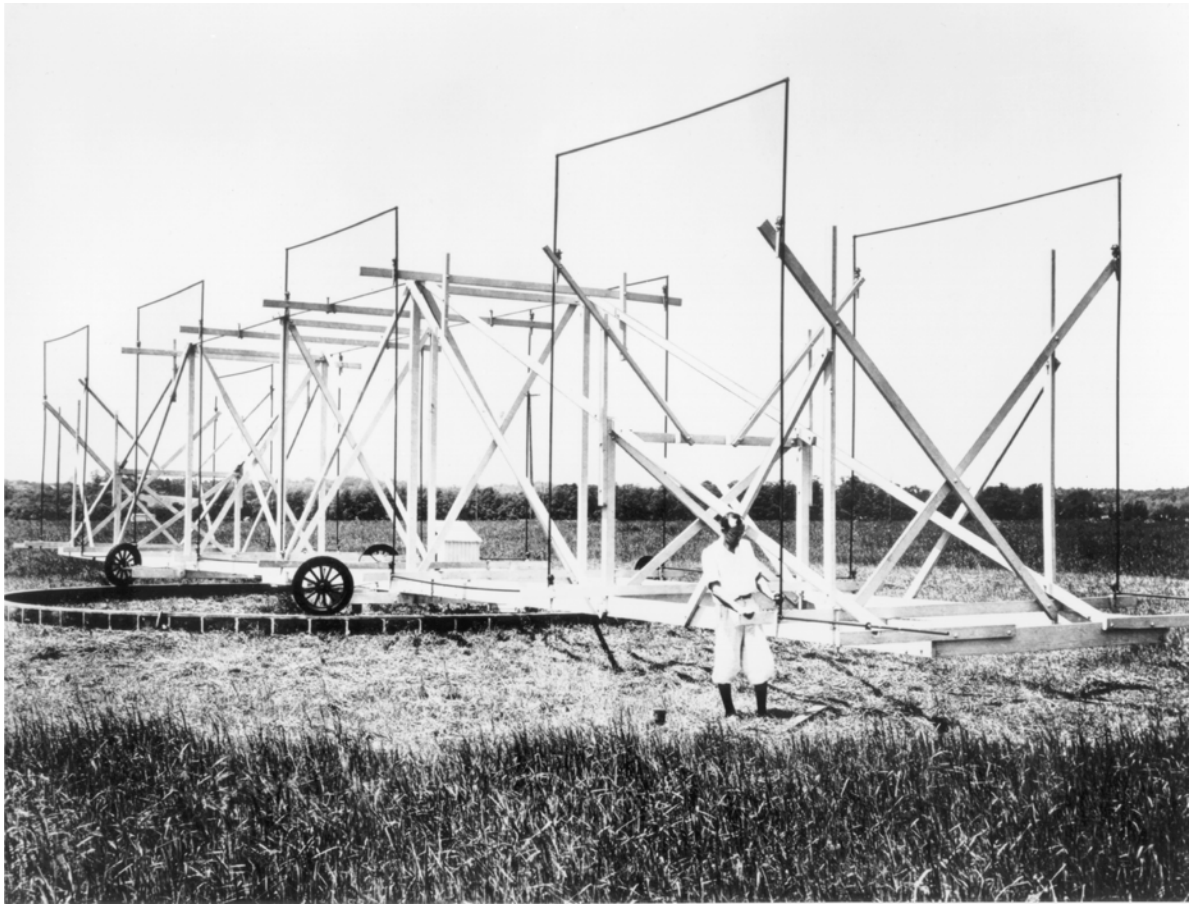
History of Radio Telescopes

A Technology Saga Triggered by Serendipity

Paul Vanden Bout

National Radio Astronomy Observatory

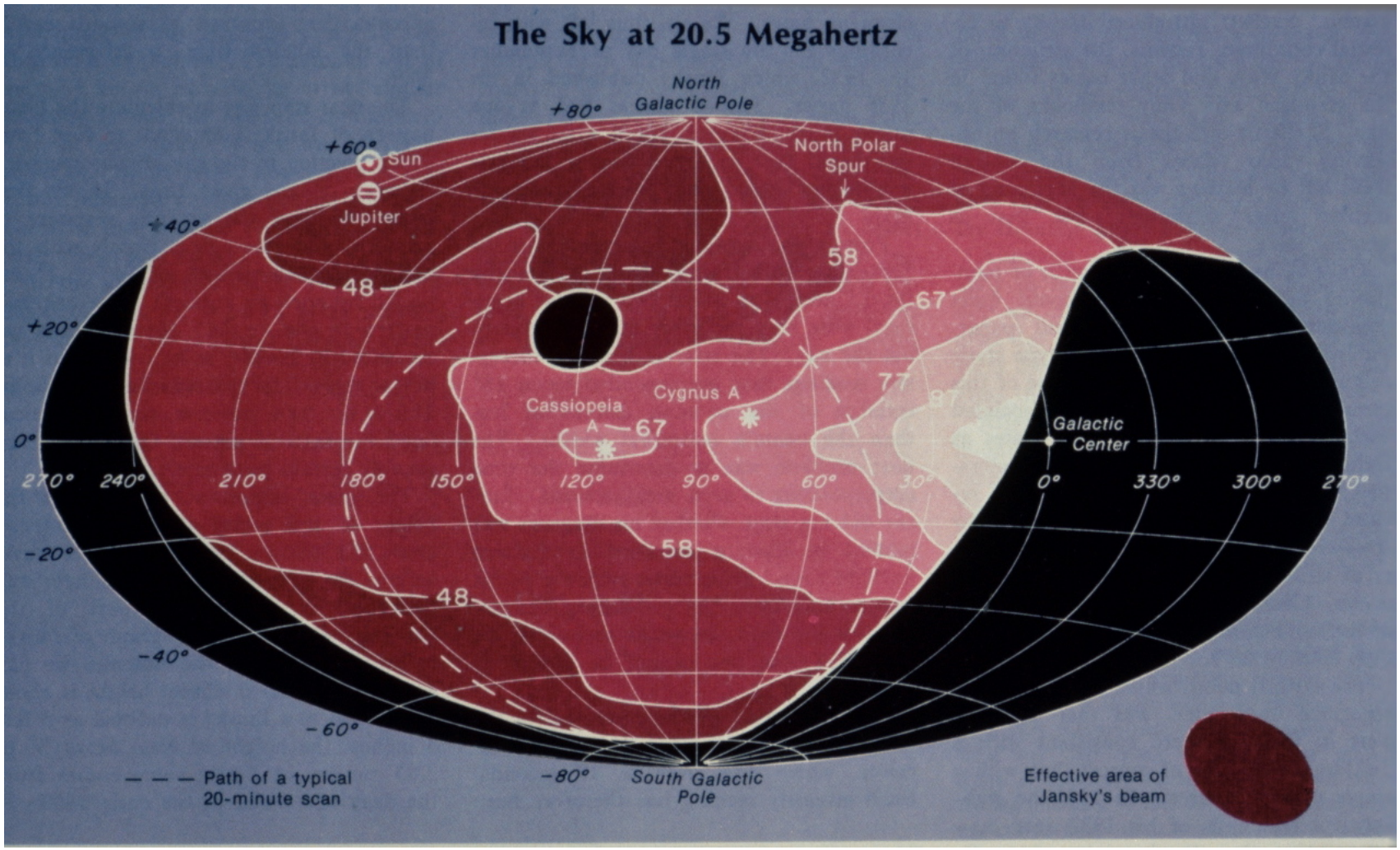
Karl Jansky - 1933



Jansky discovered radiation at λ14.6m (20.5 MHz) that moved across the sky at the sidereal rate.

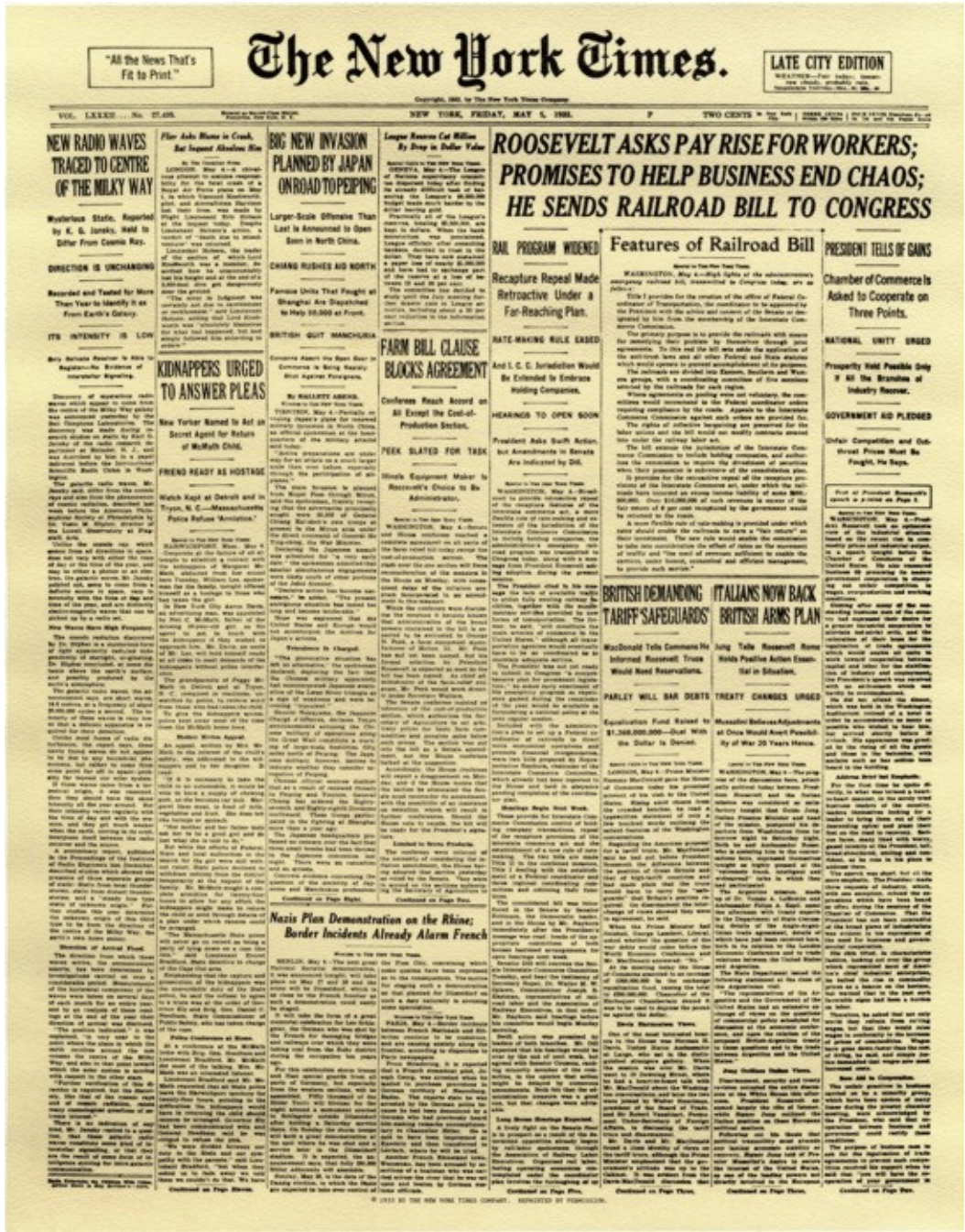
He was studying the sources of interference to “short wavelength” trans-Atlantic wireless telephony at Bell Telephone Labs.

Jansky's Sky Map (as reduced by W. T. Sullivan III)



Jansky's discovery attracted major public attention, including first page of NY Times May 5, 1933.

New Yorker Magazine opined "It has been demonstrated that a receiving set of great delicacy in New Jersey will get a new kind of static from the Milky Way. This is believed to be the longest distance anybody ever went to look for trouble."



"All the News That's Fit to Print."

The New York Times.

LATE CITY EDITION

NEW YORK, FRIDAY, MAY 5, 1933.

NEW RADIO WAVES TRACED TO CENTRE OF THE MILKY WAY

Mysterious Static, Reported by K. G. Jansky, Held to Differ From Cosmic Ray.

DIRECTION IS UNCHANGING

Recorded and Tested for More Than Year to Identify It as From Earth's Galaxy.

ITS INTENSITY IS LOW

Plane Asks Blame in Crash, But Inquest Absolves Him

KIDNAPPERS URGED TO ANSWER PLEAS

New Yorker Named to Act as Secret Agent for Return of McMath Child.

FRIEND READY AS HOSTAGE

Watch Kept at Detroit and in Tryon, N. C.—Massachusetts Police Refuse 'Invitation.'

BIG NEW INVASION PLANNED BY JAPAN ON ROAD TO PEIPING

Larger-Scale Offensive Than Last Is Announced to Open Soon in North China.

CHIANG RUSHES AID NORTH

Famous Units That Fought at Shanghai Are Dispatched to Help 50,000 at Front.

BRITISH QUIT MANCHURIA

League Reserve Cut Billion By Drop in Dollar Value

FARM BILL CLAUSE BLOCKS AGREEMENT

Conferees Reach Accord on All Except the Cost-of-Production Section.

PEEK SLATED FOR TRIX

Hindu Equipment Maker to Roosevelt's Choice to Be Administrator.

ROOSEVELT ASKS PAY RISE FOR WORKERS; PROMISES TO HELP BUSINESS END CHAOS; HE SENDS RAILROAD BILL TO CONGRESS

RAIL PROGRAM WIDENED

Recapture Repeal Made Retroactive Under a Far-Reaching Plan.

RATE-MAKING RULE EASED

And I. C. C. Jurisdiction Would Be Extended to Embrace Holding Companies.

HEARINGS TO OPEN SOON

President Asks Swift Action, but Amendments in Senate Are Indicated by Dill.

Features of Railroad Bill

PRESIDENT TELLS OF GAINS

Chamber of Commerce Is Asked to Cooperate on Three Points.

NATIONAL UNITY URGED

Prosperity Held Possible Only If All the Branches of Industry Recover.

GOVERNMENT AID PLEDGED

Unfair Competition and Cut-throat Prices Must Be Fought, He Says.

BRITISH DEMANDING TARIFF SAFEGUARDS

MacDonald Tells Commons He Informed Roosevelt Truce Would Need Reservations.

PARLEY WILL BAR DEBTS

Equalization Fund Raised to $1,360,000,000—Duel With the Dollar Is Denied.

ITALIANS NOW BACK BRITISH ARMS PLAN

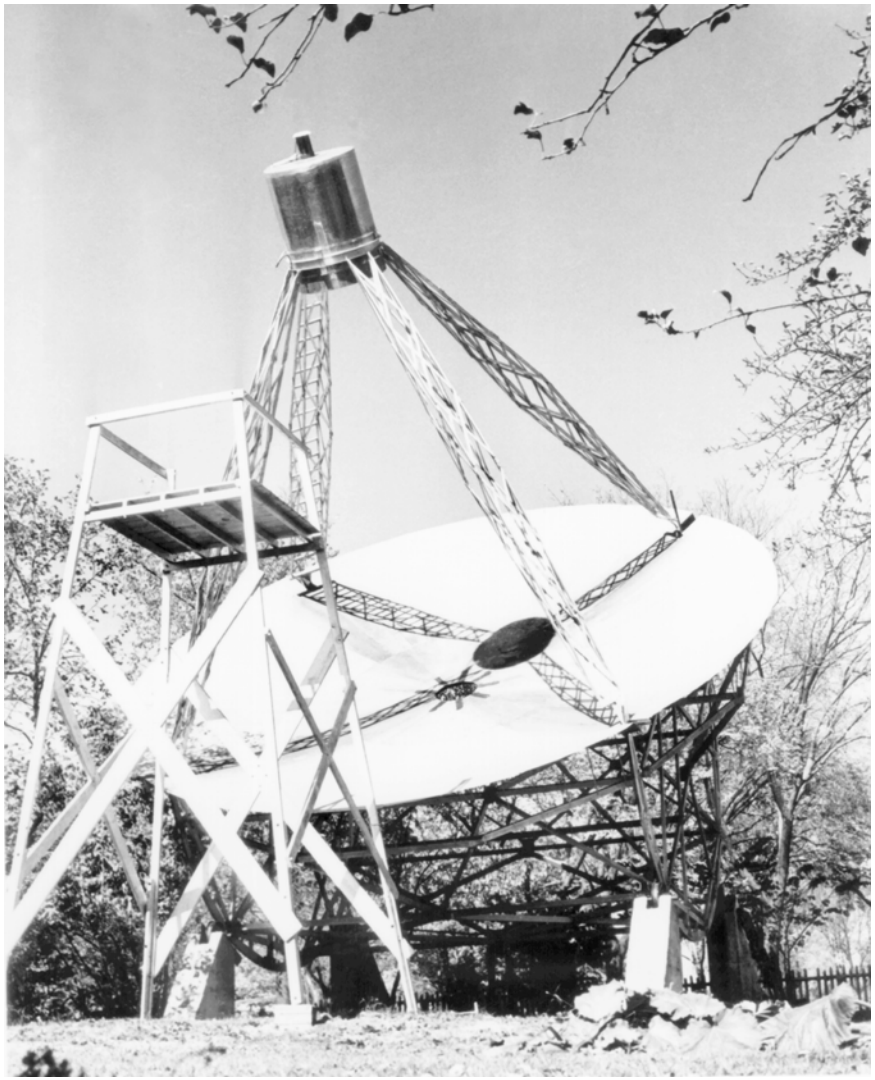
Jung Talks Roosevelt, Rome Holds Positive Action Essential in Situation.

TREATY CHANGES URGED

Mussolini Believes Adjustments at Once Would Avert Possibility of War 20 Years Hence.

Nazis Plan Demonstration on the Rhine; Border Incidents Already Alarm French

Grote Reber



In 1937, Reber built a 31-ft diameter reflector in his backyard in Wheaton IL.

Unable to duplicate Jansky's work at a high frequency (3300 MHz), he worked his way down to success at 160 MHz.

He mapped the sky in 1943 and published the results in the Astrophysical Journal [ApJ 100, 279 (1944)].

Reber's map showed emission from the plane of the Milky Way, the Galactic Center, Cyg A, and Cas A. The resolution was only 12.5 degrees.

Cas A →

Cyg A →

Galactic Center →

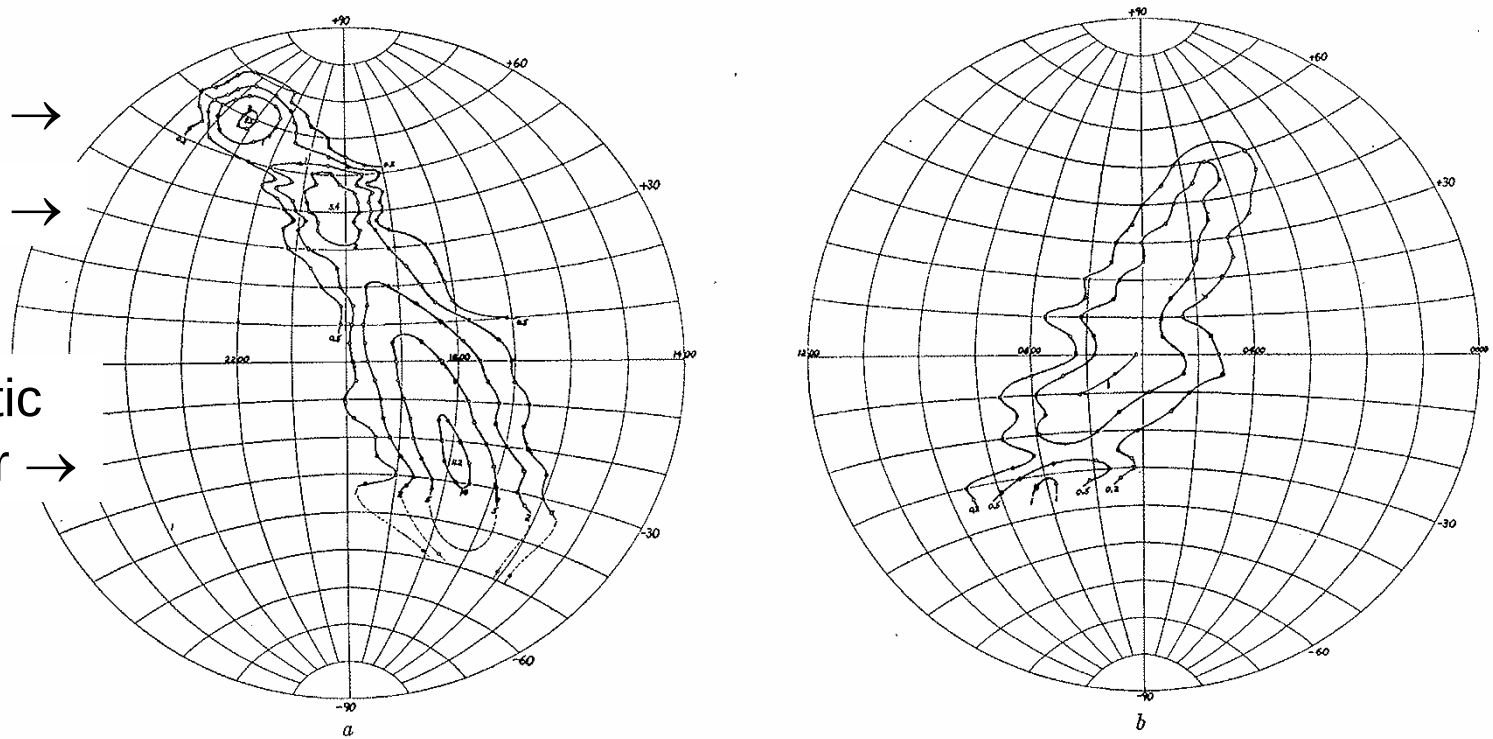
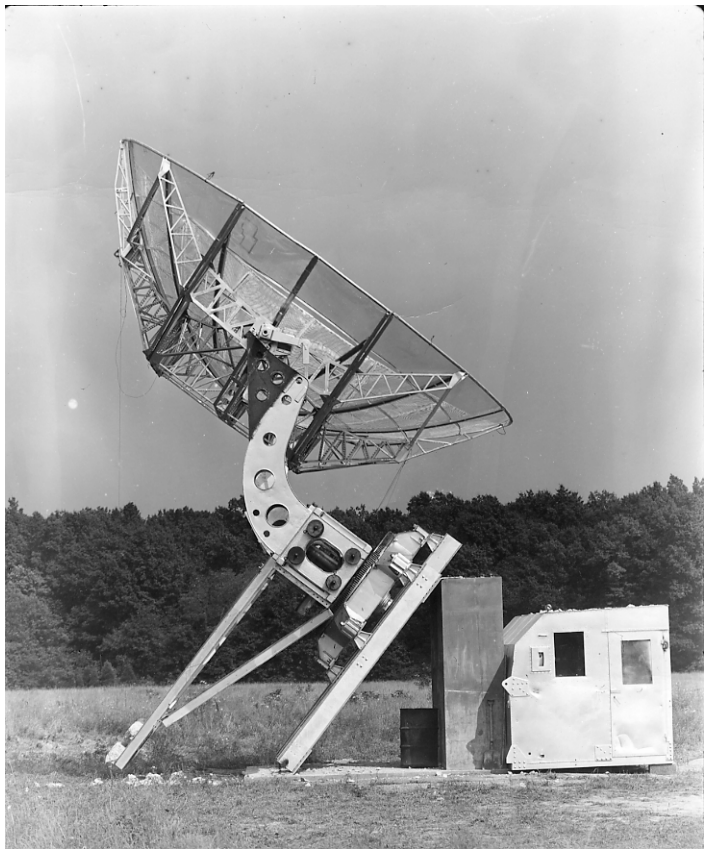


FIG. 4.—Constant intensity lines in terms of 10^{-22} watt/sq. cm./cir. deg./M.C. band

War-surplus Radio Astronomy



Würzburg paraboloids (7.5m), captured German radar reflectors, were used by a number of groups in the period following the end of World War II.

Research began on two discoveries classified during war: radio emission from meteors and solar storms.

Three Facts Driving Technology:

$$Signal \propto CollectingArea(D^2)$$

$$Noise \propto \frac{T_{sys}}{\sqrt{BW \cdot t_{int}}}$$

$$Resolution \propto \frac{\lambda}{D}$$

Requirement: big telescopes with low-noise wide-band receivers.

Flat Collecting Area Telescopes

Ohio State Big Ear (1963)

Designed by John Kraus, it had a collecting area equivalent to a 175 ft diameter dish & operated mainly at 1.4 GHz, a wavelength of 21 cm, to study HI.

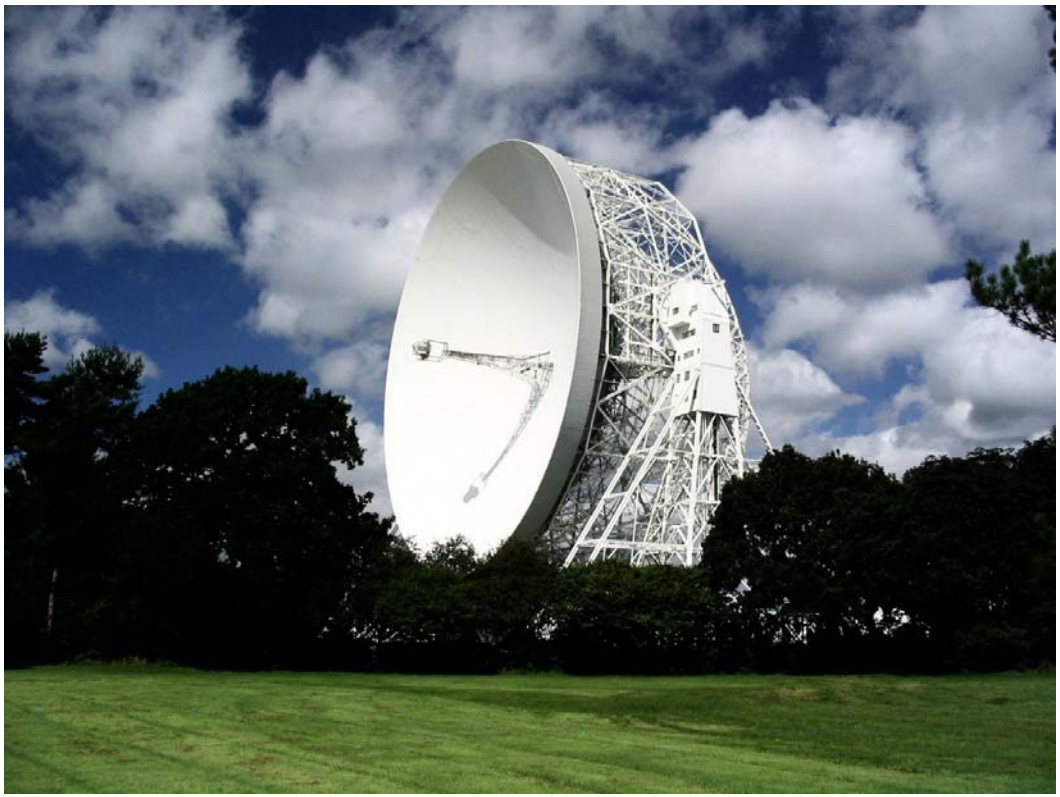
Nançay, France (1965)

Another “Kraus-design” radio telescope, still operating today.

Arecibo 305m

First opened in 1962, with upgrades in 1974 and 1996, the NAIC's Arecibo Telescope can track sources for some hours with a 600-foot patch of the 1000-foot diameter spherical surface. It operates up to 8 GHz, a wavelength of 3.8 cm. Arecibo is well-known for studies of pulsars, neutral hydrogen in galaxies, and radar astronomy of the solar system.

Mark I - Jodrell Bank Lovell Telescope (1957)



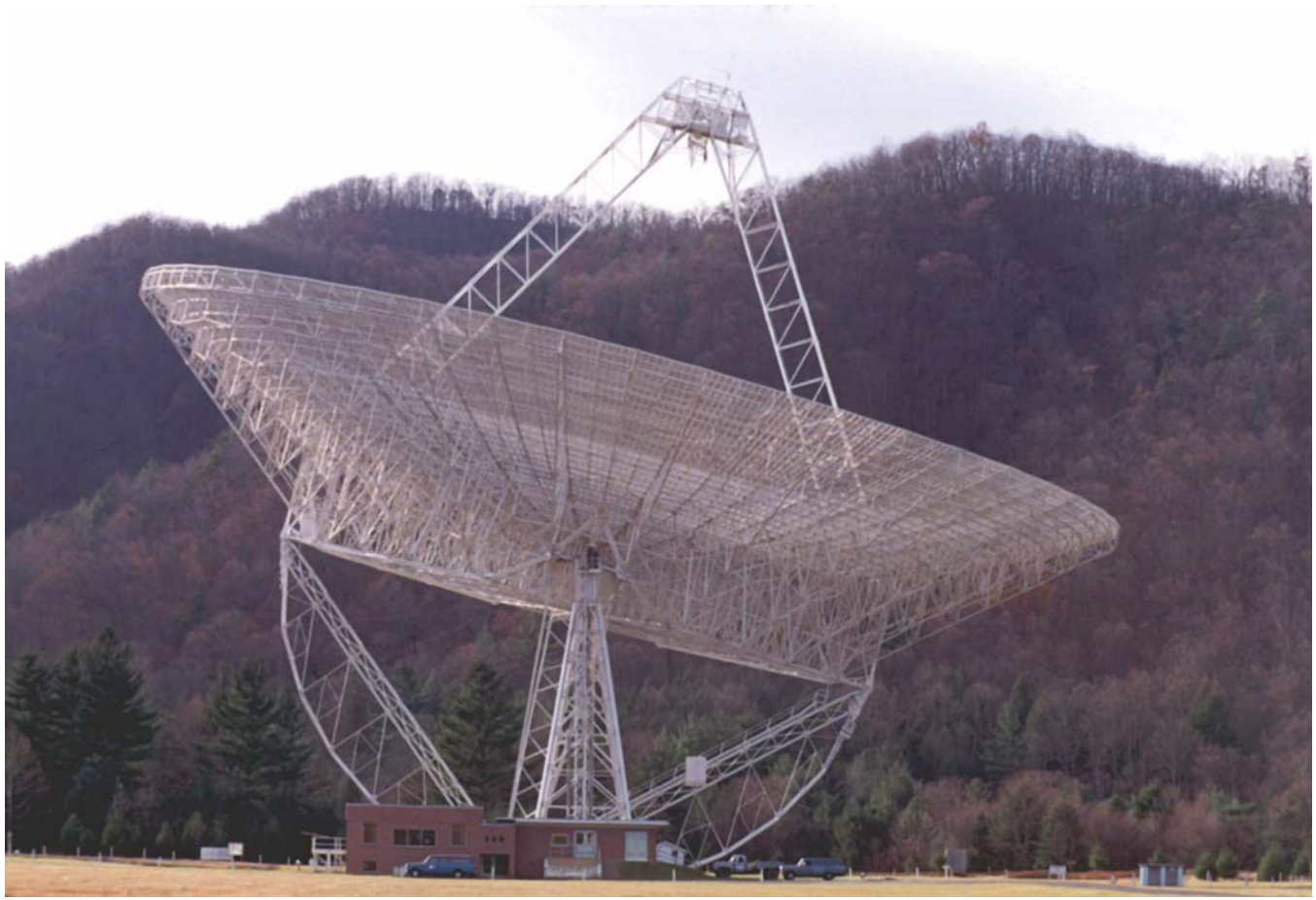
With a diameter of 76m, the Mark I is the 3rd largest fully steerable antenna.

A Fully Steerable 600 - Foot Telescope!

Navy project was cancelled in 1962 after it was realized that the 17,000 yd^3 concrete foundation was inadequate to support telescope.

Intended use: record Russian transmissions bouncing off Moon.

NRAO 300-Foot Telescope (November 15, 1988)



The Next Day

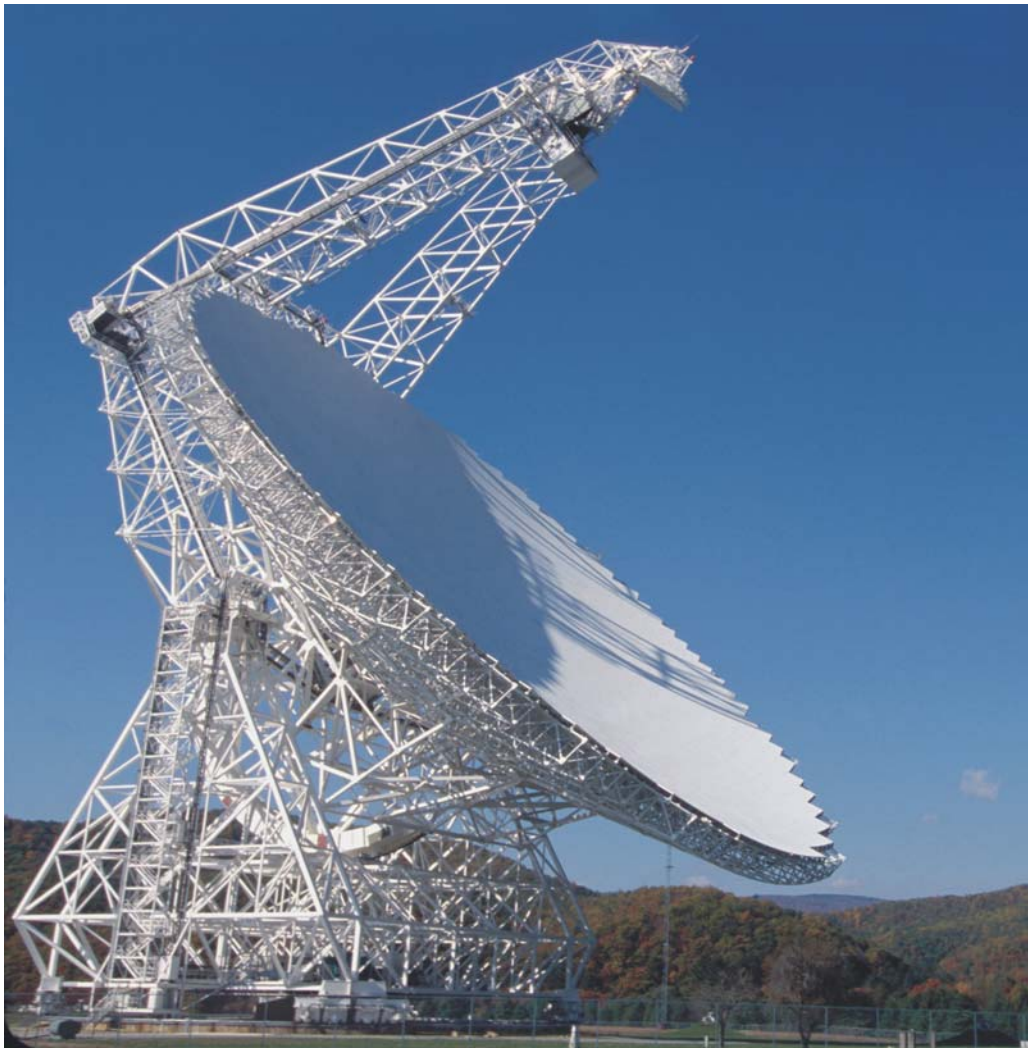
(Structural Design and Metal Fatigue are Important!)

Effelsberg 100m

The 100m Telescope of the Max Planck Institute for Radio Astronomy was completed in 1972, incorporating “homology” in its structural design.

As it moves in elevation, the surface deforms, but into a parabola. Its inner surface has been used at frequencies up to 86 GHz.

NRAO GBT - State of the Art



- 100m unblocked aperture ⇒ very low sidelobes;
- active surface ⇒ operates 290 MHz - 100 GHz;
- pointing 1˝ (rms);
- low system temps;
- fully supported remote observing;
- studies of pulsars, HI, high-z CO

Not all radio telescopes are parabolic reflectors

Image Credit: *Jocelyn Bell Burnell*

Jocelyn Bell and the telescope in Cambridge, England, used to discover pulsars.

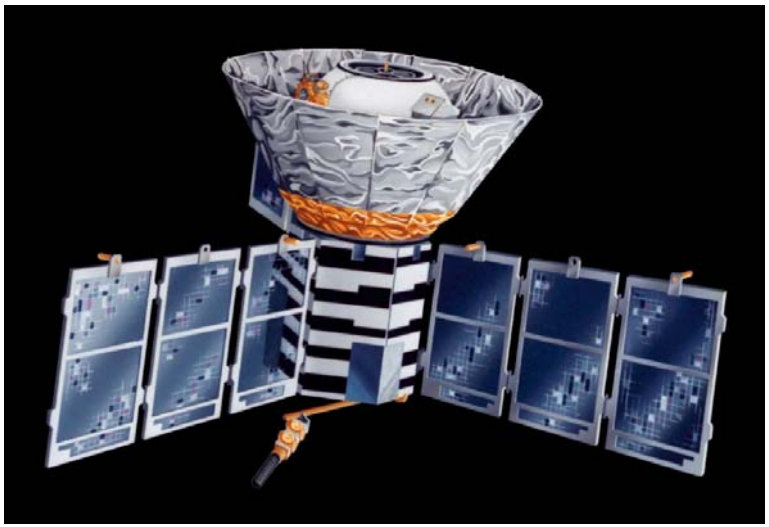
HI Horn

Harold “Doc” Ewen peers into the horn he and Edward Purcell used in 1951 to discover Galactic HI emission in the ground state hfs line at 1.4 GHz (λ 21 cm).

Echo Horn Reflector

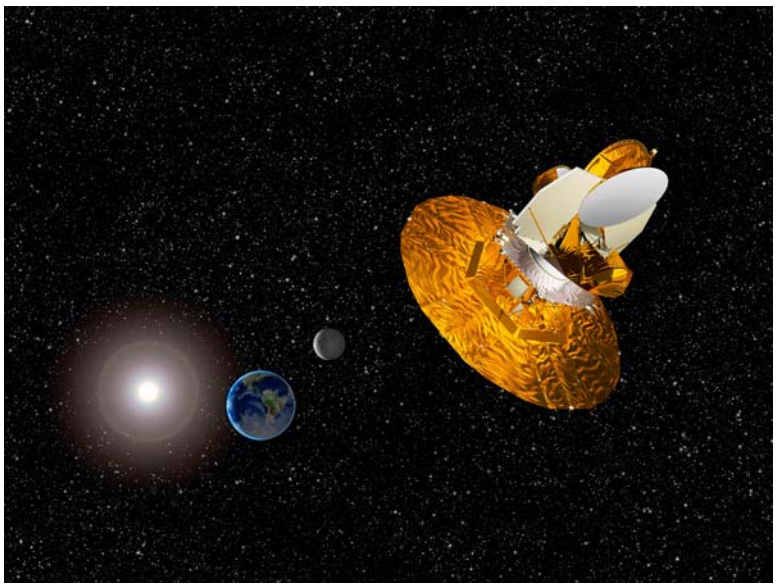
Penzias and Wilson discovered the cosmic background radiation in 1962 with the Bell Labs horn antenna, built to study possibility of space communications by first observing the Echo Balloon.

This is arguably the biggest discovery of radio astronomy.



Cosmic Background Explorer (COBE) - 1989

T(bkgd) = 2.725 $\pm$ 0.002 K

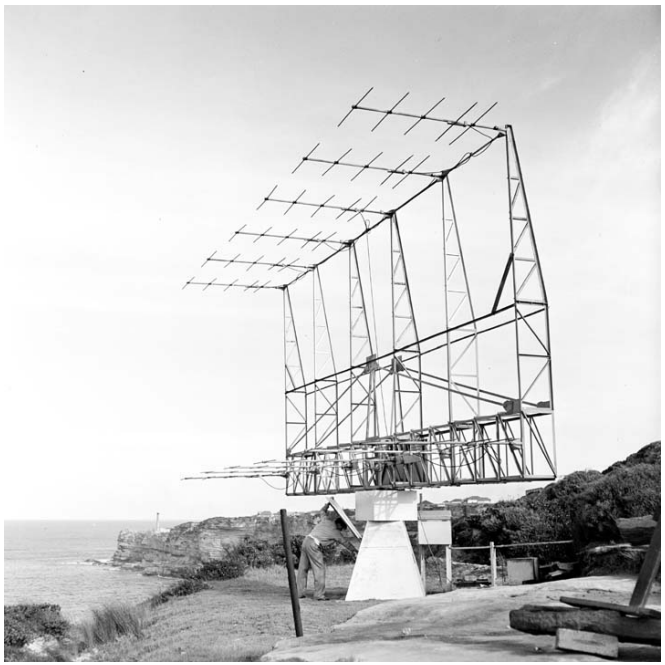


Wilkinson Microwave Anisotropy Probe (WMAP) - 2001

Density fluctuations $\Rightarrow$ parameters for the model of the cosmos.

Early Interferometry

Dover Heights (Australia) Sea Interferometer - a radio “Lloyd’s Mirror”. Showed that Cyg A was smaller than 8´ (1948).



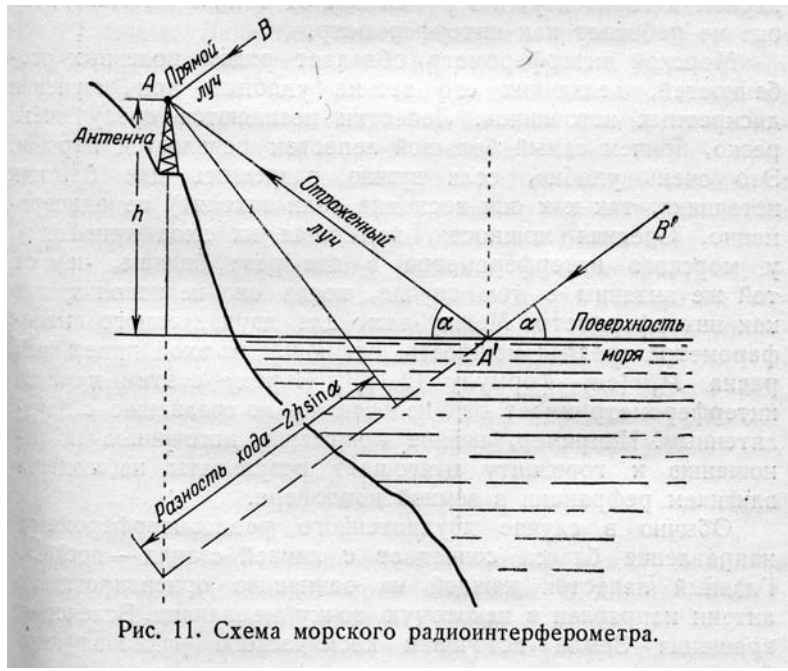
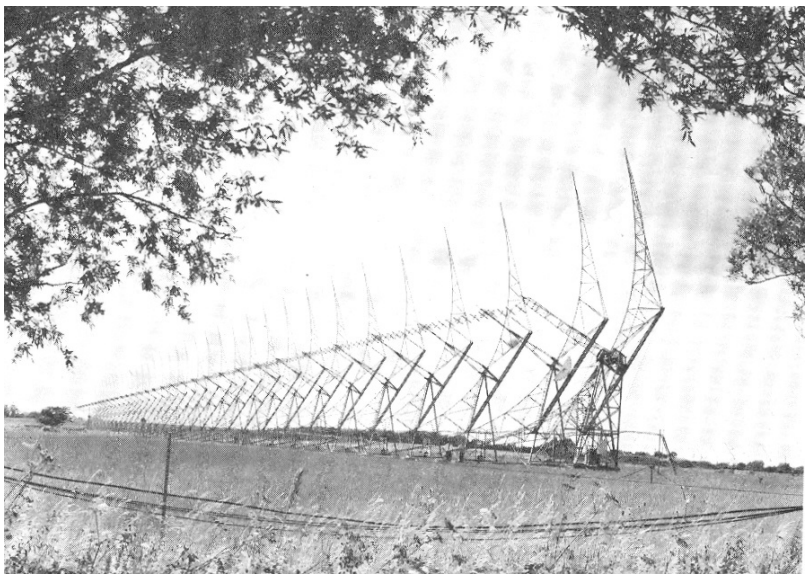


Рис. 11. Схема морского радиоинтерферометра.

F. G. Smith used an interferometer at Cambridge to locate Cyg A and Cas A to $\pm 1^s$ in R.A. and $\pm$ 40´´ Dec., allowing Baade & Minkowski to identify the sources as a “double galaxy” and Galactic SNR, respectively, using the Palomar 200-inch [ApJ 119, 206 (1954)].

Aperture Synthesis

Interferometry was under active development in the 1950s and 1960s in many locations: Australia, England, and the U.S., at NRAO (Green Bank Interferometer) & Caltech (Owens Valley).



The Cambridge 178 MHz Interferometer produced the 4C Catalog and was used to demonstrate earth rotation aperture synthesis by Martin Ryle and Ann Neville in 1962.

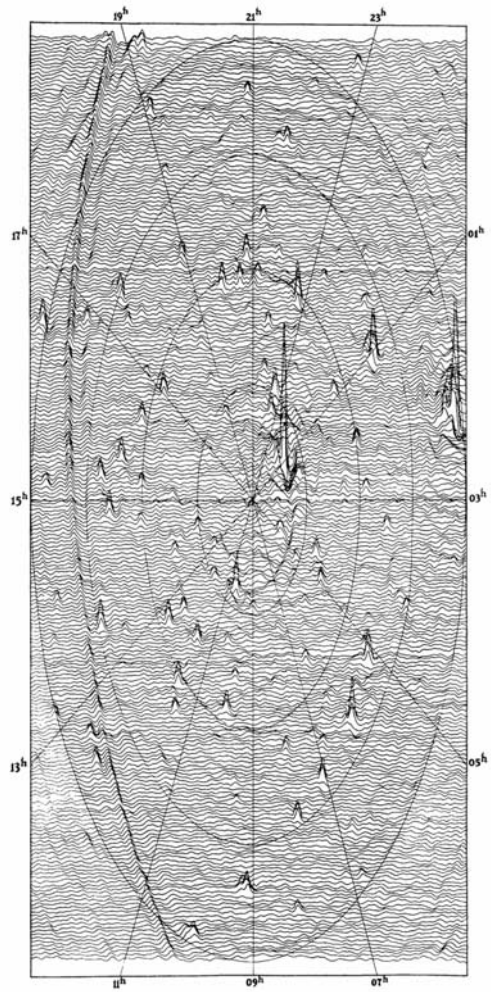
Plans for the Westerbork Synthesis Array and the Very Large Array soon followed.

“A series of observations has been made to test a new and more powerful method of aerial synthesis.”
[Ryle & Neville, MNRAS 125, 39 (1962)]

EDSAC II

Observing with different antenna spacings as the earth rotates simulates an observation with a 3400m diameter antenna - resolution 4.5´ at ~170 MHz.

2-D Fourier transform was a huge computing problem for its day, taking up EDSAC II for an entire weekend.



Very Large Array (1980)

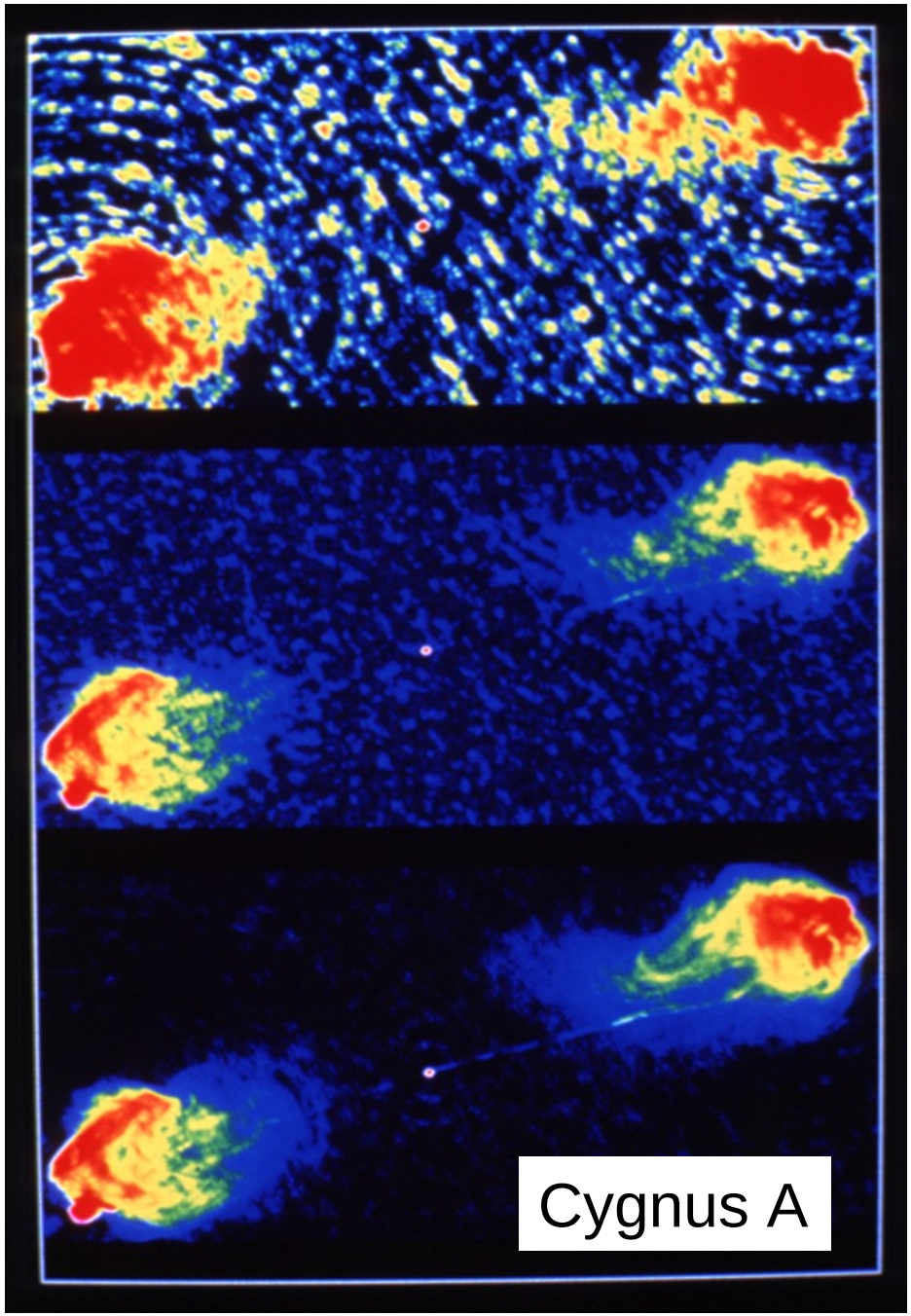
The replacment of all electronics by 2012 will improve performance by 10, that is, 10 VLAs for price of original.

Improvement in Electronics

Jansky detected three powerful (~10000 Jy) sources; the Expanded Very Large Array can see 1 μJy. This is an improvement of ~ 10^{10} in 8 decades of time.

Part of difference is collecting area. The rest is due to cooled broadband receivers: HEMT amplifiers for cm and SIS mixers for mm λ's, which now operate near the quantum noise limit ($h\nu/k$).

For reference, a cell phone on the Moon would produce a signal at earth of roughly 50,000 Jy.



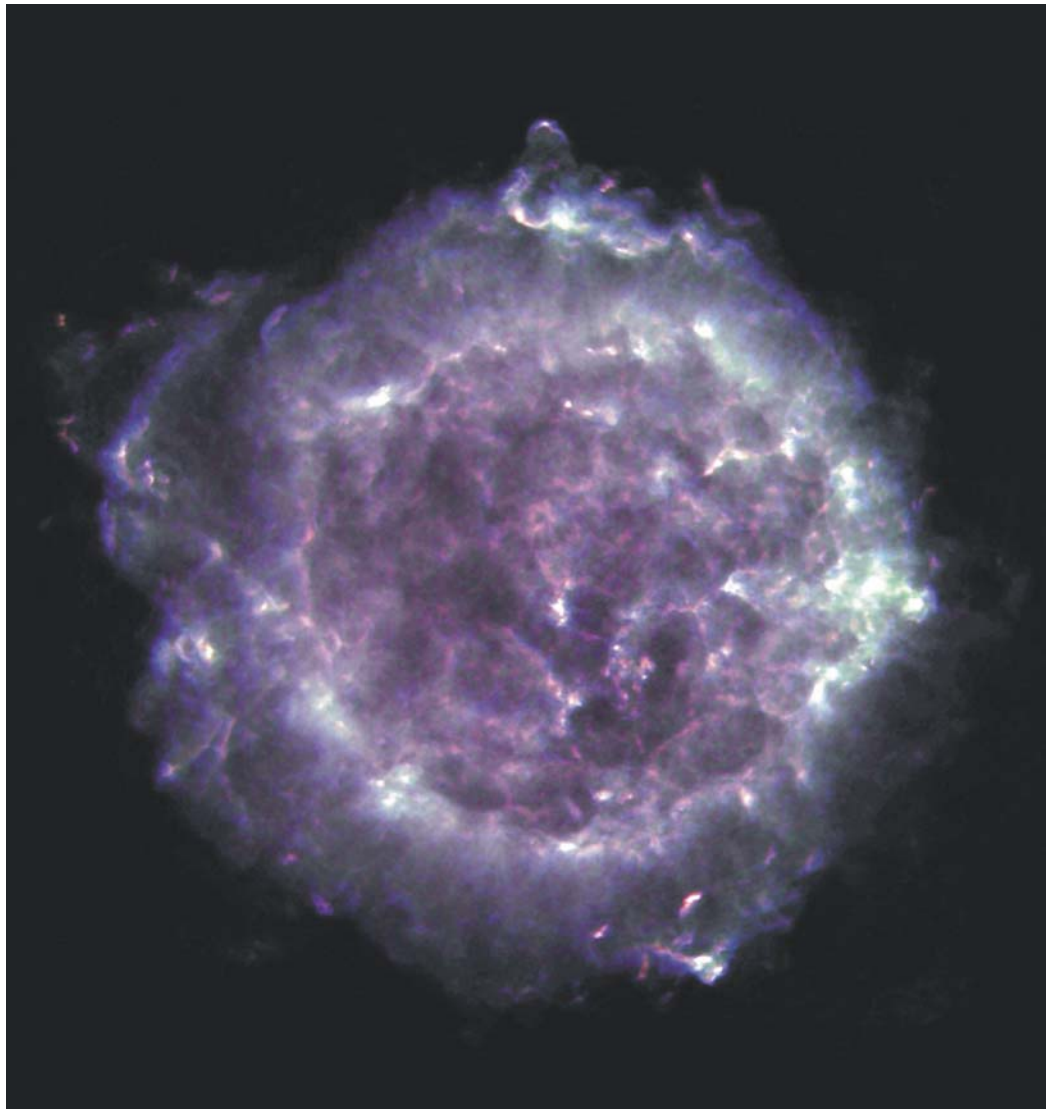
Power of Computing

A - raw image

B - beam pattern removed (deconvolution)

C - atmospheric phase errors removed (self-calibration)

Cas A with the VLA

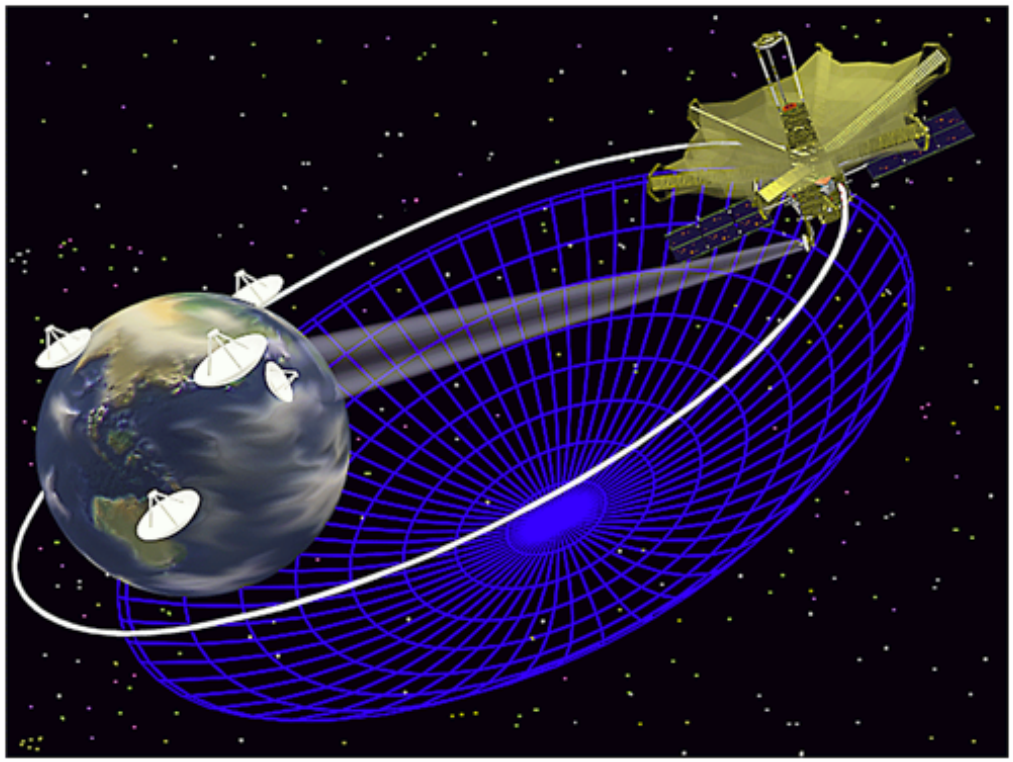


Very Long Baseline Array

Bringing recorded time-tagged signals together from widely spaced antennas by FedEx-transported magnetic tape and hard drives (and now by the internet), very long baseline interferometry achieves the highest angular resolution in astronomy at *any* wavelength: ~10s of micro-arcseconds.

The Milky Way has been surveyed by purely geometric means. Masers in central rotating disks of distant galaxies offer the opportunity to measure H_0 to 3%.

Space VLBI



Adding a space antenna with the launch of VSOP-1 (1997), extended VLBI baselines to 30,000 km.

VSOP-2 (2013)

Radioastron (2010)

Millimeter Astronomy

The NRAO 36-foot (later 12m) telescope began operation in the 1960s, soon becoming the facility where most interstellar molecules were first detected.

The NRAO 12m and many other millimeter-wave telescopes were eclipsed in power by the IRAM 30m in 1984.

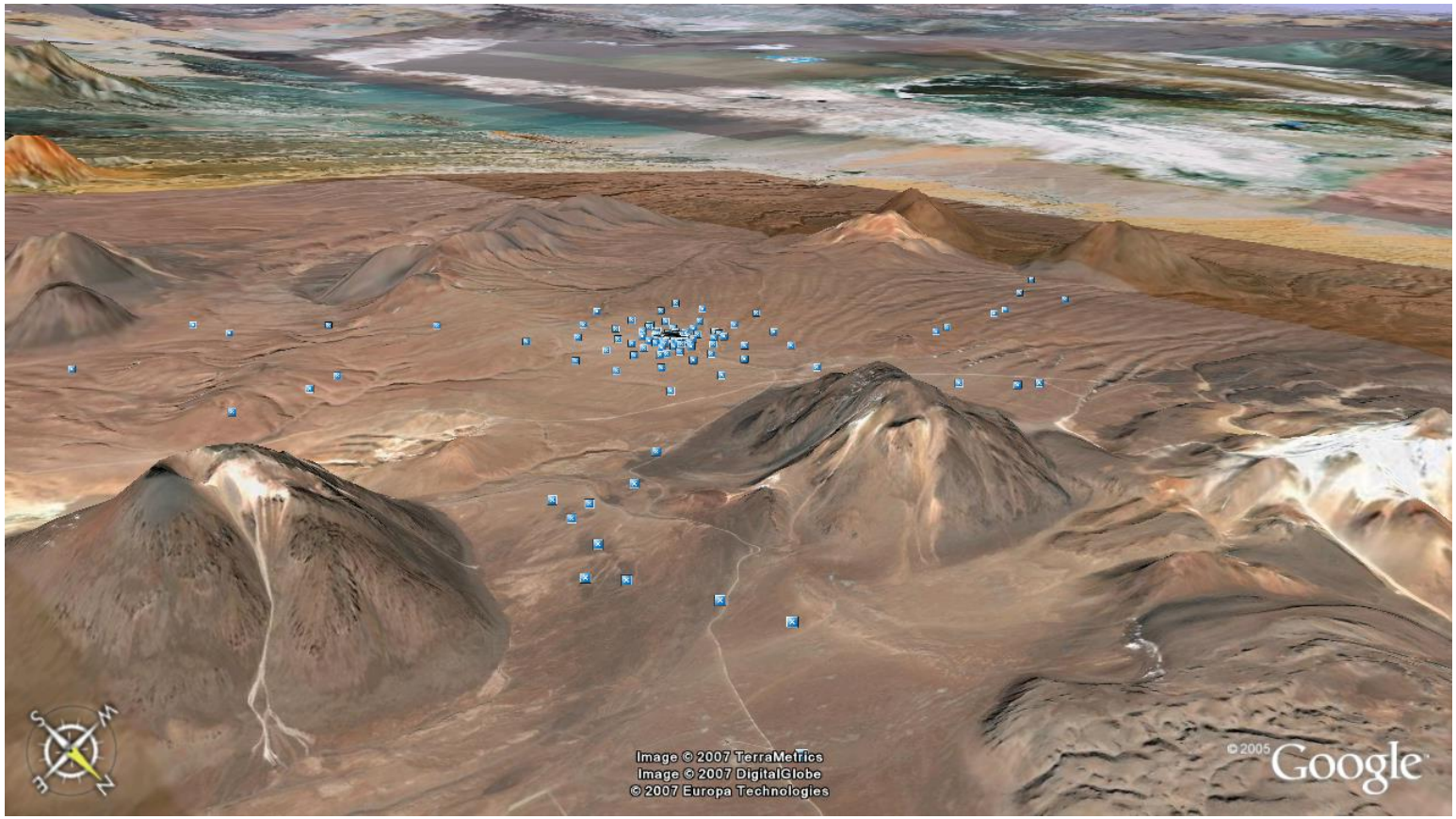
mm Interferometry

Interferometry at mm wavelengths was pioneered at the U. Calif. Hat Creek Obs., Caltech's Owens Valley Obs., and U. Bordeaux ~ 1980. The California interferometers have been combined into CARMA (below); IRAM operates an interferometer on the Plateau de Bure near Grenoble.

Altacama Large Millimeter/Submillimeter Array

- 50 (up to 64) 12m + 12 7m antennas;
- high-sensitivity receivers for all atmospheric transmission windows from 30 GHz - 1 THz (~ 0.1 mJy rms noise in 60 seconds integration at 230 GHz);
- reconfigurable - compact to extended arrays (1.5 to 0.2 arcsec, respectively, 0.2 to 15 km baselines at 230 GHz);
- high site in northern Chile for best atmospheric transmission and phase stability;
- ~ 1 B$ international project.

ALMA



The ALMA site is in the Andean altiplano at 5000m (16,500 ft).

Operations are to begin in 2013. ALMA can observe a wide range of objects: solar system, Milky Way, and galaxies from those nearby to early Universe galaxies forming during the Epoch of Re-Ionization.

One of the U.S. built antennas being carried by the custom transporter. ALMA will be reconfigured continuously, from compact to extended arrays and back again.

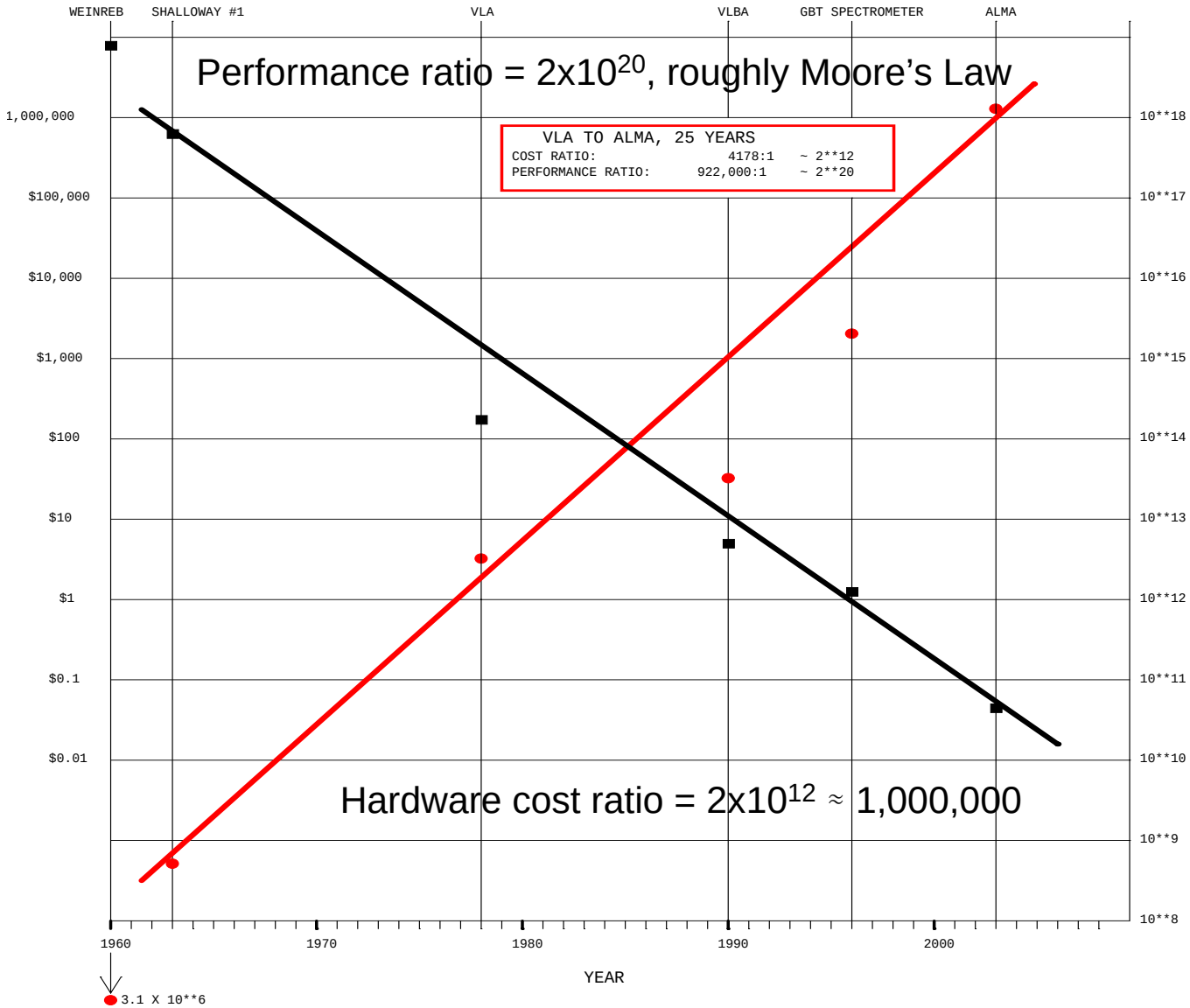
(Room to park 12 Smarts!)

ALMA Correlator Quadrant (1 of 4)

Complete correlator contains 2912 printed circuit boards and 5200 interface cables; there are more than 20 million solder joints.

It is a ~ 2 x 10^{16} flops, very limited purpose, computer.

VLA to ALMA = 25 years: Correlator Cost & Performance



Square Kilometre Array - nano-Jy high-resolution astronomy