The Development of Aperture Synthesis

Radio Astronomy & the ISM

Durango, 19 May 2011

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Today we use Aperture Synthesis Images routinely

But the path to developing the underlying concepts has a rich history involving discovery, sociology, and some incredible individuals

Radio Image of
Ionised Hydrogen in Cyg X
CGPS (Penticton)

Deep History

- 1891: Michelson defines fringe visibility
  - Gives the Fourier equations but doesn't call it a Fourier transform
- Stereo X-ray imaging
- 1912: X-ray diffraction in crystals
- 1930: van Cittert-Zernike theorem
  - Now considered the basis of Fourier synthesis imaging
  - Played no role in the early radio astronomy developments but appears in the literature after Born & Wolf *Principles of Optics* (1960)
- 1930-38: 3D X-ray tomography
  - Analogue devices to do back projection summation

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Michelson: Stellar interferometry

- 1891
  - Michelson defines fringe visibility
  - Gives the Fourier equations but doesn't call it a Fourier transform
  - notes that stellar applications will be disks so only a diameter is measured
  - no discussion of the visibility being complex
    - no way to measure phase
- 1920-21
  - Michelson and Pease measure stellar diameters

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1930 van Cittert-Zernike theorem

- The spatial coherence over a space illuminated by an incoherent extended source is described by the Fourier transform of the intensity distribution over the source.
- Now considered the basis of Fourier synthesis imaging
- Played no role in the early radio astronomy developments but appears in the literature after Born & Wolf *Principles of Optics* (1960)

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Carl Frederick August Zernike

- 1913 assistant to Kapteyn at the astronomical laboratory of Groningen University
- 1953 Nobel prize for physics for his invention of the phase contrast optical microscope
- 1930 van Cittert-Zernike theorem
  - Now considered the theoretical basis of Fourier synthesis imaging
  - But no involvement in the development of radio imaging in the Netherlands or elsewhere

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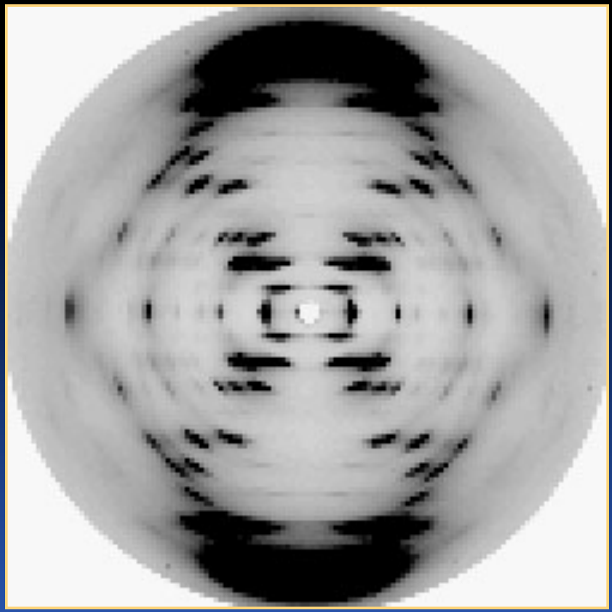
X-ray Crystallography



- 1912
  - X-ray diffraction in crystals
- 1936
  - Lipson & Beevers strips
  - Fourier synthesis calculations routine in X-ray crystallography
- 1939
  - Bragg's X-ray crystallography group flourishing at the Cavendish Laboratory
    - 2D Fourier analysis
    - phase problem,

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Cavendish ↔ Radiophysics

- WWII Radiophysics Laboratory, Sydney
  - Home of the classified radar research group
  - Little direct involvement in the war
    - research and training radar operators
  - Strong push to escape from the culture of secrecy after war
- The UK WWII researchers and equipment were transferred to a University research environment (Cavendish)
  - Ryle had direct involvement in the war analysing German radar equipment. He had to survive in a fiercely competitive environment

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Ratcliffe and Pawsey Cambridge and Sydney

- 1935
  - Pawsey PhD with Ratcliffe at Cambridge (ionosphere)
- 1940
  - Pawsey joins CSIRO Radio Physics Laboratory in Sydney but maintains strong links with Ratcliffe
  - Ratcliffe ≡ Pawsey + Bowen
- 1945
  - Pawsey investigates radio emission from the sun
- 1946-1949
  - Pawsey introduces Bracewell to duality of physical and mathematical descriptions following Ratcliffe's style
  - Bracewell sent from Sydney to work with Ratcliffe

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Ryle and the Cavendish

- 1945
  - Ryle joins Cavendish laboratory
    - uses WWII radar technology for radio astronomy
- 1946
  - Ryle and Vonberg (Nature 158, 339-340 (Aug 1946))
    - interferometric measurement of sunspots
  - introduces the use of a Michelson interferometer to measure the angular diameter of the source of the radiation and references Michelson

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Technology 1946

- 1946
  - Punched cards for Fourier series summation
  - Sea interferometer at Dover Heights
    - 26 Jan 1946
  - Michelson interferometers in Cambridge
- 1949
  - EDSAC I programmed by Wilkes could just do a 1D transform
    - 15 hrs for a 38 point transform for every 4min of data

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Fourier Synthesis - 1947

- The concept of restoring the source distribution from measurements of the Fourier components was being discussed at CSIRO radio physics *(Bracewell recollections)*

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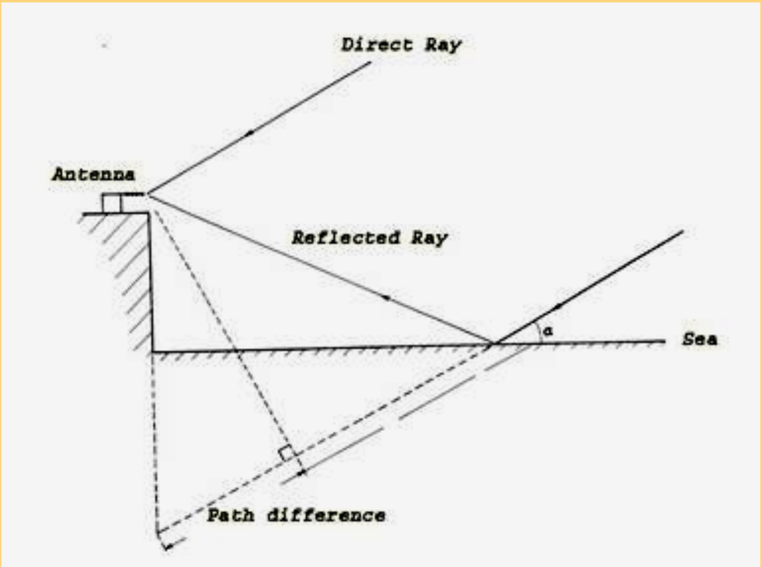
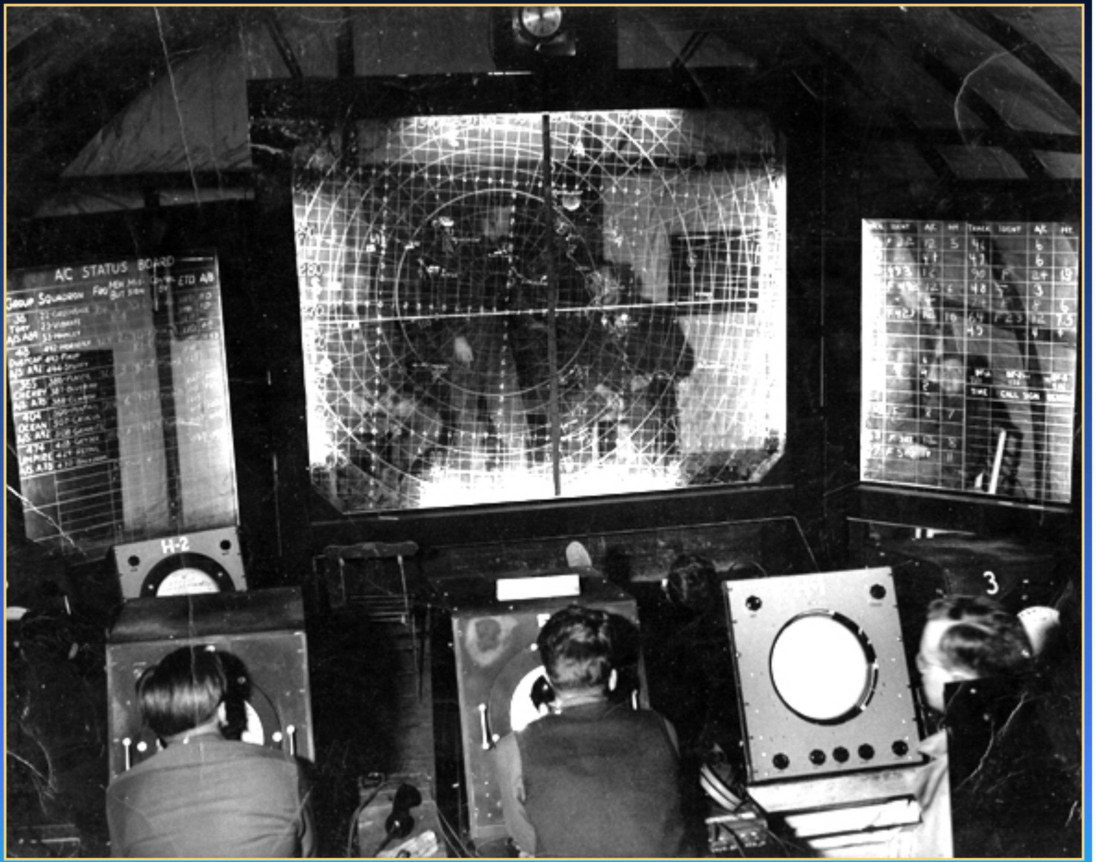
Cliff Interferometer - 1948

- Bolton, Stanley and Slee
  - 100MHz Yagi



Loyds mirror



Dover Heights 1952

McCready, Pawsey & Payne-Scott 1947

- Proc Roy Soc, Aug 1947 - received July 1946!
- Used the phase of the sea interferometer fringes (lobes) to co-locate solar emission with sunspots
- They note that its possible in princ the actual distribution by Fourier s phase and amplitude at a range of wavelength.
- They consider using wavelength a variable as unwise since the solar have frequency dependent structu
- They note that getting a range of c clumsy and suggest a different int would be more practical.


Ruby Payne-Scott

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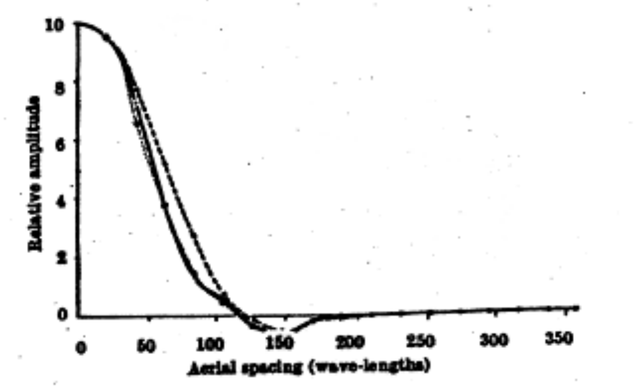
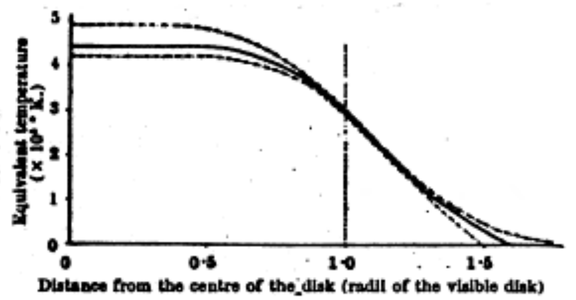
Stanier & Ryle
Cavendish Laboratory 1950

- Two element interferometer
- Stanier measured solar visibility for 17 EW spacings
- Computed the radial profile using Hollerith punched card machine
- Assumption of circular symmetry was wrong
  - Limb brightening not found





Fourier synthesis at Cambridge

- 1951
  - Machin used an array of 4 fixed and two moveable elements and measured the solar profile.
  - Analysed using Bessel functions
- 1952
  - Ryle (Proc Roy Soc) - the phase switch

$$(A+B)^2 \rightarrow AxB$$

  - Credits McCready et al (1947) for Fourier Synthesis concept
- 1953
  - O'Brien publishes the first 2D Fourier synthesis
  - moveable element interferometer ←
  - Multiple hour angles

The Australian arrays

- A time variable sun needs instantaneous coverage
- 1951
  - Christiansen bu
    - 32 steerable p
    - an SKA path f
- 1953
  - Chris Cross (Fl
  - Mills cross
- 1967
  - Paul Wild solar

The US contemplates a National Observatory

- 1954
  - Bob Dicke proposes a synthesis telescope for Greenbank
  - based on summation of interferometer responses
  - A committee decided to built a 140’ equatorially mounted dish instead and the US lost an early opportunity to become a world leader in aperture synthesis radio astronomy!
  - Committees are necessarily conservative and risk averse (Crick)

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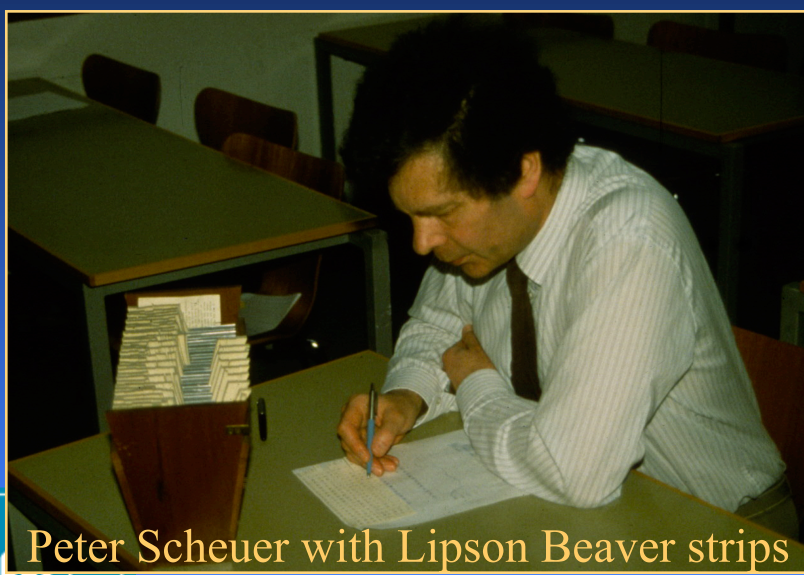
Fourier Transforms - 1953

- Lipson-Beevers strips
  - 25x25 array to 2 digits 1 person in 24 hours
- Punched card tabulator
  - 25x25 array to 3 digits in 8 hours (4 operators!)



Peter Scheuer with Lipson Beaver strips

Fourier synthesis imaging - 1954

- Bracewell and Roberts: *Arial smoothing*
  - introduces *invisible* distributions and the principal solution
- Scheuer: *Theory of interferometer methods*
  - PhD chapter 5 (unpublished)
  - Full analysis of Fourier synthesis including *indeterminate* structure
- Independent developments, but all acknowledge Ratcliffe's lectures

Christiansen and Warburton first earth rotation synthesis (1955)

- *The way in which a 2D radio brightness distribution may be derived from a number of 1D scans is not obvious. However rather similar 2D problems have arisen in crystallography and solutions for these problems, using methods of Fourier synthesis have been found.*
- Chris then takes the 1D FT of the strip and does a 2D Fourier synthesis
- Reference to O'Brian (Cambridge)

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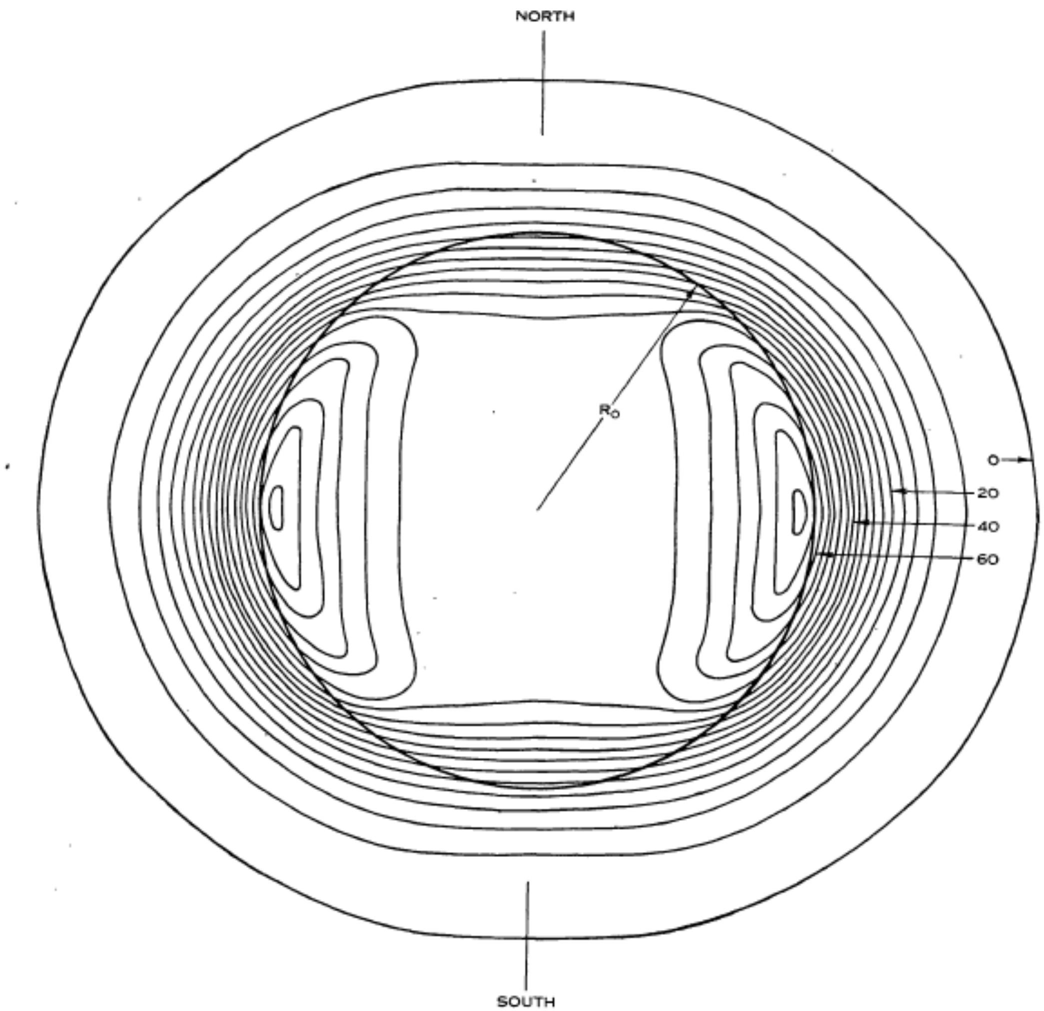
First earth rotation aperture synthesis image
The Sun at 21cm
1955



Computers and signal processing

- 1958
  - EDSAC II completed and applied to Fourier inversion problems
- 1961
  - Jennison had acquired Ratcliffe's lecture notes on the Fourier transform and publishes a book on the Fourier Transform
  - Sandy Weinreb builds the first digital autocorrelator
- 1965
  - Cooley & Tukey publish the FFT algorithm

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Hogbom and Earth Rotation synthesis

- 1958
  - Hogbom describes earth rotation synthesis to Ryle *(Radio Astronomy at the Fringe , ASP 300, pp120)*
    - Hogbom ran the calculations on EDSACII
    - Hogbom didn't think it very useful because he didn't think of using steerable antennas
  - He later realised that Ryle already understood the principal but was keeping it to himself
  - Hogbom was unaware of the other Cambridge work using earth rotation (eg O'Brien 1953)

Jan Hogbom making images: Parkes single dish

Ryle & Hewish 1960

- 1960
  - Ryle and Hewish MNRAS, 120, 220
  - The Synthesis of Large Radio Telescopes
  - no reference of any kind to Pawsey et al
  - Many references to the Mills Cross as a less practical and more complex system
- 1962
  - Ryle publishes the 1 mile telescope design
  - Probably delayed publication of the idea so others wouldn't build it before Cambridge

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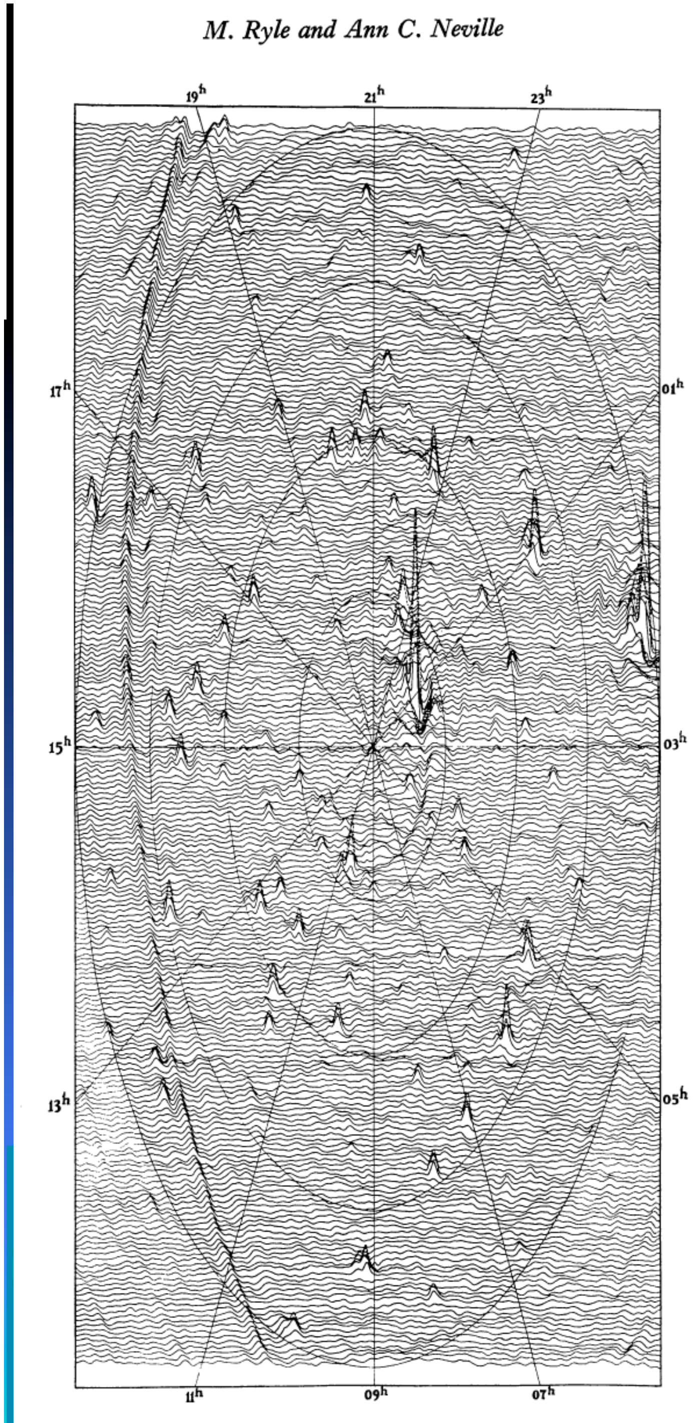

First Cambridge Earth Rotation Synthesis Image

- Ryle & Neville, MNRAS 1962
- June 1961
- North pole survey
- 4C aerials
- 178 MHz
- 7 years after Christiansen
- Similar results now being obtained by LOFAR & MWA!

The Elizabeth Waldram Story

- Ryle & Neville, MNRAS 1962
  - Elizabeth gets an acknowledgement
- Computations and graphical display using EDSACII
- Elizabeth did all the computations and ruled surface display
  - First radio image display
- Transferred to Ryle's group from X-ray crystallography
  - After being exposed to excessive radiation levels
  - First member to use the crystallography software
  - Not enthusiastically welcomed by Ryle
- Still active in the Cambridge Radio group
  - 10C surveys, AMI

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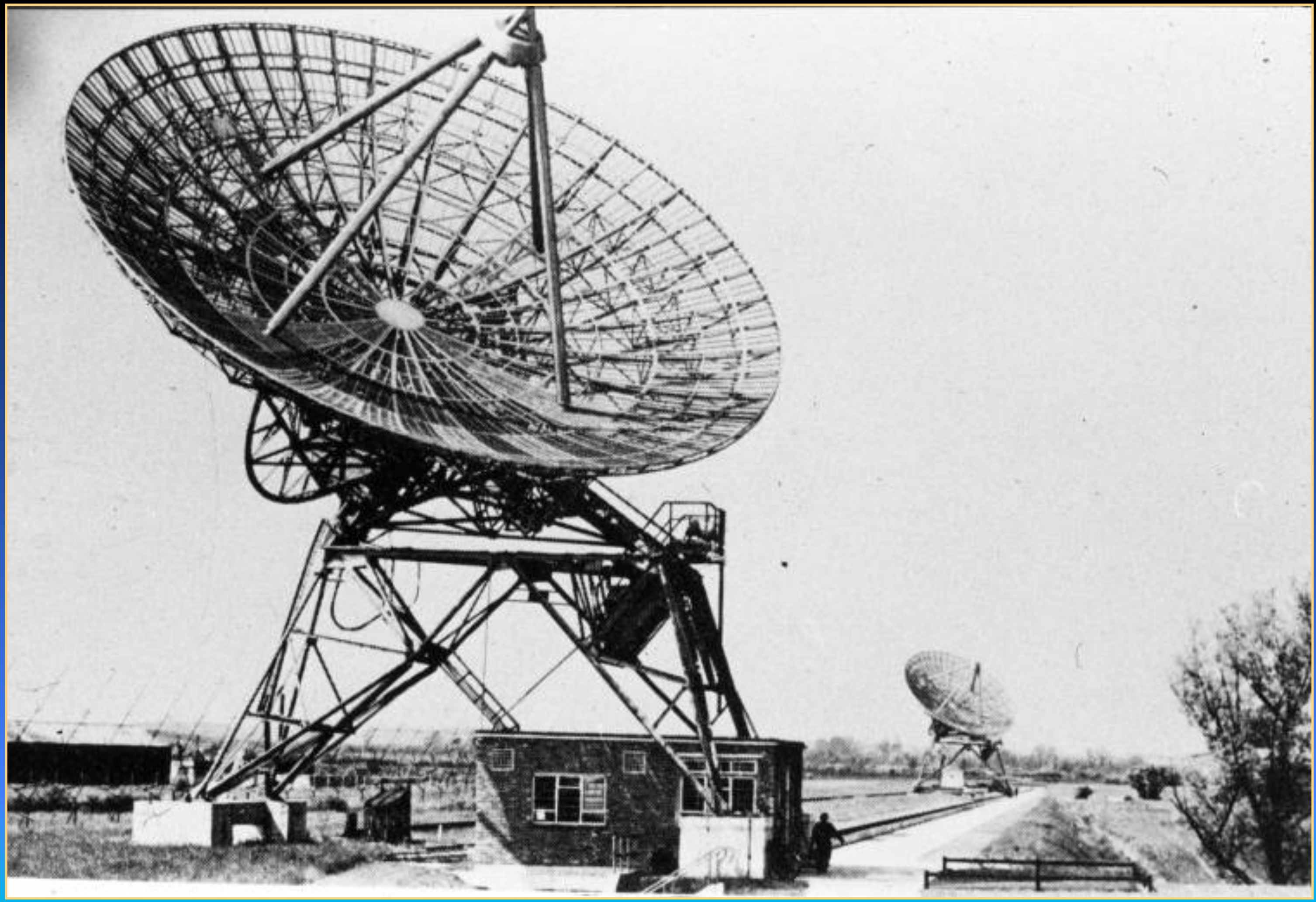
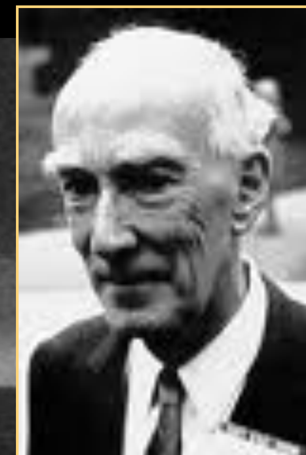
Cambridge One-Mile Telescope: 1962



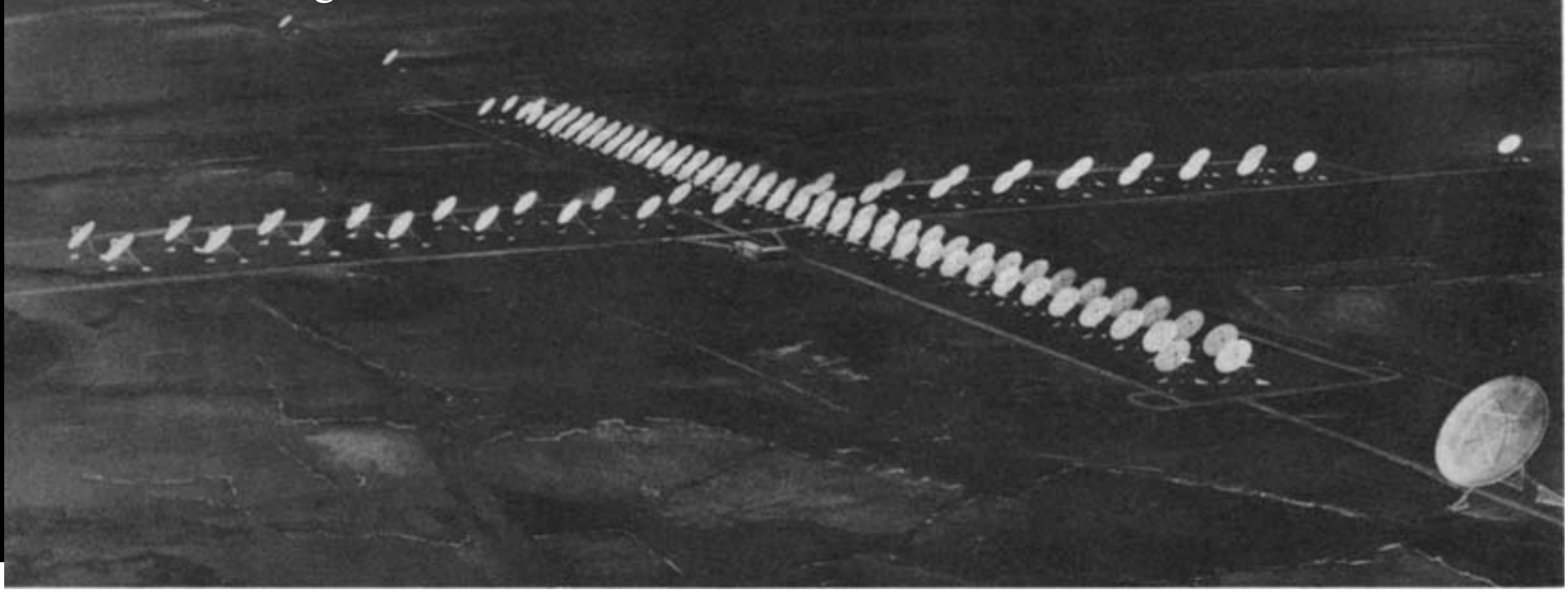
Benelux Cross
Artist impression - 1963

- Joint Netherlands – Belgium
- OEEC (now OECD) agreement
- Christiansen et al design
- 100x 30m + 1x 70m dish
- 21cm
- 1.5km

Science Goals for Benelux Cross



- Oort - OECD Symposium (1961)
  - Primary goal
    - Enough sensitivity and resolving power to study the early universe through source counts



Westerbork: 1970

- Hogbom (Cambridge)

  +

- Christiansen (Sydney)

Benelux cross → WSRT

- 12 x 25m dishes 1.5km
  - Two moveable
  - 10 redundant spacings
  - Self calibration
  - Two more dishes at 3km added later

5-km Aperture Synthesis Telescope Cambridge 1971

- 4 moveable and 4 fixed antennas
  - 16 correlations
- Achieved 1” resolution
  - comparable to optical
- Used back projection
  - Output was the images

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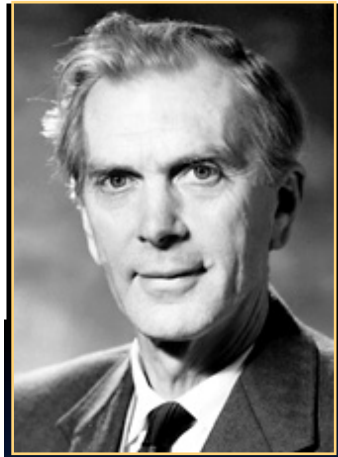

Nobel Prize 1974
Sir Martin Ryle

for his observations and inventions, in particular of the aperture synthesis technique

from the presentation

"The radio-astronomical instruments invented and developed by Martin Ryle, and utilized so successfully by him and his collaborators in their observations, have been one of the most important elements of the latest discoveries in Astrophysics."

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Parkes Variable Baseline Interferometer: 1965

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WORST UV

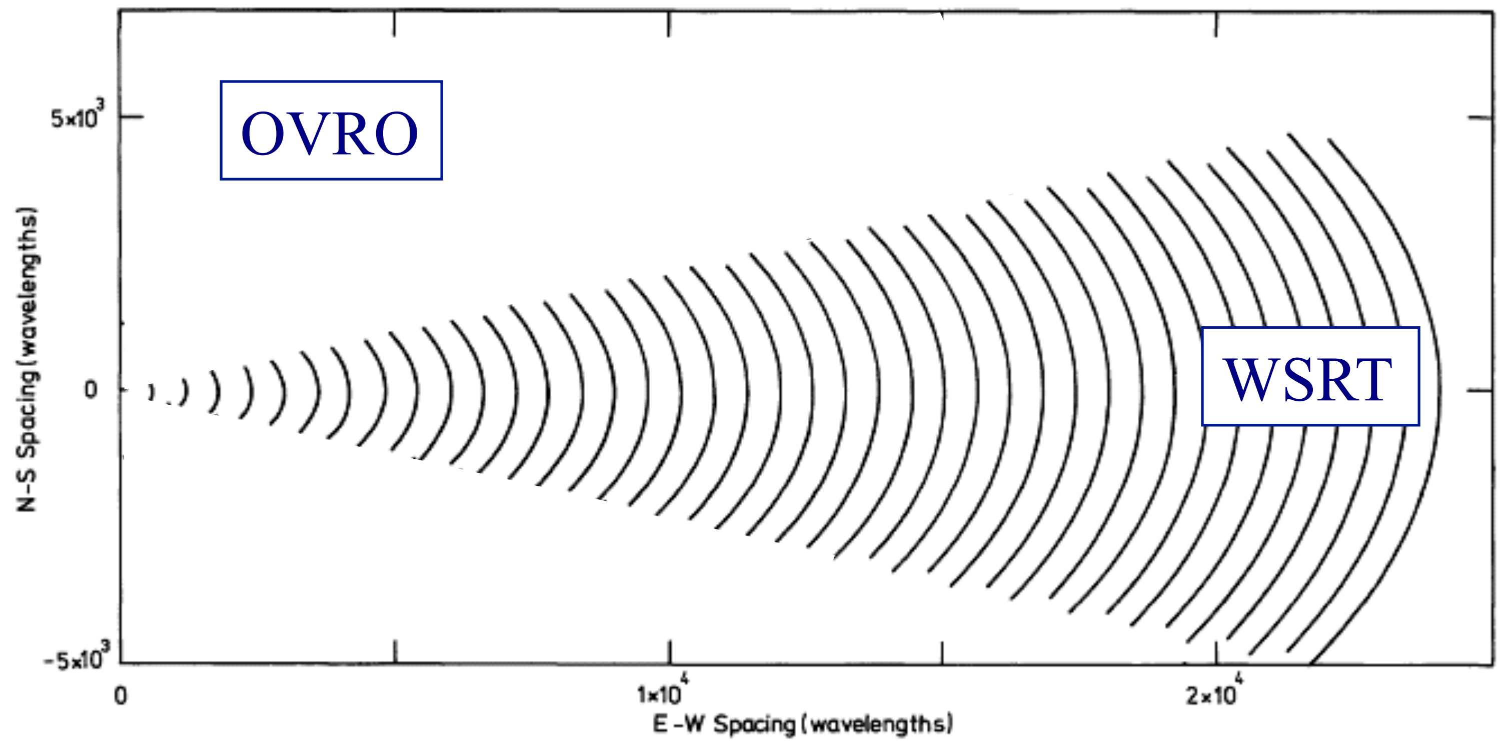
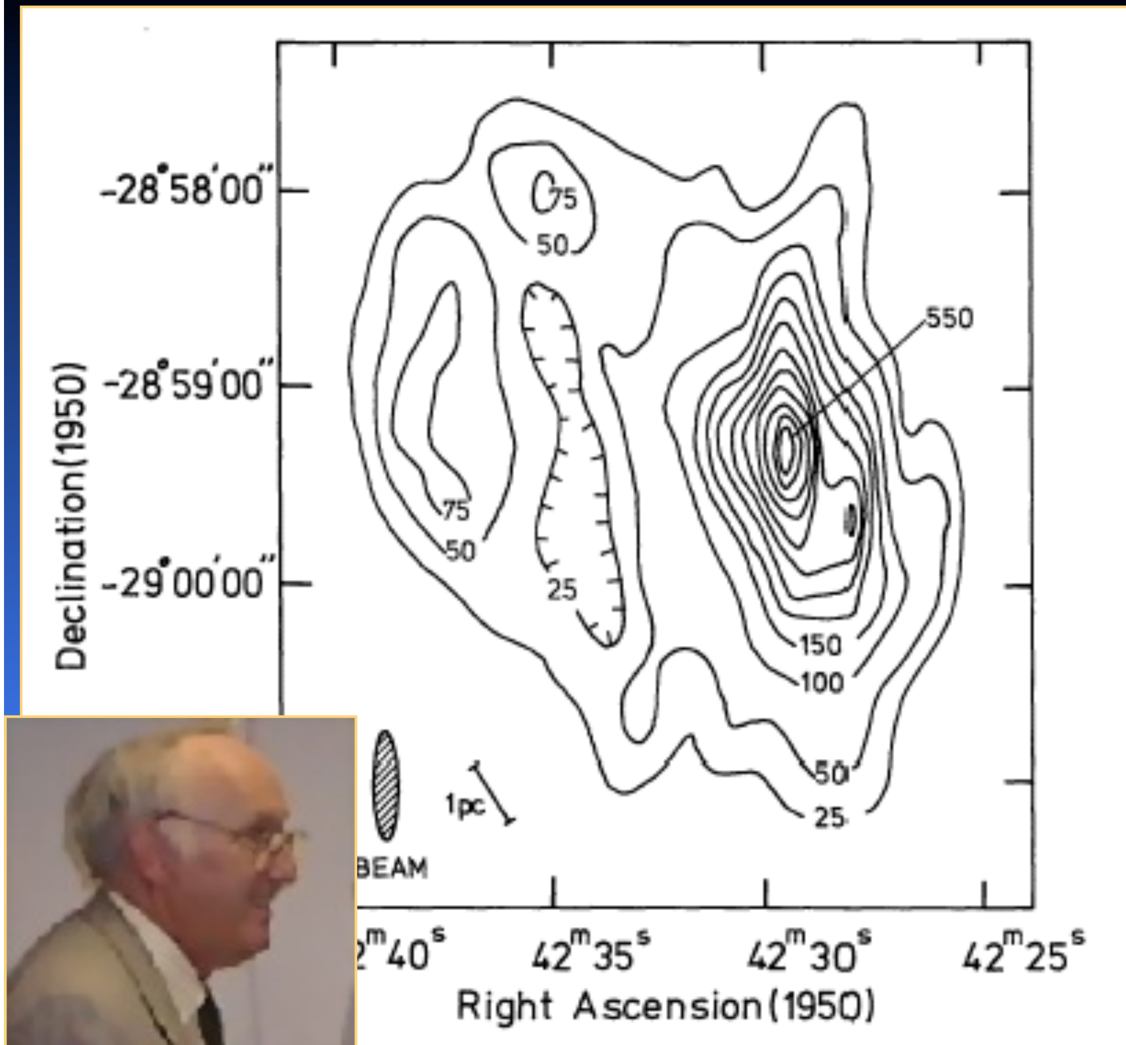


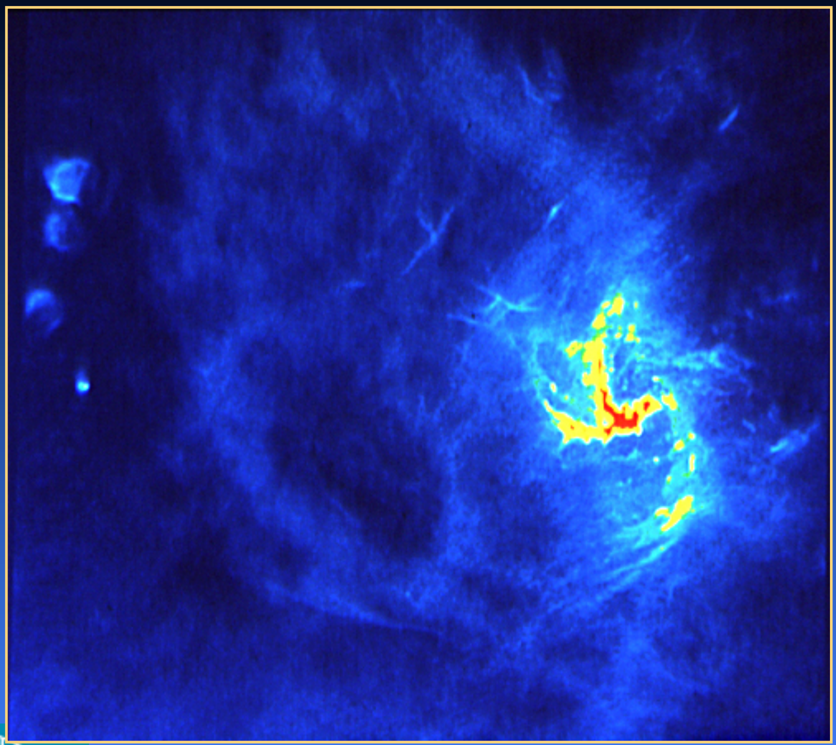
Fig. 1. Projected interferometer baselines for the observations of Sgr A. The solid lines correspond to the antenna spacings used at Westerbork, the dotted lines to those at Owens Valley

Sgr A at 5GHz - WORST



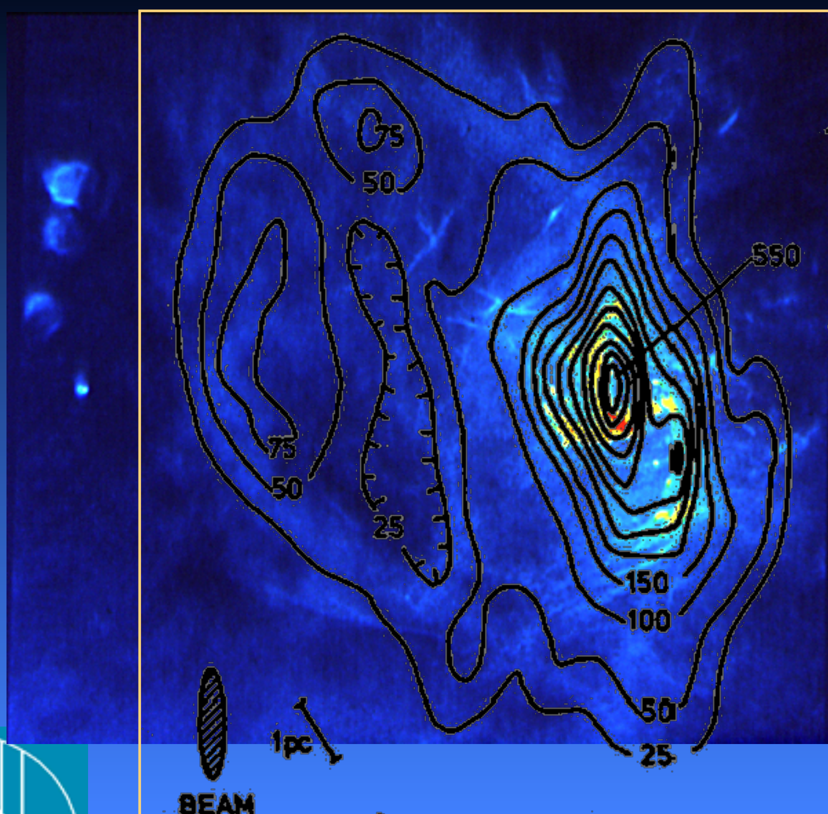
- Westerbork + OVRO
  - Ekers, Goss, Schwarrz, Downes, Rogstad
  - *A&A 43, 159 (1975)*
- SgrA West
  - Thermal source surrounding galactic centre
- SgrA East
  - Supernovae remnant behind SgrA West

VLA



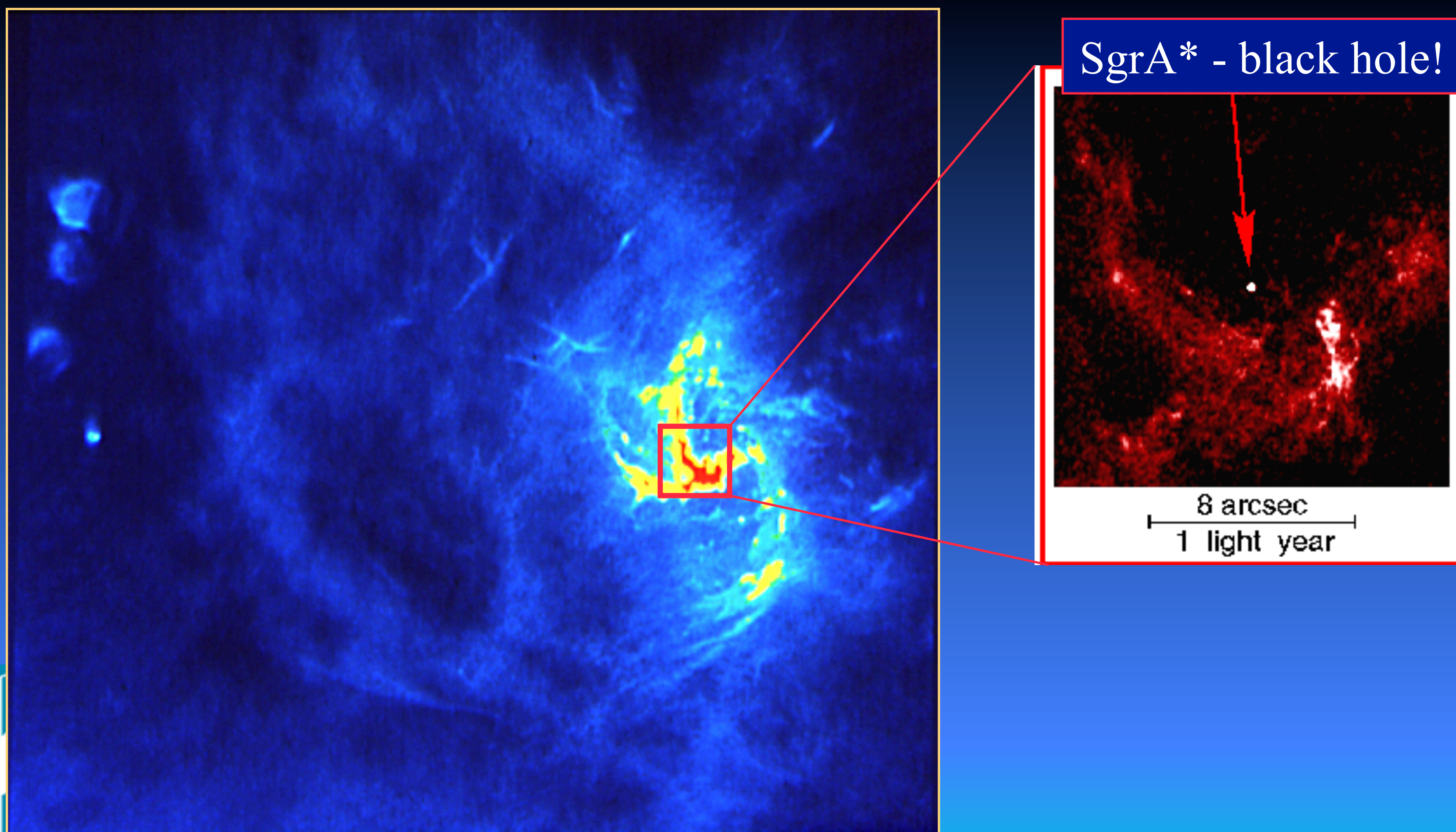
- VLA 5GHz
  - Killeen unpublished

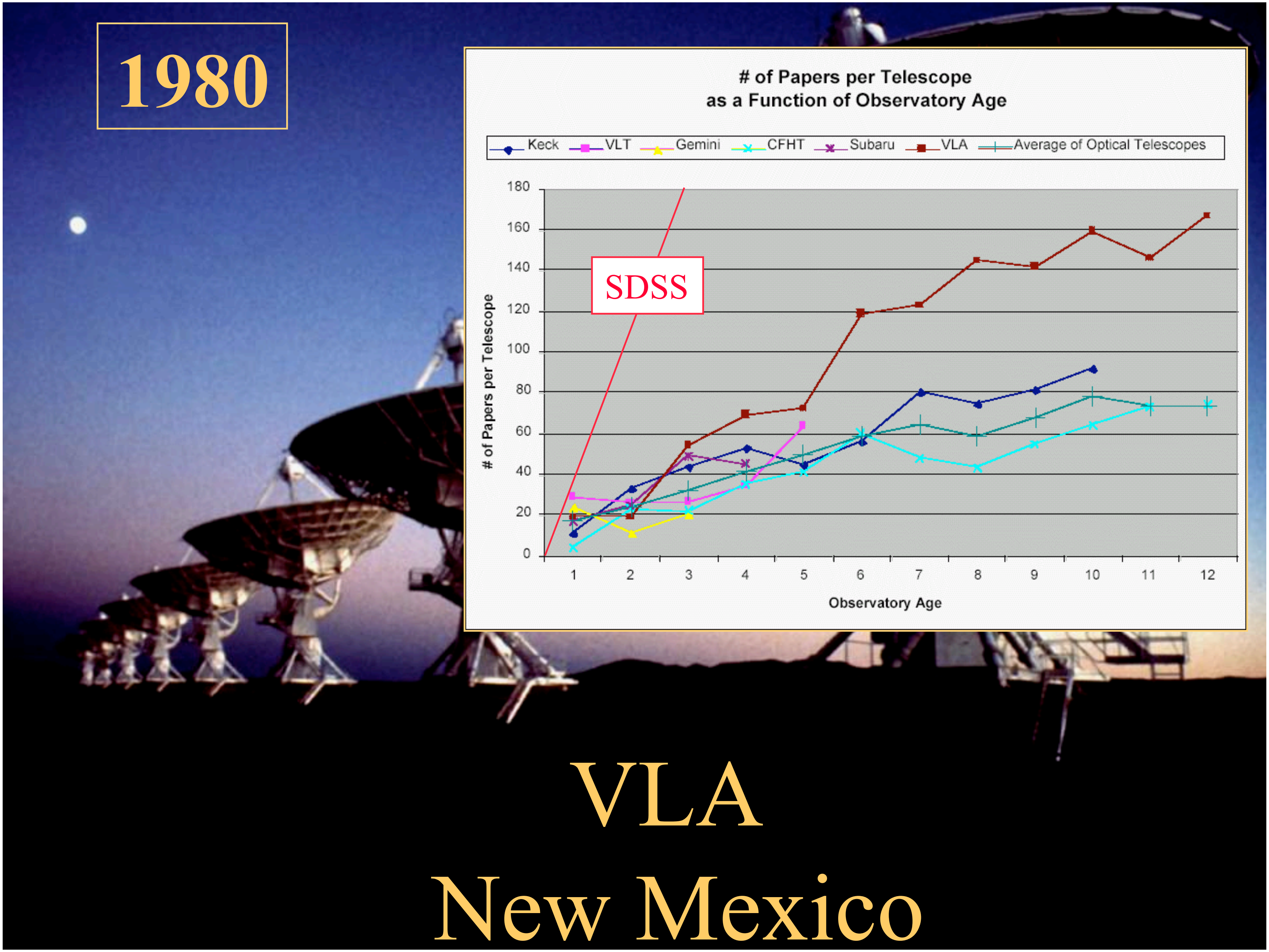
Sgr A at 5GHz - WORST



- Westerbork + OVRO
  - Ekers, Goss, Schwarrz, Downes, Rogstad
  - A&A 43, 159 (1975)
- VLA 5GHz
  - Killeen unpublished

Sgr A in the VLA era




1980
# of Papers per Telescope
as a Function of Observatory Age
Keck
VLT
Gemini
CFHT
Subaru
VLA
Average of Optical Telescopes
# of Papers per Telescope
0
20
40
60
80
100
120
140
160
180
1
2
3
4
5
6
7
8
9
10
11
12
Observatory Age
SDSS
VLA
New Mexico

US Synthesis Telescopes ⇨ VLA

- Bob Dicke 1954
- Joe Pawsey 1961-2
- John Bolton OVRO two element interferometer 1962
- NRAO 3 element interferometer 1964-5
- NRAO proposed VLA in 1967
  – Ryle – it will not work (troposphere)
  – Fixed A array configuration
  – No known way to generate the images
  – Cant keep this number of cryogenic receivers working
  – No deconvolution
  – No self calibration
- VLA operational 1980

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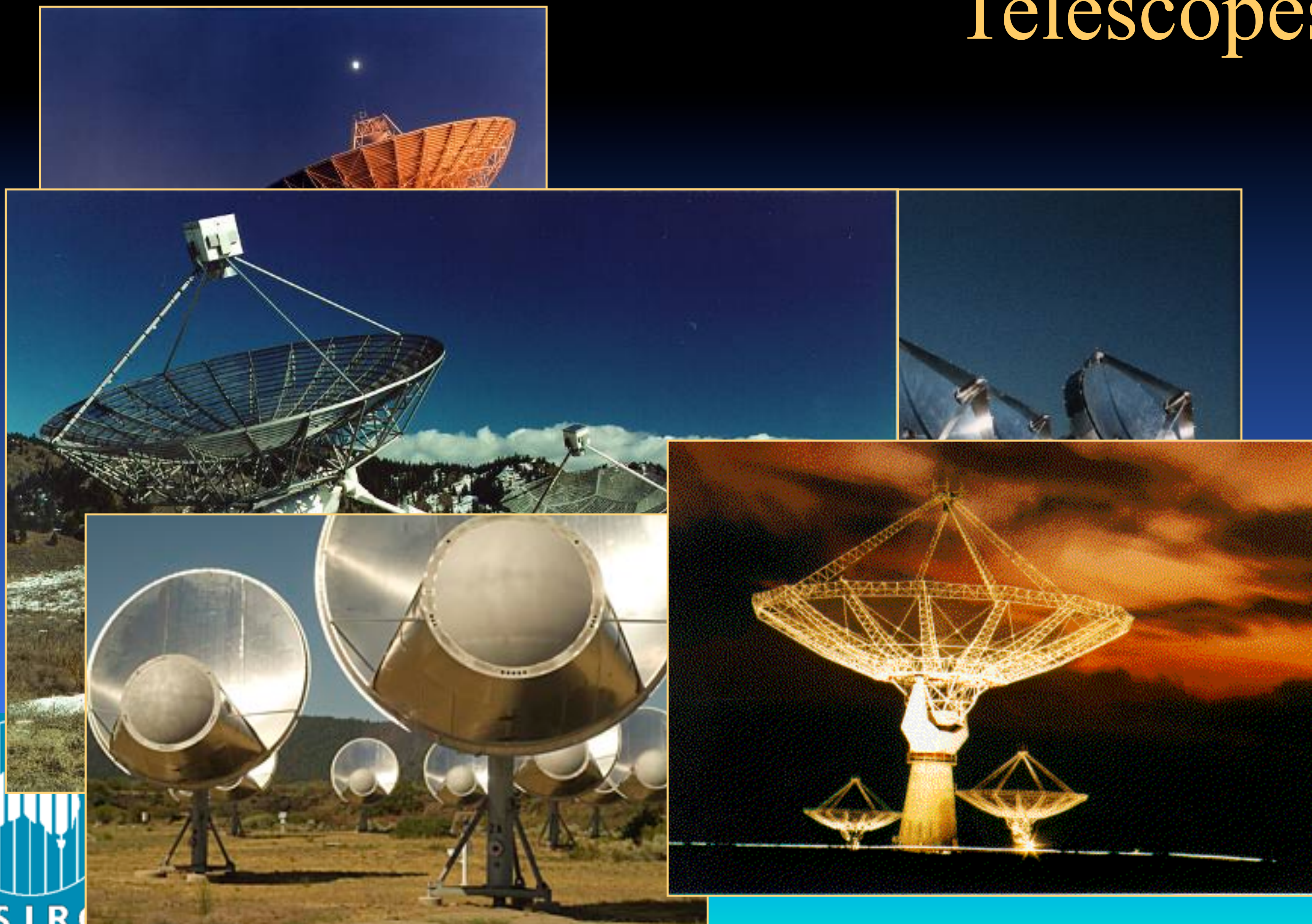
SKA 2016?

Modern Aperture Synthesis Telescopes



the Green Bank Interferometer 1964

- 3 x 25m elements
- Poor uv coverage is impetus for spatial deconvolution
- Southern lobe of Sgr_A
- Hogbom clean

Deconvolution

- 1968
  - Hogbom does first clean experiments
  - NRAO 3 element data
- 1971
  - first cleaned image published
    - Rogsstad and Shostak
- 1974
  - Hogbom publishes the CLEAN algorithm
- Use of deconvolution very controversial in the 1970's

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1980
VLA
New Mexico

Daishida Array Tokyo