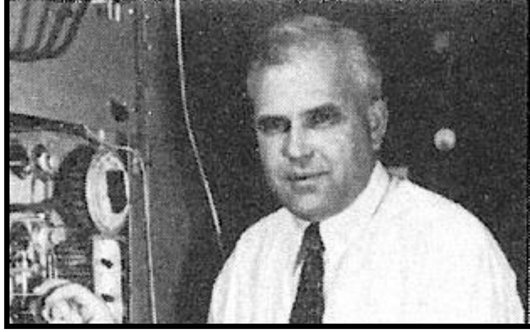
The Building

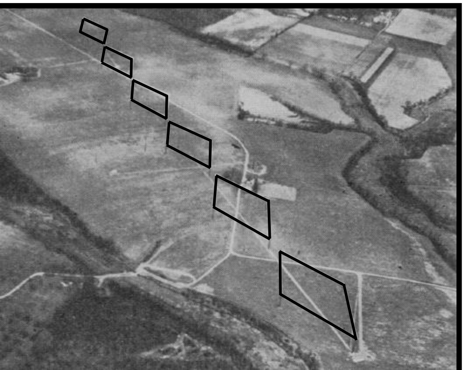
The First
(Accidental)
Radio Astronomy Interferometer



The Inventor

The Bell Labs 1935 Experimental
~ MUSA ~
Multiple Unit Steerable Antenna

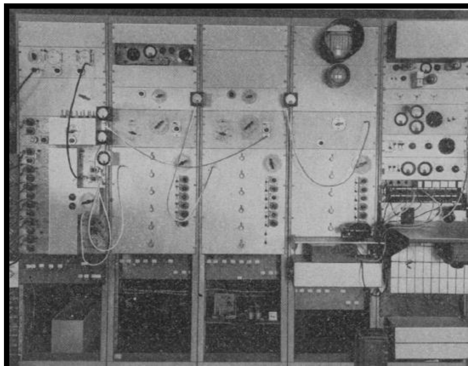
The Antenna



Bob Hayward
NRAO Senior Engineer (Retired)
Socorro, NM

AOC Lunch Talk, Socorro - 13 March 2013

The Electronics



This is not the story of which Radio Interferometer was the 1st to be intentionally used to carry out Radio Astronomy measurements.

Rather, it is the story of the Radio Interferometer that was the 1st to have detected an Astronomical Source.

So what do the “textbooks” on the History of Radio Astronomy have to say ?

(not that there are all that many textbooks since radio astronomy, at ~80 years old, is such a young science)

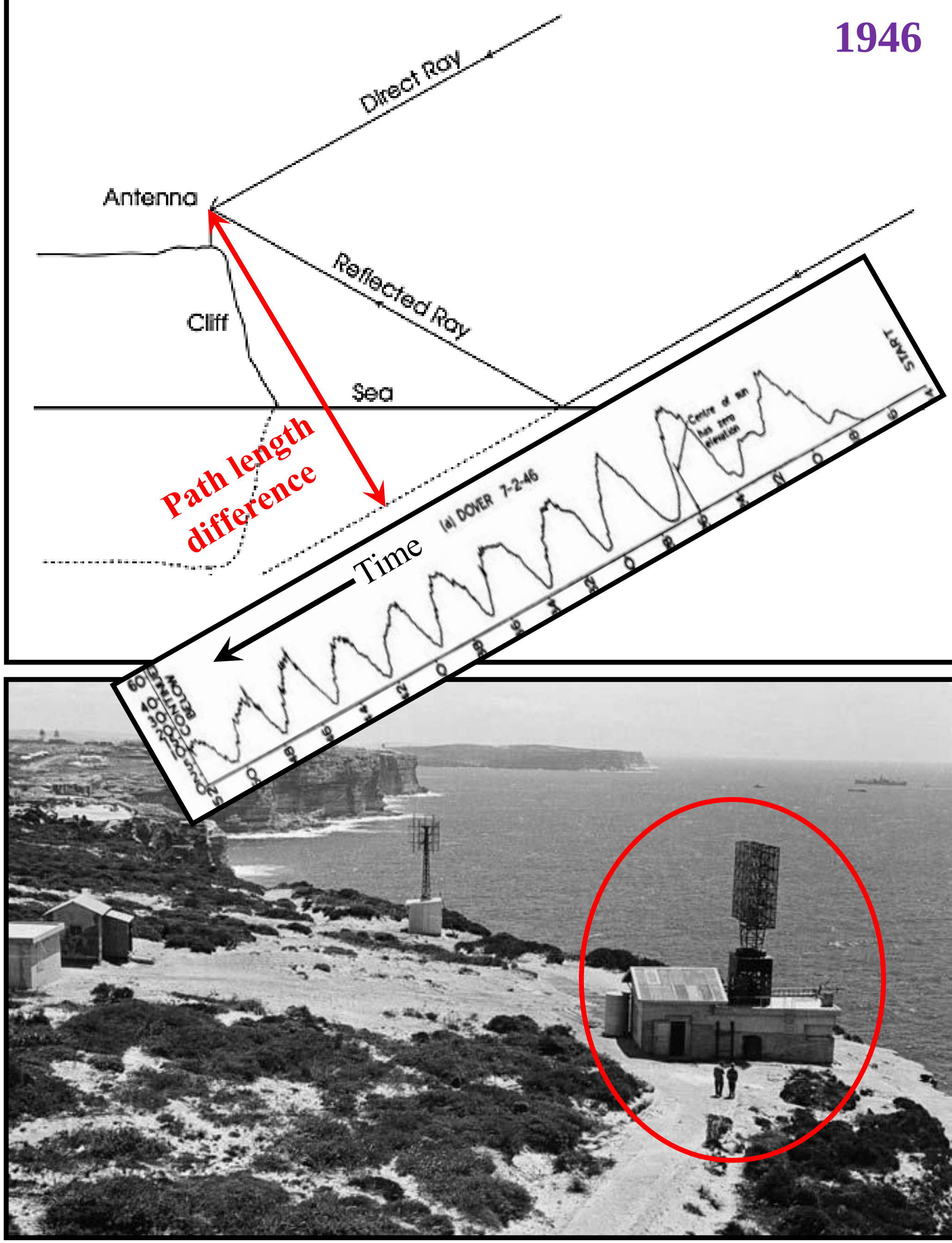
The First Interferometer Specifically intended for Radio Astronomy was the Australian *Sea (Cliff) Interferometer*

1946

The "Sea Interferometer" uses a single aerial in which the reflection off the water forms the 2nd element of the interferometer.

The technique was developed in 1946 by Joe Pawsey, Ruby Payne-Scott and Lindsay McCready of the *Radiophysics Laboratory* of the *Commonwealth Scientific and Industrial Research Organisation* (CSIRO).

They used a WWII *ShD–200 MHz Shore Defense Radar* located at the Dover Heights radar station near Sydney, Australia, to make the first interferometric measurements of an astronomical object - the Sun – at sunrise on Feb 7th 1946.

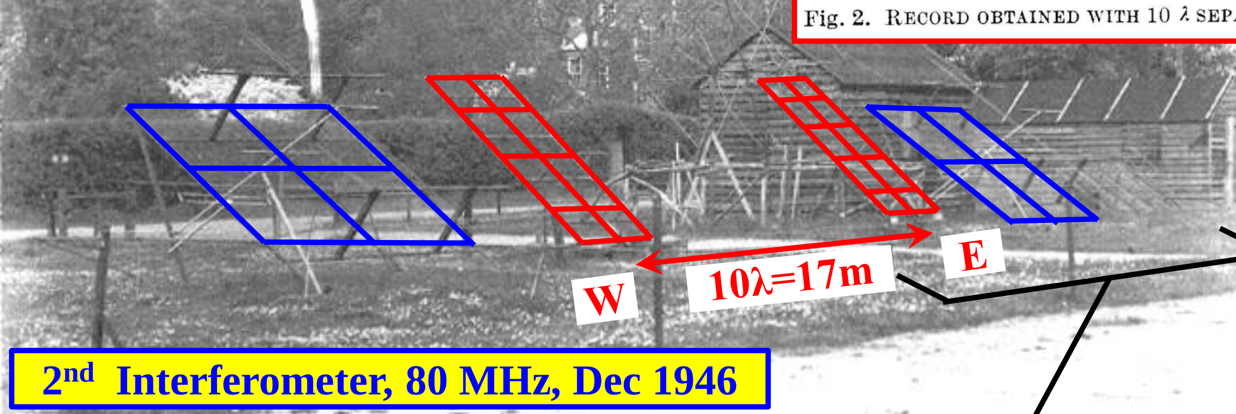


http://en.wikipedia.org/wiki/List_of_surviving_veterans_of_World_War_I
***Under the Radar – The First Woman in Radio Astronomy*, M. Goss, Springer, 2010, p.99**

The 2nd was Martin Ryle's at the Cavendish Lab, UK

1946

Figure 8.2. First observing hut (leftmost) and early antennas of Ryle's group, circa 1948 at the "Rifle Range" field station off Grange Road, Cambridge (see Fig. 8.3). Several solar interferometers are shown. From the left, (1) (in front) 80 MHz Yagi; (2) (behind) 80 MHz 4-dipole broadside array with reflecting screen; (3) 175 MHz 8-dipole array; path; (4) antenna paired with 3; (5) (in front) pair with 1; (6) (behind, cubical structure higher than shack) 214 MHz 4-Yagi array (operated as a single antenna, based on a wartime "Lightweight Warning" set); (7) pair with 2; (8) alternate pair with 3 (with polarization crossed). Ryle's house is off to the left and the tower of the main University Library is visible in the background.



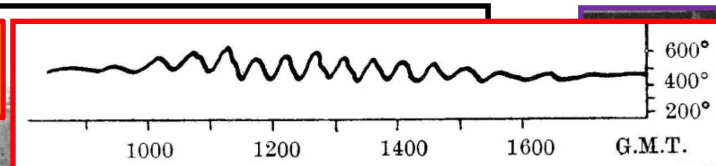
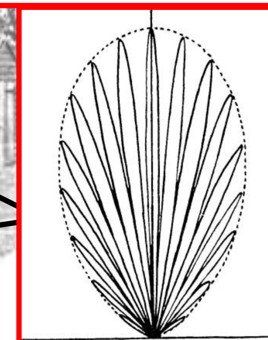
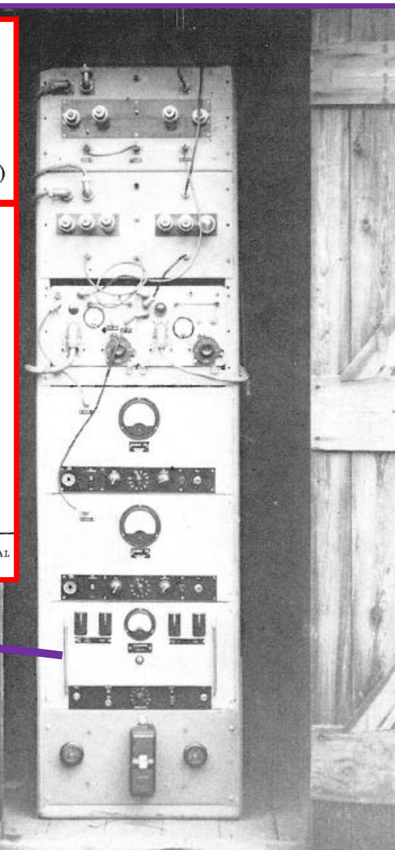


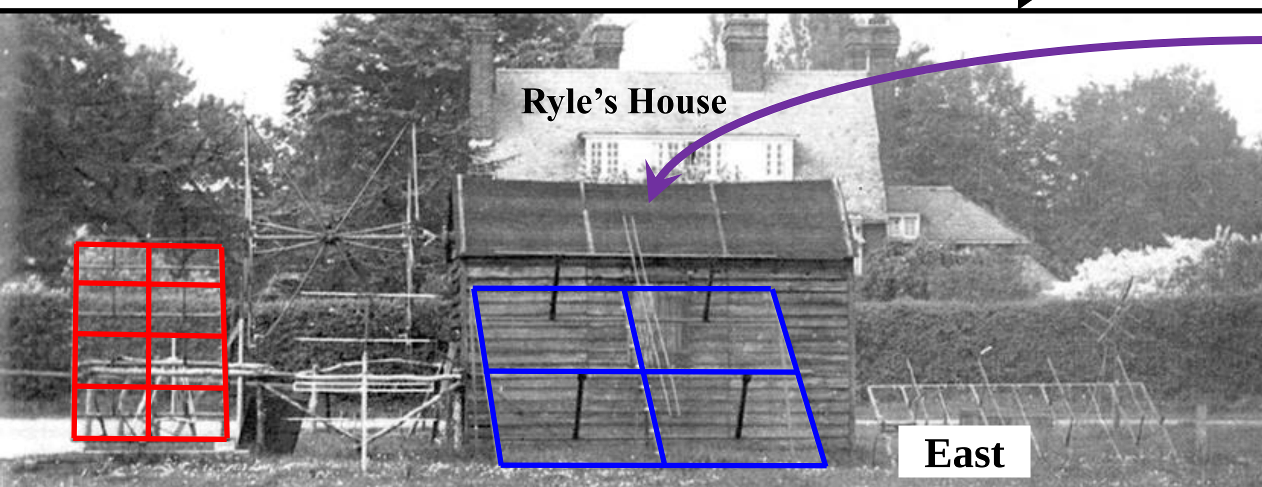
Fig. 2. RECORD OBTAINED WITH 10 λ SEPARATION (JULY 17, 1946)



POLAR DIAGRAM OF TWO 8-ELEMENT AERIAL WITH SEPARATION OF 10 λ



Receivers built in 1946 for 175 and 80 MHz, which made use of equipment from Coastal Command airborne radars, a German long-range radar and a capacity switch from a crashed Ju 88.



The wooden hut which formed the Radio Astronomy Observatory for its first few years (1945-48). The instruments shown include interferometers for 175 and 80 MHz, a transit instrument operating at 214 MHz, and polarization aerials. They were used mainly for solar observations.

Cosmic Noise: A History of Early Radio Astronomy, W.T. Sullivan, Cambridge University Press, 2009

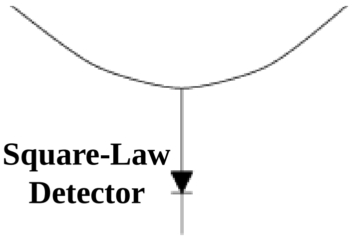
Search and Research – Professors Ryle, Kurti and Boyd, J.P. Wilson, editor, Mullard House, 1971

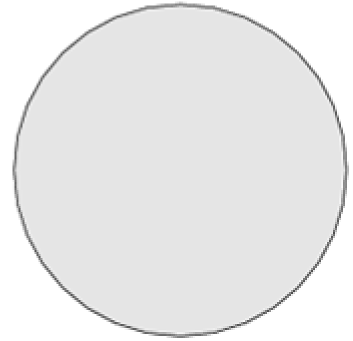
Solar Radiation on 175 Mc./s., M. Ryle & D. Vonberg, Nature, 158, 1946, p.339-340

From Single Dish to Beamformer Arrays to Aperture Synthesis - 1

1-dimensional		2-dimensional	
telescope configuration	beam cross-section	Physical aperture	beam projection

Ideal Large Single Dish

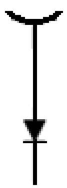


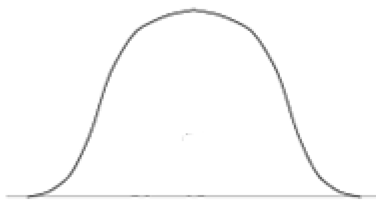


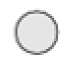
Astronomers like big dishes:
Large collecting area improves sensitivity

Large aperture improves spatial resolution.

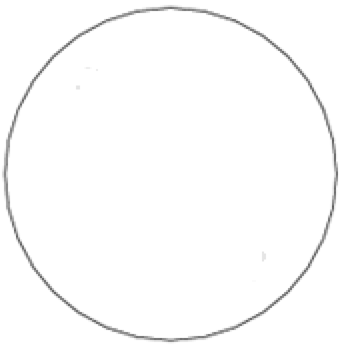
Small, Affordable Single Dish



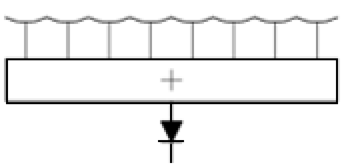




SIZE DOES MATTER !!!

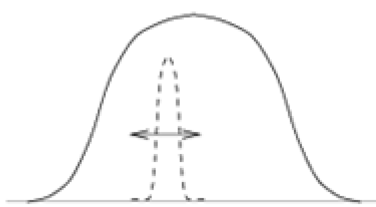


Filled Tied Array

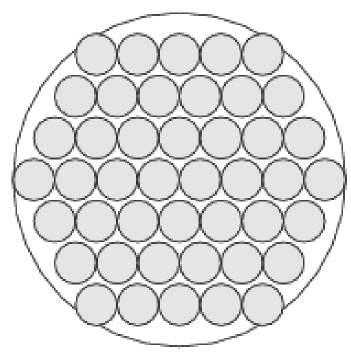


Voltage signals summed in a *beamformer* before the detector.

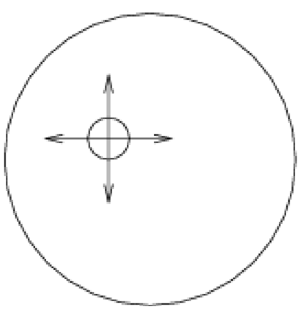
Steer Beam by…



…adjusting phases



Steer Beam by…



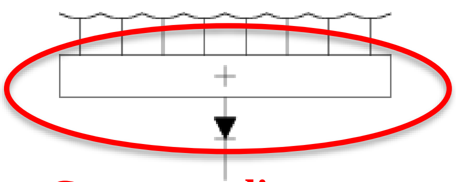
…adjusting phases

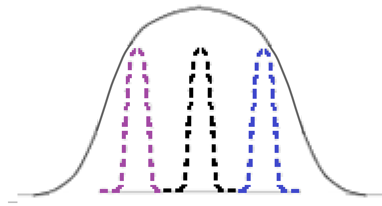
From Single Dish to Beamformer Arrays to Aperture Synthesis - 2

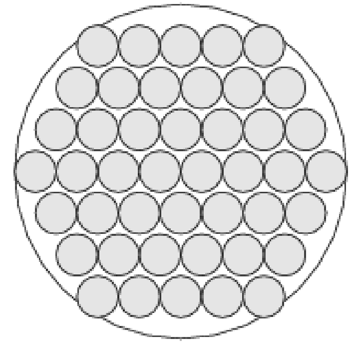
1-dimensional | 2-dimensional

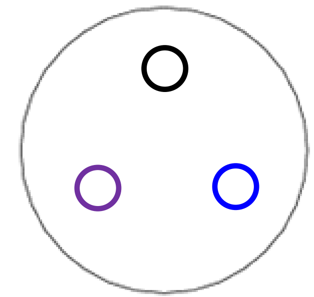
telescope configuration	beam cross-section	Physical aperture	beam projection

Filled Tied Array



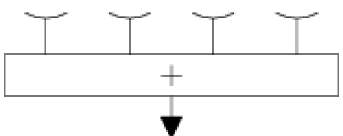


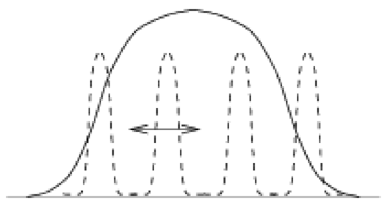


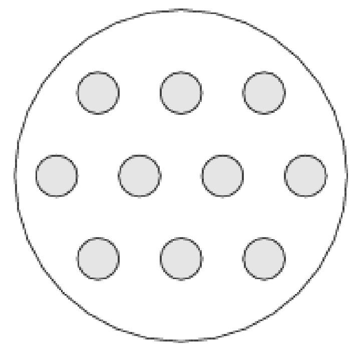


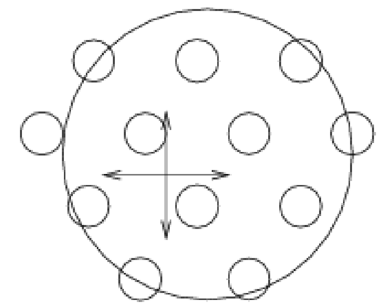
Can use splitters on each antenna output to allow for multiple beamformers.

Grating Tied Array



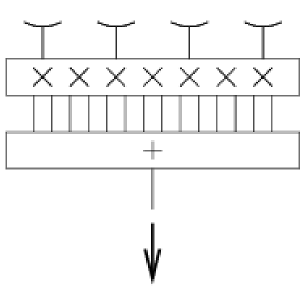






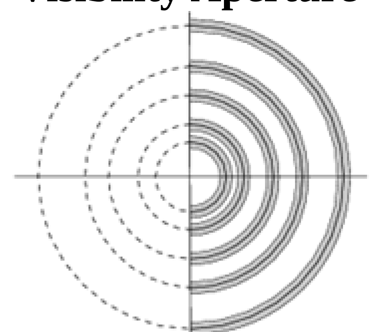
The beam pattern has grating lobes which are always present and can lead to source confusion (e.g., the early Cambridge 1C & 2C catalogs).

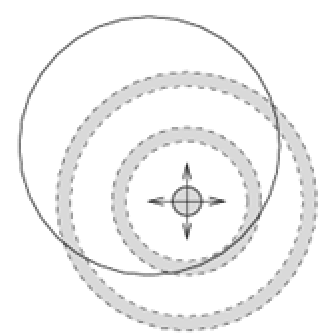
Correlation Interferometer



A correlator generates the cross products of the signals between each pair of elements. Each of these fringe visibilities is one component of the Fourier Transform of the spatial distribution of the brightness function of the observed object.

Visibility Aperture



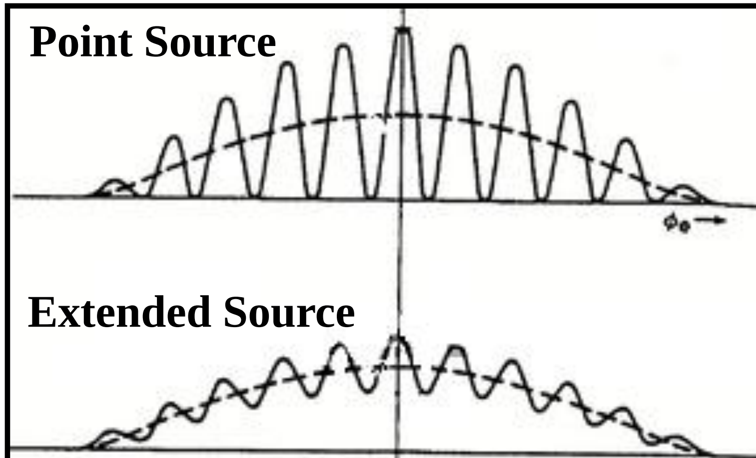


is built up as the Earth rotates

Adapted from *Instrumental Techniques in Radio Astronomy*, Johan Hamaker, Dwingeloo, NL ; http://www.astron.nl/%7Ehamaker/les4.ps

Beamforming vs. Aperture Synthesis Interferometers

- **The early radio interferometers were essentially multi-element (usually 2) beamformer arrays that were phased up as "transit" instruments.**
  - **These simple "beamformers" can improve their directionality by controlling the phase and amplitude of the wavefront incident on the array. The signals from the receiving elements were combined in such a way that those from particular angles experienced constructive interference while others experience destructive interference.**
- **The spatial aspects (i.e., shape, size, position angle, etc.) of the astronomical objects were analyzed from their fringes.**



Illumination Pattern of a 2-Element Interferometer

- **The use of interferometers to do true imaging at radio wavelengths didn't occur until Martin Ryle developed the concept of *aperture synthesis* at the University of Cambridge.**
- **During the late 1960s and early 1970s, as computers became capable of handling the computationally intensive Fourier transform, they used aperture synthesis to create the *One Mile Telescope*.**
- **Ryle was awarded the Nobel Prize in Physics in 1974 for his contribution.**
  - **Strangely enough, even in the early 1980s, Ryle didn't believe accurate interferometry could be done at frequencies above 10 GHz on baselines greater than 5 km (hence the size of Cambridge's last array, the *Five Kilometer Telescope*).**
  - **Fortunately "self-calibration", CLEAN and various other computational intensive deconvolution algorithms made it possible to create useful images from sparse & irregular baseline datasets.**
  - **Modern interferometers, such as the VLA, VLBA, WRST, MERLIN, GMRT, ATCA, KAT-7, ASKAP, etc, require powerful image processing computers.**

Radio Astronomy, J. Kraus, McGraw-Hill Inc., 1966, p.175

What about the First American Radio Interferometer…

Military patronage in the US not only led researchers in the postwar decade away from radio astronomy, but even those who did pursue it were persuaded to work at shorter wavelengths (less than 30 cm, or frequencies above 1000 MHz), a technical direction that was less successful in producing first-class research. Ever since the 1930s front-line radar development had trended toward shorter operating wavelengths that allowed superior detection and location of targets at greater distances.[134] Likewise for radio astronomy, shorter wavelengths had the potential of allowing more detailed maps of the sky, and the groups at NRL and Cornell therefore poured resources into research at wavelengths less than 20 cm.[135] NRL, the largest American group, also had a particular interest in short wavelengths because only those could provide sufficient accuracy for the Navy's desired all-weather radio sextant. Observations at microwavelengths also offered the Americans their own research niche distinct from that of the leading foreign groups. Furthermore, American budgets could handle the necessity at microwaves for the (expensive) "big dish" approach, as opposed to the cheaper interferometers and dipole arrays generally used overseas. Also pushing American radio astronomers to the use of microwaves and large dishes was influence from the US optical astronomy community (Section 17.3.2). As remarked by Scheuer in Section 17.2.2, interested astronomers such as Greenstein and Struve were naturally more comfortable and enthusiastic supporting a type of radio telescope that looked like a (proper) optical telescope, as opposed to an array of "clothes lines" scattered over a field. In fact, no interferometers existed in the US until 1953–54, when two were built at the Department of Terrestrial Magnetism, but significantly only as a result of long-term visits by Mills from Sydney and Smith from Cambridge.

by Merle Tuve (Carnegie Institution of Washington)

Cosmic Noise: A History of Early Radio Astronomy,
W.T. Sullivan, Cambridge University Press, 2009

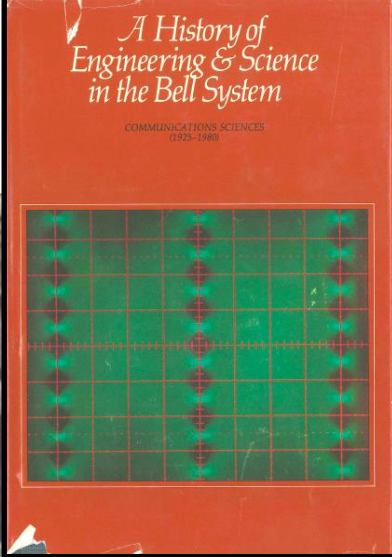
But there is More to the Story of the First Radio Interferometer…

- **The 1946 Australian and British telescopes may have been the first interferometers designed and utilized to explicitly carry out radio astronomy…**
- **…but neither of them were actually the first interferometer to detect an astronomical source at radio wavelengths.**
- **This was done - albeit accidently - in the United States over a decade earlier by the Bell Labs *Experimental MUSA*.**

Where I "Discovered" the MUSA

1.5 Overcoming the Effects of Fading

7 volumes with nearly 5,000 pages



At short wavelengths, there are interferences in reception due to waves arriving over more than one path via the highly variable ionosphere. With multiple paths, out-of-phase addition of signals can result in very deep nulls in signal reception that change as the layers move. Investigations carried out in the late 1920s and early 1930s showed that when the same signal is received on two separate antennas, the instantaneous fading is not the same on the two receivers. Spacings of as little as six wavelengths gave sufficiently low correlation to encourage combining the output from two or more receivers with separate, spaced antennas to get a resultant "post detection" combined signal that was more satisfactory than that obtained from either receiver alone. Since each receiver was sensitive to signals arriving from different angles in the vertical plane, this system did little to combat selective fading in the audio band caused by interference between signal components with large delay differences.

A different approach to the problem resulted in a receiving system called the Multiple Unit Steerable Antenna (MUSA), which was set up at Holmdel in 1936 by Friis and his collaborators.[26,27] [Fig. 5-7] This system employed sharp vertical-plane directivity, which could be electronically steered to receive signals arriving at a particular angle and exclude signals arriving at other angles. Six rhombic antennas, each about 315 ft. long, were arranged in a line to form a phased array extending about three-quarters of a mile toward England. The antenna outputs were conducted over coaxial cable to double-detection receivers, one for each antenna, located at the receiving building. Here the phasing for the array was accomplished by means of rotatable phase shifters operating at the intermediate frequency of the receivers. The phase shifters, one for each antenna, were geared together, and the favored direction in the vertical plane c… of phas… receivi… circuit to determine the angles at which waves were arriving. The other two branches were then set to receive at these angles, thus providing diversity in angle of reception. To obtain full benefit of the angular resolution afforded by the sharp directivity of the array, the different delays corresponding to the different angles were equalized by audio delay net-

Fig. 5-7. The six-element Multiple Unit Steerable Antenna (MUSA). This first electronically steerable antenna had good vertical-plane directivity and could be electronically steered with phase shifters for angular directivity, resulting in improved reception, signal-to-noise ratio, and audio quality.

works before combining in the final output. The benefits of the MUSA …ferred to one …y, due jointly …ubsequently, a 16-element antenna was built at Manahawkin, New Jersey, for operational use.

MUSA was the first electronically steerable antenna.

MUSA was the first electronically steerable antenna. The application of this pioneering work has continued into the 1980s, albeit in a much more sophisticated manner, to radar, satellites, and mobile radio.

***History of Engineering & Science in the Bell System – Communication Sciences*, S. Millman, AT&T Customer Information Center, 1984, p. 202-203**

Karl Jansky & "Star Static"

Karl Jansky with his antenna

- **Karl Jansky joined Bell Labs in 1928.**
- **He was assigned to investigate sources of atmospheric static that might interfere with short-wave (3-30 MHz) radio links that were being used for transatlantic telephone communications.**
- **While listening for the noise coming from thunderstorms, he discovered…**

  "*noise of extraterrestrial origin*"
- **He was to refer to it in his published papers as "*star static*".**
- **His famous - albeit serendipitous - discovery was made in 1932.**
- **Karl Jansky is now recognized as the *Father of Radio Astronomy*.**

***Classics in Radio Astronomy*, W.T. Sullivan, D. Reildel Publishing Company, 1982, p. Frontispiece**

Jansky's Antenna

DIRECTIONAL STUDIES OF ATMOSPHERICS AT HIGH FREQUENCIES*

KARL G. JANSKY
(Bell Telephone Laboratories, New York City)

December, 1932

<u>Frequency</u>

14.6 meters
or
20.5 MHz

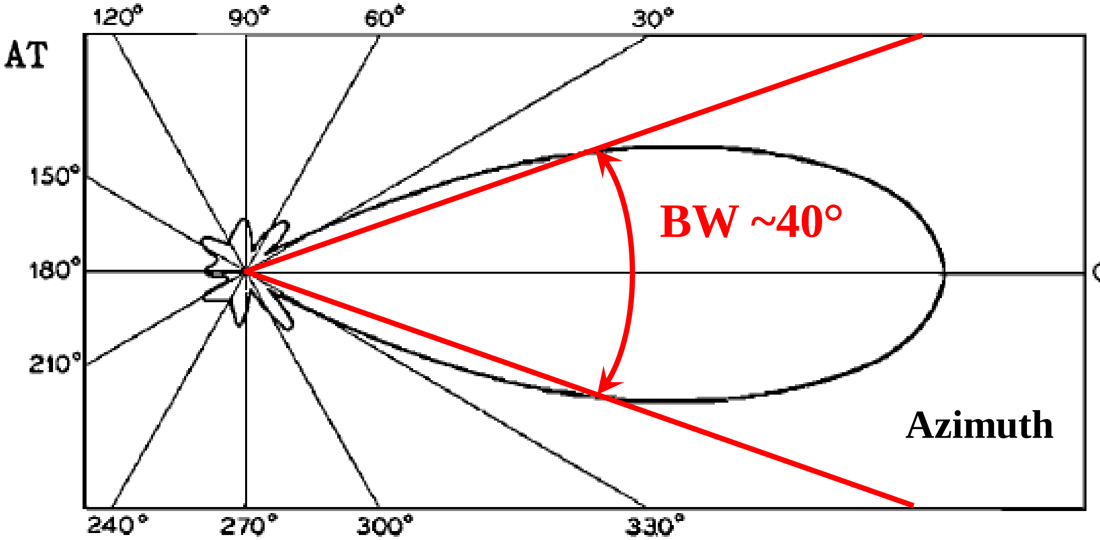


Fig. 3—Directional characteristic of array at 14.6 meters.

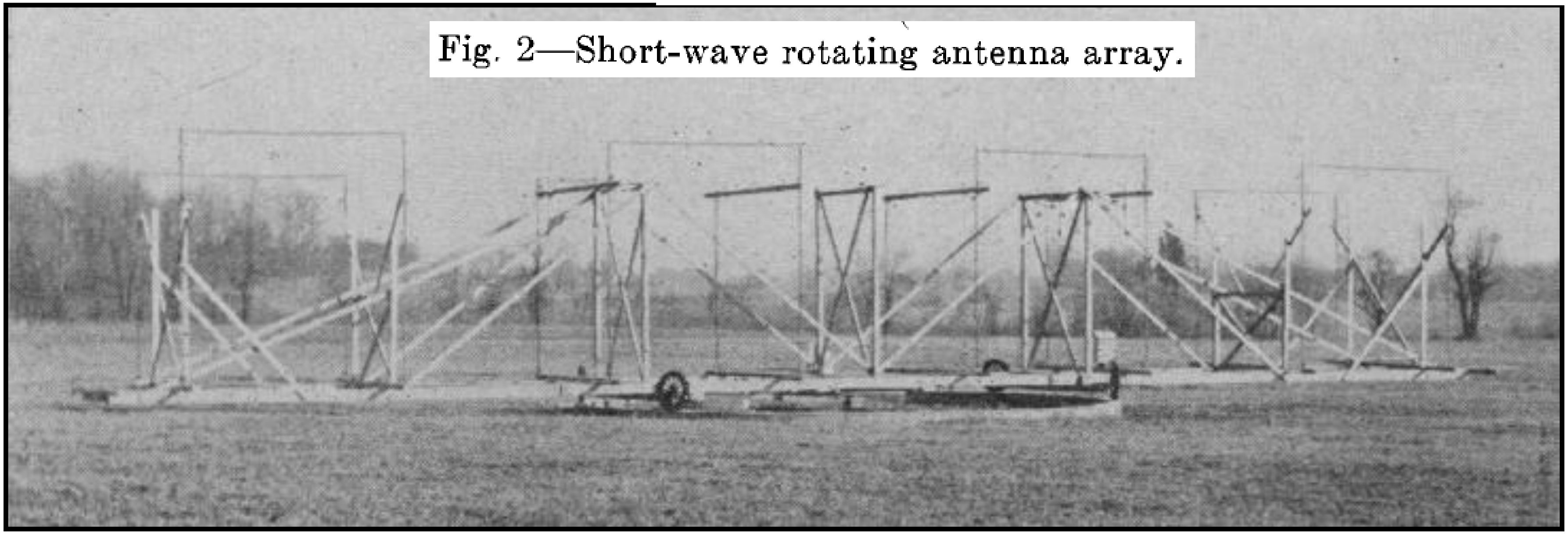


Fig. 2—Short-wave rotating antenna array.

Directional Studies of Atmospherics at High Frequencies, K.G. Jansky, Proc. of the IRE, Vol. 20, No. 12, Dec. 32, p. 1920

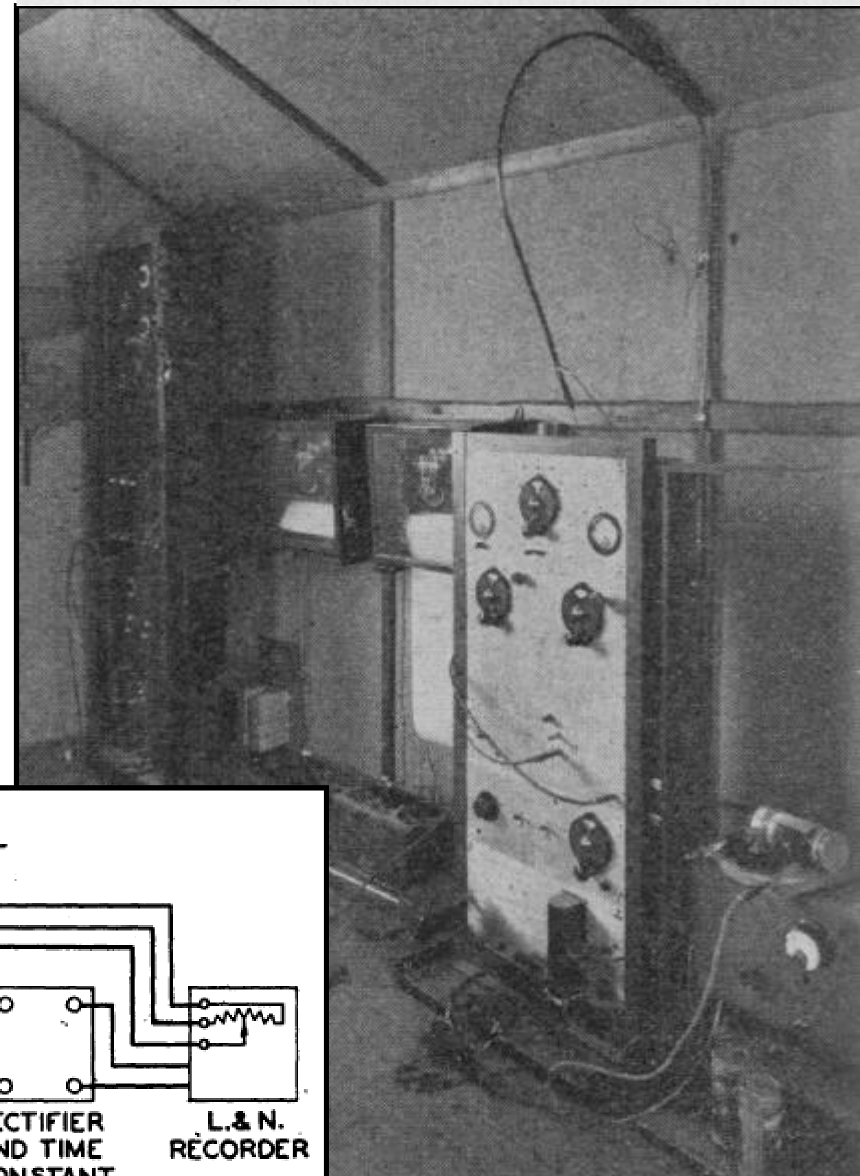
Jansky's Receiver

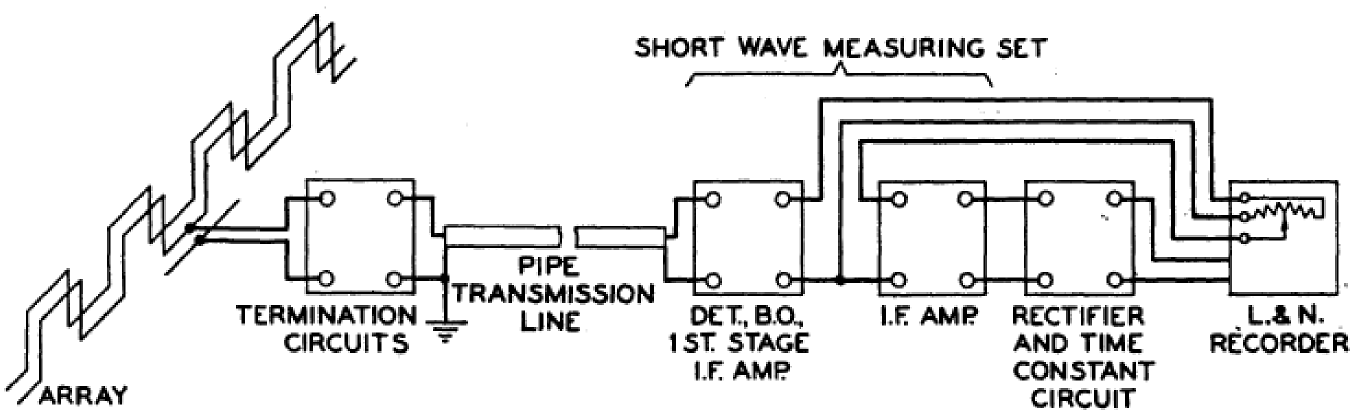
DIRECTIONAL STUDIES OF ATMOSPHERICS AT HIGH FREQUENCIES*

While Jansky's equipment was very primitive by today's standards, it was still up to the task for discovering *"star static"*.

The experiments which have been described in this paper were carried out at Holmdel, New Jersey. The writer wishes to acknowledge his indebtedness to Mr. Friis for his many helpful suggestions.

Fig. 5—Long- and short-wave static recording systems.



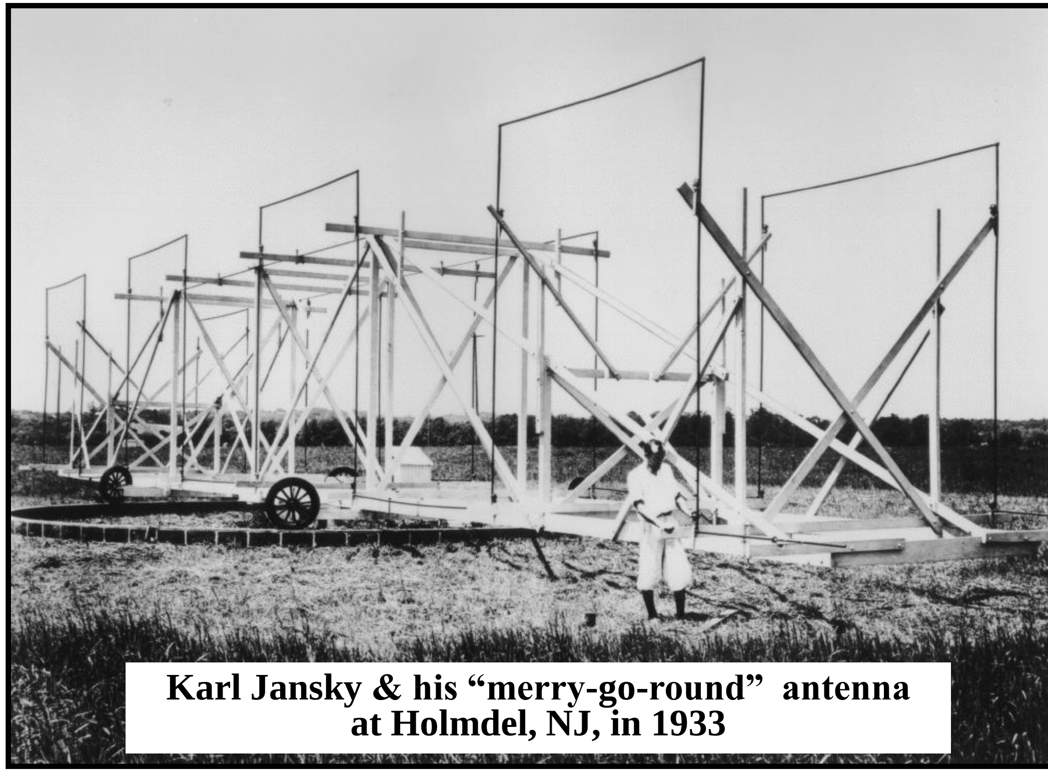


A.
SCHEMATIC DIAGRAM OF SHORT WAVE STATIC RECORDING SYSTEM

1930's "Block Diagram" (every symbol is a block)

***Directional Studies of Atmospherics at High Frequencies*, K.G. Jansky, Proc. of the IRE, Vol. 20, No. 12, Dec. 32, p. 1920**

Jansky, Bell Labs & Radio Telephony



Karl Jansky & his "merry-go-round" antenna at Holmdel, NJ, in 1933

- **The rotating aerial that Jansky had used for his study of the causes of static interference on short-wave telephony was a state-of-the-art direction finding instrument for its time.**
- **Known as a *Bruce Array*, it had been developed at Bell Labs by Edmond Bruce.**
- **It was 95-ft long and was a mass of wooden beams supporting a series of metal tubes. The structure was mounted on 4 Ford truck wheels for ease of rotation.**
- **In 1929, Jansky had initially erected his antenna in Cliffwood, NJ.**
- **A year later, it was disassembled and moved 10 miles south to the new Bell *Radio Research Laboratory* at Holmdel, NJ.**
- **Jansky's antenna, while useful for investigating static interference, was not appropriate for studying the most troublesome problem with short-waves telephone links – that of signal fading.**
- **This is where Harald Friis entered the picture with his design of the first electronically steered phased-array.**

http://www.nrao.edu/whatisra/images/jansky1.gif

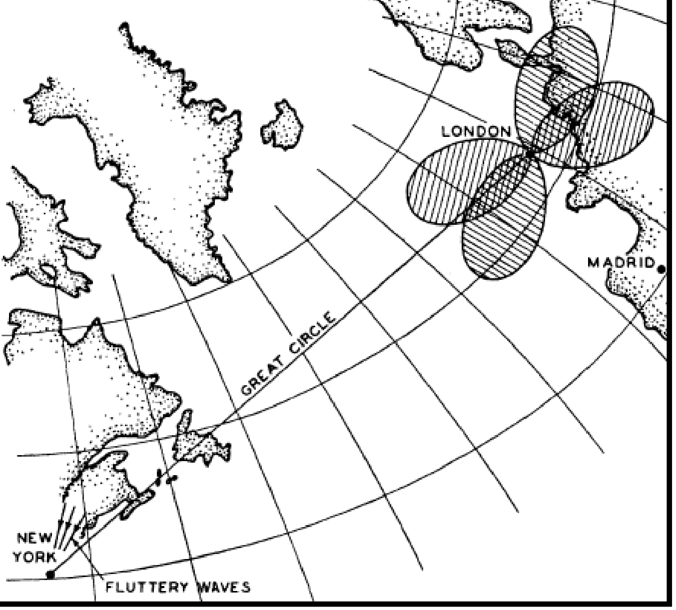
History of Transatlantic Telephone Communications

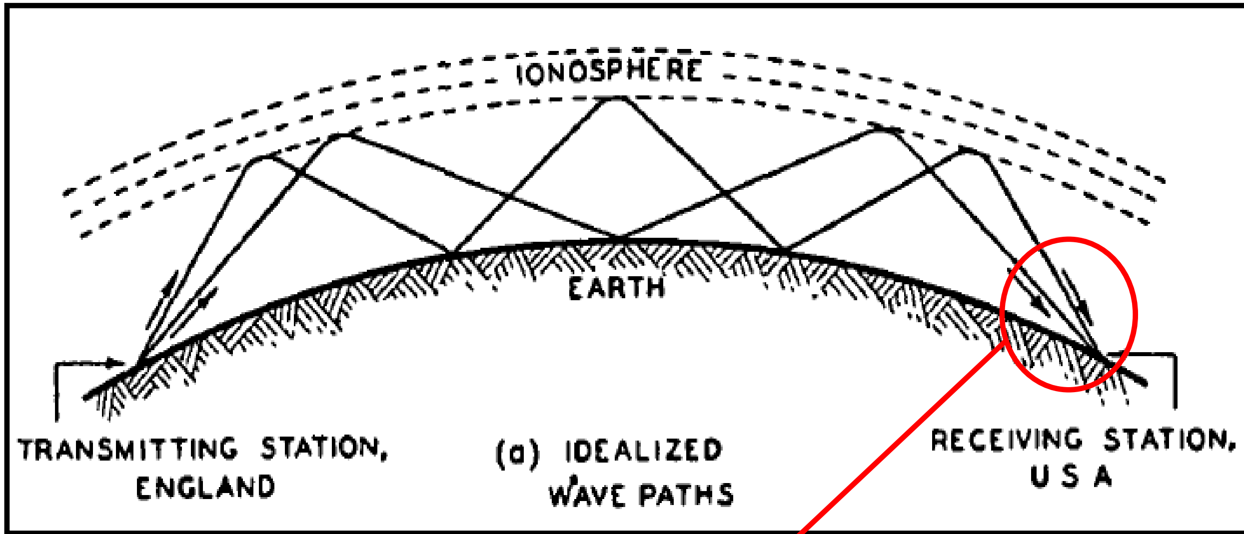
- **The first successful underwater telegraph cable across the Atlantic was put into operation in 1866. Communication was done using Morse Code.**
- **Wireless telegraphy, which meant "Morse code transmitted with Hertzian waves", was used during the 1887 to 1920 period (before the term *radio* came into use).**
- **In the 1920s, Radio Telephony began to displace Radio Telegraphy.**
-
- **The first transatlantic telephone cable (TAT-1) system, linking Newfoundland and Scotland, was inaugurated on September 1956.**
  - **The coaxial cable carried 48 telephone channels.**
  - **The total cost was about £120M. It was retired in 1978**
- **The first geostationary satellite for telecommunications over the Atlantic Ocean was *Early Bird* Intelsat I, which was launched on April 6, 1965.**
  - **It could handle 240 telephone channels (or one TV channel)**
  - **Operated by AT&T while Bell Labs built the satellite & the US ground station.**
  - **Today's satellites can handle 100's of TV channels & 100,000's of telephone calls.**
- **The first fiber optic transatlantic telephone cable, TAT-8, went into operation in 1988.**
  - **It carried 40,000 channels.**
  - **The system was built at a cost of US$335M. It was retired in 2002.**
  - **There are now about a dozen high capacity FO cables across the North Atlantic.**
- **During the period of interest for this story - the 1930s, WWII and into the 1950s - the shortwave radio circuit was the only method available for making a transatlantic telephone call.**
  - **The poor reliability of HF radio links posed many problems.**

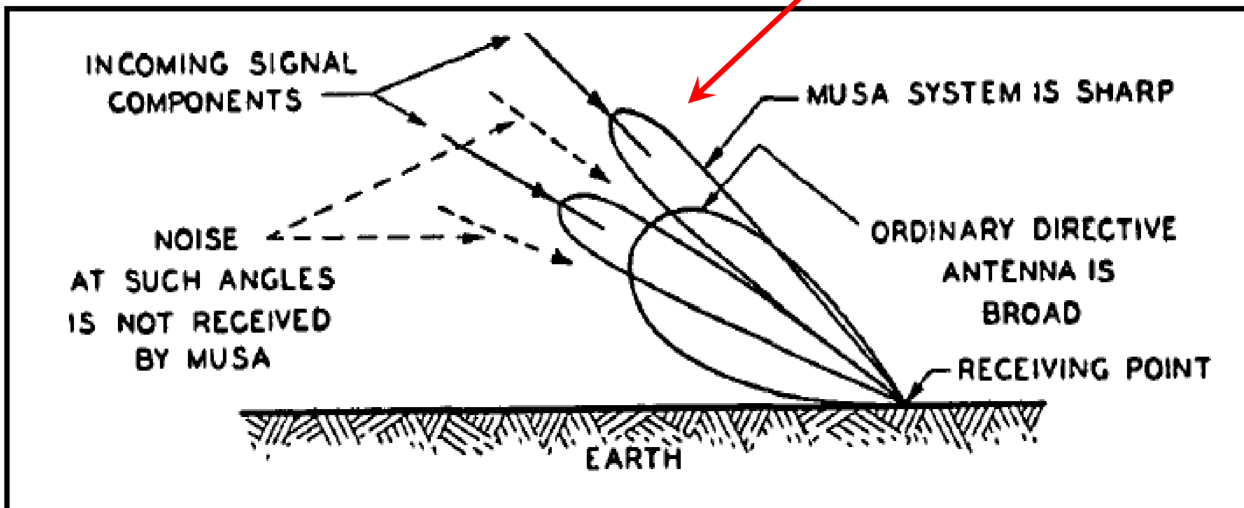
http://en.wikipedia.org/wiki/Wireless_telegraphy
http://en.wikipedia.org/wiki/Transatlantic_communications_cable
http://en.wikipedia.org/wiki/Communications_satellite

The Holmdel, NJ *Experimental MUSA*

Short Wave Radio Communication & the MUSA Concept







Physical basis for "musa" method.

- **Beginning in the mid 1920s, transatlantic telephony was done using "Short-Wave" (3-30 MHz) radio links.**
- ***Bell Labs* devoted a large amount of resources to make these systems as reliable as possible.**
- **Since short-waves bounce between the earth and the ionosphere, signals can arrive at the receiving station from multiple elevation angles. If they arrive out of phase, the multipath transmission can cause *fading*.**
- **What was needed was an antenna with better vertical directivity & a steerable beam. For these reasons, *Bell Labs* developed the MUSA.**

***Deviations of Short Radio Waves from the London-New York Great-Circle Path*, C.B. Feldman, Proceedings of the IRE, Oct 1939, 635-645**
***Researches in Radio Telephony*, R. Bown, Journal of the Institution of Electrical Engineers, Sept 1938, p. 395-402**

Multiple Unit Steerable Antenna

- **Designed by <u>C. Feldman</u> & <u>H. Friis</u> (Jansky's boss) for investigating the angles of arrival of radio signals**
- **5-20 MHz "Short Waves"**
- **Consisted of 6 Rhombic Antennas over ¾ mile long**
- **Had an electronically steerable beam in elevation from about 10° to 65°**
- **Width of beam**
  - **9.5 MHz was 16°x4°**
  - **18.6 MHz was 11°x3°**
- **The experimental MUSA had three independently steerable beams**

***A Multiple Unit Steerable Antenna for Short-wave Reception*, H.T. Friis & C.B. Feldman, Proceedings of the Institute of Radio Engineers, Vol. 25, No. 7, July 1937, p. 841-917**

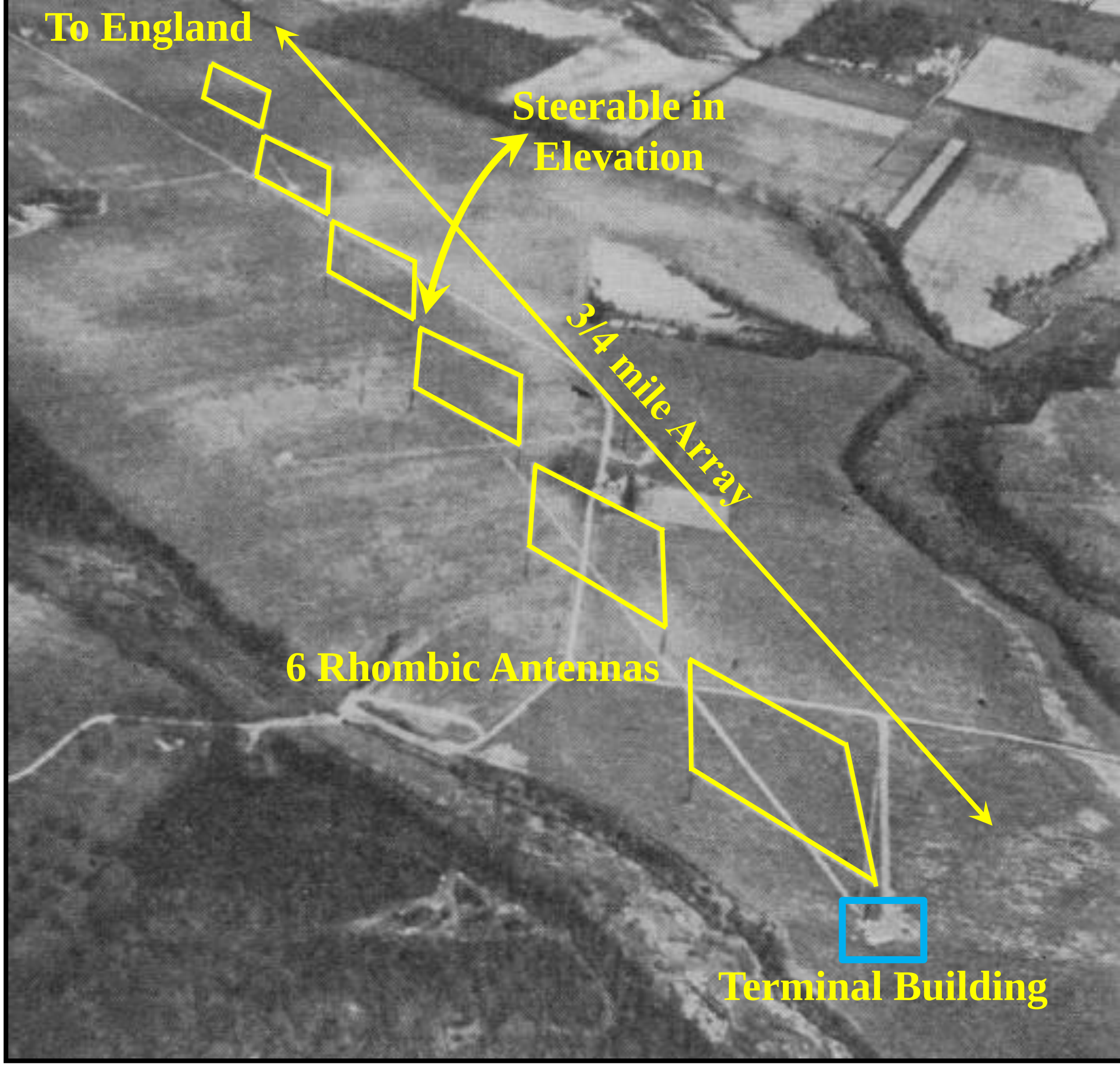
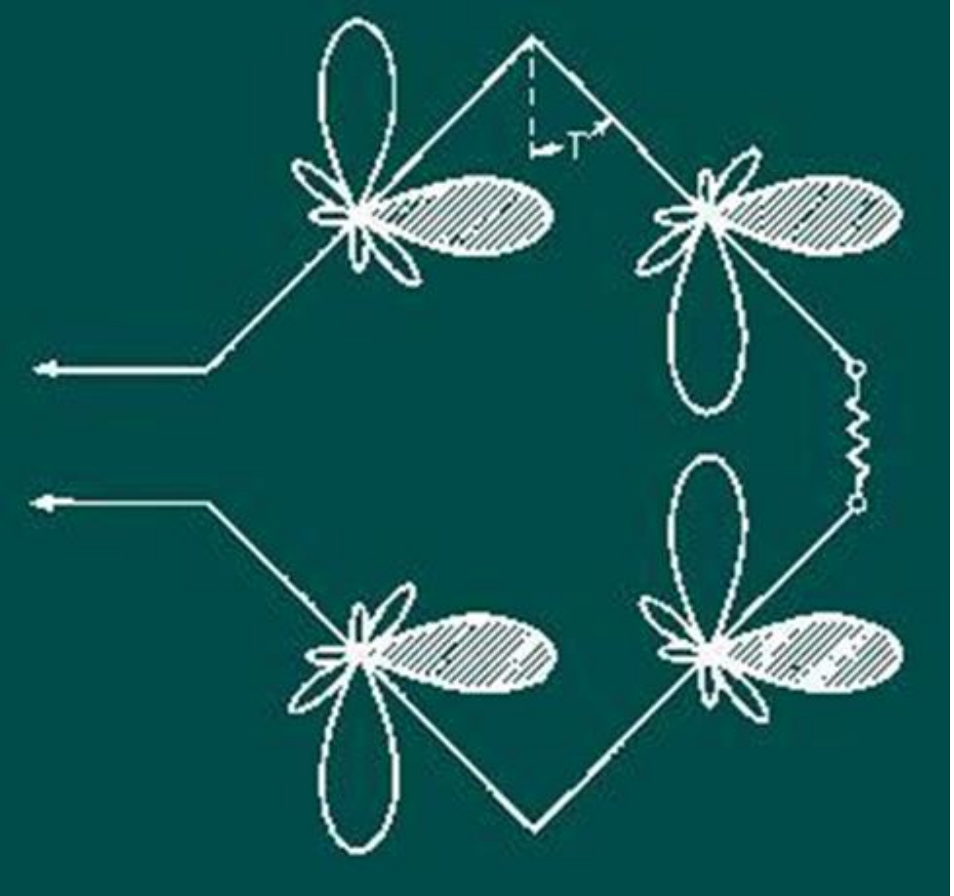


Fig. 2—Airplane view of the three-quarter-mile experimental MUSA on the receiving laboratory site located near Holmdel, New Jersey. The white line beneath the antennas is the newly filled trench in which coaxial transmission lines are buried. The building appearing in the right-hand foreground houses the receiving apparatus. The ground is flat to within ±4 feet.

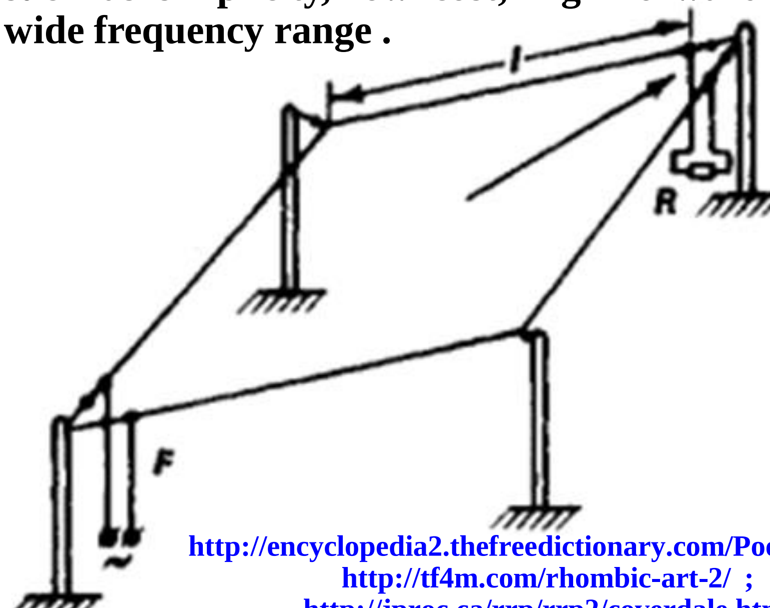
The Rhombic Antenna

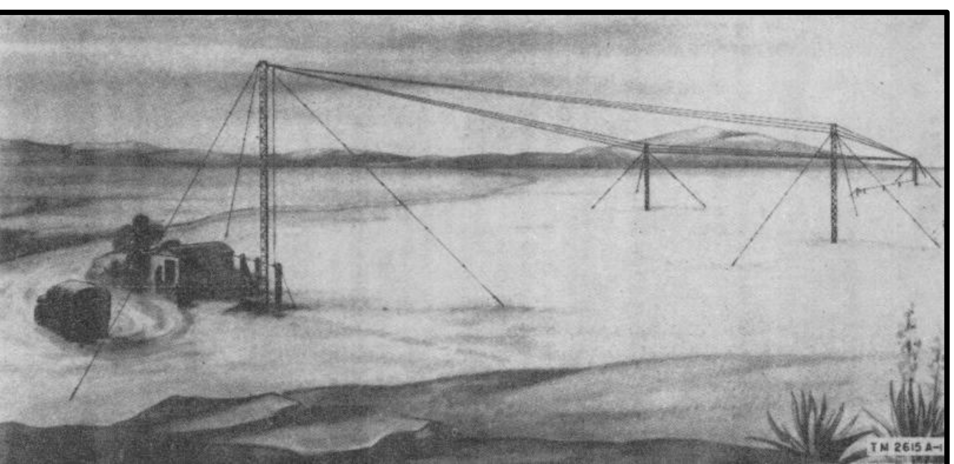


A. INDIVIDUAL RADIATION PATTERNS

B. RESULTANT RADIATION PATTERNS

The rhombic was a HF broadband directional aerial invented by Edmond Bruce & Harald Friis in 1930.
It has several advantages over other HF antennas, such as simplicity, low cost, high forward gain and wide frequency range .

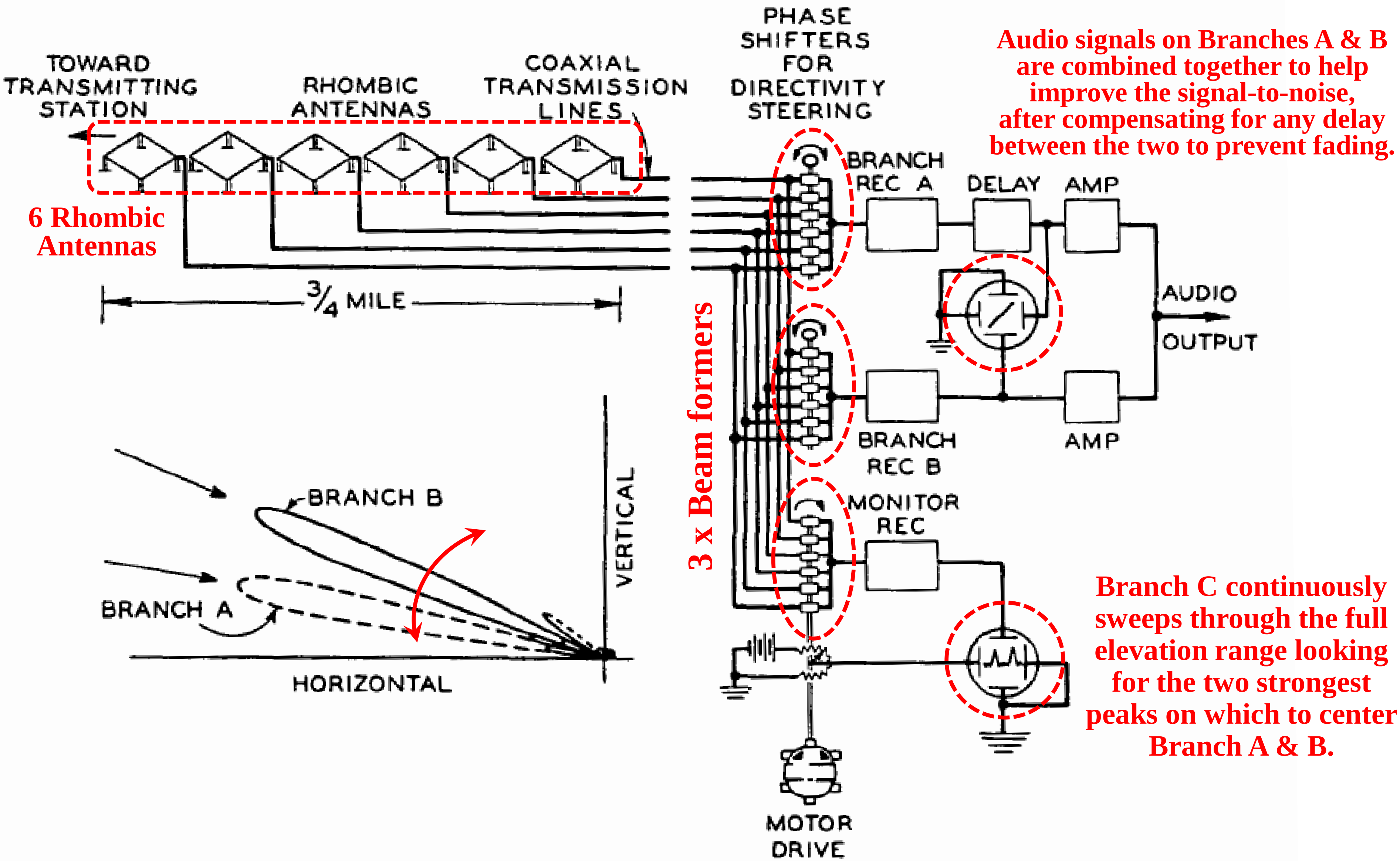




http://encyclopedia2.thefreedictionary.com/Poetic+rhyme
http://tf4m.com/rhombic-art-2/ ;
http://jproc.ca/rrp/rrp2/coverdale.html

Bell Labs Experimental MUSA at Holmdel

Simplified Diagram



Researches in Radio Telephony, R. Bown, Journal of the Institution of Electrical Engineers, Sept 1938, p. 395-402

MUSA
from the Outside

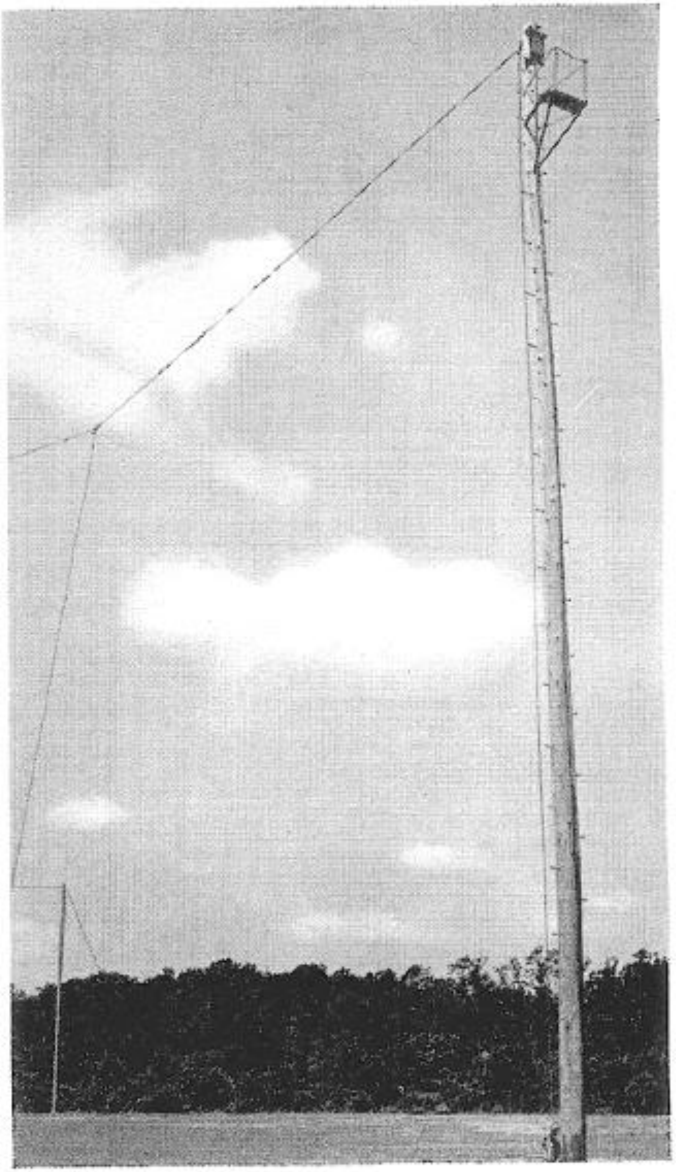


Fig. 4—At their output end each antenna is connected directly to a coupling unit, and at their termination end, the wires of each antenna are connected through three terminating resistances

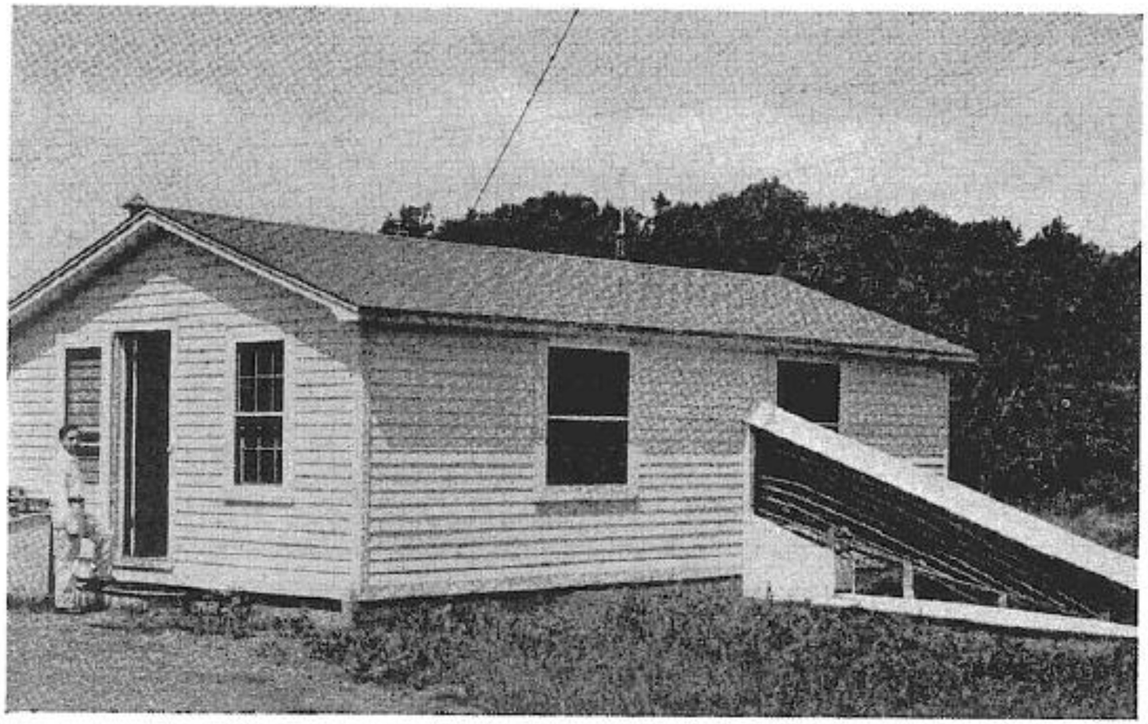


Fig. 1—The musa terminal building and the incoming coaxial transmission lines

***The Musa From the Outside*, L.R. Lowry,**
Bell Laboratories Record, Vol. 16, No. 6, Feb. 1938, p. 203

MUSA from the Inside

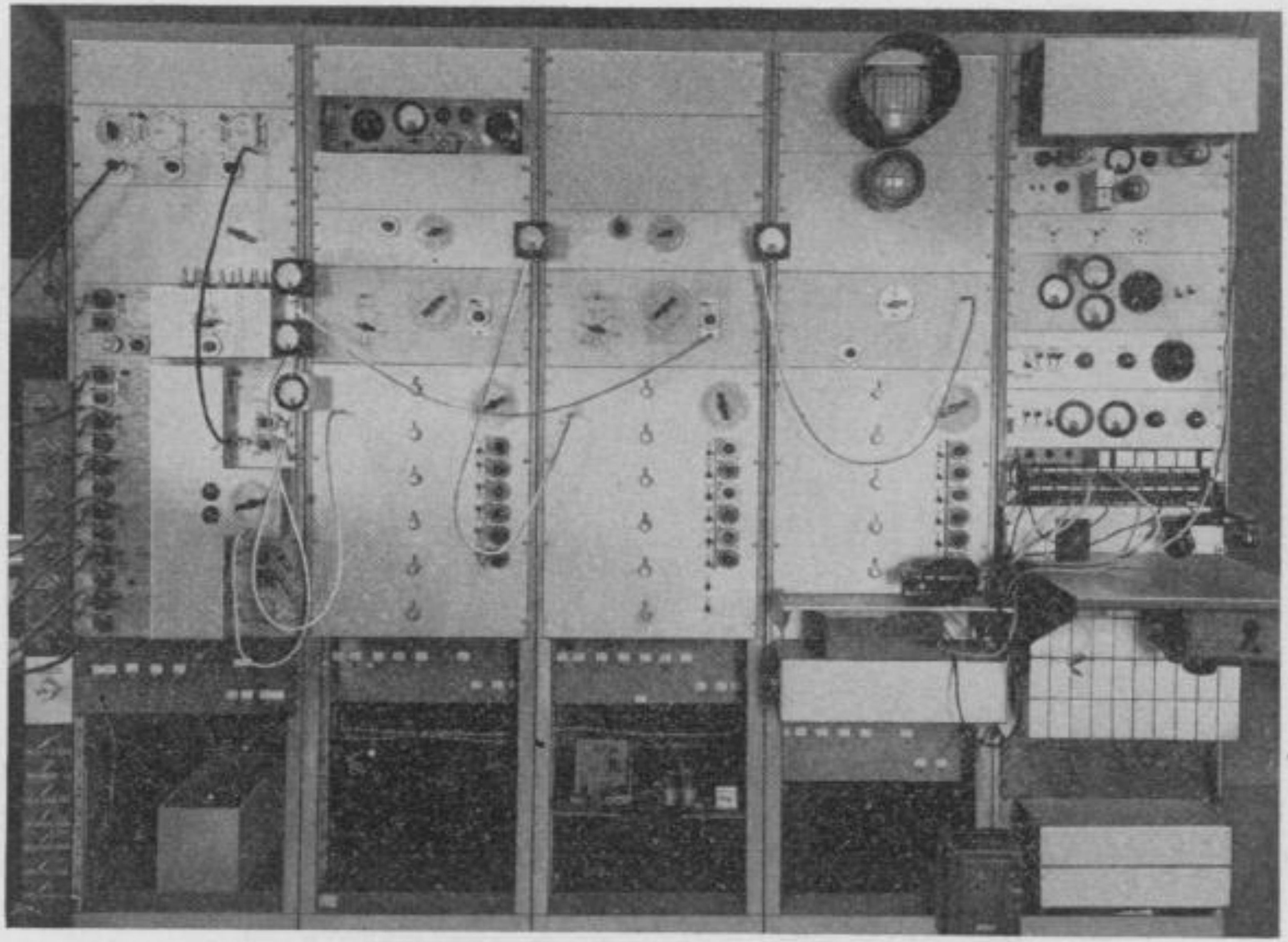
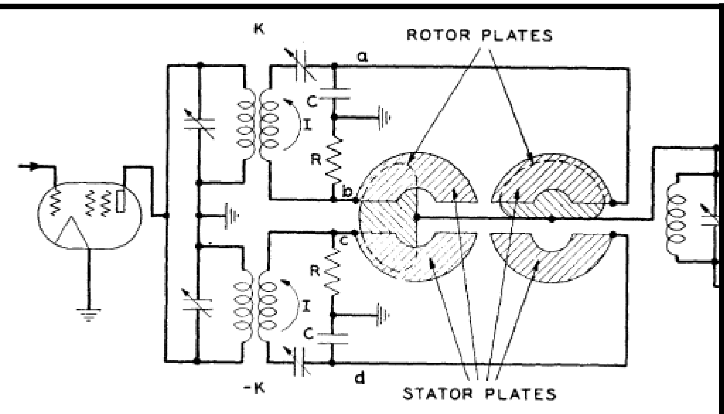


Fig. 16—Front view of the MUSA receiving equipment. The high-frequency bay is at the left and the audio-frequency bay at the right. The branch receivers are the panels directly above the phase shifting panels. The pulse receivers appear above these. At the top of the bay containing the monitoring branch equipment are the two oscilloscopes referred to in Fig. 3. The large tube with the ruled face is the monitoring oscilloscope.

A Multiple Unit Steerable Antenna for Short-wave Reception, **H.T. Friis & C.B. Feldman, Proceedings of the Institute of Radio Engineers, Vol. 25, No. 7, July 1937, 841-917**

MUSA Phase Shifter



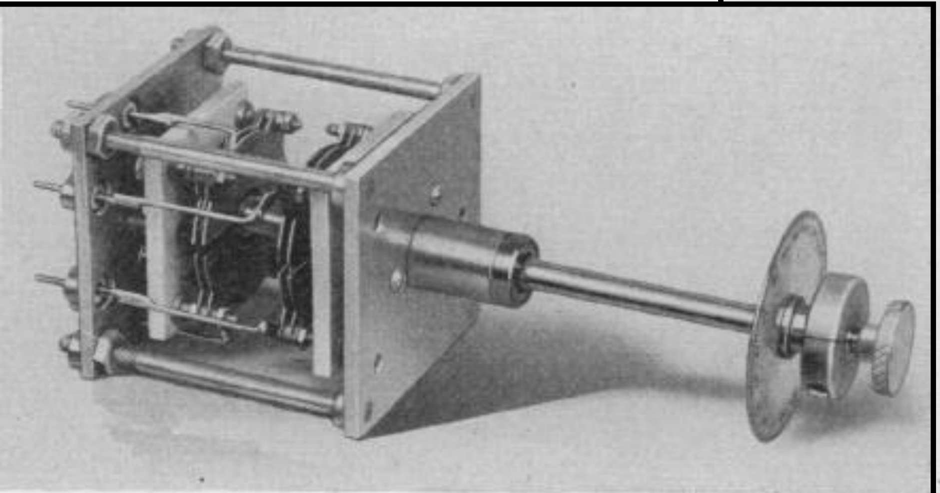


Fig. 14—The phase shifting condenser.

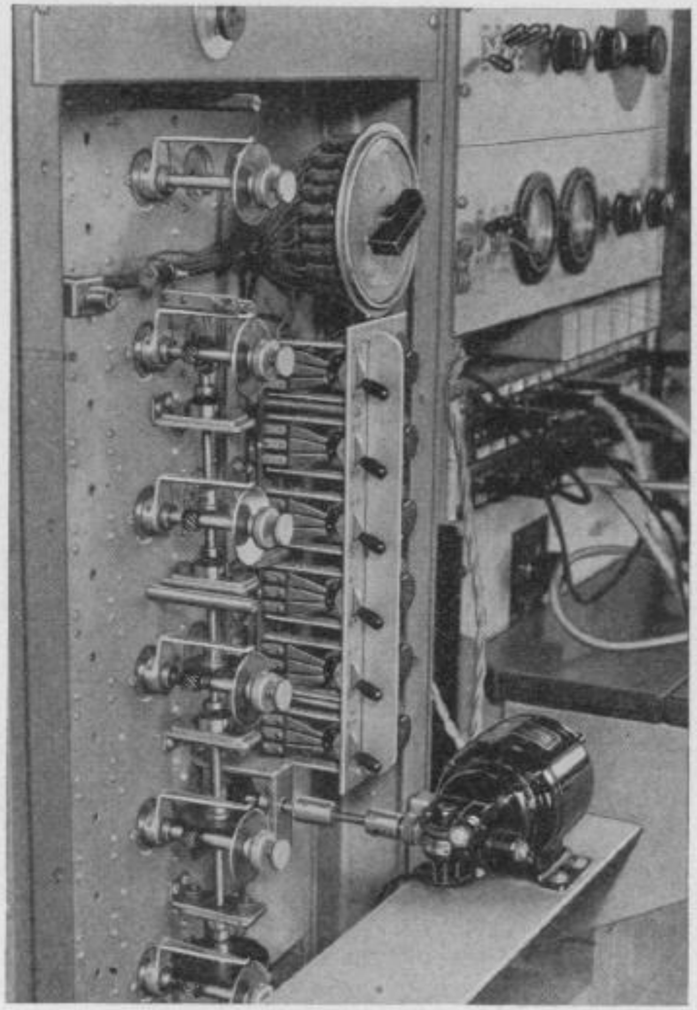


Fig. 15—Phase shifting panel of the monitoring branch. Only five of the six phase shifters are rotated for steering purposes. They are geared to the steering shaft in ratios of 1 : 1, 1 : 2, 1 : 3, 1 : 4, and 1 : 5.

***A Multiple Unit Steerable Antenna for Short-wave Reception*, H.T. Friis & C.B. Feldman, Proceedings of the Institute of Radio Engineers, Vol. 25, No. 7, July 1937, 841-917**

MUSA Antenna Inputs & Rack Rear View

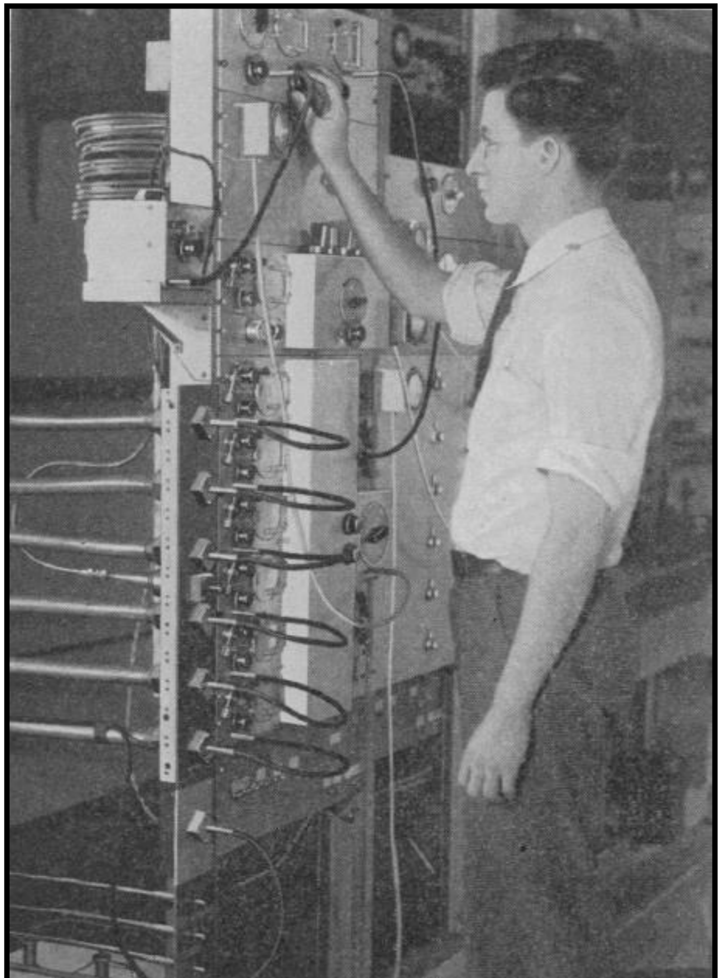


Fig. 17—View showing the six transmission lines and coaxial patch cords. The beating oscillator is mounted upon the shelf and is connected to the power amplifier (which is being adjusted by Mr. Edwards) at the top of the bay.

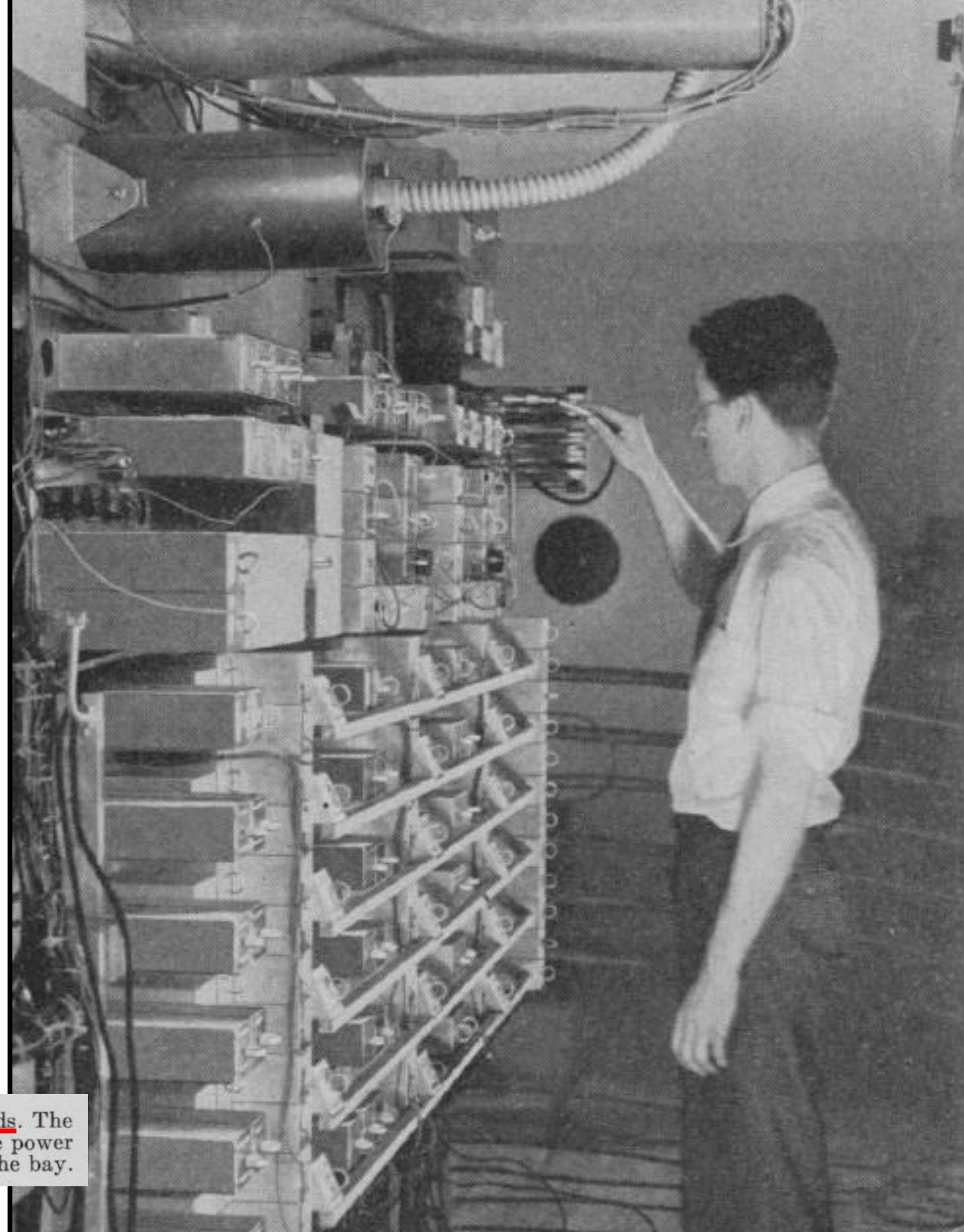


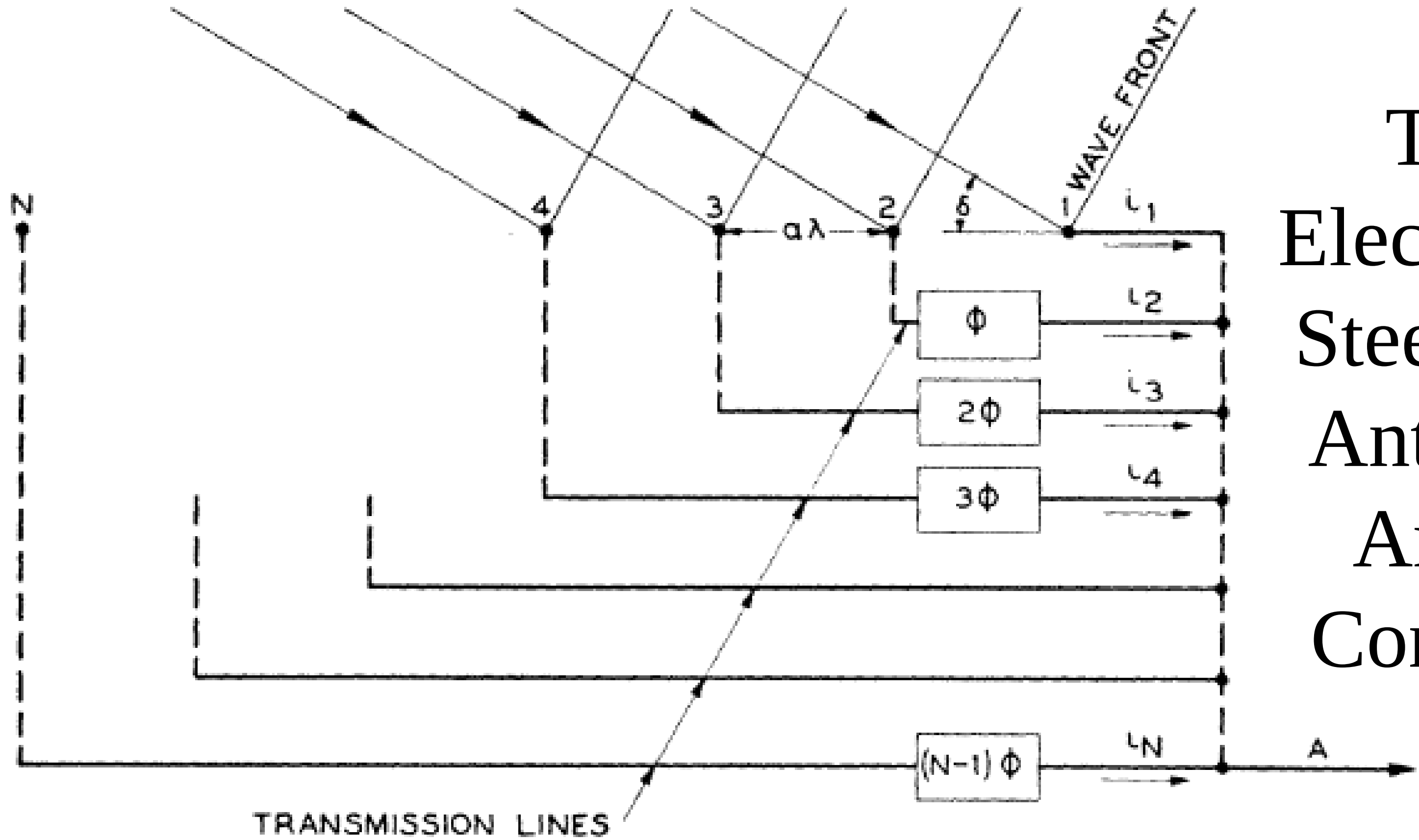
Fig. 18—Rear view of the receiving equipment. The six detector outputs feed the three branches via the square transmission lines.

A Multiple Unit Steerable Antenna for Short-wave Reception, **H.T. Friis & C.B. Feldman, Proceedings of the Institute of Radio Engineers, Vol. 25, No. 7, July 1937, 841-917**

A MULTIPLE UNIT STEERABLE ANTENNA FOR SHORT-WAVE RECEPTION*

By
H. T. Friis and C. B. Feldman
(Bell Telephone Laboratories, Inc., New York City)

Proceedings of the Institute of Radio Engineers
Volume 25, Number 7
July, 1937



The Electronic Steerable Antenna Array Concept

Fig. 1—A steerable antenna array using variable phase shifts ϕ, 2ϕ, 3ϕ, etc. The transmission lines indicated by broken lines are assumed to be of zero length. a is the spacing in free space wave lengths.

A Multiple Unit Steerable Antenna for Short-wave Reception, H.T. Friis & C.B. Feldman, Proceedings of the Institute of Radio Engineers, Vol. 25, No. 7, July 1937, 841-917

MUSA Array Pattern Analysis

$$i_1 = I\epsilon^{j\omega t}$$
$$i_2 = I\epsilon^{j\{\omega t+\phi-2\pi a(v-\cos\delta)\}}$$
$$i_3 = I\epsilon^{j\{\omega t+2[\phi-2\pi a(v-\cos\delta)]\}}$$
$$\cdot\ \cdot\ \cdot\ \cdot\ \cdot\ \cdot\ \cdot\ \cdot\ \cdot\ \cdot\ \cdot\ \cdot\ \cdot$$
$$i_N = I\epsilon^{j\{\omega t+(N-1)[\phi-2\pi a(v-\cos\delta)]\}}$$

where,

i = instantaneous current in exponential notation
ω = angular frequency
N = total number of unit antennas
a = spacing in free space wave lengths
$v = c/v$ = the ratio of the velocity of light to that of the transmission line.

The sum of the N currents is

$$A = I\epsilon^{j\omega t}\left\{1 + \epsilon^{j[\phi-2\pi a(v-\cos\delta)]} + \cdots + \epsilon^{j(N-1)[\phi-2\pi a(v-\cos\delta)]}\right\}. \quad (2)$$

This exponential series may be evaluated with the aid of the identity[12]

$$1 + \epsilon^{j\theta} + \epsilon^{j2\theta} + \cdots + \epsilon^{j(n-1)\theta} \equiv \frac{\sin\frac{n\theta}{2}}{\sin\frac{\theta}{2}}\,\epsilon^{j\frac{(n-1)\theta}{2}}.$$

Using this summation we have

$$A = I\,\frac{\sin\frac{N}{2}[\phi-2\pi a(v-\cos\delta)]}{\sin\frac{1}{2}[\phi-2\pi a(v-\cos\delta)]}\,\epsilon^{j\{\omega t+(N-1)/2[\phi-2\pi a(v-\cos\delta)]\}}. \quad (3)$$

The amplitude of A in (3) is the array directional pattern or array factor. It is zero when the numerator alone is zero, i.e., when

$$\frac{1}{2}[\phi-2\pi a(v-\cos\delta)] \neq 0, \pm\pi, \pm 2\pi \cdots \text{ and simultaneously}$$
$$\frac{N}{2}[\phi-2\pi a(v-\cos\delta)] = 0, \pm\pi, \pm 2\pi \cdots.$$

It attains its maximum value of NI when the denominator and numerator are zero simultaneously, i.e., when

$$\frac{1}{2}[\phi-2\pi a(v-\cos\delta)] = 0, \pm\pi, \pm 2\pi \cdots \text{ and}$$
$$\frac{N}{2}[\phi-2\pi a(v-\cos\delta)] = 0, \pm\pi, \pm 2\pi \cdots.$$

[12] This identity may be deduced by substituting $\epsilon^{j\theta}$ for r in the well-known formula for the sum of a geometrical progression

$$1+r+r^2+r^3+\cdots+r^{n-1} \equiv \frac{r^n-1}{r-1}.$$

Using this summation we have

$$A = I\,\frac{\sin\frac{N}{2}[\phi-2\pi a(v-\cos\delta)]}{\sin\frac{1}{2}[\phi-2\pi a(v-\cos\delta)]}\,\epsilon^{j\{\omega t+(N-1)/2[\phi-2\pi a(v-\cos\delta)]\}}. \quad (3)$$

The amplitude of A in (3) is the array directional pattern or array factor. It is zero when the numerator alone is zero, i.e., when

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$$\frac{N}{2}[\phi-2\pi a(v-\cos\delta)] = 0, \pm\pi, \pm 2\pi \cdots.$$

It attains its maximum value of NI when the denominator and numerator are zero simultaneously, i.e., when

$$\frac{1}{2}[\phi-2\pi a(v-\cos\delta)] = 0, \pm\pi, \pm 2\pi \cdots \text{ and}$$
$$\frac{N}{2}[\phi-2\pi a(v-\cos\delta)] = 0, \pm\pi, \pm 2\pi \cdots.$$

$$A'' = \frac{\sin\frac{n}{2}\left[2\pi\frac{a}{n}(1-\cos\delta)\right]}{\sin\frac{1}{2}\left[2\pi\frac{a}{n}(1-\cos\delta)\right]} \times \frac{\sin\frac{N}{2}[\phi_v-2\pi a(v-\cos\delta)]}{\sin\frac{1}{2}[\phi_v-2\pi a(v-\cos\delta)]}. \quad (6)$$

A Multiple Unit Steerable Antenna for Short-wave Reception, **H.T. Friis & C.B. Feldman, Proceedings of the Institute of Radio Engineers, Vol. 25, No. 7, July 1937, 841-917**

Vertical Directional Patterns of the Experimental MUSA

Elevation Angle vs. Wavelength & Phase Delay

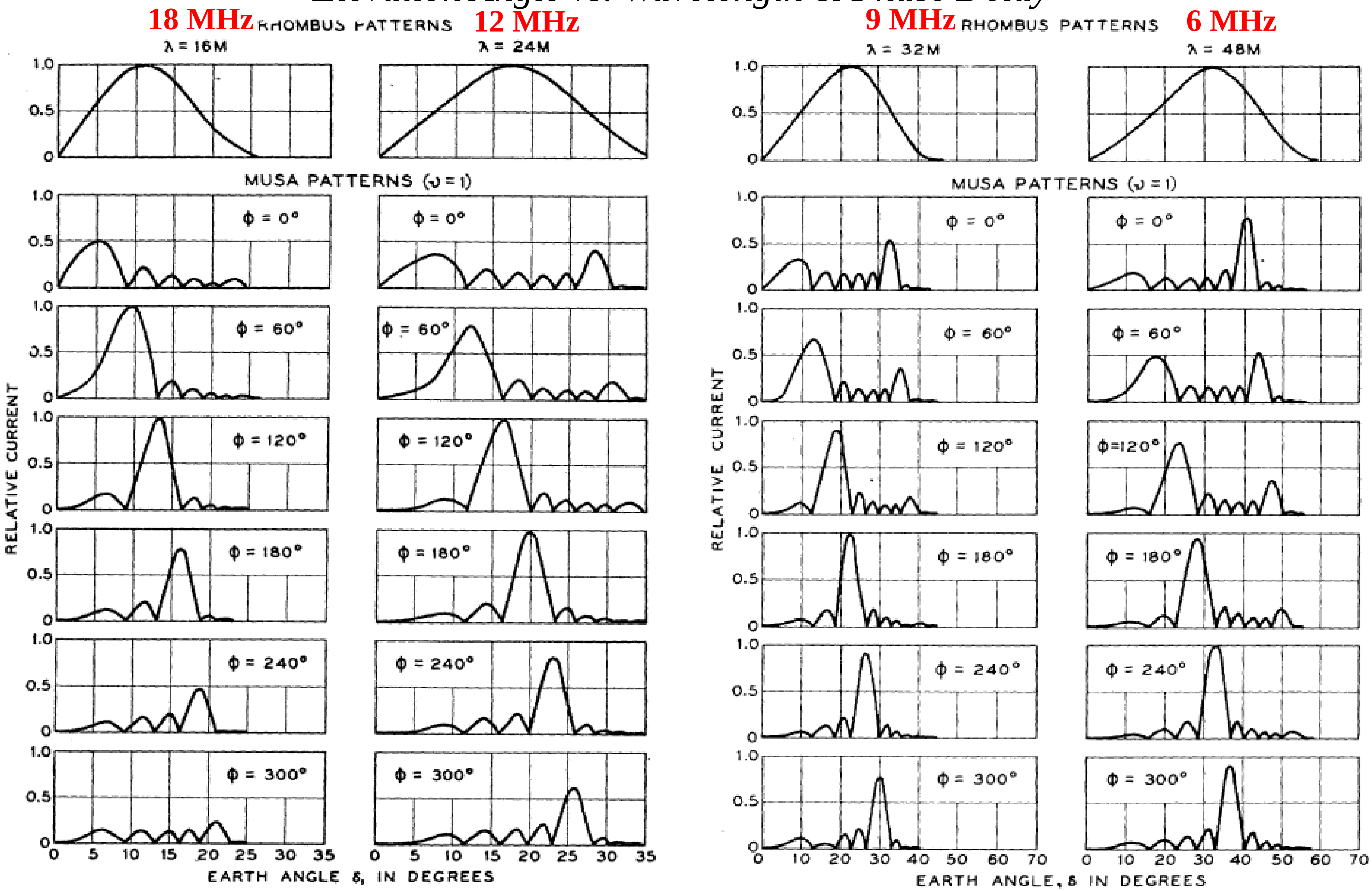


Fig. 19

Fig. 20

A Multiple Unit Steerable Antenna for Short-wave Reception, H.T. Friis & C.B. Feldman, Proceedings of the IRE, Vol. 25, No. 7, July 1937, 841-917

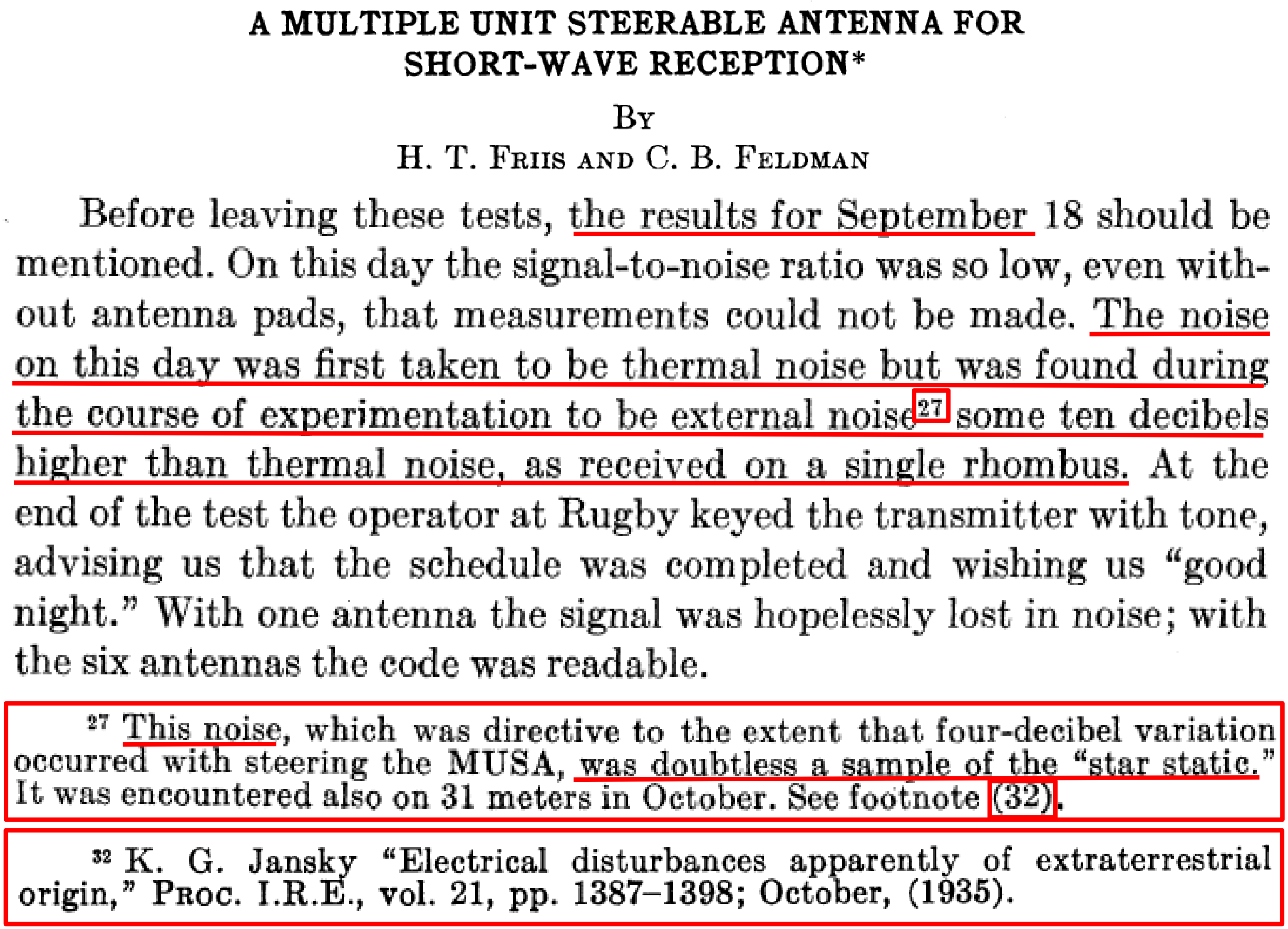
Tapering of the MUSA Array

The curves as plotted assume that the differences in transmission line loss for the various line lengths have been equalized in the intermediate-frequency circuits. By slightly tapering the amplitudes so that the antennas in the middle of the array contribute more than those near the ends a reduction of the minor lobes has been obtained at the cost of slightly widening the principal lobe. As a result of this, the directional discrimination of the experimental MUSA has been improved. All data and photographic records reported in this paper, however, were obtained before this improvement was introduced.

A Multiple Unit Steerable Antenna for Short-wave Reception, **H.T. Friis & C.B. Feldman, Proceedings of the Institute of Radio Engineers, Vol. 25, No. 7, July 1937, 841-917**

MUSA & the Detection of Jansky's ★Star Static★ at 9.5 & 18.6 MHz in 1935

1937


A MULTIPLE UNIT STEERABLE ANTENNA FOR SHORT-WAVE RECEPTION*

By

H. T. Friis and C. B. Feldman

Before leaving these tests, the results for September 18 should be mentioned. On this day the signal-to-noise ratio was so low, even without antenna pads, that measurements could not be made. The noise on this day was first taken to be thermal noise but was found during the course of experimentation to be external noise[27] some ten decibels higher than thermal noise, as received on a single rhombus. At the end of the test the operator at Rugby keyed the transmitter with tone, advising us that the schedule was completed and wishing us "good night." With one antenna the signal was hopelessly lost in noise; with the six antennas the code was readable.

[27] This noise, which was directive to the extent that four-decibel variation occurred with steering the MUSA, was doubtless a sample of the "star static." It was encountered also on 31 meters in October. See footnote (32).

[32] K. G. Jansky "Electrical disturbances apparently of extraterrestrial origin," Proc. I.R.E., vol. 21, pp. 1387–1398; October, (1935).

A Multiple Unit Steerable Antenna for Short-wave Reception,
H.T. Friis & C.B. Feldman, Proceedings of the Institute of Radio Engineers, Vol. 25, No. 7, July 1937, 841-917

Reference to Jansky's first paper in radio astronomy

MUSA & *Star Static*

Random Addition of Static

In analyzing the spaced antenna systems at the beginning of this section it was assumed that the static outputs of the antennas add on a power basis. An experimental study of this was made by measuring the static output of one unit antenna and comparing it with the static output of the six antennas combined as one MUSA branch. The circuit shown in Fig. 35 was used for these experiments. The results are tabulated in Table VIII.

TABLE VIII

Date	GMT	f_{mc}	Type of Static	Addition Max. db	Addition Min. db	Thermal Noise db
1935						
9–19	1530	18.6	star	8.5		−12
10–15	1500	9.51	star	8.0		
10–16		9.51	distant	7.5		− 6
10–22	1500	9.51	crash	8		−20
10–23	1500	9.51	distant	8		− 9
	1820	11.86	distant	8.5		
10–24	1500	9.51	star	11.4	5.4	−12
	1510	9.51	star	11.0	6.0	−12
	2045	9.51	crash	7.5		−30
11–1	1450	9.51	distant	9.0		− 8
	1830	9.51	distant	8.0		− 7
1936						
1–7	1500	9.51	distant	7.5		− 8
	1505	9.51	distant	8		− 8
1–14	0300	4.82	crash	8.2	7.3	−20
1–15	0300	4.82	crash	6.8	3.0	−30
		Average		8.0		

So what exactly was this "Star Static"?

It would remain unknown for a nearly a decade until Grote Reber analyzed the MUSA data taken by Friis & Feldman and deduced what the source really was…

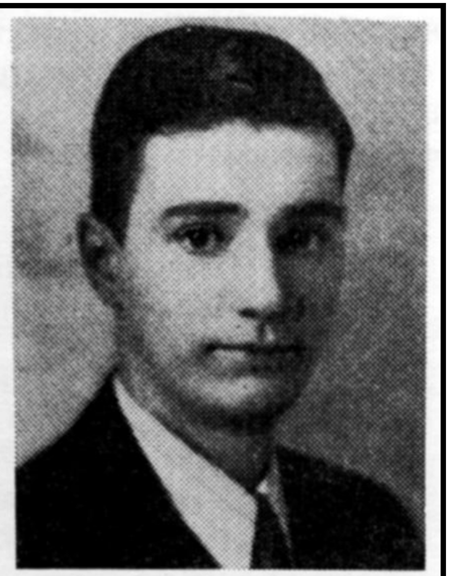
A Multiple Unit Steerable Antenna for Short-wave Reception, H.T. Friis & C.B. Feldman, Proc of the IRE, Vol. 25, No. 7, July 1937, 841-917

The Experimental MUSA and its Impact on Radio Astronomy.

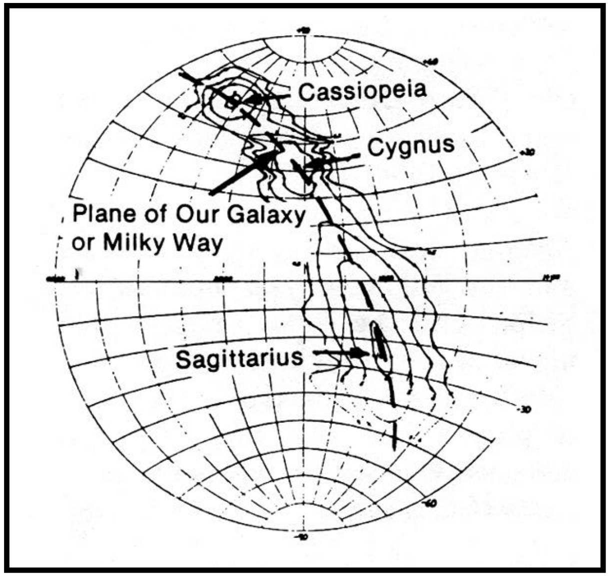
A Chronological Survey of some of the Papers in the Astronomical Literature…

Grote Reber & *Cosmic Static*

- **Grote Reber, a radio engineer & avid radio amateur, had read Jansky's articles. By 1938, he had constructed a 31-foot parabolic dish in his back yard in Wheaton, IL, and had begun his own observations of the celestial sky.**
- **Drift scans at both 9-cm & 33-cm produced negative results, so he built a new 1.9-m receiver. In April 1939 he found what he termed *cosmic static* from the center of the Milky Way.**
- **He then embarked on the first survey of the radio sky in 1941.**
- **Reber worked by day designing radio receivers at a factory in nearby Chicago. Taking the train was an hour each way. After supper he slept until midnight, and then sat in his basement and recorded the output meter readings of his receiver at one minute intervals until he left for work the next morning.**
- **By 1941 he had purchased an automatic strip chart recorder.**
- **Reber is considered to be the *world's first radio astronomer*.**



Grote Reber circa 1940.



Reber's 1944 Radio Sky at 1.9m

http://www.bigear.org/CSMO/HTML/CS13/cs13p14.htm

***Grote Reber : A Radio Astronomy Pioneer*, K. I. Kellermann, in *The New Astronomy - A Meeting to Honor Woody Sullivan on his 60th Birthday*, edited by W. Orchiston, Springer, 2005**

References to the MUSA Detection in the Scientific Literature

Cosmic Static*

GROTE REBER†, ASSOCIATE, I.R.E.

INTRODUCTION

IN 1932 Jansky[1] published the first of a series of papers[2,3,4] indicating that a certain type of static appears to come from space and in particular from the plane of the Milky Way. Very few other[5] data are available on the disturbance. Various[6] hypotheses have been advanced to account for the phenomenon but all have failed under quantitative calculation.

160-MEGACYCLE TESTS AT WHEATON, ILLINOIS

The writer became interested in this work about three years ago. It was decided to make measurements at various frequencies with equipment of high resolving power. The apparatus shown in Fig. 1 is really a transit telescope adapted to work at radio frequencies. The mirror is 31 feet in diameter and has a focal

Fig. 1—Antenna system used for the investigation of cosmic static.

* Decimal classification: R114. Original manuscript received by the Institute, September 8, 1939.

† Wheaton, Ill.

[1] K. G. Jansky, "Directional studies of atmospherics at high frequencies," PROC. I.R.E., vol. 20, pp. 1920–1932; December, (1932).

[2] K. G. Jansky, "Electrical disturbances of extraterrestrial origin, PROC. I.R.E., vol. 21, pp. 1387–1398; October, (1933).

[3] K. G. Jansky, "A note on the source of interstellar interference," PROC. I.R.E., vol. 23, pp. 1158–1163; October, (1935).

[4] K. G. Jansky, "Minimum noise levels obtained on short-wave radio receiving stations," PROC. I.R.E., vol. 25, pp. 1517–1530; December, (1937).

[5] H. T. Friis and C. B. Feldman, "A multiple unit steerable antenna for short-wave reception," PROC. I.R.E., vol. 25, pp. 841–917; July, (1937); *Bell Sys. Tech. Jour.*, vol. 16, pp. 337–419; July, (1937).

[6] Greenstein and Whipple, "The origin of interstellar radio disturbances," *Proc. Nat. Acad. Sci.*, vol. 23, pp. 177–181; March, (1937).

Cosmic Static, G. Reber, Proceedings of the Institute of Radio Engineers, Vol. 28, 1940, p 68-70

INTERPRETATION OF RADIO RADIATION FROM THE MILKY WAY

CHARLES HARD TOWNES
Bell Telephone Laboratories, Murray Hill, N.J.

Received December 20, 1946

American physicist who won the Nobel Prize in 1964 for his work in quantum electronics leading to the development of the *maser* and *laser*. He also carried out research in radio and IR astronomy.

ABSTRACT

The theory of emission of radio radiation by ionized interstellar gas is briefly discussed, and formulae are given for radiation intensity. Experimental measurements of radiation received from the Milky Way between 3×10^{10} and 9.5×10^{6} cycles per second are analyzed and compared with theory. It is shown that radiation from interstellar gas explains the observed radio radiation from the Milky Way if the density of electron gas is near 1 electron per cubic centimeter and its temperature is 100,000°–200,000° K. It appears difficult to explain such radiation, assuming the generally accepted conditions of density of 1 per cubic centimeter and temperature near 10,000° K.

Radio-frequency radiation originating outside the earth's atmosphere was first discovered by Jansky[1] at a frequency of 18 megacycles per second. Since then, Reber[2] and others[3,4] have measured the intensity of this radiation or "noise" at other frequencies and fixed its direction more exactly. Jansky[5] suggested that the radiation which he detected might have come from ionized gas in the Milky Way. Reber[6] made a rough calculation for such a mechanism, and Henyey and Keenan[7] first applied a more quantitative theory and showed that the magnitude of radio radiation from the Milky Way agrees approximately with the radiation that one might expect from free-electron collisions with protons in interstellar space. They assumed the accepted values of electron density of approximately 1 per cubic centimeter and temperature equal to 10,000° K.

[1] *Inst. Radio Engineers*, **20**, 1920, 1932.
[2] *Ap. J.*, **100**, 279, 1944.
[3] Friis and Feldman, *Inst. Radio Engineers*, **25**, 841, 1937.
[4] Hey, Philips, and Parsons, *Nature*, **157**, 296, 1946.
[5] *Inst. Radio Engineers*, **23**, 1158, 1935.
[6] *Inst. Radio Engineers*, **28**, 68, 1940.
[7] *Ap. J.*, **91**, 625, 1940.
[8] Townes, *Phys. Rev.*, **69**, 695, 1946.

Townes (at 97) inspecting his *Infrared Spatial Interferometer (ISI)* on Mt. Wilson.

Interpretation of Radio Radiation from the Milky Way,
C. Hard Townes, Astrophysical Journal,
Vol. 105, 1947, p.235
http://en.wikipedia.org/wiki/Charles_Townes
http://isi.ssl.berkeley.edu/ISI_overview.ppt

TABLE 1

COMPARISON OF EXPERIMENTAL AND THEORETICAL VALUES FOR THE MAXIMUM APPARENT TEMPERATURE OF THE MILKY WAY

Observer	Frequency (Cycles/Sec)	Max. Apparent Temperature* (° K)	Max. Theoretical Apparent Temp. Assuming $n=$ 0.63/cc, $T=$ 10,000° K	Max. Theoretical Apparent Temp. Assuming $n=$ 1.1/cc, $T=$ 150,000° K
Dicke	3×10^{10}	<30	<5	<5
Reber	480×10^6	100–200	140	140
	160×10^6	1370	1370	1370
Hey, Philips, and Parsons	64×10^6	10,600	6000	9000
Jansky	18×10^6	92,000	10,000	84,000
Friis and Feldman	9.5×10^6	120,000	10,000	140,000

* Apparent temperature is the temperature of a black body which would radiate an equivalent amount of energy at the frequency of observation.

The data of Friis and Feldman[20] (Table VII of their paper) allow one to obtain the ratio of extra-terrestrial radio noise at 9.5 megacycles, using a narrow-beam antenna, to "thermal" noise when the antenna is replaced by a terminating resistance. The result is a ratio of 15.4-decibel maximum and 9.4-decibel minimum. Feldman informs the author that the so-called "thermal" noise of this paper was actually between 3 and 5 decibels above the theoretical thermal noise level $2\,kT_r$, where T_r is the temperature of the receiver, or approximately 300° K. The antennae used were of the same type as that used by Jansky, so that 3.5 decibels may be assumed lost in receiving. Thus the maximum noise from extra-terrestrial sources corresponds to a temperature of approximately $2T_r \times 10^{2.29} =$ 120,000°. A single measurement is given at 18.6 megacycles, the temperature computed from it being 60,000°. Although this is not a maximum value, it substantiates Jansky's 92,000° result at approximately this frequency. The data of Friis and Feldman were taken incidentally to the study of an antenna system and consequently are sketchy. The direction from which noise was received is not well known, since the antenna had a number of lobes whose direction could be varied over a considerable angle. The results do show, however, that the apparent temperature at 9.5 megacycles is of the same order as that at 18 megacycles, both being extremely high.

Interpretation of Radio Radiation from the Milky Way, C. Hard Townes, Astrophysical Journal, 1947, vol. 105, p.235

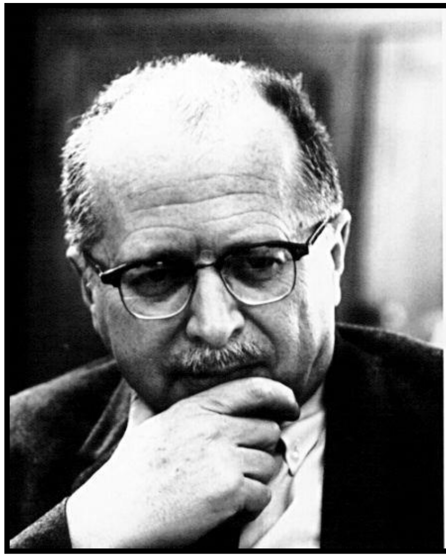
1947b

RADIO-FREQUENCY INVESTIGATIONS OF ASTRONOMICAL INTEREST.

By GROTE REBER *and* JESSE L. GREENSTEIN

ELECTROMAGNETIC energy is emitted at radio frequencies by various astronomical sources. Advances in the study of such energy have been rapid. In this review we will attempt to summarize briefly the present (1946 Sept. 15)* status of investigation in this rapidly expanding field.

In Jansky's experiments the antenna was rotatable in azimuth and fixed in altitude. The acceptance cone (conventionally defined by the width at which the power received has dropped to one-half its maximum value), was about 30° in width and 37° in height. In 1935 a large fixed antenna was used at Holmdel for reception of signals from England. The direction in altitude toward which it pointed was varied by electrical means. When terrestrial electrical noise was at a minimum, Friis and Feldman[5] noted that the received noise varied with antenna direction, at 18·6 Mc. and at 9·5 Mc. The maximum variation of angle obtainable was 20°. At 18·6 Mc. a variation of intensity of 2·5 : 1 was observed; the acceptance cone was 3° high and 11° wide. At 9·5 Mc. the variation was 4 : 1 and the acceptance cone 4° high and 16° wide. Reber computed the position in the sky at which the antenna pointed during the observations of Friis and Feldman, and found it to be in Cygnus. No accurate calibration is available, although recent estimates indicate the intensity is high. Two new conclusions appear in the work of Friis and Feldman. Cosmic static arrives from Cygnus as well as from the galactic centre in Sagittarius, and it has considerable concentration to the galactic plane. If we correct the variation of received intensity with angle for the finite resolving power of the antenna, the emitting region of the Milky Way is small.



Yerkes, and later Caltech, astronomer, who in 1953 was the chairman of the NSF's Advisory Committee on Astronomy which began the process that would lead to the creation of the NRAO.

In 1971 he chaired the NSF panel that recommended that the VLA was a project "*of the very highest urgency and priority*."

Radio-Frequency Investigations of Astronomical Interest, G. Reber & J. Greenstein, The Observatory, Vol. 67, 1947, p. 15-26
Early Years of Radio Astronomy in the U.S., B.F. Burke, in *Radio Astronomy from Karl Jansky to Microjansky*, L.I. Gurvits, S. Frey & S. Rawlings (eds), 2005

 1947b

If the radiation is assumed to be of thermal origin, the most serious observational problem is the quantitative measurement of intensities in the 10 to 30 Mc. range. Observations of Jansky, Friis and Feldman, and Franz should be repeated with particular attention to the absolute calibration, and to the correction for the low instrumental resolution encountered at long wave-lengths. Reber estimates that Jansky's 20·6 Mc. observations require an intensity of 14×10^{-22} watts/cm.^{2} cir. deg. Mc. bd. Very approximate calibrations of the work of Friis and Feldman and of Franz seem also to indicate the same order of intensity. In an as yet unpublished discussion, C. H. Townes of the Bell Telephone Laboratory has independently estimated the absolute intensities found by these workers and also concludes that they require an unexpectedly high temperature. In fact, over a range of frequency 9·5 to 480 Mc., the available observations indicate an intensity constant within less than a factor of ten.

Another investigation of the energy distribution to be expected from free-free transitions in space has been made by C. H. Townes[20]. He has attempted a classical calculation of the absorption by free-free transitions. Essentially his results agree with those of Henyey and Keenan. At frequencies below 60 Mc., $B_\nu (T_e)$ is proportional to $\nu^2 T_e$. The apparent temperature of space, T_a, required to explain an intensity larger than that given by B_ν (10,000°) varies as ν^{-2}. All theoretical investigators point out that the large energies observed by Jansky and Friis and Feldman are difficult to explain unless the electron temperature in space is of the order of 100,000°.

For thermal radiation, the signal strength should decrease at lower frequencies.

Instead it was found that the signals were far too strong, implying a "non-thermal" process must be at work. The MUSA's low-frequency, narrow-beam measurements were important data points.

The theory of *Synchrotron Emission* was not proposed until the early 1950's.

***Radio-Frequency Investigations of Astronomical Interest*, G. Reber & J. Greenstein, The Observatory, Vol. 67, 1947, p. 15-26**

COMMUNICATIONS
FROM THE
DAVID DUNLAP OBSERVATORY

Number 15

THE PRESENT STATUS OF MICROWAVE ASTRONOMY*

By RALPH E. WILLIAMSON

1. *Historical note.* In the winter of 1931 Karl G. Jansky[1] of the Bell Telephone Laboratories was making studies of the direction of arrival of high-frequency atmospheric static with a radio receiver tuned to a frequency of 20.5×10^6 cycles/sec. He discovered a faint source of static whose direction slowly changed throughout the day, and had approximately the same direction every day at the same time. He began an intensive study of this phenomenon, and determined that the variation of azimuth of the unknown source coincided with that of the sun. He continued his observations over a period of several months, and found that as the sun moved eastward, the direction from which the signal was coming remained fixed on the celestial sphere.[2] By an ingenious method he determined its approximate right ascension and declination, and showed that they coincided roughly with the direction in which astronomers placed the centre of our galactic system. His papers contain the first published evidence for the existence of extra-terrestrial radiation at radio-frequencies.

Within the next five years, Friis and Feldman[3] at the Bell Laboratories, and Potapenko and Folland[4] at the University of California also obtained evidence that sensitive short wave receivers could pick up radiation from extra-terrestrial sources.

The Present Status of Microwave Astronomy, R.E. Williamson, JRASC, Vol. 42, 1948, p. 9-32
http://rasc.ca/content/re-williamson ; http://www.astro.utoronto.ca/AALibrary/doings/DDDoings_v9n2_1976.pdf

Ralph Willliamson received his PhD (1943) in Chicago under Chandrasekhar. He was inspired to enter the field of radio astronomy after hearing Grote Reber speak at a seminar.
He spent time in Ithaca, NY, helping Charles Seeger found the *Cornell Radio Observatory* before joining the *David Dunlap Observatory* in 1946 as the department's first theorist,
He wrote the first radio astronomy paper from the *Univ of Toronto* in 1948, "*The Present Status of Microwave Astronomy*" (JRASC,42,9).
In 1953 he accepted a job *at Los Alamos Labs* & never contributed to the field again. He died in 1982.

REPORTS ON THE PROGRESS OF ASTRONOMY
RADIO ASTRONOMY

J. S. Hey

Vol. 109 No. 2, 1949

1. *Introduction.*—The investigation of astronomical phenomena by their radio emissions or by radio reflections from them has provided some striking discoveries during the last few years. This advance has been due in no small measure to the improvements in sensitivity and directivity of the radio receivers and transmitters used for radar during the war.

Observer	Wave-length metres	Maximum observed T_e	Maximum theoretical T_e assuming $n=0{\cdot}63$/c.c. $T=10{,}000$ deg. K.	Maximum theoretical T_e assuming $n=1{\cdot}1$/c.c. $T=150{,}000$ deg. K.
Dicke	0·01	(Negative Result) < 30	5	5
Reber	0·625	100–200	140	140
	1·85	1370	1370	1370
Hey, Phillips and Parsons	4·7	10,600	6000	9000
Jansky	16	92,000	10,000	84,000
Friis and Feldman	31	120,000	10,000	140,000

Radio astronomy has developed rapidly, and the number of published papers is already large. It will not be possible to discuss all of them without over-burdening the report. Consequently, not all the publications in the list of references are mentioned in the text, which attempts to outline the main trends of progress.

Reports on the Progress of Astronomy – Radio Astronomy, J.S. Hey, MNRAS, Vol. 109, 1949, p.179-214
http://www.galaxypix.com/people/people.htm?3
http://rsbm.royalsocietypublishing.org/content/48/167.full.pdf+html
http://profiles.nlm.nih.gov/ps/access/BBAPRT.pdf

One of the pioneers of radio astronomy, James Stanley Hey was a radar researcher during WWII and was responsible for 3 major early discoveries.

He detected radiation from the sun; he discovered that meteor trails produce radar echoes (thus starting a new era in meteor research) & he was the first to localize a discrete radio source (Cygnus A).

In the early 1960's at the *Royal Radar Establishment* near Malvern he built a variable spacing interferometer using two 25m reflectors on mobile mounts providing baselines of up to 1 km with an accuracy of up to 1", a major achievement at the time.

In 1973 he wrote, "*The Evolution of Radio Astronomy*" (the 1st book I ever read on the subject).
He retired in 1969 and died

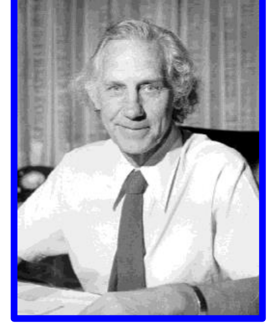
1950

GALACTIC RADIATION AT RADIO FREQUENCIES

III. GALACTIC STRUCTURE

By J. G. Bolton* and K. C. Westfold*

[Manuscript received November 4, 1950]



Keith Westford joined the CSIRO in 1949 as a theorist in *Radiophysics*. In 1961, at the *Monash University* in Melbourne, he setup a successful theoretical astrophysics group. He died in 2001.

Table 1

Surveys of Galactic Noise

Survey	Author	Frequency (Mc/s.)	Beam Width	Date of Observations
1	Friis and Feldman(10)	9·5	16° × 4°	1937
2	Jansky	18	30° × 37°	1932
3	Friis and Feldman	18	11° × 3°	1937
4	Franz(11)	30	30°	1942
5	Moxon(12)	40	35° × 70°	1946
6	Sander(13)	60	20° × 30°	1946
7	Hey, Parsons, and Phillips(14)	64	13° × 14°	1948
8	Moxon	90	35°	1946
9	Bolton and Westfold(15)	100	17°	1949
10	Reber	160	12°	1940
11	Moxon	200		1946
12	Reber(16)	480	3°	1948

Freq

The surveys 1 to 5 in this table are not considered suitable for the present investigation. The effect of ionospheric screening is not fully known for the lower frequencies and most of these surveys were made with aerials of low resolving power. Furthermore, the criterion of an optically thin galactic medium is probably not satisfied.

After WWII, John Bolton did pioneering work with the sea cliff interferometer at CSIRO. In 1955 he led the effort at Caltech to build the *Owens Valley Radio Observatory*. Returning to Australia in 1961, he became the Director of the *Parkes Observatory*. He died in 1993.

Galactic Radiation at Radio Frequencies. III. Galactic Structure, J.G. Bolton & K.C. Westfold, Australian Journal of Scientific Research, Vol. 3, 1950, p.251
http://www.phys-astro.sonoma.edu/brucemedalists/bolton/index.html
http://www.adm.monash.edu.au/records-archives/archives/emeritus/emeritus-80-89.html

THE ORIGIN OF GALACTIC RADIO-FREQUENCY RADIATION

1951

J. H. Piddington

(Received 1951 January 30) *

Summary

The results of observations of the intensity and distribution of radio-frequency radiation from the Galaxy at frequencies from 9·5 to 3000 Mc./s. have been collected. Some of these data are used to determine spectrum curves of the radiation from chosen regions of the Galaxy.

TABLE I

Observer	Frequency f (Mc./s.)	Equivalent temperature deg. K. T_A	T_B	T_C	ζ (T_e = 5000 deg. K.)	$\frac{T_A f^2}{\zeta} \times 10^{-20}$	$\frac{T_B f^2}{\zeta} \times 10^{-20}$
Friis and Feldman (**18**)	9·5	$2·4 \times 10^5$	...	...	0·161	1·34	...
Shain (**17**)	18·3	$2·0 \times 10^5$	75000	50000	0·155	4·34	1·63
Moxon (**19**)	40	67000	11900	8500	0·147	7·30	1·29
Hey, Parsons and Phillips (**11**)	64	21000	3100	2200	0·143	6·02	0·889
Moxon (**19**)	90	7700	...	...	0·139	4·48	...
Bolton and Westfold (**16**)	100	6000	720	490	0·139	4·32	0·518
Reber (**14**) (modified)	160	2180	...	...	0·134	4·16	...
Allen and Gum (**15**)	200	1190	120	70	0·132	3·62	0·364
Reber (**13**) (modified)	480	145	16·6	...	0·123	2·72	0·311
Piddington and Minnett (**20**)	1200	17·9	...	...	0·114	2·26	...
Piddington and Minnett (**20**)	3000	2·77	...	...	0·105	2·36	...

(*a*) Friis and Feldman (**18**) have measured galactic radiation at 9·5 Mc./s. which Townes (**8**) has interpreted as indicating an equivalent temperature of $1·2 \times 10^5$ deg. K. Reber and Greenstein (**37**) have estimated the direction of the beam as being in the constellation of Cygnus, so that T_A will be somewhat higher.

John Hobart Piddington was born in Australia in 1910. He carried out research on the reflection of radio waves by the ionosphere and troposphere at the *Univ. of Cambridge* and was awarded a PhD in 1938. During WWII he played a leading role in the secret development of Australian radar defenses at *Sydney University* and then at the *Radiophysics Lab* of CSIRO. From 1945 to 1947, he was engaged in the development of the Australian version of Distance Measuring Equipment (DME) for civilian aviation. In 1947, he became interested in radio astronomy and helped contributed to Australia's leadership role in this emerging field of science. In 1956 he gave up observational astronomy to concentrate on theoretical astrophysics. He died in 1997.

The Origin of Galactic Radio-Frequency Radiation, J.H. Piddington, MNRAS, Vol. 111, 1951, p.45-63
http://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=04065265
http://www.eoas.info/biogs/P000711b.htm
http://csiropedia.csiro.au/display/CSIROpedia/Piddington%2C+Jack+Hobart

A Paper to be presented

at the A.A.A.S. Meeting in Boston

Symposium: Radio Astronomy

Date and Place: Saturday, December 26, 1953; afternoon session at the American Academy of Arts and Sciences, 26 Newberry Street, Boston, Massachusetts.

Speaker: Dr. Grote Reber, Research Corporation (paper to be presented, because of Dr. Reber's absence at the Boston Meeting, by Dr. John D. Kraus of Ohio State University.

Topic: GALACTIC RADIO WAVES

The next published measurements were in 1937 by Friis and Feldman, also of the Bell Telephone Laboratories. They constructed the antenna equipment shown on the second slide. It was used as receiving terminal of a transatlantic radio link from England. These rhombics are in a line about 3/4 mile long from end to end. The main acceptance lobe is about 2½ degrees wide at a wavelength of 16 meters. By adjusting the electrical phasing between the various frequencies down to 9.51 megacycles (31.6 meters). At 18 megacycles the steering was limited to an altitude variation of about 20 degrees above the horizon. They were able to demonstrate that at suitable times the magnitude of the star static could be greatly changed by swinging the beam over this limited angle. Thus the source in the sky must be quite small. The writer computed the celestial position and found it to be in the region of Cygnus. It is now apparent they were observing the presently known source near declination $+40^{\circ}$ and right ascension 20 hours.

Radio Astronomy, R. Reber, presented by J. Kraus, American Academy of Arts & Science Symposium, Dec 26, 1953
http://jump.cv.nrao.edu/dbtw-wpd/Textbase/Documents/grgnp12261953.pdf

OBSERVATIONS OF COSMIC NOISE AT 9·15 Mc/s

1954

By C. S. HIGGINS* and C. A. SHAIN*

[*Manuscript received April 22, 1954*]

Summary

From observations made at a frequency of 9·15 Mc/s, with an aerial of beam width 29° between half-power points and directed to Dec. —32°, a curve of equivalent aerial temperature, as a function of sidereal time, is derived.

The temperatures observed were of the order of 10^6 °K. The curve is compared with curves derived for similar conditions by calculation from the results of observations at 18·3 Mc/s and at 100 Mc/s. It is found that the equivalent temperatures increase rapidly with decreasing frequency, but the ratio of maximum to minimum temperature decreases with frequency.

It is shown that " atmospheric " noise levels observed by the standard techniques sometimes contain a large contribution from cosmic noise at this frequency.

Observations in this range of frequencies are rare, the only published work at a frequency close to 10 Mc/s consisting of a few measurements at 9·5 Mc/s by Friis and Feldman (1937) which were made during tests of the original MUSA aerial. A recent paper (Shain and Higgins 1954) presented the results of a detailed survey of a restricted region of the sky at 18·3 Mc/s, but the results of some earlier work at the same frequency (Shain 1951), in which a strip of the sky was scanned by a fixed aerial directed to a constant declination, have already been used by Piddington (1951) and Brown and Hazard (1953) for comparison with their theoretically predicted intensities. Observations with such a fixed aerial are much simpler to make than a general survey and, since equipment was available which could be readily adapted for the purpose, an attempt was made to obtain similar observations at a frequency of 9·15 Mc/s. The present paper describes the results of these observations.

Observations of Cosmic Noise at 9.15 Mc/s, C.S. Higgins & C.A. Shain, Australian Journal of Physics, vol. 7, 1954, p.460
http://www.atnf.csiro.au/news/newsletter/feb05/Shame_about_Shain.htm ; http://arxiv.org/ftp/arxiv/papers/1012/1012.5137.pdf

Alexander Shain was born in 1922. He received a BSc from the Univ of Melbourne and joined the CSIR in 1943. During WWII he worked on radar. In the post-war years at *Radiophysics* he championed low frequency radio astronomy, first at the *Hornsby Valley Field Station* and later at *Fleurs*, where, two years after the *Mills Cross was completed*, the *Shain Cross* became operational in 1956. This new cross, consisting of a series of dipoles on ~1 km long N-S and E-W arms, worked at a frequency of 19.7 MHz & had a beam width of 1.4°. It was used to survey of the galactic plane, map Centaurus A and monitor radio bursts from Jupiter. When Shain died in 1960, Australia lost one of its pioneers, and its leading authority on decametric radio emission.

Charles Higgins worked closely with Shain at *Hornsby* and *Fleurs*. He later became interested in Solar radio astronomy.

The Distribution of Cosmic Radio Background Radiation*

H. C. KO†, MEMBER, IRE

1958

Hsien Ching Ko was born in Formosa in 1928. He received his PhD from the Ohio State University in1955. In 1952 he joined the staff of the *Ohio State Radio Observatory* and later became Professor of Elec. Engineering & Astronomy. He worked on various research problems in radio astronomy and radio physics, including cosmic radio emission, radio star scintillation, theory of radiation, and the development of antennas and receivers for radio astronomy.

TABLE I

SURVEYS OF COSMIC RADIO BACKGROUND RADIATION

Observers		Frequency (mc)	Antenna Beamwidth (deg)
1. Reber and Ellis[1]	Australia 1956	0.5–2.0	
2. Friis and Feldman[2]	US-BTL MUSA‘37	9.5, 18.6	16° ×4°, 11°×3°
3. Higgins and Shain[3]	Aust CSIRO 1954	9.15	31° ×26°
4. Jansky[4]	US-BTL 1933	20.5	30° ×37°
5. Shain and Higgins[5]	Aust-CSIRO 1954	18.3	17° ×17°
6. Shain[6]	Aust-CSIRO 1957	19.7	1.4°×1.4°
7. Fränz[7]	France 1942	30	30° ×30°
8. Herbstreit and Johler[8]	US-NBS 1948	25–110	
9. Cottony and Johler[9]	US-NBS 1952	25–110	
10. Moxon[10]	UK-Admiralty ‘46	40, 90, 200	35° ×70°
11. Sander[11]	UK-RRDE 1946	60	20° ×30°
12. Hey, Parsons, and Phillips[12]	UK-RRDE ‘48	64	13° ×14°
13. Baldwin[13]	UK-Cambridge‘55	81	2° ×15°
14. Mills[14]	Aust-CSIRO 1956	85.7	0.8°×0.8°
15. Bolton and Westfold[15]	Aust-CSIRO 1950	100	17° ×17°
16. Hanbury Brown and Hazard[16]	UK-JBO ‘53	158.5	2° ×2°
17. Reber[7]	US-Wheaton 1944	160	12° ×12°
18. Allen and Gum[18]	Aust-CSIRO 1950	200	25° ×25°
19. Dröge and Priester[19]	Germ-Stockert ‘56	200	16.8°×16.3°
20. Ko and Kraus[20]	US-OSU 1957	250	1.2°×8°
21. Atanasijevic[21]	France 1952	255	10° ×10°
22. McGee, Slee, and Stanley[22]	Aust-CSIRO ‘56	400	2° ×2°
23. Seeger, Westerhout, and van de Hulst[23]	NL 1956	400	2° ×2°
24. Reber[24]	US-Wheaton 1948	480	4° ×4°
25. Piddington and Trent[25]	Aust-CSIRO 1956	600	3.3°×3.3°
26. Denisse, Leroux, and Steinberg[26]	France‘55	910	3.5°×3.5°
27. Westerhout[27]	NL 1956	1360	1.9°×2.8°

Freq

In 1956, the 25m radio telescope at Stockert, Germany, was the world’s largest →

The Distribution of Cosmic Radio Background Radiation, H.C. Ko, Proc. of the IRE, 1958
http://www2.ece.ohio-state.edu/~hemami/xper8.pdf ; Contributors, IEEE Trans on Military Electronics, Vol 8 , Iss 3, 1964, p. 299
http://www.panoramio.com/photo/55520888?source=wapi&referrer=kh.google.com

Hectometer Cosmic Static

GROTE REBER

IEEE TRANSACTIONS ON MILITARY ELECTRONICS

July-October 1964

Summary—A review is made of radio astronomy development starting with Jansky at 15-m wavelength and progressing to 30, 60, 144, 576, and 2100 m. Electromagnetic wave propagation through the ionosphere by the *O*, *X*, *Z*, and *Y* modes including various aberrations is discussed. Methods of overcoming atmospherics are outlined. Preliminary findings at hectometer waves and the cosmological implications are mentioned. The different outlook upon the structure of the universe appears to be a more enticing aspect of the study than details about the contents of the Milky Way. Equipment technology is entirely omitted. A comprehensive list of references to the literature is included, along with four figures.

30 METERS WAVELENGTH

The first observations of cosmic static at a wavelength of 30 meters were made by Friis and Feldman [6] during 1936 while testing an antenna for transatlantic radio telephony. Their brief tabulations show the radiation is coming from the region of Cygnus and the intensity is very high. The next observations were made by Shain and Higgins [7] during 1951 and 1952 using an antenna better suited to radio astronomy purposes. The fixed beam width was 31°N/S by 26°E/W and pointed

[6] H. T. Friis and C. B. Feldman, "A multiple unit steerable antenna for short-wave reception," *Bell Tech. J.*, vol. 16, pp. 337–419; July, 1937. See p. 397 and 413.

[7] C. A. Shain and C. S. Higgins, "Observations of cosmic noise at 9.15 Mc," *Australian J. Phys.*, vol. 7, pp. 460–470; September 1954.

Cygnus A (3C 405) is one of the strongest radio sources in the sky, and would become one of the most famous.

It was discovered by Reber in 1939.

In 1951, it was one of the first "radio stars" to be identified with an optical source.

By 1953, Jennison & Das Gupta showed it to be a double source.

Cygnus A would become the first *radio galaxy*.

Like most radio galaxies, it contains an active galactic nucleus with two jets protruding in opposite directions from the galaxy's center. At the ends of the jets are two lobes with "hot spots" of more intense radiation at their edges.

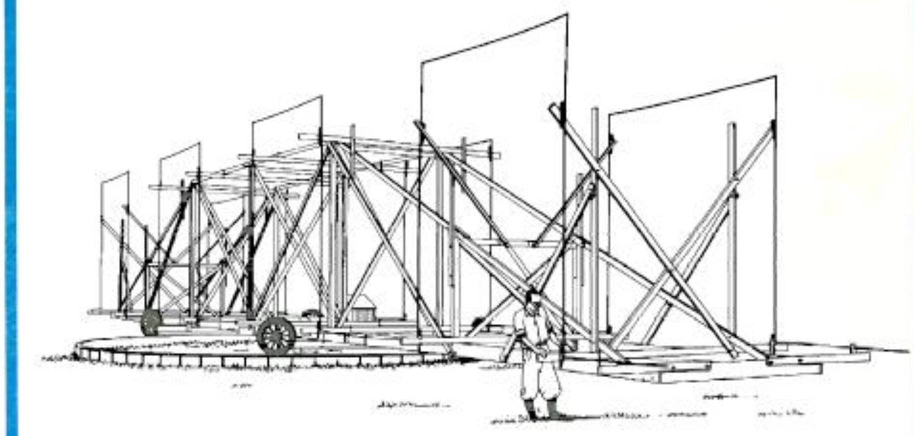
Hectometer Cosmic Static, G. Reber, IEE Trans. On Military Electronics, Jul-Oct 1964, p.257-263

SERENDIPITOUS DISCOVERIES IN RADIO ASTRONOMY

Proceedings of a Workshop held at the National Radio Astronomy Observatory Green Bank, West Virginia on May 4, 5, 6, 1983

Honoring the 50th Anniversary Announcing the Discovery of Cosmic Radio Waves by Karl G. Jansky on May 5, 1933

Edited by K. Kellermann and B. Sheets



1983

RADIO ASTRONOMY BETWEEN JANSKY AND REBER

Grote Reber
Bothwell, Tasmania, Australia

The Bell Technical Journal, July 1937, carries a long article by Friis and Feldman entitled "Multi-Unit Steerable Antenna" which consisted of six rhombic antennas stretched out in a line along the greatest diagonal of the diamond. The main beam was only a degree or two wide in elevation angle. Operating frequency was in the range of 10 to 20 MHz. The elevation angle could be raised or lowered, or steered, by changing the phase between elements of the antenna. The assembly also had high side lobes, particularly above the main beam. Among data on page 413, are some about star static of Jansky. The intensity was found to change as the main beam was raised or lowered. Fortunately, dates, times, elevation and azimuth are given. I was able to reduce this and found the direction being examined was in Cygnus.

GROTE REBER'S OBSERVATIONS ON COSMIC STATIC

K. I. KELLERMANN
National Radio Astronomy Observatory,[1] 520 Edgemont Road, Charlottesville, VA 22903; kkellerm@nrao.edu

THE ASTROPHYSICAL JOURNAL, 525: 371–372, Centennial Issue

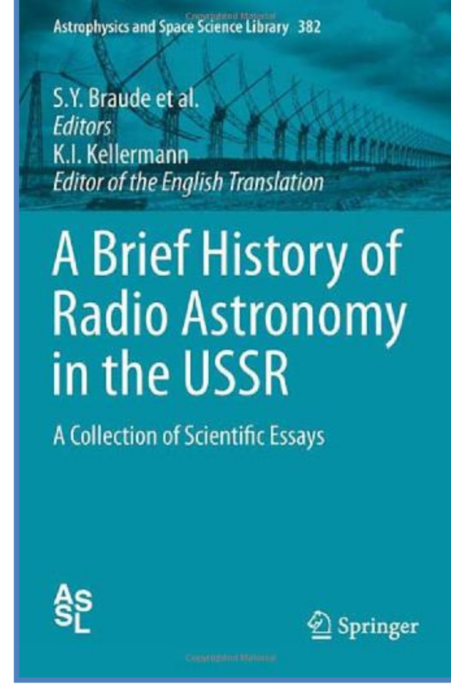
Following Karl Jansky's reports of meter-wavelength radiation from the Galaxy (Jansky 1933), only a few scattered attempts were made to confirm or extend these remarkable results (Potapenko & Folland 1936; Friis & Feldman 1937) or to understand their implication for astronomy and astrophysics (Langer 1935; Whipple & Greenstein 1937). Grote Reber realized that further progress would require better angular resolution in order to more accurately locate the source of radio emission, as well as multiwavelength observations that might give clues to the underlying physical processes.

Friis, H. T., & Feldman, C. B. 1937, Proc. IRE, 25, 841
Hey, J. S. 1946, Nature, 157, 47
Jansky, K. G. 1933, Proc. IRE, 21, 1387
Langer, R. M. 1935, Phys. Rev. Abstracts, 49, 209
Potapenko, G. W., & Folland, D. F. 1936, Science News Letter 131
Reber, G. 1940a, Proc. IRE, 28, 68
———. 1940b, ApJ, 91, 621
———. 1944, ApJ, 100, 279
———. 1946, Nature, 158, 945
Reber, G. 1948, Proc. IRE, 36, 1215
———. 1958, Proc. IRE, 46, 15
———. 1983, in Serendipitous Discoveries in Radio Astronomy, ed. K. Kellermann & B. Sheets (Green Bank: NRAO), 71
———. 1984, in The Early Years of Radio Astronomy, ed. W. T. Sullivan III (Cambridge: Cambridge Univ. Press), 43
Southworth, G. S. 1945, J. Franklin Inst., 239, 285
Sullivan, W. 1982, Classics in Radio Astronomy (Dordrecht: Reidel)
Whipple, F. L., & Greenstein, J. L. 1937, Proc. Natl. Acad. Sci., 23, 177

Grote Reber's Observations of Cosmic Static, **K. Kellermann, ApJ, Vol 525, 1999, p. 371-372**

MUSA & the USSR

2012



Chapter 8 **S.Y. Braude and A.V. Megn**

The Development of Radio Astronomy Research at the Institute of Radio Physics and Electronics of the Academy of Sciences of the Ukrainian SSR

Radio astronomy research at the Institute of Radio Physics and Electronics of the Academy of Sciences of the Ukrainian SSR (IRFE) began with studies of the propagation of radio waves with various wavelengths (from Very High Frequency to medium-wave) above the interface between two media and in a plasma. This work was first carried out in the Department of Radio-Wave Propagation, which was created in 1945 in the Physical Technical Institute of the Academy of Sciences of the Ukrainian SSR under the scientific supervision of S. Ya Braude. Beginning in 1955, when IRFE was organised, based on the Physical Technical Institute, this work was continued in three departments of the new institute.

Radio-oceonographic studies required directive antennas to radiate signals and then receive the scattered signals from particular areas of the sea surface, with the possibility of rapidly changing the direction of the antenna beam in space. In contrast to centimetre, decimetre and metre wavelengths, which were used for radar at that time, the need to develop electrical rather than mechanical methods for directing the antenna beam of a radiating system arose for short- and more long-wavelength radio waves. At that time, only one highly-directive short-wavelength antenna was known: the "Musa" antenna, with electrical pointing of the beam in ?hour angle, which was developed in the 1930s for short-wave communications between the USA and England.

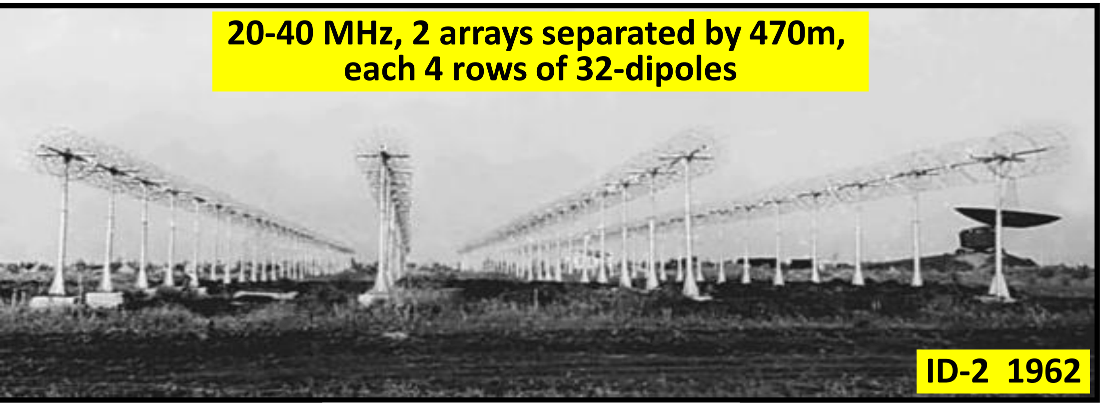
It is not obvious from this description whether USSR scientists actually knew about the MUSA way back in the early days of Soviet radio astronomy or whether this is just a modern day assessment.

Most MUSA systems were steerable in elevation only.

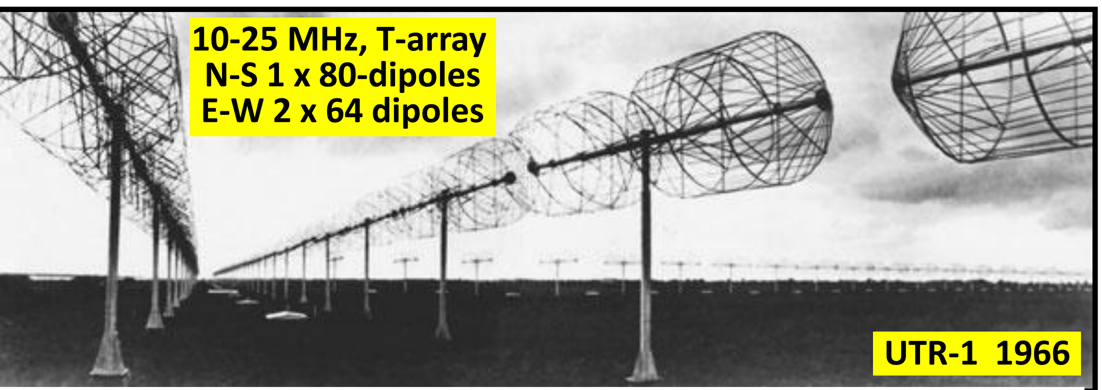
***The Development of Radio Astronomy Research at the Institute of Radio Physics and Electronics of the Academy of Sciences of the Ukrainian SSR*, S. Y. Braude & A. V. Megn, in *A Brief History of Radio Astronomy in the USSR*, Edited by S. Y. Braude et. al., Springer, 2012, p.182**

The USSR & Decimetric Arrays

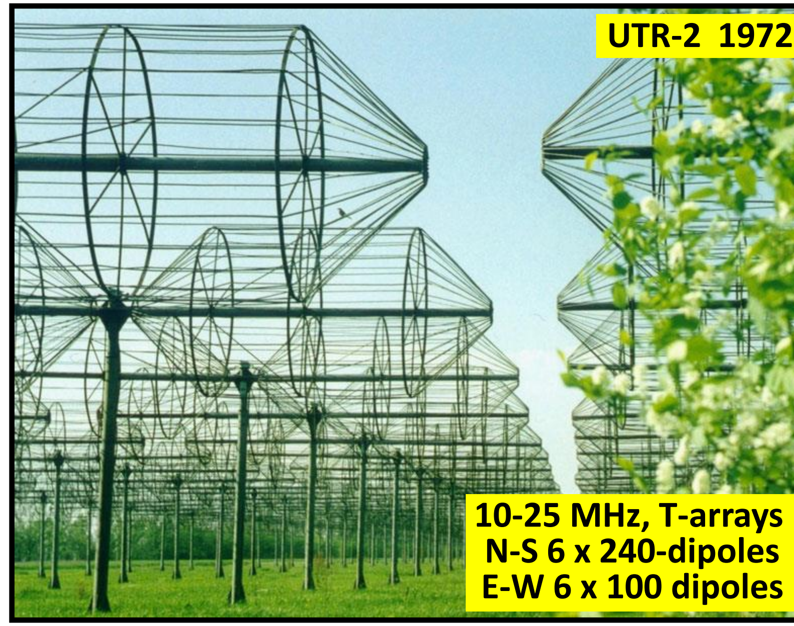
Antenna arrays of the second version of the ID-1 interferometer



Western ID-2 antenna



North–South antenna of the UTR-1 radio telescope, comprised of 80 oscillators



North–South antenna of the UTR-2 radio telescope, comprised of 1440 oscillators

The Development of Radio Astronomy Research at the Institute of Radio Physics and Electronics of the Academy of Sciences of the Ukrainian SSR, S. Y. Braude & A. V. Megn, in *A Brief History of Radio Astronomy in the USSR*, Edited by S. Y. Braude et. al., Springer, 2012, p.181-203

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Early Astronomers = Reber | United States | England | Australia | Ryle ???

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- *Reports on the Progress of Astronomy – Radio Astronomy*, J.S. Hey, MNRAS, Vol. 109, 1949, p.179-214

1950s

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- *Observations of Cosmic Noise at 9.15 Mc/s*, C.S. Higgins & C.A. Shain, Aust Jour Physics, vol. 7, 1954, p.460
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1960s to Now

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- *Grote Reber's Observations of Cosmic Static*, K. Kellermann, ApJ, Vol 525, 1999, p. 371-372
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The 2nd Experimental Array at Holmdel… *The "Broadside" MUSA*

Deviations of Short Radio Waves from the London-New York Great-Circle Path*

1939

Proceedings of the I.R.E. *October, 1939*

C. B. FELDMAN†, ASSOCIATE MEMI

Summary—*During the past year experiments have been made to determine the frequency of occurrence and extent of deviations of short radio waves from the North Atlantic great-circle path. For this purpose the multiple-unit steerable antenna (Musa), described to the Institute at its 1937 convention, has been used to steer a receiving lobe horizontally. This is accomplished by arraying the unit antennas broadside to the general direction from which the waves are expected to arrive. The Musa combining equipment then provides a reception lobe in the horizontal plane, steerable over a limited range of azimuth. Two such Musas have been used, one of which possesses a wide steering range but is blunt, while the other is sharp but is restricted in range. Transmissions from England have been studied with this equipment at the Holmdel, N. J., radio laboratory of the Bell Telephone Laboratories. Comparisons of results obtained on transmission from antennas directed toward New York with those from antennas otherwise directed have, to a limited degree, given results representative of the effects of horizontally steerable transmitting directivity. Observations made on these British transmissions during the past eight months have disclosed the following characteristics:*

1. *During "all-daylight" path conditions, the usual multiplicity of waves distributed in or near the great-circle plane, which constitutes normal propagation, has been predominant. Usually neither ionosphere storms nor the catastrophic disturbances associated with short-period fade-outs seem to affect the mode of propagation.*
2. *In contrast to 1, during periods of dark or partially illuminated path conditions, the great-circle plane no longer provides the sole transmission path. The extent to which other paths are involved varies greatly. Propagation during ionosphere storms of moderate intensity usually involves paths deviated to the south of the great circle, during afternoon and evening hours, New York time.*

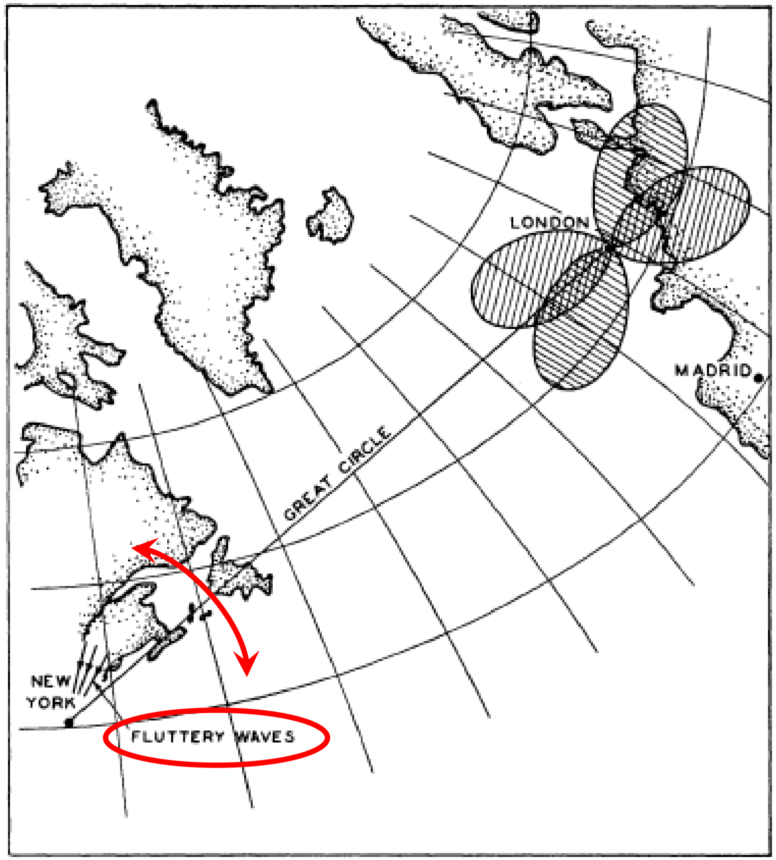


Fig. 1—Directional patterns of two British Broadcasting Corporation transmissions (9.58 and 9.51 megacycles) compared in 1936. The northerly directed antenna greatly emphasized radiation scattered from northern latitudes, and produced flutter fading.

***Deviations of Short Radio Waves from the London-New York Great-Circle Path*, C.B. Feldman, Proceedings of the Institute of Radio Engineers, Oct 1939, 635-645**

The Broadside MUSA

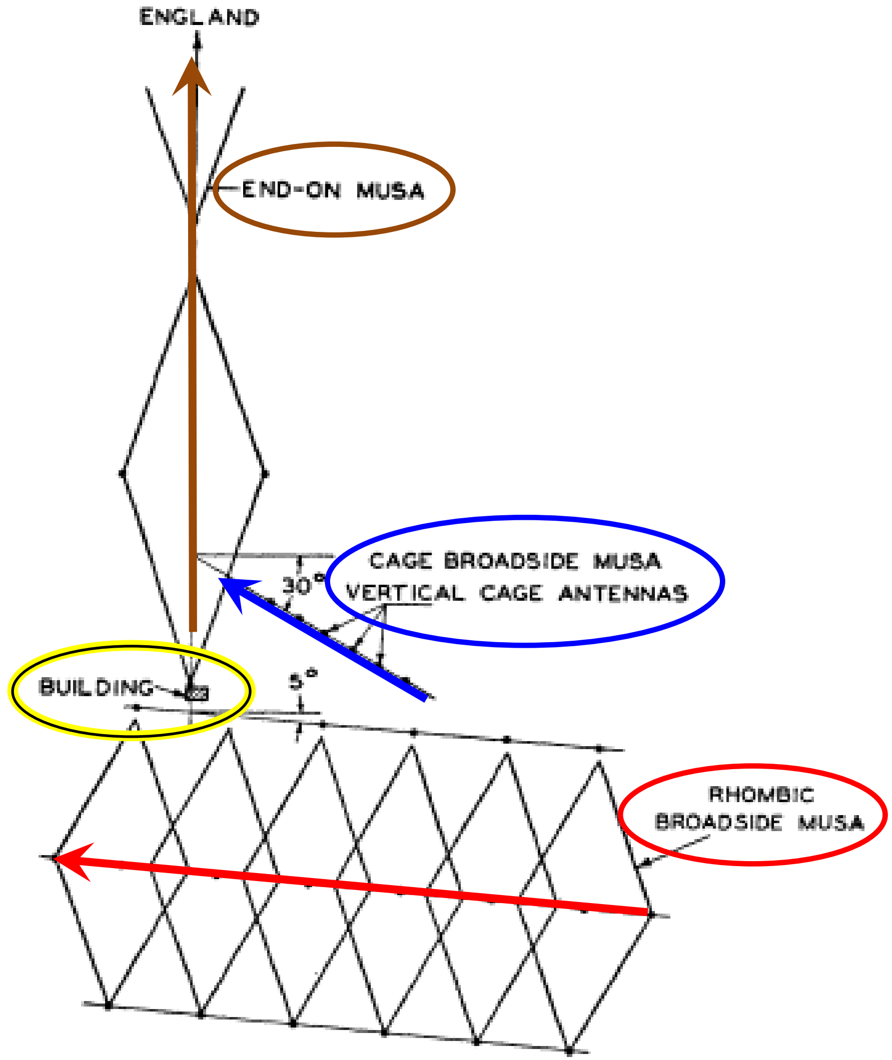


Fig. 2—Layout of steerable antennas at the Holmdel laboratory. Two of the six rhombic unit antennas of the end-on Musa are shown, in addition to the two broadside Musas, each comprising six antennas. The cage antennas are spaced 15 meters and the rhombic antennas 43 meters, center to center.

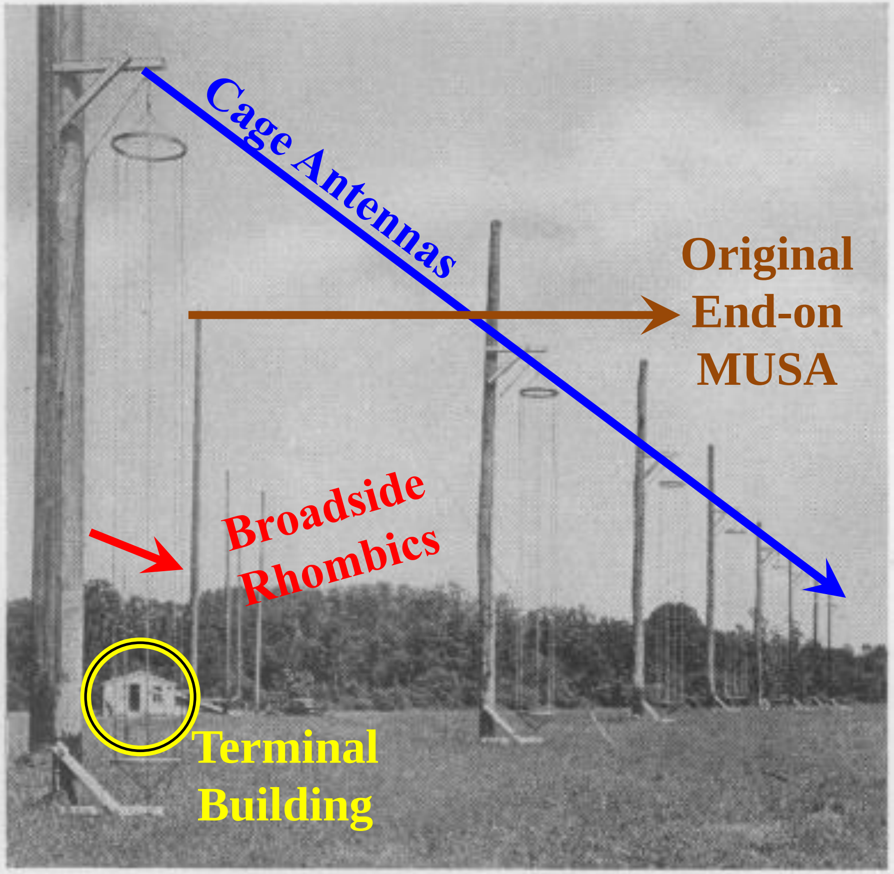


Fig. 3—The cage antennas comprising the wide-range broadside Musa. The end cages are used as dummies.

- **The horizontally steerable MUSA used 2 different types of broadside arrays:**
  - **6 *Cage* antennas to give a wide steering range but with a broad beam**
  - **6 *Rhombic* antennas to give a sharp beam but over a restricted range**

***Deviations of Short Radio Waves from the London-New York Great-Circle Path*, C.B. Feldman, Proc of the IRE, Oct 1939, 635-645**

MUSA with Horizontal Steering

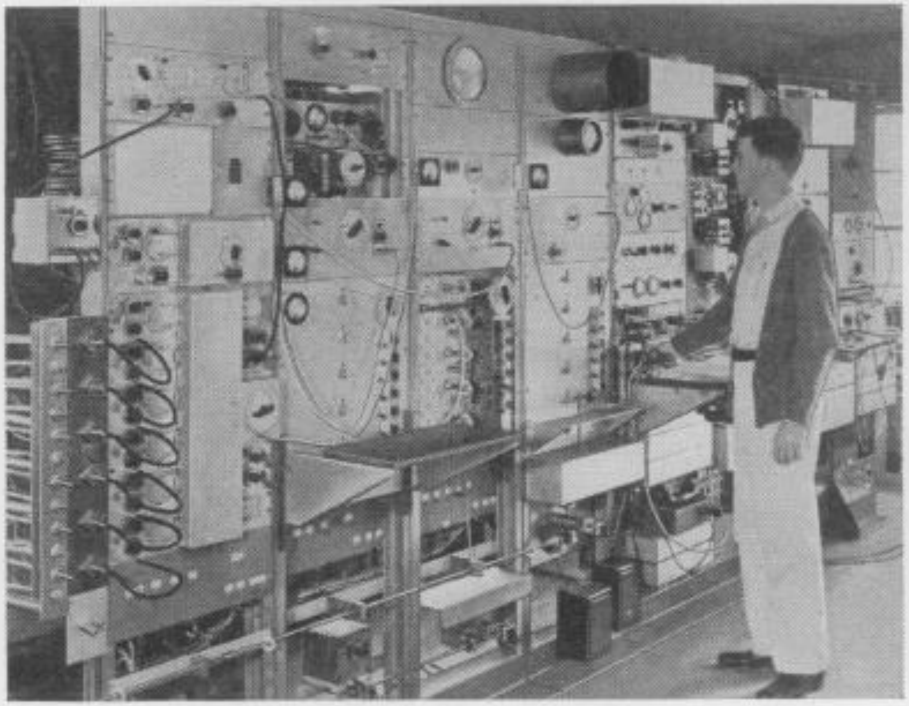


Fig. 4—View of experimental Musa receiving equipment. The three sets of transmission lines from the three Musas terminate in coaxial jacks and can be connected, one set at a time, to the receiver input circuits by means of coaxial patching cords shown at the left. Mr. Edwards, who was closely associated with the work, appears in the photograph.

18 MHz **9 MHz**

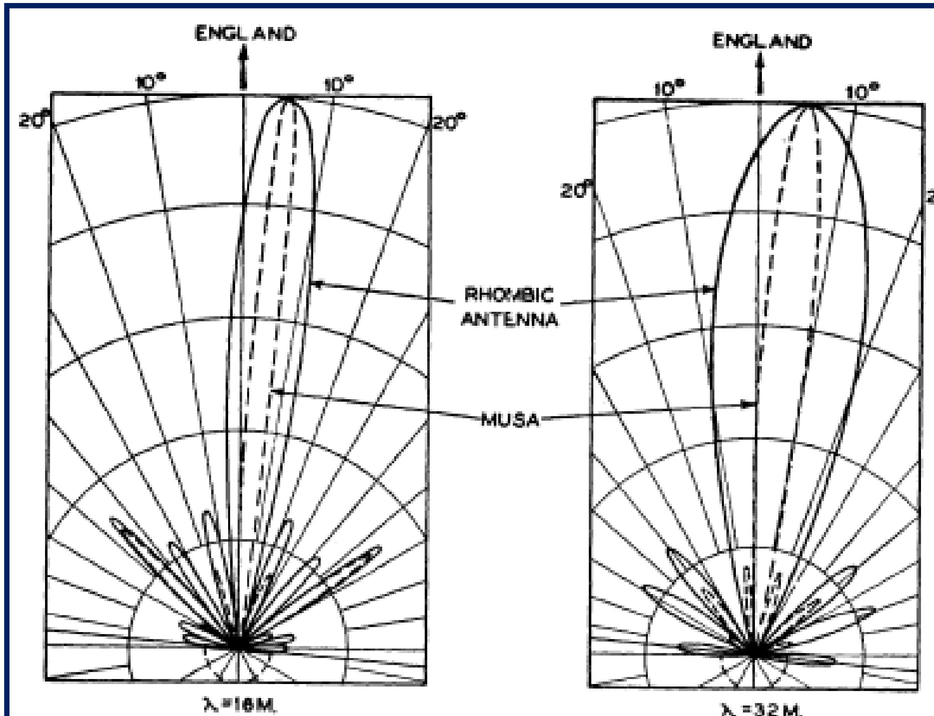


Fig. 7—Sample directional patterns of the rhombic broadside Musa. The steering range is confined to the range defined by the rhombic antenna patterns which are here shown for typical vertical angles.

CONCLUSIONS : "*Our general experience strongly indicates that wide-range azimuthal steering of both the transmitting & receiving antennas holds promise of recovering many decibels transmission loss during afternoon and evening hours, particularly during ionosphere storms*."

"There is, however, something to be gained by providing azimuthal steering at the receiver alone."

Unfortunately there was no mention in this paper of detecting any more "Star Static"

Deviations of Short Radio Waves from the London-New York Great-Circle Path, **C.B. Feldman, Proceedings of the Institute of Radio Engineers, Oct 1939, 635-645**

And now for the rest of the story…

Harald Friis

NJ Newspaper Article on Friis' 1971 Autobiography

"Seventy-Five Years in an Exciting World"

THE DAILY REGISTER

Red Bank, Freehold
Long Branch

Monmouth County's Home Newspaper for 92 Years

RED BANK, N.J., MONDAY, JUNE 21, 1971

Friis retired from Bell Labs in 1958 and became a research consultant to Hewlett-Packard. He held 31 patents.

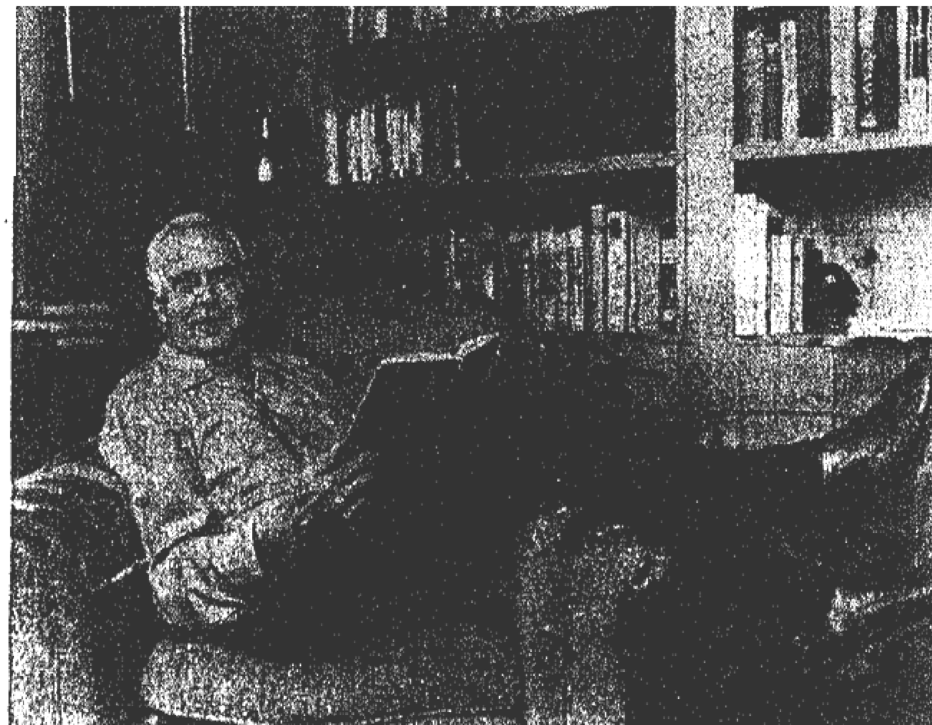
Rumson's Famous Inventor Tells His Own Life Story

RUMSON — Harald T. Friis, acknowledged as one of the great inventors of this century, has written a book.

It is a little book, an autobiography entitled "Seventy-five Years in an Exciting World." The 78-year-old inventor, now retired, says he wrote it for fun.

In 57 pages, a story is put down so simply, so directly and is written with such honesty that its beauty is at times almost painful.

Dr. Friis spent most of his career with the Bell Telephone System. He served as director of radio research as well as head of research in high frequency and electronics. He is known for major technological breakthroughs that included coaxial and submarine cable systems, design of the first commercial superheterodyne receiver, developments in radar, antennas and microwave systems (for which he is most famous).



AUTHOR-INVENTOR — Harald T. Friis, inventor of microwave transmission and receiving systems, relaxes in characteristically boyish manner in Rumson home with his autobiography, "Seventy-five Years in an Exciting World." He says, "If I hadn't invented these things, somebody else would have in a very few months.

The Dailiy Register, Monmouth Newspaper, 21 June 1971
http://209.212.22.88/data/rbr/1970-1979/1971/1971.06.21.pdf

Seventy-five Years in an Exciting World

1971

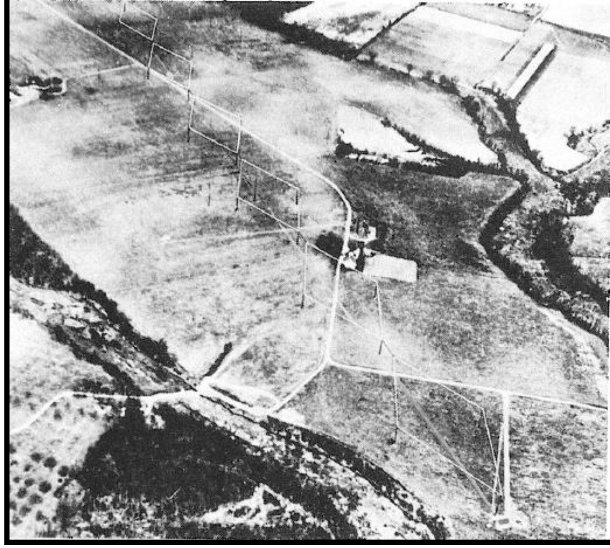
HARALD T. FRIIS

Sharpless and Feldman studied the angles of arrival of short waves and built my six-antenna MUSA (Multiple Unit Steerable Antenna) system, in which the phases of the signals from the antennas were combined at the intermediate frequency. I have never been so excited as the day we fired up the complete equipment, looked at the picture on the cathode-ray-tube and found that it gave us the angles of arrival of the signals from England.

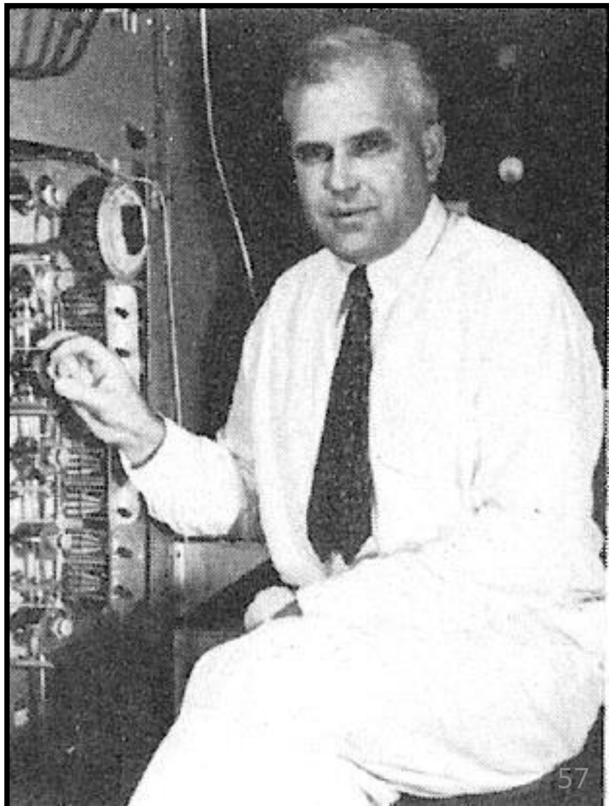
MUSA made it possible to unravel the complicated transmission phenomena of short-wave transmission. It also improved double-side band reception so much that it was decided to build a commercial system. A project engineer was given the job, and a 20-antenna system with the receivers located at the middle of the antennas was built at Manahawkin, New Jersey, and in England. I wanted a much cheaper 10-antenna system with the receivers at the end of the antennas, but could not convince the bosses. The 20-antenna system worked all right and performed better than a simple 3-antenna diversity system, but it was entirely too expensive.

Sun spots do raise havoc with short-wave propagation at times and years later the short-wave circuits had to yield to transatlantic speech cables and the 20-antenna systems are now dismantled. MUSA systems are technically sound, and a small and economic system could be used to advantage and should appear in short-wave circuits where cables are too expensive.

Transatlantic radio circuits are now alive again. This time it is microwave radio via satellites that is replacing speech cable. It looks like no system is good for more than 20 years.



The 6-antenna MUSA at Holmdel, N.J., and Harald at its receiver tuning controls.



Seventy-Five Years in an Exciting World, H. Friis, San Francisco Press, 1971, p 24-27

Seventy-five Years in an Exciting World

HARALD T. FRIIS

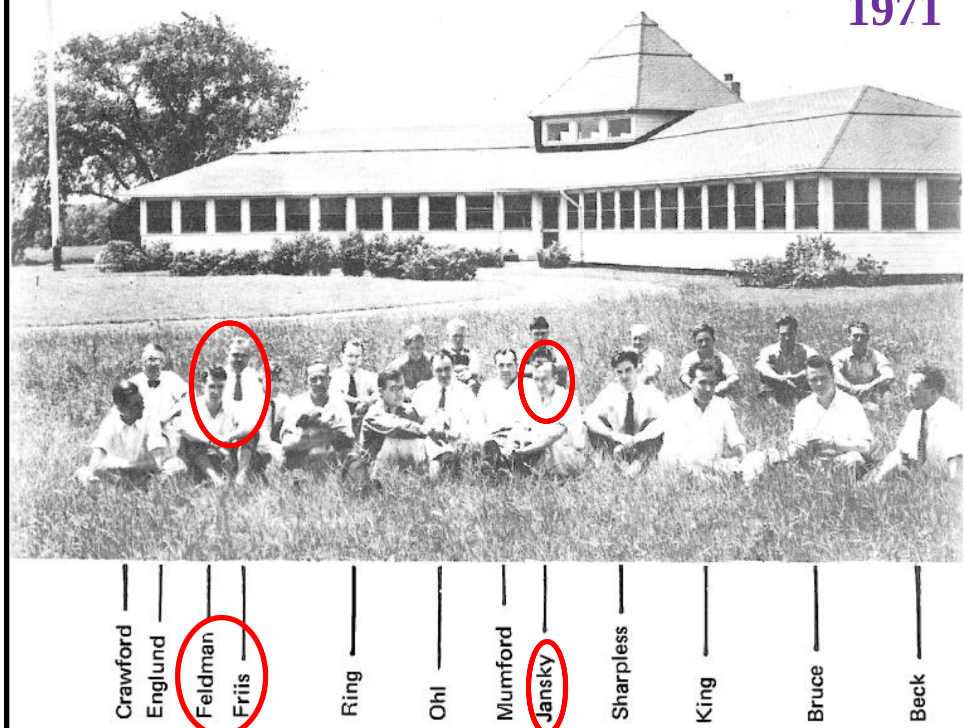
1971

Now, back to technical work at Cliffwood. With my low-noise receiver and a loop antenna, I noticed in 1928 that the output noise was not always like static, but could be a steady type of hiss noise. I concluded that part of it was J. B. Johnson noise, well known at much lower frequencies, but several Bell Lab scientists at 463 West Street said that I could never measure such low noise signals. I proved it was Johnson noise by heating a small resistance in series with the loop antenna and finding that the noise was proportional to the temperature of the resistance. This discovery led eventually, in 1942, to my noise-figure rating of radio receivers. John Pierce encouraged me to publish a paper on Noise Figures in 1943. It is interesting that a paper on noise ratings of receivers appeared in a British journal just before my paper was published and that its author [illegible] prac- tically the same wording that I had used i[illegible] mo- randum, which was transmitted [illegible] rly nineteen forties.

The Friis Formulas – he was the first to calculate the noise performance of a multistage radiometer system consisting of cascaded amplifiers & resistive losses.

Th[illegible] e T[illegible] I th[illegible] noise N[illegible] due to the Johnson no[illegible] Kelvin (63° Fahrenheit) or N = N[illegible] to $1.38 \times 10^{-23} \times 290$ BG = 4×10^{-21} BG watt[illegible] B is the bandwidth of the receiver and G its gain. Or, the equivalent input noise is $NF \times 4 \times 10^{-21}$ B watts.

This may seem a little complicated to the nontechnical reader, but it is very important to the microwave engineer. He can now calculate the signal-to-noise ratio in the output of a microwave receiver when he knows the received signal power and the noise figure. It pleases me to have started the use of the term 'available' power that everybody uses now.



Englund and Friis with their engineers in front of the laboratory at Holmdel, N.J., in 1930.

I worked with the other engineers and, for example, assigned Karl Jansky to measure the direction of static at short waves. He found that radio waves originate from stars, and Professor E. V. Appleton once told Dr. M. J. Kelly that this was Bell Labs' most important contribution to science. This was the beginning of radio astronomy.

To refute some derogatory statements about the Bell Labs that John Pfeiffer made in his book *The Changing Universe*, I have recently published a short paper on Karl's career. His brother, C. M. Jansky, thanked me for the paper and thought it was excellent; and Ralph Bown wrote: ' It seems to me that this little masterpiece of sober factual writing completely demolishes the innuendos already published, and leaves no grounds for further ones.'

***Seventy-Five Years in an Exciting World*, H. Friis, San Francisco Press, 1971, p 24-27**

The MUSA Patent

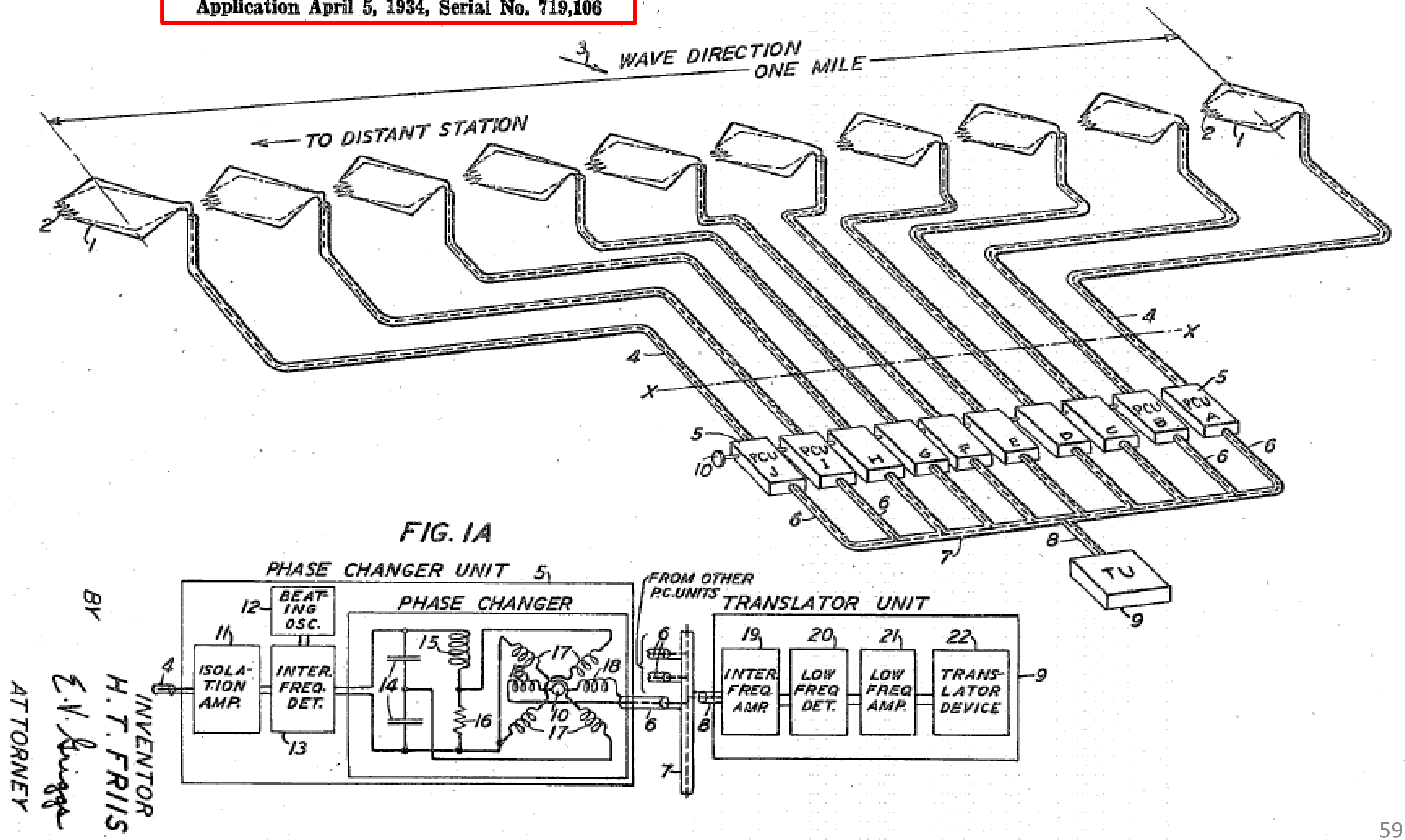
UNITED STATES PATENT OFFICE

2,041,600

RADIO SYSTEM

Harald T. Friis, Rumson, N. J., assignor to Bell Telephone Laboratories, Incorporated, New York, N. Y., a corporation of New York

Application April 5, 1934, Serial No. 719,106



This invention relates to radio communication systems and more particularly to methods of and means for obtaining controllable and sharp directive transmission and/or reception in such systems.

What is claimed is:

1. A method of radio communication which comprises energizing a plurality of paths of different lengths in the transmission medium between two stations and receiving at any given instant wave energy propagated along only one

UNITED STATES PATENT OFFICE

Patented May 19, 1936

2,041,600

RADIO SYSTEM

Harald T. Friis, Rumson, N. J., assignor to Bell Telephone Laboratories, Incorporated, New York, N. Y., a corporation of New York

This is was happens when you let lawyers write the technical specs.

Alas, there a no CLAIMS made about being able to detect "Star Static"!!

plane, separate phase changers included between said antennas and a common receiver and means for simultaneously varying said changers.

4. A method of improving radio communication utilizing a plurality of directive antenna units, which comprises placing the units array so that the major lobes of their characteristics are similarly pointed the same set or cluster of incoming tions, obtaining a movable istic or cone for the array in the array cone at all times only one of said incoming regardless of changes in said

5. A m... sharp directivity in a radio ...ing a plurality of directive a... ...anged in a directive array and co... translation device, means for moving ...tive lobe of each unit, and means for moving a directive characteristic of said array, which comprises moving the unit directive lobes to include in a single plane containing the cooperating station the same angular operating range and moving the major directive lobe or cone of the array characteristic to include a portion of said range.

phase changer... ...ises absorbing on each unit ... same two directions, conduc... received from one direction ...and the energy received from ...tion to the other receiver, and ...the outputs of the receivers.

...method of improving radio communica... utilizing a plurality of directive antenna units arranged in an end-on array, the maximum lobe of the directive characteristic of each of which is not wider than the operating range, means for moving each unit lobe and means for rotating the array directive characteristic, which comprises employing for a given array length a sufficient number of units to insure a spacing between adjacent major lobes or cones of the array directive characteristic greater than the angular range, positioning the unit lobes so as to include substantially all wave directions in said range, rotating the array characteristic to include in one of its major directive lobes or cones the direction of the wave of maximum intensity, and upon a directive change in said wave direction again rotating said characteristic to include in one of its major directive lobes or cones the direction corresponding to the wave of maximum intensity.

9. A method of simultaneously receiving different signals without fading utilizing a plurality of directive antenna units arranged ... array, means for rotating the array ... characteristic for one signal, a sec... ...ing the array directive ch... another signal, and two rece... ...mprises receiving on each u... ...rected waves of the first men... ...ifferently directed waves of ... ...nal, rotating the first menti... ...ic so that its major lobe in... ...ion of only one of the first ...es, rotating the second mentioned ...ic so that its major lobe includes the ...n of only one of the second mentioned ...es, supplying the energy absorbed from the first mentioned wave to one receiver and that absorbed from the second mentioned wave to another receiver.

There were 18 "claims" in all, (jumping over 10 thru 16)

17. In a radio communication system, an end-on array comprising a plurality of directive antenna units oriented to receive vertically polarized waves, a second end on array comprising a plurality of directive antenna units oriented to receive horizontally polarized waves, the axes of said array being included, substantially, in a plane containing a cooperating station, two sets of adjustable phase shifters, two receivers, and an ultimate receiver connected to said two receivers, the first mentioned array being connected through one set of phase shifters to one receiver and the second mentioned array being connected through the other set of phase shifters to the second receiver.

18. In a radio receiving system, an end-on array comprising a plurality of rhombic antenna units oriented for effective operation over the same angular range, two sets of adjustable phase shifters each uni-controlled and connected to said array, a recorder connected to one set of phase shifters, and a receiver connected to the other set.

Friis after MUSA

Technical University of Denmark DTU

Doctor of Technology Degree
Herald Trap Friis - 20 Sept 1938

"A Multiple Unit Steerable Antenna for Short-Wave Reception"

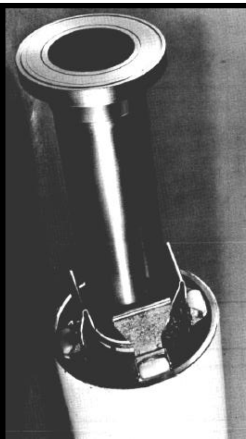
In 1938 I went home to Denmark to defend a D.Sc. thesis on MUSA at mv old technical college. One of my opponents was my old teacher, Professor P. O. Pedersen, and he passed me. Another opponent embarrassed me. He had evidently not read the thesis and thought that our 600-foot-long antennas were only a few feet long. It was not a nice trip because war was looming.

In 1941, after working on the MUSA, Friis went on to invent the *reflector horn antenna* with Alfred Beck. It was developed further by D.C. Hogg. A large version was used by Penzias & Wilson to detect the Cosmic Microwave Background.

In 1954, Friis conceived of the *billboard reflector* for use in tropospheric scatter communications. These were used in the *Distant Early Warning (DEW) Line*, the Alaska *White Alice* system, and for the *Ballistic Missile Early Warning System* (BMEWS).

Friis died in 1976, at age 83 of a stroke in Palo Alto, CA

Into 1962, Friis worked on the development of tightly wound helix waveguide for use in a low-loss, mm-wave communication system. Fiber optics would soon displace this technology but it would end up being used on the VLA for its signal transmission. Some of the 60-mm helix guide was donated by BTL.



http://www.dtu.dk/English/Research/Doctorates/Dr,-d-,techn,-d-,%20degrees.aspx
Seventy-Five Years in an Exciting World, H. Friis, San Francisco Press, 1971, p 24-27
http://en.wikipedia.org/wiki/Horn_antenna
http://www.williamson-labs.com/troposcatter.htm
WT4 Millimeter Waveguide System: The WT4/WT4A Millimeter-Wave Transmission System, D. Alsberg et al, Bell System Technical Journal, Vol 56:, No.10, Dec 1977

Meanwhile,
back at Holmdel…

The early years of RADIO ASTRONOMY

REFLECTIONS FIFTY YEARS AFTER JANSKY'S DISCOVERY

Edited by

W. T. SULLIVAN, III

The Early Years of Radio Astronomy: Reflections Fifty Years after Jansky's Discovery,
W. T. Sullivan, Cambridge University Press, 1984

Jansky & the MUSA

1935

In a 1935 Letter to his Father

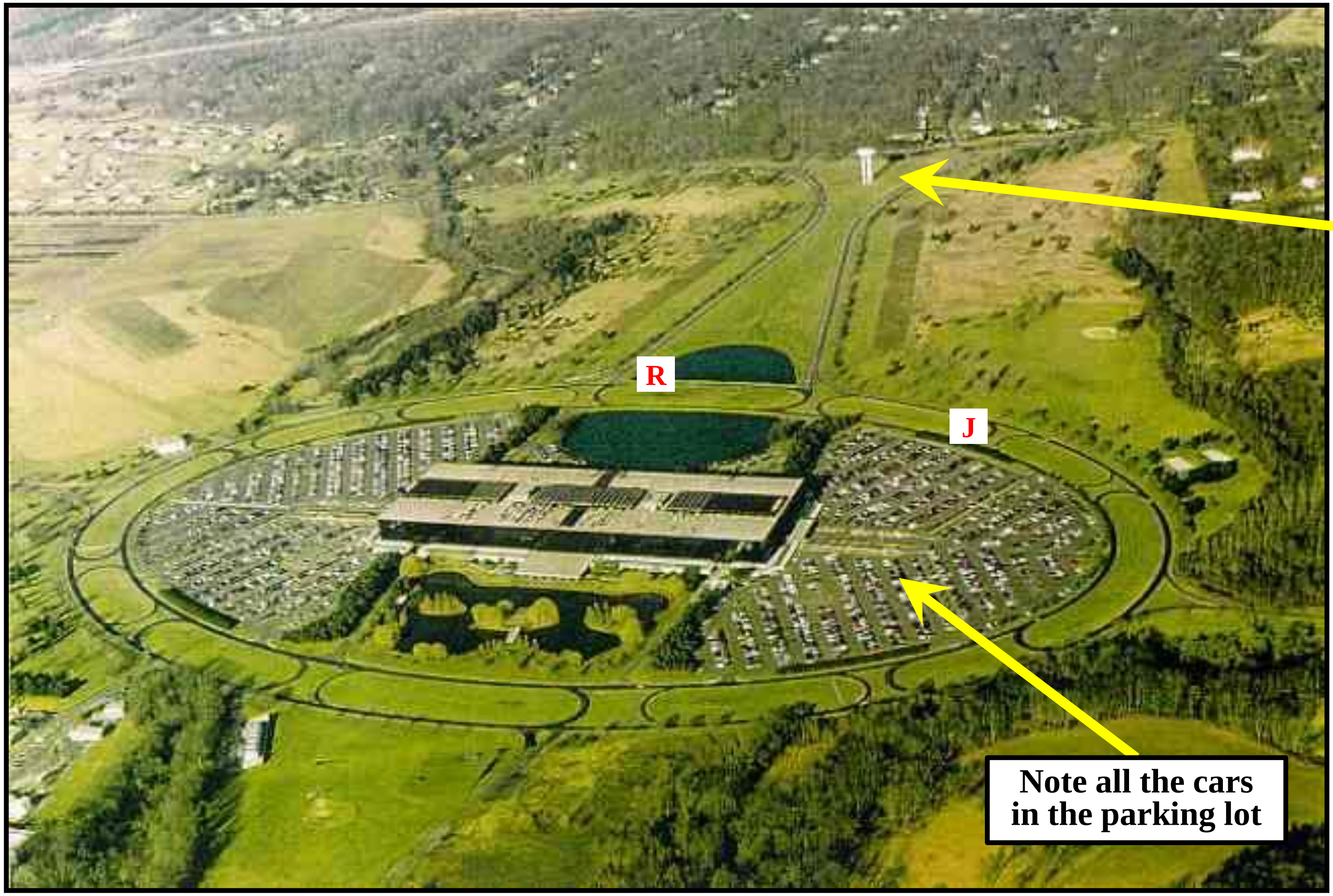
KARL JANSKY AND THE DISCOVERY OF EXTRATERRESTRIAL RADIO WAVES
Woodruff T. Sullivan, III

During the last hour of work this last week I got my ultra-shortwave apparatus for measuring star static working and immediately detected the static on 10 meters. I will now make a study of it in the range of 3.5 to 12 meters.[13] Also they have discovered that they get it on their new big antenna system with which they are studying the direction of arrival of signals.[14] In fact it appears that this star static, as I have always contended, puts a definite limit upon the minimum strength signal that can be received from a given direction at a given time, and when a receiver is good enough to receive that minimum signal, it is a waste of money to spend any more on improving the receiver. Friis is really beginning to show a little interest! [KJ:CJ, 20 September 1935]

14. The "big antenna system" was the Multiple Unit Steerable Antenna (MUSA), a 3/4 mile long array of six rhombics operating over a range of 5 to 25 MHz. MUSA was able to change its elevation angle of maximum response (through quickly and automatically adjustable relative phasing of its elements) and thus follow signals varying in arrival angle as a result of ionospheric fluctuations. In 1937 Friis and C.B. Feldman published a detailed description of this system, including even a few individual measurements in the autumn of 1935 of star static on 10 and 19 MHz.

The Bell Labs *Holmdel Complex* in its Heyday (1970s)

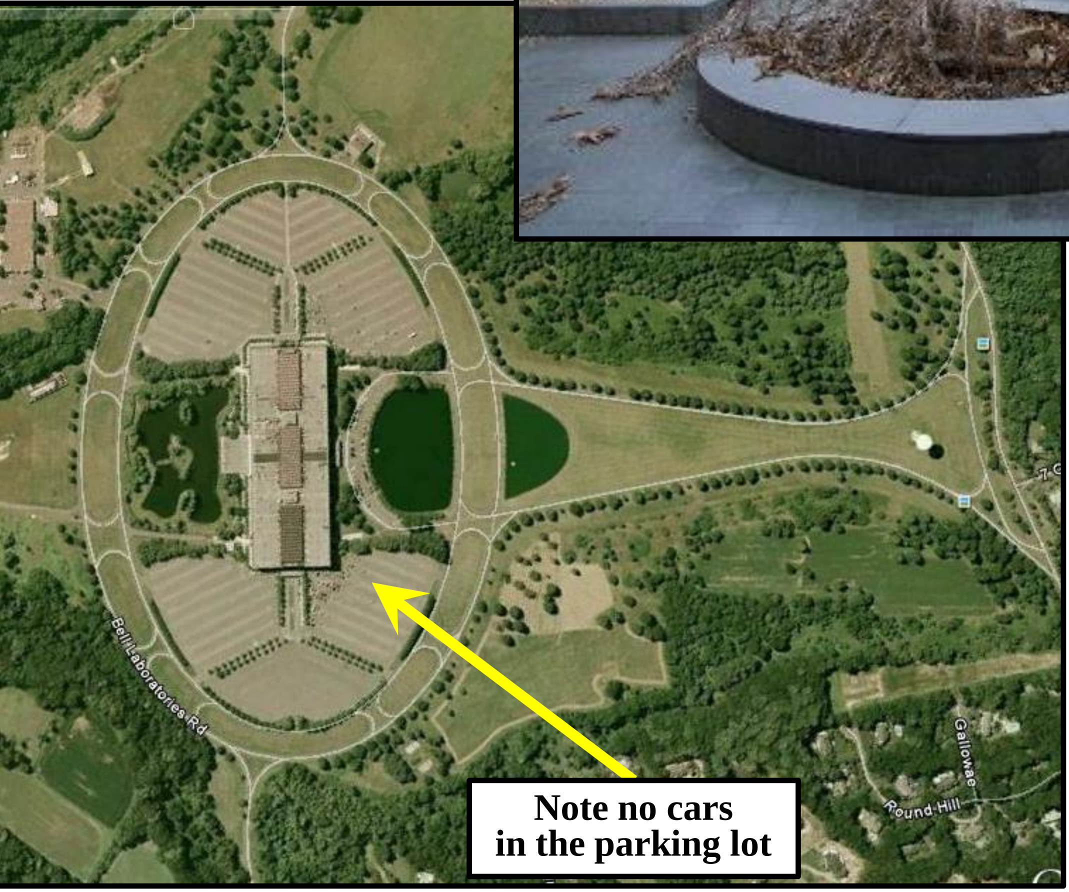
- **Where Karl Jansky and Harald Friis had – serendipitously - discovered "star static" and radio astronomy was born, 30 years before the famous *Bell Labs* research complex was built in the early 1960's.**
- **The 2 million sq. ft. building contained over 4,000 to 5,000 *Bell Labs* scientists & engineers.**



The water tower on the 472-acre complex was designed to look like a transistor, the most famous Bell Lab invention.

www.telephonecollectors.org/pictures/?id=135818990 ; mainline.brynmawr.edu/Courses/cs240/fall2009/bell-labs-watertower.jpg

Bell Labs Holmdel Complex Today



Google Earth & http://tkurdzuk.blogspot.com/
www.nj.com/news/index.ssf/2008/08/abandoned_bell_labs_could_make.html

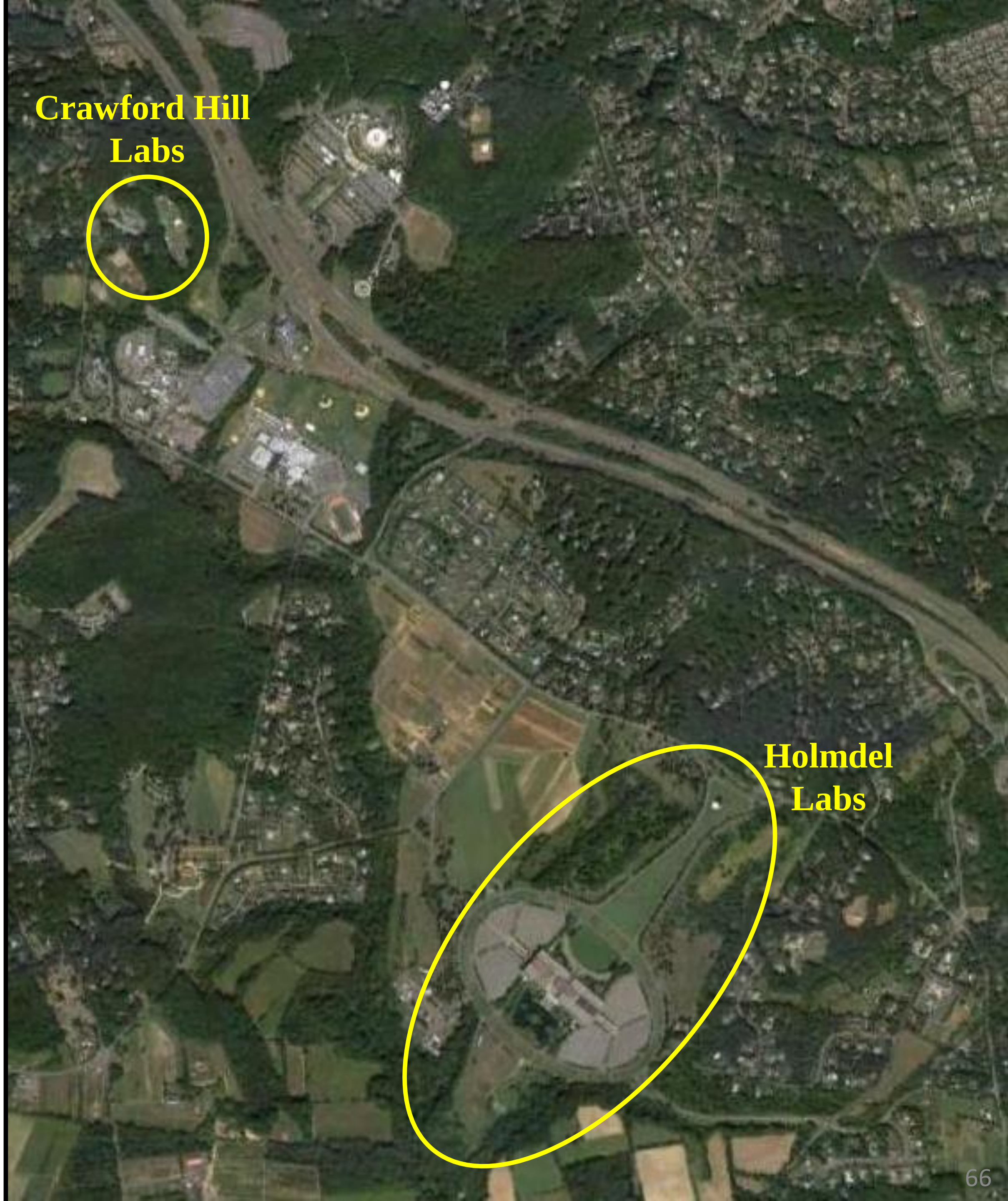
After the government enforced divestiture of AT&T in 1984, Bell Labs was taken over by Alcatel-Lucent.

The company eventually closed the facility in 2006 and sold it.

The world's largest lab now sits abandoned.

Bell Labs, NJ
Holmdel & *Crawford Hill* Laboratories

The two most famous Bell Labs facilities, at least as far as radio astronomers are concerned, are located within 2 miles of each other (as the crow flies).



Google Earth

Bell's Crawford Hill Lab, Holmdel, NJ

The sole remaining presence of Bell Labs in Holmdel is a small research group of Alcatel-Lucent working on optical networking and wireless technologies.

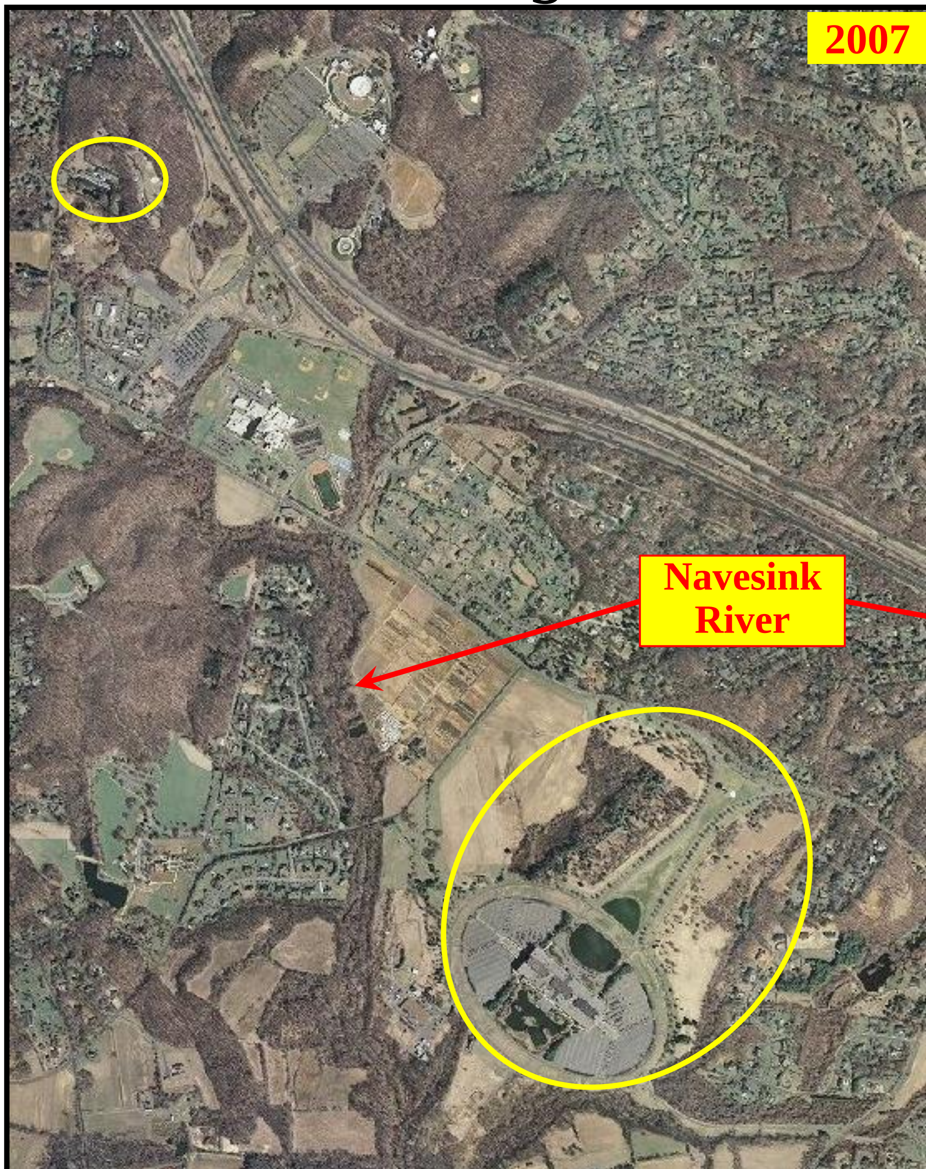
Where Penzias & Wilson Discovered the Cosmic Microwave Background.

In 1989 the CMB horn antenna was designated a National Historic Landmark.

Google Earth ; http://commons.wikimedia.org/wiki/File:Bell_Labs_Horn_Antenna_Crawford_Hill_NJ.jpg

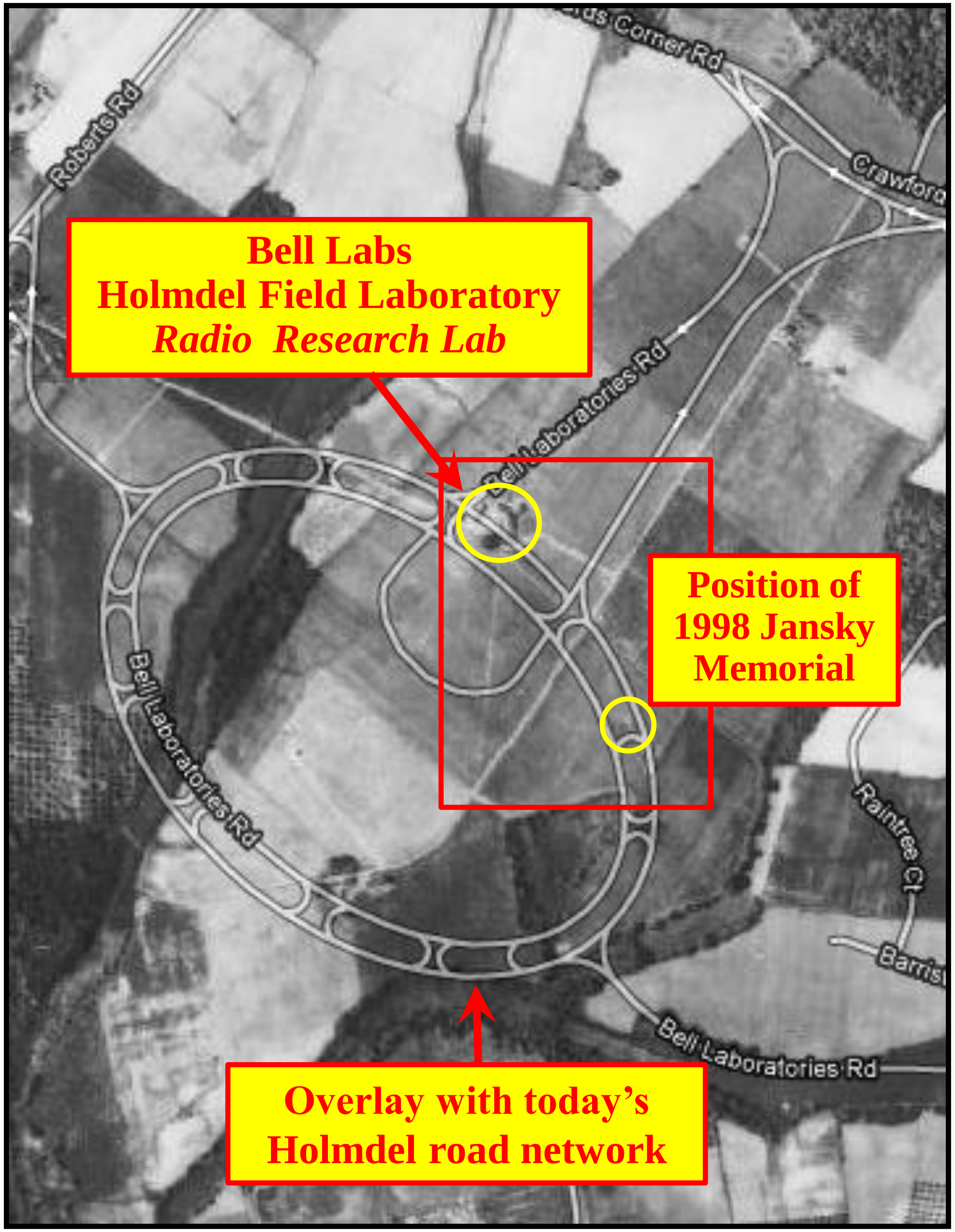
Holmdel & Crawford Hill Bell Labs

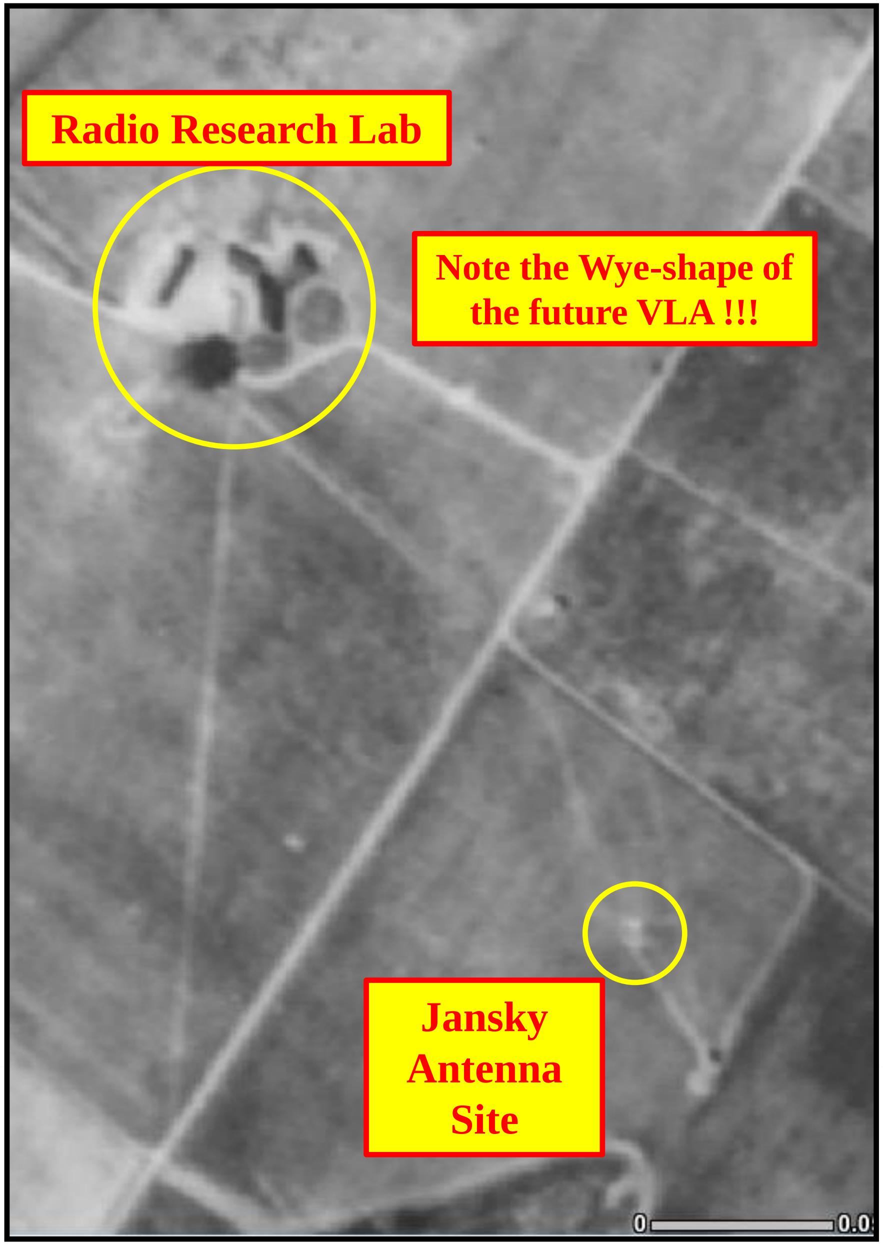
Satellite Image-2007 *Aerial Photo-1931* *(Thanks to FDR)*



http://njgin.state.nj.us/dep/DEP_iMapNJDEP/viewer.htm

Aerial Photo of Jansky's Lab & Telescope - 1931





http://njgin.state.nj.us/dep/DEP_iMapNJDEP/viewer.htm

The Jansky Antenna Site Over Time

http://www.historicaerials.com/

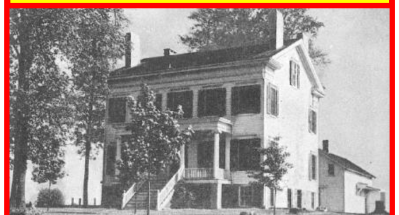
MUSA Location

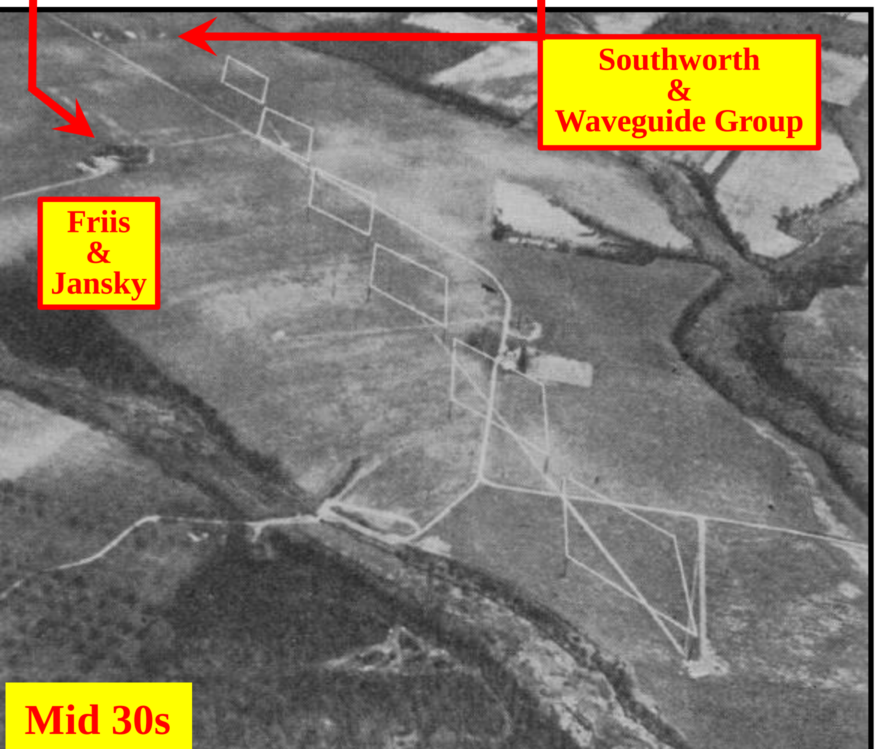
High-altitude 1930s photo taken before MUSA built.

Identifying features like the Navesink River, a pit, two large buildings & the road network, the approximate location of the MUSA can be determined.

Radio Research Lab

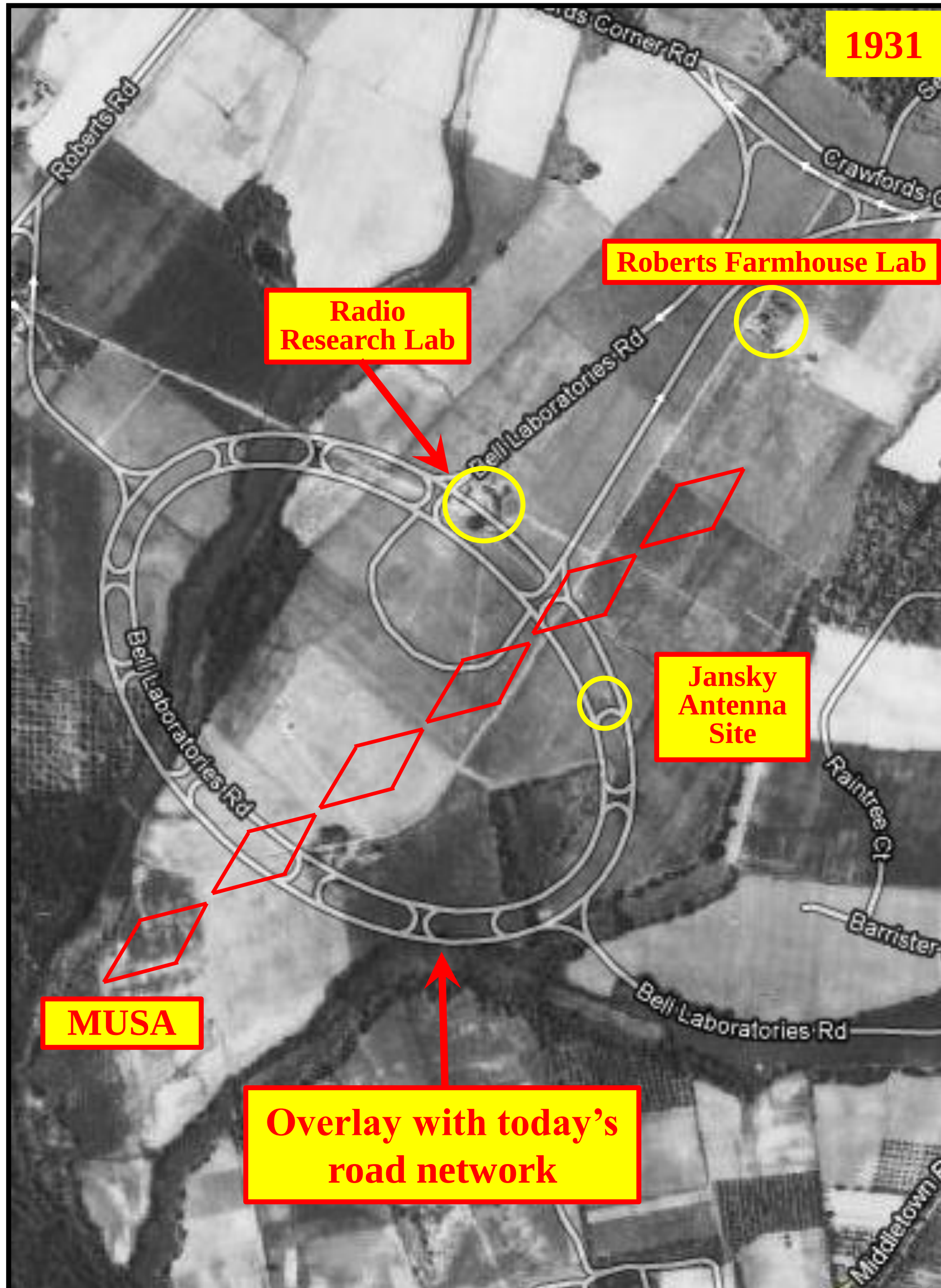
Roberts Farmhouse Lab





A Multiple Unit Steerable Antenna for Short-wave Reception,
H.T. Friis & C.B. Feldman, Proc IRE, Vol. 25, No. 7, July 1937, 841-917

http://njstateatlas.com/1930/



How Good of an Astronomical Radio Telescope would the MUSA have made?

- **The Experimental MUSA was built to measure the direction of multi-path signals from short-wave transatlantic telephone links. But what if Bell Labs had allowed it to carry out radio astronomy observations, how good of an instrument would it have been?**
- **It was pointed to the northeast (i.e., London) rather than to the south, so not being a transit instrument would have obvious drawbacks.**
  - **But the Australian Seacliff Interferometer at Dover Heights was pointed to the east.**
- **Being an end-on array, it only improved directionality in elevation.**
  - **But the single-element Seacliff Interferometer was also selective in elevation.**
  - **And broadside arrays, like the early Ryle two-element interferometers, only improved directionality in azimuth.**
- **Had they built as a N-S transit instrument, the MUSA's multiple beams could sweep the sky 3 times faster than any of the early Australian or British interferometers.**
  - **Multiple beams in radio astronomy didn't occur until 1968 when Bernard Mills *Molonglo Observatory Synthesis Telescope* (MOST) in Australia provided 3 east-west fan beams using a time shared mode.**
- **The MUSA used a rather low frequency which was ideal for short-wave telephony.**
  - **But early radio telescopes did not operate all that much higher. Grote Reber's first successful observations in 1939 were at 160 MHz, the Australians were at 200 MHz, and Cambridge at 175 MHz and later at 80 MHz.**
- **The MUSA's 5-20 MHz frequency range gave it a 4:1 bandwidth ratio.**
  - **Modern wideband receiver designs have achieved ratios of 2:1 and are desperately seeking bandwidth ratios of 3:1 or higher.**
- **The commercial MUSA systems at *Manahawkin* & *Cooling Marsh* built in 1940 had 2½ times better directivity in elevation while observing simultaneously with 4 beams at 2 different frequency bands. How many interferometers can do this even today…**

MUSA Legacy

The Musa Connector

WIKIPEDIA
The Free Encyclopedia

Main page
Contents
Featured content
Current events
Random article
Donate to Wikipedia

Interaction

Toolbox

Print/export

Article Discussion

Musa connector

From Wikipedia, the free encyclopedia

The **Musa** connector (Multi-User Steerable Array) is a type of coaxial connector, originally developed for the manual switching of radar signals. It had a characteristic impedance of 50 Ω[1], and was adopted for use in the emerging broadcast industry. By the time the first 'high definition' television first appeared in 1936, the connector was used as standard, unlike many popular types of coaxial connector it is engaged and disengaged by a straight push-pull action, making it ideal for patch bays.

Used in telecommunications and video, the connector has performed well but with the modern high definition signal now being broadcast, the mismatch between the original 50 Ω connector and the standard 75 Ω, used in almost every device in the broadcast industry, has become apparent.

References [edit]

1. ^ Ohm is where the art is - Publication: IBE - International Broadcast Engineer; Date: Tuesday, April 1, 2003

http://en.wikipedia.org/wiki/Musa_connector & http://uk.farnell.com/unbranded/323-010/musa-connector/dp/5096110

The MUSA Connector

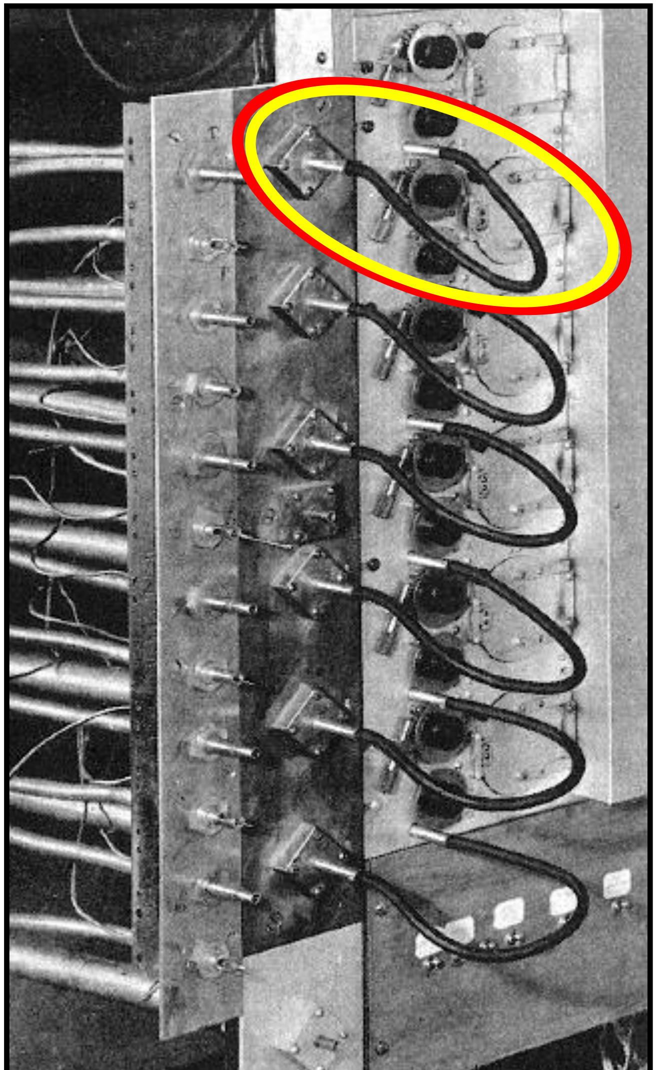
Broadcast & Video Applications

BELL LABORATORIES RECORD

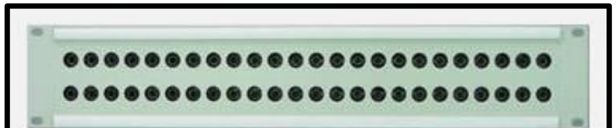
Musa Apparatus

By W. M. SHARPLESS
Radio Research Department

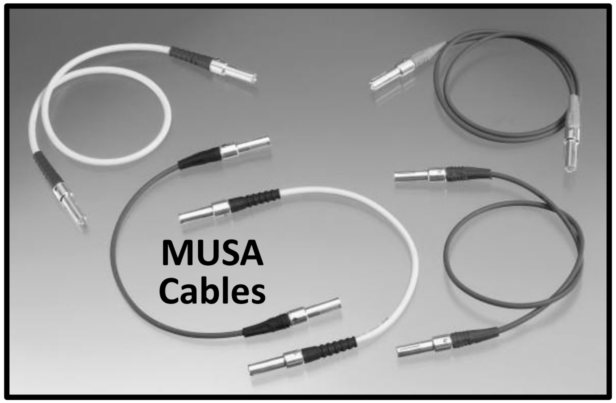
JANUARY 1938



Here the MUSA connector is used in a video patch panel rack. The push fit allows for fast &easy connections.

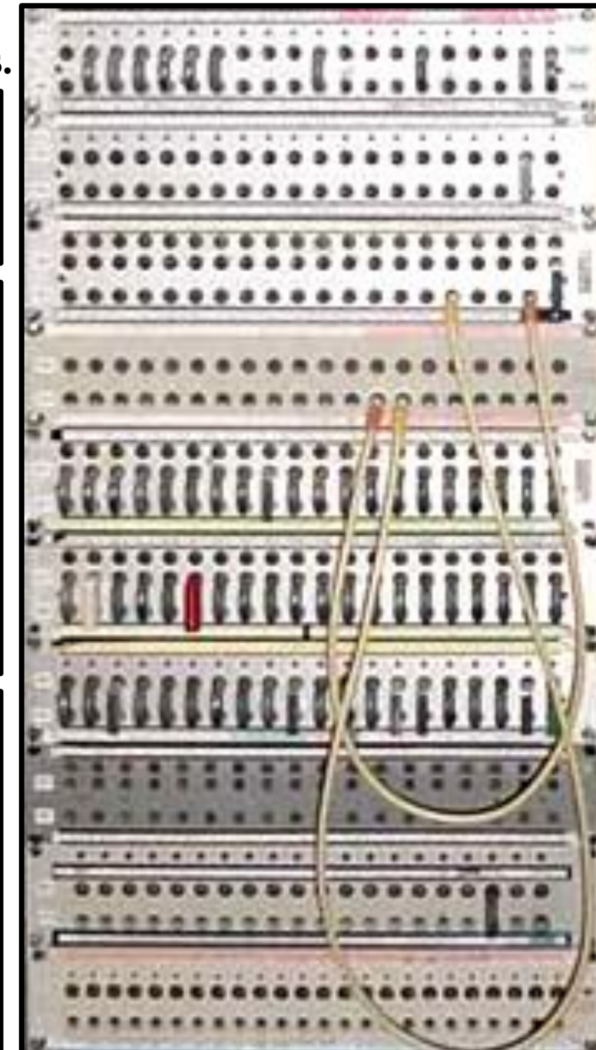


MUSA Patch Panel



MUSA Cables

MUSA U-Links



Musa Apparatus, W.M. Sharpless, Bell Laboratories Record, Vol. 16, No. 5, Feb. 1938, p. 195
https://intranet.rave.ac.uk/pages/viewpage.action?pageId=3768
https://intranet.rave.ac.uk/display/FComm/Central+Apparatus+Room+%28CAR%29

MUSA Conclusion - 1

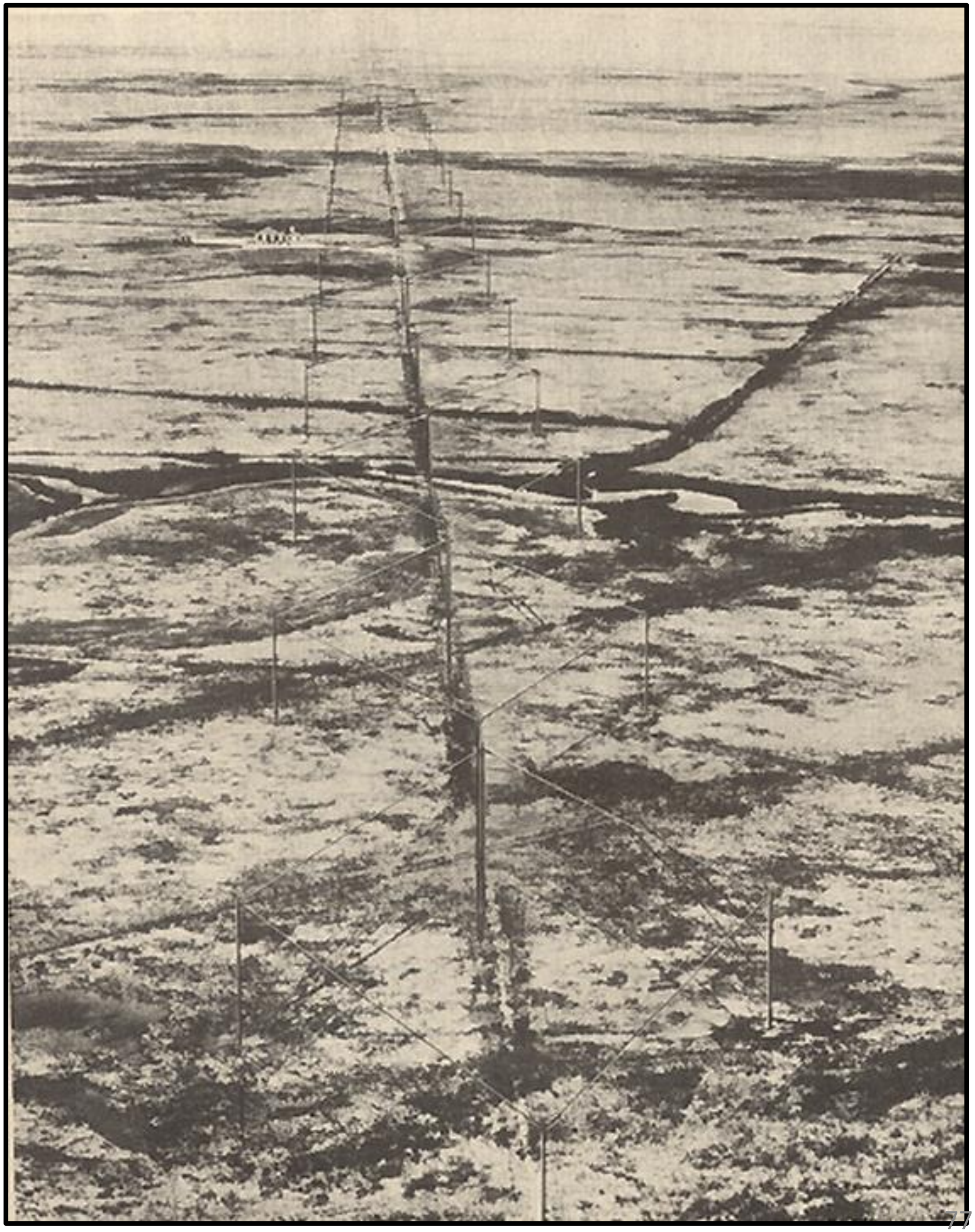
- **The Bell Labs Experimental *Multiple Unit Steerable Antenna* built at Holmdel in 1935 to study transatlantic 3-30 MHz Short-Wave telephone communications, was the first electronically steerable phased-array.**
- **This ¾-mile long MUSA designed by Friis & Feldman with its six Rhombic aerials was the first interferometer to detect a celestial source.**
- **We now know that the *star static* it found at 9.5 & 18.6 MHz came from the Cygnus region.**
- **The Holmdel MUSA was not only the first American interferometer to detect an extraterrestrial object, it was indeed the first in the world, beating the Aussies & the Brits by nearly a decade.**
- **While the CSIRO Sea interferometer and the Cambridge 2-element interferometer, both built in 1946, were the first to “intentionally” observe a celestial source, the Experimental MUSA did detect – however inadvertently - cosmic static in October 1935. This was less than 3 years after Jansky’s equally serendipitous discovery.**
- **The Experimental MUSA’s result was referenced by many of the pioneers in radio astronomy, including…**
  - **Jansky, Reber, Townes, Greenstein, Williamson, Hey, Bolton, Piddington, Shain, Ko, Sullivan & Kellermann**
  - **But surprisingly (or perhaps not) completely ignored by Ryle and his group at Cambridge (perhaps their “not invented here” syndrome).**

MUSA Conclusion - 2

- **The MUSA's data points at 9.5 & 18.6 MHz were used by pioneering radio astronomers to help realize that the detected emission at low frequencies was non-thermal.**
- **The Friis & Feldman 1937 paper provided a detailed analysis of the beam pattern of phased-arrays, including the effect of tapering the amplitude response towards the end of the array to improve sidelobe response.**
- **Although the direction of its beam was fixed in azimuth, it's elevation angle could be easily steered between 10-65° by adjusting the phasing of its 6 Rhombic antenna elements.**
- **It had 3 independently steerable beams, long before any astronomical interferometer made use of multiple beams.**
- **Like Jansky in 1932, Friis & his MUSA for a second time allowed Bell Labs to serendipitously pioneer the way in radio astronomy.**
- **Two larger commercial MUSAs – each 2-miles long with 16-Rhombic elements – were built by 1940 to improve transatlantic telephone communication links during the coming Solar Maximum.**
  - **They had dual-frequency receivers, each with 4 independent beams.**
  - **These were the most expensive commercial radio receivers ever built.**
  - **The cost of the receiving station was about £50K in 1940 (or $5M today).**
  - **They operated until the mid 1960s before being replaced by satellites.**

The story continues in…

The Commercial MUSAs



***Rhombic Antenna Design*, A. E. Harper, D. Van Nostrand Company, Inc., 1941**
http://tf4m.com/att-array-of-rhombic-antennas/

The  End

Any Questions ?

(from those who are still awake)

Postscript:

What came after the Bell Labs Experimental MUSA ?

The Commercial Transatlantic MUSAs at

Manahawkin, NJ

&

Cooling Marsh, England

1940

A Single-Sideband Musa Receiving System for Commercial Operation on Transatlantic Radiotelephone Circuits*

F. A. POLKINGHORN†, FELLOW, I.R.E.

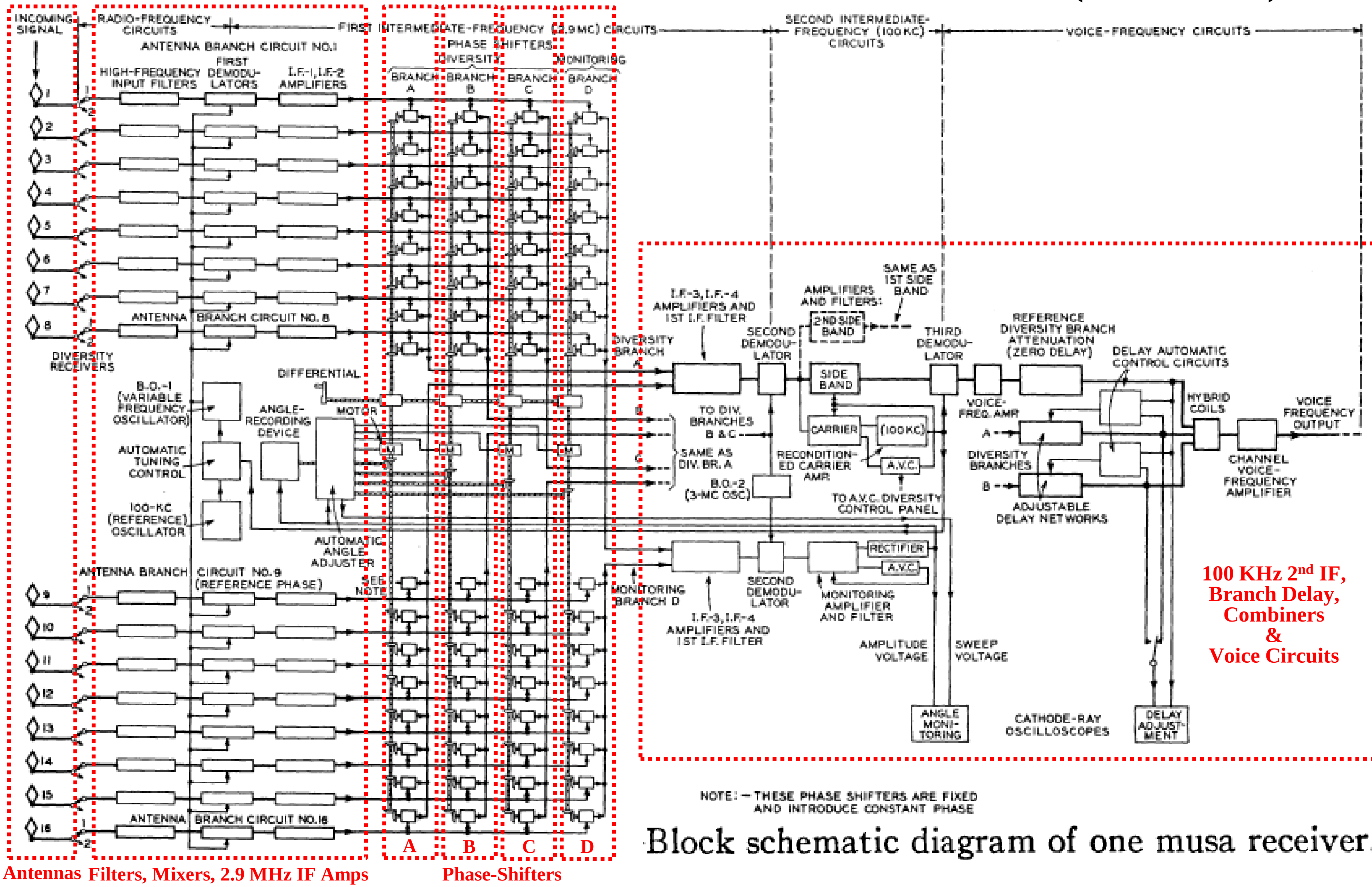
IN THE operation of short-wave radiotelephone circuits fading is observed which is caused by the combination at the receiving antenna of waves which arrive at different vertical angles and which have traveled from the transmitter over paths of different lengths. This fading may be mitigated by increasing the directivity of the receiving antenna in the vertical plane so as to favor the waves arriving over one path to the exclusion of the others.[1,2] It is not possible, however, to increase this directivity to any great extent with an ordinary antenna system before it is found that the signal arrives outside the angular range of the antenna an appreciable part of the time. To overcome this difficulty Friis and Feldman experimented with a receiving system consisting of a number of antennas, each having moderate directivity and each connected by a separate transmission line to a receiver where the outputs are phased by a variable phase-shifting system in such a manner as to give a system of high, variable directivity. A system of this kind, which they called a "musa" system from the initial letters of "multiple-unit steerable antenna," was built and found to give under most transmission conditions an improvement in the grade of circuit which could be obtained.[3] Accordingly, it was decided that a commercial system should be built for use on the circuits of the American Telephone and Telegraph Company from England. A corresponding system of modified design has been built by the British General Post Office.[4] The purpose of this paper is to review a

Outline Description of Receivers

A block schematic of one channel of the commercial musa system is shown in Fig. 1. The 16 rhombic antennas are placed in a line two miles long in the direction of the English transmitting station. Separate transmission lines lead from each antenna to a building placed a little to one side of the rear of the ninth antenna. Two receivers, only one of which is shown in the figure, are connected in parallel to each transmission line. Each receiver is designed to receive five specific frequencies, ranging from 4810 to 18,620 kilocycles, assigned to the corresponding transmitter in England.

A Single-Sideband Musa Receiving System for Commercial Operation on Transatlantic Radiotelephone Circuits, A. Polkinghorn, Proceedings of the Institute of Radio Engineers, April 1940, 157-170

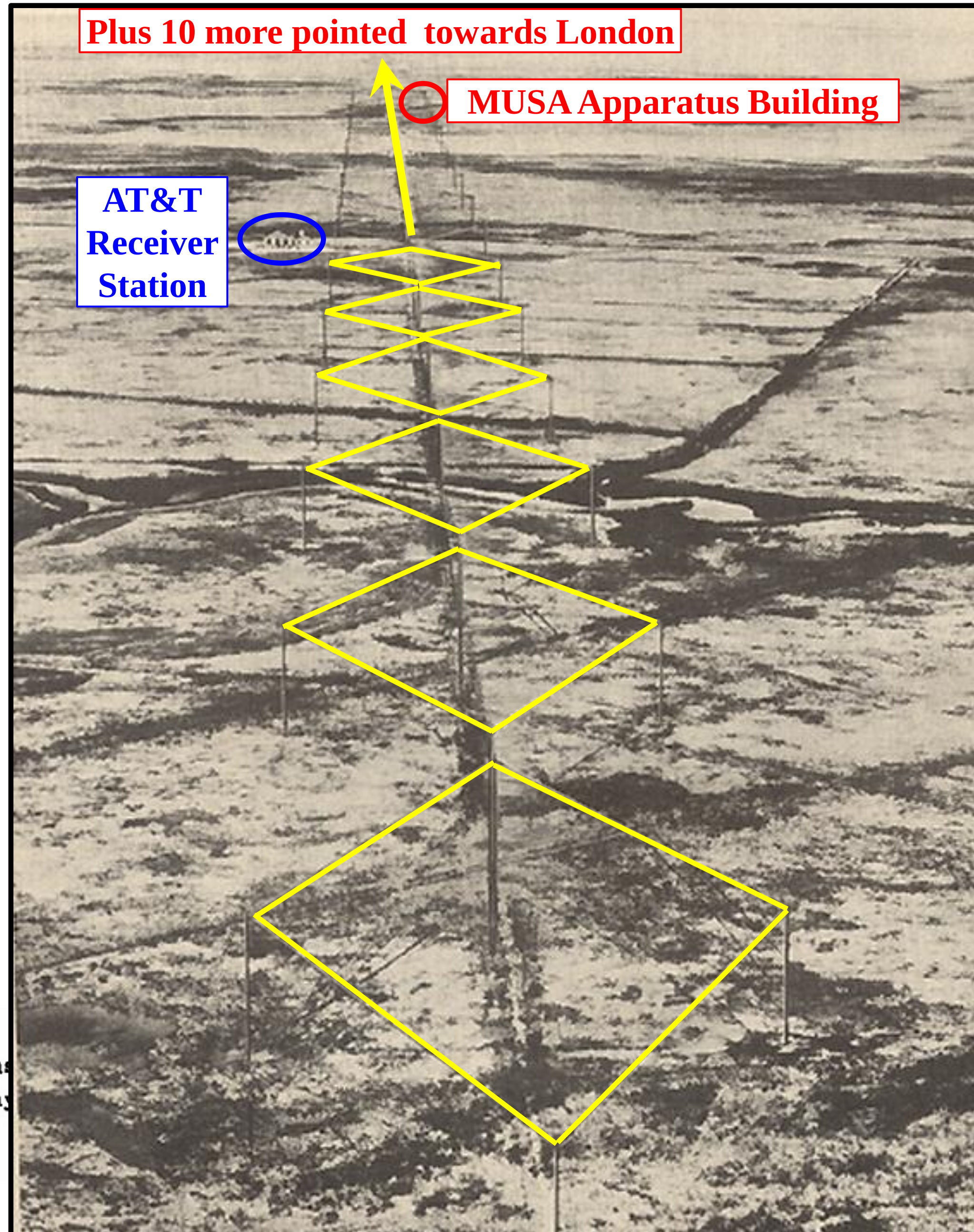
Manahawkin MUSA Receiver (1 of 2)



Block schematic diagram of one musa receiver.

A Single-Sideband Musa Receiving System for Commercial Operation on Transatlantic Radiotelephone Circuits, **A. Polkinghorn, Proceedings of the Institute of Radio Engineers, April 1940, 157-170**

Aerial View of the American MUSA at Manahawkin, NJ c.1941



Array of rhombic antennas, American Telephone and Telegraph transatlantic radiotelephone receiving station.

The rapid advances in transoceanic radio communication have been closely paralleled by the development of the various forms of directional antenna systems, including coil antennas[1], arrays of verticals[2,3,4], wave antennas[5], rhombic antennas[6,7], and arrays of rhombics[8].

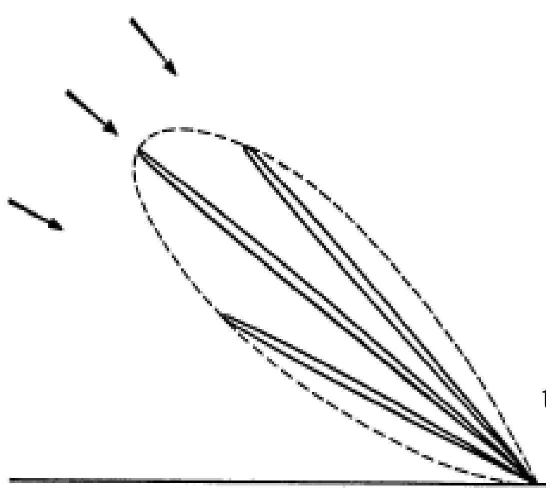
Rhombic Antenna Design, A. E. Harper, D. Van Nostrand Company, Inc., 1941
http://tf4m.com/att-array-of-rhombic-antennas/

The Commercial MUSAs:

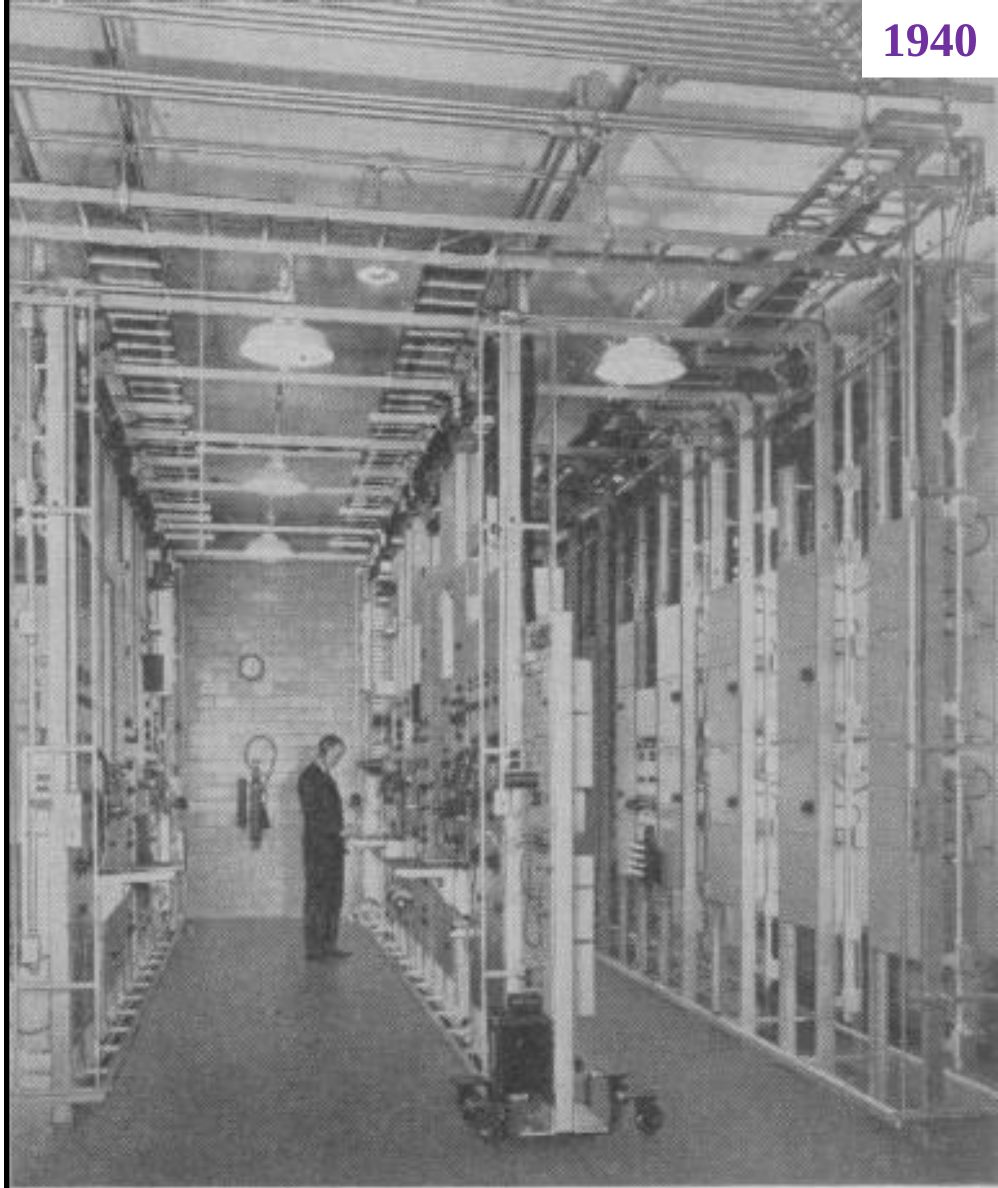
AT&T at Manahawkin, NJ
&
British Post Office at Cooling Marsh, UK

1940

- Built in the late 1930s prior to the solar maximum in the 1940’s.
- Consisted of 16 Rhombic antennas in an array that was 2 miles long.
- These MUSAs were dual-frequency receivers, each with 4 independent beams (for a total of 8 independent beams)
- The Cooling Marsh MUSA used 1,079 “valves” (vacuum tubes).
- Cost of the Cooling Marsh MUSA was ₤50K (or about $4.8M today).
- Operated between 1940 & mid 1960’s when it was finally supplanted by communication satellites.



3 beams are combined to improve the S/N, while the 4th beam continuously sweeps in elevation looking for the 3 strongest peaks



View inside the of the Manahawkin Apparatus Building

Fig. 2—View of musa receivers.

A Single-Sideband Musa Receiving System for Commercial Operation on Transatlantic Radiotelephone Circuits, A. Polkinghorn, Proceedings of the Institute of Radio Engineers, April 1940, 157-178

Manahawkin MUSA Phase-Shifters

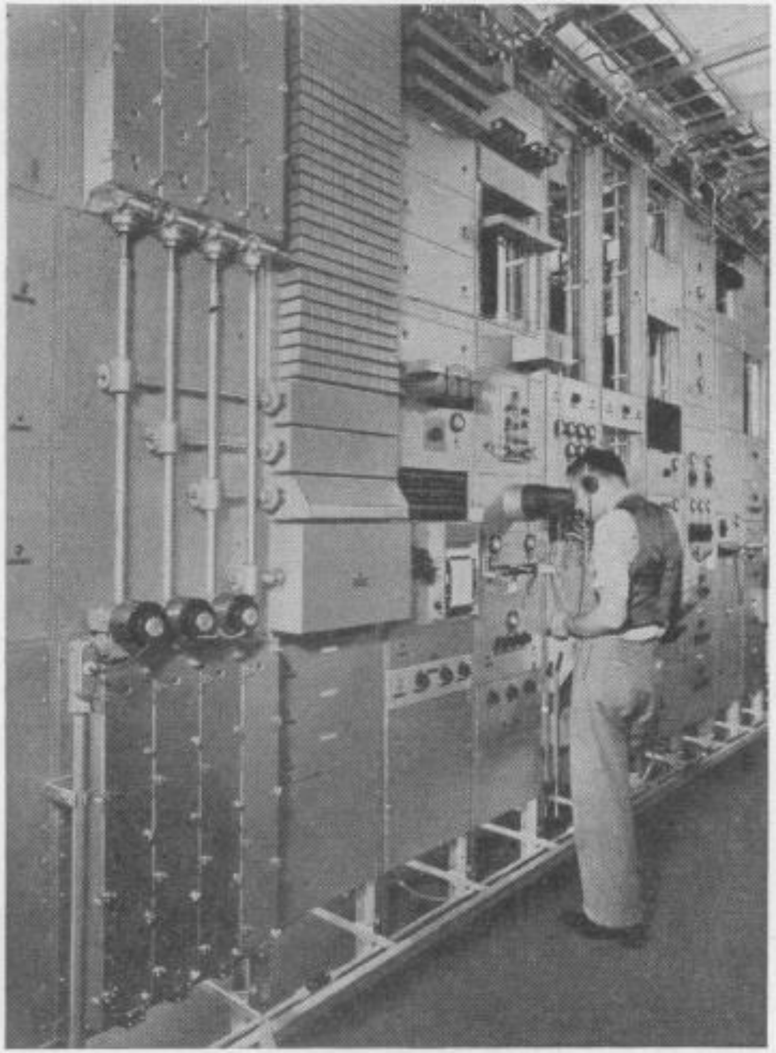


Fig. 6—View of second row of bays showing phase-shifter-drive system (left).

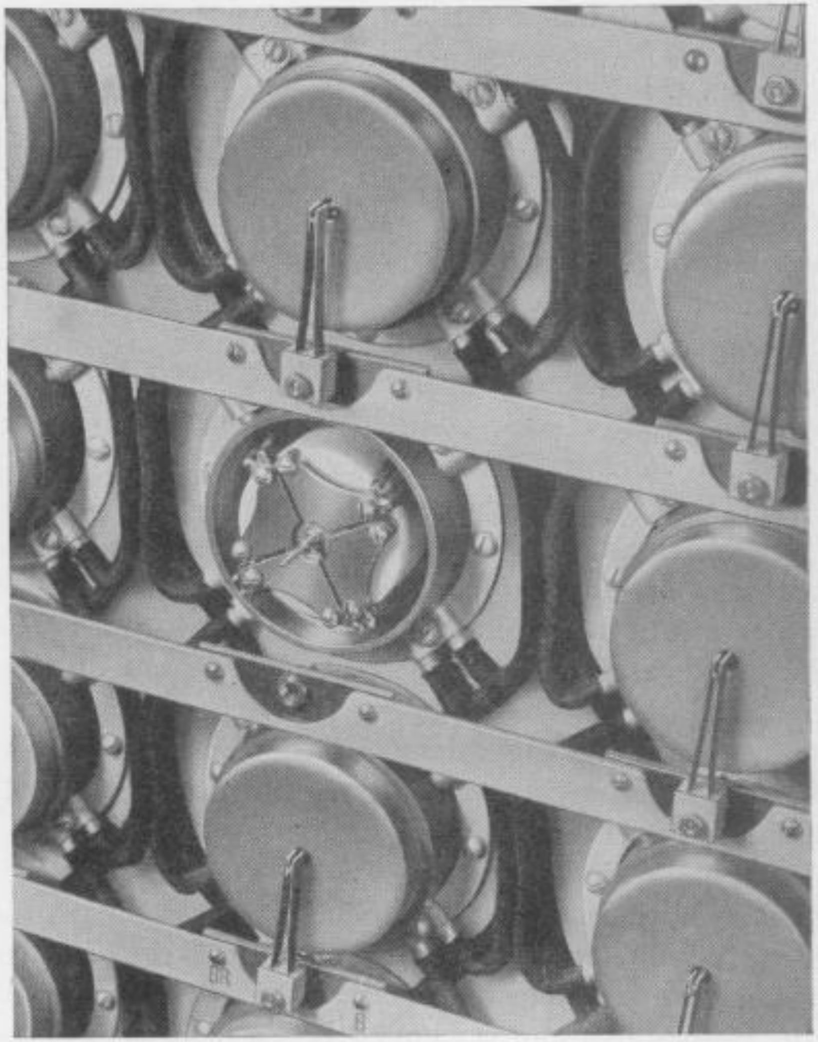


Fig. 7—Portion of a group of phase-shifting condensers. Brush and cover removed from center condenser to show construction.

***A Single-Sideband Musa Receiving System for Commercial Operation on Transatlantic Radiotelephone Circuits*, A. Polkinghorn, Proceedings of the Institute of Radio Engineers, April 1940, 157-170**

Commercial MUSA Beam Pattern

The 16-element, 2-mile long Manahawkin and Cooling Marsh MUSAs produced fairly sharp beams with a side-lobe response that was more than adequate for the transatlantic telephony link.

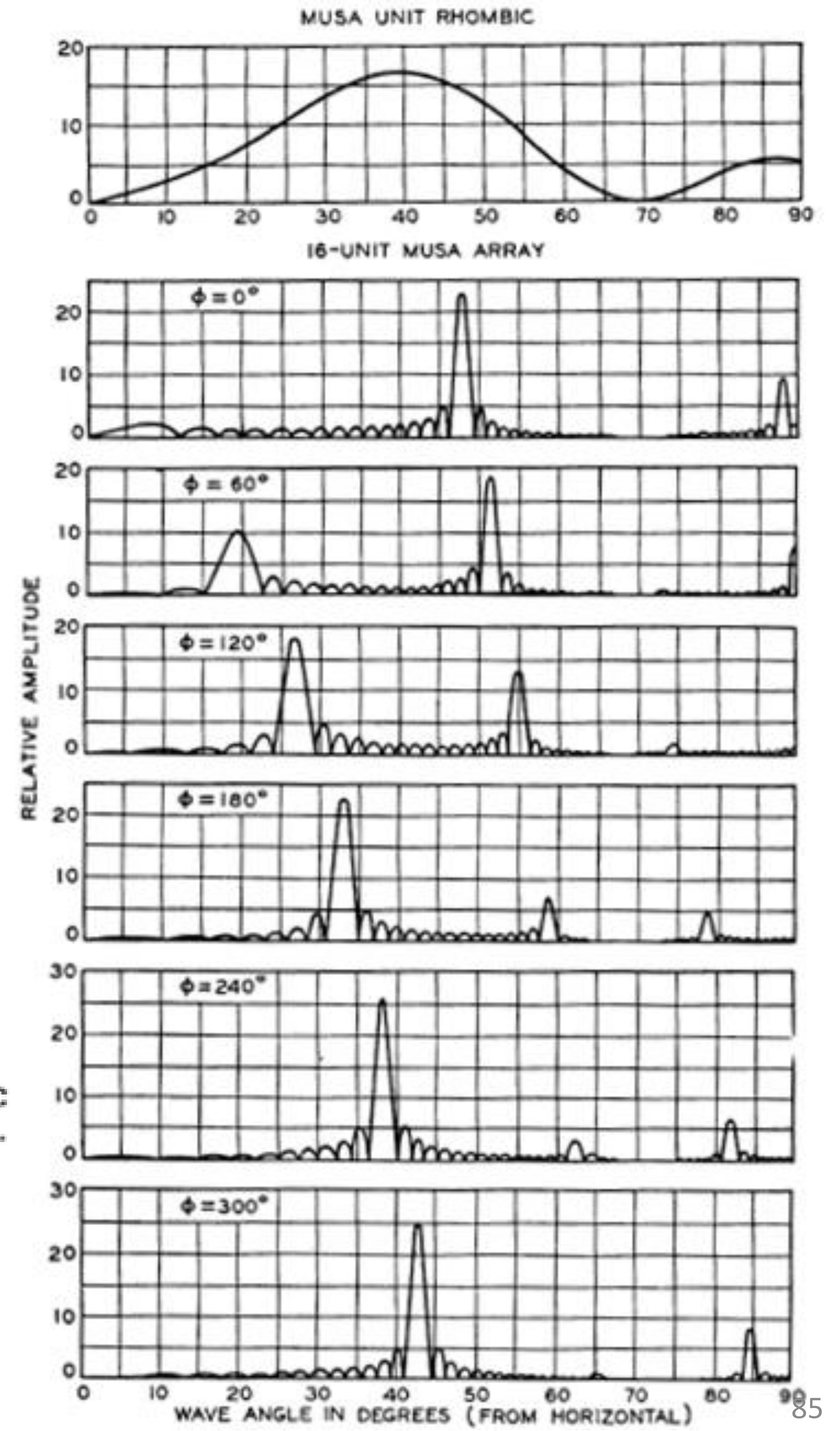


Fig. 3—Directive diagram in the vertical plane of a unit rhombic antenna and the 16-unit musa array. Frequency, 4700 kilocycles. ϕ = phase-shifter setting.

A Single-Sideband Musa Receiving System for Commercial Operation on Transatlantic Radiotelephone Circuits, A. Polkinghorn, Proceedings of the Institute of Radio Engineers, April 1940, 157-170

ERIE COUNTY INDEPENDENT
APRIL 7, 1938

CAPE VINCENT EAGLE
Thursday, April 14, 1938

THE NAPLES NEWS,
Wednesday September 14, 1938

ANTENNA TWO MILES LONG FOR OVERSEA 'PHONE LINK

As a further improvement in the Bell System's transatlantic telephone service, the American Telephone and Telegraph Company will establish a new type of short wave receiving station, with an antenna two miles long, at Manahawkin, N. J. There the company recently acquired a 2,500-acre tract of meadow land to provide ample room for the station, to be placed in operation by the summer of 1939.

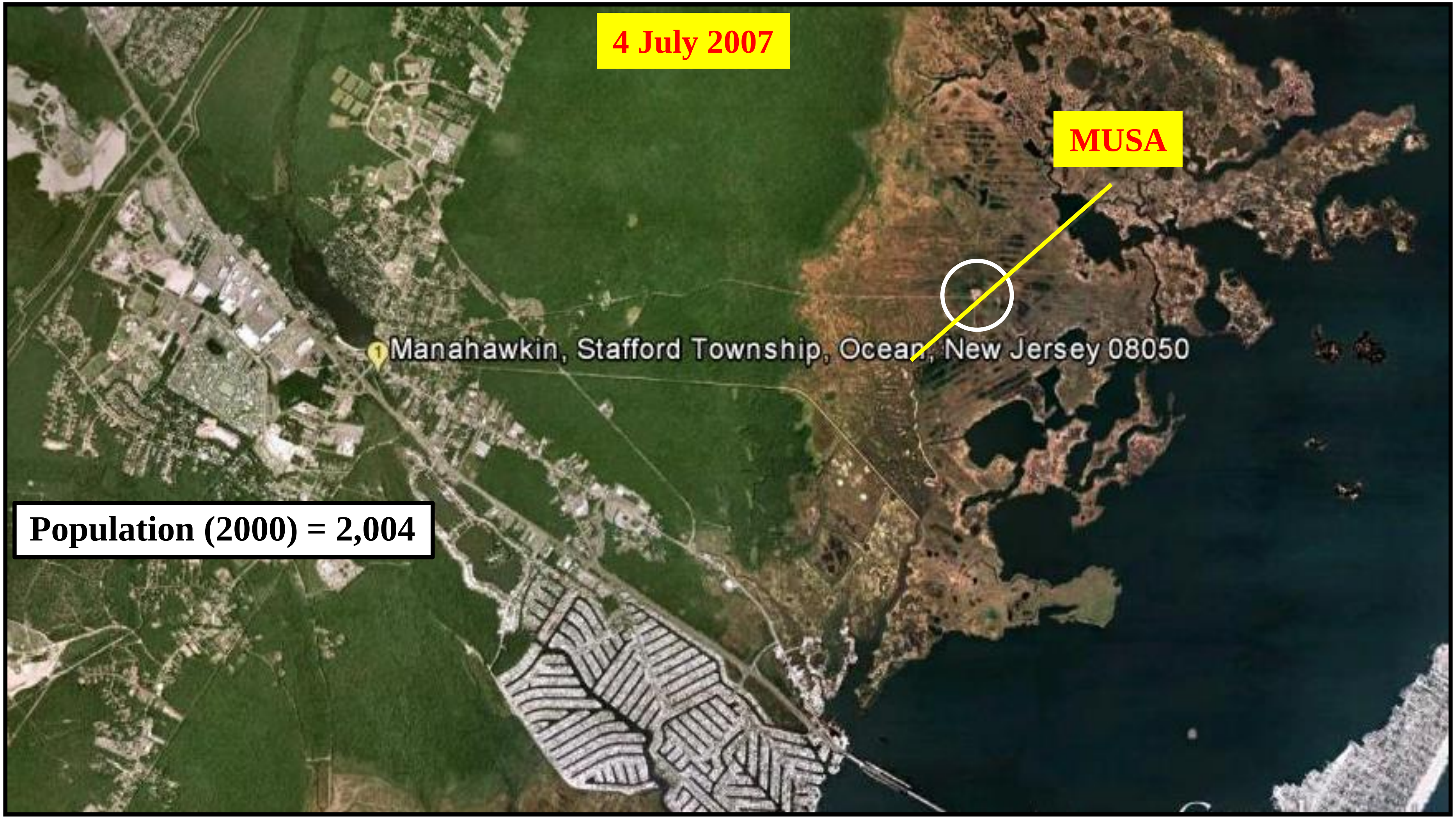
The giant antenna for the station will be of the new "steerable" type recently developed by the Bell Telephone Laboratories in New York City. This equipment greatly reduces "fading," static and other electrical disturbances, and is expected to be especially helpful during the approaching period of maximum sunspot activity, when short wave transmission is difficult. It will consist of sixteen separate antenna units linked by coaxial cables along its two miles in length, pointing towards the overseas transmitting station at Rugby, England.

Incoming signals from the European station will pass from Manahawkin over wire lines to the Long Distance Building in New York City. There they will pass through the overseas control room and switchboard to their destination.

http://fultonhistory.com/Newspaper%2013/Naples%20NY%20News/Naples%20NY%20News%20%201938-1939/Naples%20NY%20News%20%201938-1939%20-%200549.pdf

AT&T "Manahawkin" Radio Station

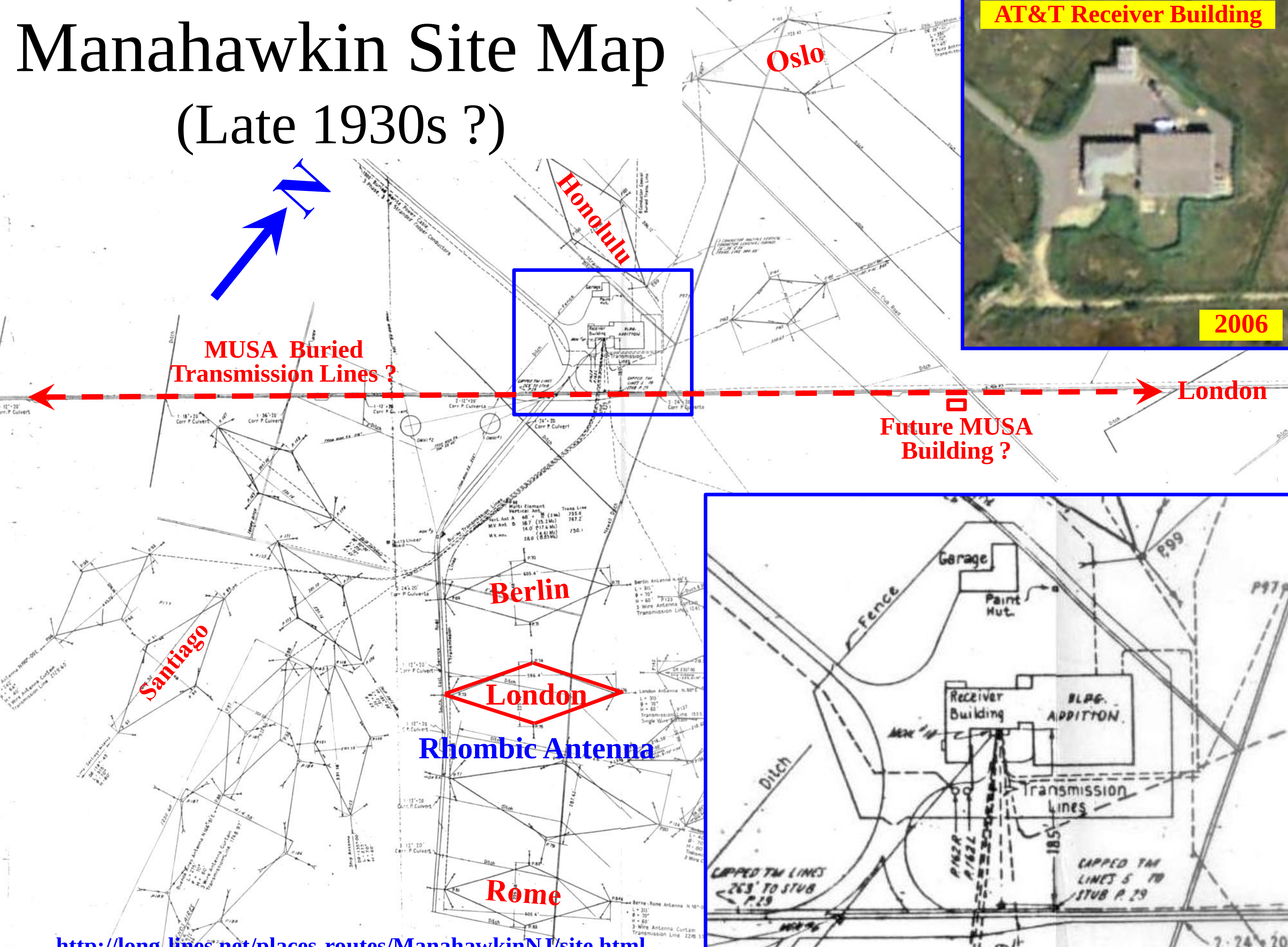
From 1830, it was identified as a Lenape word meaning "*Land of Good Corn*." More recent scholarship suggests it may mean something more like "*fertile land sloping into the water*."



Google Earth
http://twp.stafford.nj.us/town-square/history-of-stafford-township/
http://en.wikipedia.org/wiki/Manahawkin,_New_Jersey

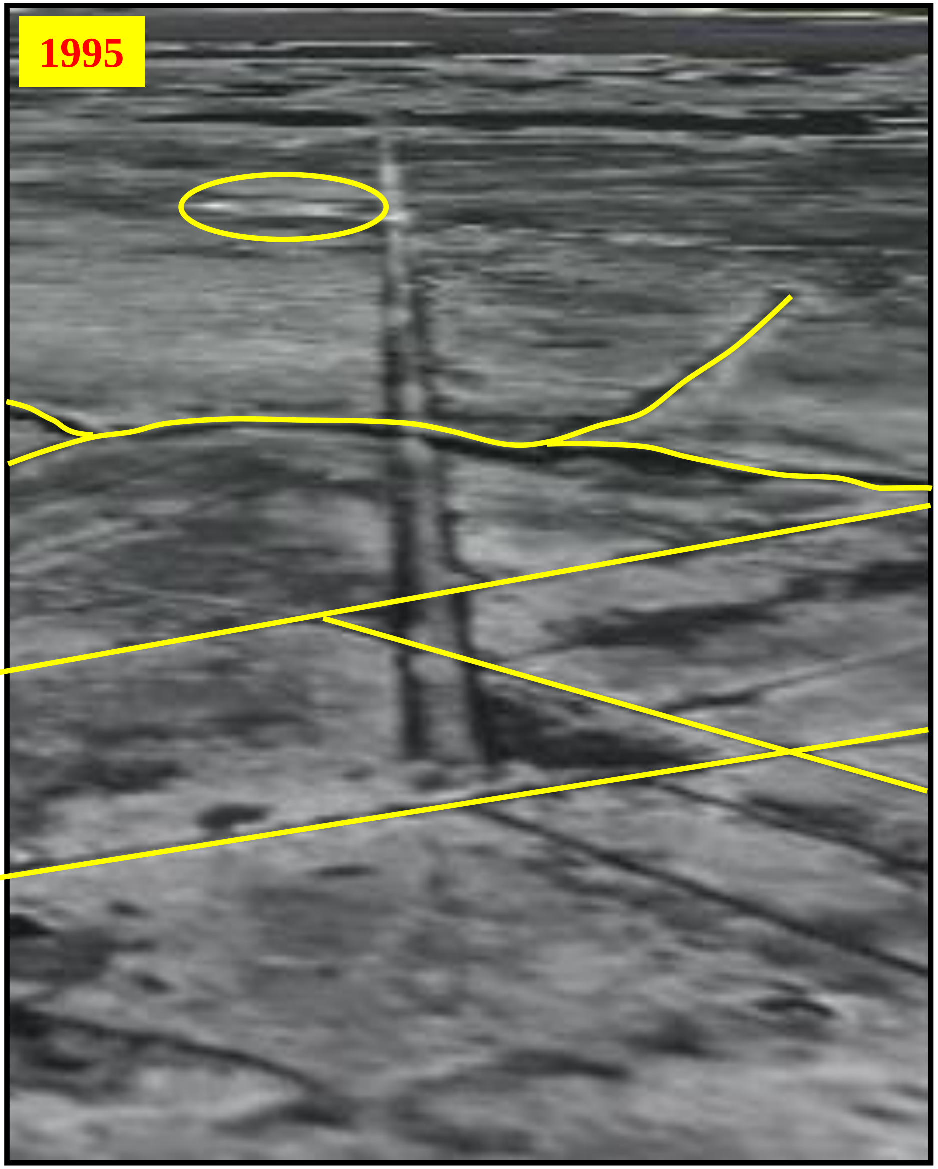
Manahawkin Site Map

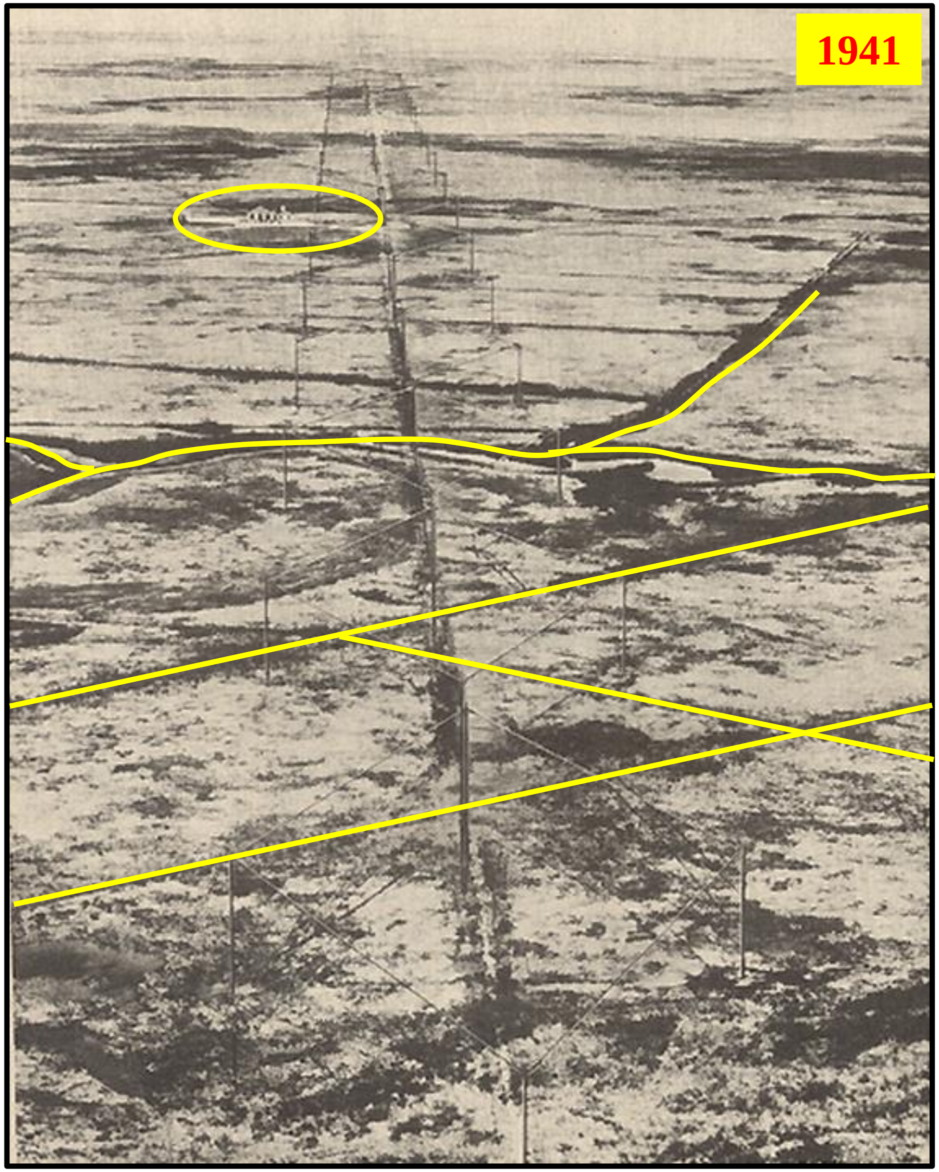
(Late 1930s ?)



http://long-lines.net/places-routes/ManahawkinNJ/site.html

Manahawkin MUSA – Then & Now





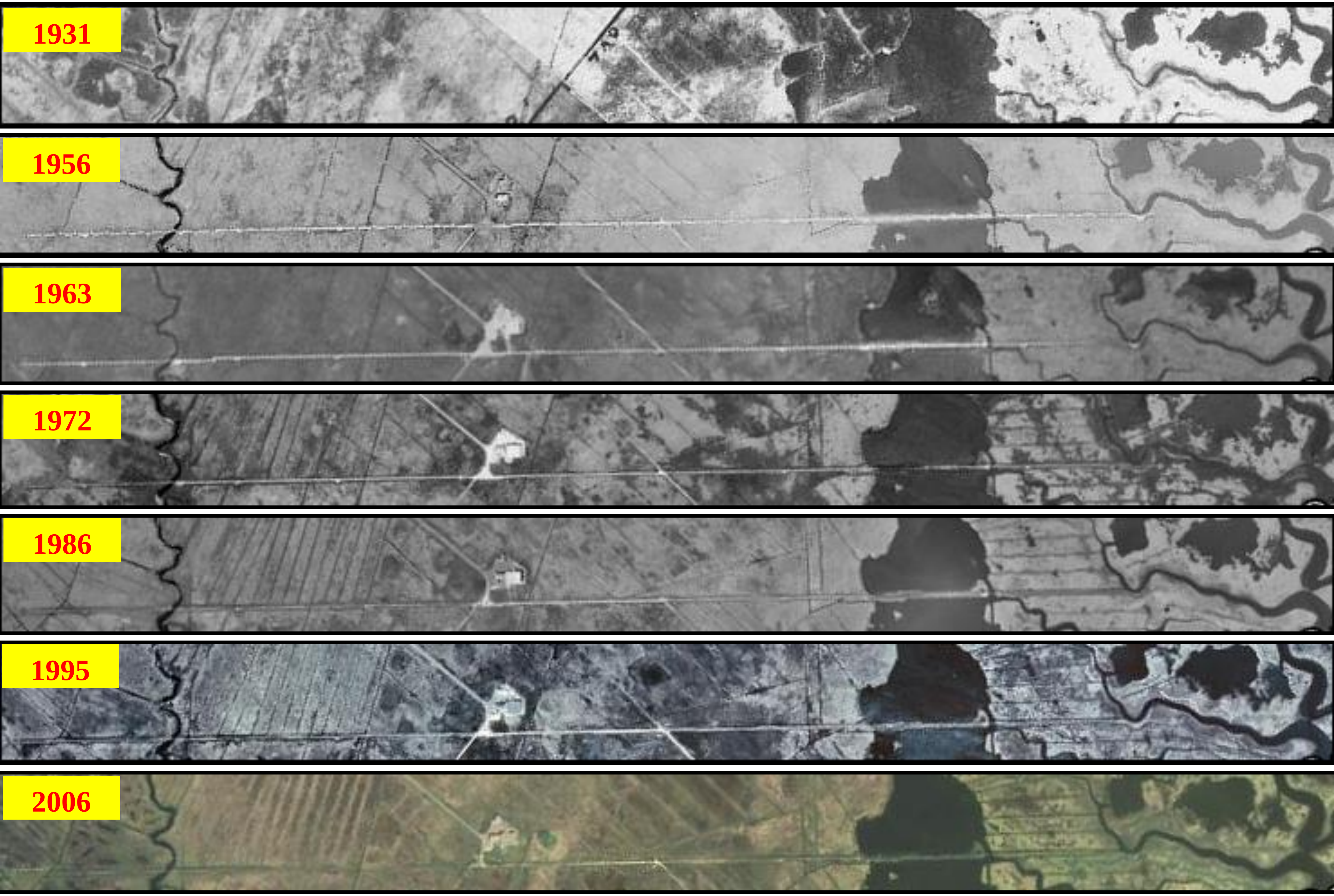
***Rhombic Antenna Design*, A. E. Harper, D. Van Nostrand Company, Inc., 1941**
http://tf4m.com/att-array-of-rhombic-antennas/
Google Earth (28 March 1995)

Manahawkin MUSA (15 July 2006)

At this resolution, we can't see the poles (or the holes) that once belonged to any of the rhombic antennas, assuming they still exist.

Google Earth

The Manahawkin MUSA Over 75 Years



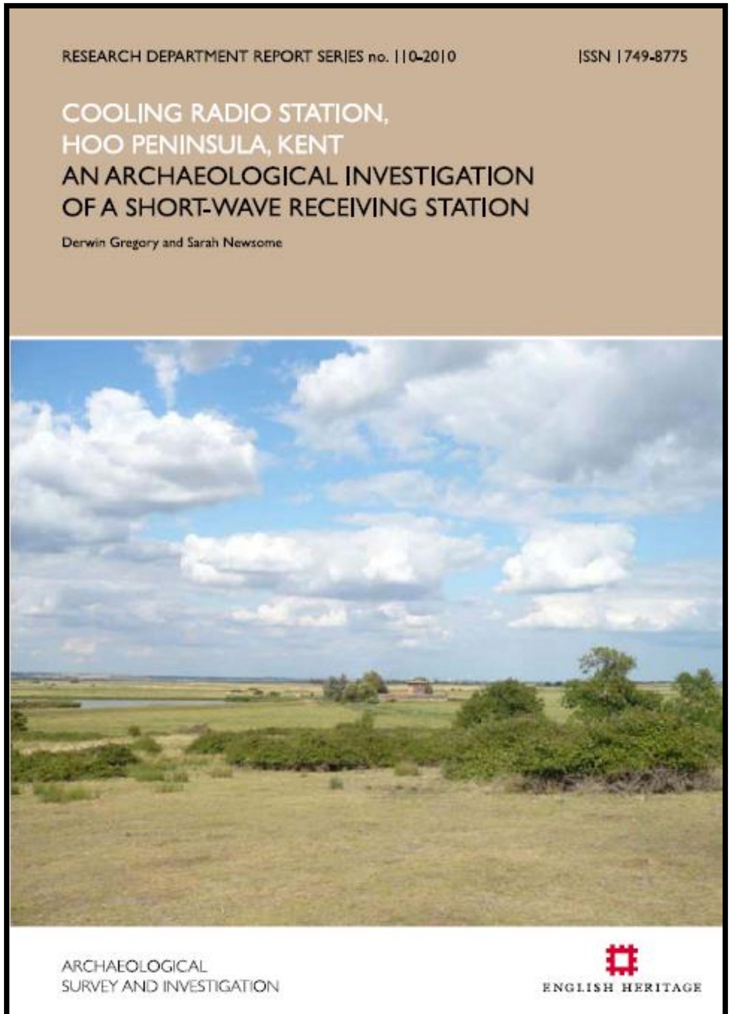
http://www.historicaerials.com/

The British General Post Office MUSA at the *Cooling Marsh Station*

SUMMARY

In August 2010, English Heritage's Archaeological Survey and Investigation team carried out an investigation of the remains of Cooling Radio Station. The station was constructed in 1938 to house the 'Multiple Unit Steerable Antenna' (MUSA) system developed by Friis and Feldman in the 1930s. The MUSA array was the last major technological development in the short-wave communication era and represented the ultimate short-wave receiving system. It is believed that only two other stations using the MUSA system were built in the world: the experimental array constructed near Holmdel, New Jersey, and one other full array at Manahawkin, New Jersey. Unlike the mechanical operating system employed at Manahawkin, Cooling Radio Station was unique as it was controlled by an electrical phase-shifting system. In total, the receiving equipment at Cooling utilised 1,079 valves making it both complicated and expensive. The MUSA system was probably the most complex radio receiver ever built and gave valuable service between the 1940s and 1960s. Prior to the

2010



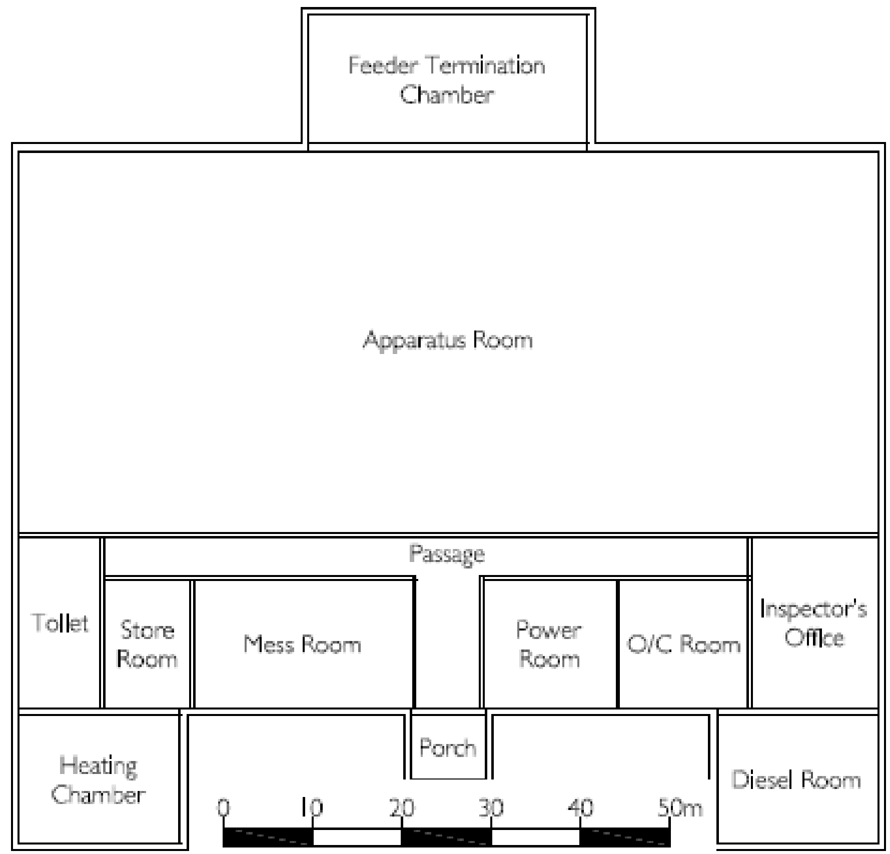
RESEARCH DEPARTMENT REPORT SERIES no. 110-2010 ISSN 1749-8775

COOLING RADIO STATION,
HOO PENINSULA, KENT
AN ARCHAEOLOGICAL INVESTIGATION
OF A SHORT-WAVE RECEIVING STATION

Derwin Gregory and Sarah Newsome

ARCHAEOLOGICAL
SURVEY AND INVESTIGATION

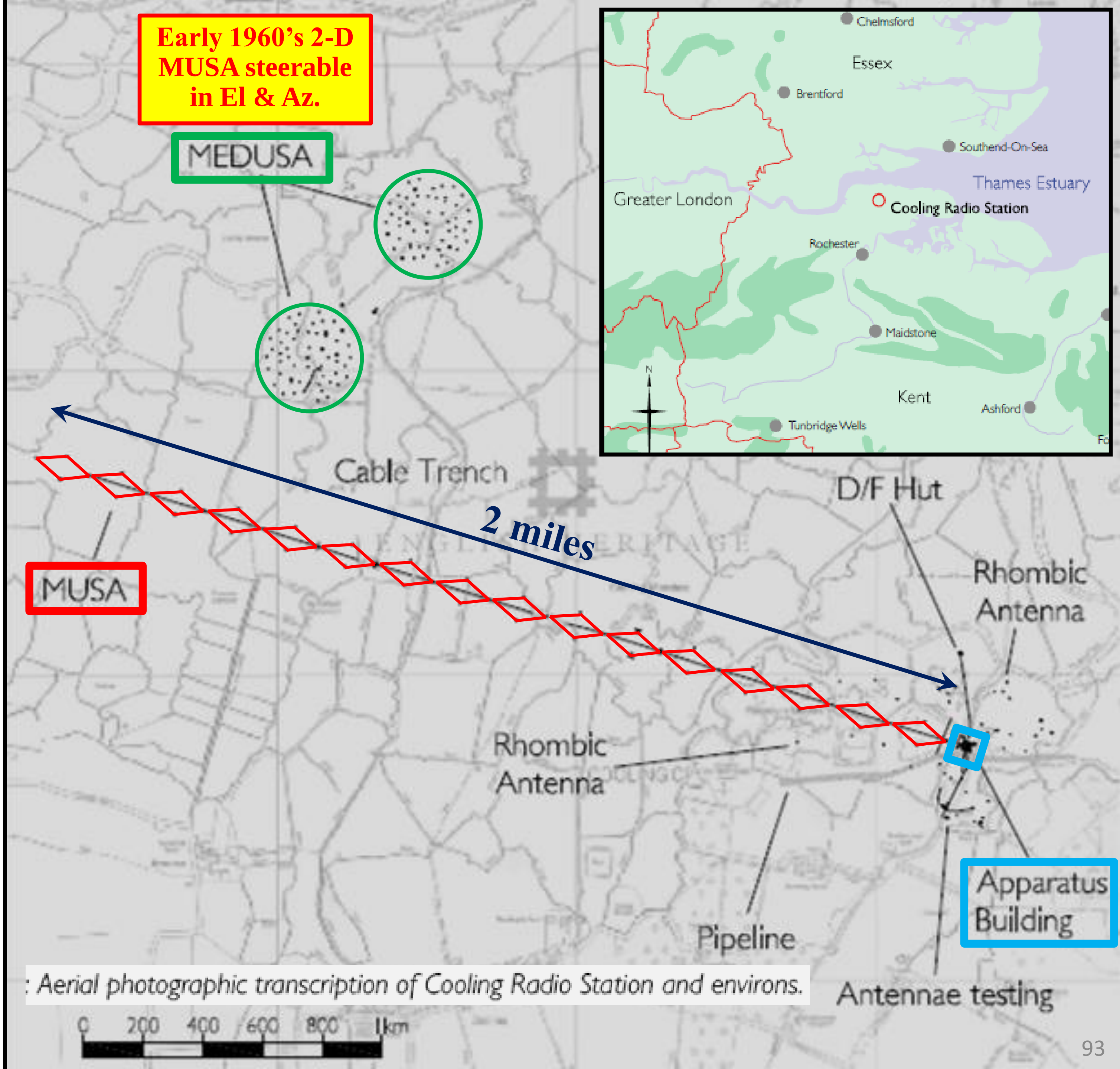
ENGLISH HERITAGE



Cooling Radio Station, Hoo Peninsula, Kent - An Archaeological Investigation of a Short-Wave Receiving Station,
D. Gregory & S. Newsome, English Heritage, Research Department Report Series No. 110-2010

Cooling Marsh Station *Map*

Cooling Radio Station, Hoo Peninsula, Kent - An Archaeological Investigation of a Short-Wave Receiving Station, **D. Gregory & S. Newsome, English Heritage, Research Department Report Series No. 110-2010**



WIRELESS SECTION: CHAIRMAN'S ADDRESS

1938

By A. J. GILL, B Sc.(Eng.), Member.*

(*Address delivered 2nd November*, 1938.)

I.E.E. JOURNAL, VOL. 84.

At Cooling the aerial system will consist of an array of 16 unit antennae placed along the great-circle path between the transmitter and receiver (see Fig. 20). The total length of the array will be approximately 2 miles, with the receiving station located at the end remote from the transmitter. The output from each unit antenna will be conveyed to the receiver by means of a separate buried coaxial transmission line.

The signal/noise ratio advantage of the ray diversity system compared with the unit antenna depends in practice on the polar distribution of the radio noise or static which obtains in a given case. If, however, we assume that the static is negligible and that the major source of noise is the thermal-agitation voltage in the first tuned circuit of the receiver, a 16-element system should present a signal/noise gain of 16 times in power, owing to the combination of the 16 equal signal voltages in phase and the combination of the 16 sets of noise voltages in random phase. That is, the signal increases in power 256 times while the noise increases only 16 times. The improvement in signal/noise ratio is thus $10 \log_{10} 16$, or 12 db.

The antenna system comprises 16 rhombic antennae, the spacing between centres being 656 ft.

Each unit rhombic antenna is 60 ft. high, the side is 315 ft., and the included angle between the sides is 140°

The loss on the longest line is expected not to exceed 6 db. at 20 Mc./sec. The lines are buried in the earth to minimize changes in length due to temperature variations and so to avoid the necessity for expansion joints.

There is no signal-frequency amplification, but adequate protection against the image channel is obtained by the use of 3·1 Mc./sec. as the first intermediate frequency, together with a signal-frequency filter. The other intermediate frequencies are 600 and 100 kc./sec.

Tapering in this receiver can be effected by adjustment of the gains of the 16 first intermediate amplifier stages by grid-bias control; grading may thus be introduced at will by operating a single switch.

The initial equipment at Cooling will consist of two receivers, each suitable for two speech channels. The equipment is mounted on standard 19-in. racks and for the two receivers consists of 88 bays. The total length of the receivers will therefore be about 110 ft. with an average height of about 8 ft. and the number of valves in use will be 1 079 for the two receivers. This seems a lot of equipment, but when it is realized that these receivers will give an improvement of about 1 000 over a simple receiver the complication becomes worth while.

Wireless Section: Chairman's Address, A.J. Gill, Journal of the Institution Electrical Engineers, Vol. 84, Issue 506, 1939, p. 248-260

Cooling Radio Station

By

Frank R. Turner

One of the unusual aspects of the system was the aerial antenna installation. It consisted of sixteen antennae spaced over two miles on the great circle path to the transmitter and connected to the receiving building by buried coaxial cable. Each of the sixteen antennae was mounted on four sixty feet high poles spaced at six hundred and fifty feet centres.

The coaxial feeder cable was over sixteen miles long and encased in two inch (50mm) diameter copper tubing made up of thousands of twenty feet lengths joined with soldered plumbing fittings. Inside the tube were ceramic spacers to seperate the 5/8" (15mm) thick copper core from the sheath. The copper tubing was buried approximately twenty seven inches (675mm) deep and had over 4,500 joins throughout its total length.

Inevitably, due to the marshland surrounding the main building, there were leaks within the sixteen miles of copper tubing that had adverse effects on the operation of the radio station.

The installation of a compressor, which pumped pressurised air through the tubing kept out water but leaks were nevertheless unavoidable. Tracing the leaks posed many problems and it was decided early on to introduce a pungent smelling but harmless gas into the tubing to assist in detecting the leaks. From time to time therefore small amounts of Amyl Mercaptan were injected into the system.

Initial tests were carried out in which a man walked a two mile length sniffing for the pungent smelling gas which would escape through any pinhole or faulty join.

These tests were not really effective on a windy day and so it was decided to introduce a sniffer dog to do the job. An attempt was therefore made to train a dog to detect the injected Amyl Mercaptan gas but this was not such an easy solution. Eventually, a Labrador dog named "Rex of Ware" was trained and used briefly at Cooling with some excellent results. However, the dog soon got wise to the meat proferred for finding a leak and after a while started to invent leaks just to receive the reward.

A Gravesend man, Mr Cyril Stampton, a former wartime Royal Navy submarine service radio operator, was employed at the Cooling Radio Station from 1946 onwards and it was his responsibility to constantly check the underground copper tubing for leaks. He reckons that whilst employed at Cooling he must have renewed almost all of the 4,500 copper joins.

During the war years this radio station regularly transmitted conversations between Winston Churchill and President Roosevelt in the United States of America. The Cooling Radio Station, which did sterling work throughout the war and the post war period remained in use until 1965 when satellite communications eventually made it redundant.

The Cooling Radio Station, **Gravesend at War Series No. 5, F.R. Turner, Self Published, 2000**

The Cooling Marsh Radio Station - Then

Figure 2: Cooling Radio Station under construction (still from Jennings 1938 © Royal Mail Group Ltd 2011, courtesy of The British Postal Museum & Archive).

Figure 10: Cooling Radio Station apparatus building (courtesy of Frank Turner).

Figure 12: Laying the feeder tubes (still from Jennings 1938 © Royal Mail Group Ltd 2011, courtesy of The British Postal Museum & Archive).

Figure 26: Armed guard outside Cooling Radio Station presumed to be during the Second World War (courtesy of Frank Turner).

Cooling Radio Station, Hoo Peninsula, Kent - An Archaeological Investigation of a Short-Wave Receiving Station,
D. Gregory & S. Newsome, English Heritage, Research Department Report Series No. 110-2010

The Cooling Marsh Radio Station - Now

All that remains of the *Apparatus Building* is the bottom floor & *Generator Room*

Figure 34: The remains of Cooling Radio Station (© English Heritage).

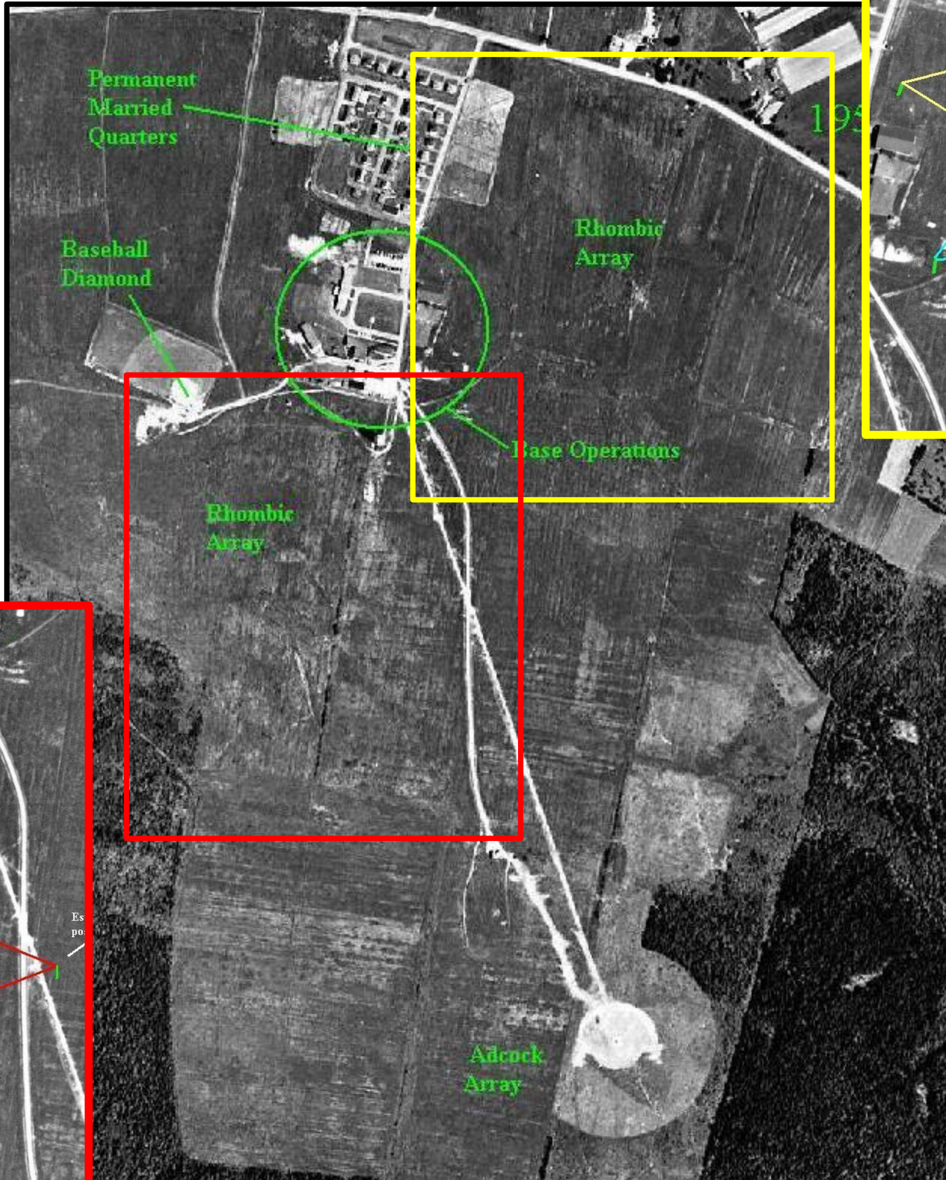
Figure 40: The eastern elevation of the remains of Cooling Radio Station. Later additions to the generator room are clearly visible (© English Heritage).

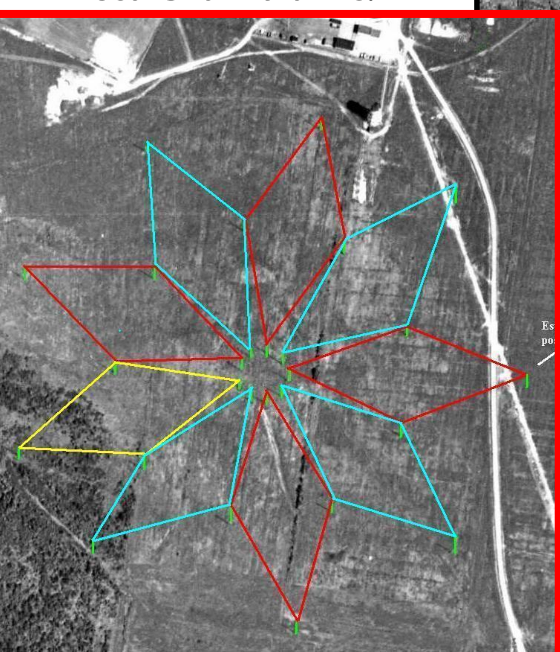
***Cooling Radio Station*, D. Gregory & S. Newsome, English Heritage, Research Department Report Series No. 110-2010**
Google Earth ; http://www.kenthistoryforum.co.uk/index.php?topic=7798.0

Tangent : Rhombic Antenna Arrays

HMCS Coverdale

This *Special Wireless Station* was located south of Moncton, NB and was used by the Canadian Navy from 1942-1971 as a High Frequency Direction Finding (HF/DF) facility. It also assisted in Signals Intercept and Search & Rescue operations for aircraft in distress. During WWII the station was used to monitor & track German U-Boats. After the war, it tracked Soviet submarines, as well as other North Atlantic sea & air traffic.





With one array of 9 antennas, the long axis of any single antenna is spaced every 40 degrees of the compass rose. By installing a second array close to the first and offsetting it by 20 degrees, it results with an antenna pointing every 20 degrees of the compass rose.

When the signals from all of the antennas feeding the Operations Building, an operator could select any one of the 18 rhombic antennas an obtain a bearing in 20 degree increments.

http://jproc.ca/rrp/rrp2/coverdale.html ; http://luxexumbra.blogspot.com/2005_05_01_archive.html

Backup Slides

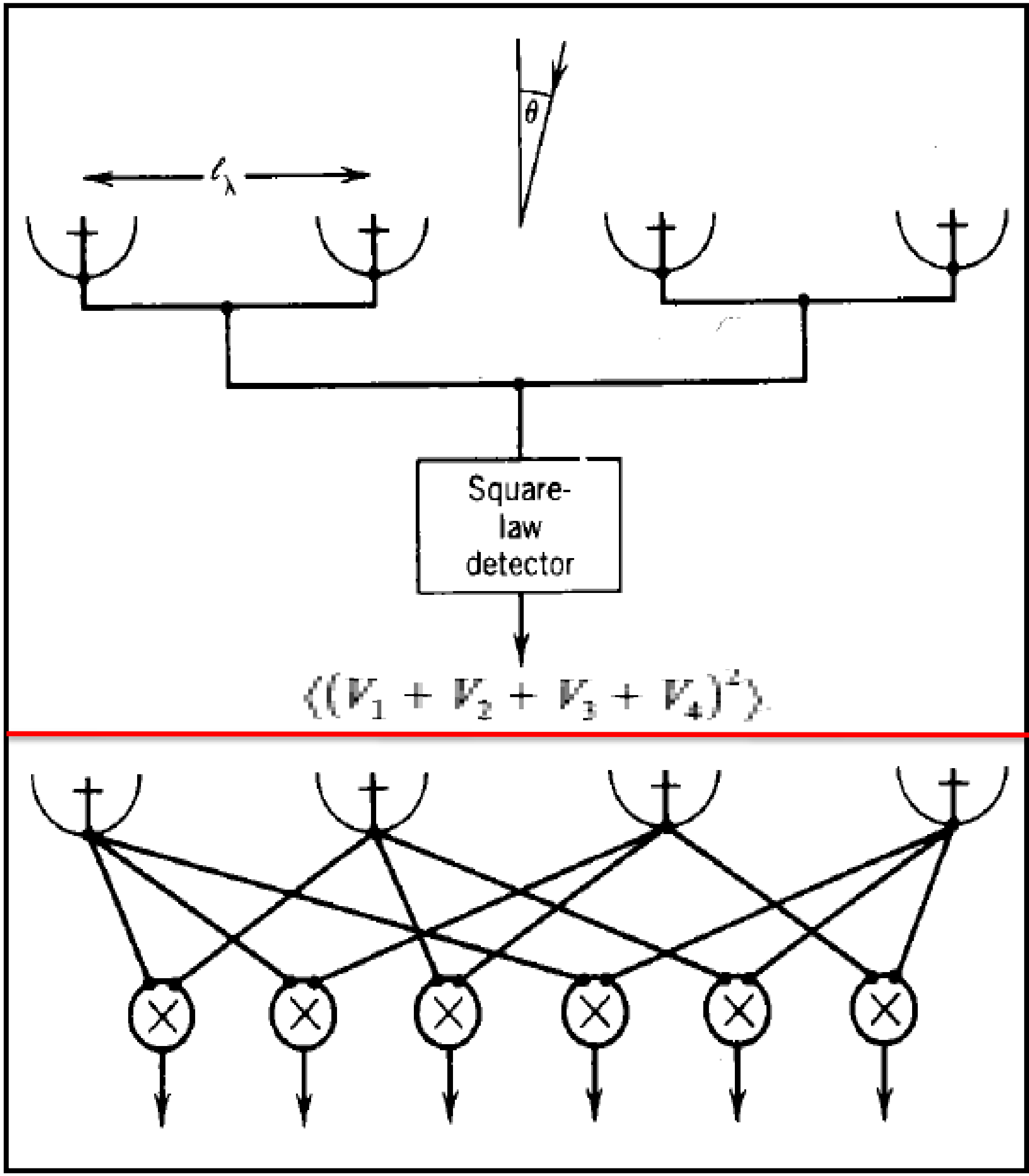
Distinction Between Phased & Correlator Arrays

<u>Phase Array:</u>

- **The voltage signals from the antennas are combined in a branching network which forms the sums in the square-law detector.**
- **The beam pattern can be scanned across the sky by inserting phase-shifters on the antenna outputs.**

<u>Correlator Array:</u>

- **The correlator generates the cross products of all the signal voltages.**
- **Each produces an output which is one component of the Fourier Transform of the spatial distribution of the brightness of the observed object.**
- **All the same terms in the expanded phased-array expression are present except for the self-products (i.e., representing spatial frequencies near the u,v origin).**
- **A correlator array gathers data at much greater rate than a phased array unless the latter is equipped to form many beam simultaneously. In fact the phased array would be slightly more sensitivity because it measures the self products.**
- **It is cheaper to do the Fourier Transform in software than it is to built large numbers of beamformers.**



Interferometry and Synthesis in Radio Astronomy,
Thompson, Moran & Swenson, 1998, p.122

October 18th, 1947

xxxxxxxxxxxxxxxxxxxxxxxx

XXXXXXXXXX
P.O. Box 4868
Cleveland Park Station
Washington 8, D.C.

Mr. K. G. Jansky
P.O. Box 107
Red Bank, New Jersey

Dear Mr. Jansky:

A great deal has transpired since I last saw you in May. The Central Radio Propagation Laboratory of the National Bureau of Standards has embarked on a substantial investigation of cosmic and solar radio waves and I have been fortunate enough to be chosen to supervise this program.

The Public Relations Office of NBS has requested me to write a semi-technical article on cosmic static for the popular scientific press. Two copies of the text are enclosed with this letter. It will probably be placed in "Tel-Tech" or "Electronics". Any comments or alterations will be appreciated. To help illustrate this article, I would like to secure a picture of your antenna as shown on page 119 of the December 1934 issue of the Bell Laboratory Record. To be suitable for reproducing purposes, it should be a sharp high-contrast print with a glossy finish. The size should be about 8 x 11 inches.

From time to time, I am called upon to make short talks on the general subject of cosmic static and it is my custom to review the field from your discovery, down to the latest developments. In general, I try to adjust the subject to the level of experience of the audience. In any case, one picture is worth a thousand words, so I would appreciate a slide showing your antenna. Also a slide of the MUSA shown on page 342 of the July 1937 issue of Bell Technical Journal would be desirable.

If any charges are associated with the making of the above print and slides, I will be pleased to see that they are defrayed, upon receipt of a bill.

Next time you are in Washington, please contact me at the below address and I will be glad to show and explain our undertaking on celestial radio waves.

Very truly yours,

Grote Reber, Radio Physicist
Experimental Ionospheric Research Section
Central Radio Propagation Laboratory

Grote Reber Letter to Karl Jansky 18 Oct 1947

Reber's letter to Jansky includes a draft copy of the article *Cosmic Radio Investigations*, which would appear in Radio News in 1948.

http://jump.cv.nrao.edu/dbtw-wpd/Textbase/Documents/grgc-reber-jansky-10181947.pdf

Karl Jansky Reply to Grote Reber 21 Oct 1947

BELL TELEPHONE LABORATORIES
INCORPORATED
463 WEST STREET NEW YORK 14
CHELSEA 3-1000

21 October 1947

IN REPLY REFER TO

Box 107, Red Bank, N. J.

REPLYING TO

MR. GROTE REBER
P.O. Box 4868
Cleveland Park Station
Washington 8, D. C.

Dear Mr. Reber:

I am pleased to hear that you are to continue your work on cosmic and solar noise at the National Bureau of Standards. Congratulations! Other duties here at Holmdel have kept me so busy that I have had very little time to spend on such studies. I hope that things clear up a bit in the not too distant future.

Your article on Cosmic Radio Investigations sounds very good to me. The only comment I have to make is that you might add something on the theories as to the source of the phenomena, something about the work of C. H. Townes and J. L. Greenstein.

Your request for pictures and slides has been referred to our publication department. If you don't get what you want from them soon, let me know and I'll see what I can do for you.

I have kept one copy of your article. I hope you have no objections.

Very sincerely yours,

Karl G. Jansky

KARL G. JANSKY

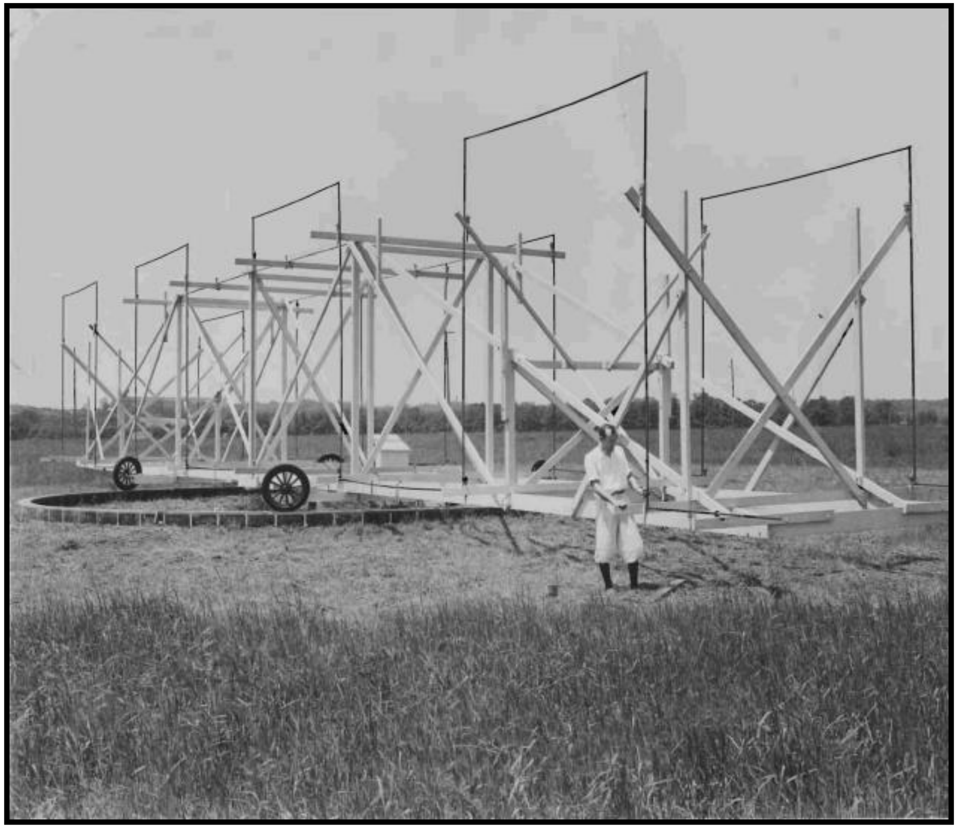
Jansky laments to Reber not being able to work on *cosmic noise.* (Maybe soon, he says but, alas, it never happens).

He says nothing about the MUSA, but did send Reber an 8" x 11" picture of it, along with one of his own antenna.

http://jump.cv.nrao.edu/dbtw-wpd/Textbase/Documents/grgc-jansky-reber-10211947.pdf

The 2 pictures Jansky sends to Reber

21 Oct 1947



http://jump.cv.nrao.edu/dbtw-wpd/Textbase/Documents/grgc-jansky-reber-10211947.pdf