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March 2014 / CALIM

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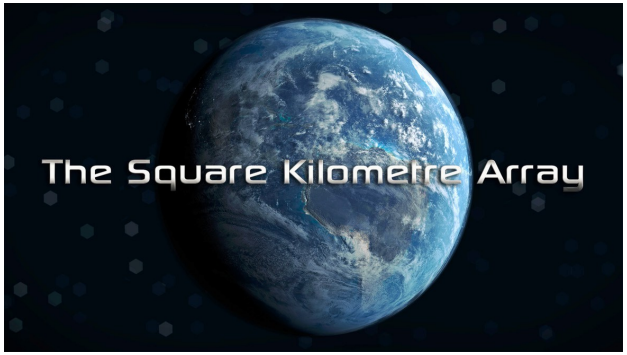
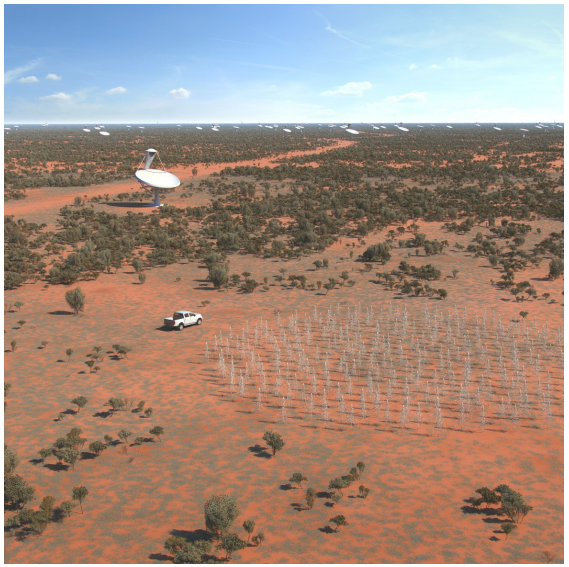
SKA Phase 1 Compute and Power Analysis

SKA analysis goals



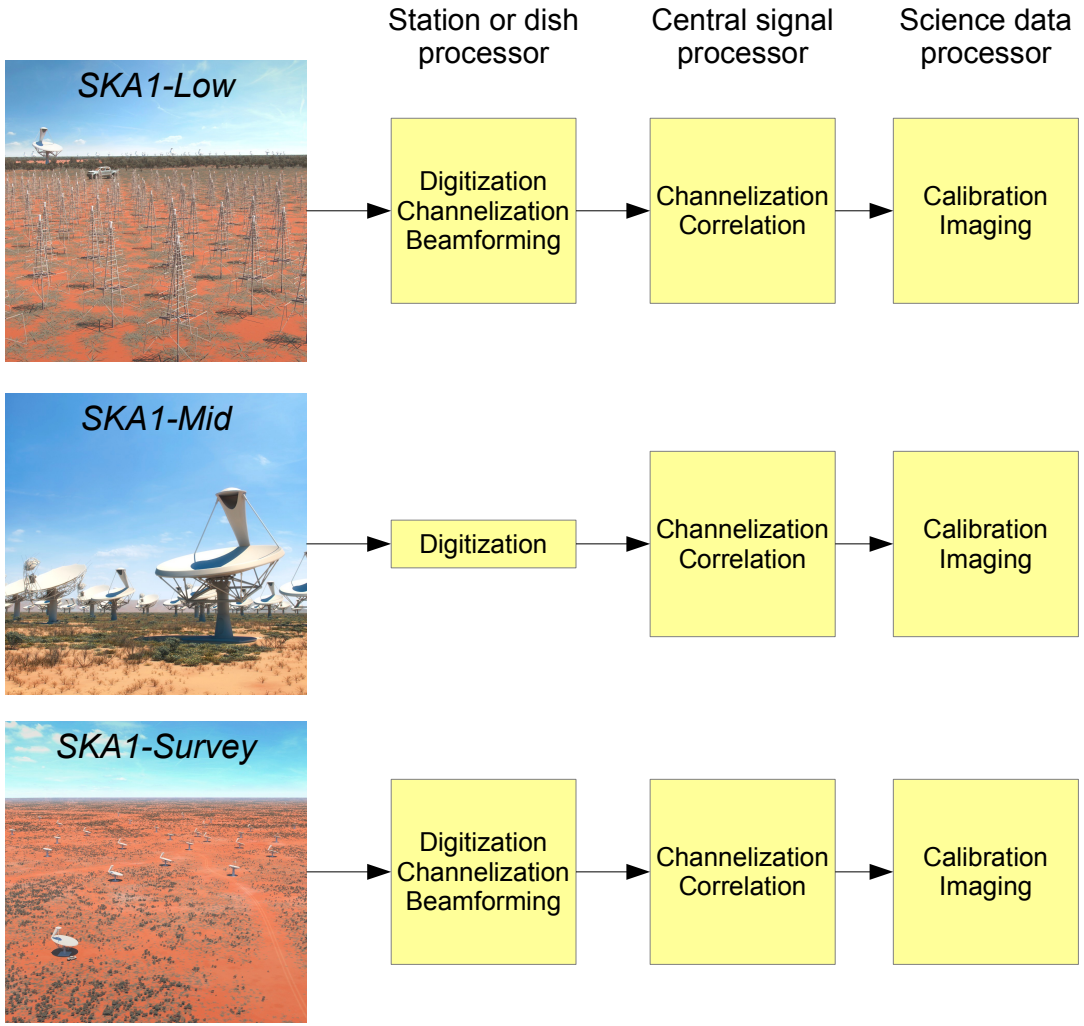
- Understand **compute distribution** for sky imaging with SKA phase 1
- How do these properties relate to the **required compute system**?
  - Flops
  - Energy usage



- Scaling laws retrieved from literature and derived for LOFAR
- Power consumption estimates using Top500 historical data

 Image credit: SKA Organisation

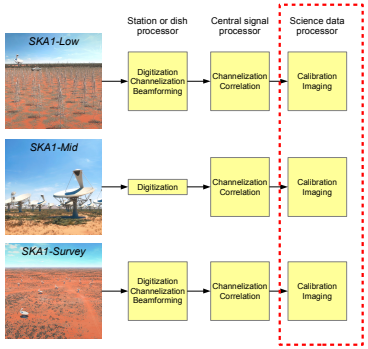
Architecture for digital compute pipeline

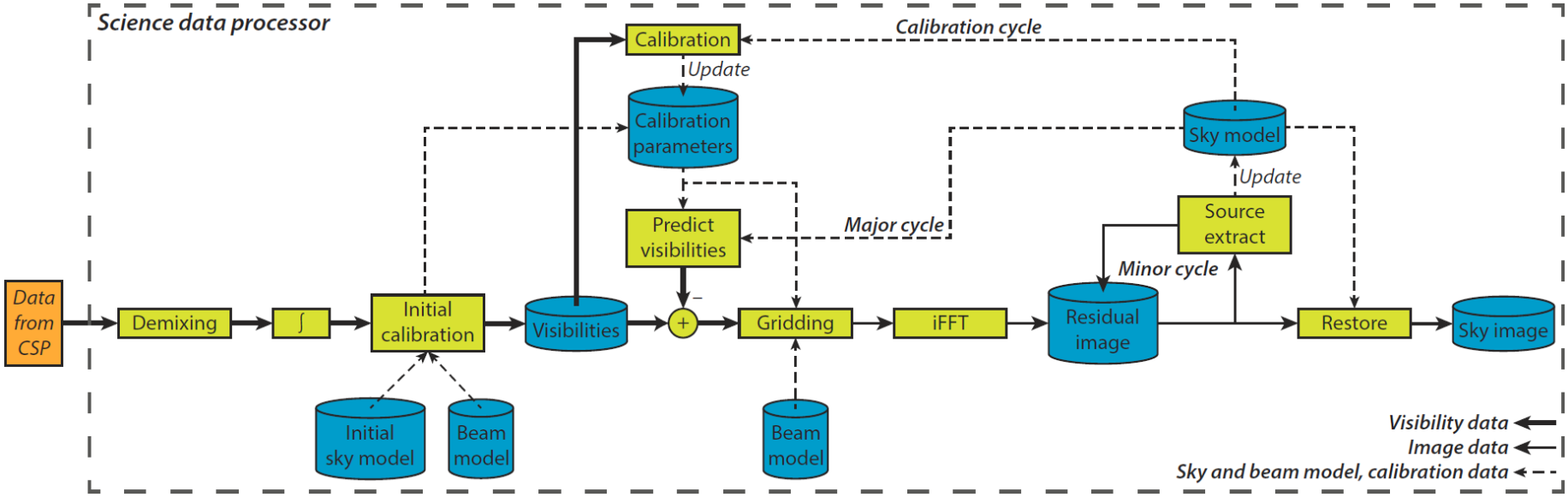


- *One model for SKA1-Low, SKA1-Mid, and SKA1-Survey*

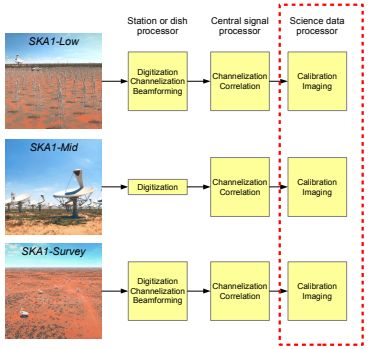
Image credit: SKA Organisation

Architecture for the science data processors





Compute cost of gridding

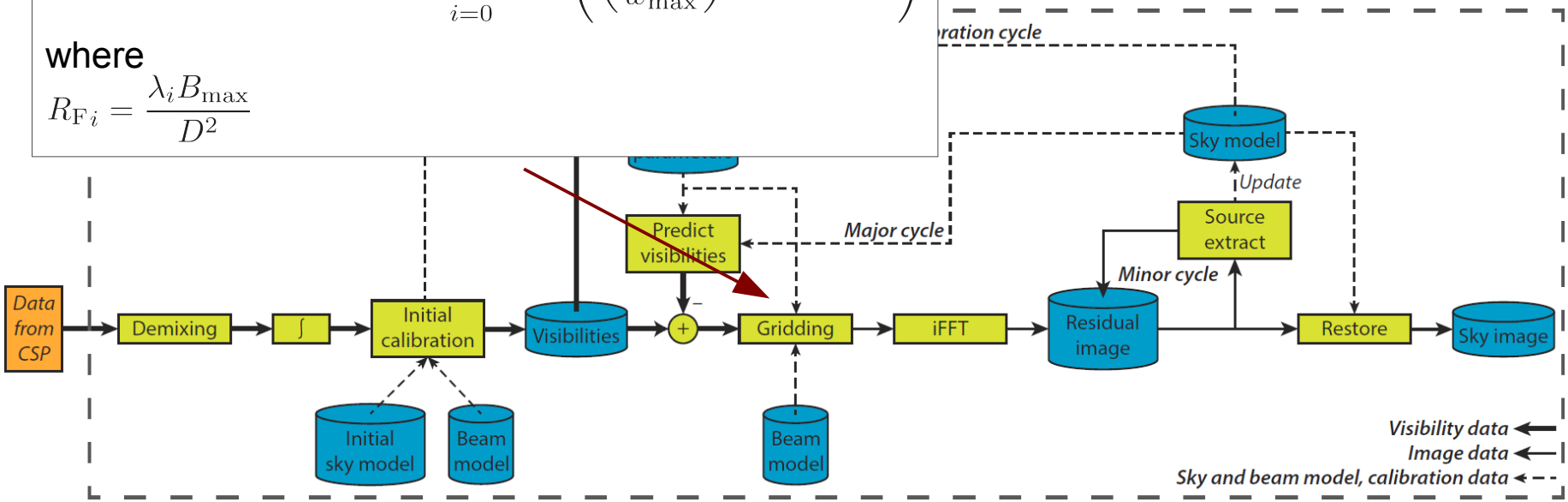


W-Projection [1] (and other sources):

$$C_{\mathrm{grid}} = N_{\mathrm{op}} 2 V_{\mathrm{chan}} T_{\mathrm{obs}} \sum_{i=0}^{N_{\mathrm{image-chan}}-1} \left(\left(\frac{w_{\mathrm{rms}}}{w_{\mathrm{max}}} \right)^2 R_{\mathrm{F}i}^2 + R_{\mathrm{A}}^2 \right)$$

where

$$R_{\mathrm{F}i} = \frac{\lambda_i B_{\mathrm{max}}}{D^2}$$



[1] T. Cornwell, K. Golap, and S. Bhatnagar, *"The noncoplanar baselines effect in radio interferometry: The w-projection algorithm,"* Selected Topics in Signal Processing, IEEE Journal of, vol. 2, no. 5, pp. 647–657, 2008

Computing AW-projection kernels

- Last FFT on oversampled data dominates [2]
- Estimate compute based on average kernel size

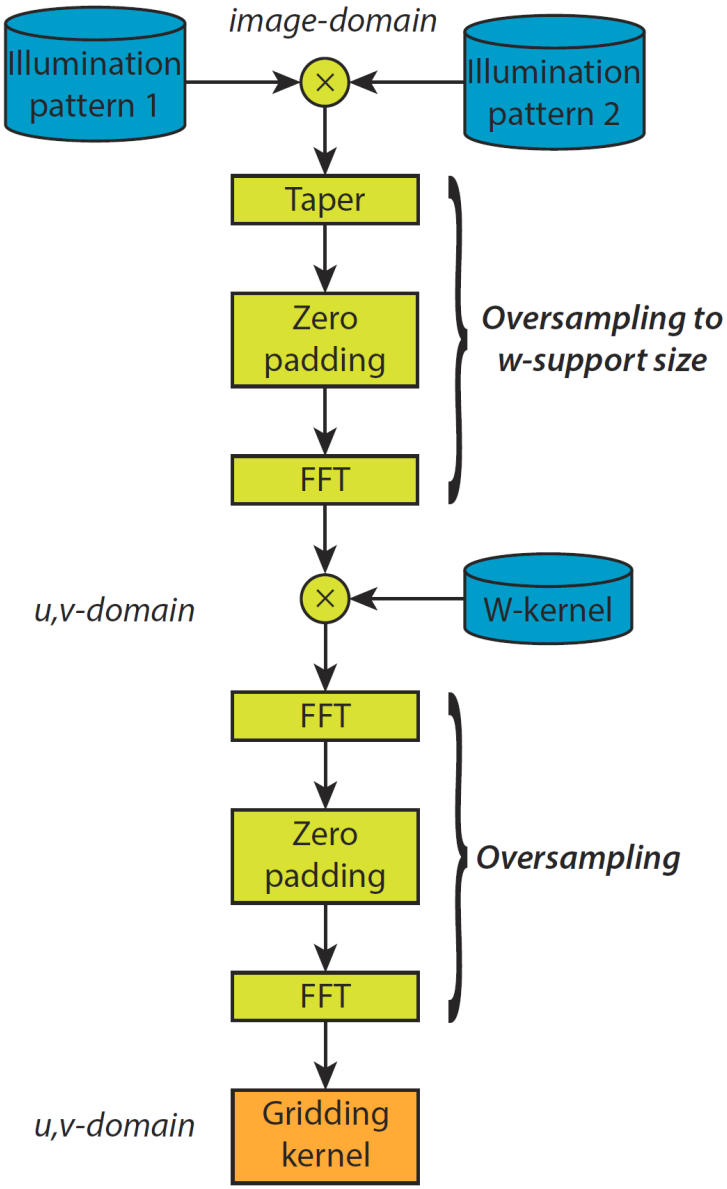
$$R_{\mathrm{ave},i} = \frac{w_{\mathrm{rms}}}{w_{\mathrm{max}}} \frac{\lambda_i B_{\mathrm{max}}}{D^2}$$

- Compute cost of last FFT

$$C_{\mathrm{a-kernel}} = \frac{T_{\mathrm{obs}}}{\Delta_t} \sum_{N_{\mathrm{baseline}}} \sum_{i=0}^{\lceil \frac{\Delta f_{\mathrm{image}}}{\Delta_v} \rceil - 1} 5 O^2 R_{\mathrm{ave},i}^2 \log_2 \left(O^2 R_{\mathrm{ave},i}^2 \right)$$

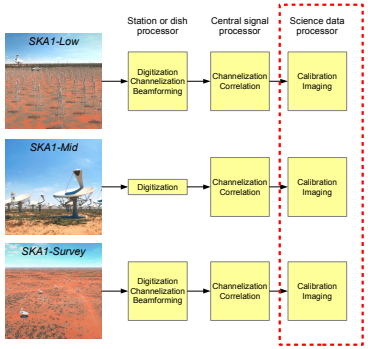
- Time and channel stability Δ_t, Δ_v , oversampling O

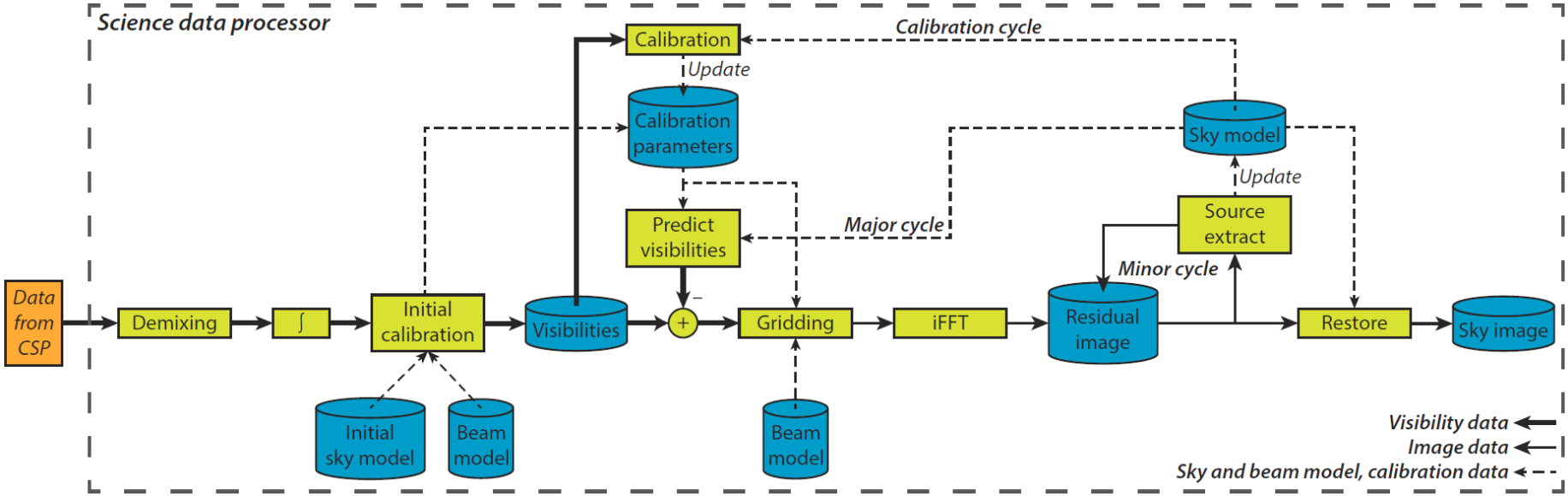
- *Improve by using actual distribution in w*



[2] C. Tasse, B. van der Tol, J. van Zwieten, G. van Diepen, S. Bhatnagar, *"Applying full polarization A-Projection to very wide field of view instruments: An imager for LOFAR"*, in Astronomy and Astrophysics, 2012

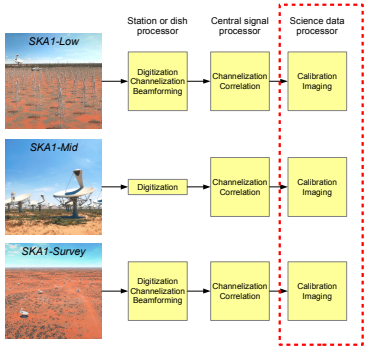
Compute costs for source extract and predict

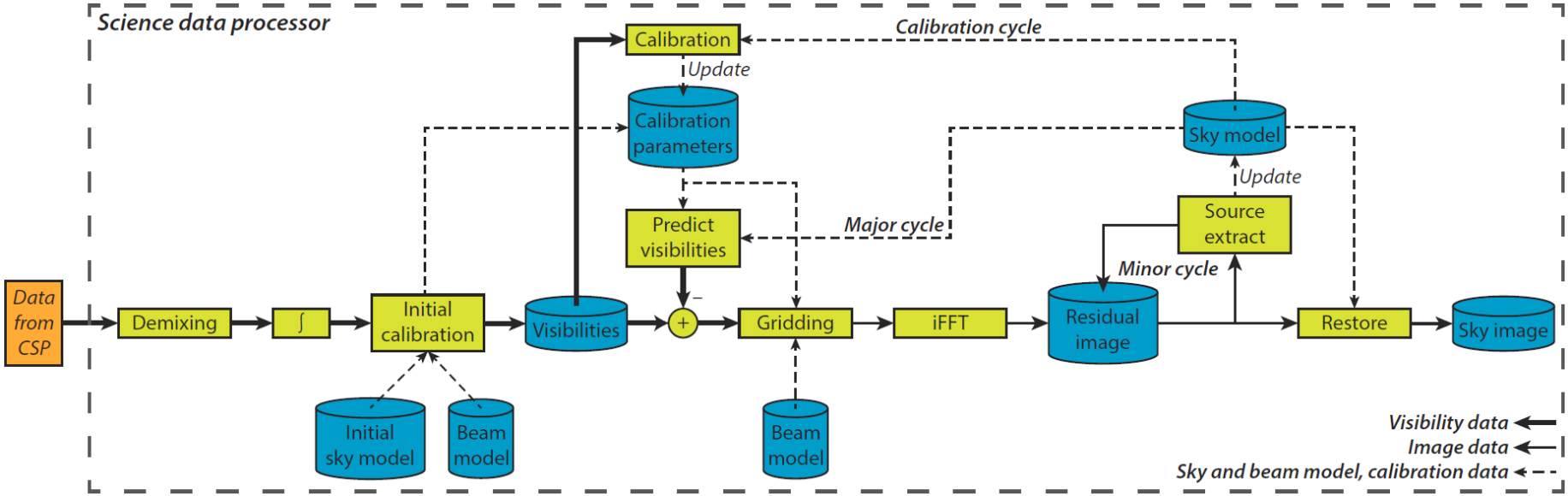




- Source extract: **subtract PSF** of image per source
  - One multiply-accumulate per pixels per source
- Prediction of visibilities with forward FFT and degridding step in major cycle
  - Similar compute requirements as forward gridding

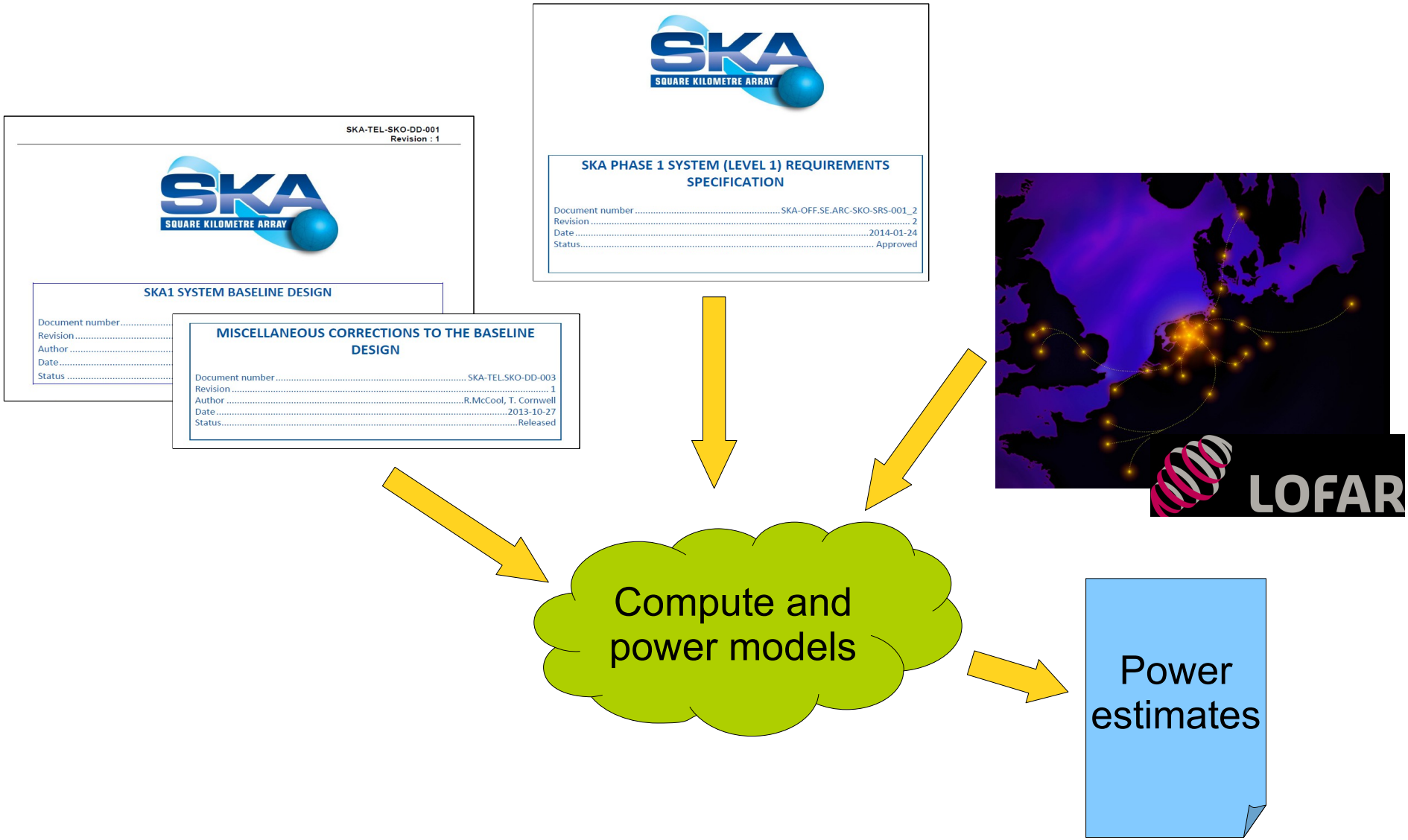
Further model improvements



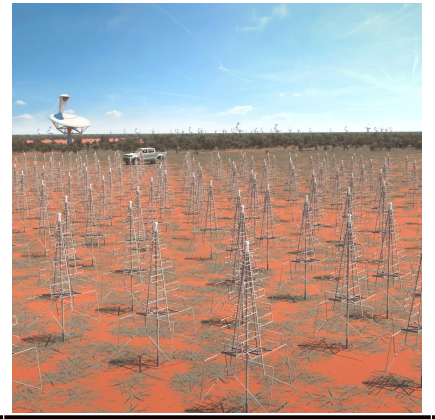


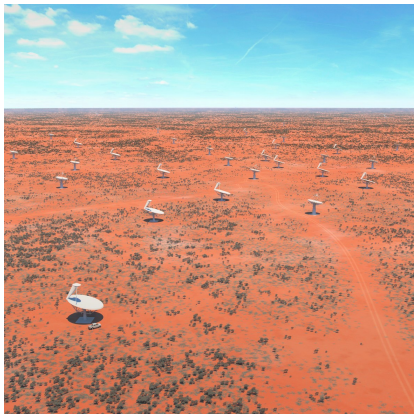
- No calibration (demixing) routines modeled
  - Compute expected to be dominated by gridding

Model parameters retrieved from various sources



Primary parameters from SKA documentation





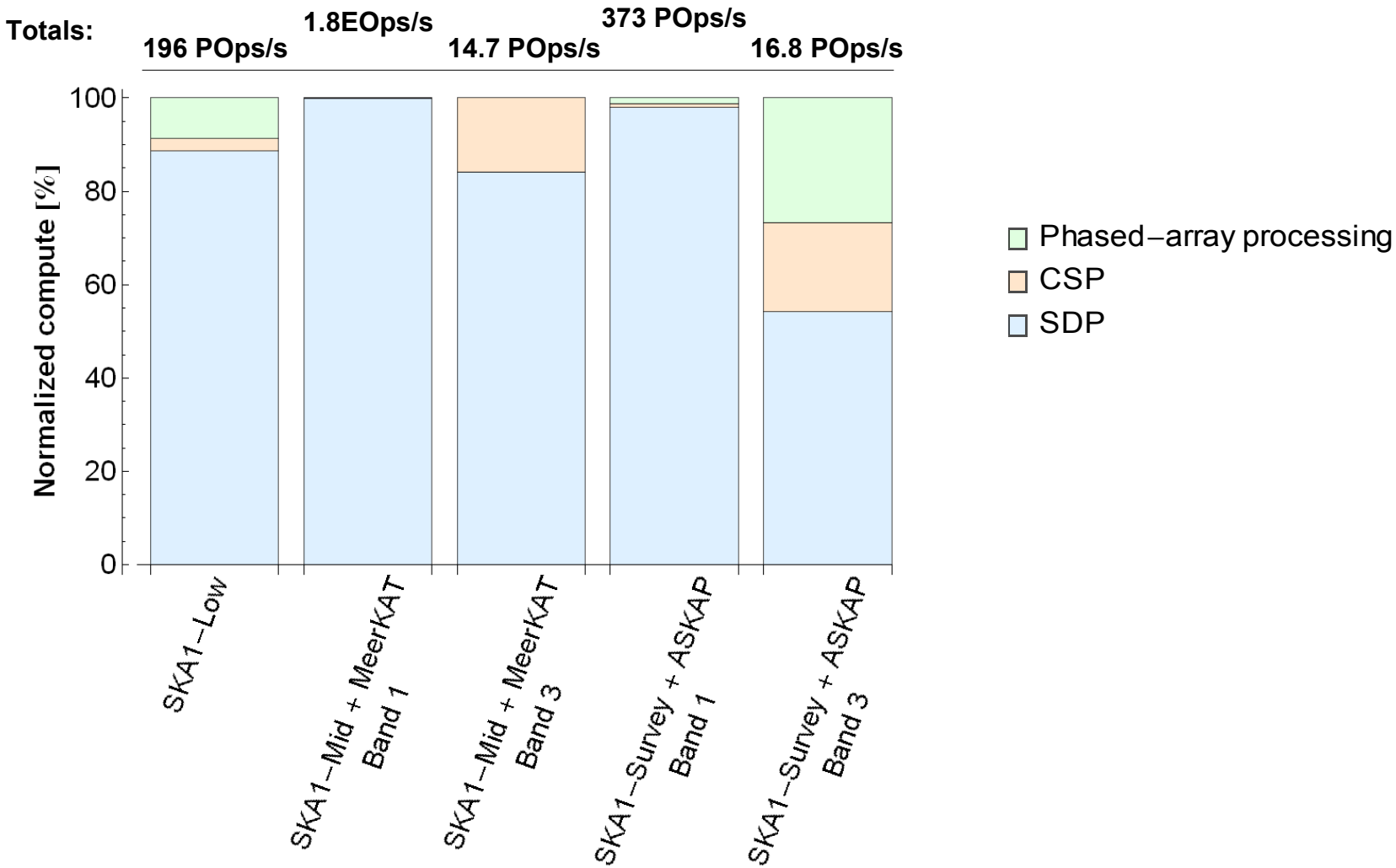
	SKA1-Low	SKA1-Mid + MeerKAT	SKA1-Survey + ASKAP
Stations or dishes	1024	254	96
Antennas	256	-	94
Polarizations	2	2	2
Beams	1	1	36
Frequency range	50 MHz – 350 MHz	350MHz – 13.8 GHz	350MHz – 4 GHz
Bandwidth	300 MHz	1 GHz – 2.5 GHz (435 MHz – 2 GHz)	500 MHz
Channels (bands)	262144 (2048)	262144 (-)	262144 (2048)
Longest baseline (dump time)	70 km (0.6 s)	200 km (0.08 s)	50 km (0.3 s)
Core baseline (dump time)	6 km (6.6 s)	9 km (1.6 s)	10 km (1.2 s)

 Image credit: SKA Organisation

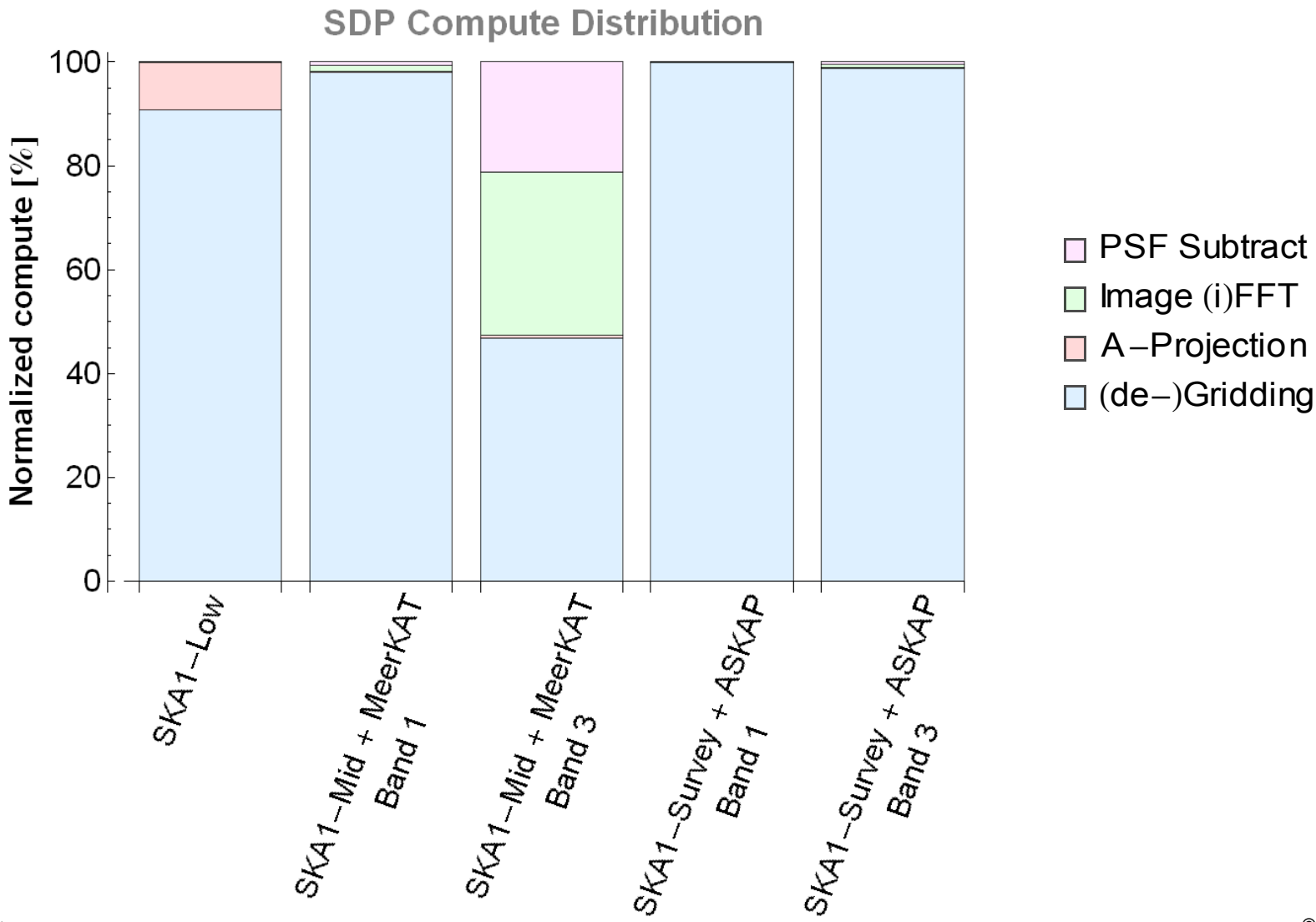
Missing parameters based on experience with LOFAR

- Observation time: 20 minutes (= length of one calibration interval)
  - 3 Calibration cycles
  - 10 Major cycles
  - 100 Minor cycles
- A-projection stability
  - 30 seconds (SKA1-Low), 300 seconds (SKA1-Mid/Survey)
  - 700 kHz

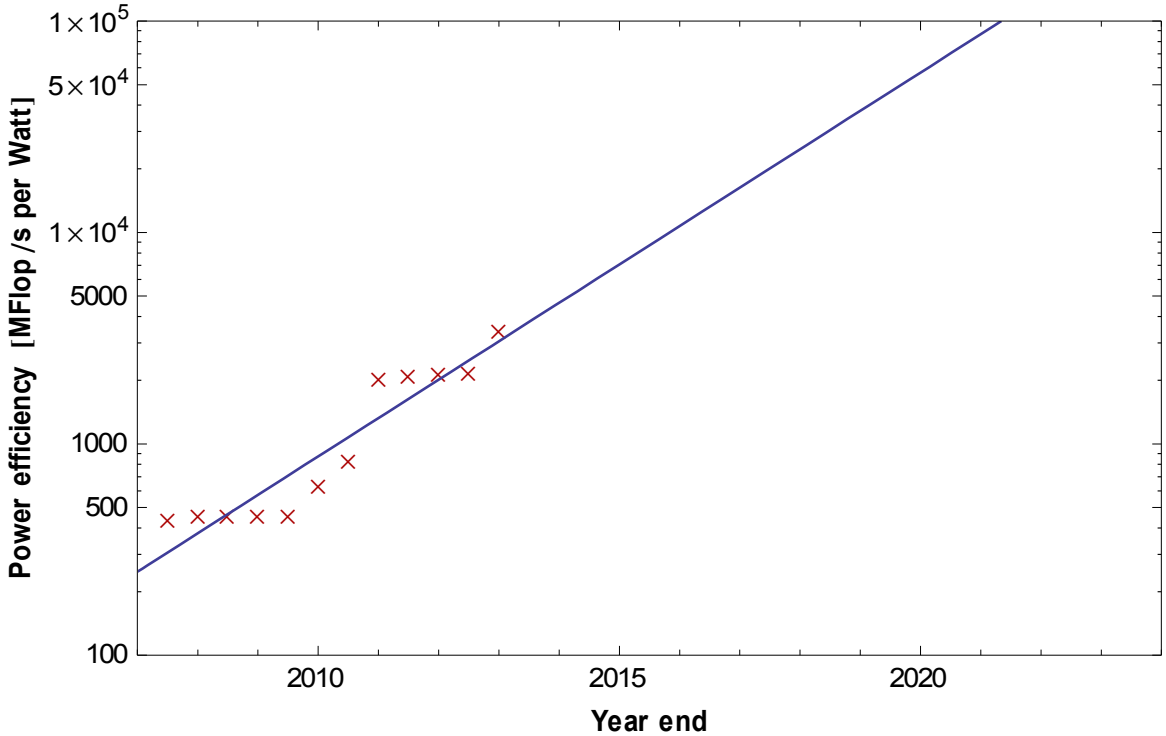
Full array and full bandwidth imaging



Full array and full bandwidth imaging

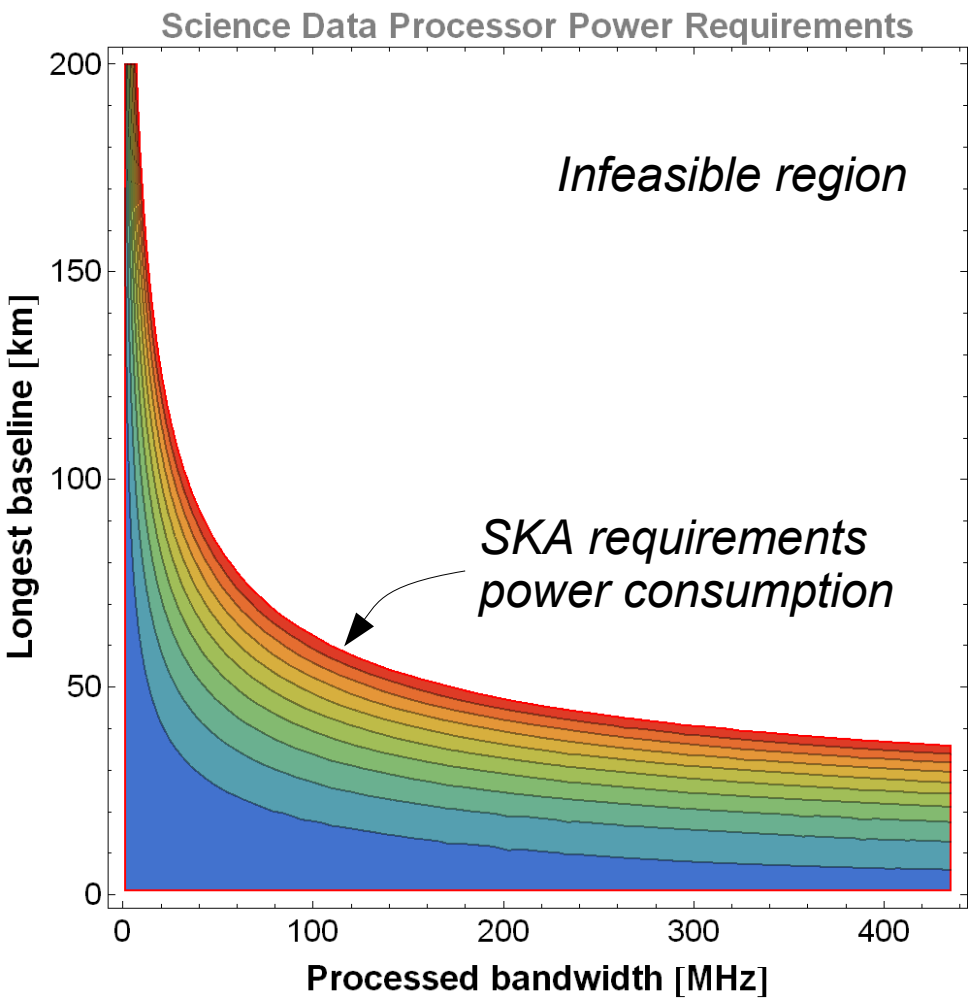


Top 500 power efficiency in 2018



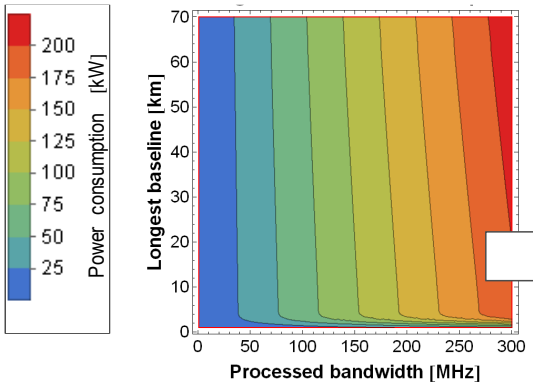
- LinPACK power efficiency
- Best machine from each Top 500 list since June 2008
- Estimate for November 2018 list: ~25 GFlop/s per Watt

Power budget constraints



Central signal processor power requirements

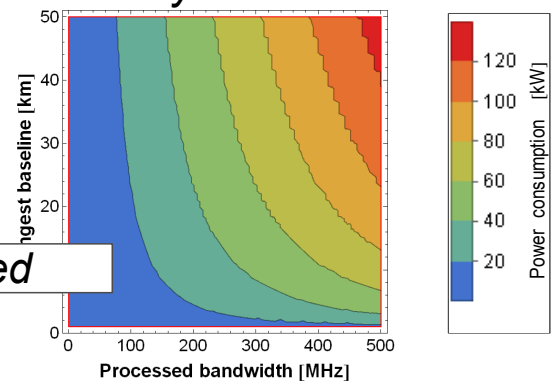
SKA1-Low



Requirement: 1 MW combined

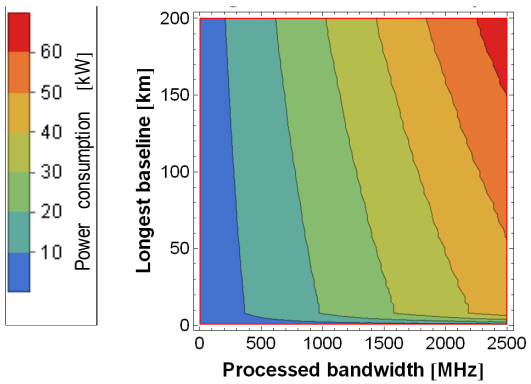
Combined 365 kW estimated

SKA1-Survey + ASKAP band 1



2018

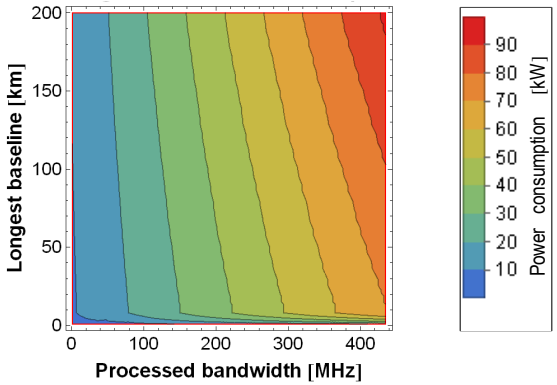
SKA1-Mid band 5



Requirement: 2.5 MW

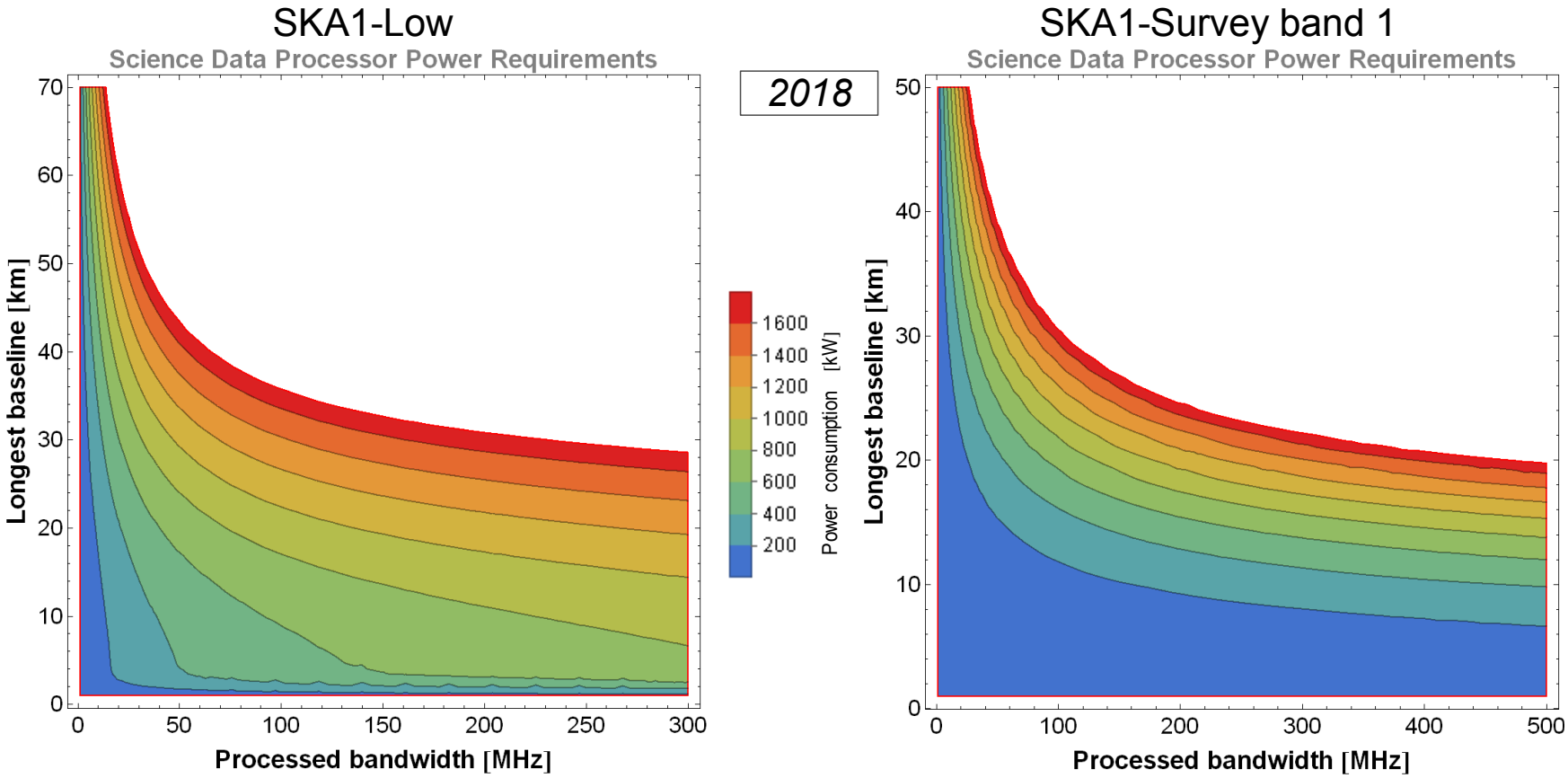
Max 170 kW estimated
Pulsar pipeline?

SKA1-Mid MeerKAT band 3



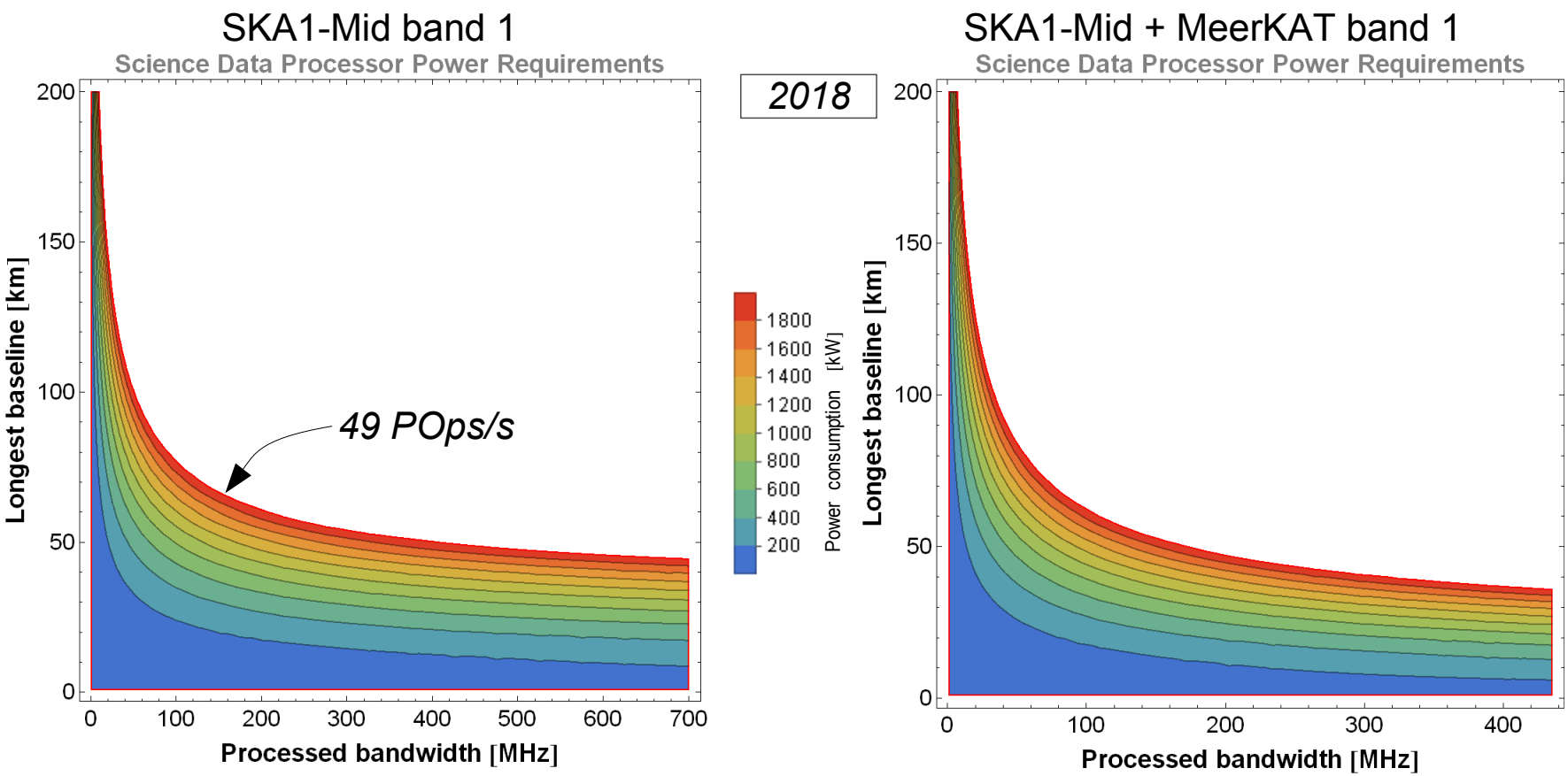
- Power equally distributed over SKA1-Low and SKA1-Survey (simultaneous observations)

SKA1-Low and SKA1-Survey SDP power budget: 3.5 MW



- Power equally distributed over SKA1-Low and SKA1-Survey (simultaneous observations)
- Baseline dependent time/frequency averaging

SKA1-Mid SDP power budget: 2 MW



- Baseline dependent time/frequency averaging

Ample power budget for CSP

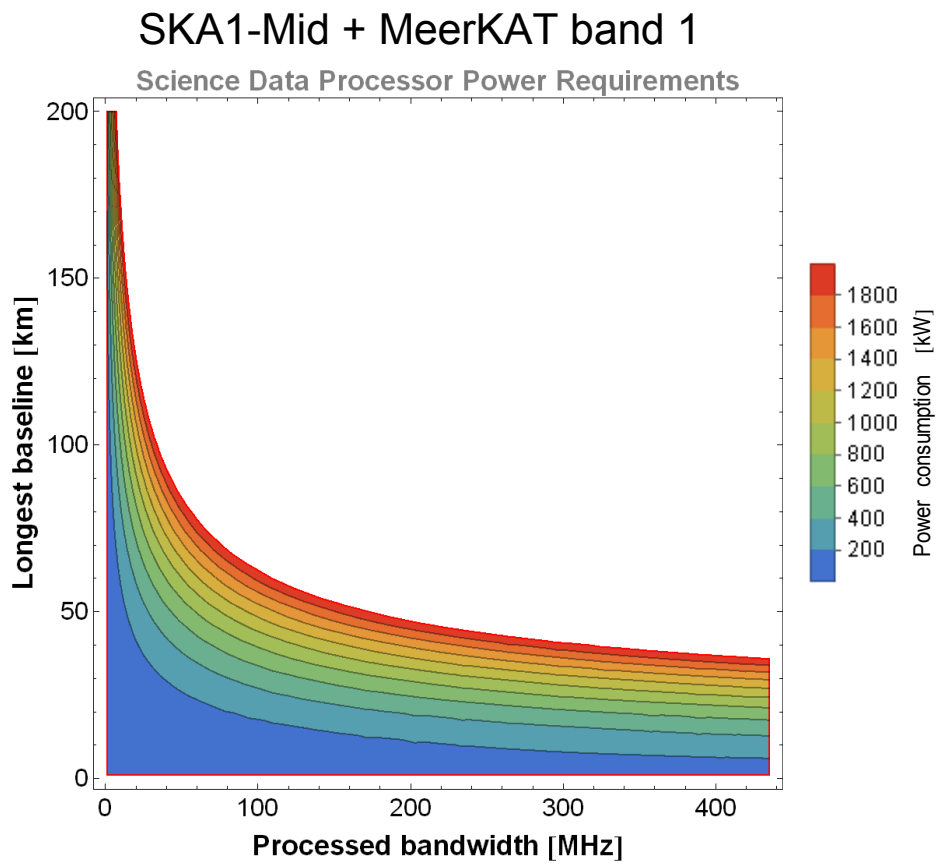
- Given 1 and 2.5 MW requirement: 635 and 170 kW needed

- A “software” correlator easily fits in the power budget
- Power budget of CSP and SDP askew for sky imaging

- Requirements for other modes? E.g. SKA1-Mid pulsar search?

Power budget constraining SDP

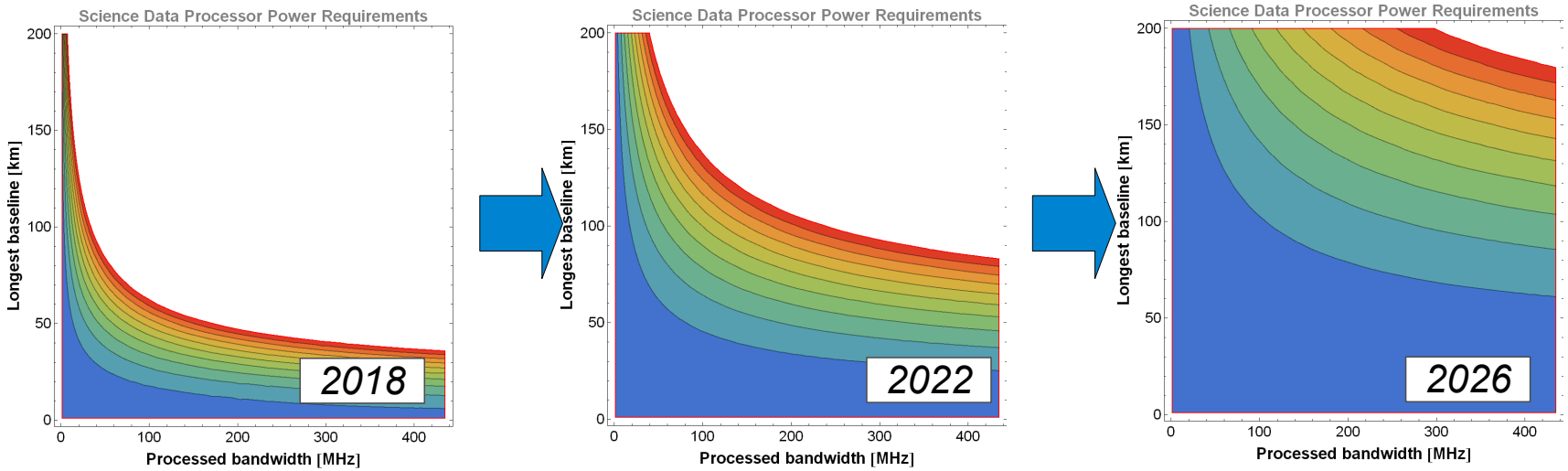
- What do the astronomers want?
  - *Match with SKA phase 1 science cases*



Increase scientific performance without modifying power budget

- Wait for technology to improve power efficiency over time?

SKA1-Mid + MeerKAT band 1

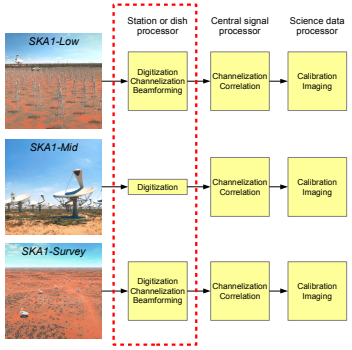


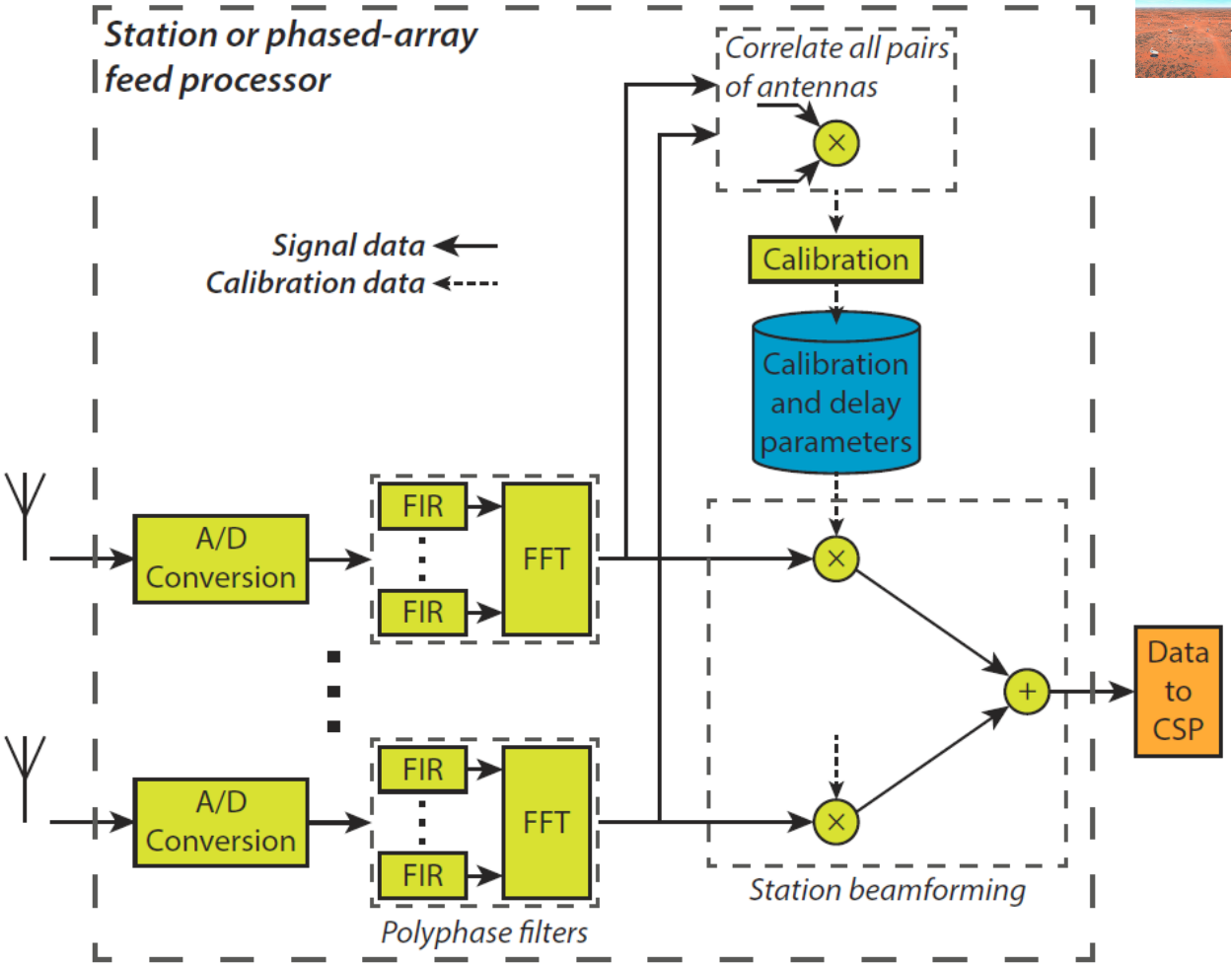
- Top 500 is based on general-purpose hardware such as CPUs and GPUs
  - Use dedicated accelerators for intensive steps such as gridding
    - FPGAs, ASICs,...

Questions

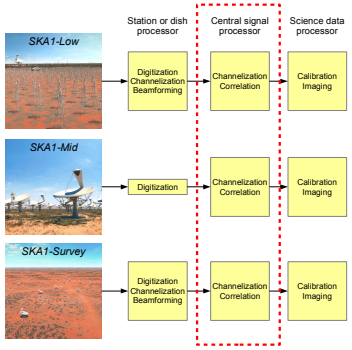
Backup slides

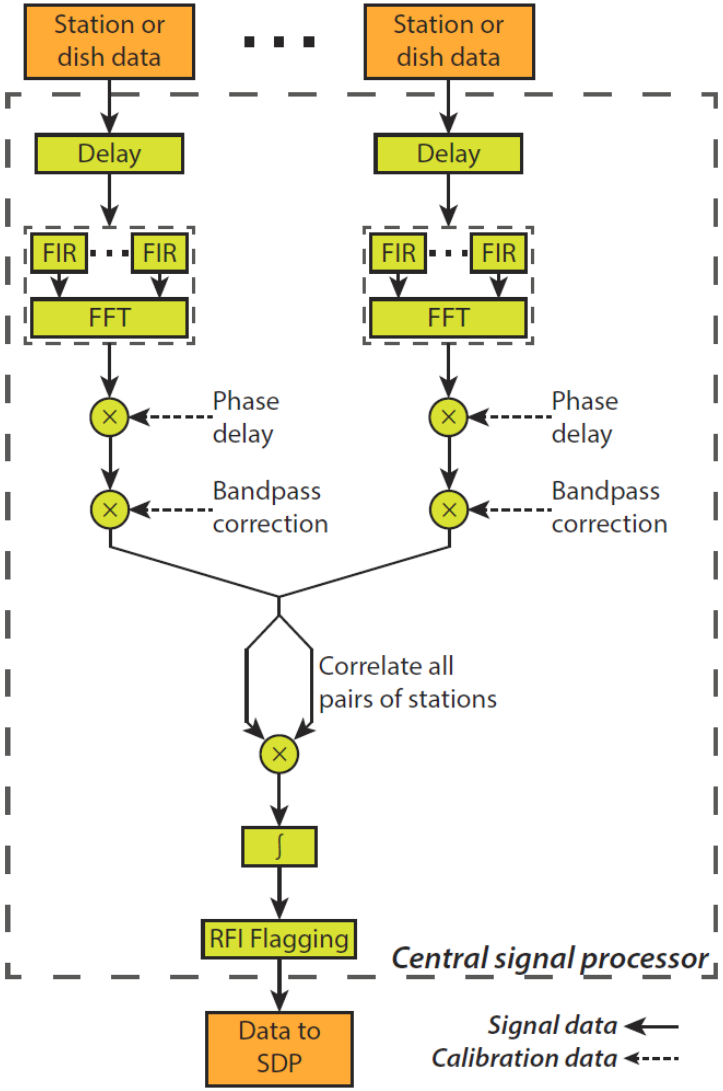
Architecture for phased-array processing



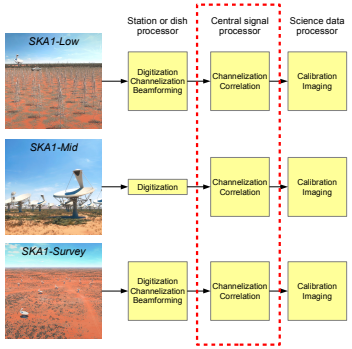


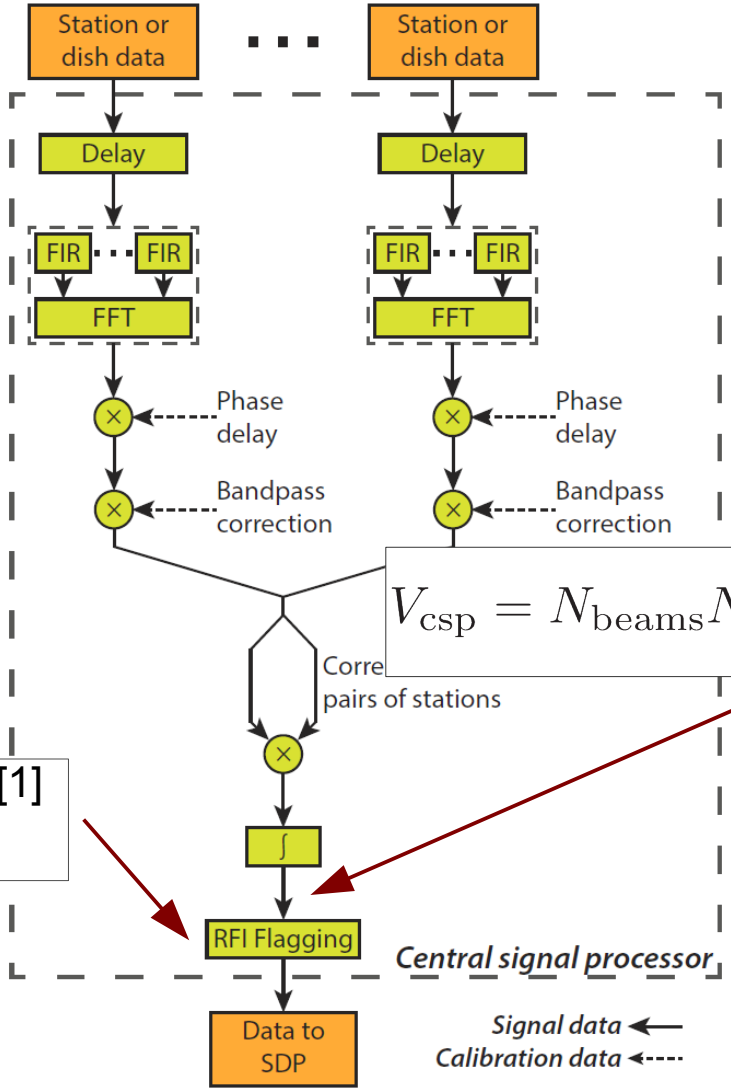
Architecture for the central signal processors





Architecture for the central signal processors





$$V_{\mathrm{csp}} = N_{\mathrm{beams}} N_{\mathrm{channels}} 0.5 N_{\mathrm{pol}}^2 N_{\mathrm{stat}}^2 \frac{1}{\tau_{\mathrm{csp}}}$$

AOFlagger used by LOFAR [1]

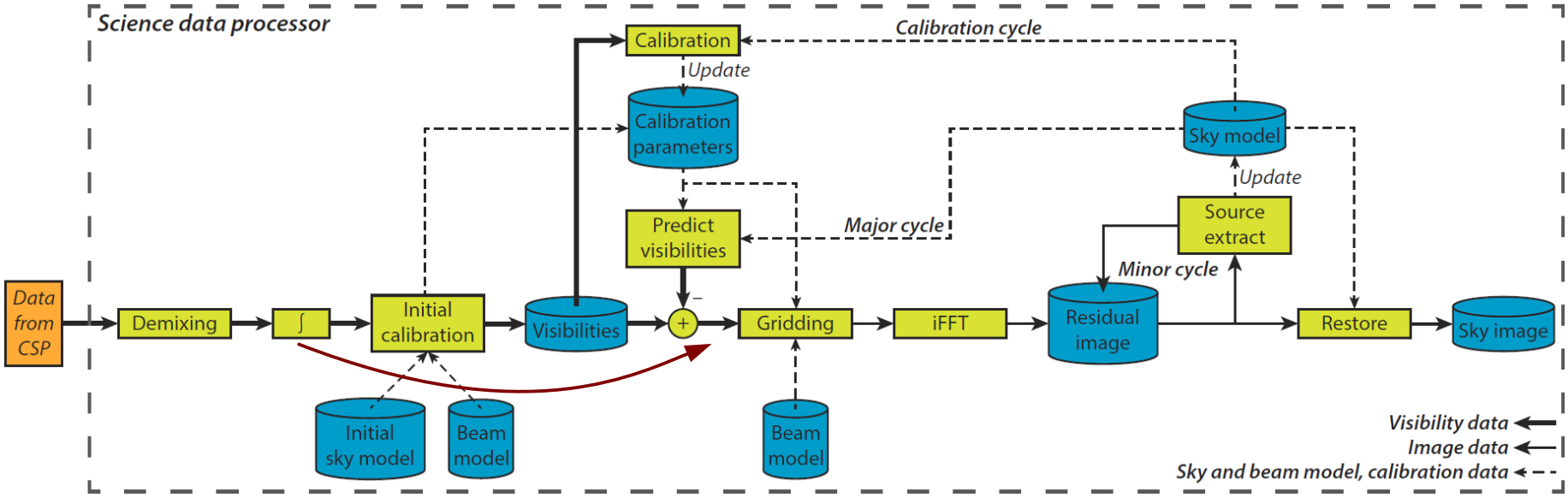
$$R_{\mathrm{rfi}} = 278 V_{\mathrm{csp}}$$

[1] A. R. Offringa, A. G. de Bruyn, S. Zaroubi, and M. Biehl, *"A LOFAR RFI detection pipeline and its first results,"* in Proceedings of Science, RFI2010, 2010.

Baseline dependent averaging

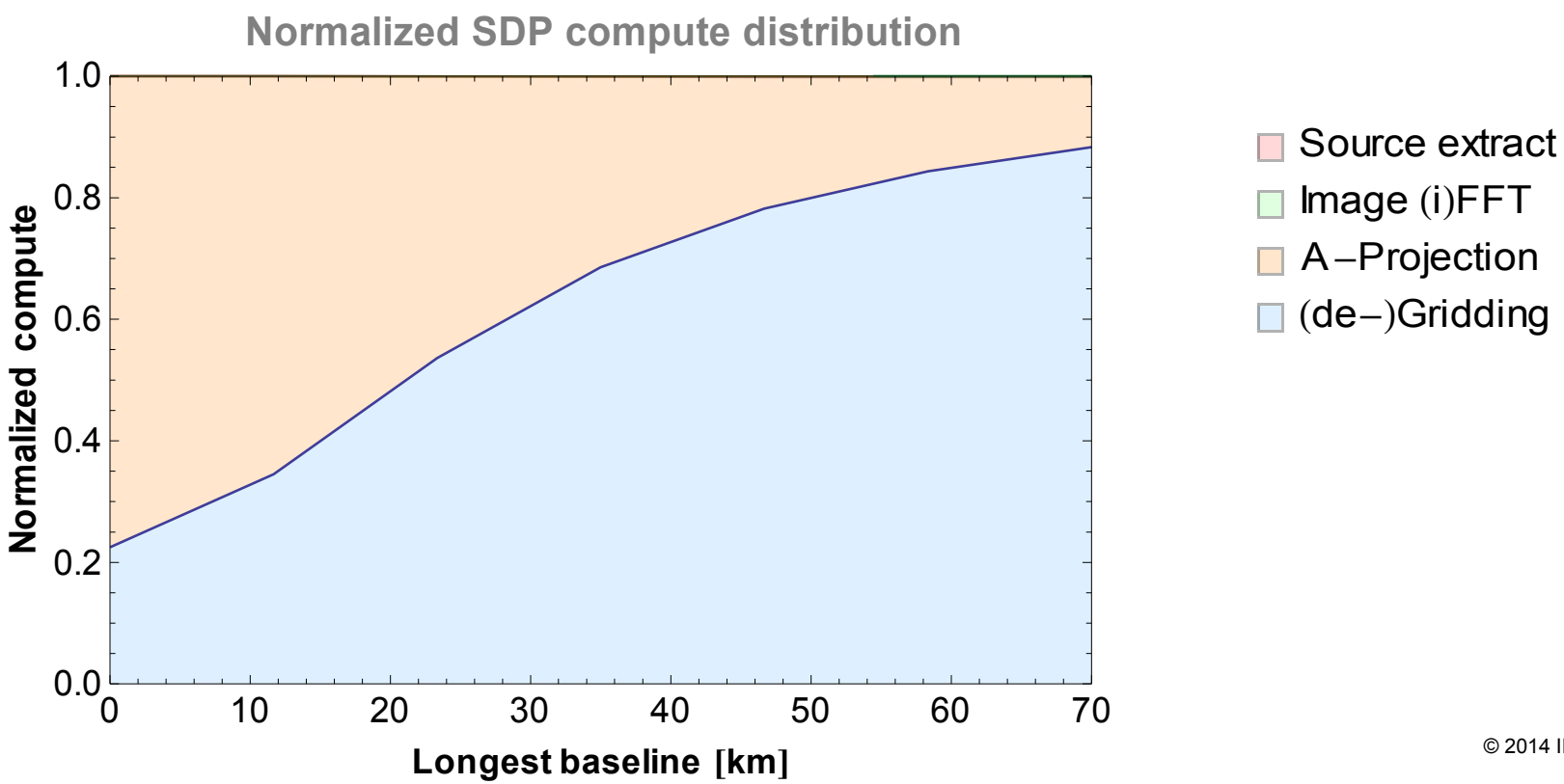
	SKA1-Low 1 zone	SKA1-Low 2 zones
SDP	159 POps/s	884 POp/s

- With one dump time, gridding performs the averaging step on the image
  - Save compute by introducing before gridding
- No impact on presented models as calibration is not included



Gridding complexity vs A-projection complexity

Gridding: $\mathcal{O}\left(\frac{\lambda^3 B_{\max}^4}{D^6}\right)$ A-projection: $\mathcal{O}\left(\frac{\lambda^2 B_{\max}^2}{D^4}\log_2\frac{\lambda^2 B_{\max}^2}{D^4}\right)$



Full array and full bandwidth imaging

		SKA1-Low	SKA1-Mid + MeerKAT	SKA1-Survey + ASKAP
Station/dish processing	One station	17 TOps/s	-	46 TOps/s
	All stations	17 POps/s	-	4 POps/s
CSP	Low band	5 POps/s	565 TOps/s	3 POps/s
	High band	-	2 POps/s	3 POps/s
SDP	Low band (% de-/gridding)	159 POps/s (99%)	2 EOps/s (98 %)	366 POps/s (99%)
	High band (% de-/gridding)	-	12 POps/s (47 %)	9 POps/s (99 %)

SKA1-Low parameters

▼ Default parameters for instrument SKA1-Low

Parameter Name	Value
Instrument	SKA1-Low
Band	
Instrument is phased array	True
Antenna count	256
Polarizations count	2
Beam count	1
Signal bandwidth of feed [Hz]	$3. \times 10^{8}$
Max signal bandwidth processed [Hz]	$3. \times 10^{8}$
Sub-band count in stations	2048
Channel count	262144
FIR tap count in PFBs	8
Station or dish diameter [m]	35
Maximum baseline length [m]	70000
Core baseline length (zone 2) [m]	6000
CSP dump time [s]	0.6
Lowest signal frequency in band [Hz]	50000000
Phased-array correlator dump time [s]	1
Phased-array calibration table update rate [s]	240
Observation time [s]	1200.
SDP minor cycle count	100
SDP major cyclc count	10
SDP calibration cycle count	3
SDP power constraint [W]	3.5×10^{6}
CSP power constraint [W]	$1. \times 10^{6}$
Station or dish distribution function	SKA1LowStationCount
A-projection kernel time stability [s]	30
A-projection kernel frequency stability [Hz]	700000

▼ Derived parameters

Parameter Name	Value
Channel bandwidth [Hz]	1144.41
Station or dish count	1024
Sub-band bandwidth [Hz]	146484.
SDP integrated channel width [Hz]	2288.82
SDP integrated channel count	131072
SDP image channel count	131072
SDP all baselines dump time [s]	0.6
SDP core baselines dump time [s]	6.6

SKA1-Mid parameters (band 1)

▼ Default parameters for instrument SKA1-Mid

Parameter Name	Value
Instrument	SKA1-Mid
Band	Band 1
Instrument is phased array	False
Polarizations count	2
Beam count	1
Channel count	262144
FIR tap count in PFBs	8
Station or dish diameter [m]	15
Maximum baseline length [m]	200000
Core baseline length (zone 2) [m]	8000
CSP dump time [s]	0.08
Observation time [s]	1200.
SDP minor cycle count	100
SDP major cyclc count	10
SDP calibration cycle count	3
SDP power constraint [W]	2000000
CSP power constraint [W]	2.5×10^6
Station or dish distribution function	SKA1MidDishCount
A-projection kernel time stability [s]	300
A-projection kernel frequency stability [Hz]	700000
Lowest signal frequency in band [Hz]	350000000
Signal bandwidth of feed [Hz]	$1. \times 10^9$
Max signal bandwidth processed [Hz]	$7. \times 10^8$

▼ Derived parameters

Parameter Name	Value
Channel bandwidth [Hz]	3814.7
Station or dish count	190
SDP integrated channel width [Hz]	3814.7
SDP integrated channel count	262144
SDP image channel count	262144
SDP all baselines dump time [s]	0.08
SDP core baselines dump time [s]	2.24

SKA1-Mid + MeerKAT parameters (band 1)

▼ Default parameters for instrument SKA1-Mid + MeerKAT

Parameter Name	Value
Instrument	SKA1−Mid + MeerKAT
Band	Band 1
Instrument is phased array	False
Polarizations count	2
Beam count	1
Channel count	262144
FIR tap count in PFBs	8
Station or dish diameter [m]	12
Maximum baseline length [m]	200000
Core baseline length (zone 2) [m]	9000
CSP dump time [s]	0.08
Observation time [s]	1200.
SDP minor cycle count	100
SDP major cyclc count	10
SDP calibration cycle count	3
SDP power constraint [W]	2000000
CSP power constraint [W]	2.5×10^6
Station or dish distribution function	SKA1MidMeerKATDishCount
A−projection kernel time stability [s]	300
A−projection kernel frequency stability [Hz]	700000
Lowest signal frequency in band [Hz]	580000000
Signal bandwidth of feed [Hz]	$1. \times 10^9$
Max signal bandwidth processed [Hz]	4.35×10^8

▼ Derived parameters

Parameter Name	Value
Channel bandwidth [Hz]	3814.7
Station or dish count	254
SDP integrated channel width [Hz]	3814.7
SDP integrated channel count	262144
SDP image channel count	262144
SDP all baselines dump time [s]	0.08
SDP core baselines dump time [s]	1.6

SKA1-Survey + ASKAP parameters (band 1)

▼ Default parameters for instrument SKA1-Survey + ASKAP

Parameter Name	Value
Instrument	SKA1-Survey + ASKAP
Band	Band 1
Instrument is phased array	True
Antenna count	94
Polarizations count	2
Beam count	36
Sub-band count in stations	2048
Channel count	262144
FIR tap count in PFBs	8
Station or dish diameter [m]	12
Maximum baseline length [m]	50000
Core baseline length (zone 2) [m]	10000
CSP dump time [s]	0.3
Phased-array correlator dump time [s]	1
Phased-array calibration table update rate [s]	240
Observation time [s]	1200.
SDP minor cycle count	100
SDP major cyclc count	10
SDP calibration cycle count	3
SDP power constraint [W]	3.5×10^6
CSP power constraint [W]	$1. \times 10^6$
Station or dish distribution function	SKA1SurveyASKAPDishCount
A-projection kernel time stability [s]	300
A-projection kernel frequency stability [Hz]	700000
Lowest signal frequency in band [Hz]	350000000
Signal bandwidth of feed [Hz]	$5. \times 10^8$
Max signal bandwidth processed [Hz]	$5. \times 10^8$

▼ Derived parameters

Parameter Name	Value
Channel bandwidth [Hz]	1907.35
Station or dish count	97
Sub-band bandwidth [Hz]	244141.
SDP integrated channel width [Hz]	7629.39
SDP integrated channel count	65536
SDP image channel count	65536
SDP all baselines dump time [s]	0.3
SDP core baselines dump time [s]	1.2

SKA1-Low details

```
SKA1-Low

Station:
    PPF: 14.1312 TOps/s
    Beamforming: 1.2288 TOps/s
    Correlation: 1.31072 TOps/s
    Calibration: 1.78957 GOps/s

Total compute per station: 16.6725 TOps/s
Total compute for all 1024 stations: 17.0726 POps/s

CSP:
    PPF: 60.8256 TOps/s
    Correlation: 5.03316 POps/s
    RFI flagging: 254.72 TOps/s

Total compute: 5.34871 POps/s
Estimated power consumption: 216.226 kWatt (L1 Requirement: 1. MWatt)

SDP:
    A-Projection: 8.37162 POps/s
    Gridding: 83.3551 POps/s
    iFFT: 59.2219 TOps/s
    Deconvolution: 94.3718 TOps/s
    FFT: 53.2997 TOps/s
    A-Projection: 7.53446 POps/s
    Degridding: 75.0196 POps/s

Total compute: 174.488 POps/s
Estimated power consumption: 7.05382 MWatt (L1 Requirement: 3.5 MWatt)


▼ Additional data
  Gridding:
      Minimum Rf: 342.857
      Maximum Rf: 48.9799
      Average Rf: 111.196
      wrms/wmax (estimate): 0.3128
      Ra (estimate): 7
      Corrected minimum w-term: 107.246
      Corrected maximum w-term: 15.3209
      Corrected average w-term: 34.7821
  Imaging:
      Pixels: 6000
```

SKA1-Mid details (band 1)

```
SKA1-Mid Band 1

CSP:
    PPF: 48.26 TOps/s
    Correlation: 404.32 TOps/s
    RFI flagging: 46.0395 TOps/s

Total compute: 498.62 TOps/s
Estimated power consumption: 20.1571 kWatt (L1 Requirement: 2.5 MWatt)

SDP:
    A-Projection: 897.71 TOps/s
    Gridding: 660.055 POps/s
    iFFT: 6.41213 POps/s
    Deconvolution: 8.38861 POps/s
    FFT: 5.77092 POps/s
    A-Projection: 807.939 TOps/s
    Degridding: 594.049 POps/s

Total compute: 1.27638 EOps/s
Estimated power consumption: 51.5988 MWatt (L1 Requirement: 2. MWatt)


▼ Additional data
  Gridding:
      Minimum Rf: 761.905
      Maximum Rf: 253.969
      Average Rf: 418.52
      wrms/wmax (estimate): 0.3128
      Ra (estimate): 7
      Corrected minimum w-term: 238.324
      Corrected maximum w-term: 79.4415
      Corrected average w-term: 130.913
  Imaging:
      Pixels: 40000
```

SKA1-Mid + MeerKAT details (band 1)

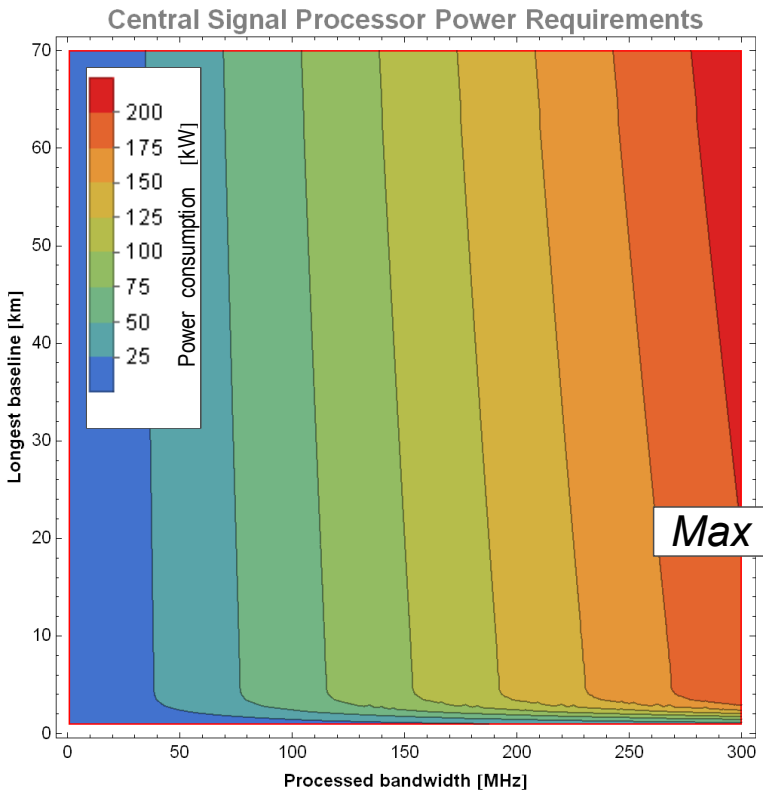
```
SKA1-Mid + MeerKAT Band 1

CSP:
    PPF: 64.516 TOps/s
    Correlation: 449.033 TOps/s
    RFI flagging: 51.1308 TOps/s

Total compute: 564.68 TOps/s
Estimated power consumption: 22.8277 kWatt (L1 Requirement: 2.5 MWatt)

SDP:
    A-Projection: 1.54976 POps/s
    Gridding: 916.417 POps/s
    iFFT: 10.2299 POps/s
    Deconvolution: 13.1072 POps/s
    FFT: 9.20694 POps/s
    A-Projection: 1.39478 POps/s
    Degridding: 824.776 POps/s

Total compute: 1.77668 EOps/s
Estimated power consumption: 71.8239 MWatt (L1 Requirement: 2. MWatt)


▼ Additional data
  Gridding:
      Minimum Rf: 718.391
      Maximum Rf: 410.51
      Average Rf: 536.031
      wrms/wmax (estimate): 0.3128
      Ra (estimate): 7
      Corrected minimum w-term: 224.713
      Corrected maximum w-term: 128.408
      Corrected average w-term: 167.671
  Imaging:
      Pixels: 50000
```

SKA1-Survey + ASKAP details (band 1)

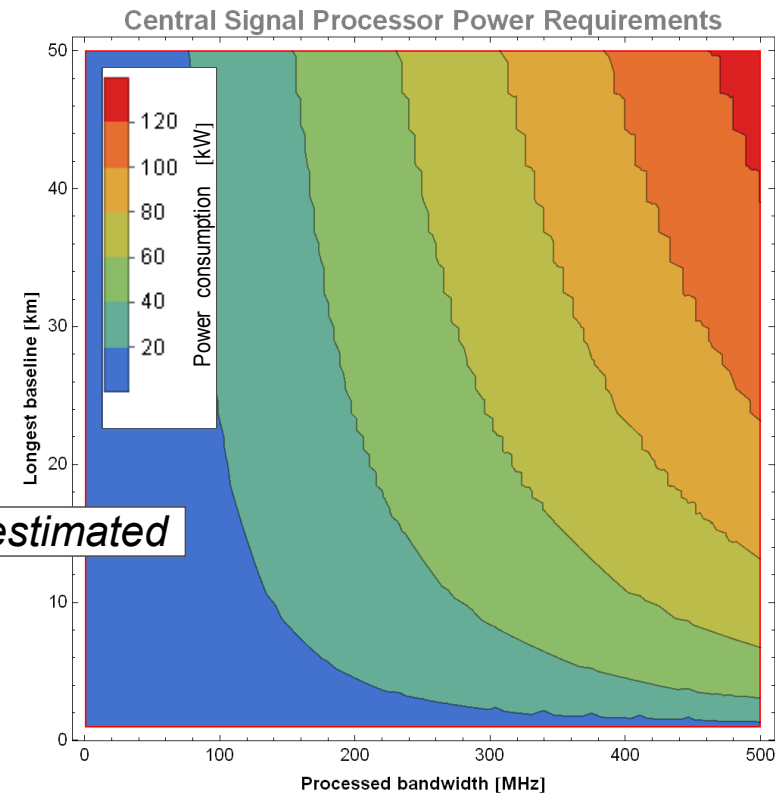
```
SKA1-Survey + ASKAP Band 1

Station:
    PPF: 8.648 TOps/s
    Beamforming: 27.072 TOps/s
    Correlation: 10.6032 TOps/s
    Calibration: 241.282 MOps/s

Total compute per station: 46.3234 TOps/s
Total compute for all 97 stations: 4.49337 POps/s

CSP:
    PPF: 345.708 TOps/s
    Correlation: 2.70979 POps/s
    RFI flagging: 164.566 TOps/s

Total compute: 3.22007 POps/s
Estimated power consumption: 130.174 kWatt (L1 Requirement: 1. MWatt)

SDP:
    A-Projection: 27.6812 TOps/s
    Gridding: 192.154 POps/s
    iFFT: 139.363 TOps/s
    Deconvolution: 204.8 TOps/s
    FFT: 125.426 TOps/s
    A-Projection: 24.9131 TOps/s
    Degridding: 172.938 POps/s

Total compute: 365.614 POps/s
Estimated power consumption: 14.7803 MWatt (L1 Requirement: 3.5 MWatt)


▼ Additional data
  Gridding:
      Minimum Rf: 297.619
      Maximum Rf: 122.55
      Average Rf: 184.856
      wrms/wmax (estimate): 0.3128
      Ra (estimate): 7
      Corrected minimum w-term: 93.0952
      Corrected maximum w-term: 38.3337
      Corrected average w-term: 57.823
  Imaging:
      Pixels: 12500
```

SKA1-Low and SKA1-Survey CSP power budget: 1 MW

SKA1-Low



SKA1-Survey + ASKAP band 1

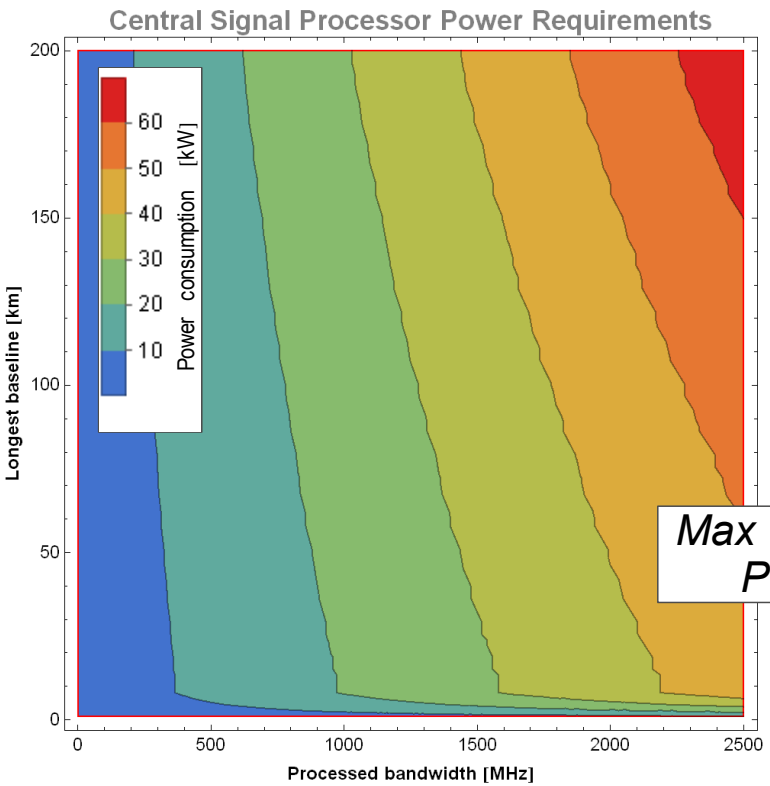


Max 365 kW estimated

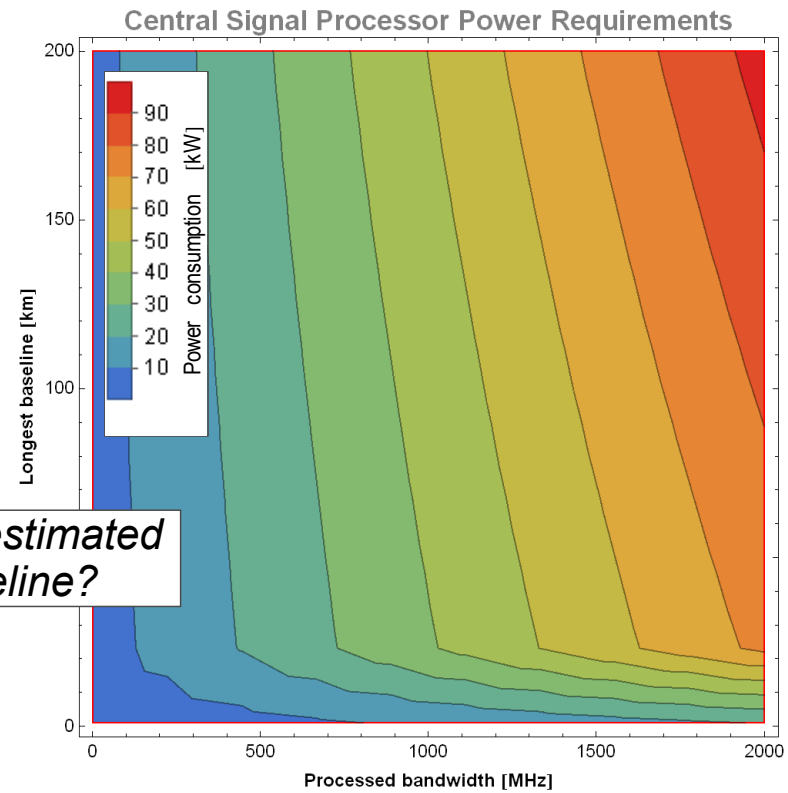
- Power equally distributed over SKA1-Low and SKA1-Survey (simultaneous observations)

SKA1-Mid CSP power budget: 2.5 MW

SKA1-Mid band 5

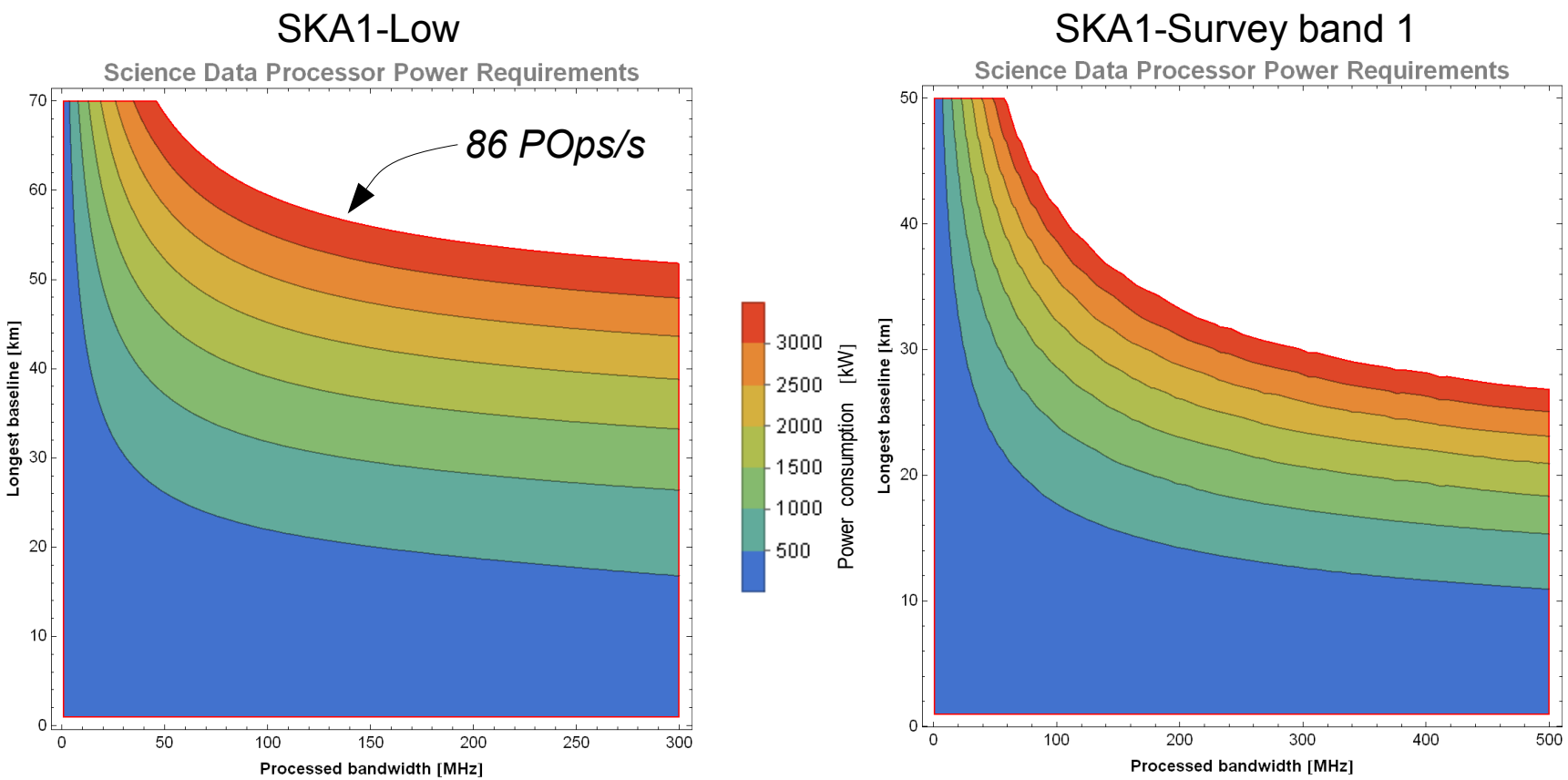


SKA1-Mid MeerKAT band 3



Max 170 kW estimated
Pulsar pipeline?

SKA1-Low and SKA1-Survey SDP power budget: 3.5 MW



- 3.5 MW for both SKA1-Low and SKA1-Survey
- Baseline dependent time/frequency averaging