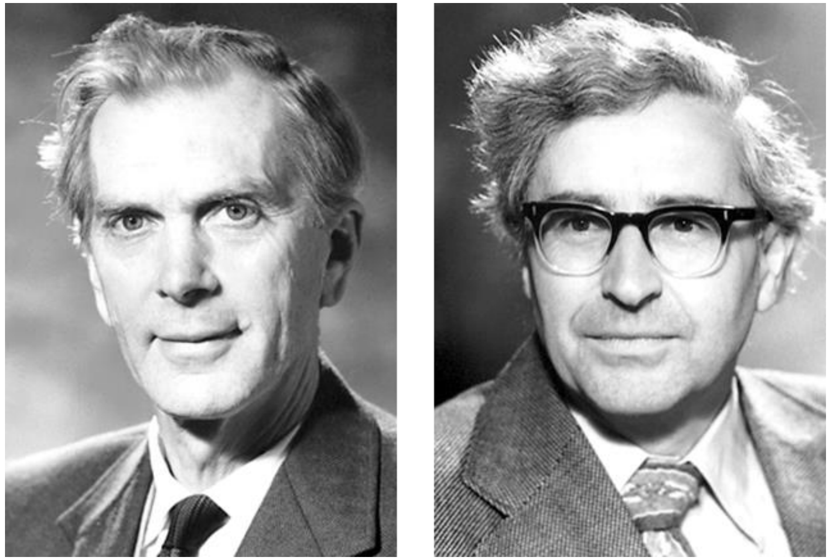
Radio Astrophysics and the Rise of High Energy Astrophysics

Two Anniversaries

- The Centenary of the Birth of Martin Ryle (1918-1984)
- The 50th Anniversary of the Announcement of the Discovery of Pulsars (1968)

The 1974 Nobel Prize

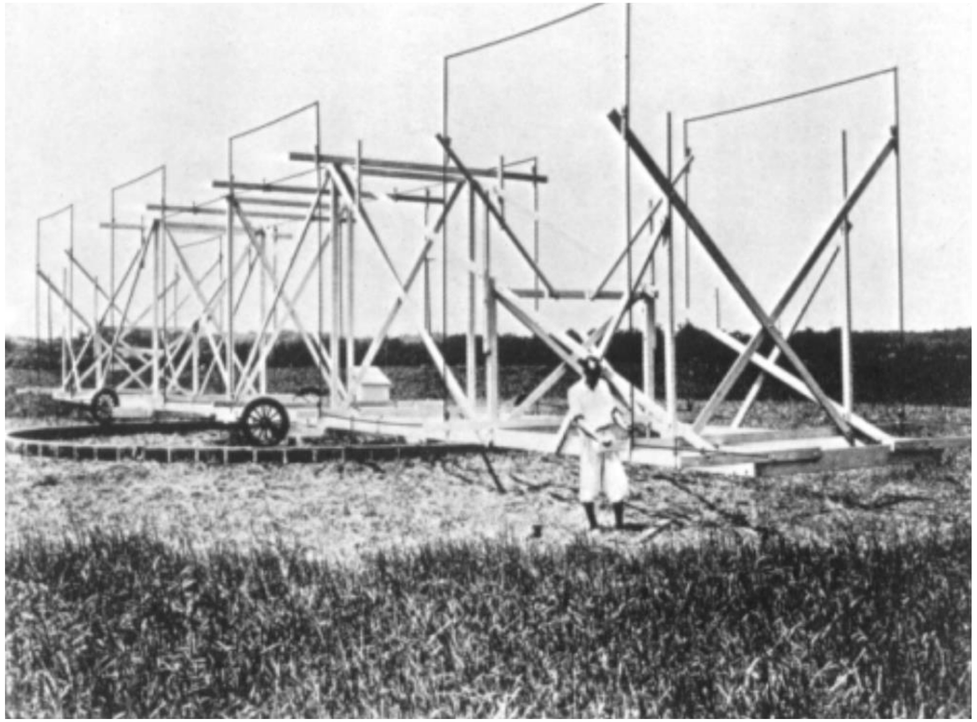
Martin Ryle and Antony Hewish were awarded the first Nobel Prize for Astrophysics in 1974. The citation reads:

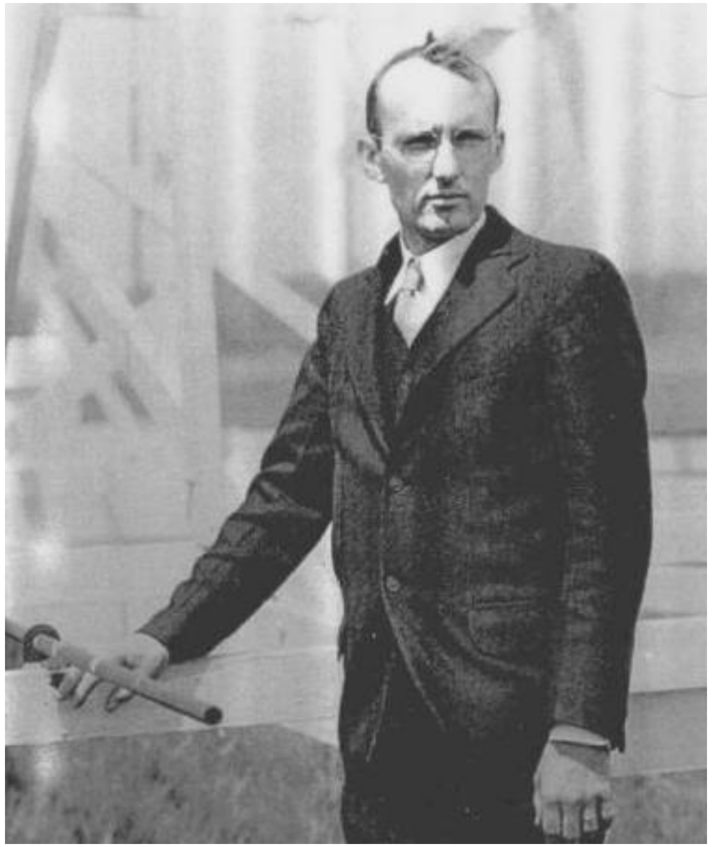


> *"for their pioneering research in radio astrophysics: Ryle for his observations and inventions, in particular of the aperture synthesis technique, and Hewish for his decisive role in the discovery of pulsars"*

Their experimental work was central to the realisation that General Relativity is essential in order to understand High Energy Astrophysical phenomena.

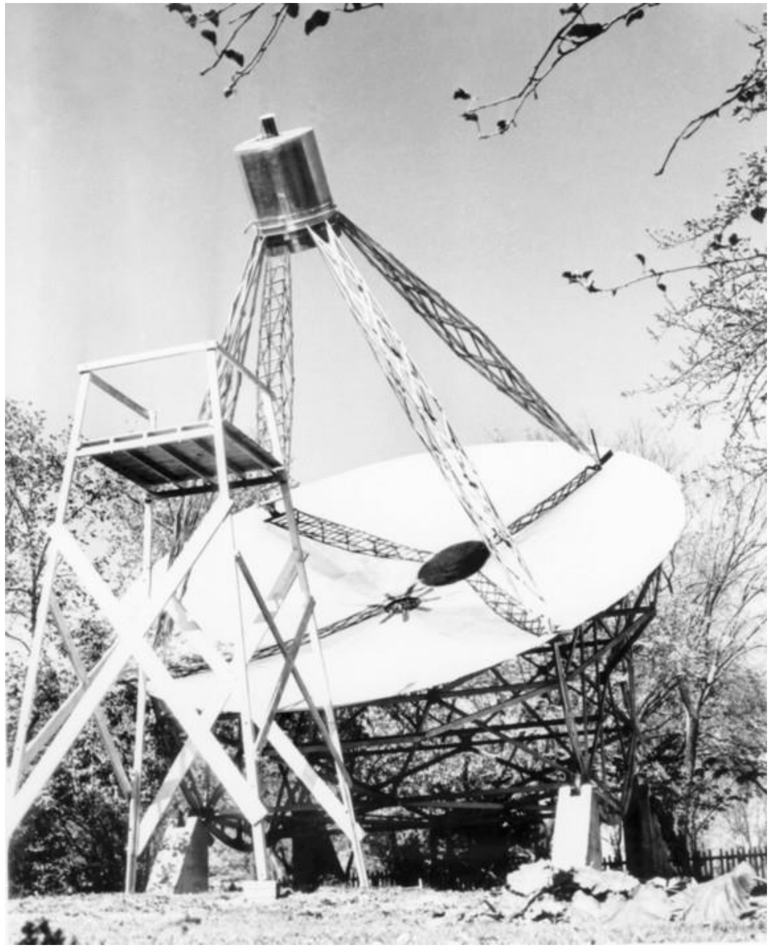
The Origins of Radio Astronomy





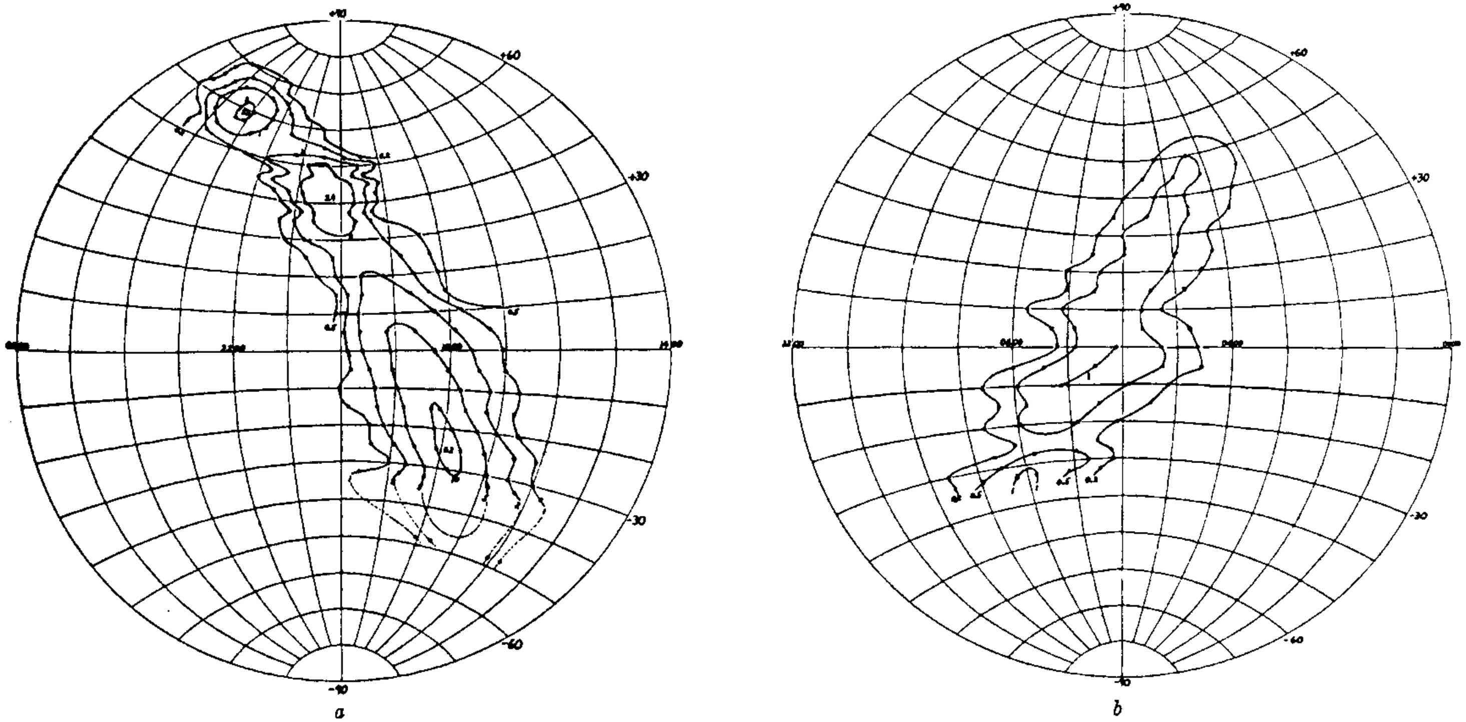
In 1933 radio waves from our Galaxy were discovered by Karl Jansky at the Bell Telephone Laboratories.

Grote Reber



Grote Reber followed up this discovery with his own home-made radio telescope.

The Origins of Radio Astronomy



Radio waves from the Galaxy were mapped by Grote Reber by 1940. Little attention was paid to this work by professional astronomers.

The Origins of Radio Astronomy

After the War, a number of University Groups began to investigate the nature of the cosmic radio emission. The principal groups involved were at Cambridge, Manchester and Sydney.

The Cambridge efforts were led by Martin Ryle who assembled a brilliant team of young physicists to attack these problems.

The Cambridge Radio Astronomy Group in the early 1950s

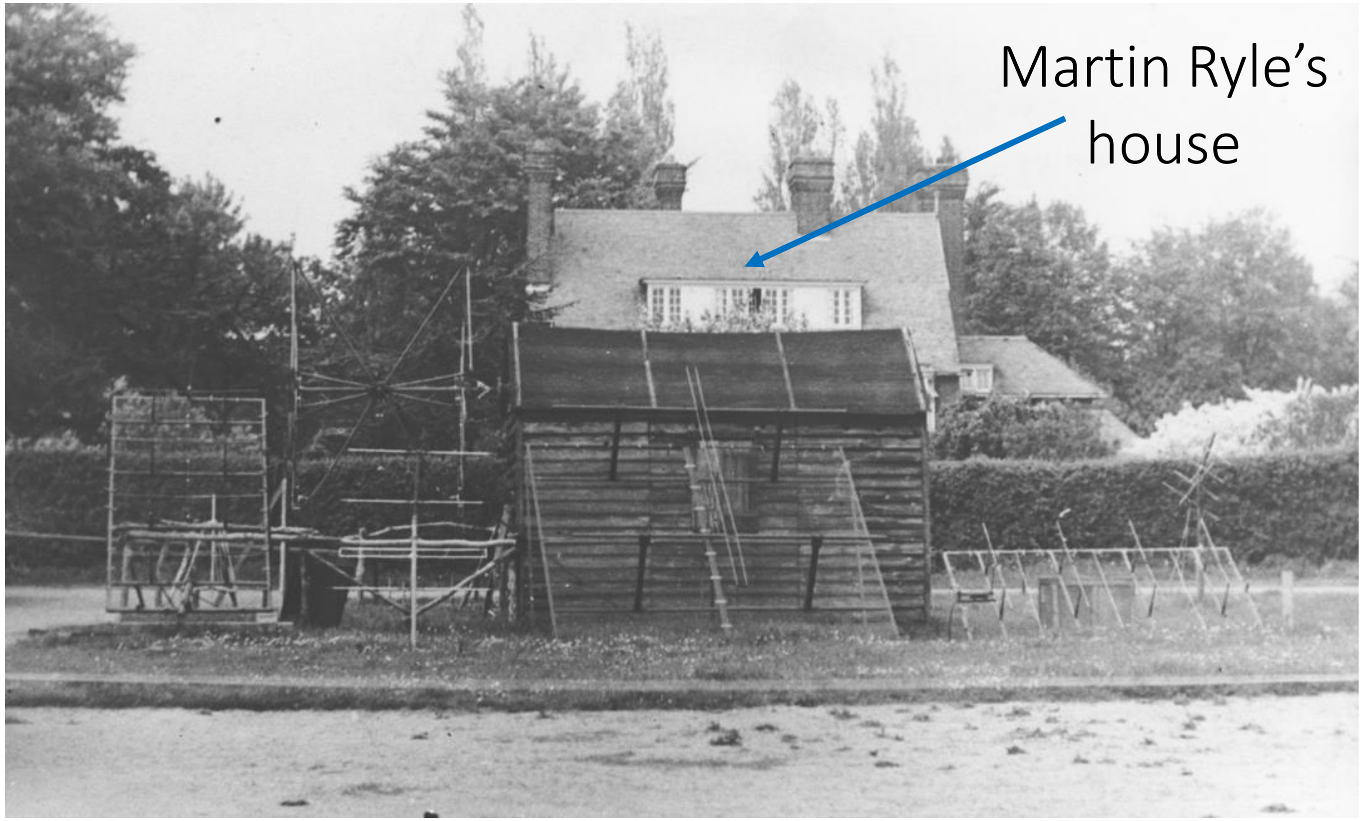
The Challenges

The Group was remarkably tight-knit and everyone contributed to the various technical challenges. Among the major problems were:

- The need to achieve higher angular resolution and sensitivity.
- The need to understand the origin and nature of the ‘twinkling’ or ‘scintillation’ of radio sources.

From the very beginning, Ryle and Hewish worked on both problems.

Radio Observatory at the University Rifle Range


Martin Ryle's house

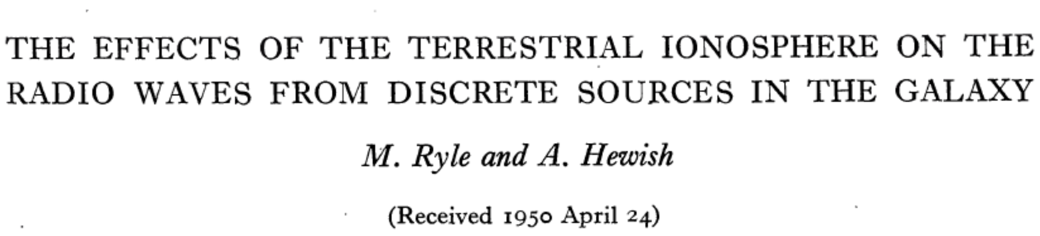
The rifle range was beside the University Rugby Ground. There was no money – everything was built from scrap and German war booty.

1C Survey (1951)

Graham Smith and Martin Ryle
building the 1C aerial

The 1C radio telescope

Ryle and Hewish Papers



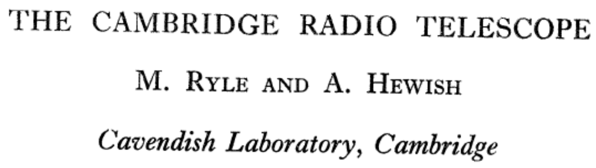
THE EFFECTS OF THE TERRESTRIAL IONOSPHERE ON THE RADIO WAVES FROM DISCRETE SOURCES IN THE GALAXY

M. Ryle and A. Hewish

(Received 1950 April 24)

1950

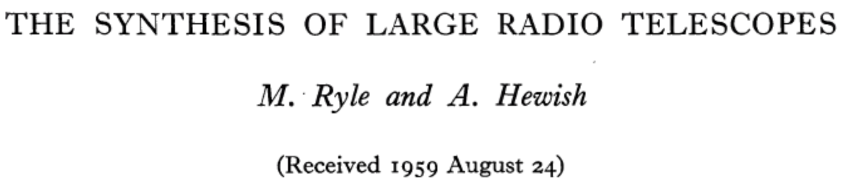
1955



THE CAMBRIDGE RADIO TELESCOPE

M. Ryle and A. Hewish

Cavendish Laboratory, Cambridge



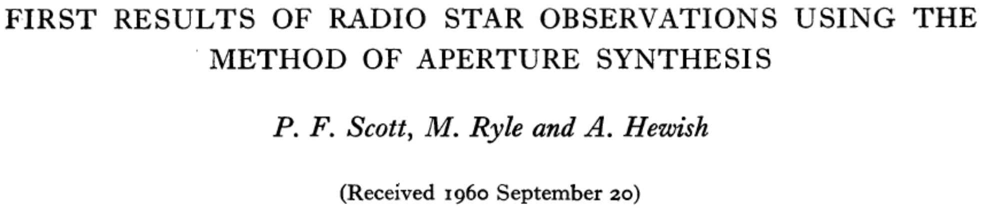
THE SYNTHESIS OF LARGE RADIO TELESCOPES

M. Ryle and A. Hewish

(Received 1959 August 24)

1960

1961



FIRST RESULTS OF RADIO STAR OBSERVATIONS USING THE METHOD OF APERTURE SYNTHESIS

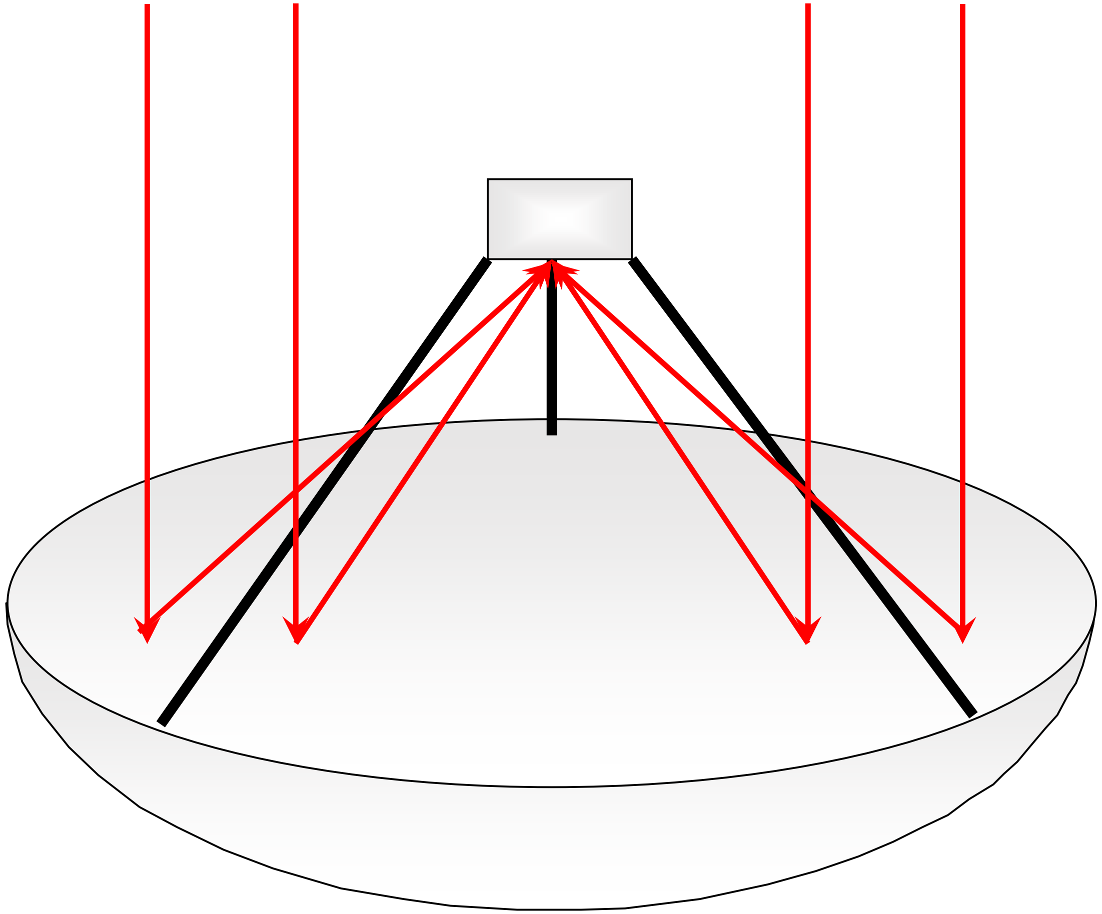
P. F. Scott, M. Ryle and A. Hewish

(Received 1960 September 20)

Martin Ryle and Earth-Rotation Aperture Synthesis

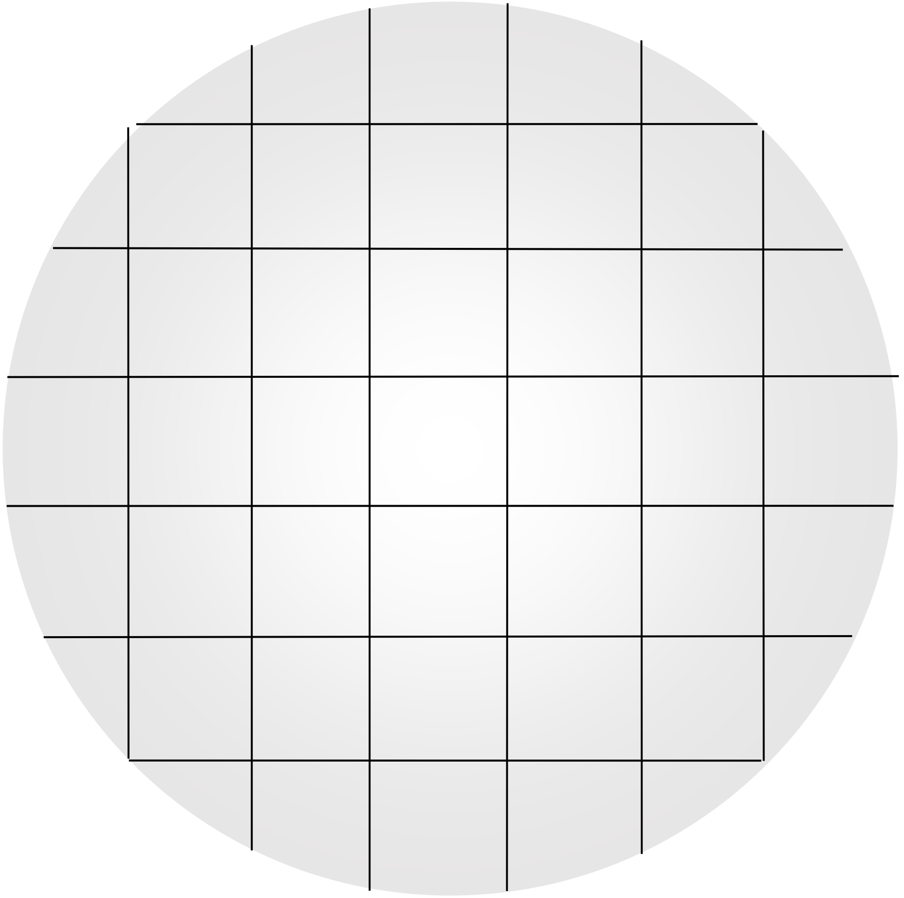
Martin Ryle's contribution of genius was the practical implementation of Earth-rotation aperture synthesis which resulted in high angular resolution and high sensitivity images of the radio sky.

How Telescopes Work



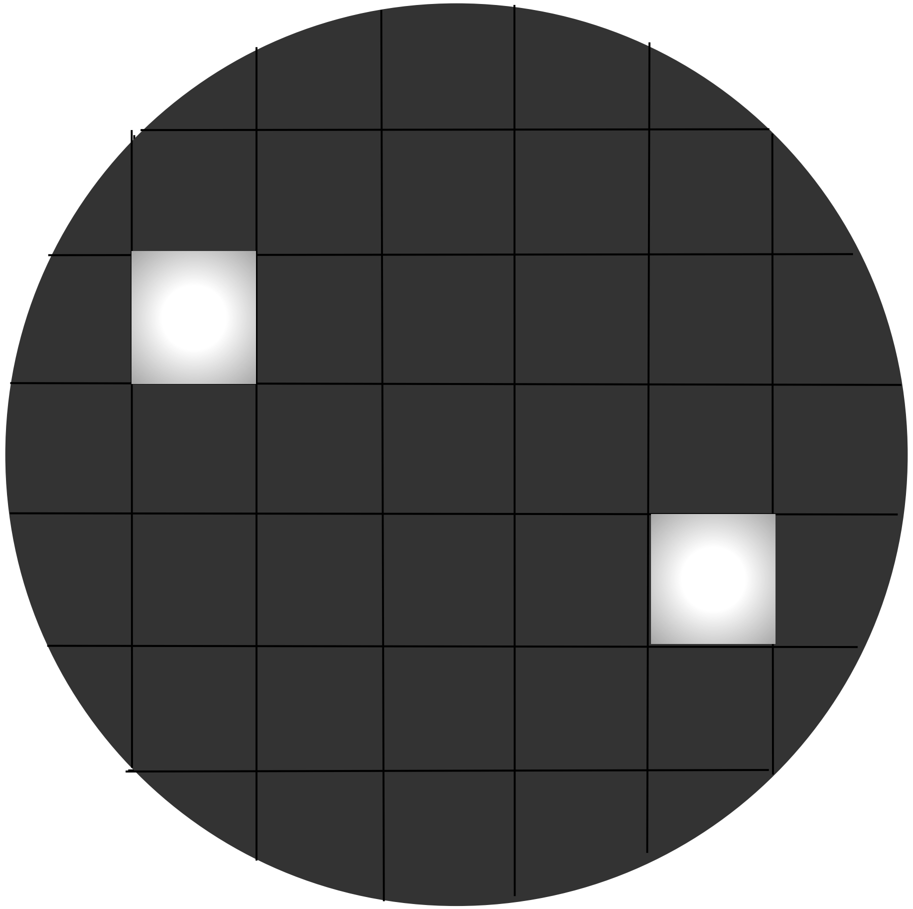
Conventional telescopes reflect the light of a distant object from a parabolic surface to a focus.

How Telescopes Work



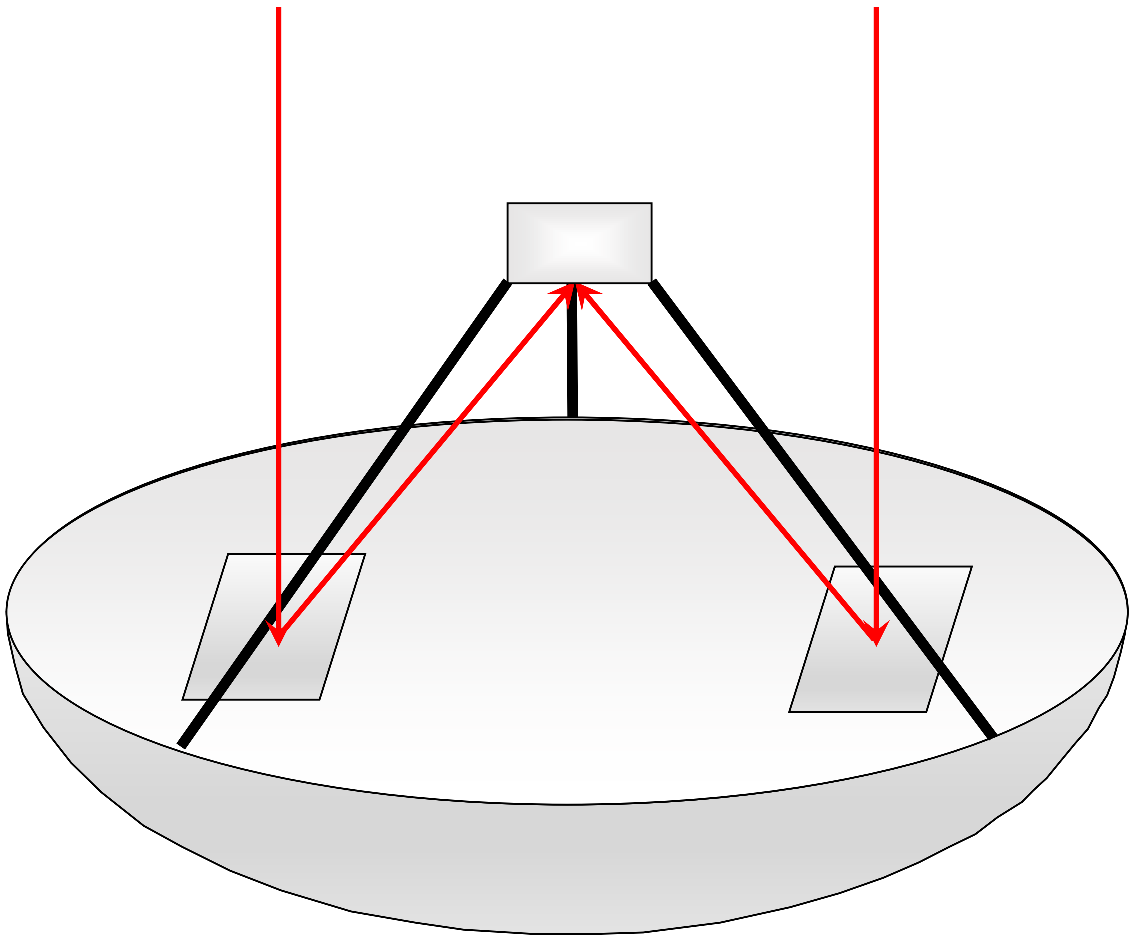
The shape of the surface is designed so that the signals reflected from all parts of the mirror travel the same distance from the distant object to the focus.

A Partially Filled Telescope

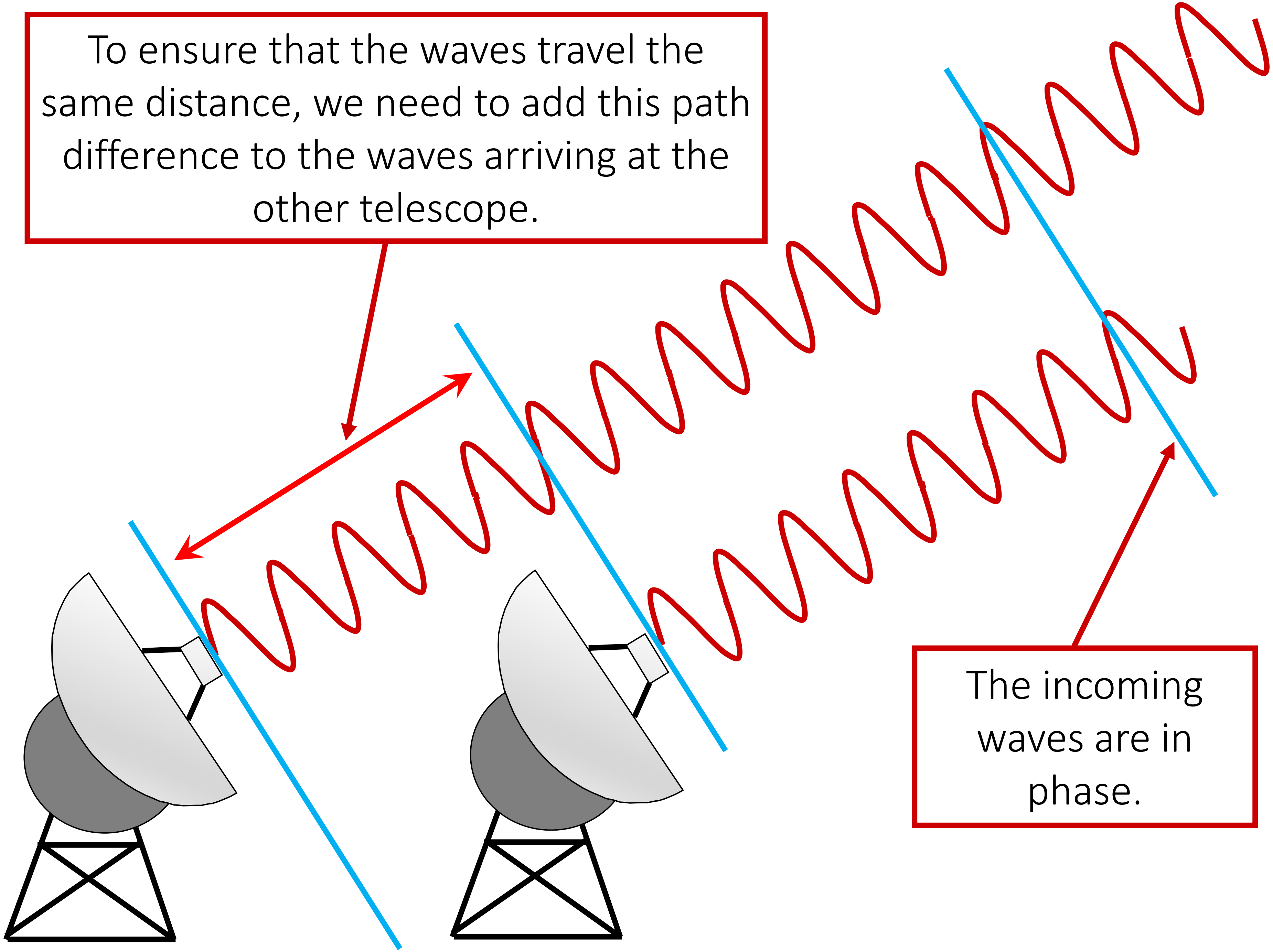


The radio astronomers realised, however, that the reflecting surfaces do not need to be part of the same surface. Suppose we cover up most of the surface of the mirror.

How Telescopes Work

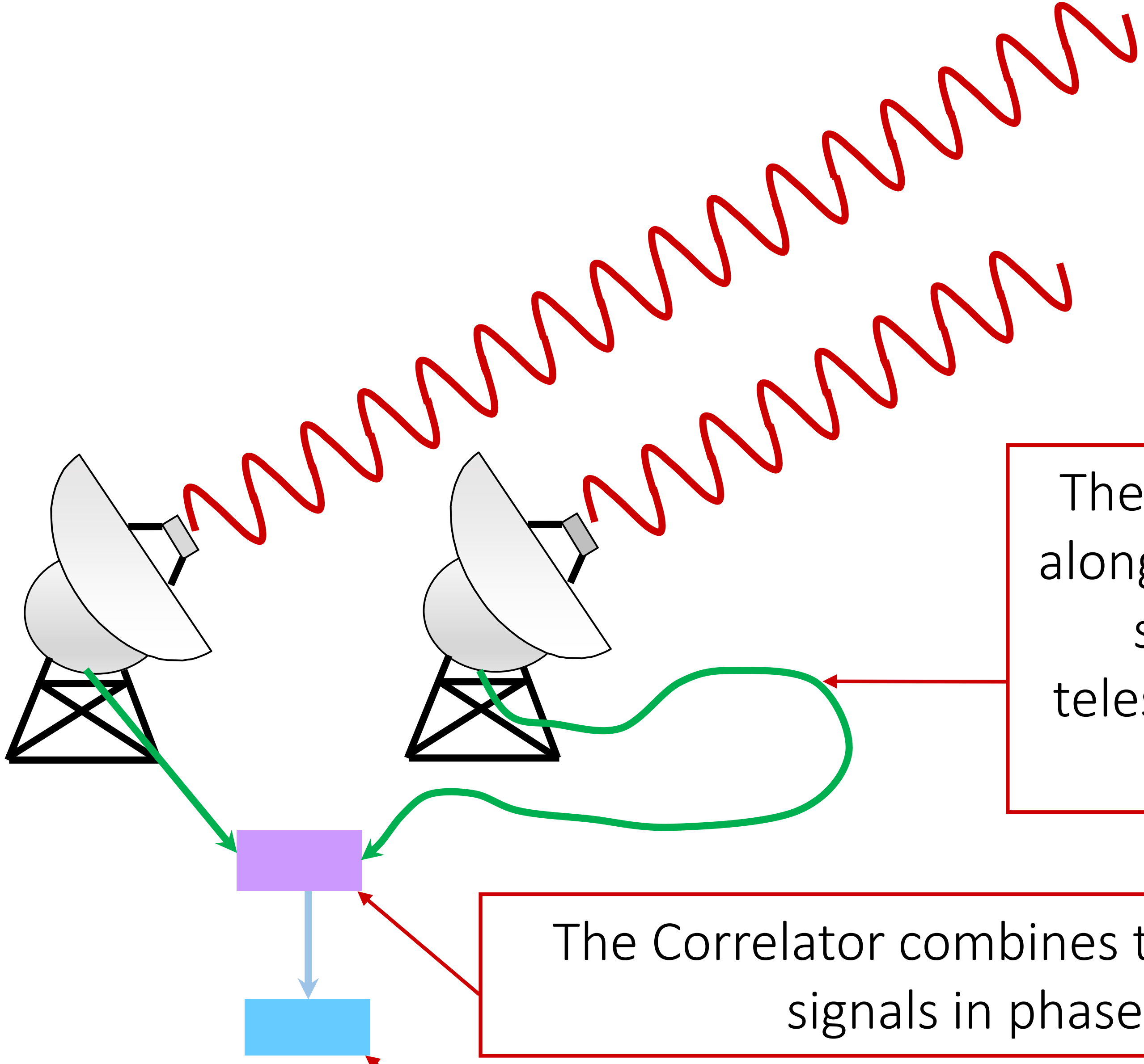


We can still combine the radiation from the uncovered sections to create an image of the distant object, if we arrange the path lengths to the focus to be the same.



To ensure that the waves travel the same distance, we need to add this path difference to the waves arriving at the other telescope.

The incoming waves are in phase.

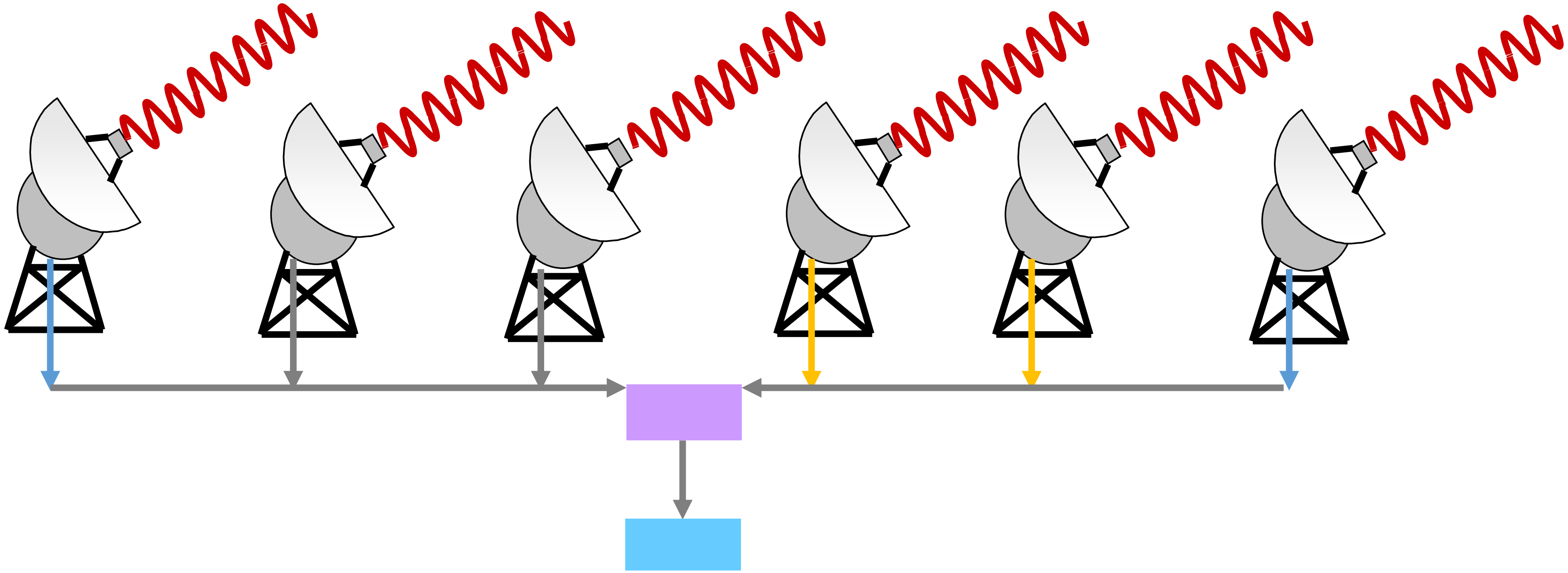


The electrical signals travel along a delay line so that the signals from the two telescopes are combined in phase.

The Correlator combines the electric signals in phase.

Using computers, the image is reconstructed from the correlated signals.

Increasing the number of antennae increases the number of possible pairings of antennae. The more different baselines there are, the more detailed the astronomical image obtained. Short baselines where the antennas are close to each other provide large-scale structure. Long baselines provide the fine detail.



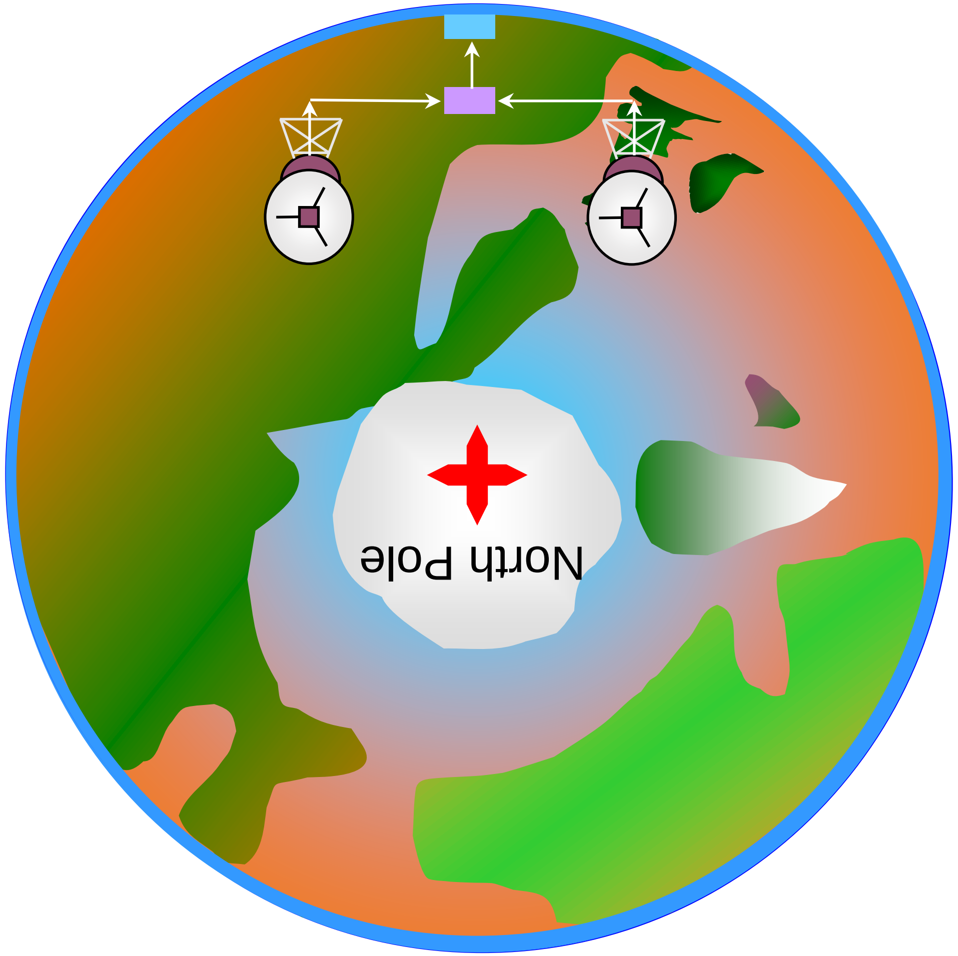
Observation using a 6-antenna interferometer (15 baselines)

Two-dimensional structure

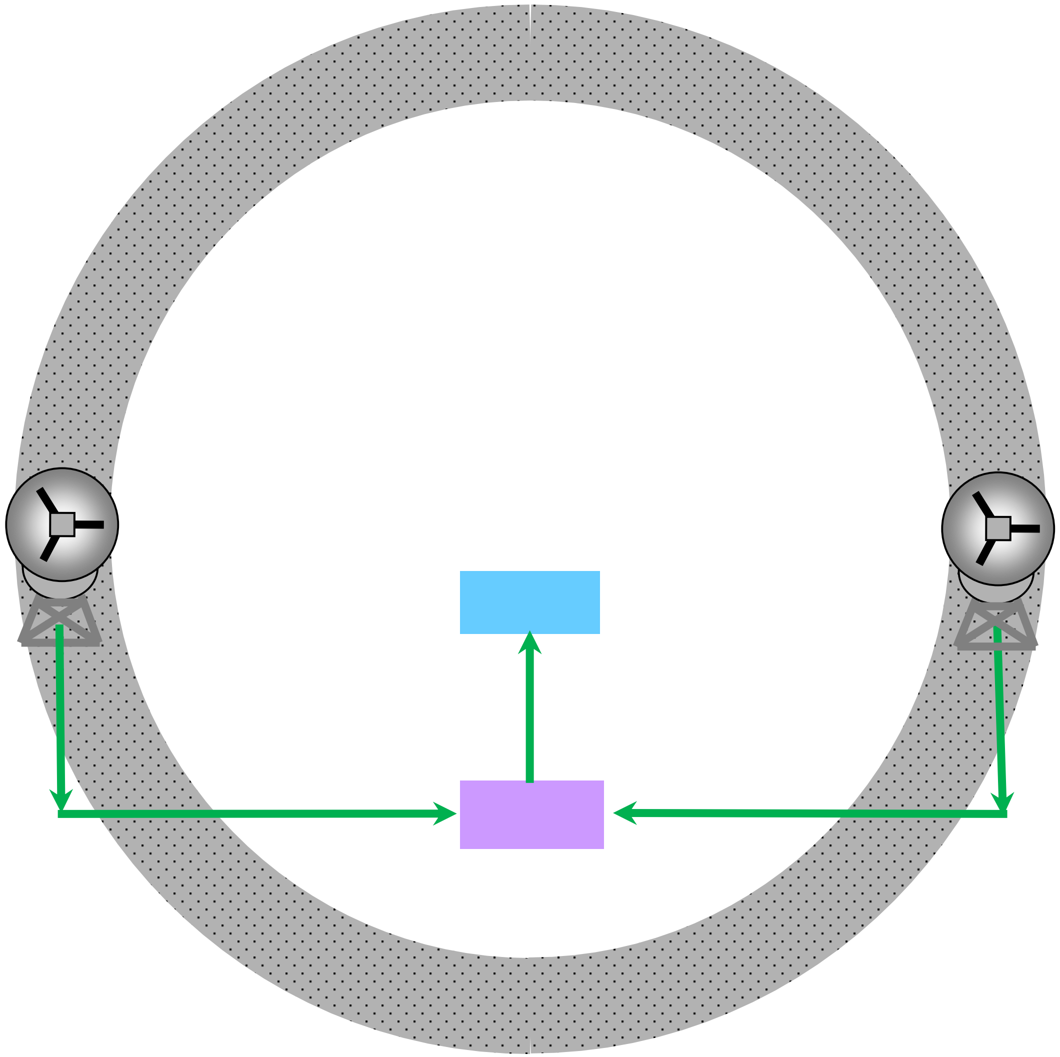
A baseline provides information about the structure of the observed object only in one dimension. Ideally, an interferometer should therefore be made up of many antennas covering a large two dimensional area.

Martin Ryle and his colleagues pioneered the concept that it is simpler to build a 1-D East-West interferometer and to use the Earth's rotation to carry one telescope about another and so obtain information appropriate to the annulus of that diameter.

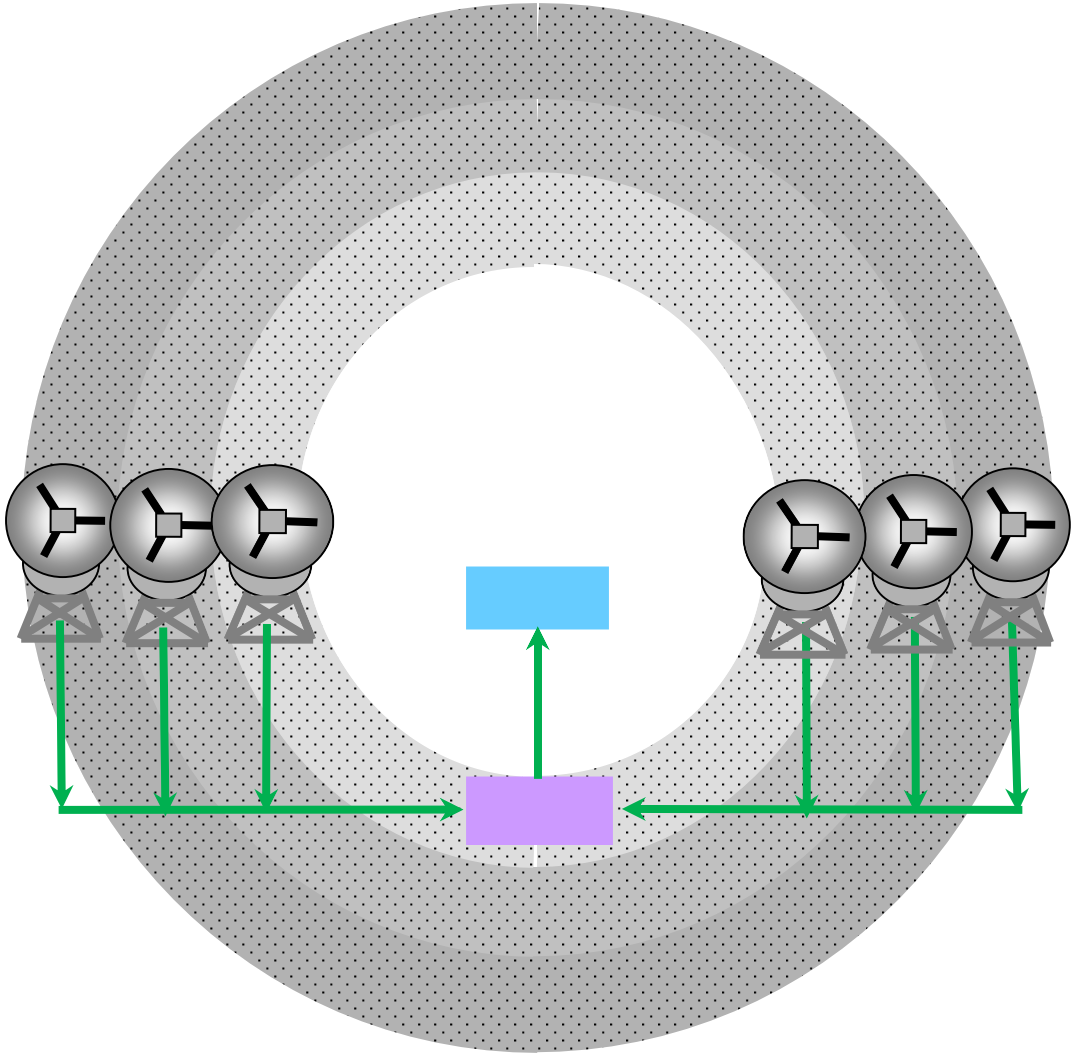
If we observe the Earth from Polaris, the Pole Star, the baseline of a pair of telescopes rotates about the midpoint of the baseline.



Over a 12 hour period, an East-West baseline swings through an 180° angle as seen from the sky.

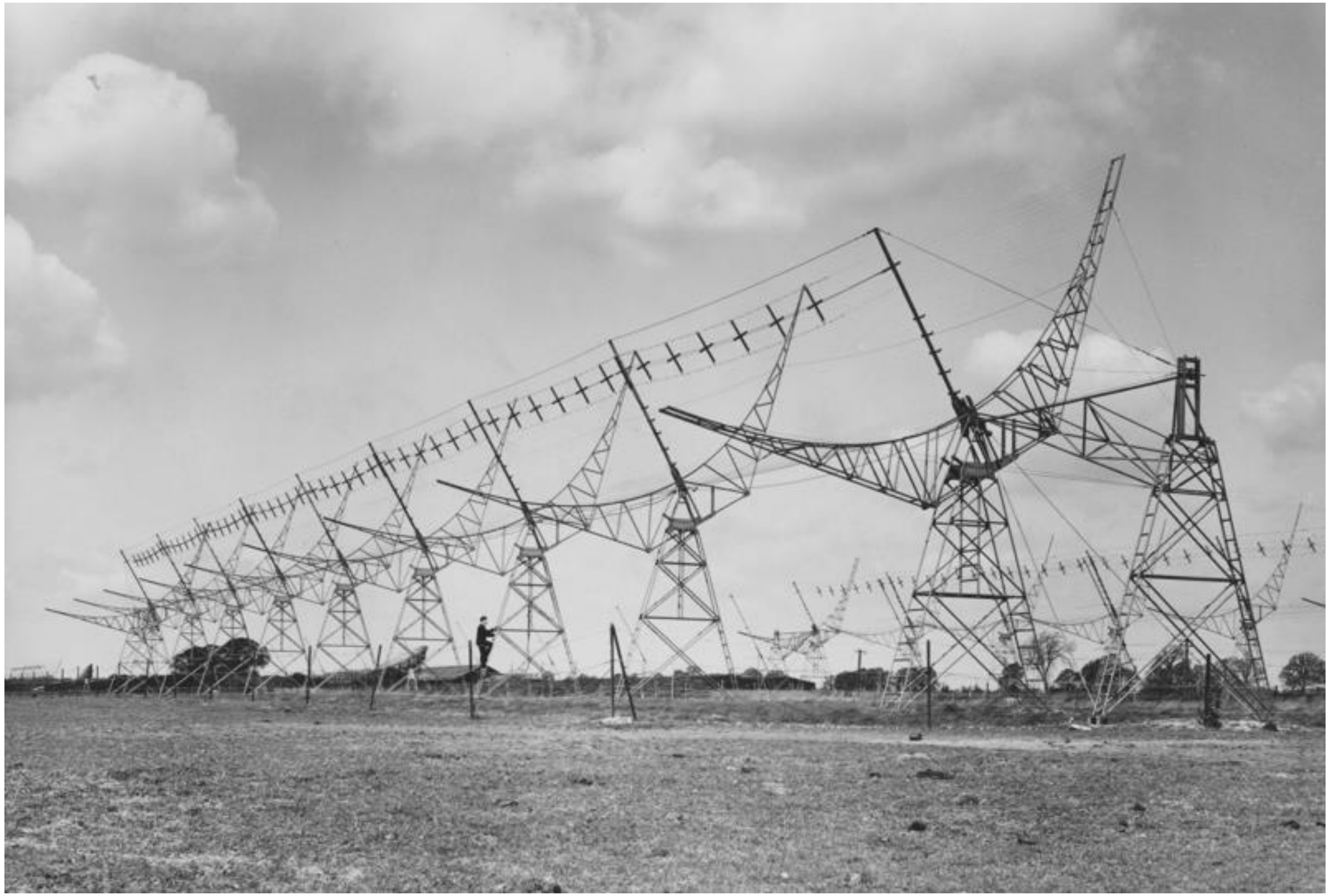


Thus, in 12 hours, the little telescopes sweep out an annulus which contains all the information which would be received by this annulus of a large telescope.



By adding together a number of baselines with different spacings, the equivalent of a single telescope with diameter equal to the longest baseline can be synthesised.

2C Survey (1955)

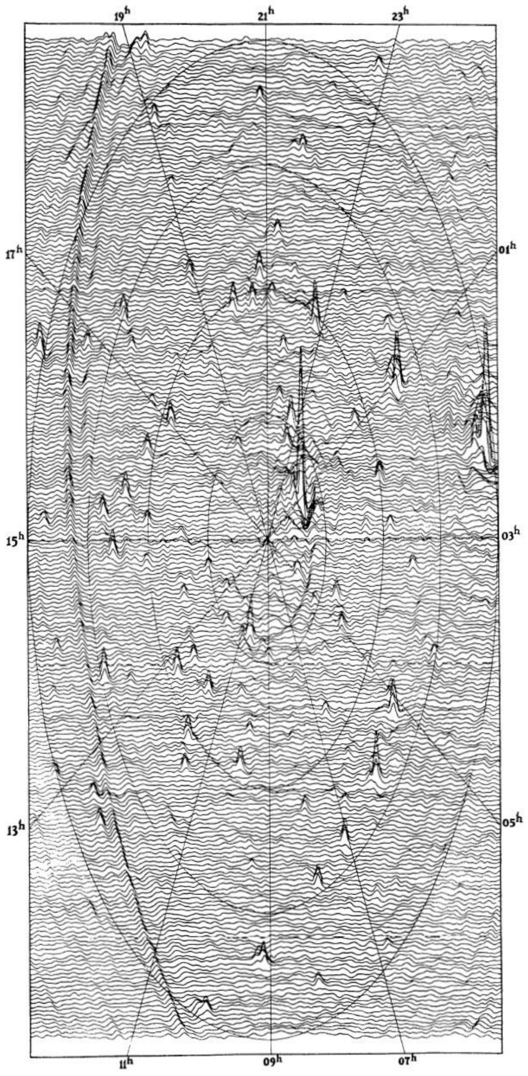


The 2C radio telescope at the Rifle Range site

The 4C Radio Telescope (1959-1967)

The long 4C radio telescope at the Lord's Bridge Observatory

The North Pole Survey of Ryle and Neville (1962)



The first major survey carried out using the full two-dimensional mapping technique by Martin Ryle and Ann Neville demonstrated the remarkable power of the Earth-rotation synthesis technique. Every received in the Observatory was needed to make the observations.

The Technological Challenges

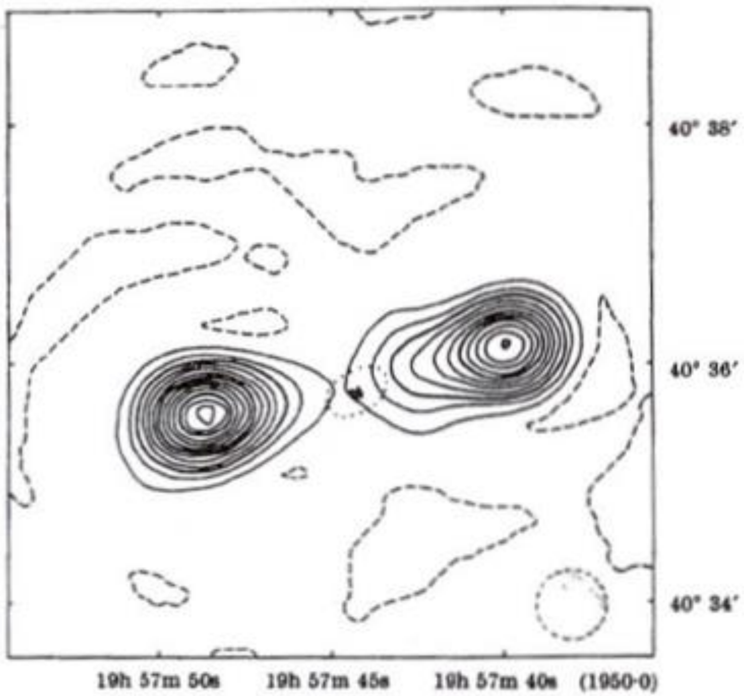
The implementation of fully steerable aperture synthesis radio telescopes required a great deal of innovation in electronics, path compensation and computation.

- Phase-switching receivers.
- Path compensation by switching in different lengths of cable as the telescopes tracked a region of sky.
- Fast reduction of the data to convert the observations into maps – the introduction of Fast Fourier transforms.
- Calibration, elimination of interference, receiver stability, etc.

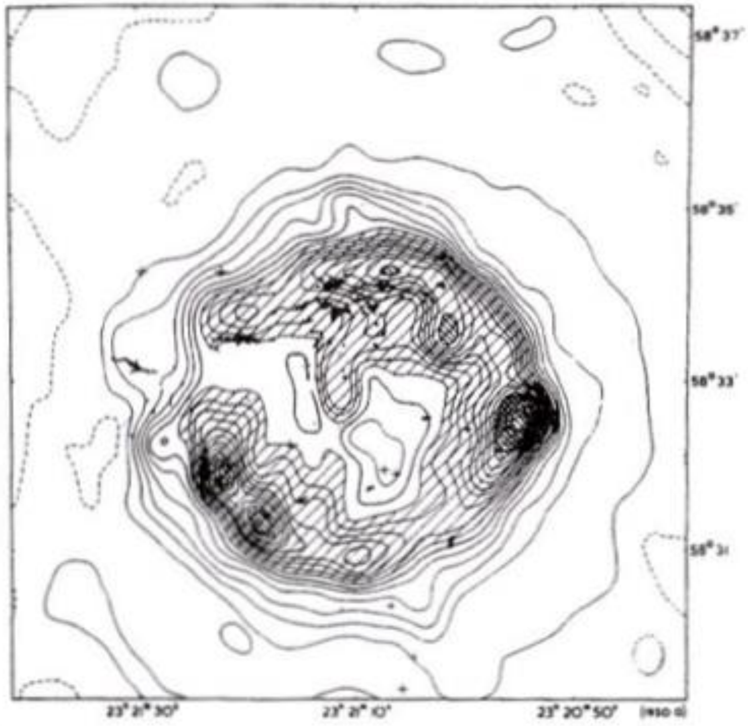
The One-Mile Telescope

The One-Mile Telescope was the world's first fully-steerable Earth-rotation aperture synthesis radio telescope.

First One-Mile Telescope Images (1965)



Cygnus A
Radio Galaxy



Cassiopaeia A
Supernova remnant

The 5-kilometre (Ryle) Telescope

The next step was to extend these techniques to higher frequencies with larger numbers of telescopes – the 5-km radio telescope. This resulted in much higher angular resolution and sensitivity.

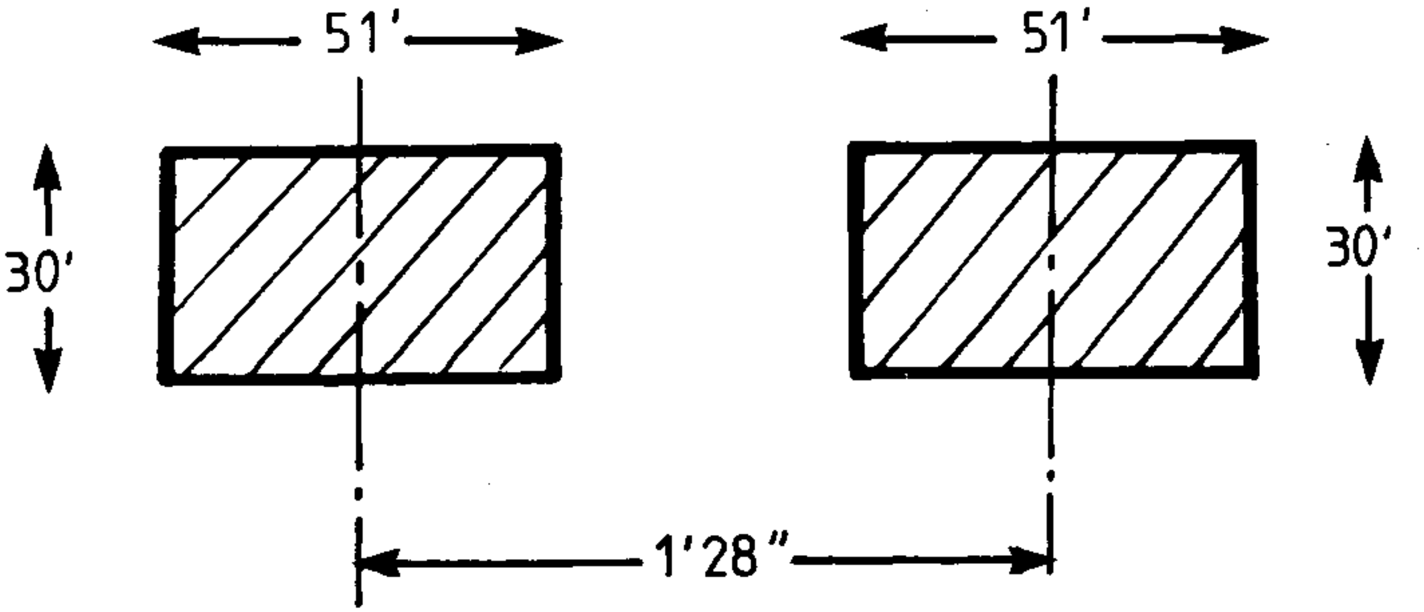
The 5-kilometre (Ryle) Telescope

Over a 25 year period,

- the sensitivity of radio astronomical observations increased by a factor of about one million.

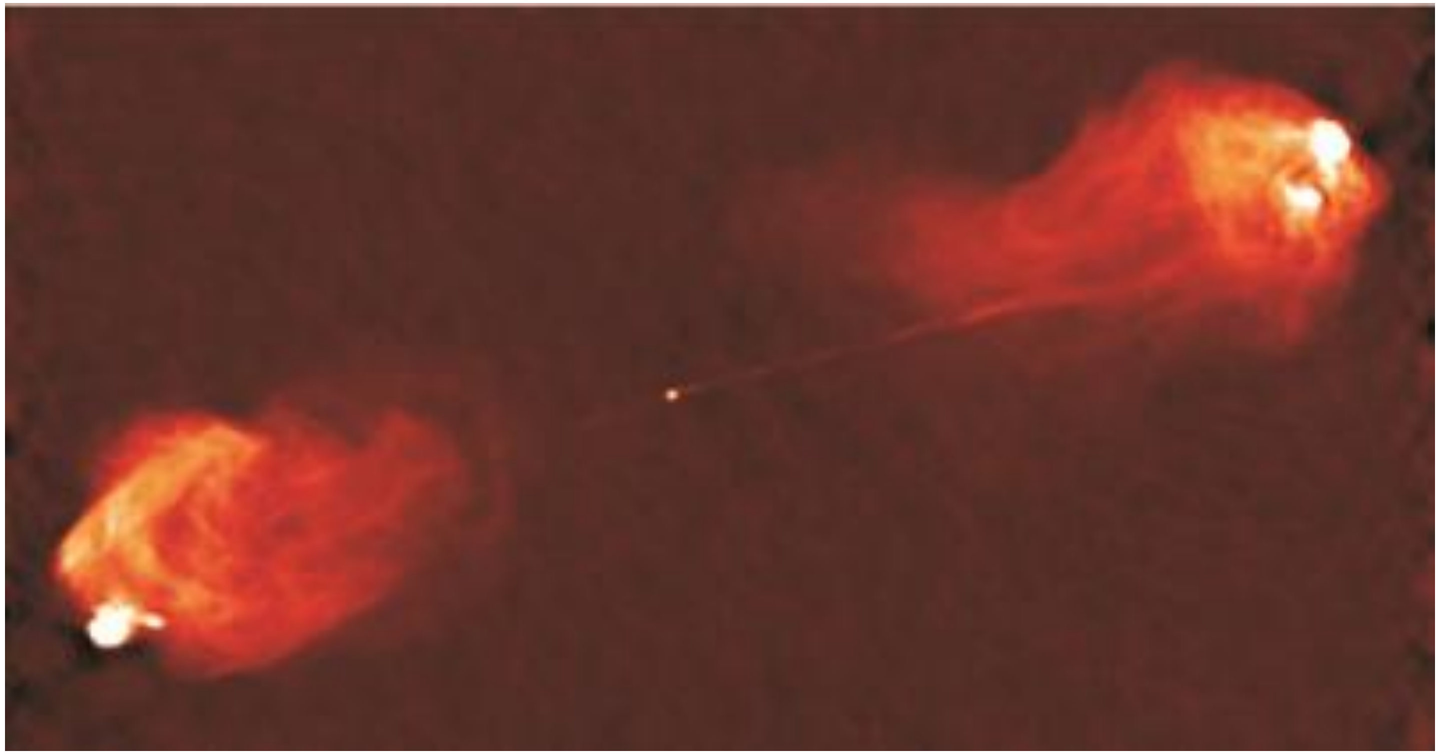
- the imaging capability of the telescope system improved from several degrees to a few arcseconds, comparable to that of ground-based optical telescopes.

The Radio Source Cygnus A



The pioneering intensity interferometric reconstruction of Cygnus A by Jennison and Das Gupta at Jodrell Bank in 1953.

The Radio Source Cygnus A



NRAO-VLA radio image of Cygnus A

The superb imaging by the VLA showed how the radio lobes are powered by jets of high energy particles.

The Impact of Radio Astrophysics

- The discovery of Galactic and extragalactic radio sources revealed the importance of relativistic astrophysics for astrophysics in general.
- Enormous energies in relativistic particles and magnetic fields were needed to account for the radio emission.
- The role of relativistic jets.
- The extreme variability of some of the most luminous sources led to the realisation that supermassive black holes had to be involved.
- Evidence for the cosmological evolution of the populations of radio sources, both radio galaxies and quasars.

Thomas Gold at the banquet of the first Texas Symposium (1963)

At the closing dinner of symposium, Thomas Gold made the remark,

‘Everyone is pleased:

- the relativists who feel they are being appreciated, who are suddenly experts in a field which they hardly knew existed;
- the astrophysicists for having enlarged their domain, their empire by the annexation of another subject - general relativity.’

Aperture Synthesis Radio Telescopes

All radio telescope arrays now use the technique of aperture synthesis.

Ionospheric Scintillation

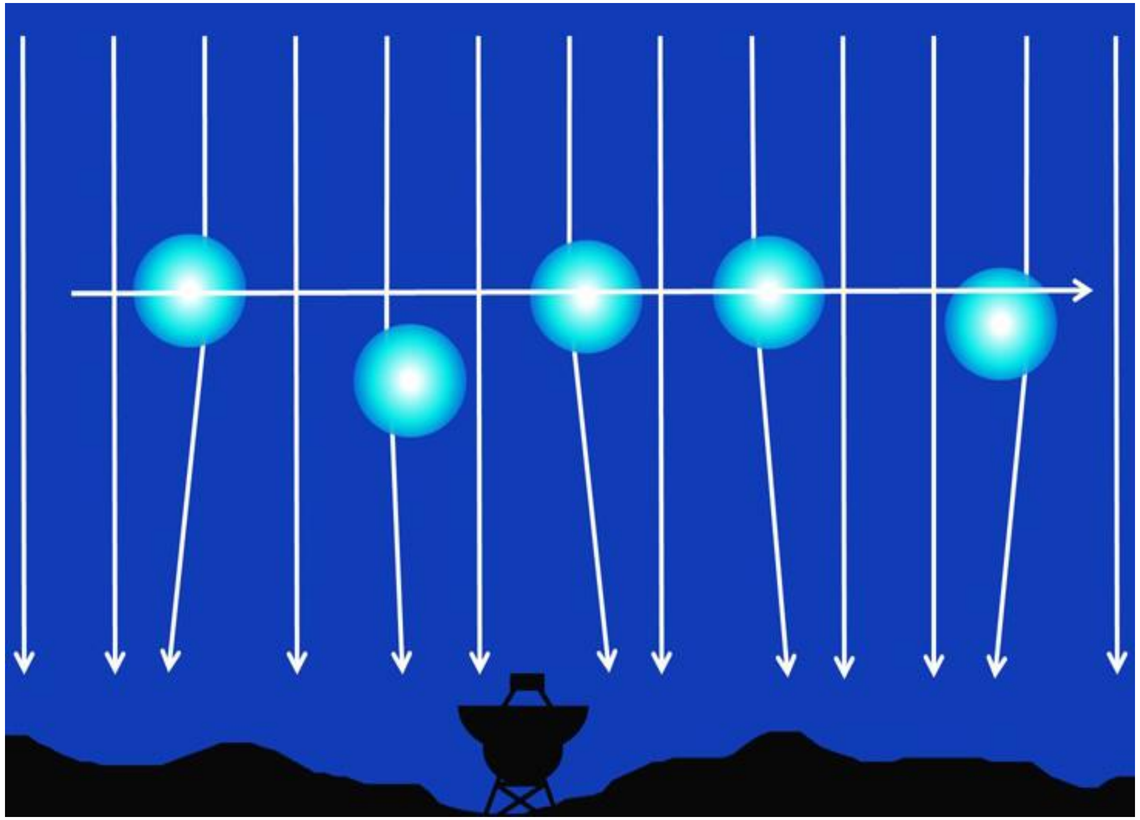
Beginning in 1950, Tony Hewish's research included the understanding of the scintillation of the intensities of radio sources because of irregularities in the intervening plasma clouds. These could be in the ionosphere, the interplanetary or the interstellar media. The theory was worked out in detail by Hewish in 1951 and 1952.

The Diffraction of Radio Waves in Passing through a Phase-Changing Ionosphere. Proc. Roy. Soc., **209**, 81-96, 1951.

The Diffraction of Galactic Radio Waves as a Method of Investigating the Irregular Structure of the Ionosphere. Proc. Roy. Soc., **214**, 494-514, 1952.

Ionospheric Scintillation

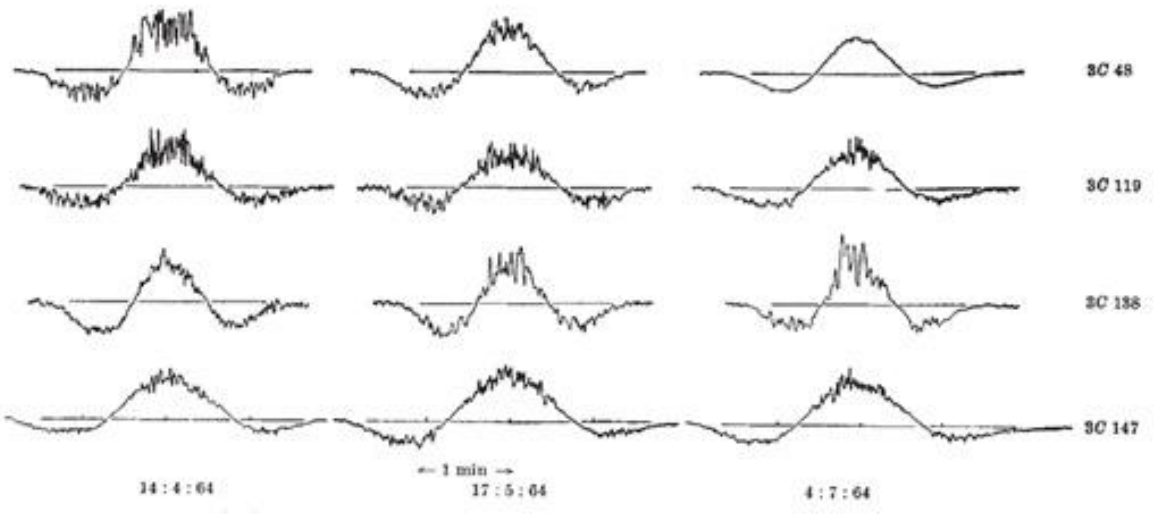
The radio waves are deflected by the plasma irregularities in the ionosphere. The pattern of irregularities moves across the trajectories of the incoming waves, causing the observed intensity of the radiation detected by the radio telescope to fluctuate.



Hewish showed that the ionospheric fluctuations were on a scale of 2 to 10 km at a height of 400 km and moved steadily at 100 to 300 m s^{-1}.

Interplanetary Scintillation

In 1954, Hewish noted that small angular diameter radio sources would display strong scintillations because of plasma irregularities in the interplanetary medium.



In 1964, Hewish, Scott and Wills found these scintillations among the compact 3CR radio sources observed at different solar elongations. They described how these observations could be used to map the outflowing solar wind.

The 4.5-acre (1.8 hectare) array

Hewish realized that a large low-frequency scintillation array would address three important astronomical problems.

- The small diameter radio sources were often quasars and so these objects could be discovered by this means.
- Their angular sizes could be estimated.
- The structure and velocity of the solar wind could be determined.

Hewish was awarded a grant of £17,286 to design and build the 4.5 acre array. The large array would allow fluctuating intensities on the time-scale of one tenth of a second to be determined.

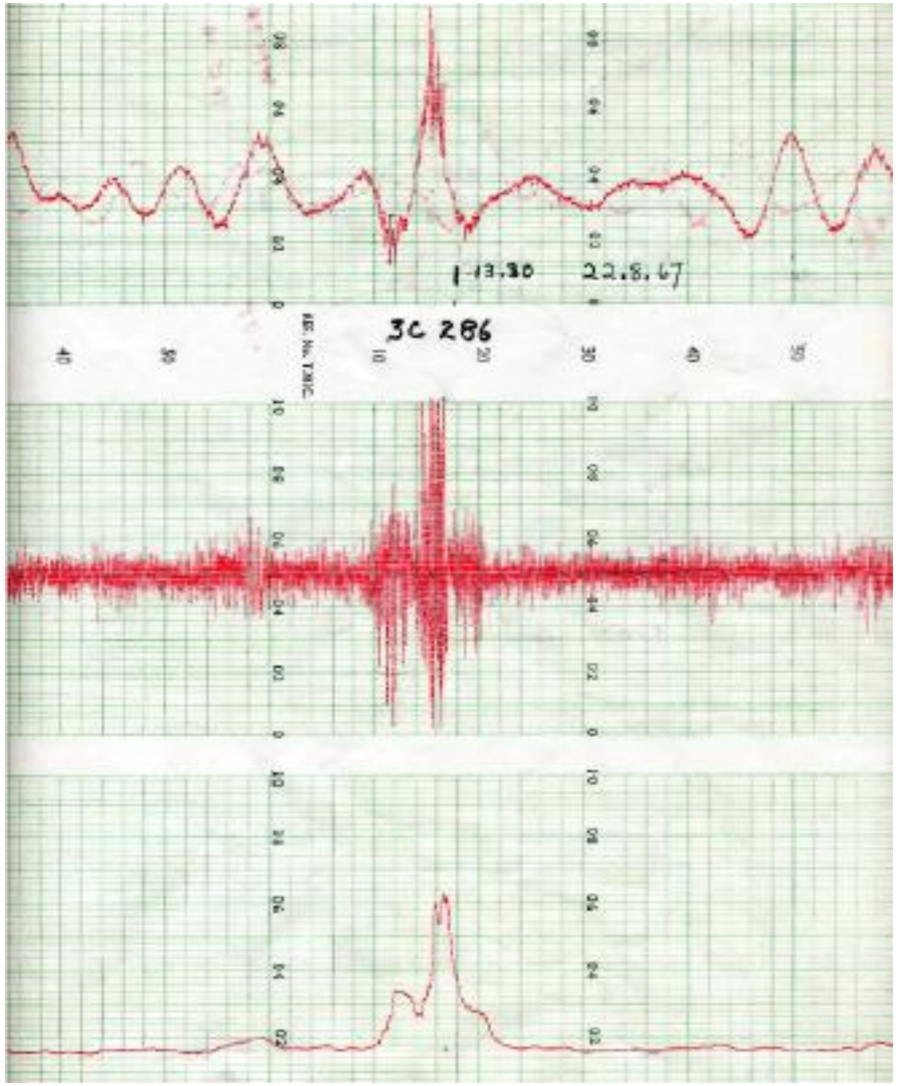
Jocelyn Bell joins the Project

Jocelyn Bell (-Burnell) joined the 4.5 acre array project as a graduate student in October 1965. She was fully involved in the construction of the array, including knocking posts into the ground, and then became responsible for the network of cables connecting the dipoles of the array.

Commissioning the Array

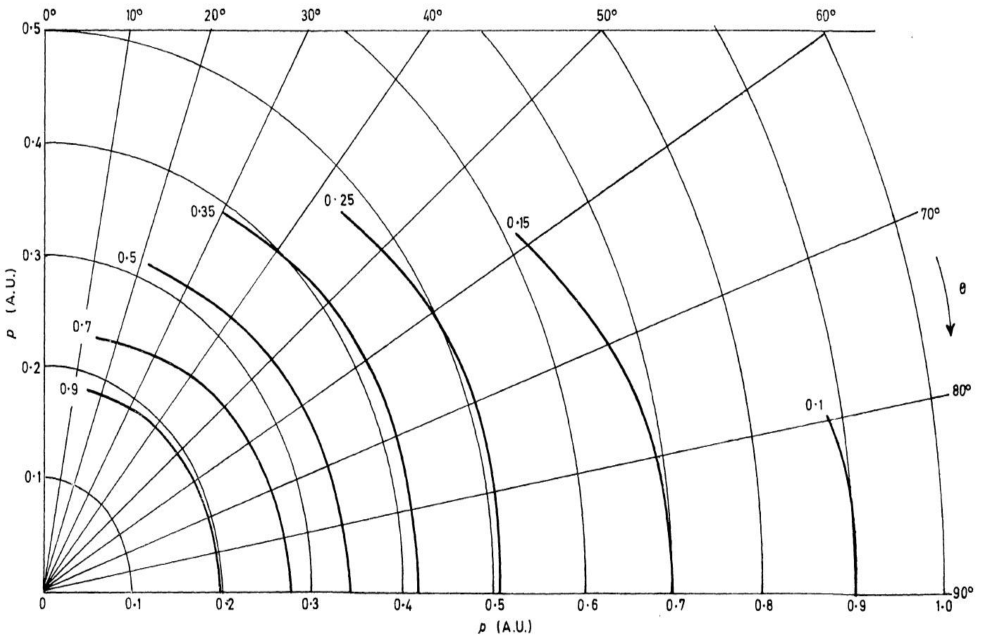
The telescope was commissioned in July 1967 with the objective of mapping the sky once a week so that the variation of scintillation with solar elongation could be studied. A key feature was that the scintillations could be measured in real time.

Real-time evaluation of the scintillation index



Illustrating the scintillation of the compact radio source 3C 286. The strong scintillations can be compared with their absence in the other sources in the trace. The top trace shows the raw data, the middle panel the scintillating component alone and the bottom trace the power in the scintillations.

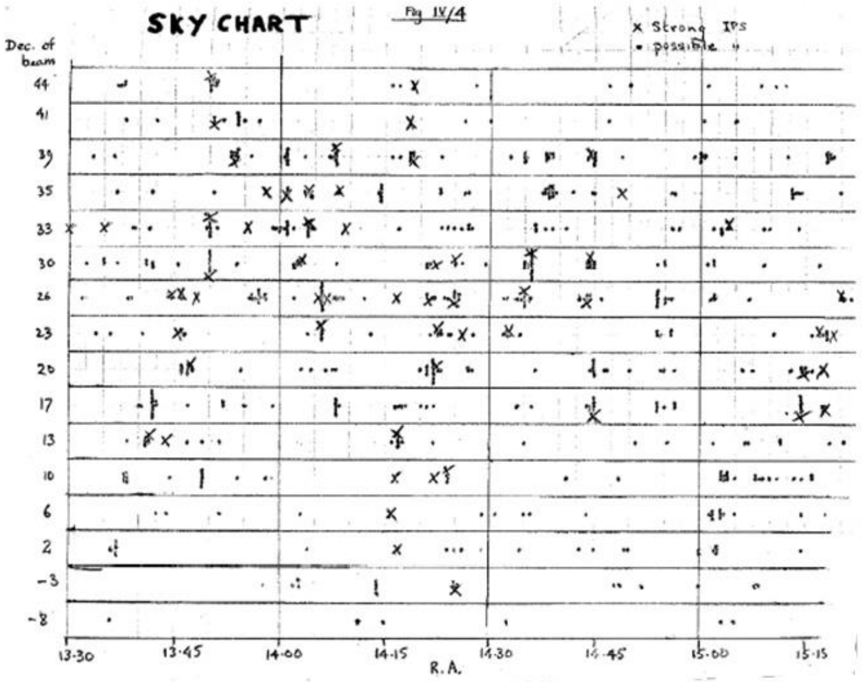
Meanwhile ….



Leslie Little and Hewish worked out a plot showing the magnitude of the scintillations (the scintillation index) as a function of heliocentric coordinates. The Sun is at zero coordinates in the radial direction (abscissa) and perpendicular to the ecliptic plane (ordinate)

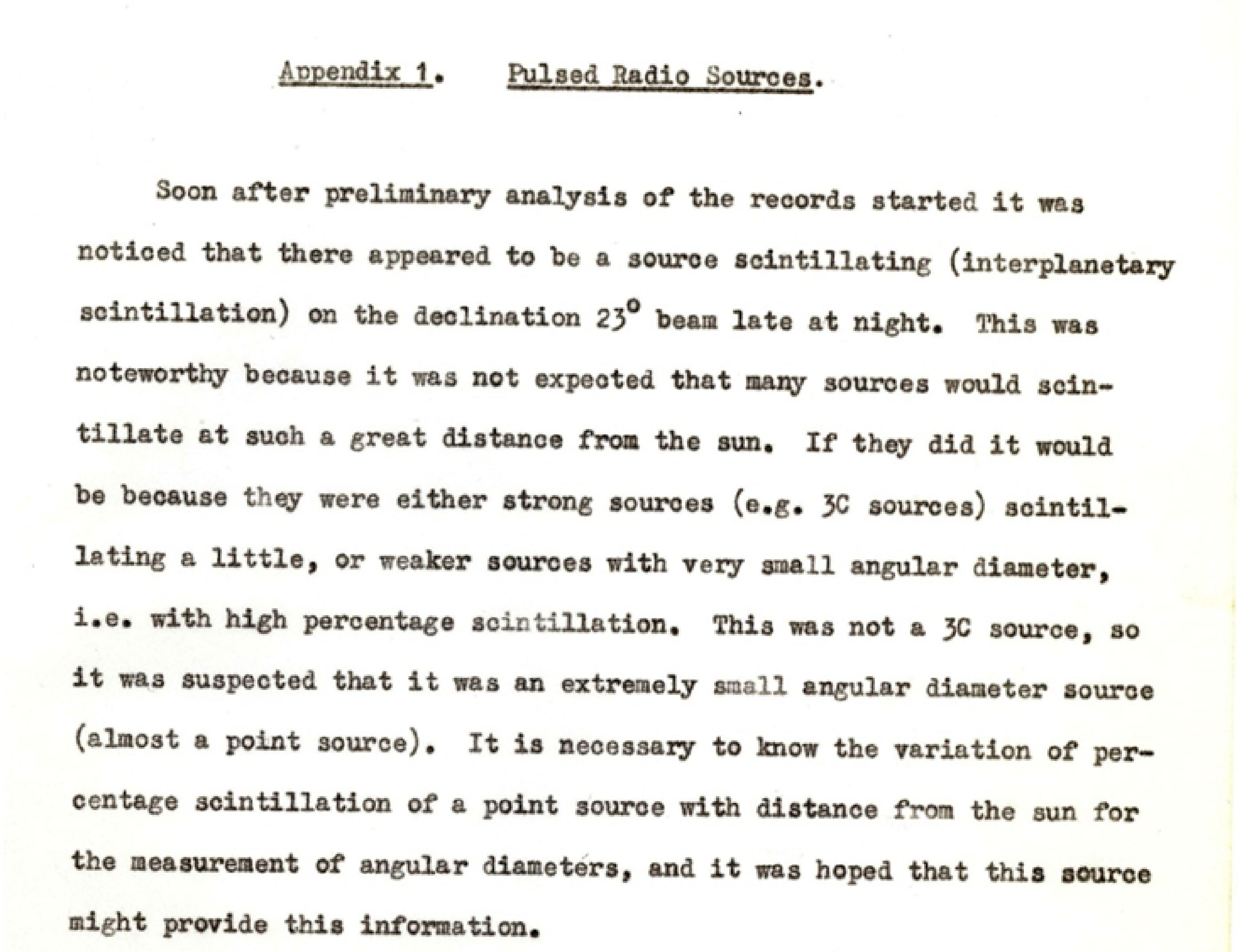
(L.T. Little and A. Hewish, Monthly Notices of the Royal Astronomical Society, ***134****, 221-237, 1966).*

Jocelyn’s sky charts



Hewish suggested that Bell create sky charts for each strip of the sky each day, noting all the scintillating sources. If the scintillating sources were present on successive weeks at the same position, they were likely to be real sources - if they were interference, for example, a tractor, they would not recur at the same astronomical coordinates. This was a very demanding task, meticulously carried out entirely by hand by Jocelyn.

Appendix 1 of Jocelyn Bell's PhD Dissertation

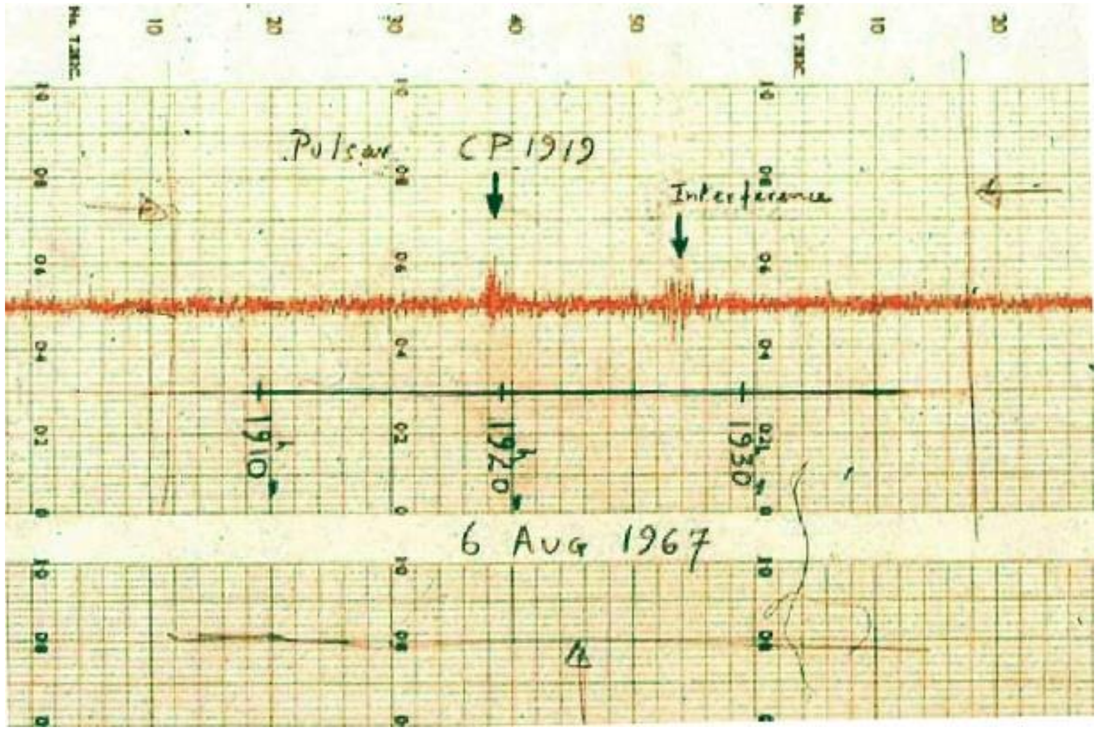


Appendix 1. Pulsed Radio Sources.

Soon after preliminary analysis of the records started it was noticed that there appeared to be a source scintillating (interplanetary scintillation) on the declination 23° beam late at night. This was noteworthy because it was not expected that many sources would scintillate at such a great distance from the sun. If they did it would be because they were either strong sources (e.g. 3C sources) scintillating a little, or weaker sources with very small angular diameter, i.e. with high percentage scintillation. This was not a 3C source, so it was suspected that it was an extremely small angular diameter source (almost a point source). It is necessary to know the variation of percentage scintillation of a point source with distance from the sun for the measurement of angular diameters, and it was hoped that this source might provide this information.

The discovery of pulsar CP1919 was made by Jocelyn on 6 August 1967. The story of its discovery is told in the short two-page Appendix 1 of her PhD dissertation.

Discovery of pulsars

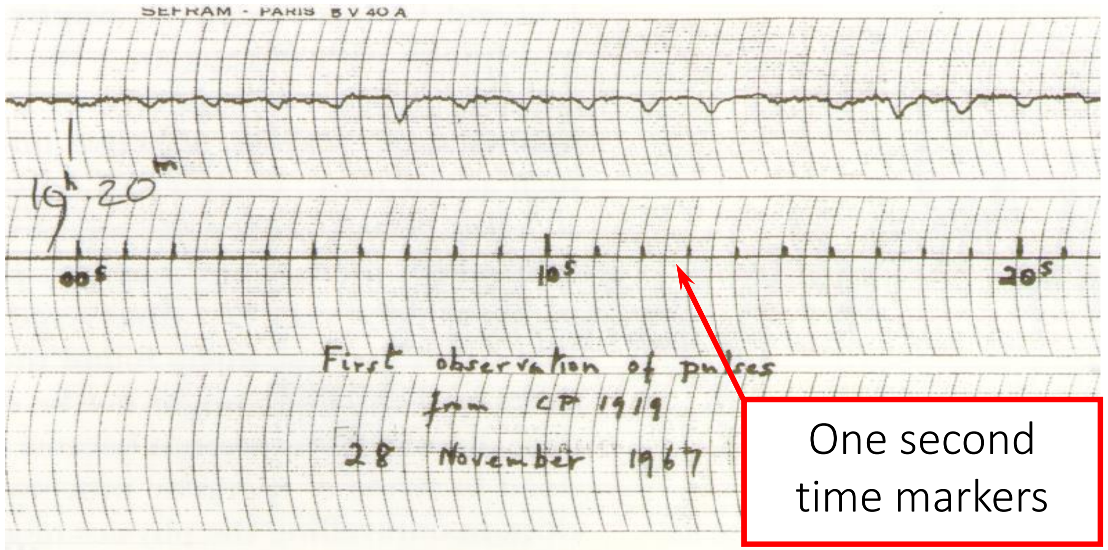


The remarkable feature of the strange source was that it scintillated at roughly the 100% level in the anti-solar direction, quite contrary to the scintillation models of Little and Hewish. The source was highly variable and not always present.

Discovery of pulsars

Jocelyn Bell (-Burnell) with the discovery records of the first pulsar to be discovered PSR 1919.

The pulses detected separately for the first time



One second time markers

The source was not observed again until 28 November 1967, now with a much shorter time-constant in the receiver system. The pulses were detected separately for the first time. The signal consisted entirely of pulses with period 1.33 sec and stable to better than one part in 10^6.

The Analysis

The following two months were what Hewish described as the most exciting of his scientific career. Nothing like this had been observed in astronomy before and they had to be absolutely certain of the correctness of the observations:

- All sources of terrestrial inference had to be excluded.
- If the source were associated with extra-terrestrial emissions, including the notorious “Little Green Men (LGM)”, the motion of a planet about the parent star would be easily detectable. The motion of the Earth about the Sun was observed, but no orbital motion of the source.

The Analysis

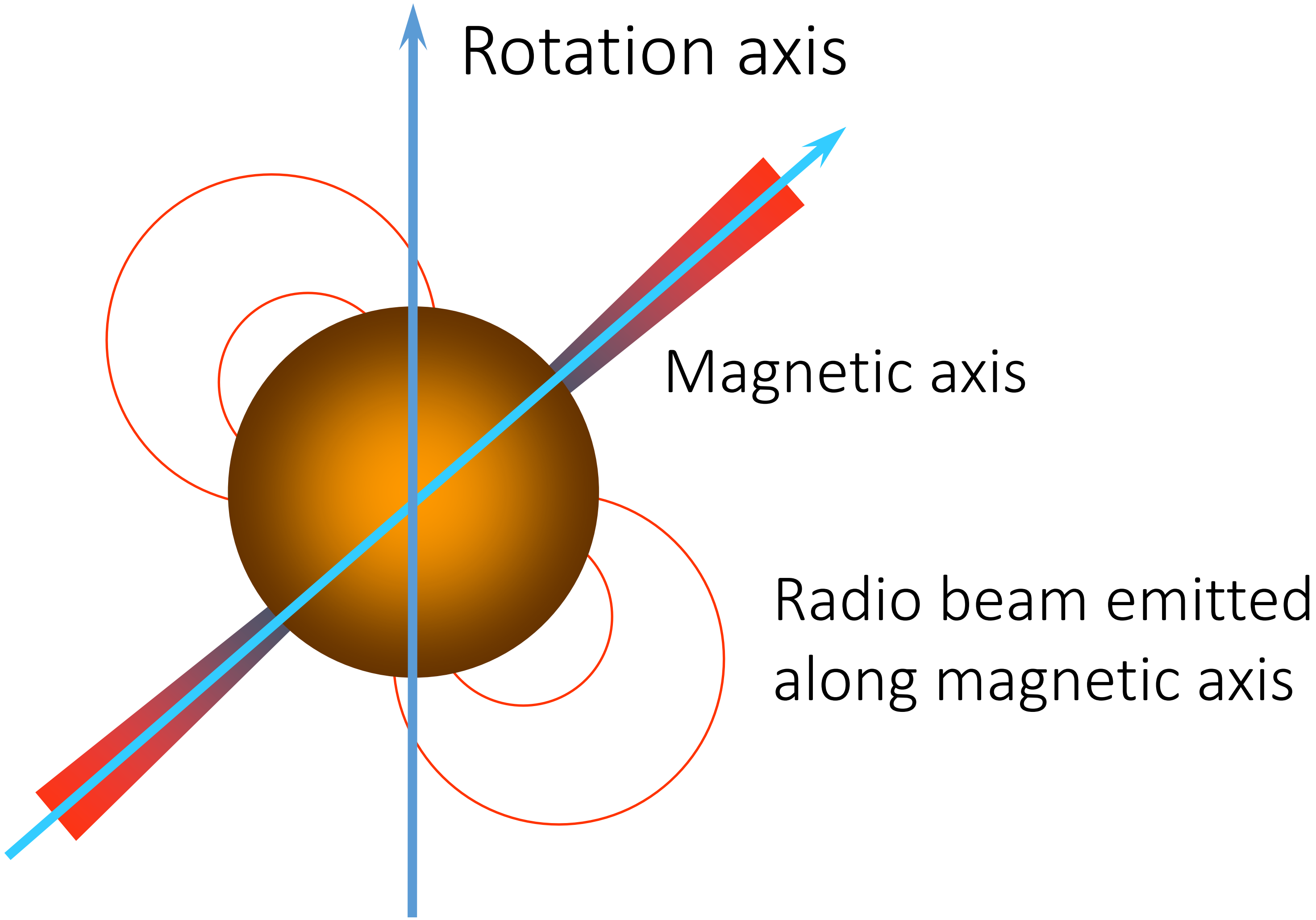
- The low frequency signals displayed dispersion, the high frequency signals arriving earlier than the low frequencies. This enabled a rough distance of 65 pc (about 200 light years) to be estimated for the source.
- Three other similar sources were discovered by Bell including one with a period of only 0.25 seconds.

The discovery was kept under tight wraps. I was in the next door office to Hewish at the time and I knew nothing about what was going on until he gave a lecture about the discovery in the week before the *Nature* paper was published.

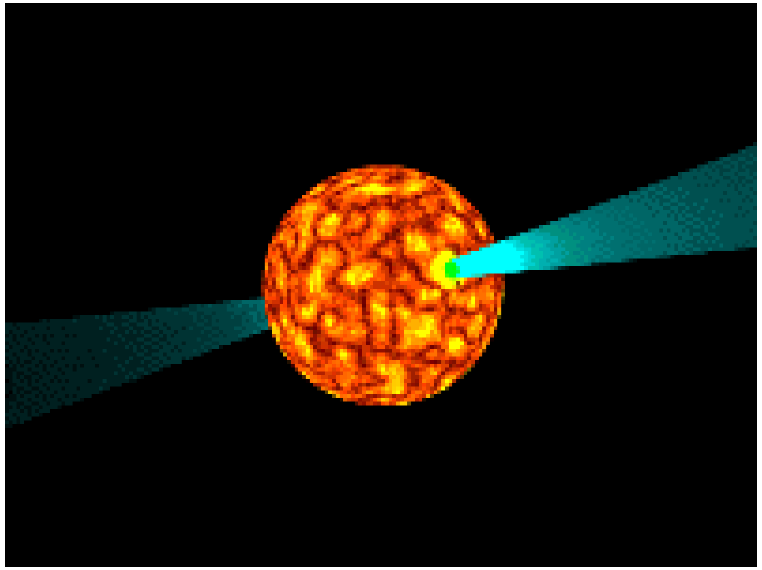
(A. Hewish, S.J. Bell, J.D.H. Pilkington, P.F. Scott and R.A. Collins, Nature, ***217****, 709-13, 1968).*

Pulsars as magnetised, rotating neutron stars

Within a few months, Thomas Gold convincingly identified the pulsars with magnetized, rotating neutron stars.



The Origin of the Pulses



The radio pulses are caused by beams of very high energy particles escaping from the poles of the magnetised rotating neutron.

The Rest is History

- Very soon after their discovery, large numbers of pulsars were discovered.
- Neutron stars were discovered in binary X-ray sources in 1972 by the UHURU X-ray Observatory.
- In 1975, Hulse and Taylor discovered the close binary neutron star pair PSR 1913+16, providing precision tests of General Relativity and the acceleration of their orbits due to gravitational radiation.

Epilogue

- Martin Ryle ceased to be involved in radio astrophysics after the completion of the 5-km telescope. His interests changed to wind energy and opposing nuclear energy and nuclear weapons.
- Tony Hewish continued the expansion of the array and used the scintillation technique to study ‘interplanetary weather’.
- Jocelyn Bell remains a distinguished member of the UK science community. In June 2007, she was created Dame Jocelyn Bell-Burnell. She has been President of the UK Institute of Physics and President of the Royal Society of Edinburgh.