The Evolution of Indirect Imaging in Radio Astronomy

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Summary

- Indirect imaging history
 - Optical, X-ray crystallography, Medical
- Radio astronomy developments
 - Cambridge, UK & Sydney, Australia
- Interferometers & Fourier Synthesis
- Image processing algorithms



Indirect Imaging

- 1891: Michelson defines fringe visibility
 - Gives the Fourier equations but doesn't call it a Fourier transform
- 1896: 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

X-ray Crystallography

- 1912
 - X-ray diffraction in crystals
- 1936
 - Fourier synthesis calculations routine in X-ray crystallography
 - Lipson & Beevers strips
- 1939



- Bragg's X-ray crystallography group flourishing at the Cavendish Laboratory
 - 2D Fourier analysis
 - The 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



Ratcliffe and Pawsey Cambridge and Sydney

- 1935
 - Pawsey PhD with Ratcliffe at Cambridge (ionosphere)
 - Pawsey meets Bhabha at Cambridge.
- 1940
 - Pawsey joins CSIRO Radiophysics Laboratory in Sydney but maintains strong links with Ratcliffe in Cambridge
- 1945
 - Pawsey investigates radio emission from the sun
- 1946-1949
 - Pawsey introduces Bracewell to duality of physical and mathematical descriptions following Ratcliffe's style
 Processell cont from Sydney to work with Detailiffe
 - Bracewell sent from Sydney to work with Ratcliffe

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
 - Nature 158, 339-340 (Aug 1946)



 introduces the use of a Michelson interferometer to measure the angular diameter of the source of the radiation and references Michelson

Cliff Interferometer - 1948 • Bolton, Stanley and Slee – 100MHz Yagi



Loyds mirror



20June2007

SIRO

Nobel Lecture

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 principal to determine the actual distribution by Fourier synthesis using the phase and amplitude at a range of height or wavelength.
- They consider using wavelength as a suitable variable as unwise since the solar bursts are likely to have frequency dependent structure.



They note that getting a range of cliff height is clumsy and suggest a different interference method would be more practical.

McCready, Pawsey & Payne-Scott 1947

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Joe Pawsey

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Ruby Payne-Scott

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





Technology 1940s

- 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



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

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

- Credits McCready et al (1947) for Fourier Synthesis concept
- 1953

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- 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 build the Po
 - 32 steerable paraboloids
 - an SKA path finder
- 1953
 - Chris Cross (Fleurs)
 - Mills cross
- 1967
 - Paul Wild solar heliog
 - Uses J2 synthesis
 - electronic summation o





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



Fourier Transforms - 1953

- Lipson-Beevers strips
 - 25x25 array to 2 digits 1 person in 24 hours
- Punched card tab
 - 25x25 array to 3



Peter Scheuer with Lipson Bee

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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 earth rotation synthesis (1955)

- Chris takes the 1D FT of each strip distribution & does a 2D Fourier synthesis using all strips
 - 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.
- Reference to O'Brian (Cambridge)
- Swarup calculates the Fourier Transforms
 More than 1 month with electronic calculator



9 Dec 2013

The m-wavelength sky: R D Ekers

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



 Problem of correcting weights in back projections

Christiansen and Warburton, Aust J Phys 8, 474 (1955)

The m-wavelength sky: R D Ekers

SOUTH

Computers and signal processing

• 1958

- EDSAC II completed and applied to Fourier inversion problems
- 360 38-point 1D transforms took 15 hours (Blyth)
- Output was contours!
- 1961
 - Jennison had acquired I Fourier transform and p Transform
 - Sandy Weinreb builds t
- 1965

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Cooley & Tukey publis
 the FFT algorithm



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



M. Ryle and Ann C. Neville



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!

Cambridge One-Mile Telescope: 1962







Westerbork: 1970

- Hogbom (Cambridge)
- Christiansen (Sydney)

Benelux cross \rightarrow 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







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."

Nobel Prize (medicine) 1979 Cormack & Hounsfield

- Computer Assisted Tomography (CAT)
- Cormack found a mathematical solution in 1963-1964 based on the Radon transform
- Bracewell & Riddle (1967) [Swarup]
 - introduced a convolution of the strip scan to correct for radial weighting when using image plane back projection method
- Hounsfield solved the technical problems and made the first image in 1972

- With no knowledge of Cormack's work!



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
 - Analogue imaging machine (no digital computer solution)
 - Cant keep this number of cryogenic receivers working
 - No deconvolution
 - No self calibration

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VLA operational 1980

the Green Bank Interferometer 1964

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

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of Papers per Telescope as a Function of Observatory Age



VLA

New Mexico

Deconvolution

- 1962: Moffet using model fitting (OVRO)
 Ekers (Parkes), Fomalont (OVRO)
- 1968: Hogbom does first clean experiments
 - NRAO 3 element data
 - Bad UV coverage
 - First cleaned image published in 1970
 - Rogsstad and Shostak (OVRO HI image)
- 1974

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- Hogbom publishes the CLEAN algorithm
- Ables introduces Max Entropy Method (MEM)
- Idea introduced from geophysics
- Use of deconvolution very controversial in the 1970's
 - Super resolution

Radio Astronomy returns the favour

- Clean v MEM debate rampant in radio astronomy community
- X-ray crystallography needs algorithms to estimate phase
- Ramesh Narayan & Rajaram Nityananda, RRI (1983)
 - The arguments in favour of one or the other form [of entropy] are based on information theory.....verging sometimes on the metaphysical.
 - In our view, the MEM is just a variational way of incorporating our a priori information that the sky consists of sharp peaks on a flat background.
 - The relevance of MEM to crystallography then become obvious.



Proc Indian Acad Sci <u>92</u>, 341-358 (1983)

Self Calibration

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- 1958: Phase and amplitude closure
 - Jennison (Jodrell Bank)
- 1977: Redundant spacing interferometry
 - Hamaker, O'Sullivan, Noordam (Westerbork)
 - Equivalence to adaptive optics
- 1974-79: Phase closure in VLBI imaging
 - Rogers, Yee, Readhead, Cotton....
- 1980: Antenna based calibration
 - Clark, Schwab (VLA)
- 1983: Cornwall: Self cal ≡ phase closure ≡ adaptive optics
 Triple correlation



Nobel Prizes for Indirect Imaging

- 1907 (physics)
 - Michelson optical interferometer
- 1974 (physics)
 - Ryle Aperture Synthesis Radio Telescope
- 1979 (medicine)
 - Cormack & Hounsfield CAT scan
- 1985 (chemistry)
 - Hauptman & Karle structural invariance
- 2003 (medicine)

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Lauterbur & Mansfield - MRI

Mosaicing

• 1975 WSRT

- Needed short spacing for spectral line synthesis
- Difficulty in obtaining adequate single dish data
- Primary beam scanned interferometer invented
 - Ekers & Rots IAU-C49 76, 61 (1979) see Astroph 1212.3311
- 1983-1988 VLA (VTESS)
 - Cornwell explores algorithms for mm arrays
 - Cornwell A&A 202, 316 (1988)
 - MEM joint deconvolution algorithm (VTESS)
- 1990 ATCA (MOSMEM, MOSSDI)

- routine use results from an effective implementation

Lessons to be Learned

- Note the key role played by technology
 - Especially digital computers
- Need to adapt to changing technology
 - Changing on time scales shorter than construction
- Value of interdisciplinary interactions
- Open culture
 - Potential advantage for the astronomy community
 - Medical has complex privacy issues
 - Geophysical exploration very competitive
- Imaging techniques are just as rewarding as the astronomy!