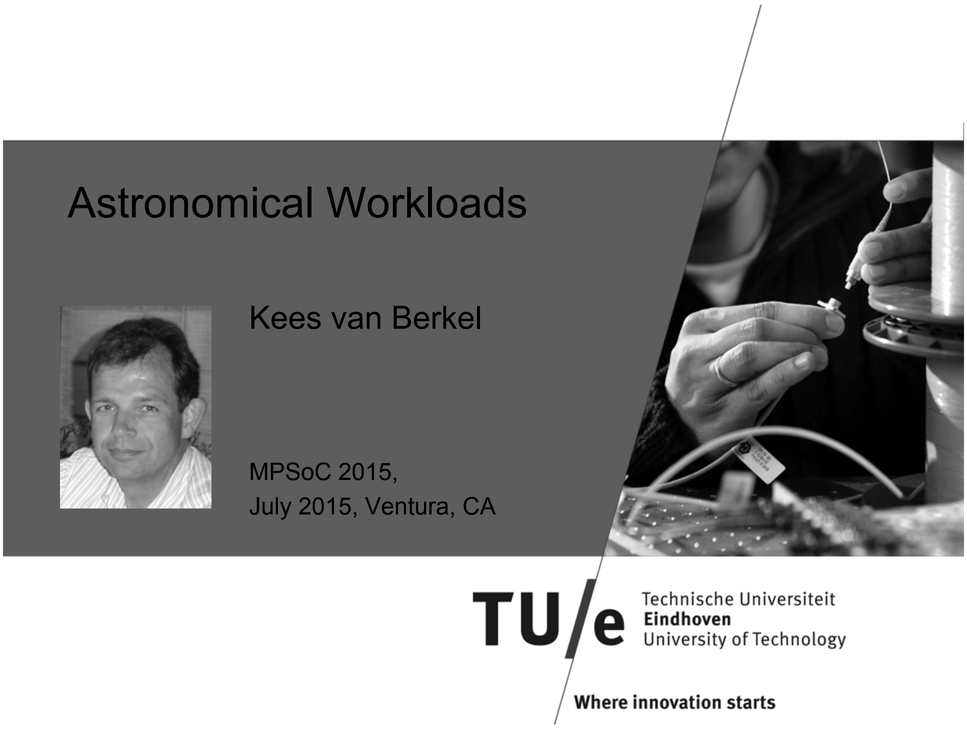

Astronomical Workloads

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MPSoC 2015,
July 2015, Ventura, CA

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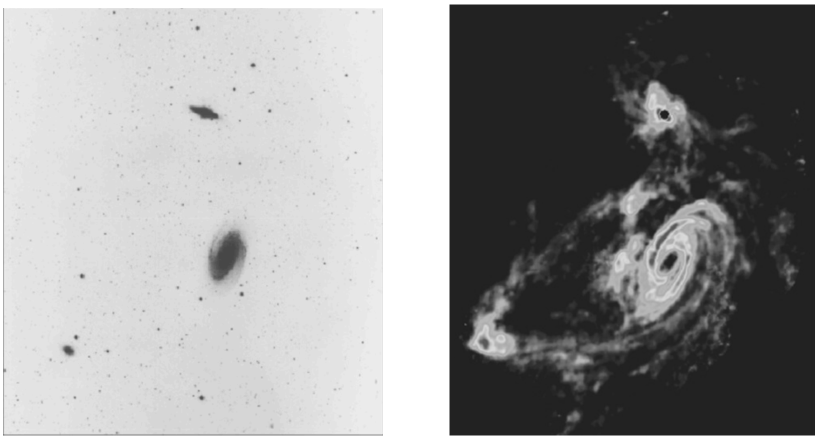
Where innovation starts

Radio Astronomy

Tidal interactions in the M81 group



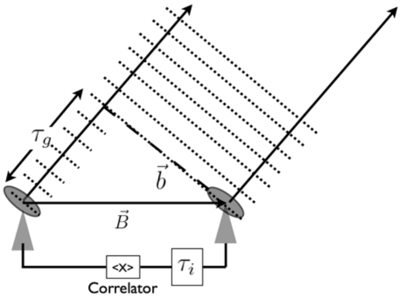
stellar light distribution

21cm HI distribution

Image courtesy of NRAO/AUI

Interferometry

Westerbork Synthesis Radio Telescope:
14 dishes, D=25m, B=3km [NL,1956]



2-element interferometer.
Output of the correlator:

$$V_\nu(\mathbf{r_1}, \mathbf{r_2}) = \langle \mathbf{E}_\nu(\mathbf{r_1}) \mathbf{E}^*_\nu(\mathbf{r_2}) \rangle$$

with v the observation frequency
and * denoting complex conjugation

Van Cittert–Zernike theorem [1934-38]

correctorelator output

sky intensity

speed of light

$$\mathsf{V}_\nu(\mathbf{r}_1,\mathbf{r}_2) \approx \int I_\nu(\mathbf{s}) e^{-2\pi i \nu \mathbf{s}\cdot(\mathbf{r}_1-\mathbf{r}_2)/c} d\Omega$$

solid angle

base line vector,
separating the 2 antennae

Adding geometry (assuming “narrow field”):

$$V_\nu(u,v) = \iint I_\nu(l,m) e^{-2\pi i(ul+vm)}\, dl\, dm$$

2D Fourier transform!

where *(l, m)* are sky-image coordinates
and *(u, v)* are coordinates of the base-line vector

[1], [2], [3]

Van Cittert–Zernike theorem [1934-38]

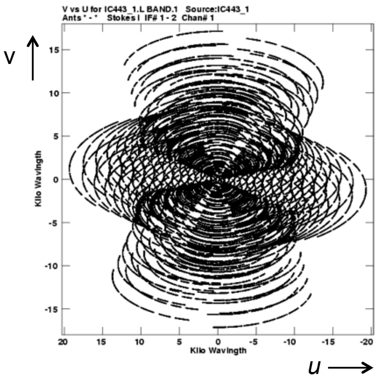
In principle:

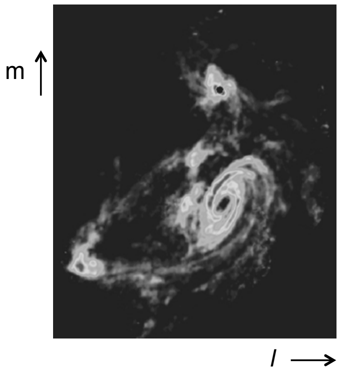
(u, v) coverage
(A, φ) at (u,v)

$\xrightarrow{\text{I-FFT}}$

$\xleftarrow[\text{FFT}]{}$

(l,m) image
pixel intensity





W-projection, W-snapshot [2008/12, Cornwell et al]

However, Van Cittert–Zernike theorem “wide-field”

$$V(u, v, w) = \int \frac{I(\ell, m)}{\sqrt{1 - \ell^2 - m^2}} e^{-2\pi i[u\ell+vm+w(\sqrt{1-\ell^2-m^2}-1)]} d\ell dm$$

Visibilities are 3D *(u, v, w)*, due to earth’ curvature (Fresnel diffraction).

Choose as convolution function $G(\ell, m, w) = e^{-2\pi i[w(\sqrt{1-\ell^2-m^2}-1)]}$
and let *G˜(u, v, w)* be the Fourier transform of *G(l, m, w).*

Then, using the Fourier convolution theorem (W-projection):

$$V(u, v, w) = \tilde{G}(u, v, w) * V(u, v, w = 0)$$

W-snapshot
= *W-projection* applied piecemeal to a series of snapshots. [4], [5]

Deconvolution (CLEAN, Högbom 1974)

$$I(l, m) \xrightarrow{\text{FFT}} V(u, v, w{=}0) \xrightarrow{**\tilde{G}(u, v, w)} V(u, v, w)$$

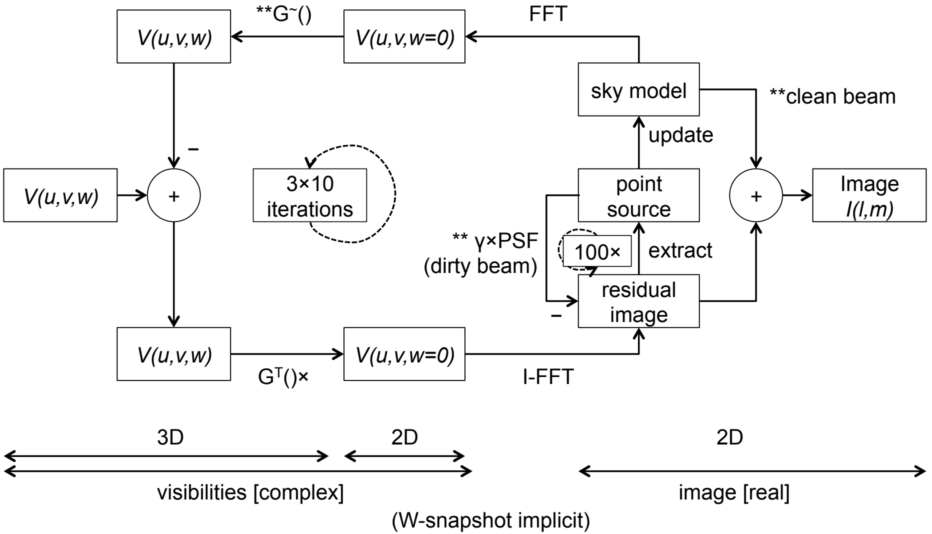
Can be computed straightforwardly, but cannot be inverted easily, because *V(u, v, w)* provides only a finite number of noisy samples (and a variety of other reasons, including antenna beam forms).

CLEAN (next slide) is an iterative *deconvolution* algorithm.

(Under certain conditions CLEAN converges to a solution that is the least-squares fit of the FFT algorithm.)

[1], [3]

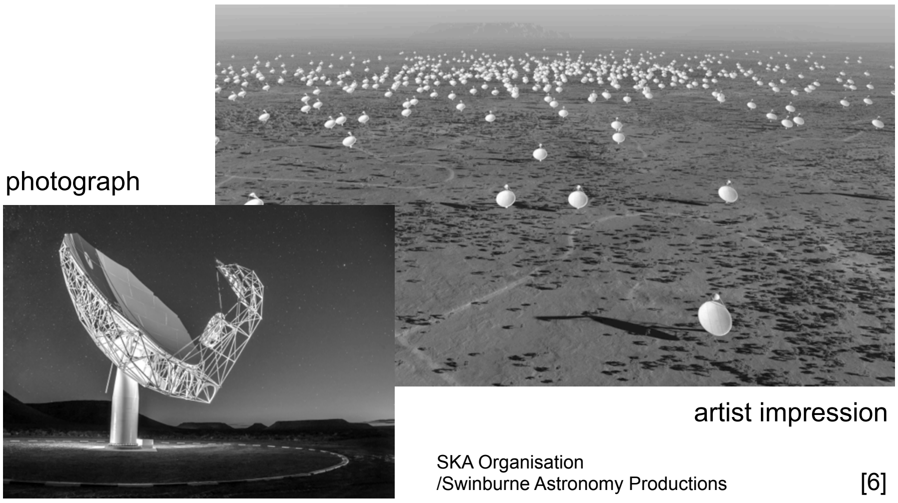
Imaging (W-projection/snapshot + CLEAN)



**G˜()
FFT
V(u,v,w)
V(u,v,w=0)
sky model
**clean beam
update
V(u,v,w)
+
3×10 iterations
point source
+
Image I(l,m)
** γ×PSF (dirty beam)
100×
extract
residual image
V(u,v,w)
G^T()×
V(u,v,w=0)
I-FFT
3D
2D
2D
visibilities [complex]
image [real]
(W-snapshot implicit)

SKA1-mid [South Africa]: science in 2020

Towards a Square Kilometer Array



photograph

artist impression

SKA Organisation
/Swinburne Astronomy Productions [6]

Imaging: compute load for SKA1-mid

quantity	unit	^{10}log	note
# base lines		5.5	$2^2 \times$(#dishes + #stations)^2 = $(2\times254)^2$
dump rate	s^{-1}	1	(integration time = 0.08s)$^{-1}$
observation time	s	3	
# channels		5	“image cube” for spectral analysis
# visibilities / observation		*14.5*	*= input to imaging (≈ 10^{16} Byte)*
# ops /visibility /iteration		4.5	convolution, matrix multiply, (I)FFT
# major iterations		1.5	(3×calibration) × (10×major)
# ops /observation		*20.5*	
# ops /sec	*Hz*	*17.5*	≈ 1 exa-op / 1 exaflop

- #operations/visibility depends on #snapshots
- calibration loop (3×) around imaging loop
- data type: double|single precision, floating|fixed point?

[7], [8], [9]

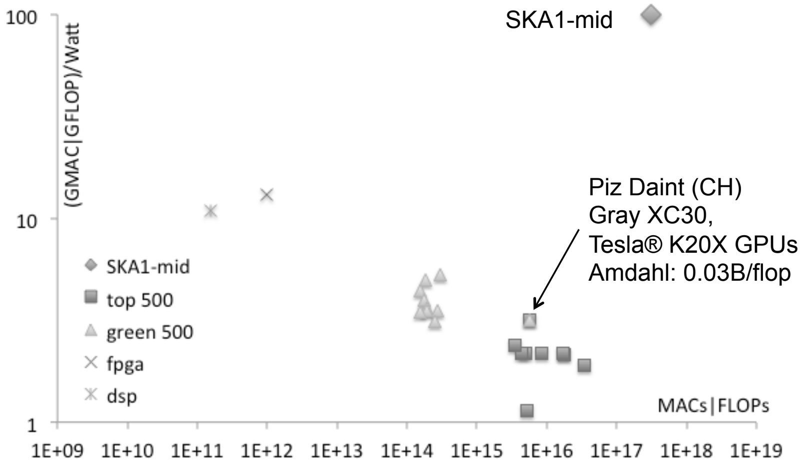
Imaging: where is the parallelism?

quantity	unit	^{10}log	note
# ops / sec	*Hz*	*17.5*	*= imaging compute load*
margin (for inefficiencies)		0.5	very aggressive / optimistic
machine	*flop*	*18*	*= 1 exaflop*
# clock frequency	Hz	9	
# channels in parallel		5	☺, all independent data streams!
simd ? tiles ? pipelining		4	☹, challenging!

Concerns on efficiency:

- data sets are large (≈ 10^{16} Bytes for visibilities),
- and some algorithms are low on compute intensity (high i/o) and or irregular, (e.g. FFT typically 20% efficiency on a CPU | GPU),
- Hence manual optimization of code likely essential.

EXAflops in 2015?



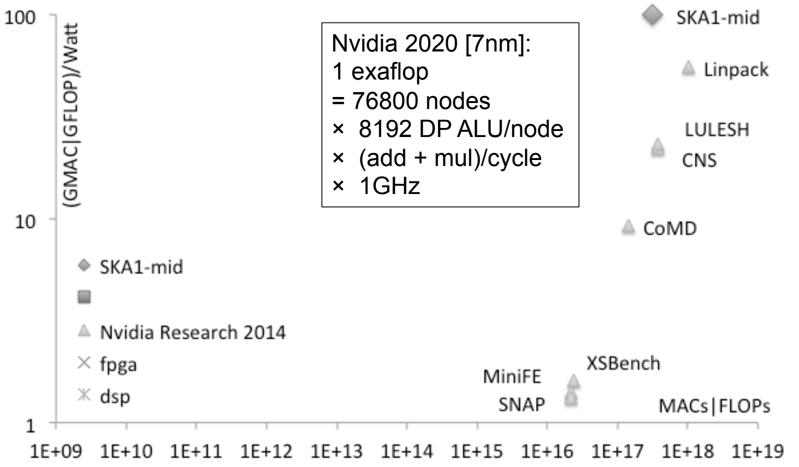
SKA1-mid

Piz Daint (CH)
Gray XC30,
Tesla® K20X GPUs
Amdahl: 0.03B/flop

- *net* SKA1-mid computation load "*2020*" versus
- *gross* (peak) compute performance "*2015*"

[10]

EXAflops in 2020?



Nvidia 2020 [7nm]:
1 exaflop
= 76800 nodes
× 8192 DP ALU/node
× (add + mul)/cycle
× 1GHz

A huge spread per application in achievable FLOPs and GFLOP/Watt!

[11]

Astronomical workloads

Exaflop algorithms?

- Can we expect algorithm innovation beyond w-snapshot+CLEAN?
- Trade lower hot FLOPs (w-snapshot) vs higher cool FLOPs (w-projection)?
- Where can we afford single precision? (Fixpoint?)

Exaflop machines?

- Will GPUs be the obvious accelerator? or will FPGAs or DSPs surprise us?
- Amdahl memory ratio (Byte/flop)?

Exaflop mapping?

- Which forms of parallelism for highest efficiency? (Next to channel ||)
- What levels of efficiency are achievable?

Exaflop requirements?

- When will exaflop SKA1 power consumption be affordable?
- Will SKA2 (>100x) … ?

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