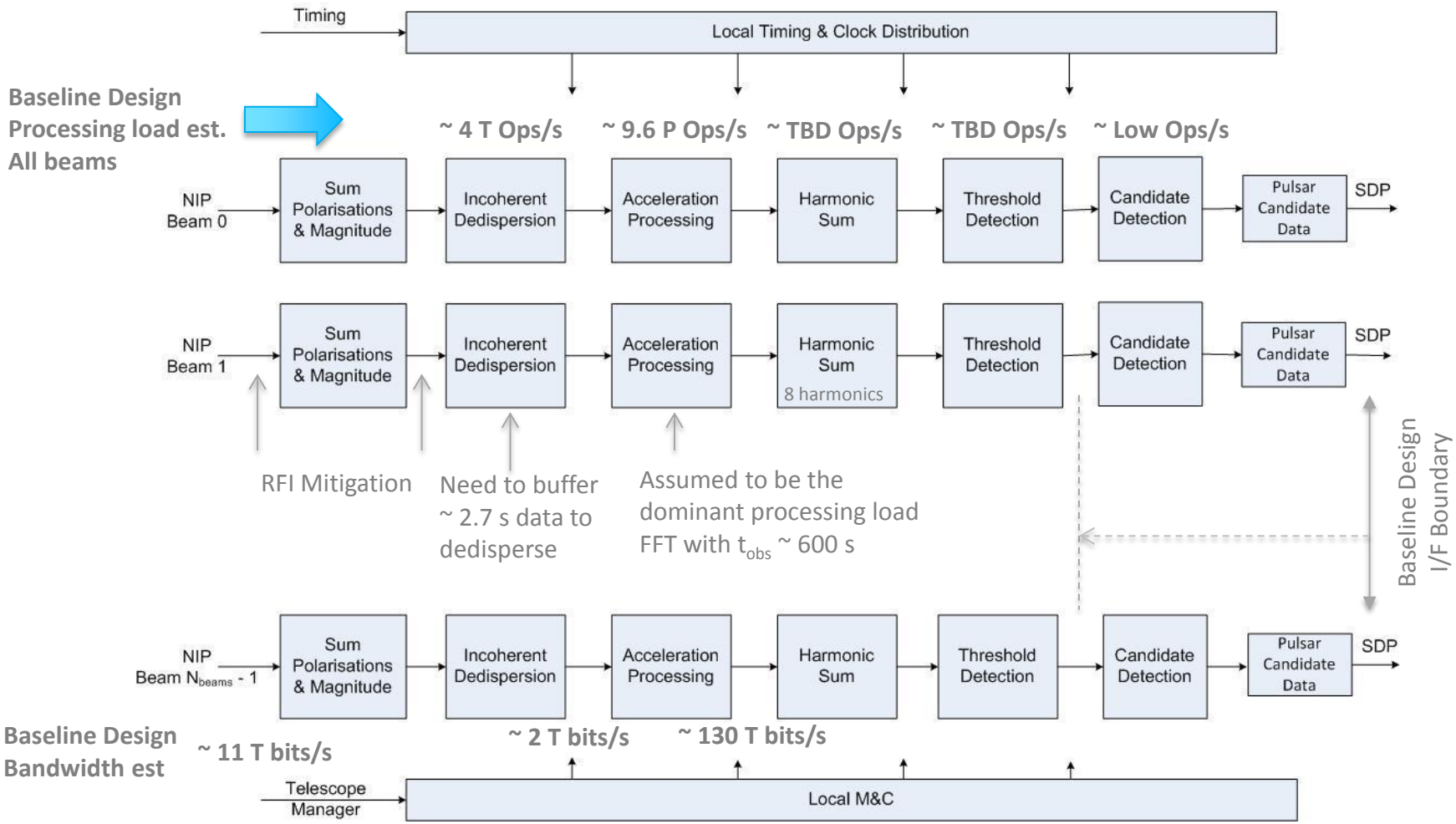




Ransom Eikenberry Middleditch 2002

$* \ \delta a = \frac{8ct_{samp}}{{t_{obs}}^2}$ **Baseline design $\pm$100ms^{-2}

Baseline Design
Pulsar Search Processing Chain



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Note: processing loads and data rates are rough estimates

Pulsar Processing loads

Dedispersion[1]

$N_{bms}N_{DM}N_{chan}/t_{samp}$:Brute force dedispersion

Or

$N_{bms}N_{DM}\log_2(N_{DM})/tsamp$:Taylor tree dedispersion in 64 subbands

Acceleration Processing (Binary Search)[5]

$N_{bms}N_{DM}N_{acc}N_{samp}\log_2(N_{samp})/t_{obs}$ *

Where:

$Nsamp = t_{obs}/t_{samp}$, t_{obs} =600s, t_{samp} = 50us

Harmonic Sum

$N_{bms}N_{DM}N_{acc}N_{harm}N_{samp}/t_{obs}$; Baseline design assumes 8 harmonics (is this enough?)

Threshold Detection

Not sized

Candidate Filtering

Not Sized

Pulsar Timing*

Nbms x 5 x Nsamp x $\log_2$(Nsamp) x overlap x FFT rate

Nbms x 5 x Nsamp x $\log_2$(Nsamp) x overlap x IFFT rate

* Likely to include pre and post FFT processing too.

** To also include correlation multiply but this load is low

Baseline Design
Rudimentary Equipment Estimates

- The baseline design provided rudimentary equipment estimates for example:
- Server + 2 GPUs projected to 2016 technology freeze:
  - 20 T Flops per node
  - 750 Watts per node
  - Efficiency of 10%
- 648 56 Gbps port Infiniband switch
  - Aggregate bandwidth 75 T b/s Non blocking
  - 10kWatts per switch
- Potentially **250 cabinets** dissipating **5 MW** for Pulsar Search based on Baseline Design parameters for a Server hosted GPU implementation.
- Pulsar Timing is negligible in comparison

References

1. Accelerating incoherent dedispersion: B. R. Barsdell et al.
2. Pulsar searches and timing with the Square Kilometre Array R. Smits et al.
3. The pulsar spectral index distribution S. D. Bates et al Feb 2013
4. SKA1 System Baseline Design SKA-TEL-SKO-DD-001
5. High-Level SKA Signal Processing Description WP2-040.030.010-TD-001
6. Pulsar survey with SKA phase 1 R.Smits et al 2011
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8. Handbook of Pulsar Astronomy, Lorimer & Kramer
9. Bhat et al. 2004 ApJ 605 759