Radio Astronomy Image Formation in the SKA Era

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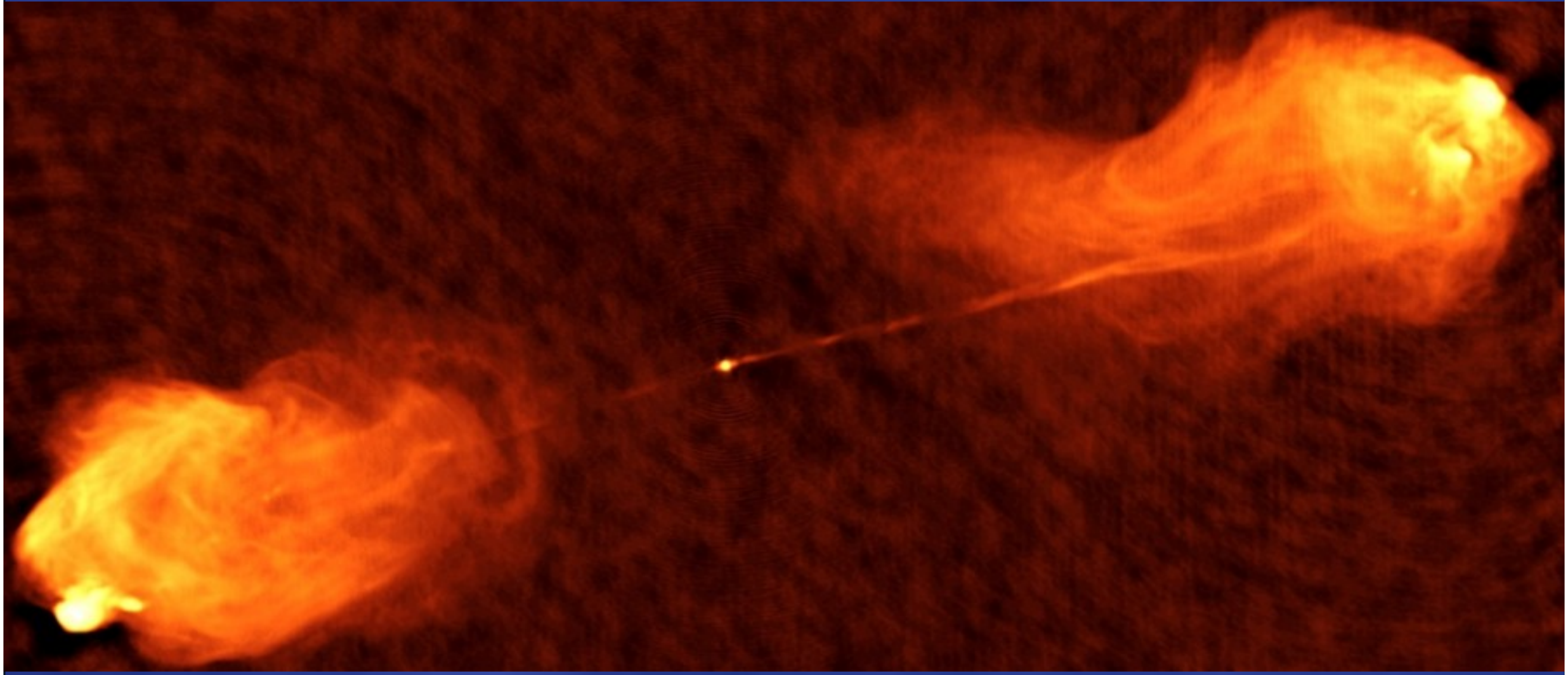
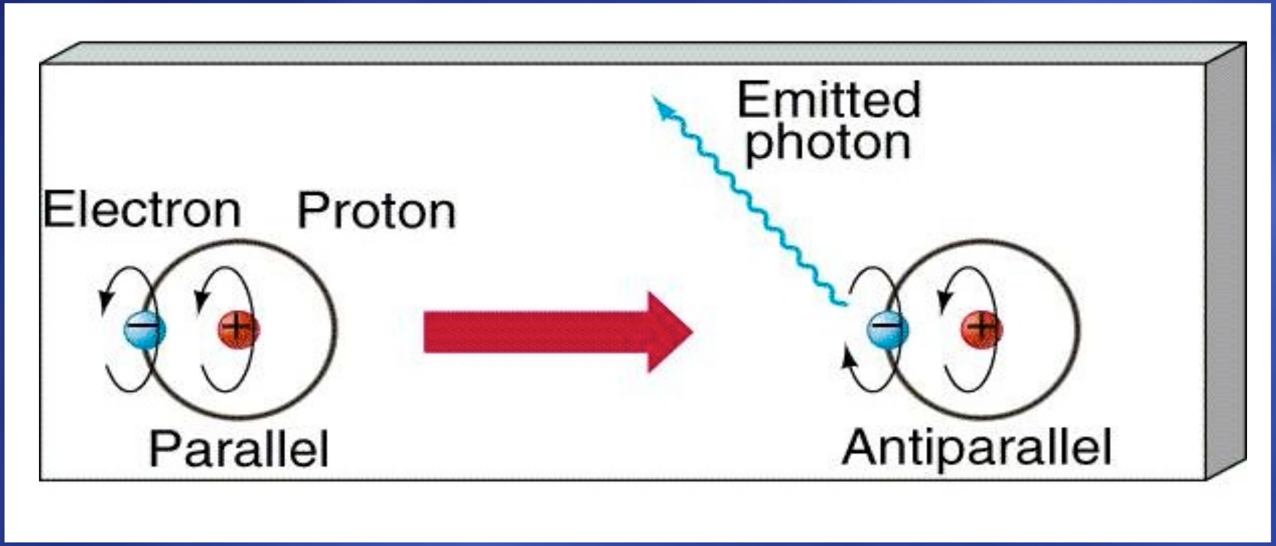
Introduction—the science

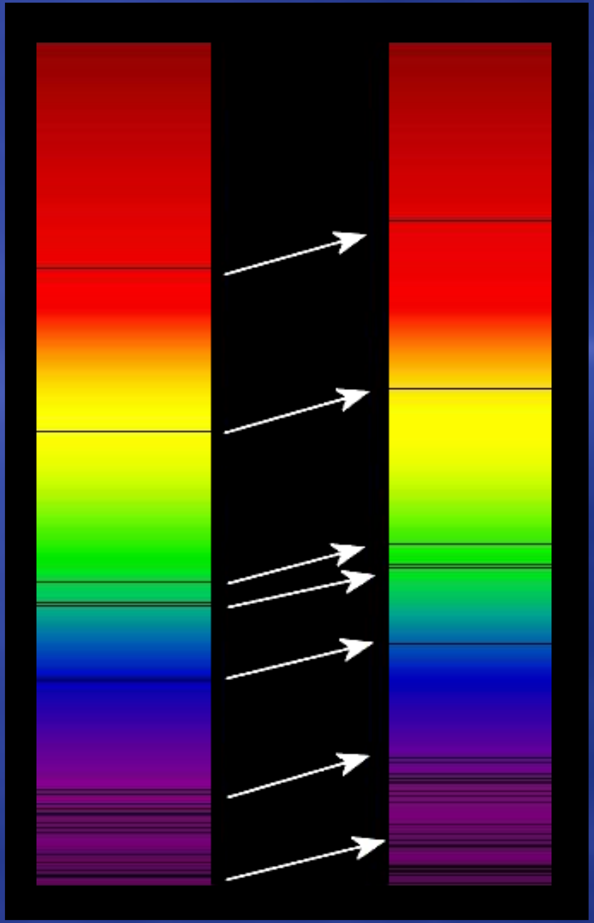
- Cygnus A (a quasar)



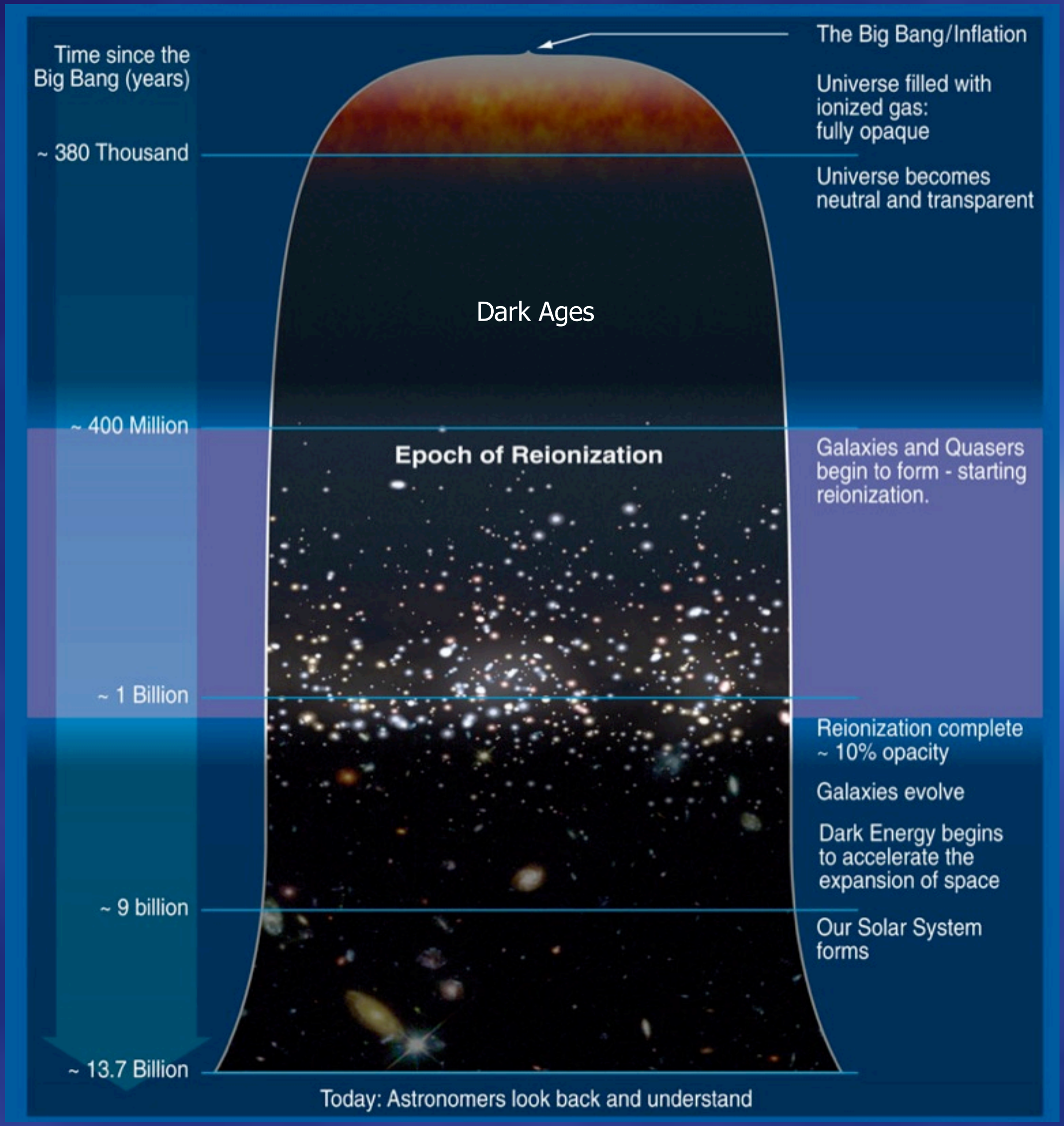
Introduction—the science

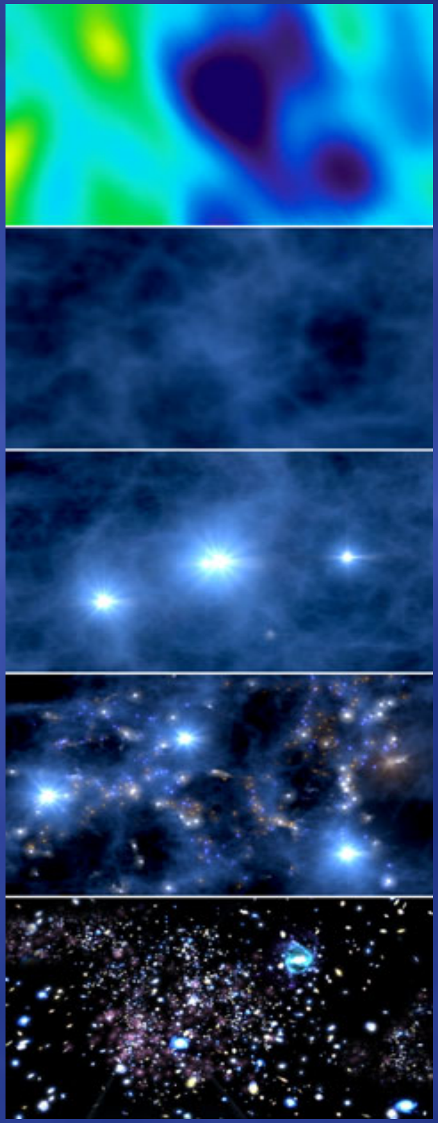
- Blackbody radiation; synchrotron radiation
- Spectral line due to neutral hydrogen (1420 MHz)
- Redshift ("Doppler")--up to a factor 10!





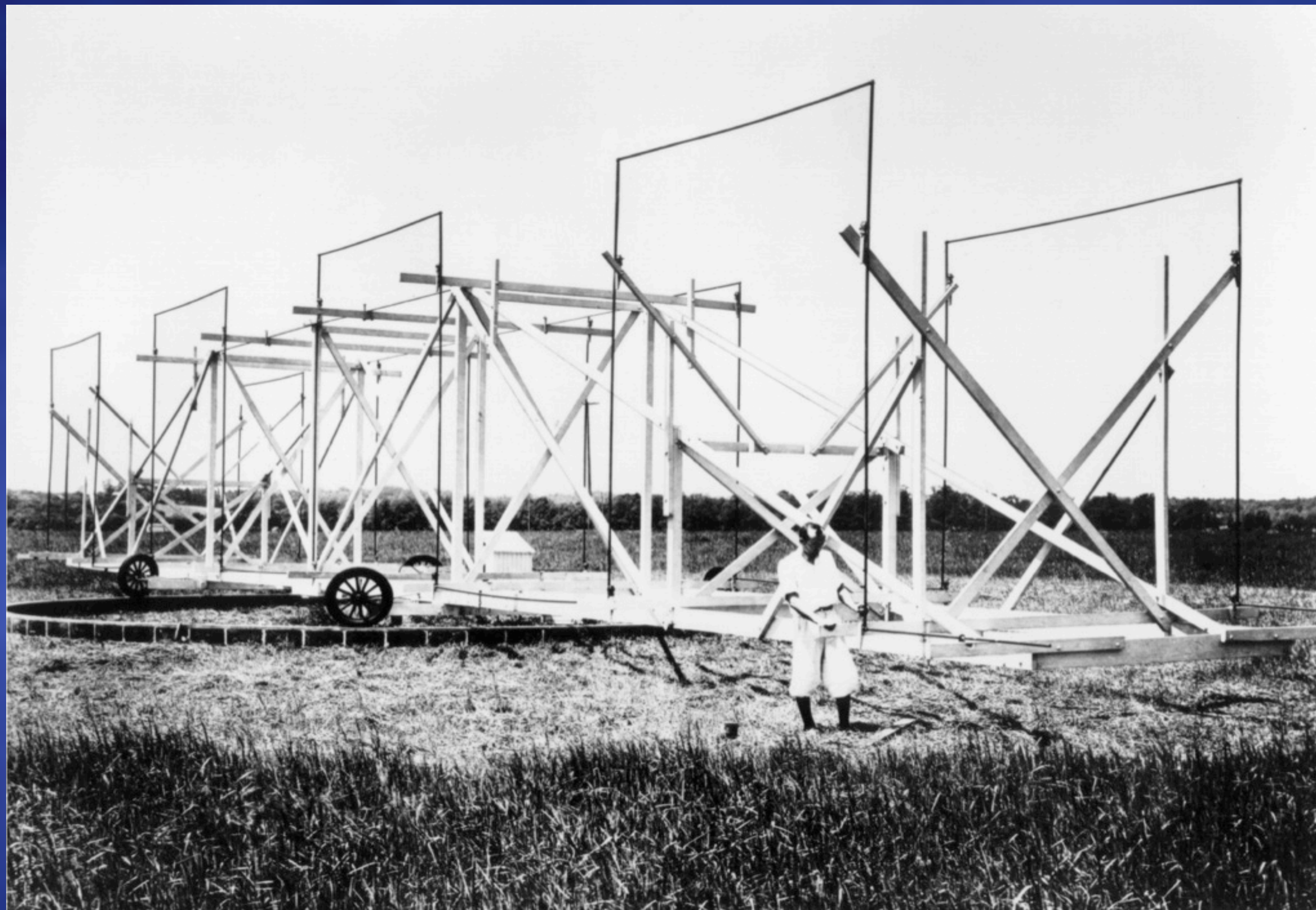
Introduction—the science





Introduction—the instruments

- Karl Jansky, Bell Labs (1928), 20 MHz



Introduction—the instruments

- Oort/van der Hulst (1950s), prediction and discovery of the HI 21 cm line (1420 MHz)

- Dwingeloo (Netherlands), 1956
- Jodrell Bank (Manchester, UK), 1957

  76 m

Introduction—the instruments

- Effelsberg, Germany (1972) 100m
- Arecibo, Puerto Rico (1960) 305m
- "FAST", Guizhou, China (2016), 500m

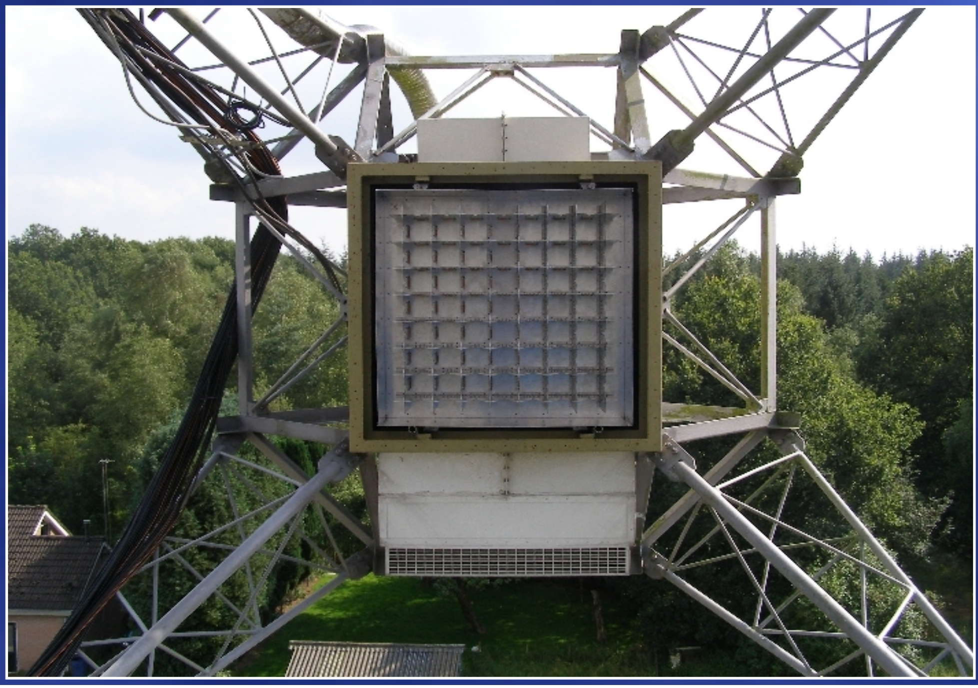
Introduction—the instruments

- Westerbork, Netherlands (1970), 14 dishes
- Very Large Array, New Mexico (1980), 27 dishes

New instruments – Focal Plane Arrays

Westerbork upgrade (2017)

- 8 x 8 phased array
- 37 beams for faster surveys
- Beamshape control

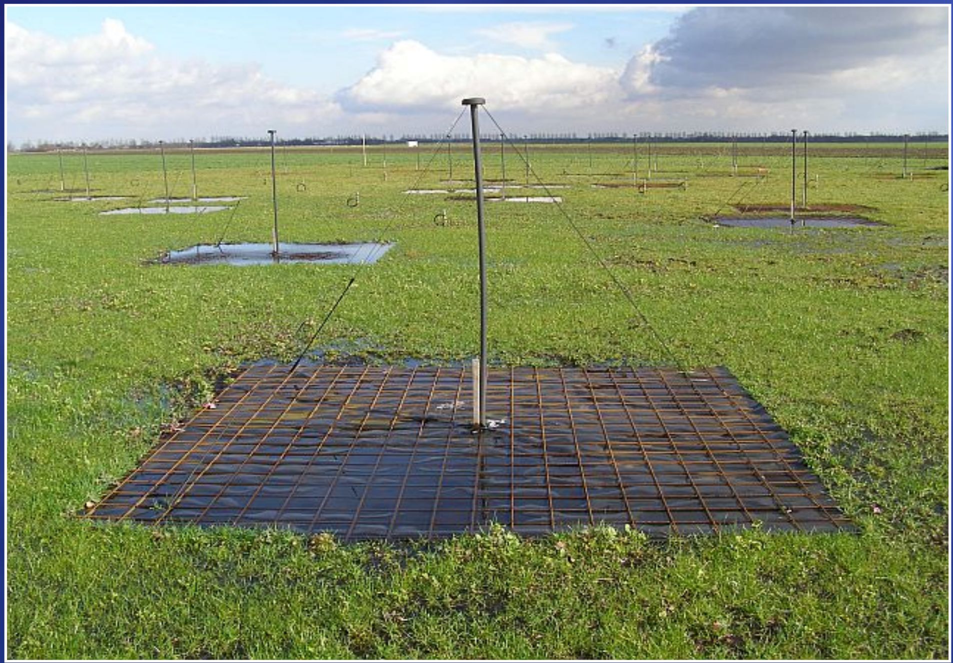


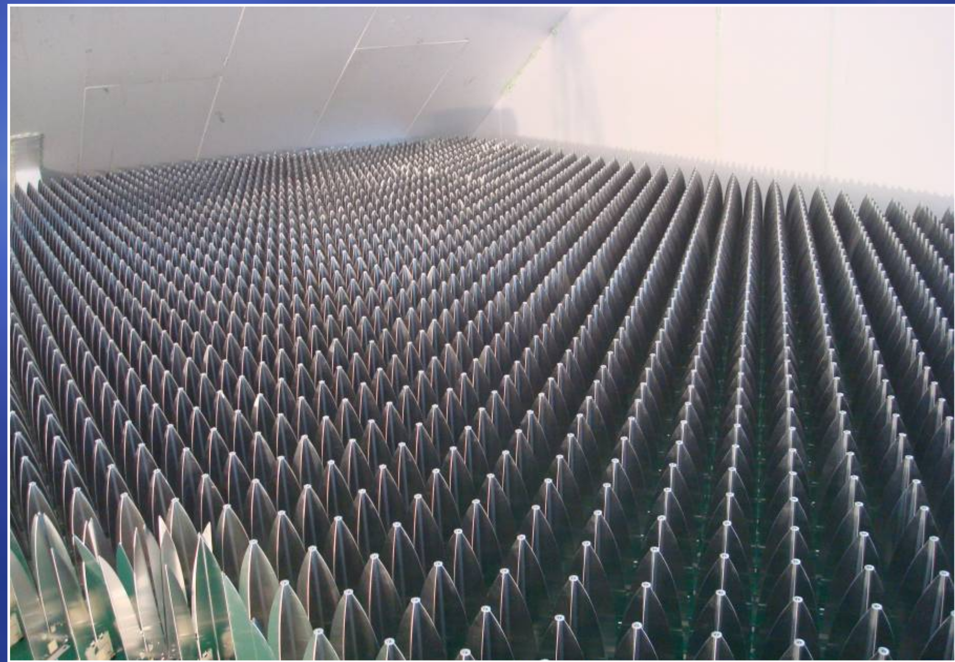
New instruments – Aperture Arrays

The new era: massive phased arrays

(a) Sparse phased arrays

(b) Dense phased arrays





- LOFAR (Europe), 100,000 antennas
- EMBRACE (NL), prototype AA

LOFAR radio telescope array (2008)

Design parameters

- 38 stations (Netherlands)
- 13+ additional stations in Germany, UK, Sweden, France, Poland, Ireland, …

- ~1000 antenna elements/station
- Dense core, 24 stations within 3.5 km

- Lowband array: 10-90 MHz
- Highband array: 110-240 MHz
- Resolution ~1 kHz

- 8 simultaneous beams
- Up to 48 MHz per beam

Designed and operated by ASTRON

LOFAR radio telescope array

Station parameters

- Each station has 2 high band array substations, and 96 low band antennas
- Beamformed output mimicks a telescope dish

- 24 core stations
- 14 NL remote stations
- 13+ international stations

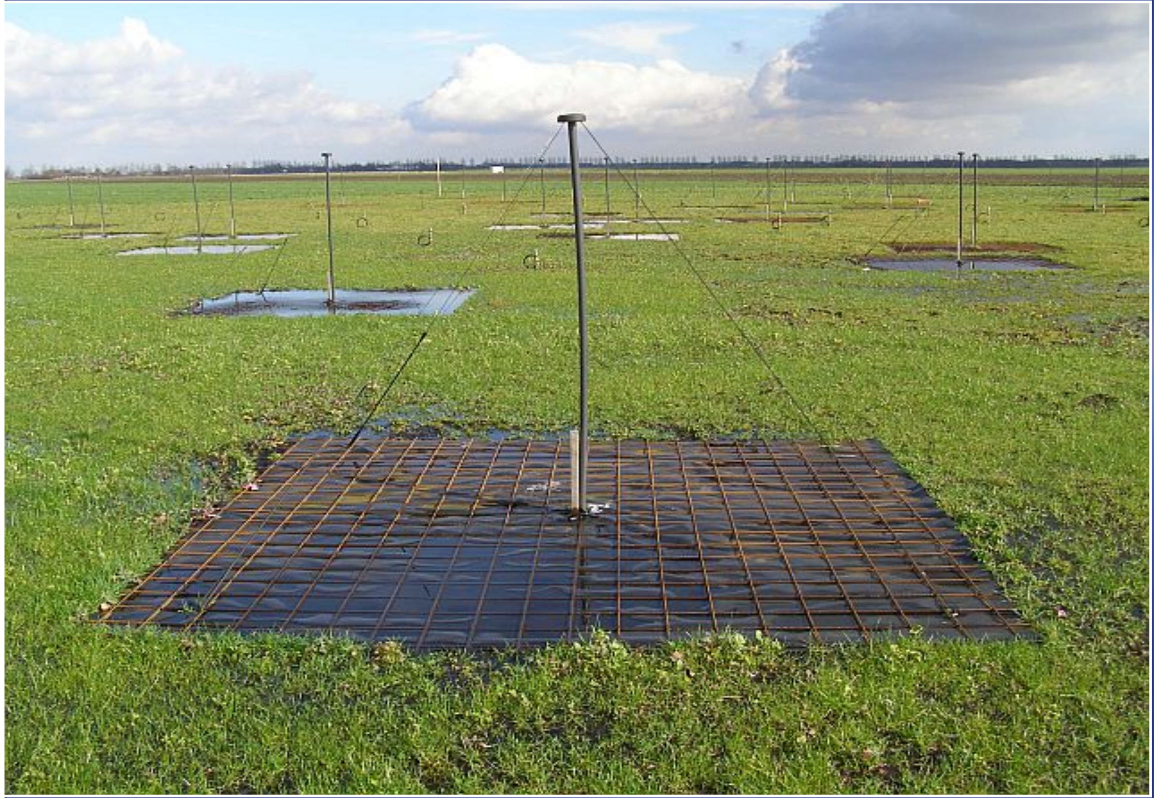
LOFAR core stations

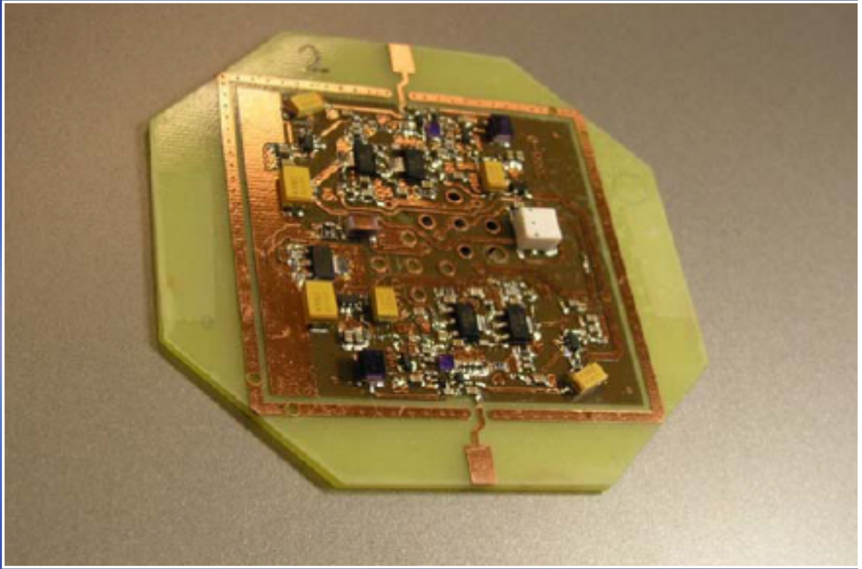
Core station parameters

- `Superterp': 6 stations, diameter 300m
- 24 core stations within 3.5 km

LOFAR lowband antennas

- 10-90 MHz
- Dipole antenna, 96 dipoles per station



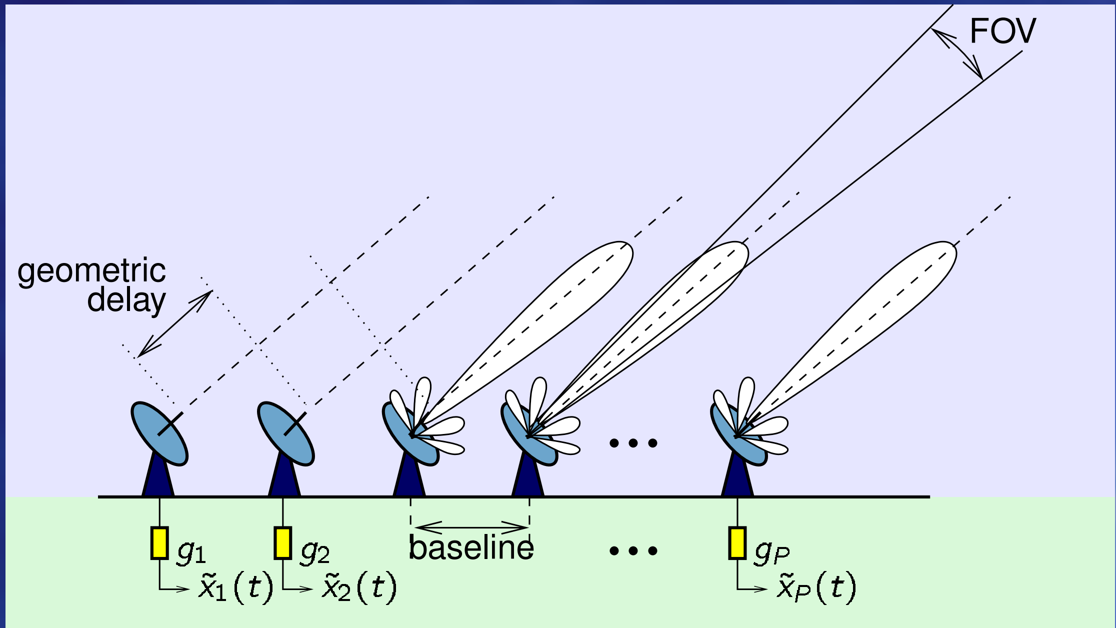


LOFAR high-band array

- 120-240 MHz
- Each tile is 5 x 5 meter and has 4 x 4 ‘spider’ antennas encapsulated in polystyrene
- 24 tiles form a sub-station
- 2 substations per station (total 768 antennas)

Basic concepts of interferometry

Observations



Consider P antennas, Q sources, N samples per short-term interval (STI), a single subband:

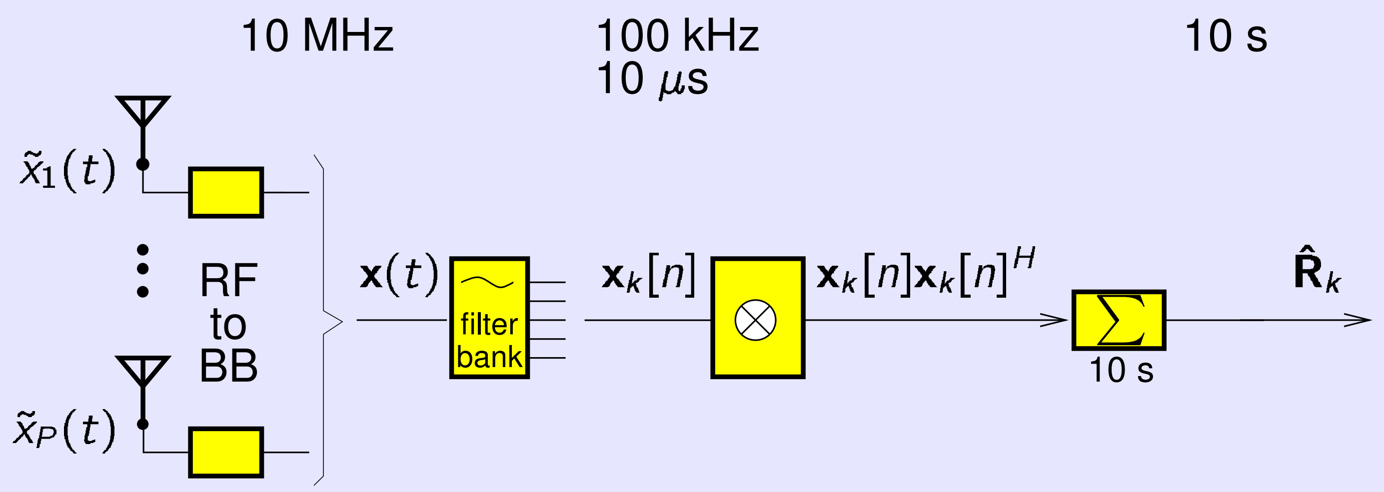
$$\mathbf{x}_k[n] = \mathbf{A}_k \mathbf{s}_k[n] + \mathbf{n}_k[n], \qquad n = 1, \cdots, N$$

where $\mathbf{A}_k = [\mathbf{a}_1, \cdots, \mathbf{a}_Q]$ of size $P \times Q$ is the array response matrix.

Index k represents “slow time” and/or frequency index.

Basic concepts of interferometry

Correlations



From the measurements, compute

$$\hat{\mathbf{R}}_k = \frac{1}{N}\sum_{n=1}^{N} \mathbf{x}_k[n]\mathbf{x}_k[n]^H$$

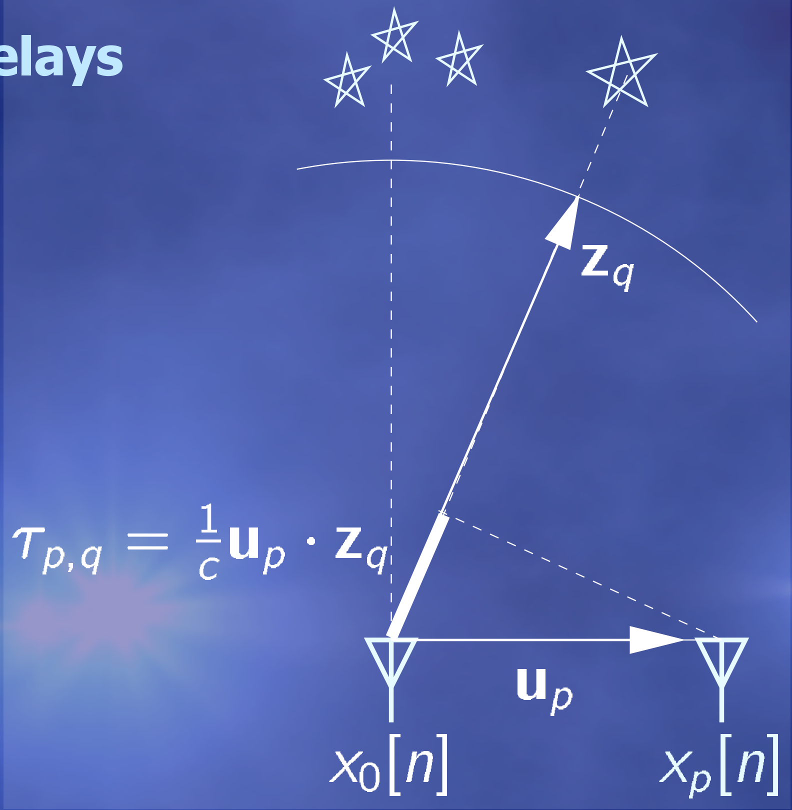
A filter bank splits the signal into subbands to satisfy narrowband conditions.

The stationarity of $\mathbf{R}_k$ is limited due to earth rotation.

Basic concepts of interferometry

Array response due to geometric delays

- $\mathbf{u}_p$: antenna position in meter (time varying as the earth rotates)
- $\mathbf{z}_q$: source direction (unit vector with direction cosines)



Ideally, the response to a source only depends on the geometric delays, which, under narrowband conditions, can be represented by phase shifts:

$\mathbf{A}_k$ has entries $$a_{p,q} = e^{-\mathrm{j}2\pi f_c \tau_{p,q}} = e^{-\mathrm{j}\frac{2\pi}{\lambda}\mathbf{u}_p^T \mathbf{z}_q}$$

Basic concepts of interferometry

Narrow-band and stationarity conditions

$$a_{p,q} = e^{-j2\pi f_c \tau_{p,q}} = e^{-j\frac{2\pi}{\lambda}\mathbf{u}_p^T \mathbf{z}_q}$$

- Narrowband condition: $f_c\tau \approx$ constant for $f_c \in (f_{\min}, f_{\max})$

  $\Rightarrow$ Determines maximum processing bandwidth, function of array diameter D

- Stationarity condition: $f_c\tau \approx$ constant while $\mathbf{u}_p$ rotates (earth rotation)

  $\Rightarrow$ Determines maximum processing time (STI), also function of array diameter

- In practice, also calibration parameters are introduced to model antenna gains, amplifier gains, ionosphere, $\cdots$.

Basic concepts of interferometry

Measurement equation

The model for $\hat{\mathbf{R}}_k$ is

$$\mathbf{R}_k := E\{\mathbf{x}_k[n]\mathbf{x}_k^H[n]\} = \mathbf{A}_k \boldsymbol{\Sigma}_\mathrm{s} \mathbf{A}_k^H + \boldsymbol{\Sigma}_\mathrm{n}$$

$\boldsymbol{\Sigma}_\mathrm{s} = \mathrm{diag}\{\boldsymbol{\sigma}_s\}$: source powers corresponding to the directions in $\mathbf{A}_k$,

$\boldsymbol{\Sigma}_\mathrm{n} = \mathrm{diag}\{\boldsymbol{\sigma}_\mathrm{n}\}$: noise covariance (diagonal, known from calibration).

Model options

- Q point sources (small number), each represented by one column in $\mathbf{A}_k(\boldsymbol{\theta})$, where $\boldsymbol{\theta}$ are the DOAs — "gridless";
- Alternatively, each pixel contains a source (possibly with zero power), hence $\mathbf{A}_k$ is known and can be very wide. E.g., $Q = 3000 \times 3000$ pixels.

  We will consider this case.

Basic concepts of interferometry

Imaging problem formulation

- Data model:

$$\mathbf{R}_k = \mathbf{A}_k \boldsymbol{\Sigma}_s \mathbf{A}_k^H + \boldsymbol{\Sigma}_\text{n}$$

- Without the noise, a single entry of $\mathbf{R}_k$ (called a *visibility*) is

$$V_{ij,k} := (\mathbf{R}_k)_{ij} = \sum_{q=1}^{Q} \sigma_q^2 a_{i,q} \overline{a_{j,q}} = \sum_{q=1}^{Q} I(\mathbf{z}_q)\, e^{-j\frac{2\pi}{\lambda}(\mathbf{u}_i(k) - \mathbf{u}_j(k))^T \mathbf{z}_q}.$$

This is called the *measurement equation* and has the form of a Fourier transform.

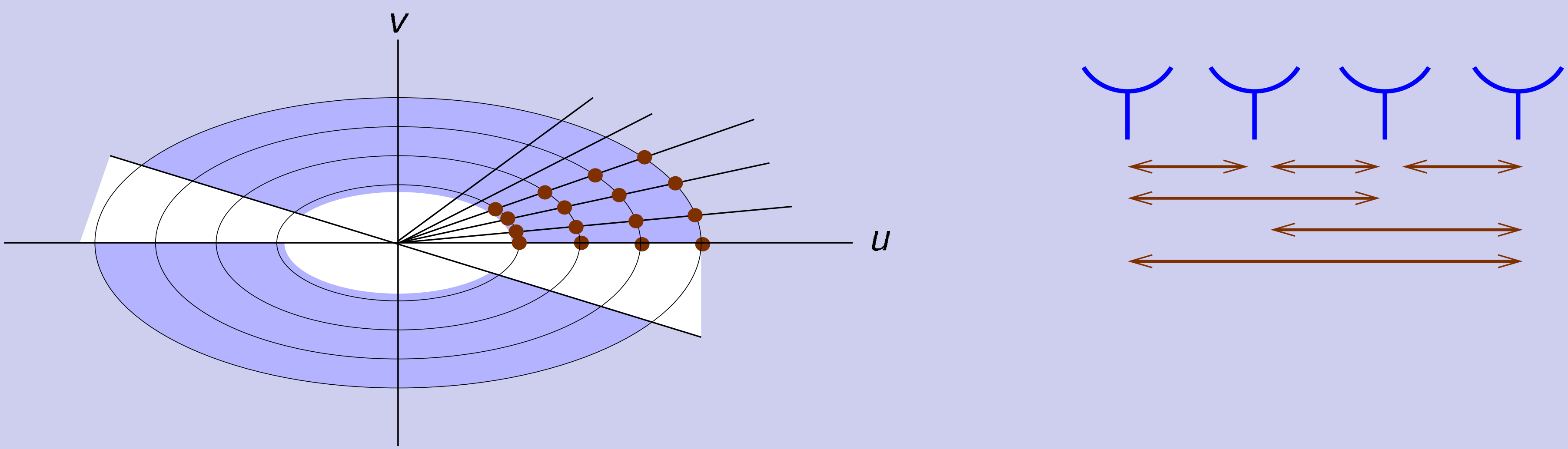
- $I(\mathbf{z}_q) = \sigma_q^2$ is the brightness (power) in direction $\mathbf{z}_q$.

For a discrete point-source model: $I(\mathbf{z}) = \sum_{q=1}^{Q} \sigma_q^2 \delta(\mathbf{z} - \mathbf{z}_q)$.

$I(\mathbf{z})$ is the image (called the *map*).

Basic concepts of interferometry

Baseline samples



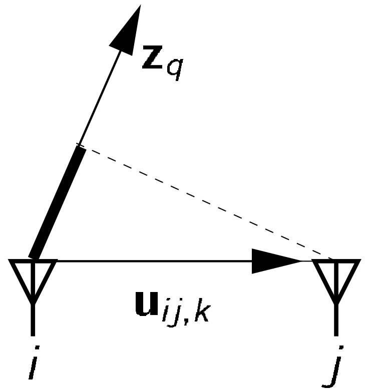
- $\mathbf{u}_{ij,k} = \frac{2\pi}{\lambda}(\mathbf{u}_i(k) - \mathbf{u}_j(k))$ is called a *baseline*, with vector coordinates $\mathbf{u} = (u, v, w)$.
- With P antennas, we have at most P^2 independent baselines (visibility samples). But we obtain more samples as the earth rotates or if we consider multiple frequencies (scaling by λ).

Basic concepts of interferometry

Fourier-based image formation

- Measurement equation:

$$V_{ij,k} = \sum_{q=1}^{Q} I(\mathbf{z}_q)\, e^{-\mathrm{j}\mathbf{u}_{ij,k}^T \mathbf{z}_q}$$



- Try inverting the Fourier transform:

$$I_D(\mathbf{z}) := \sum_{i,j,k} V_{ij,k}\, e^{\mathrm{j}\mathbf{u}_{ij,k}^T \mathbf{z}}$$

This *dirty image* is not quite equal to the true image $I(\mathbf{z}) = \sum_{q=1}^{Q} I(\mathbf{z}_q)\,\delta(\mathbf{z}-\mathbf{z}_q)$.

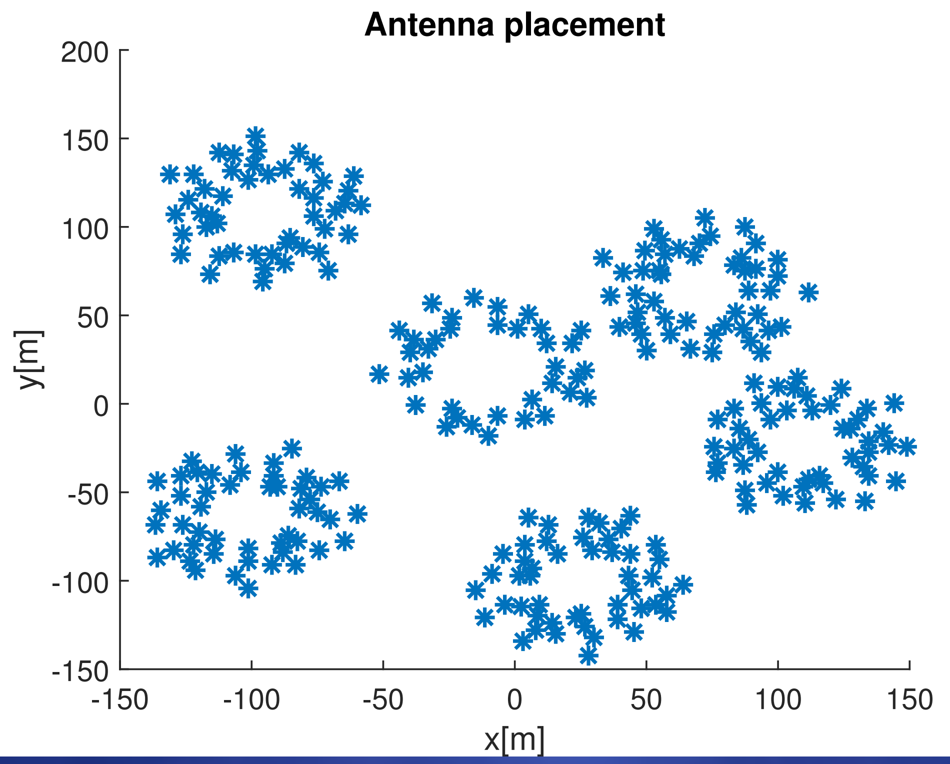
- To see this, insert the measurement equation:

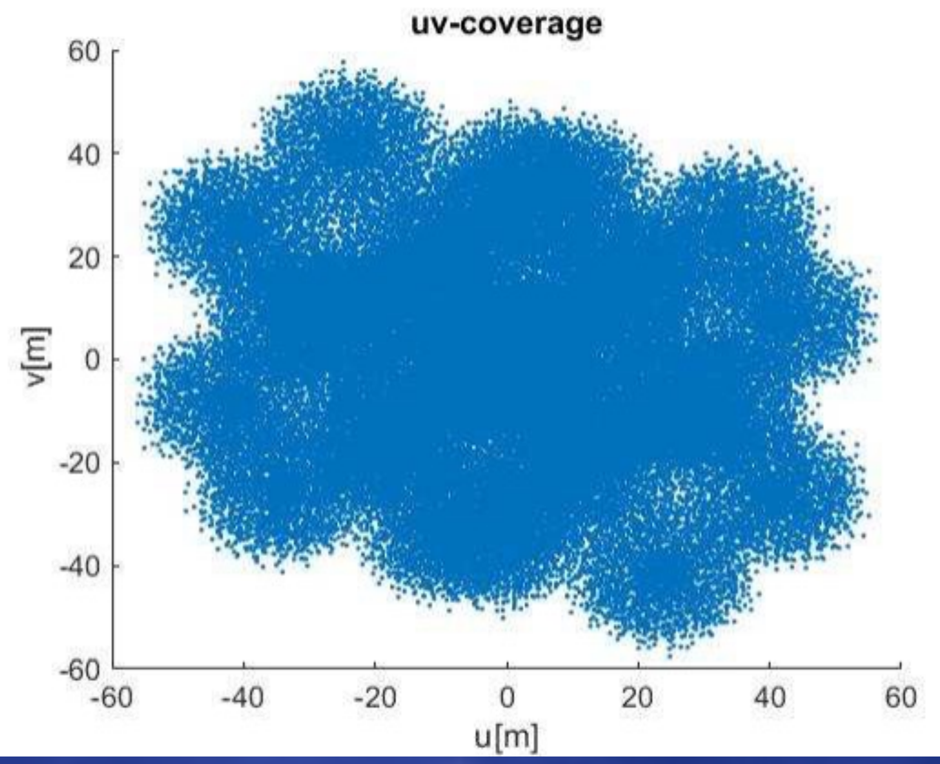
$$I_D(\mathbf{z}) = \sum_{i,j,k}\sum_{q} I(\mathbf{z}_q) e^{\mathrm{j}\mathbf{u}_{ij,k}^T(\mathbf{z}-\mathbf{z}_q)} = \sum_{q} I(\mathbf{z}_q) B(\mathbf{z}-\mathbf{z}_q) = I(\mathbf{z}) * B(\mathbf{z})$$

where the PSF $B(\mathbf{z}) = \sum_{i,j,k} e^{\mathrm{j}\mathbf{u}_{ij,k}^T \mathbf{z}}$ is called the *dirty beam* — a function of the available (u, v) samples.

Basic concepts of interferometry

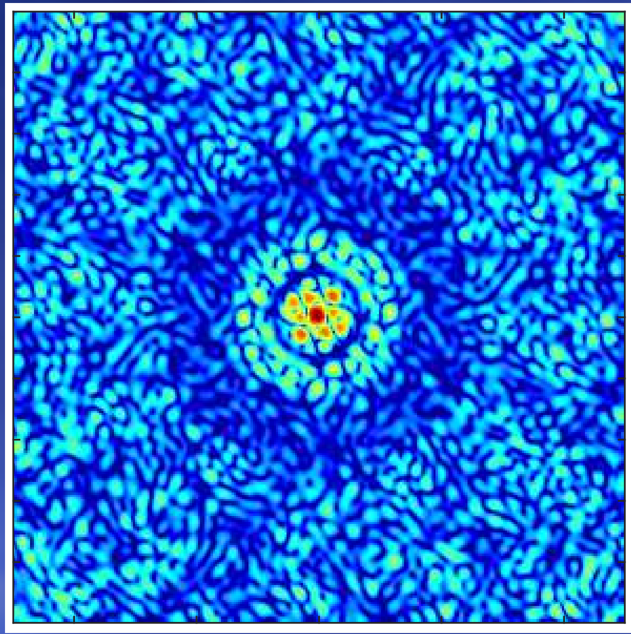
- LOFAR "Superterp" antenna configuration
  P = 288 antennas, max baseline 326 m
- (u,v) samples (snapshot)





Basic concepts of interferometry

PSF (dirty beam), dB scale, range 0..-35 dB

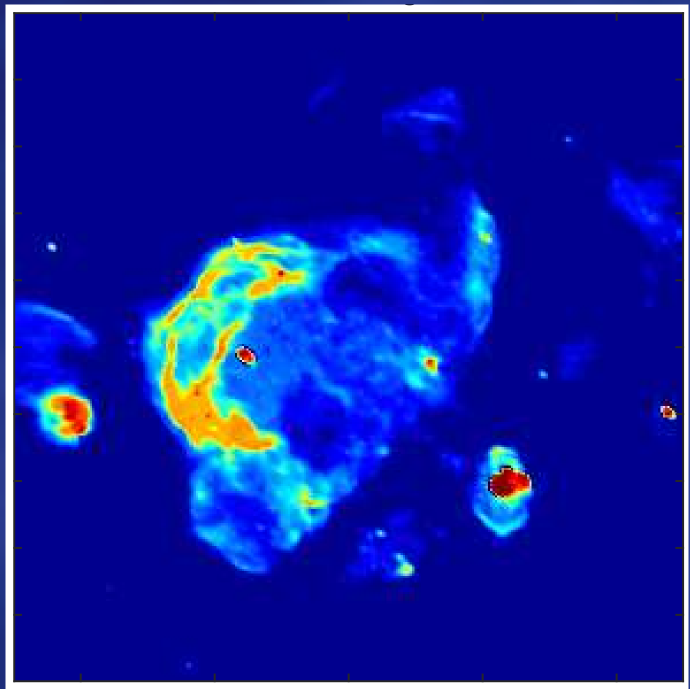


Beamsize (resolution) is inversely proportional to the array diameter; sidelobes cause *confusion*. Could use windowing (tapering).

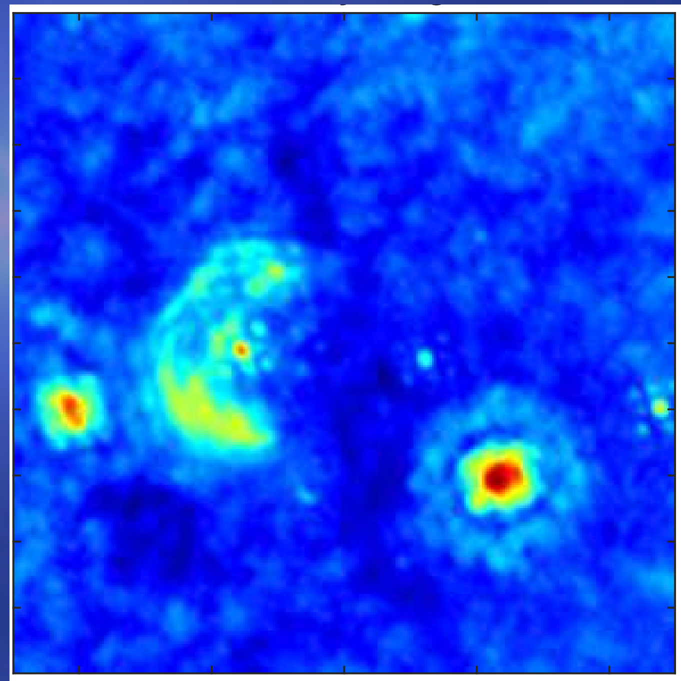
Basic concepts of interferometry

Test on model image: W28 superremnant (from CASA Guides)

- From the image, correlation data is computed and corresponding measured data $\mathbf{x}[n]$ is generated, with added noise; $N = 10^5$ samples.
  Operating frequency: 58:975 MHz, single time snapshot



Test image in dB (0 till -35 dB)
Q=84681 pixels



MF dirty image

Basic concepts of interferometry

Deconvolution: The CLEAN algorithm

A source at location $\mathbf{z}_q$ has a response $B(\mathbf{z}-\mathbf{z}_q)$ in the dirty image.

CLEAN tries to locate sources one by one from the peaks in the image:

$$\text{for } q = 1, 2, \cdots$$

$$\left[\begin{array}{lcl} \mathbf{z}_q &=& \arg\max_{\mathbf{z}} \; I_D(\mathbf{z}) \\ \hat{\sigma}_q^2 &=& I_D(\mathbf{z}_q)/B(\mathbf{0}) \\ I_D(\mathbf{z}) := I_D(\mathbf{z}) - \gamma\hat{\sigma}_q^2 B(\mathbf{z}-\mathbf{z}_q)\,, & & \forall \mathbf{z} \end{array}\right.$$

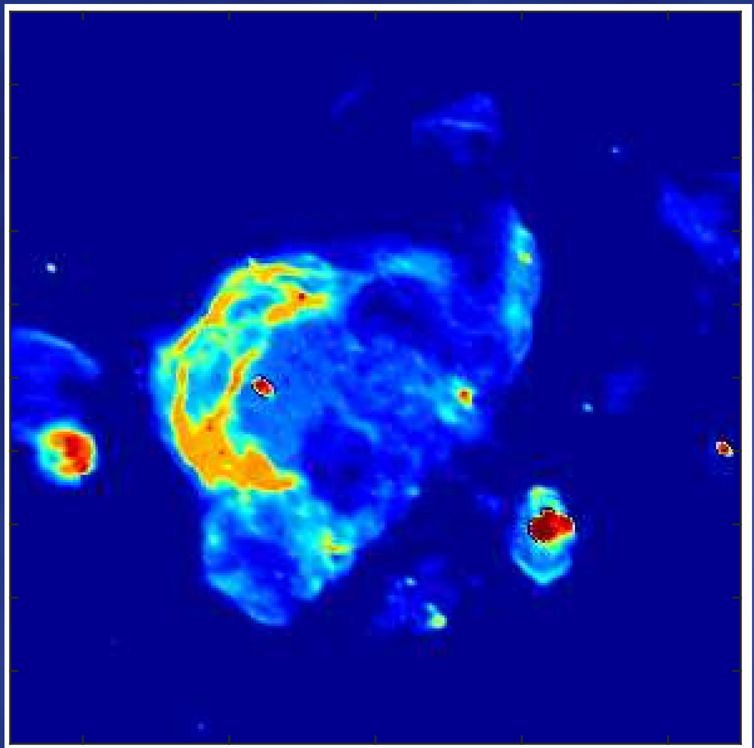
$$I_{clean}(\mathbf{z}) = I_D(\mathbf{z}) + \textstyle\sum_q \gamma\hat{\sigma}_q^2 B_{synth}(\mathbf{z}-\mathbf{z}_q), \quad \forall \mathbf{z}\,.$$

- $B_{synth}(\mathbf{z})$ is a ‘synthetic beam”, usually a Gaussian bell-shape.
- Instead of the subtractions on the dirty image, it is considered more accurate to do the subtractions on the sample covariance matrix $\hat{\mathbf{R}}$ instead,

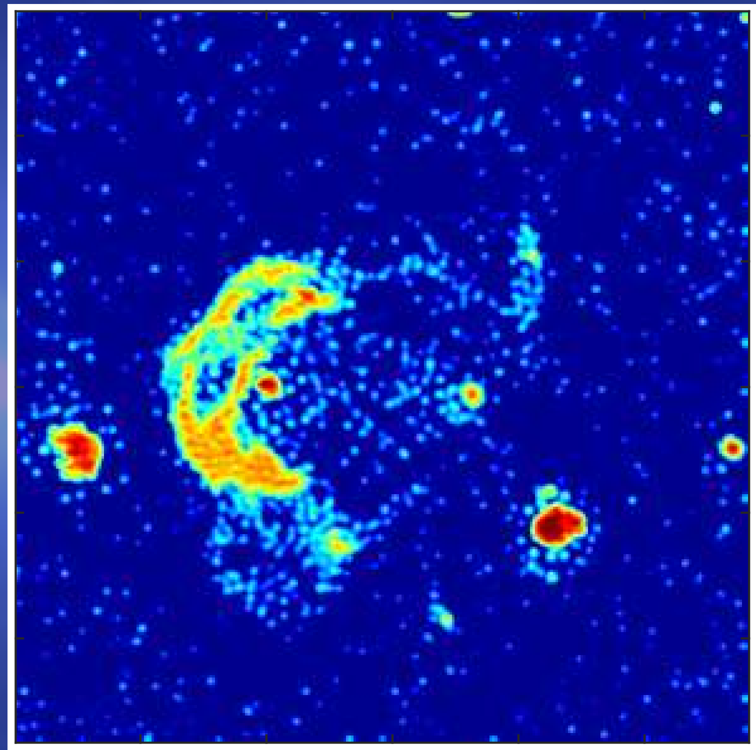
$$\hat{\mathbf{R}} := \hat{\mathbf{R}} - \gamma\hat{\sigma}_q^2 \mathbf{a}(\mathbf{z}_q)\mathbf{a}(\mathbf{z}_q)^H$$

Basic concepts of interferometry

The CLEAN algorithm



Original image



CLEAN + postprocessing

10 outer, 500 inner iterations (~1 min)

Basic concepts of interferometry

Rewrite in array processing language

- Computing the dirty image is equal to (dropping index k for simplicity):

$$I_D(\mathbf{z}) = \mathbf{a}^H \mathbf{R}\,\mathbf{a}\,, \qquad (\mathbf{a})_i \equiv e^{-\mathrm{j}\mathbf{u}_i^T \mathbf{z}}$$

Indeed,
$$I_D(\mathbf{z}) = \sum_{i,j} (\mathbf{R})_{ij} \overline{(\mathbf{a})_i} (\mathbf{a})_j = \sum_{i,j} (\mathbf{R})_{ij} e^{\mathrm{j}(\mathbf{u}_i - \mathbf{u}_j)^T \mathbf{z}}$$

More general: beamformed image

For the ith pixel, let $\mathbf{w}_i$ be a spatial beamformer, and compute

$$\sigma_i = \mathbf{w}_i^H \mathbf{R} \mathbf{w}_i\,, \qquad i = 1, \cdots, Q$$

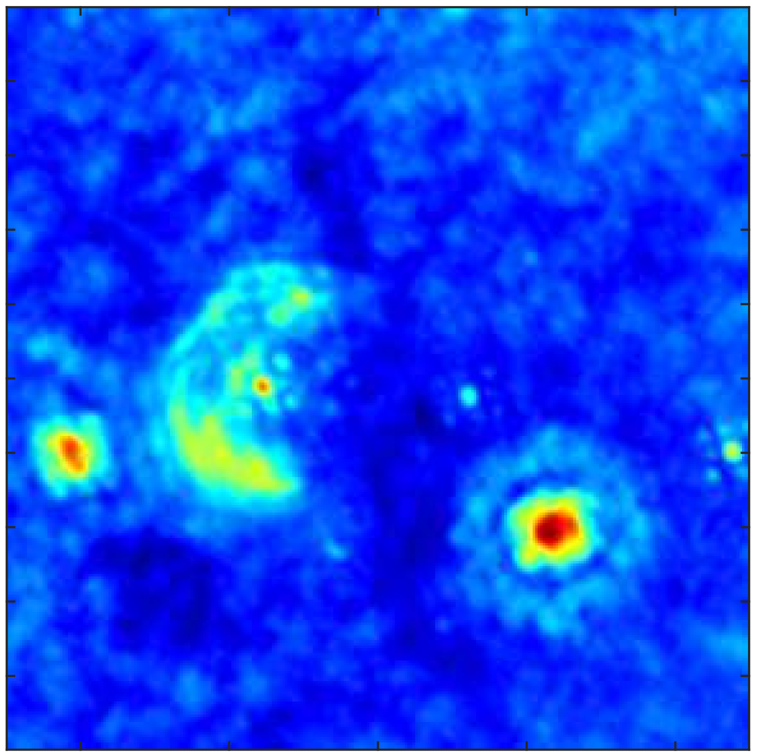
Minimum Variance Distortionless Response (MVDR) solution

Setting $\mathbf{w}_i = \dfrac{\mathbf{R}^{-1}\mathbf{a}_i}{\mathbf{a}_i^H \mathbf{R}^{-1} \mathbf{a}_i}$ leads to the MVDR dirty image (where $\mathbf{w}_i^H \mathbf{a}_i = 1$)

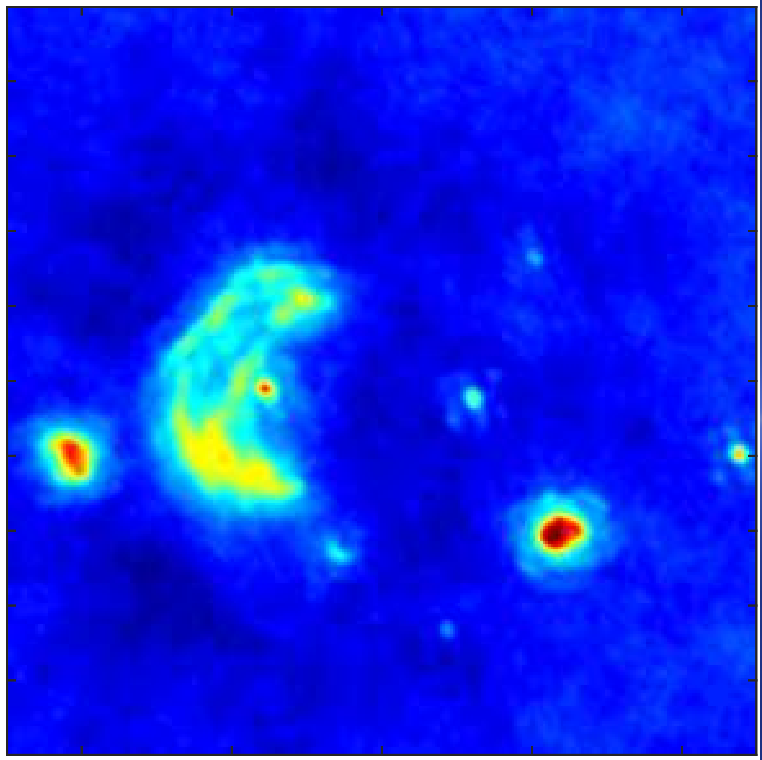
$$\sigma_{\mathrm{MVDR},i} = \frac{1}{\mathbf{a}_i^H \mathbf{R}^{-1} \mathbf{a}_i}$$

Basic concepts of interferometry

Beamformed images



MF image (classical dirty image)



MVDR dirty image; dB scale

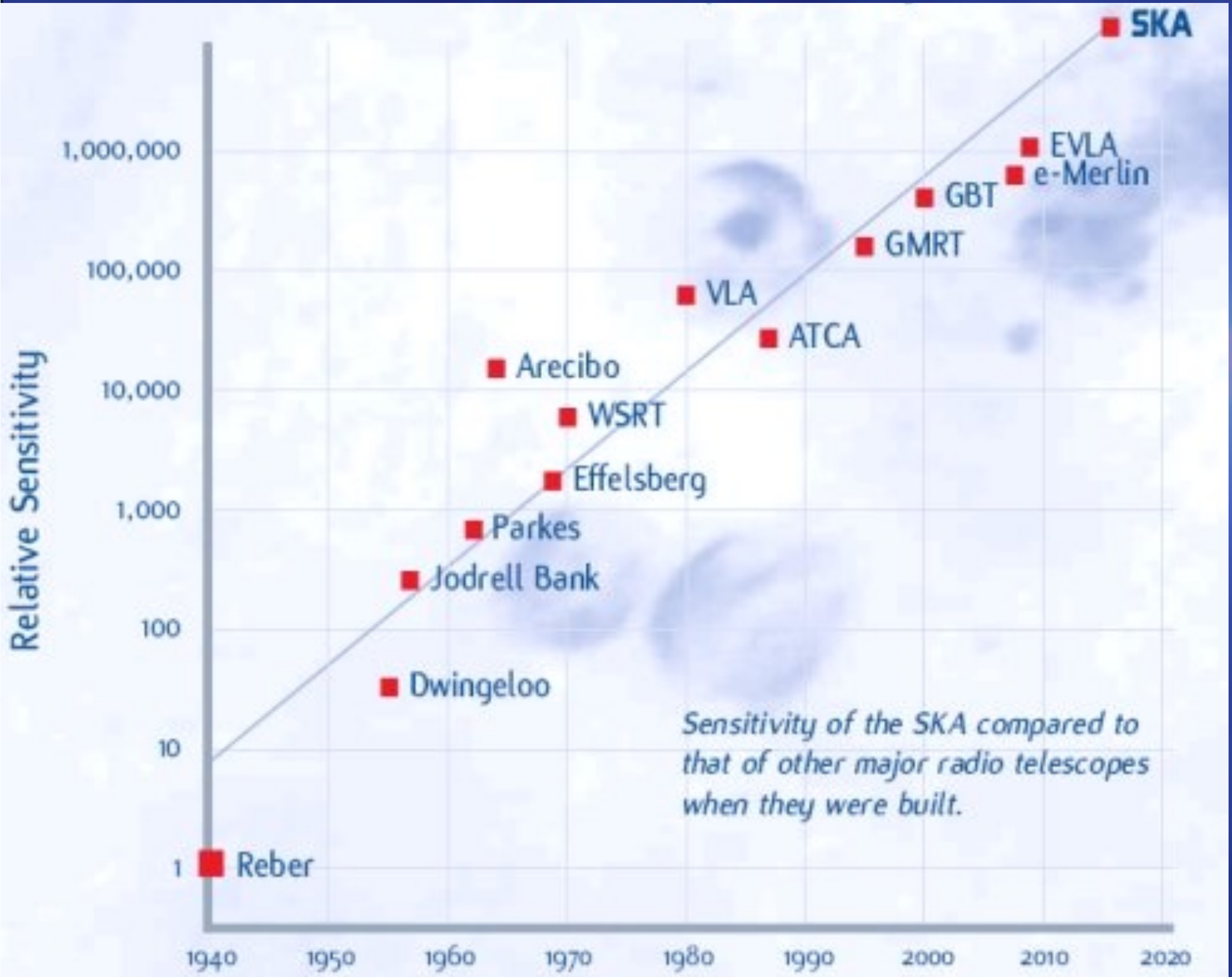
We can derive:

$$0 \leq \sigma_{true} \leq \sigma_{MVDR} \leq \sigma_{MF}$$

New instruments

Sensitivity evolution (1940-2010)

- Exponential: doubles every 3 years



Other parameters

- Resolution
- Freq. range, bandwidth
- Survey speed (FoV)

SKA science drivers

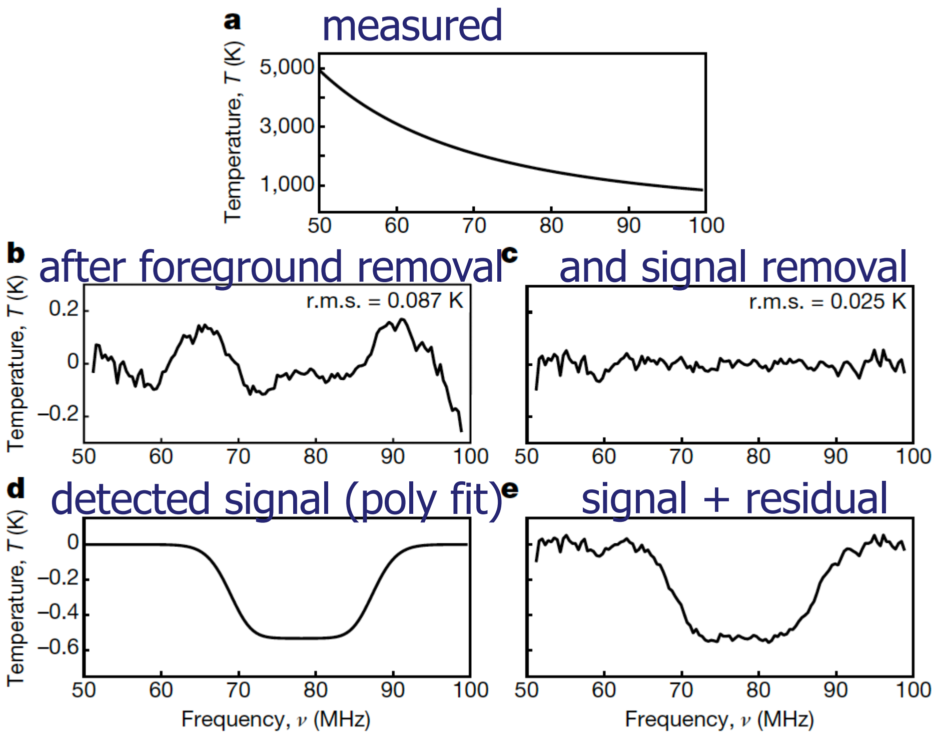
- Early universe:
  - Dark Ages and EoR: first star formation
  - Galaxy formation and evolution
- Cosmic magnetism
- Gravitation (pulsar timing)
- Origins of life

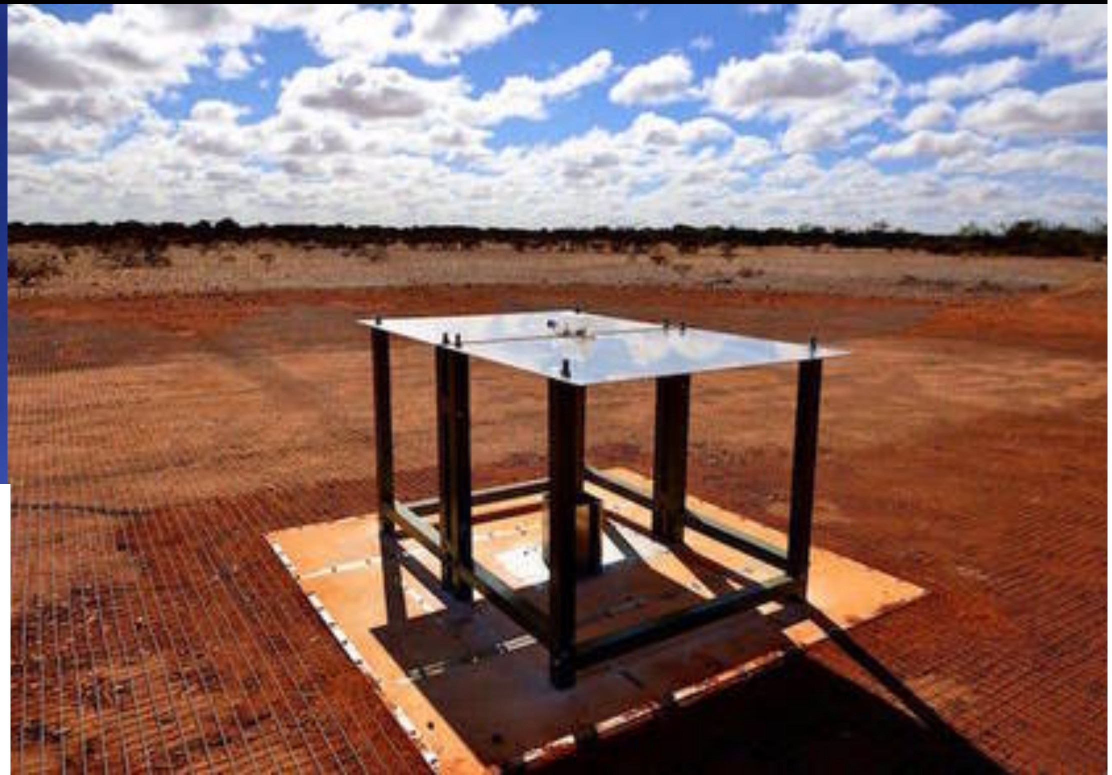
First EOR detection (?): EDGES telescope

- **EDGES telescope at MRO**

  Single dipole blade antenna (2x1 m)

  Published in Nature, Mar 2018 (Judd Bowman e.a.):





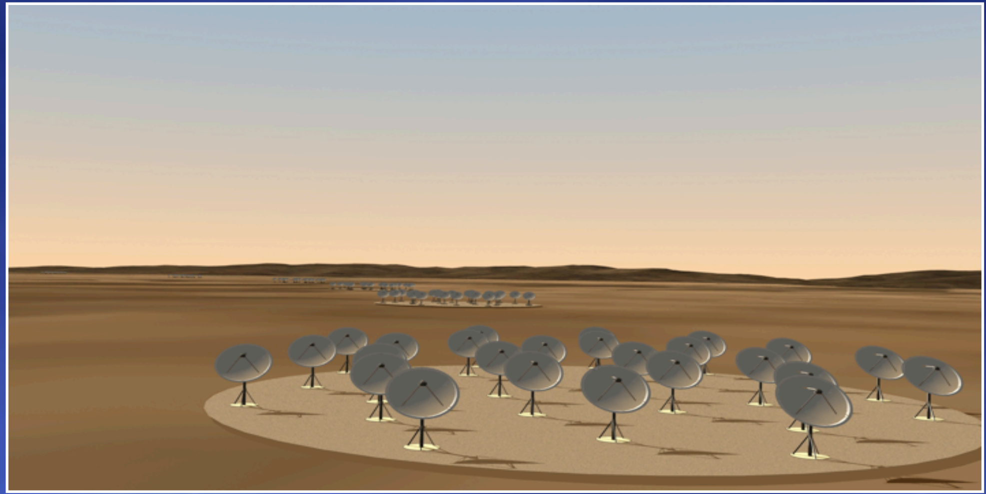
Detected EOR based on 100 h all-sky observations and parameterized (polynomial) models of the sky foreground and EOR spectrum

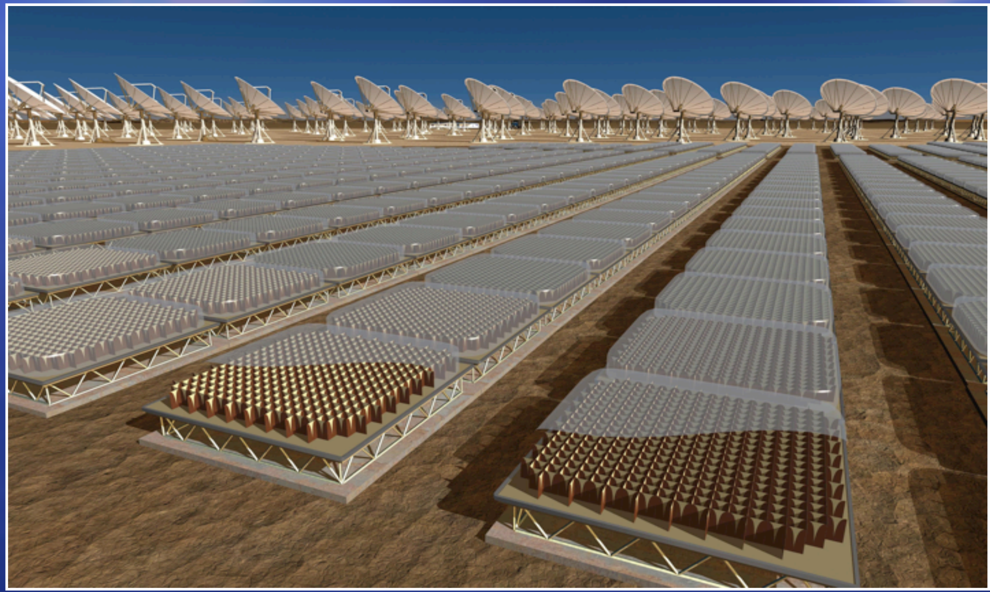
SKA is aimed to image this signal

The Square Kilometer Array

Initial design parameters (2010)

- Operational in 2019/2023
- 1.000.000 m^2: sensitivity 50 x VLA
- 70 MHz--25 GHz; instantaneous bandwidth 0.25 x f_c
- Core 5 km has 50% of elements); max 3000 km
- Combination of sparse phased arrays of dipoles, dense aperture arrays, dishes with focal plane arrays
- 50 instantaneous beams

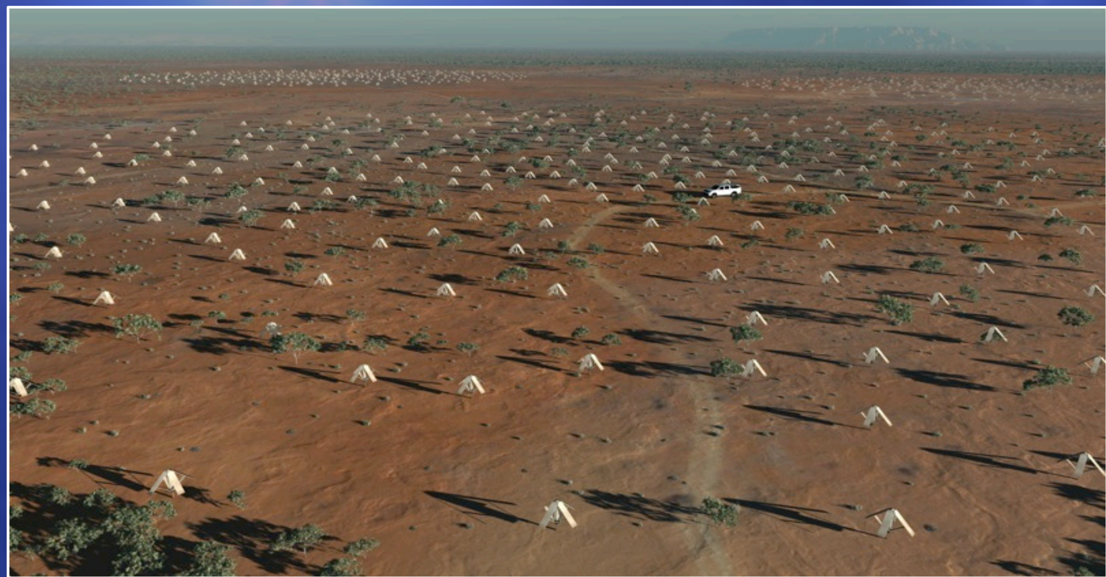




The Square Kilometer Array

SKA1-Low (2013 param.)

- Aperture array with 250,000 log-periodic elements
- 866 stations, 90 km diameter
- 50 MHz—350 MHz
- Location: Western Australia



The Square Kilometer Array

Initially considered

- 400 MHz—1.4 GHz
- 250 dense aperture array stations
- Location: Southern Africa

SKA1-Mid (2013 param.)

- 350 MHz—3 GHz (…14.5 GH
- 190+64 dishes (MeerKAT)
  with single-pixel feeds
- Location: Southern Africa

2018: 64 dishes commissioned

SKA Precursor: MRO site

Murchison Radio-astronomy Observatory (MRO) site

Western Australia (Boolardy station)

- **Australian SKA Pathfinder (2019)**

  36 identical 12-metre wide dish antennas, 18 currently operational

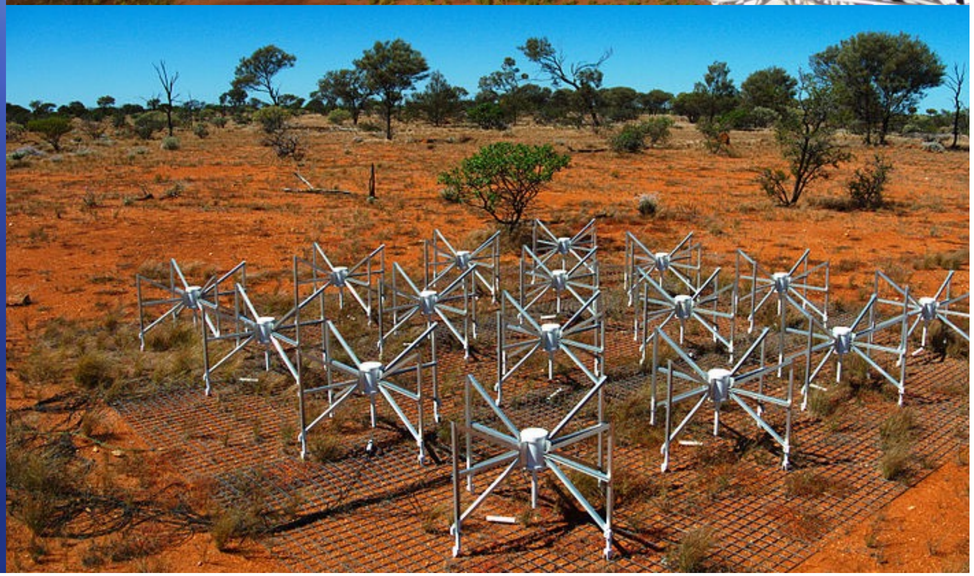
  Phased Array Feed (PAF) receivers (giving survey speed)

- **Murchison Widefield Array (2013)**

  80-300 MHz; 2048 dipole antennas in 128 tiles (4 x 4); max baseline ~ 3 km

  Total BW 30 MHz; resolution 40 kHz x 0.5 s

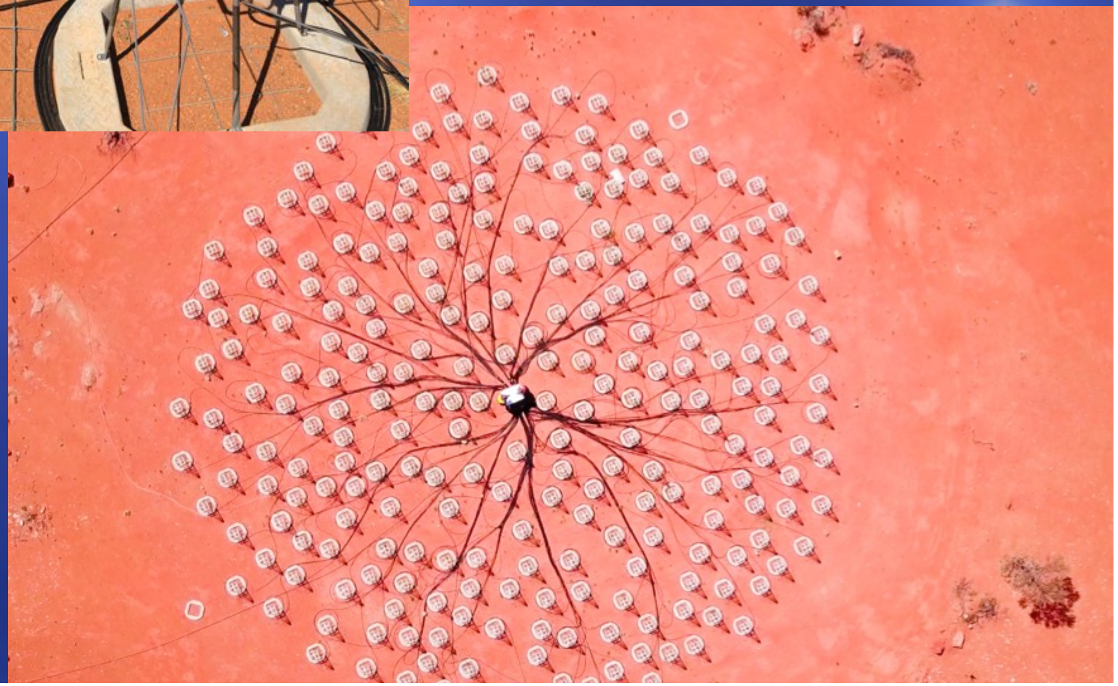
  2018: upgrade to 256 tiles over 6 km



SKA Precursor: MRO site

- **SKA1-Low** prototype station 256 low-frequency antennas (AAVS1)

Completed 25 May 2018



SKA – signal processing requirements

Quest for higher performance

- Higher resolution ⇒ longer baselines ⇒ { shorter integration time (due to earth rotation); more (narrower) subbands }
- Higher sensitivity ⇒ larger number of antennas (grouped in stations), longer observing times, better calibration (direction dependent)
- Higher survey speed ⇒ larger total bandwidth, larger FOV, multiple beams, direction dependent calibration

Results in larger data sets, higher computational demands, and the need for better algorithms

Also: cannot store all "raw" correlation data for later processing, need new intermediate data products (snapshot images, plus $\cdots$).

SKA – signal processing requirements

Typical numbers (SKA1-Low, 2013 design parameters) [Dewdney'13]

Frequency range: 50–300 MHz, sampled using log-periodic (somewhat directional) antennas.

Max baseline 100 km (later scaled down to 65 km), station diameter 35 m.

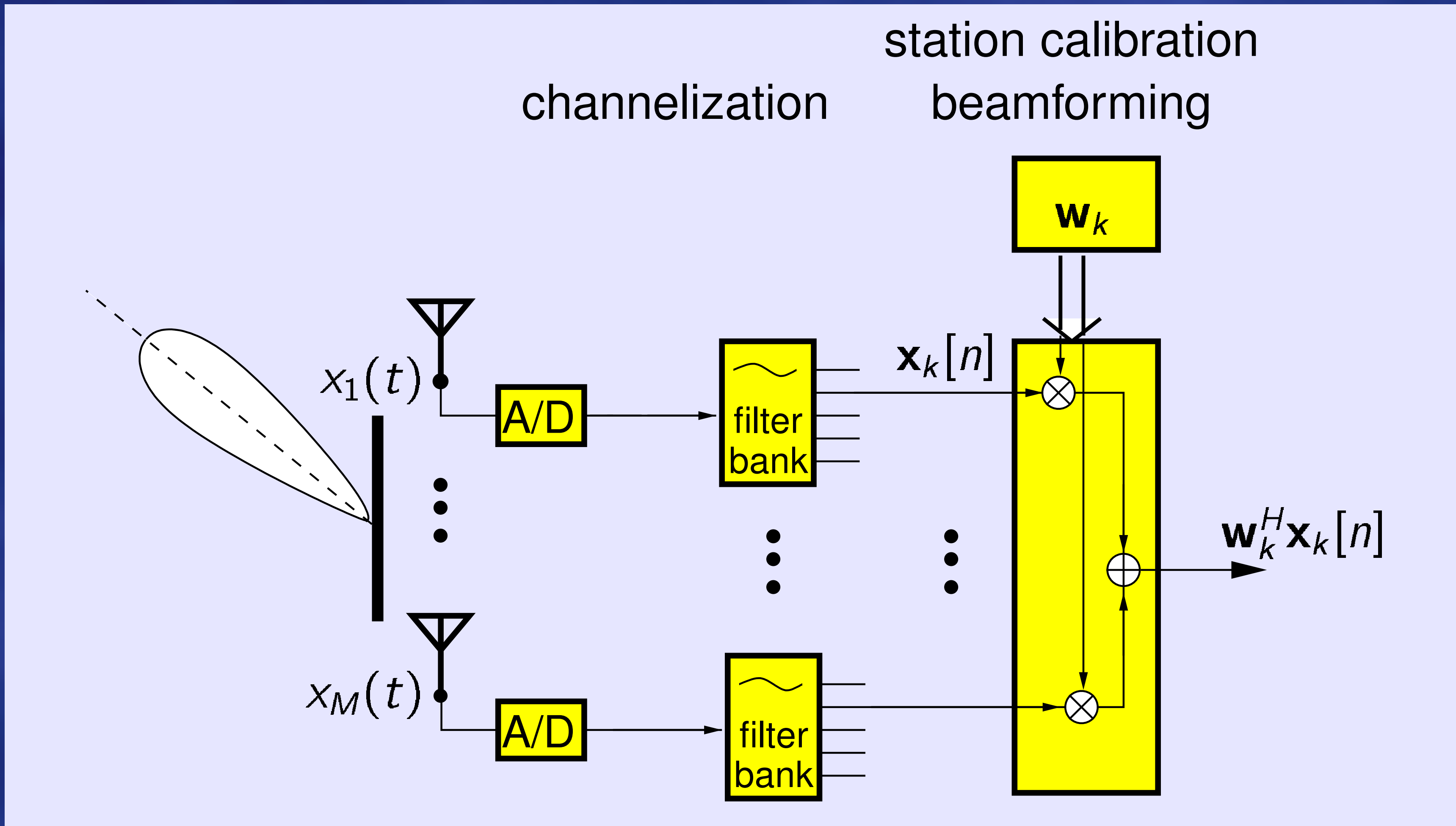
Raw data

250 MHz bandwidth (2 polarizations), 2×4 bit per complex sample; 286 antennas/station; 911 stations (later scaled down to 512), i.e. $> 260,000$ antennas

Total: 286 GBps (one station); **260 TBps** (all stations)

SKA – signal processing requirements

Station processing



SKA – signal processing requirements

Station processing

- Station beamforming reduces raw data rate by a factor 286 to **1 GBps (1 station)**
- Number of coarse frequency channels depends on station diameter (e.g. $D = 35$ m $\Rightarrow$ BW $\ll 8.6$ MHz). But narrower subbands are used e.g. for station calibration processing.

	one station	*1024 stations*
Channelization (polyphase filter bank)	14.1 TOps/s	
Beamforming	1.2 TOps/s	
Calibration	1.3 TOps/s	
Total	16.7 TOps/s	17.1 POps/s
Rate	1.2 GBps	1.2 TBps

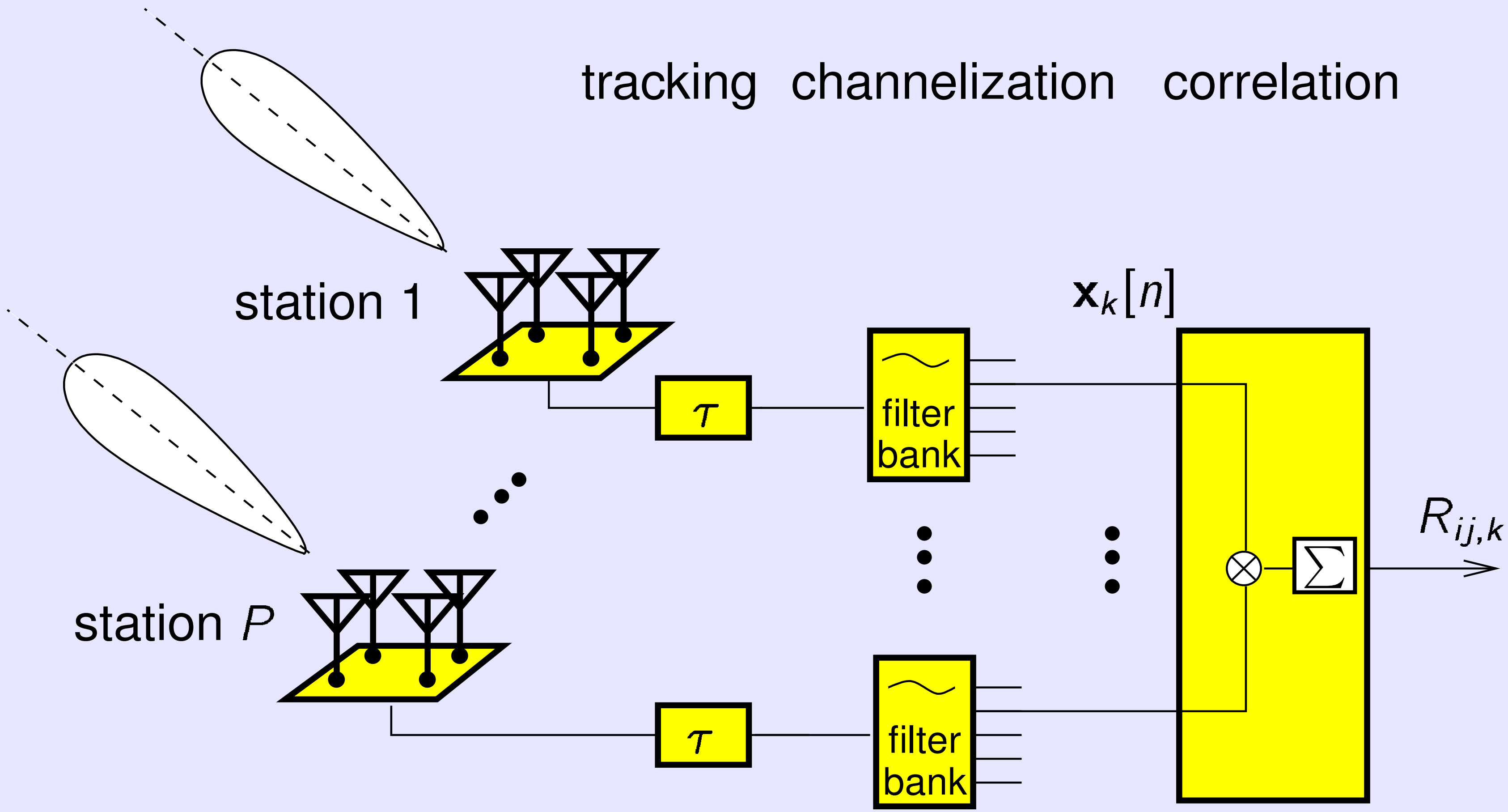
M	10^6
G	10^9
T	10^{12}
P	10^{15}

[Jongerius'16, not based on current parameters]

SKA – signal processing requirements

Central signal processing

At a central location, the beamformed data from stations are correlated, and averaged over short time intervals.



SKA – signal processing requirements

Maximum integration time

Based on earth rotation: $T < 1200\frac{D}{B}$ $\Rightarrow$ Output data rate per channel : $R = \frac{1}{1200} \cdot \frac{B}{D}$

Number of subband channels

For the complete instrument, the longest baseline B determines the narrowband constraint (to avoid bandwidth smearing).

The maximum subband bandwidth is (taking into account the reduced FOV)

$$W_{chan} \ll \frac{D}{B} f_{\min} \quad \Rightarrow \quad W_{chan} = 0.1 \cdot \frac{D}{B} f_{\min}$$

For a total bandwidth W_{tot}, the number of subband channels is proportional to

$$N_{chan} = \frac{W_{tot}}{W_{chan}} = 10 \cdot \frac{B}{D} \frac{W_{tot}}{f_{\min}}$$

The main drivers for complexity are thus P^2 and the ratios $\left(\frac{B}{D}\right)^2$ and $\frac{W_{tot}}{f_{\min}}$.

SKA – signal processing requirements

Central signal processing

- With P stations, the correlation matrices have size $P \times P$.

  SKA1-Low (2013) asked for $P = 911$ stations.

- Number of frequency channels depends on instrument diameter.

  $B = 100$ km for SKA1-Low $\Rightarrow$ BW $\ll 4.2$ kHz

  Design: **250,000 channels** with $W_{chan} = 1$ kHz.

- Integration time is limited due to earth rotation.

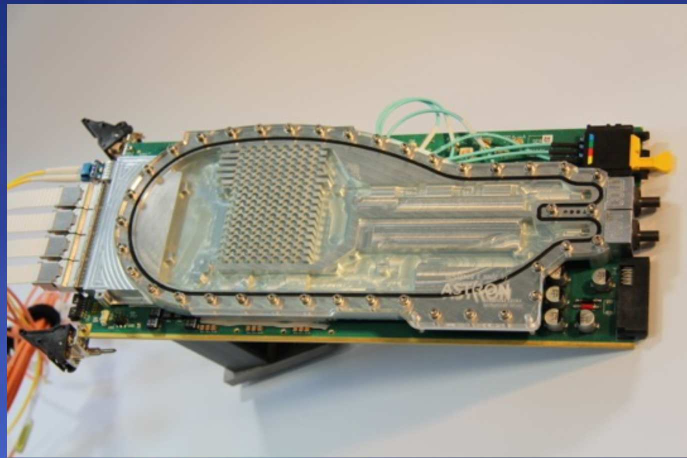
  With $B = 100$ km (longest baseline), $D = 25$ m (station diameter), the maximal integration time is $T \ll 0.4$ sec

Output data: complex correlation matrices of size 911×911 times 250,000 channels, each 0.4 sec, times 4 polarizations

SKA – signal processing requirements

Central signal processing

Channelization	60.8 TOps/s
Correlation	5.0 POps/s
RFI flagging	0.3 POps/s
Total	5.3 POps/s
Rate	7.3 TBps (!)



288 "Gemini" FPGA boards (ASTRON)

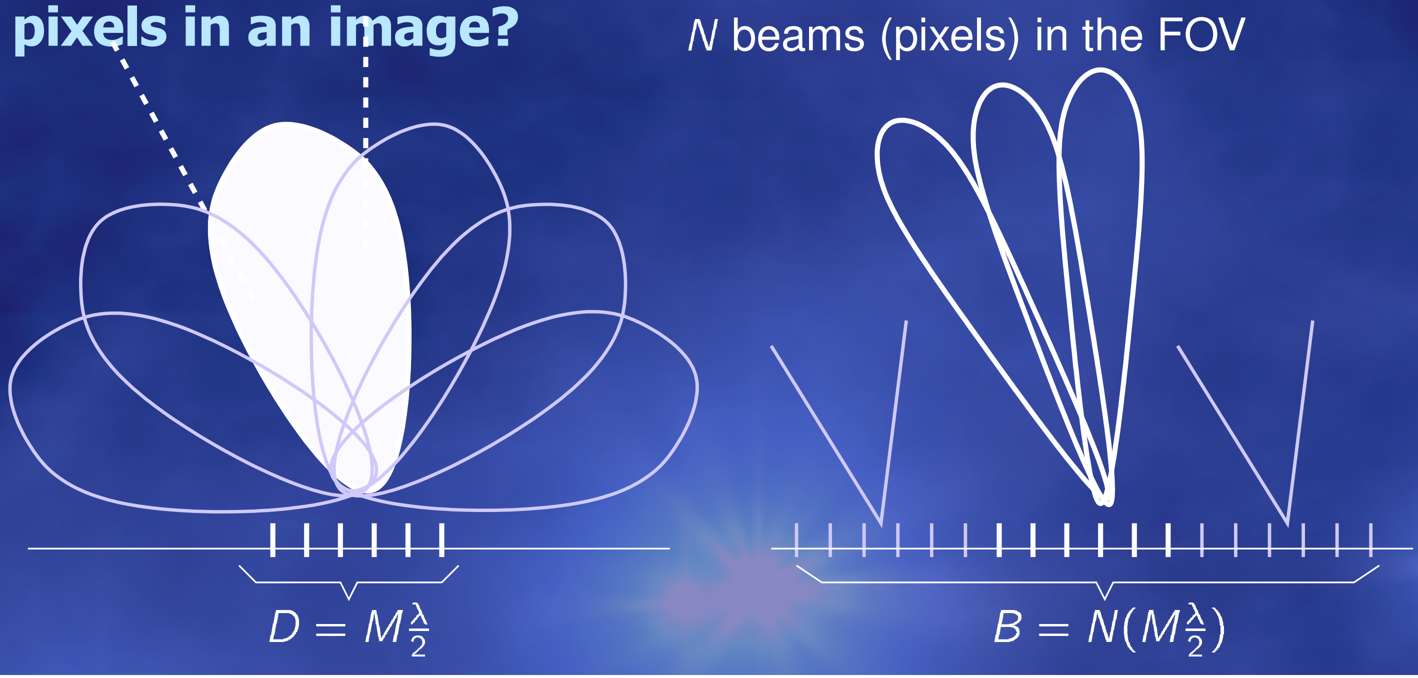
M	10^6
G	10^9
T	10^{12}
P	10^{15}

- Note that the correlator produces six times more output "data" than flows in (due to $P \Rightarrow P^2$ and short integration length).
- "Baseline dependent averaging" [analyzed in Wijnholds'15] exploits the fact that up to 90% of the baselines are short and can be integrated over longer times and larger bandwidths. This reduces the datarate by a factor 10 (about 700 GBps).
- Hardware limitations perhaps not flops but bandwidth.

SJ Wijnholds, AG Willis, S Salvini, "Baseline-dependent averaging in radio interferometry", MNRAS 2018

SKA – signal processing requirements

How many pixels in an image?



- **Uniform linear array of N stations (each M antennas), 1 dimension**

$$\left.\begin{array}{r}\text{Station diameter: } D = M\frac{\lambda}{2} \\ \text{Max baseline: } B = N(M\frac{\lambda}{2})\end{array}\right\} \quad \Rightarrow \quad N = \frac{B}{D} \text{ pixels}$$

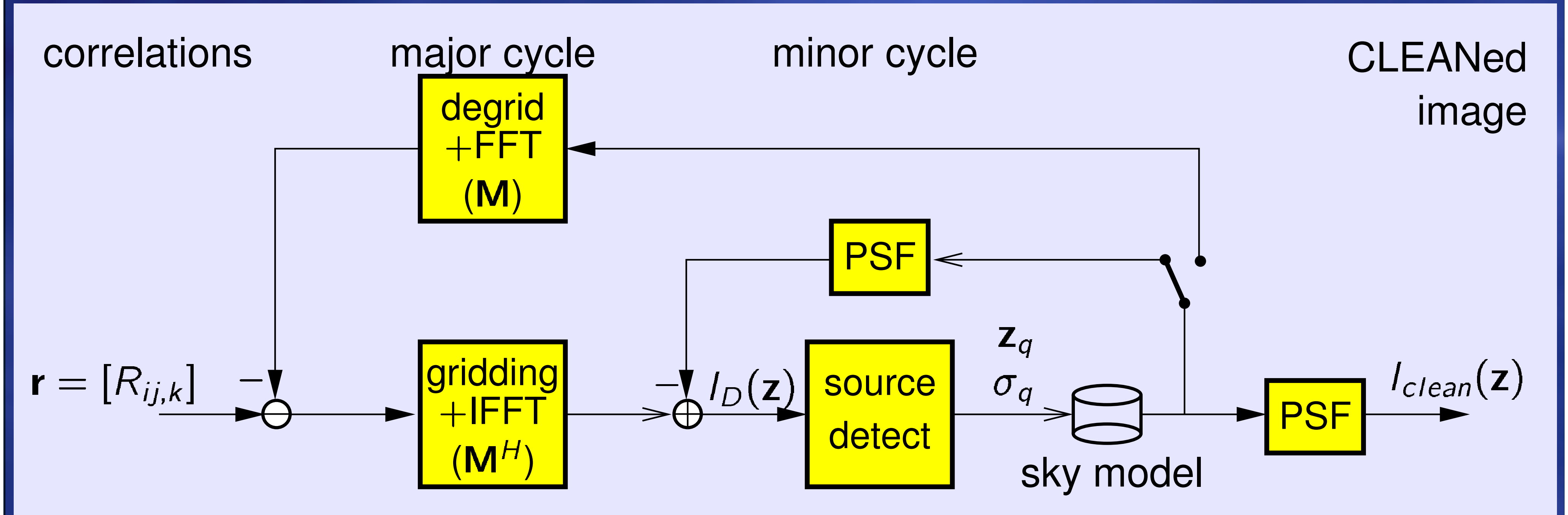
For 2 dimensions, we obtain images of size $N \times N$.

- SKA1-Low (2013): $D = 35$ m, $B = 100$ km $\Rightarrow N \sim 3000$

SKA – signal processing requirements

Science Data Processing

Science Data Processing is the actual image formation step. Also calibration parameters are estimated and applied.



SKA – signal processing requirements

Science Data Processing

Gridding + IFFT (dirty image)	84 POps/s
Source subtraction (image domain)	94 TOps/s
FFT + degrid (visibility predict)	75 POps/s
Total	158 POps/s

M	10^6
G	10^9
T	10^{12}
P	10^{15}

Direction-dependent calibration: add 213 POps/s (?)

Resulting power requirements: at least 630 kW (SKA-1 Low) for the CPUs, and much more for the data transport from/to storage. Also consider data rearrangements . . .

Conclusion: Improved imaging algorithms cannot be much more complex…

Image formation

- Data model (measurement equation): $\mathbf{R}_k = \mathbf{A}_k \boldsymbol{\Sigma}_s \mathbf{A}_k^H + \boldsymbol{\Sigma}_n$.
- Vectorized data model: $\mathbf{r}_k = \text{vec}(\mathbf{R}_k)$; vectorized image: $\boldsymbol{\sigma}_s = \text{vecdiag}(\boldsymbol{\Sigma}_s)$

$$\mathbf{r}_k = (\mathbf{A}_k^* \circ \mathbf{A}_k)\boldsymbol{\sigma}_s + \boldsymbol{\sigma}_{n,k} = \mathbf{M}_k \boldsymbol{\sigma}_s + \boldsymbol{\sigma}_{n,k}, \qquad \text{where } \mathbf{M}_k := \mathbf{A}_k^* \circ \mathbf{A}_k$$

Notation: $\circ$: Khatri-Rao product (column-wise Kronecker product)

- Stack for all STI's (+freq bins) k: $\boxed{\mathbf{r} = \mathbf{M}\boldsymbol{\sigma}_s + \boldsymbol{\sigma}_n}$
- Observations: $\hat{\mathbf{r}} = \mathbf{r} + \boldsymbol{e}$,

where $\boldsymbol{e}$ is finite sample noise, zero mean with covariance $\mathbf{C}_{\mathbf{e},k} = \frac{1}{N}\mathbf{R}_k^T \otimes \mathbf{R}_k$.

Image formation problem

Given $\hat{\mathbf{r}}$ and $\mathbf{M}$, can we recover $\boldsymbol{\sigma}_s$?

First step: subtract or project out $\boldsymbol{\sigma}_n$ from $\hat{\mathbf{r}}$ (for simplicity, no change in notation; also dropping subscript k).

Image formation

Initial approach: Least Squares

The LS RA imaging problem is

$$\hat{\boldsymbol{\sigma}} = \arg\min_{\boldsymbol{\sigma}} \|\hat{\mathbf{r}} - \mathbf{M}\boldsymbol{\sigma}\|_2^2.$$

The solution satisfies the normal equations

$$\mathbf{M}^H\mathbf{M}\hat{\boldsymbol{\sigma}} = \mathbf{M}^H\hat{\mathbf{r}},$$

$\hat{\boldsymbol{\sigma}}_{\text{MF}} = \mathbf{M}^H\hat{\mathbf{r}}$ is the MF dirty image, and $\mathbf{M}^H\mathbf{M}$ represents the convolution of the image pixels with the beampattern of the array.

- For large number of pixels Q, $\mathbf{M}^H\mathbf{M}$ is ill conditioned or not even invertible, and a solution cannot be obtained without regularizing assumptions.
- Taking a pseudo-inverse of $\mathbf{M}^H\mathbf{M}$ using a truncated SVD suppresses high frequencies and results in a Gibbs phenomenon effect.

Next – to the moon

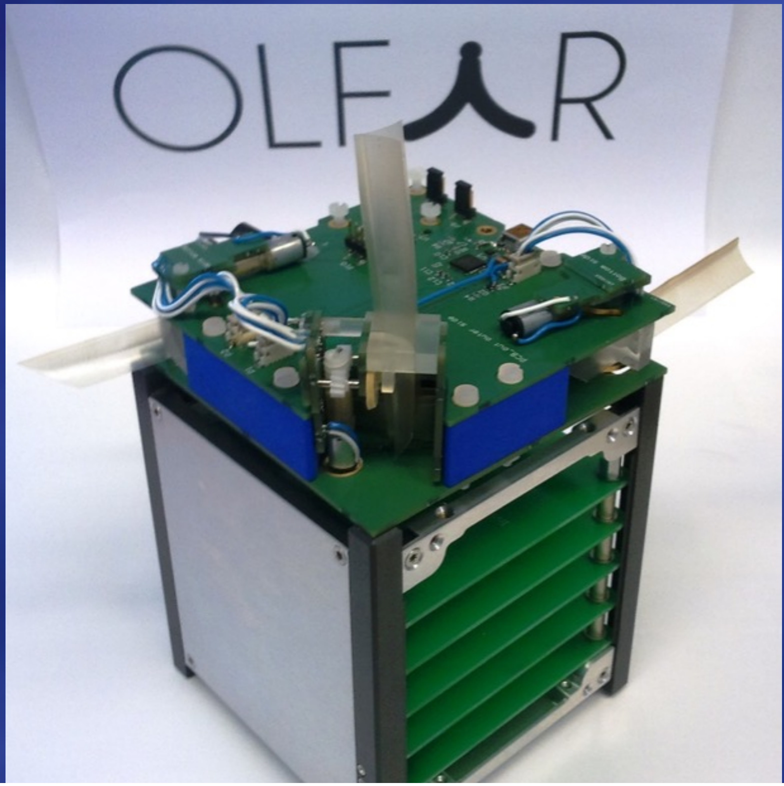
Netherlands-China Low-Frequency Explorer (20 May 2018)

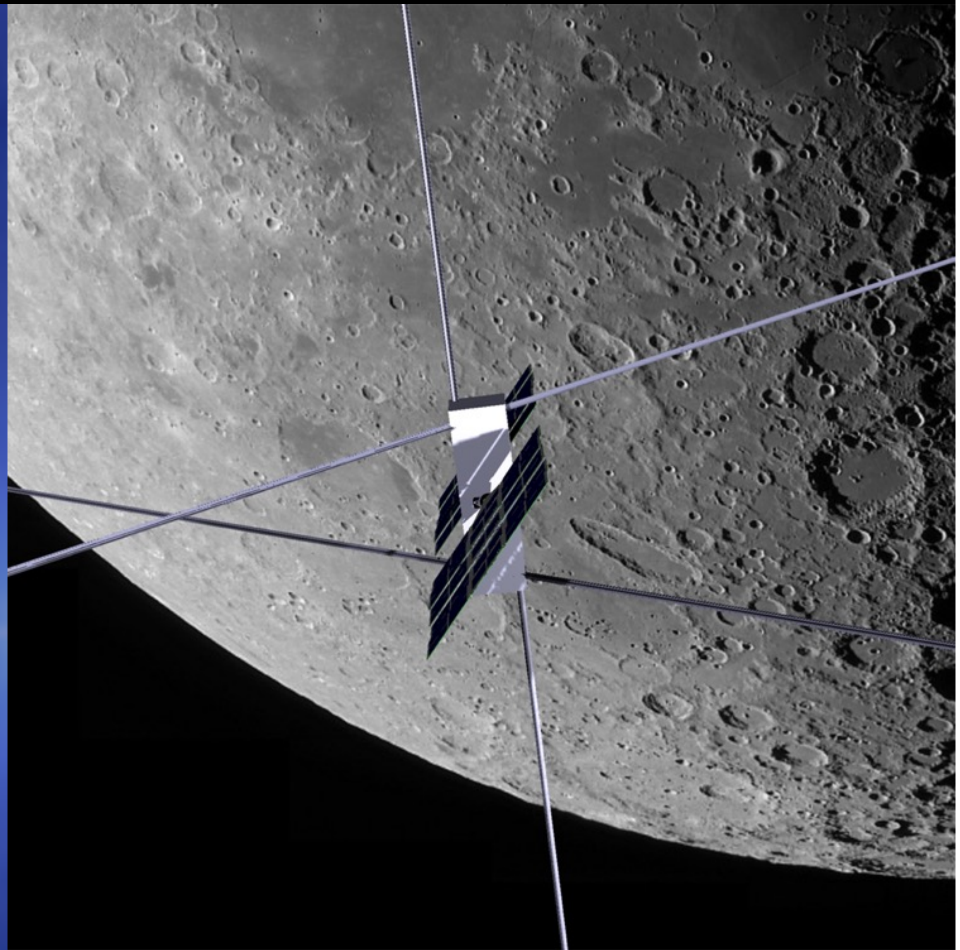
- Piggyback on a relay satellite for the Chinese lunar explorer mission (Chang'e 4)
- 3 antennas (orthogonal dipoles), (80 kHz till) 1-80 MHz
- Also: launch of two moon-orbiting microsatellites for testing interferometry at 1-30 MHz (but one failed?)

Next – to the moon

OLFAR – orbiting low frequency array, design concept

- Swarm of some 50 nano-satellites, orbiting the moon

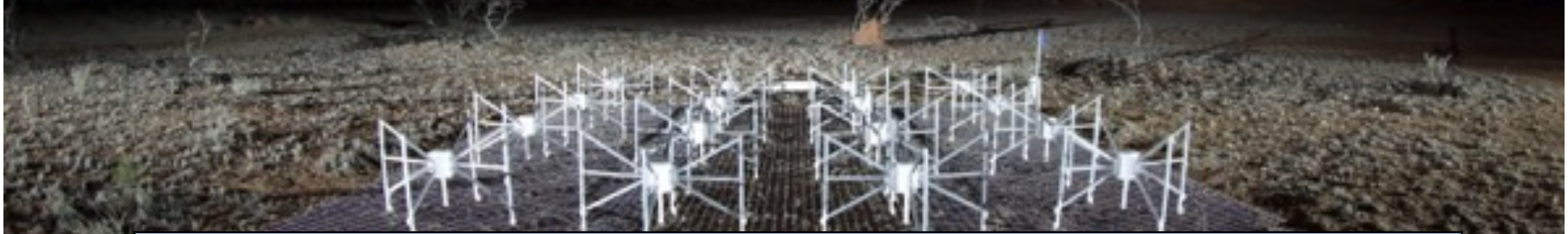




Conclusions

Radio astronomy is an interesting application area for Array Signal Processing

- Imaging and deconvolution
- Interference reduction using subspace techniques
- Calibration



Thanks to collaborators: Amir Leshem, Albert-Jan Boonstra, Stefan Wijnholds, Sebastiaan van der Tol, Millad Sardarabadi, Shahrzad Naghibzadeh, Raj Rajan, …

A.J. van der Veen, S.J. Wijnholds, A.M. Sardarabadi, **Signal Processing Tools for Radio Astronomy**, in *S. Bhattacharryya e.a. (Ed.), Handbook of Signal Processing Systems,* 3rd ed., Springer, pp. (40 pp.), July 2018.