The First Radio Astronomy Interferometer

Bob Hayward
NRAO Senior Engineer (Retired)
Socorro, NM

13 March 2013

The Building

The Inventor

The First Radio Astronomy Interferometer

The Bell Labs 1935 Experimental

~ MUSA ~

Multiple Unit Steerable Antenna

The Antenna

The Electronics

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The First (Accidental) Radio Astronomy Interferometer

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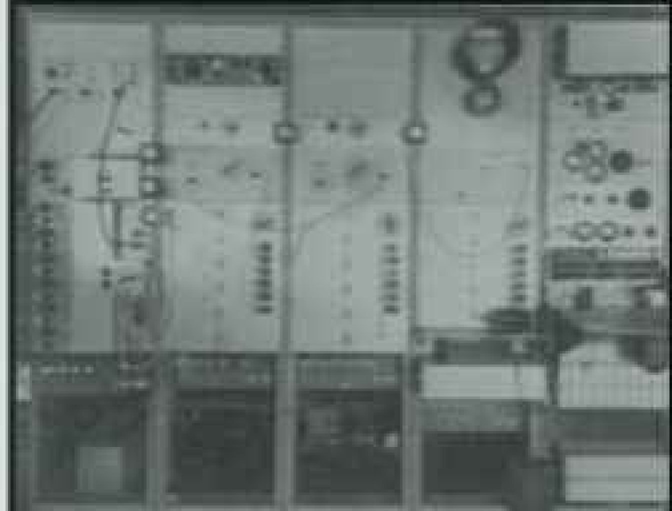

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Rather, it is the story of the Radio Interferometer that was the 1st to have detected an Astronomical Source.

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

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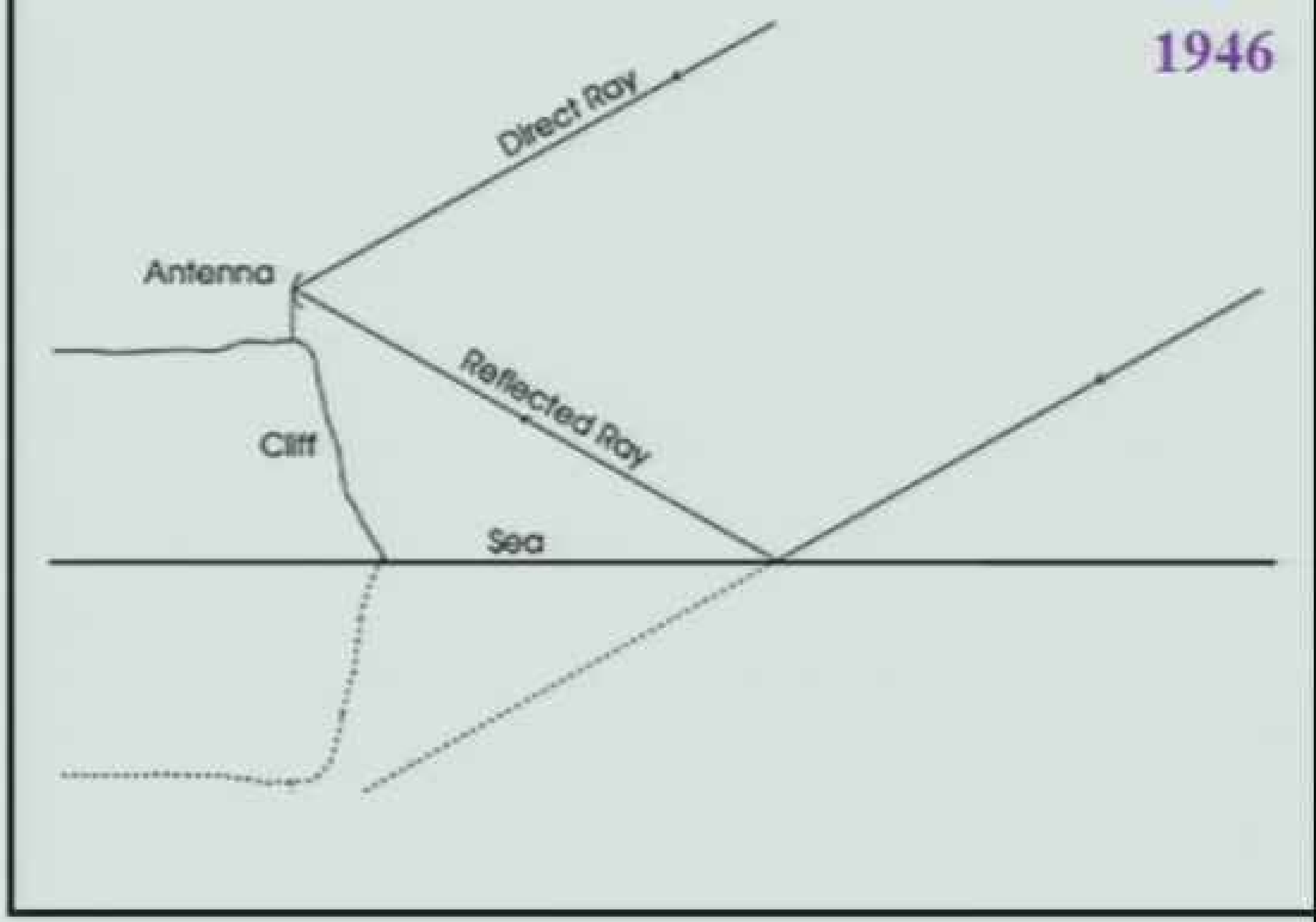
Rather, it is the story of the Radio Interferometer that was the 1st to have detected an Astronomical Source.

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.

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

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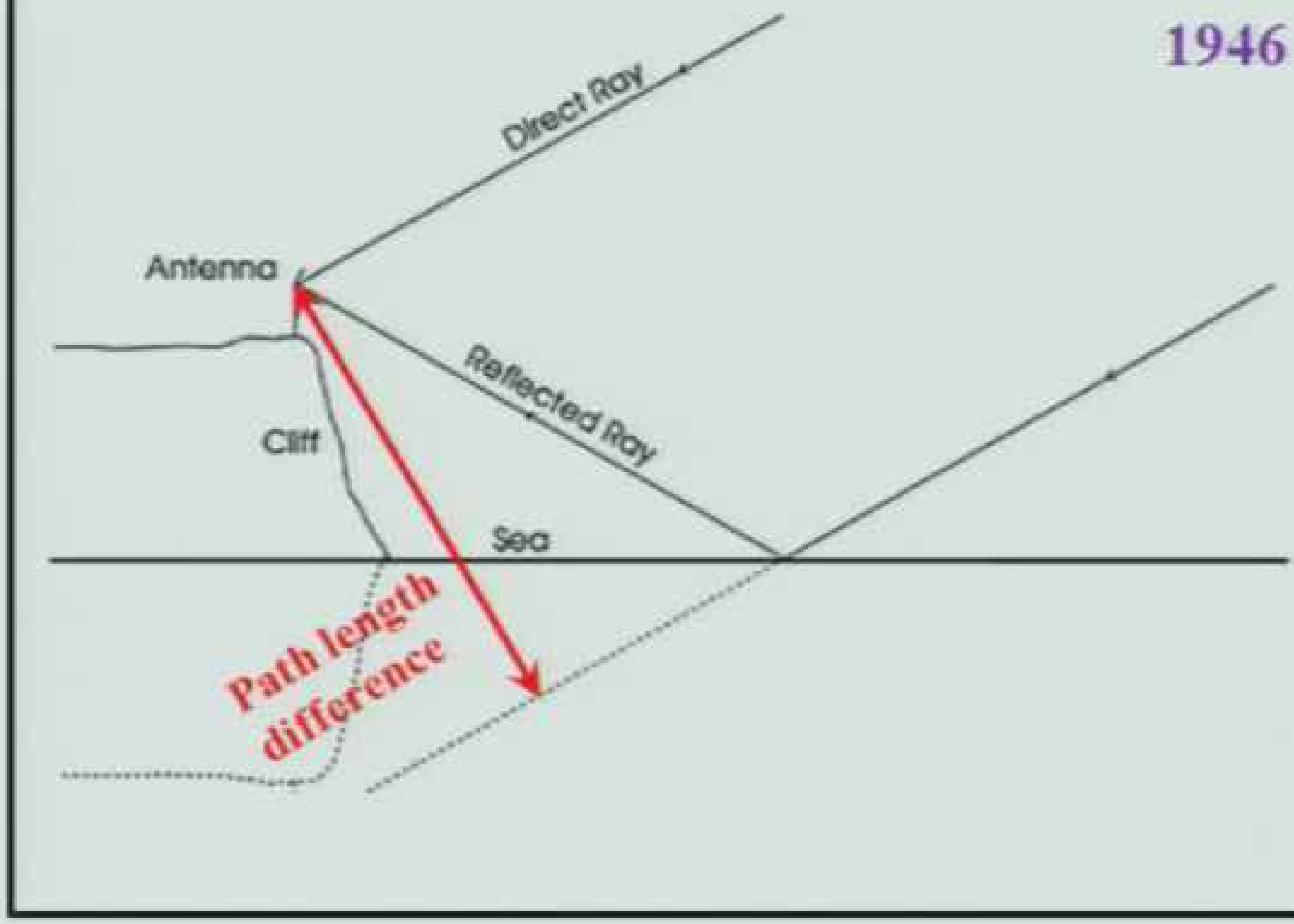

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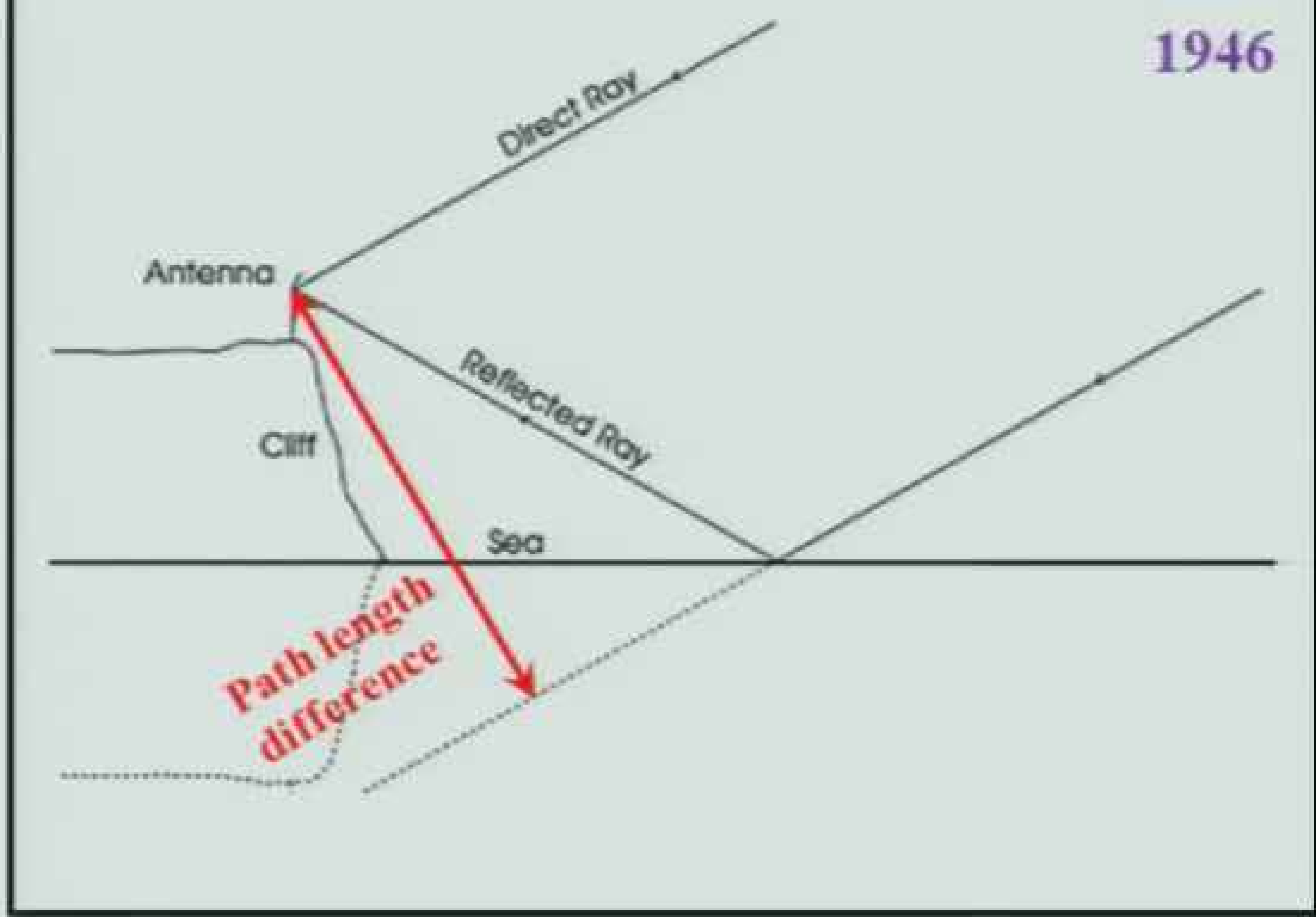

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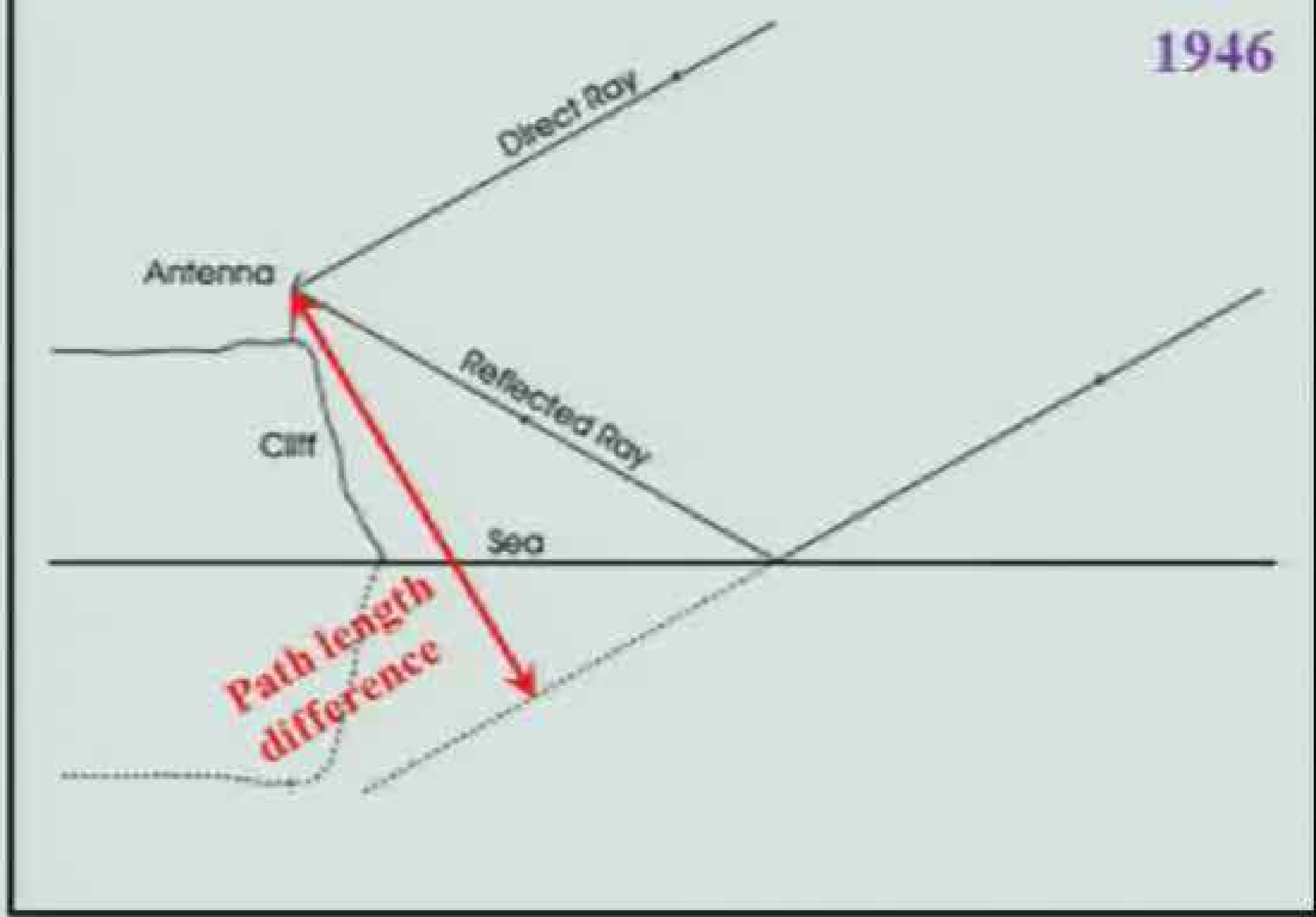

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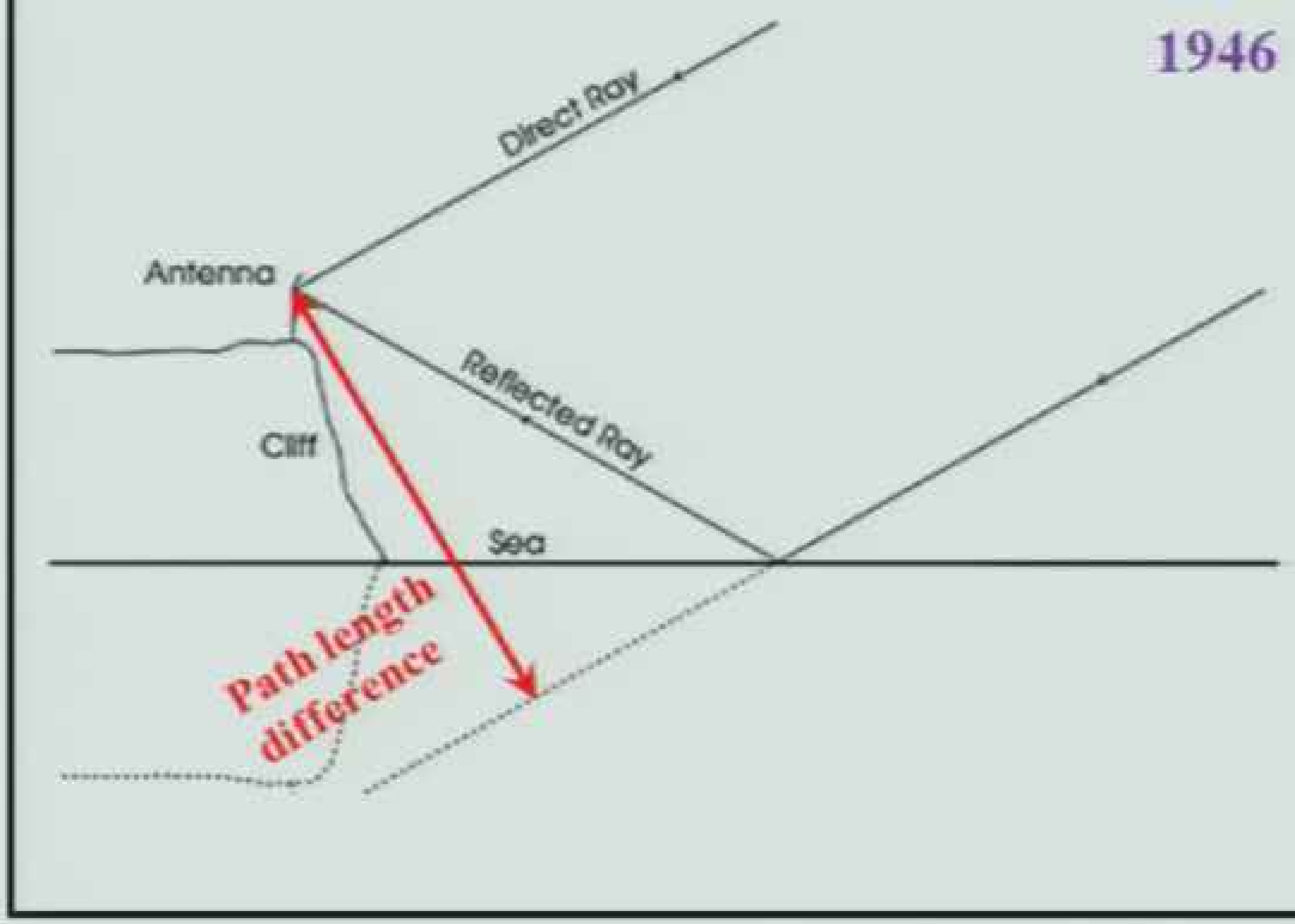

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The 2nd was Martin Ryle's at the Cavendish Lab, UK

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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.

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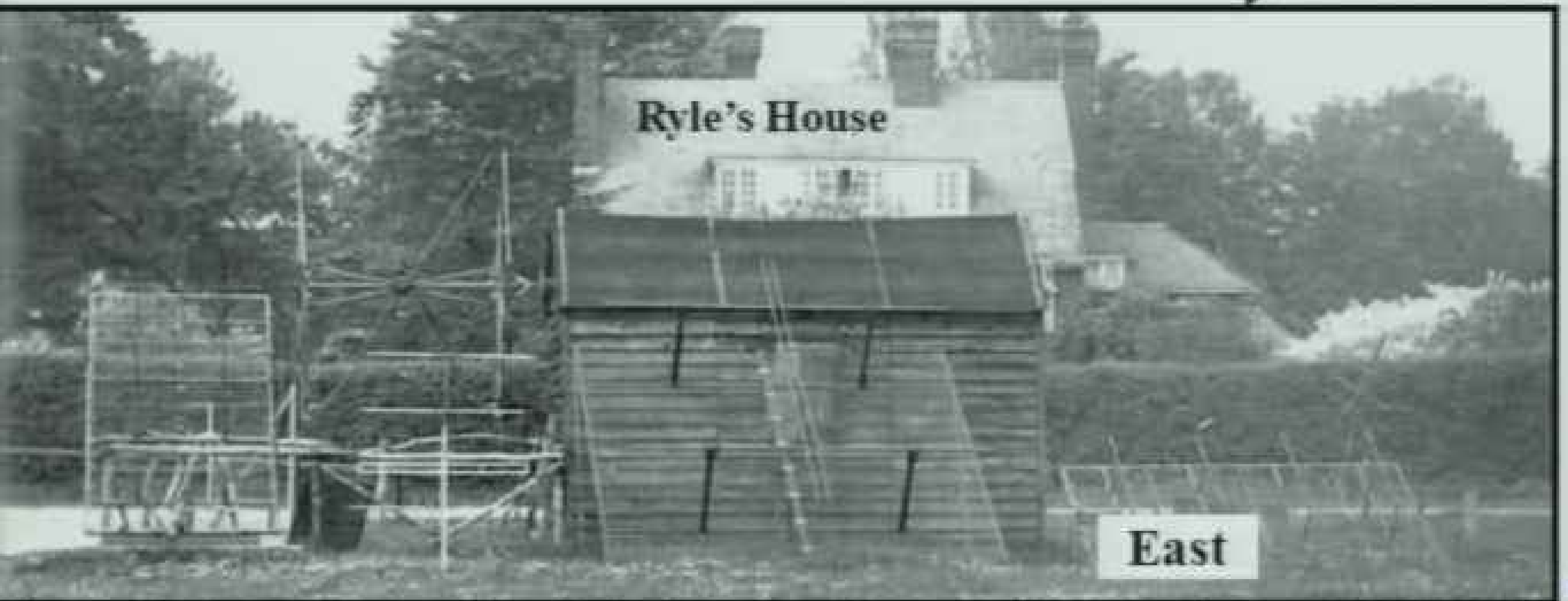

The wooden hut which formed the Radio Astronomy Observatory for its first few years (1945-48). The instruments shown include interferometers for 175 and 80 MHz, a transit instrument operating at 214 MHz, and polarization aerials. They were used mainly for solar observations.

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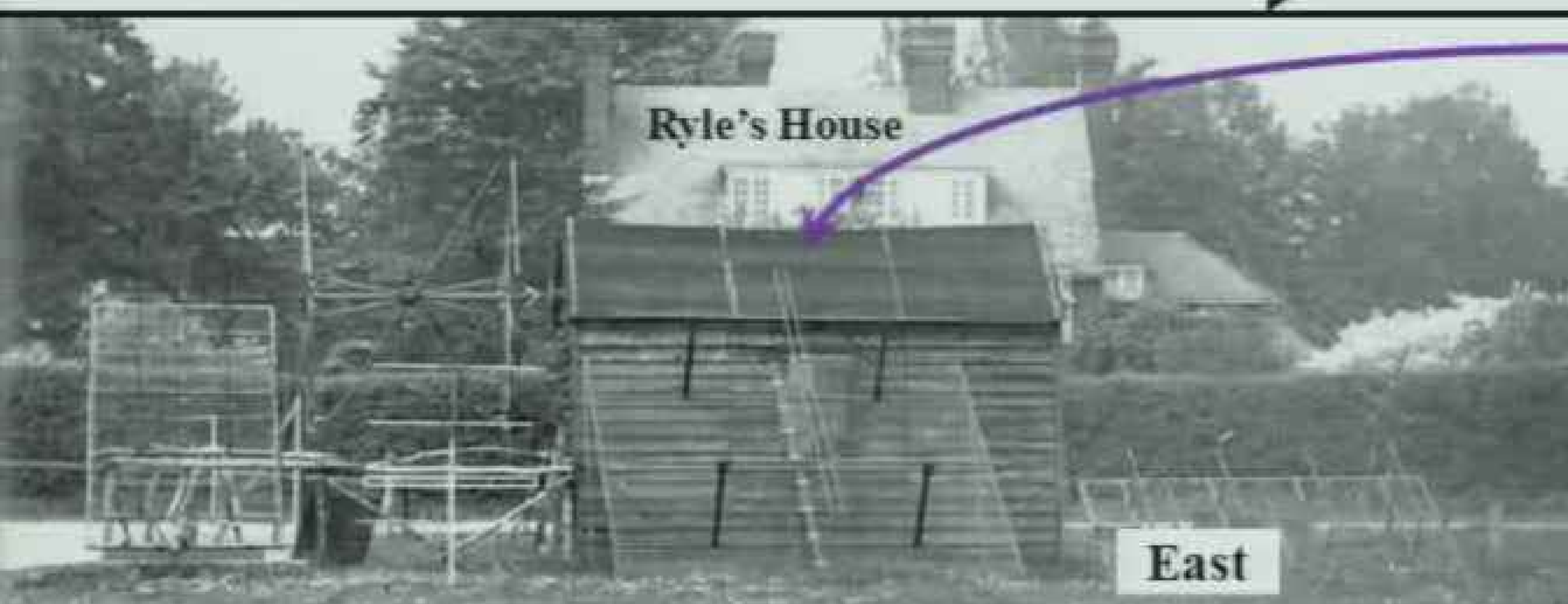

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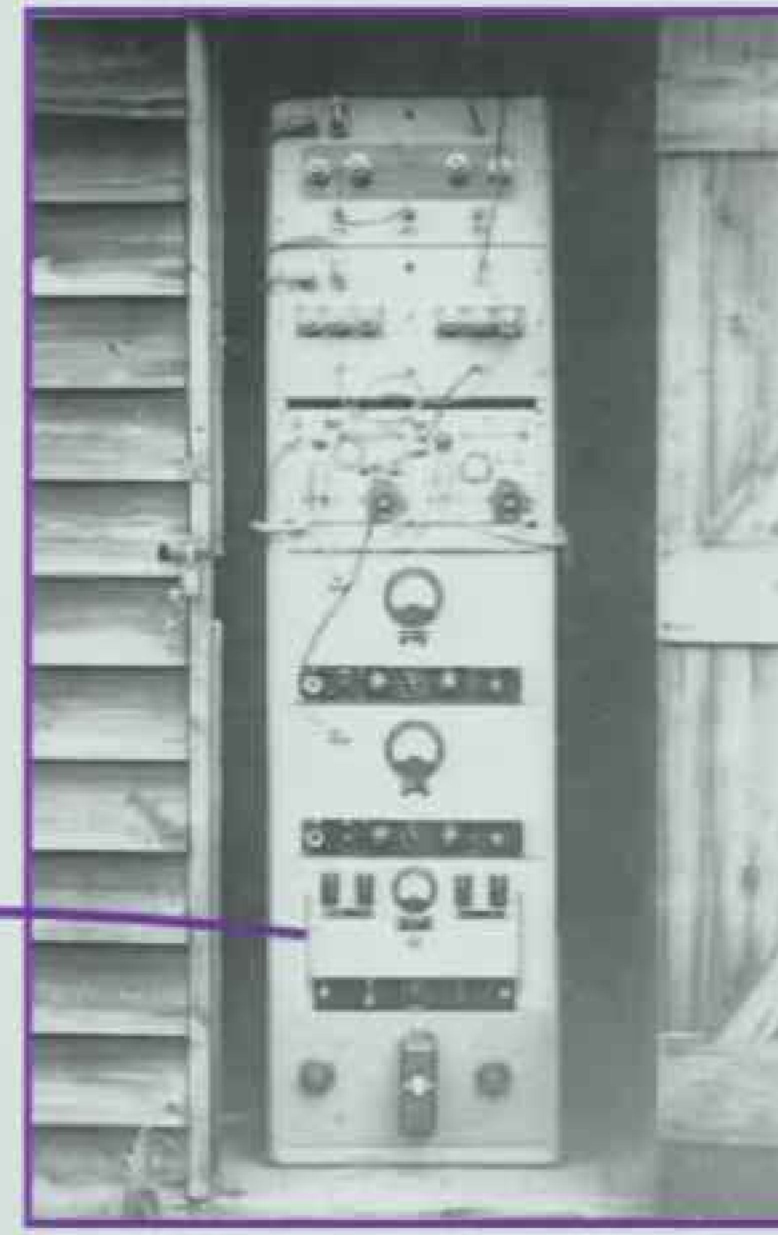

Receivers built in 1946 for 175 and 80 MHz, which made use of equipment from Coastal Command airborne radars, a German long-range radar and a capacity switch from a crashed Ju 88.

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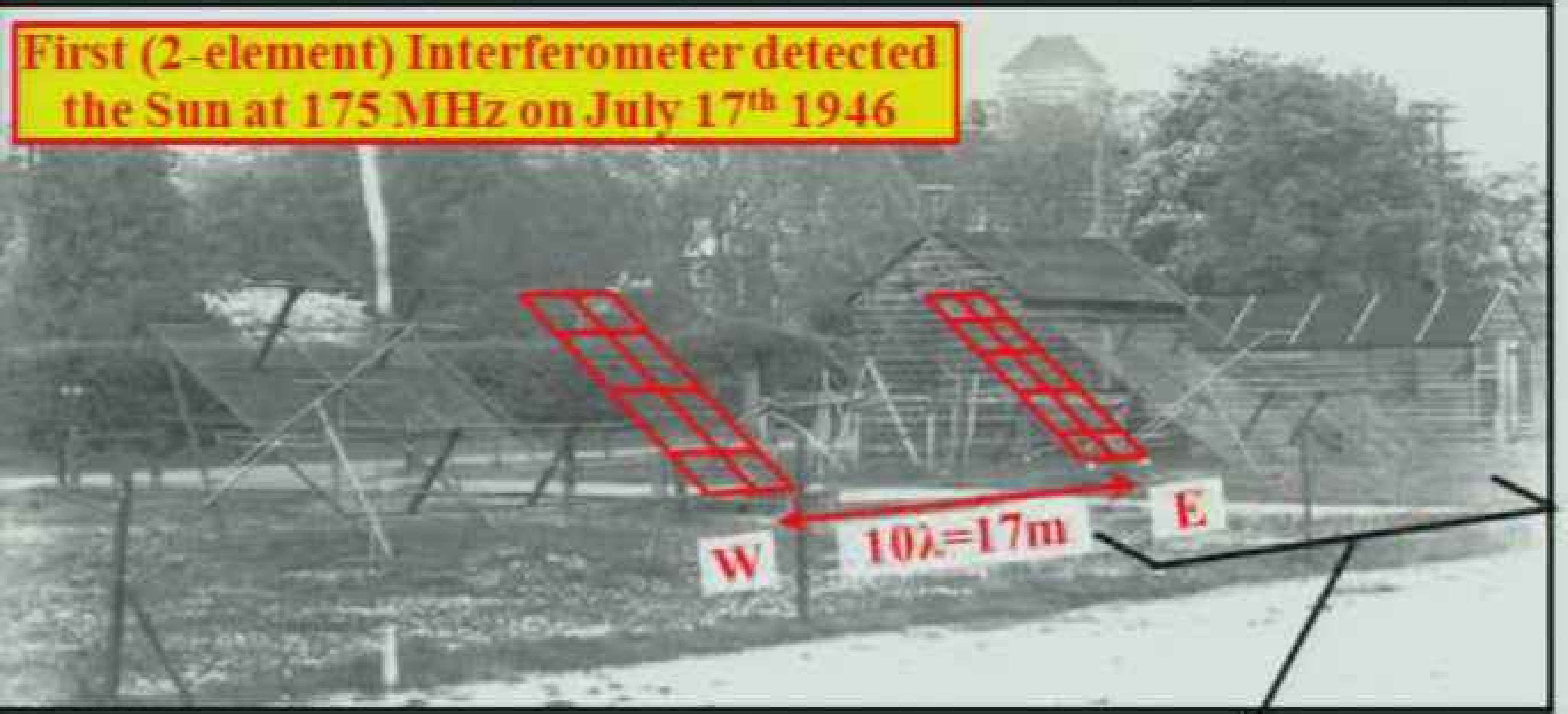

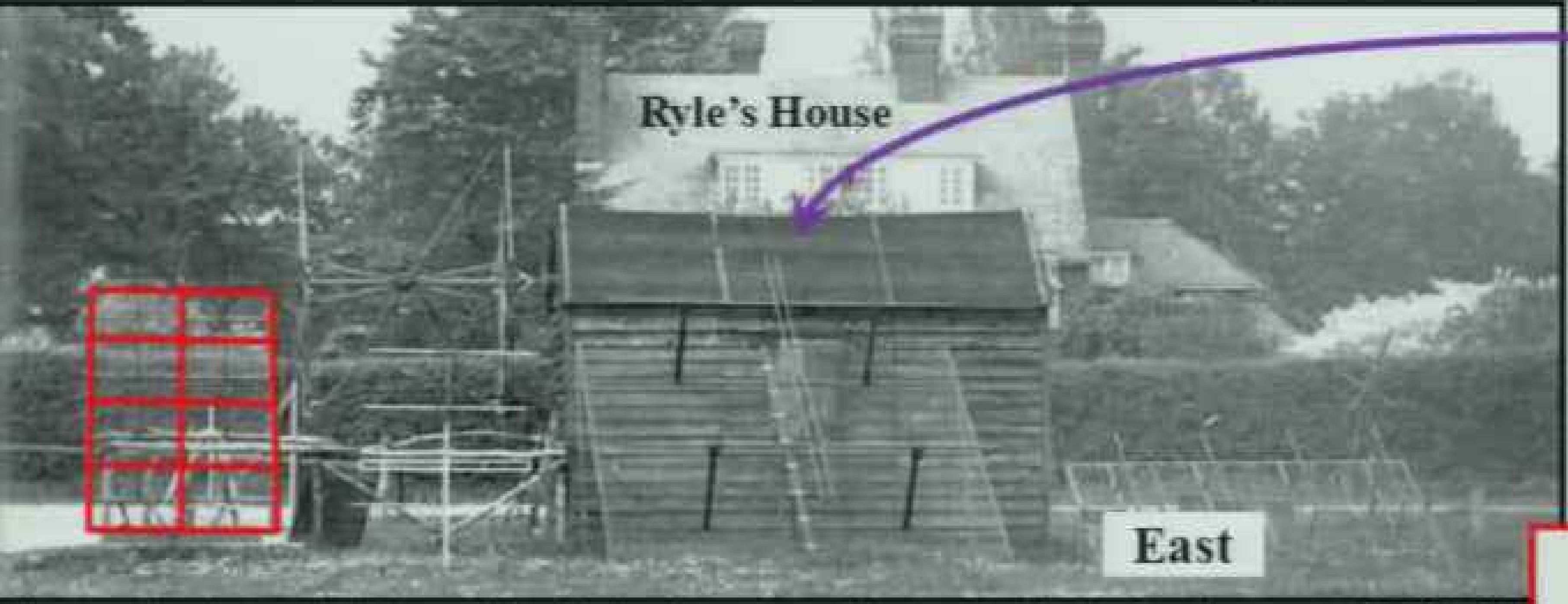

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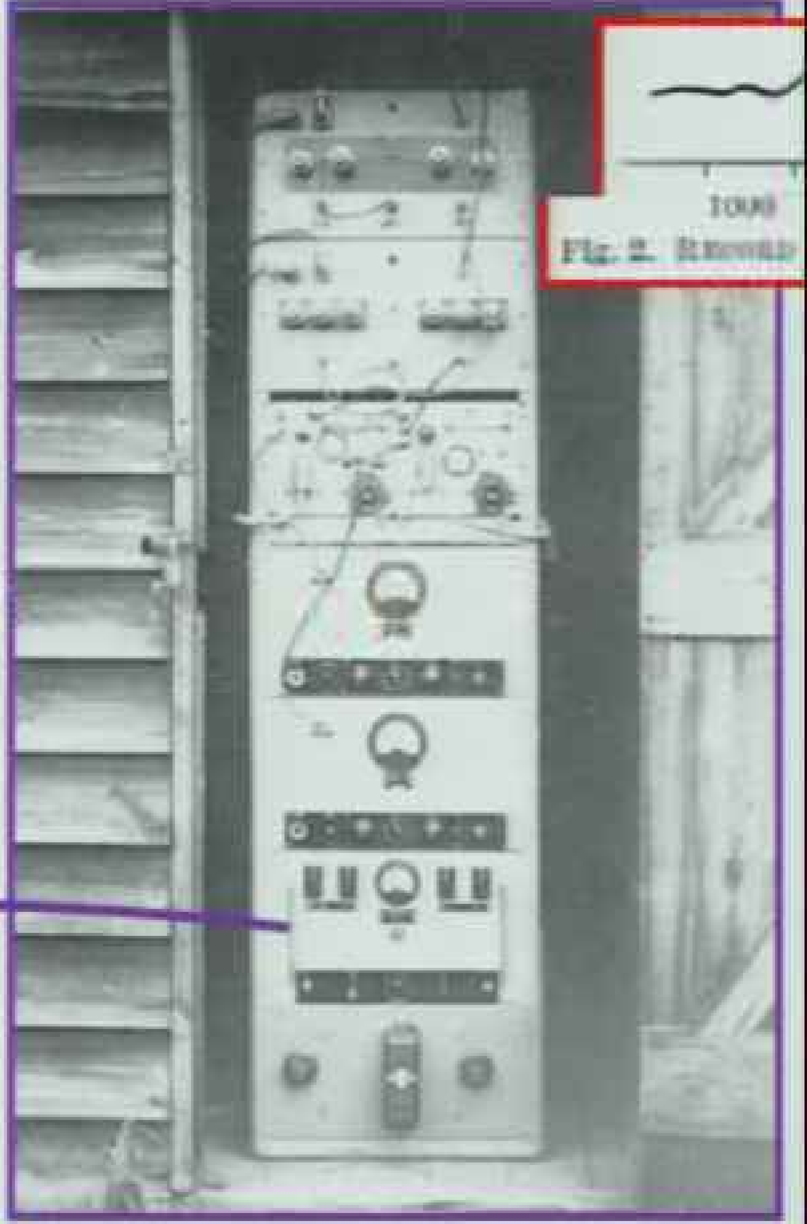

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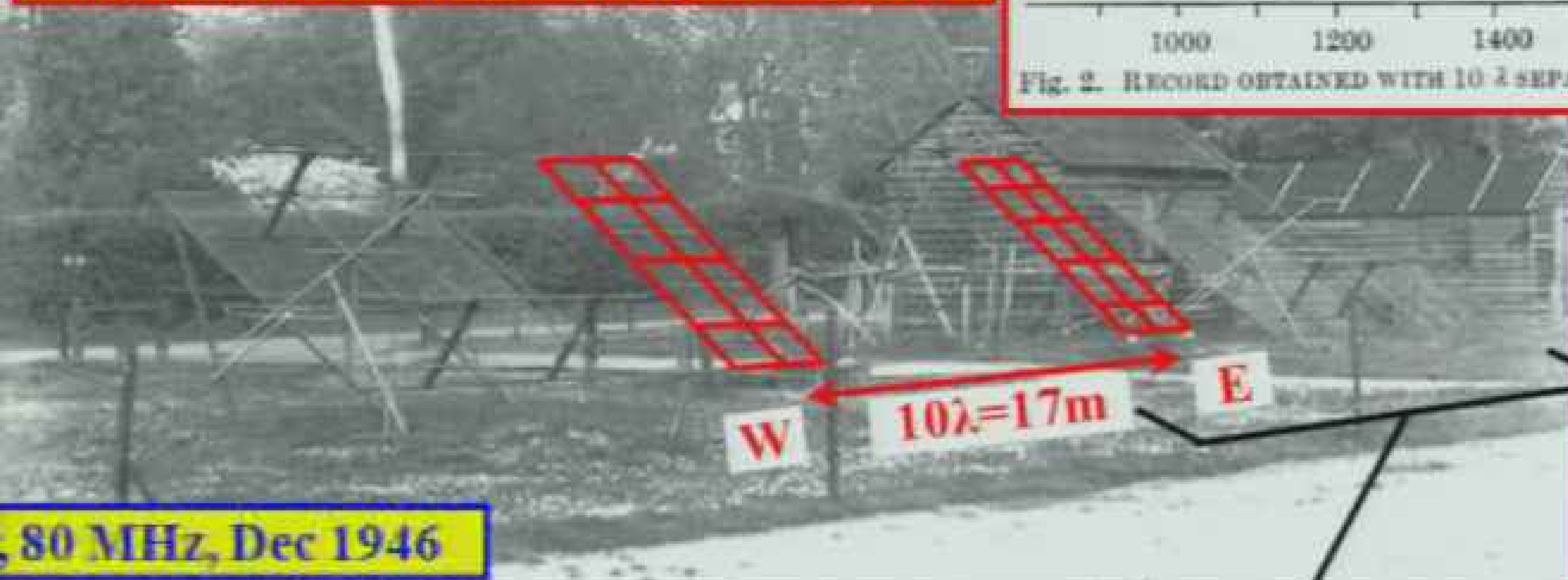


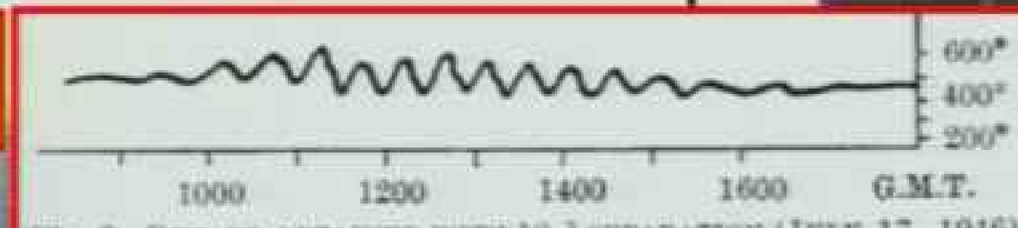
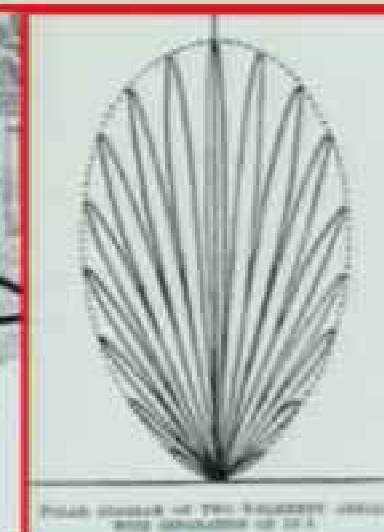
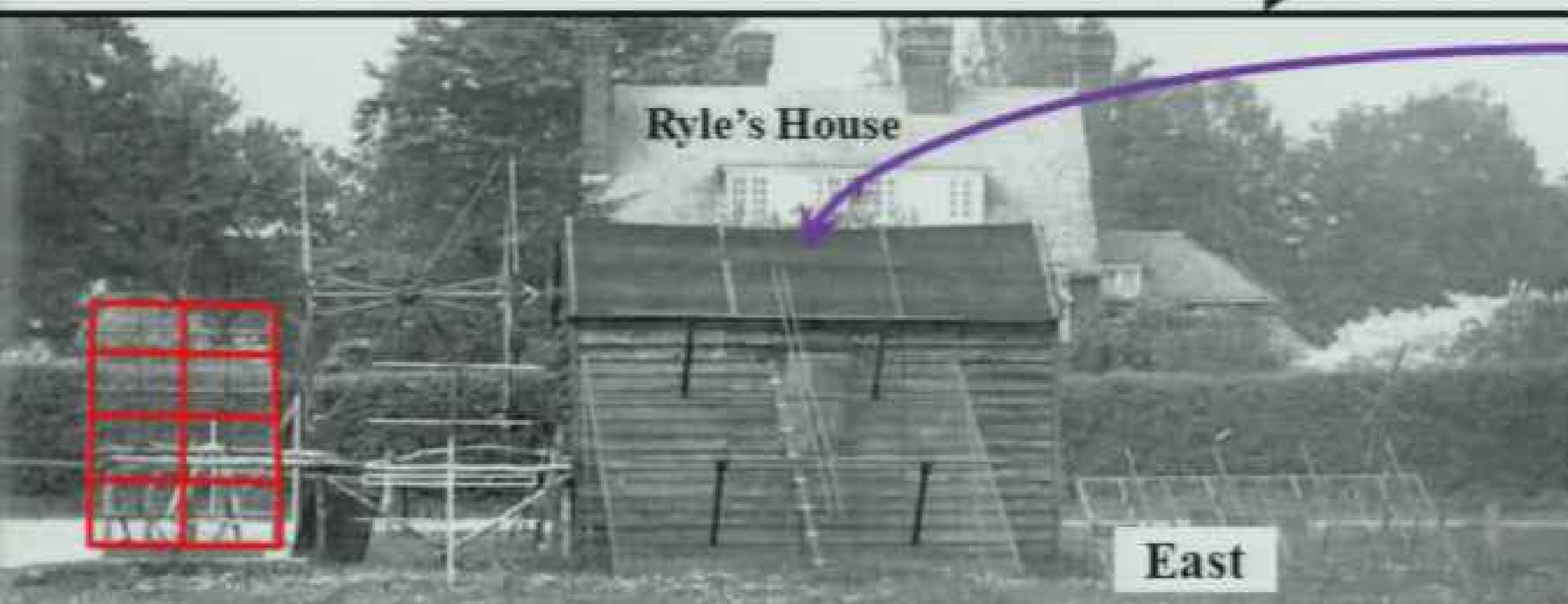


Fig. 2. RECORD OBTAINED WITH 10 λ SEPARATION (JULY 17, 1946)





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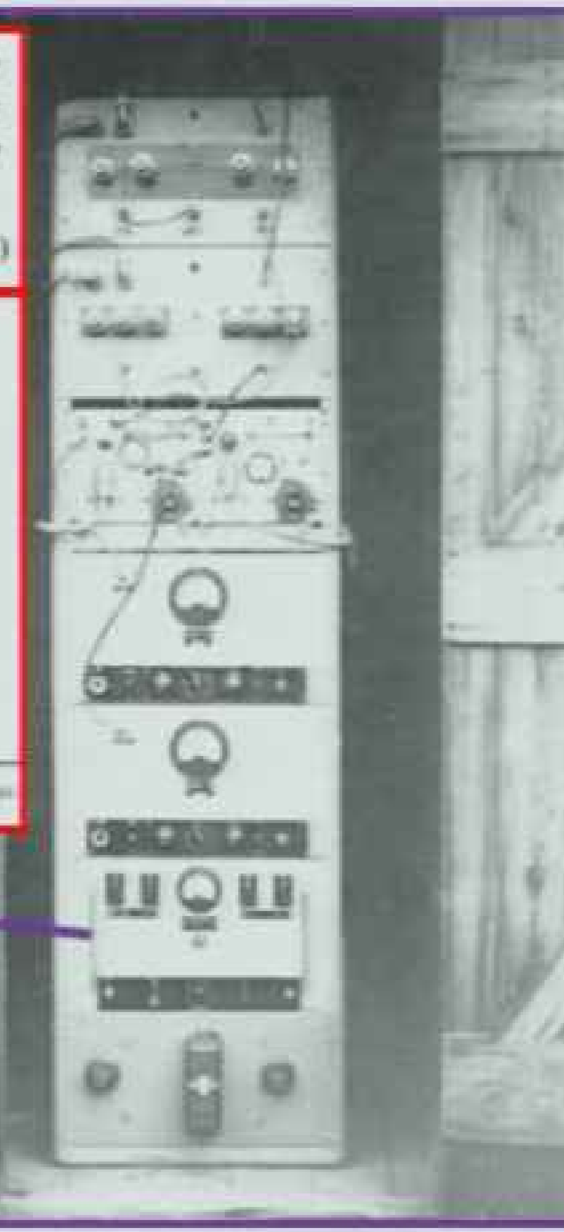

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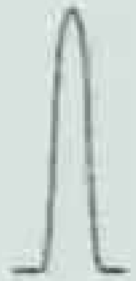
From Single Dish to Beamformer Arrays to Aperture Synthesis - 1

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

Ideal Large Single Dish



1-dimensional

From Single Dish to Beamformer Arrays to Aperture Synthesis - 1

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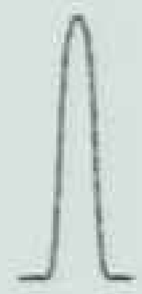
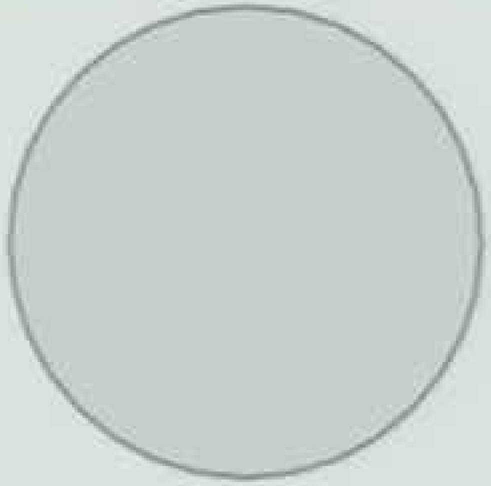
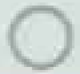




Astronomers like big dishes:
Large collecting area improves sensitivity



Large aperture improves spatial resolution.

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

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1-dimensional | 2-dimensional

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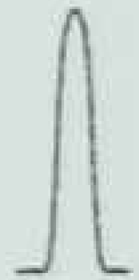

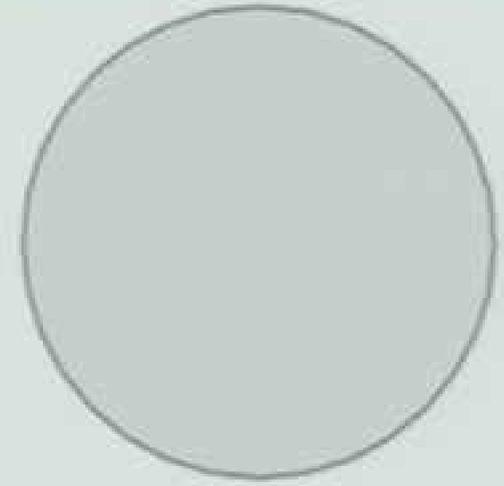

Astronomers like big dishes:
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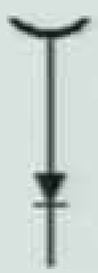
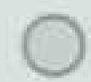
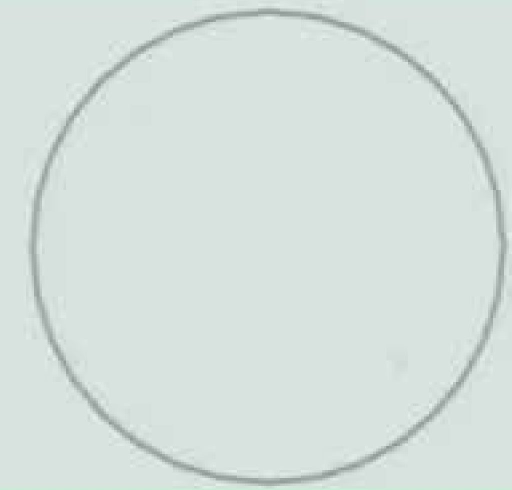
Large aperture improves spatial resolution.

Small, Affordable Single Dish





SIZE DOES MATTER !!!

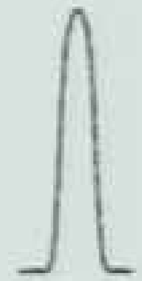


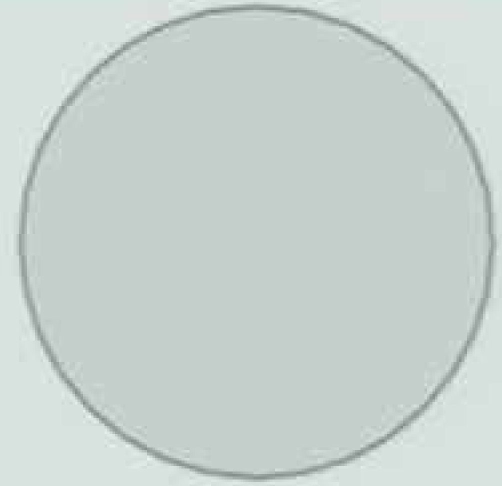
From Single Dish to Beamformer Arrays to Aperture Synthesis - 1

1-dimensional | 2-dimensional

telescope configuration	beam cross-section	Physical aperture	beam projection

Ideal Large Single Dish





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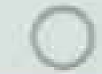

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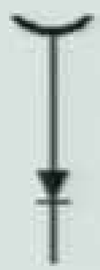

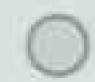

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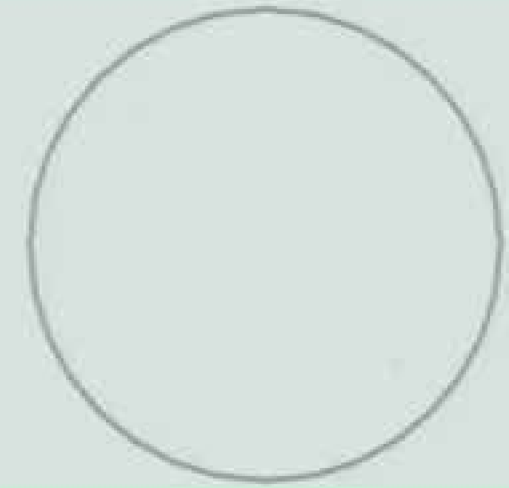
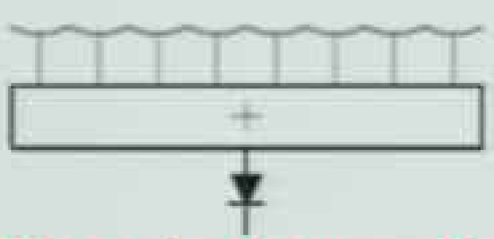
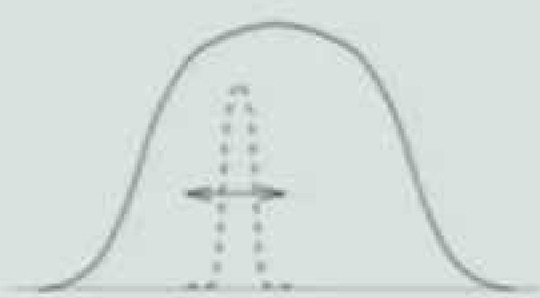
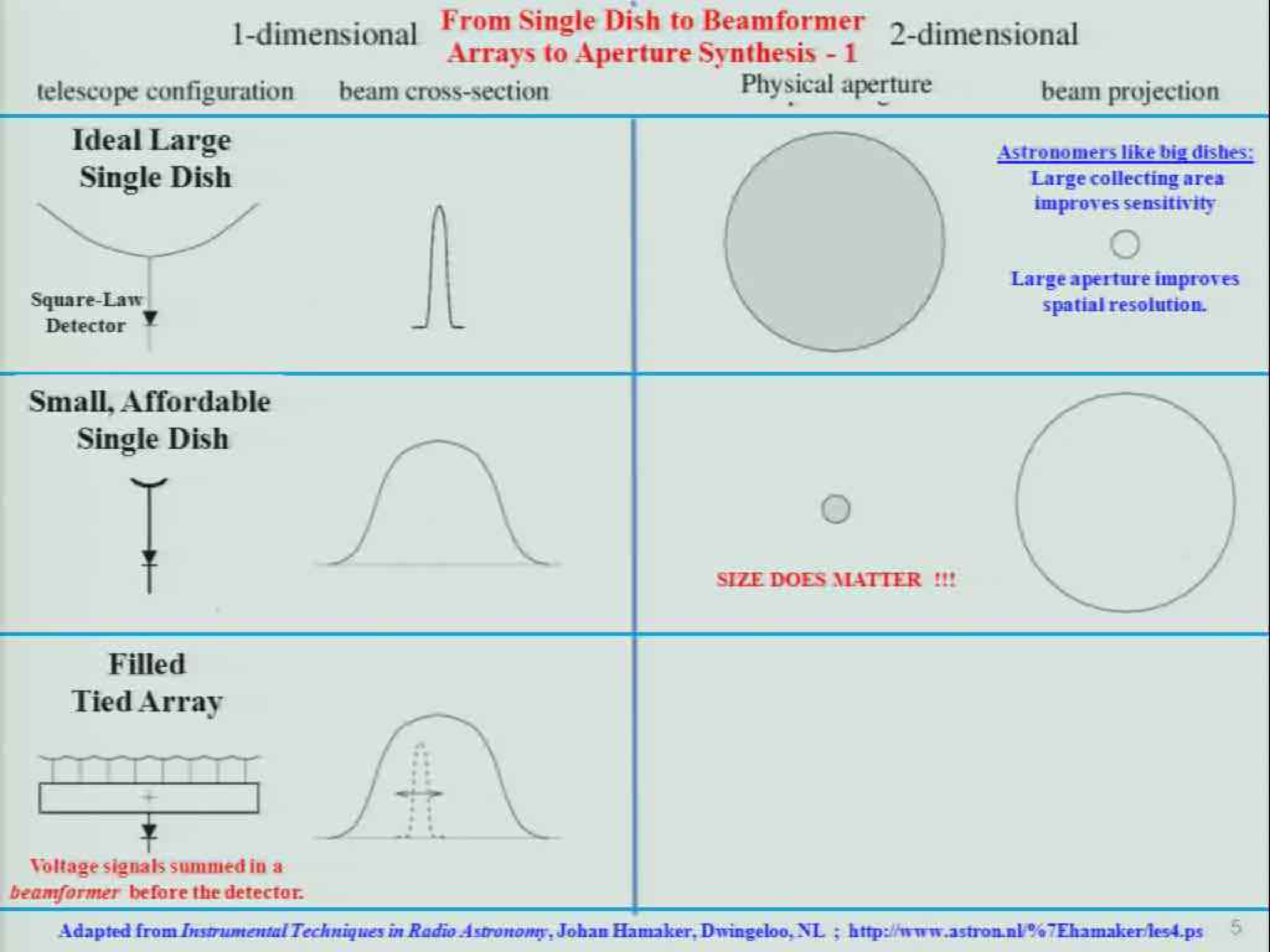


Filled Tied Array



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




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
Square-Law
Detector
Astronomers like big dishes:
Large collecting area
improves sensitivity
Large aperture improves
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Small, Affordable
Single Dish
SIZE DOES MATTER !!!
Filled
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Voltage signals summed in a
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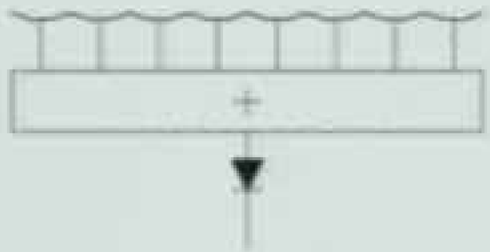
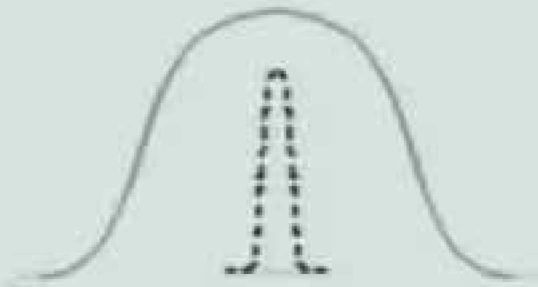
5

1-dimensional **From Single Dish to Beamformer Arrays to Aperture Synthesis - 2** 2-dimensional

telescope configuration | beam cross-section | Physical aperture | beam projection

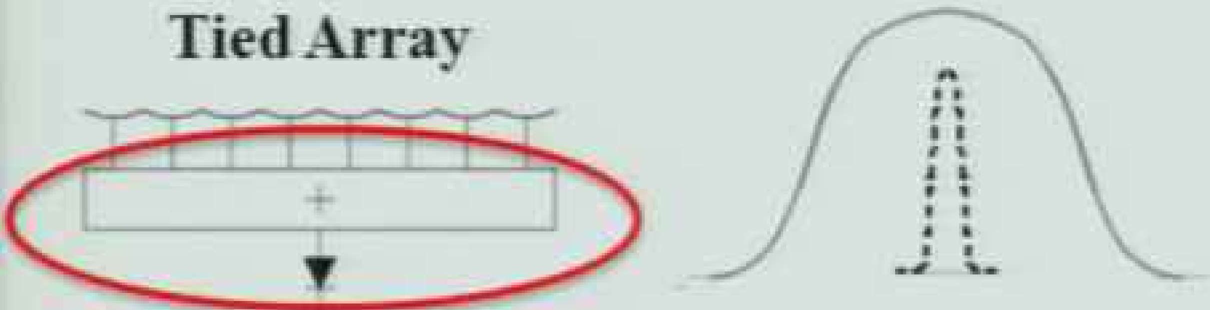
Filled Tied Array

1-dimensional **From Single Dish to Beamformer Arrays to Aperture Synthesis - 2** 2-dimensional

telescope configuration | beam cross-section | Physical aperture | beam projection

Filled Tied Array



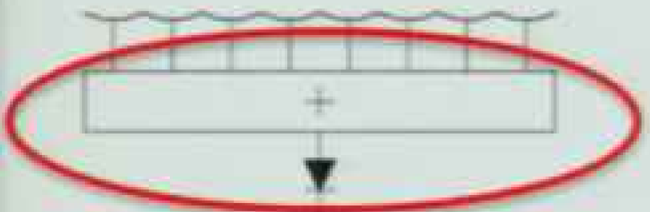
Can use splitters on each antenna output to allow for multiple beamformers.

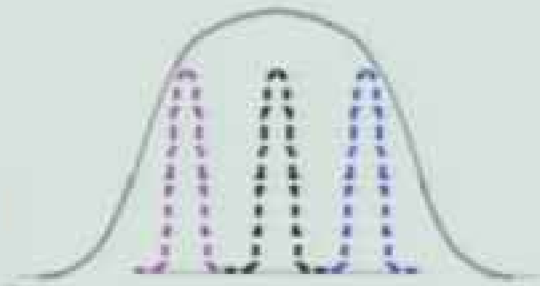
From Single Dish to Beamformer Arrays to Aperture Synthesis - 2

1-dimensional | 2-dimensional

telescope configuration	beam cross-section	Physical aperture	beam projection

Filled
Tied Array





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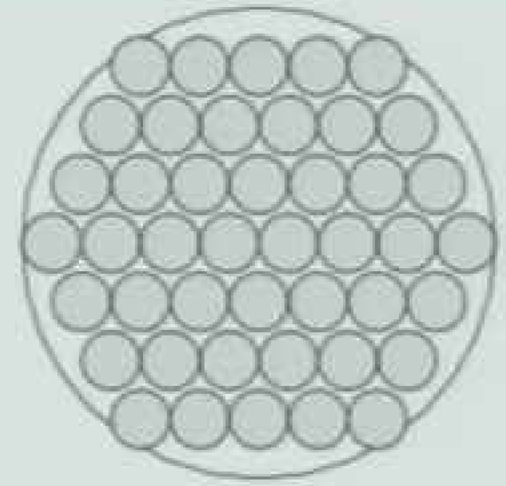
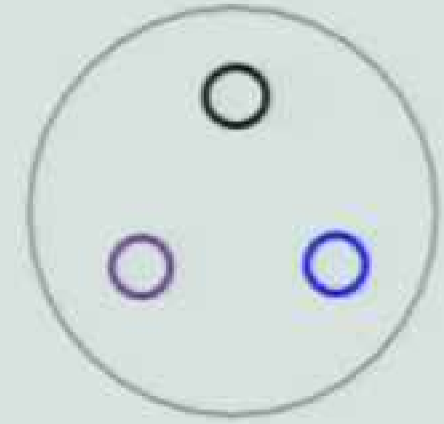


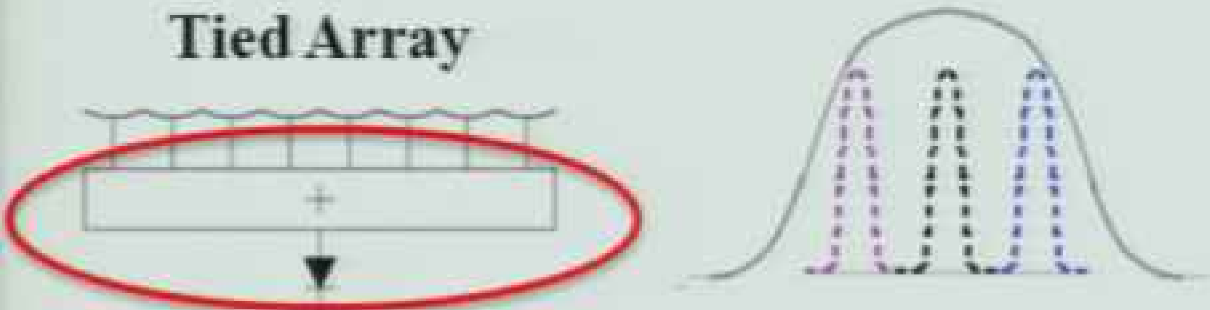


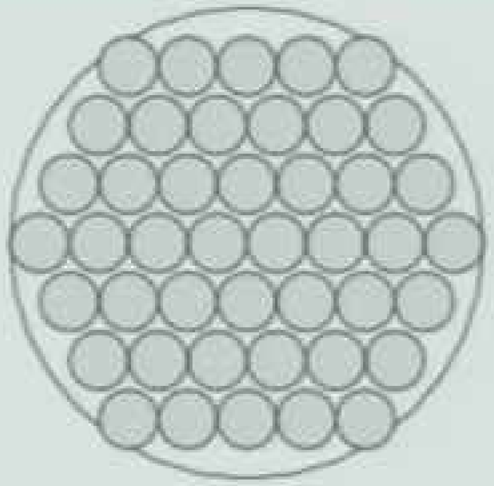
From Single Dish to Beamformer Arrays to Aperture Synthesis - 2

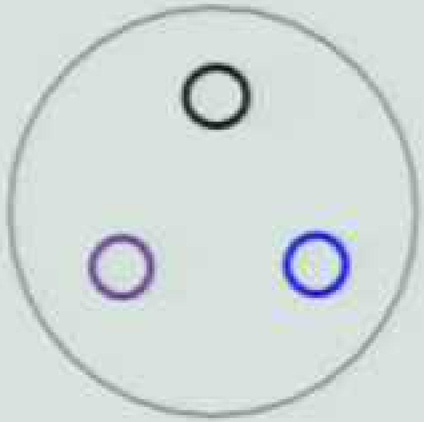
1-dimensional | 2-dimensional

telescope configuration | beam cross-section | Physical aperture | beam projection

Filled Tied Array







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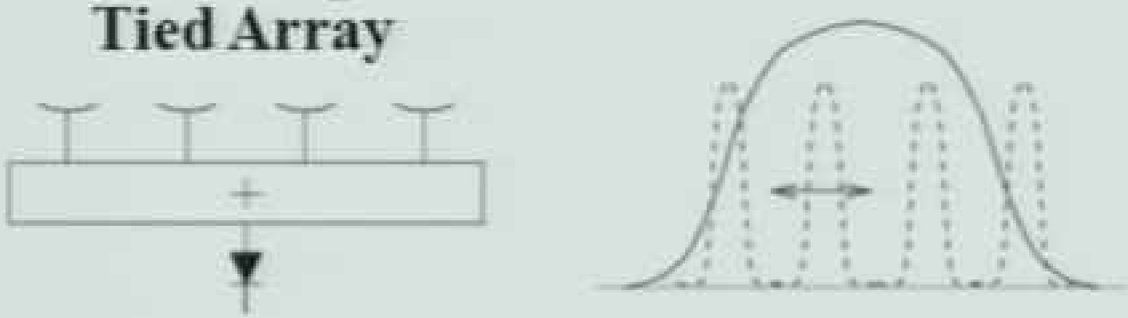
Grating Tied Array



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

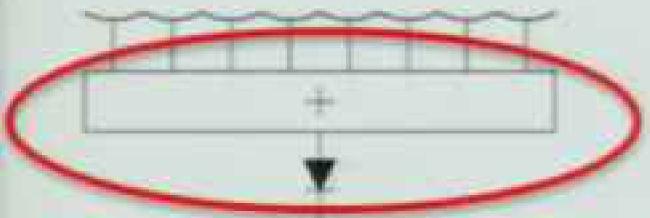
1-dimensional

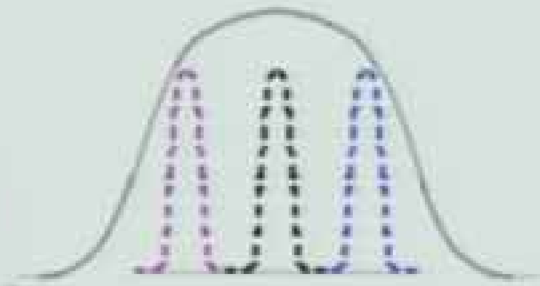
From Single Dish to Beamformer Arrays to Aperture Synthesis - 2

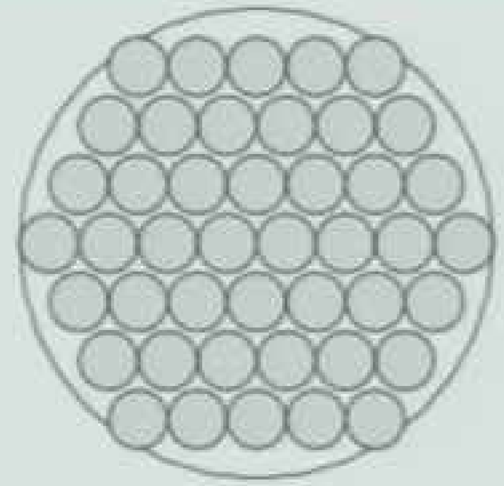
2-dimensional

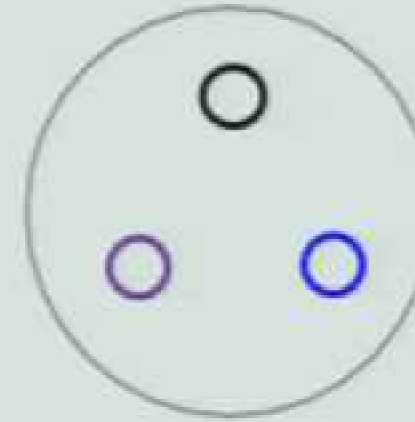
telescope configuration | beam cross-section | Physical aperture | beam projection

Filled Tied Array









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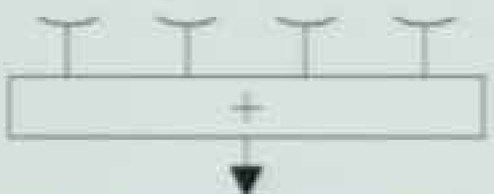
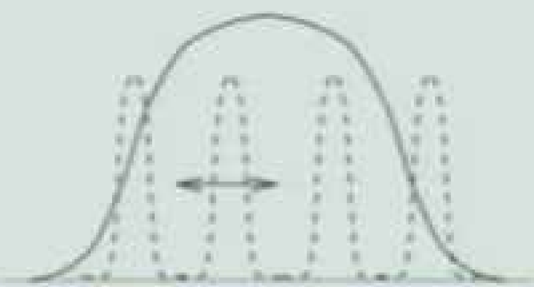


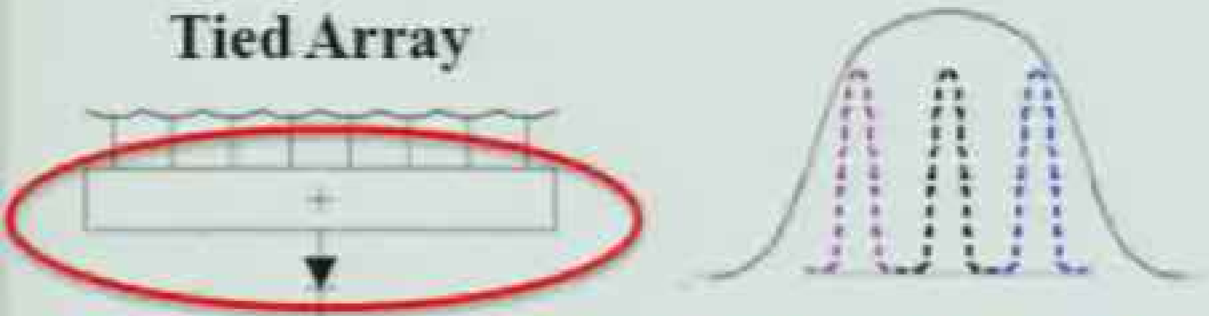


The beam pattern has grating lobes which are always present and can lead to source confusion (e.g., the early Cambridge 1C & 2C catalogs).

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



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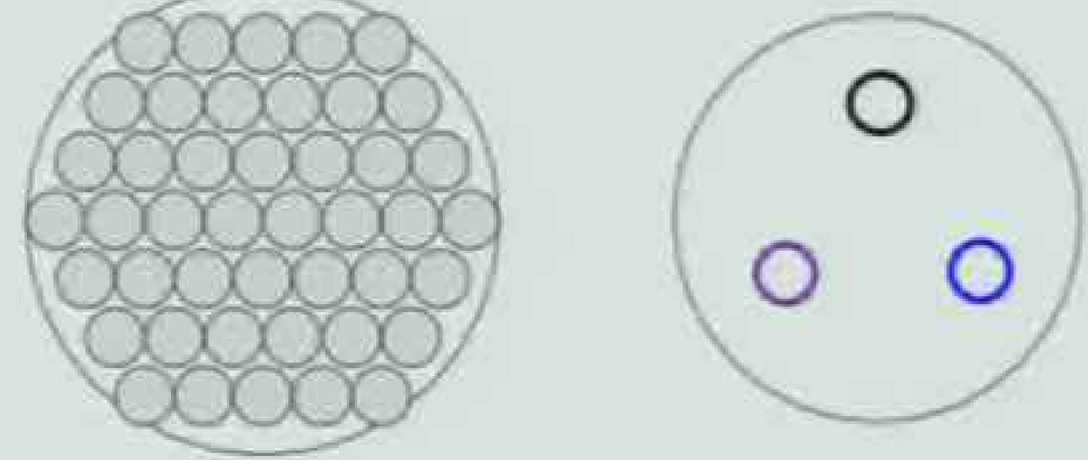

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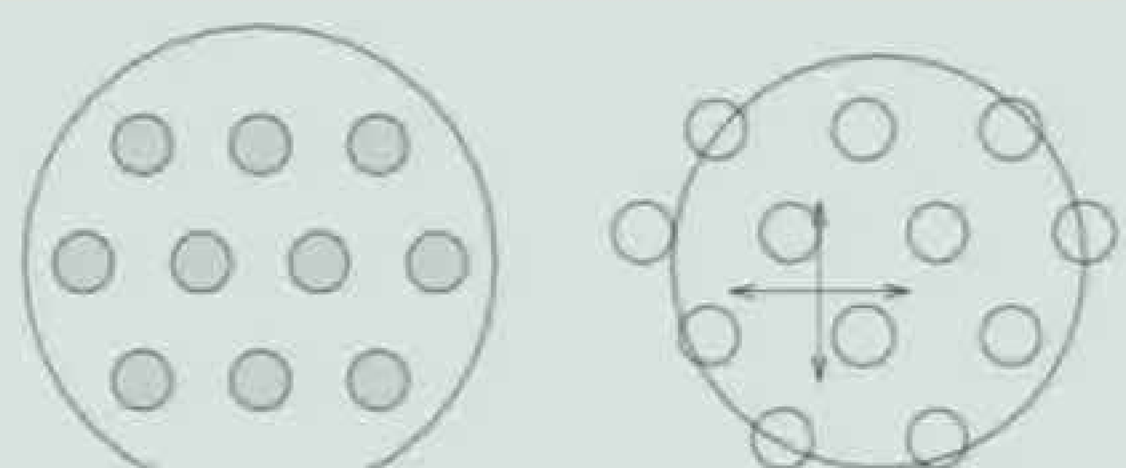
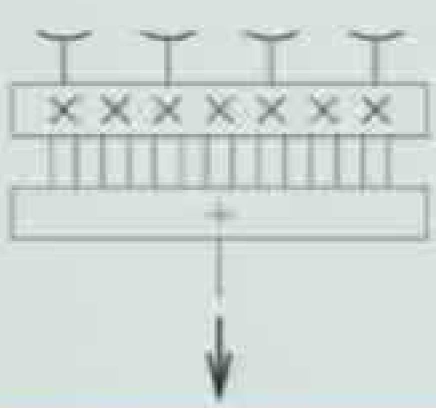


Correlation Interferometer



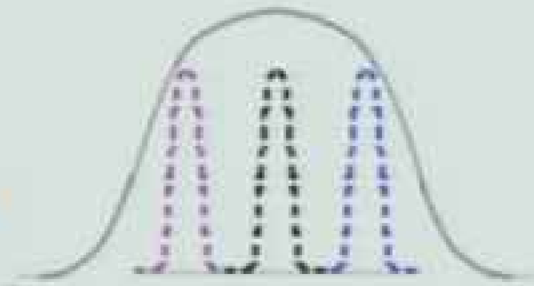
A correlator generates the cross products of the signals between each pair of elements. Each of these fringe visibilities is one component of the Fourier Transform of the spatial distribution of the brightness function of the observed object.

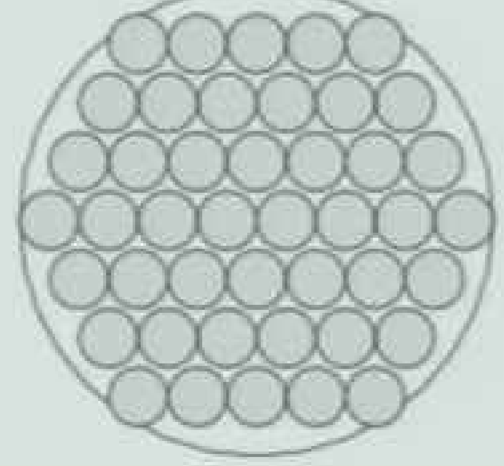
Adapted from *Instrumental Techniques in Radio Astronomy*, Johan Hamaker, Dwingeloo, NL ; http://www.astron.nl/%7Ehamaker/les4.ps

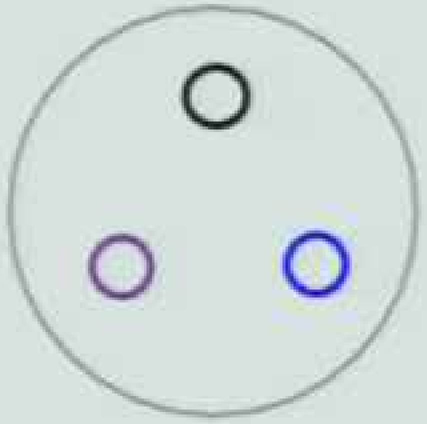
1-dimensional **From Single Dish to Beamformer Arrays to Aperture Synthesis - 2** 2-dimensional

telescope configuration	beam cross-section	Physical aperture	beam projection

Filled Tied Array







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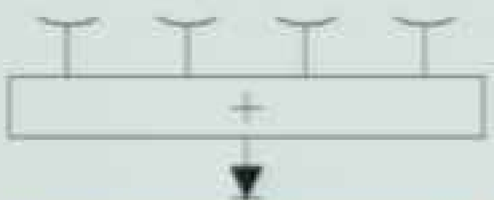
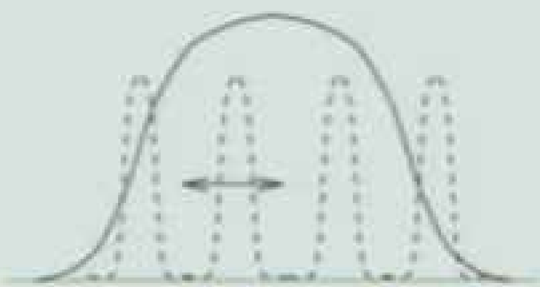
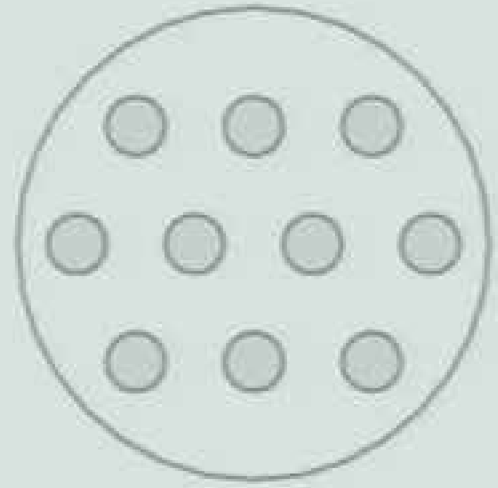
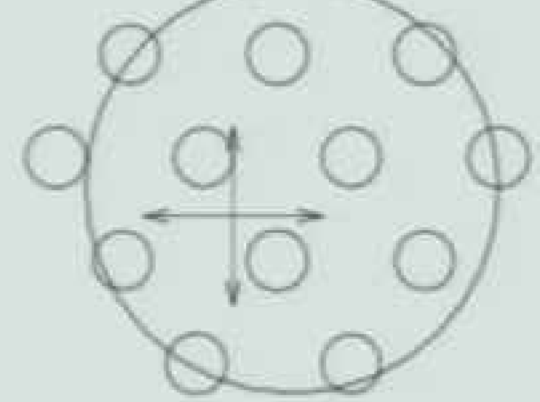
Grating Tied Array









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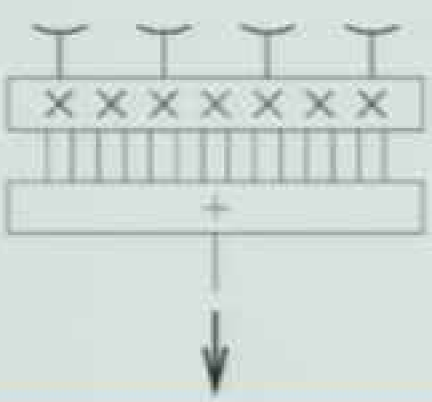

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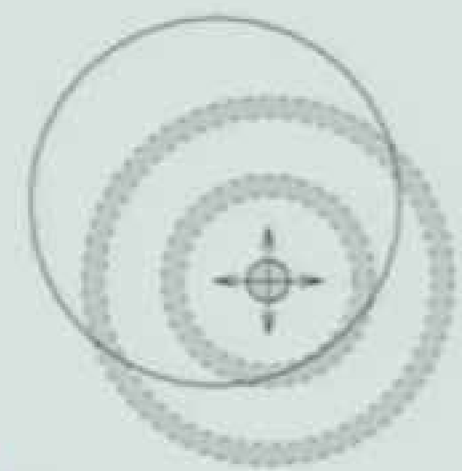
Visibility Aperture



is built up as the Earth rotates

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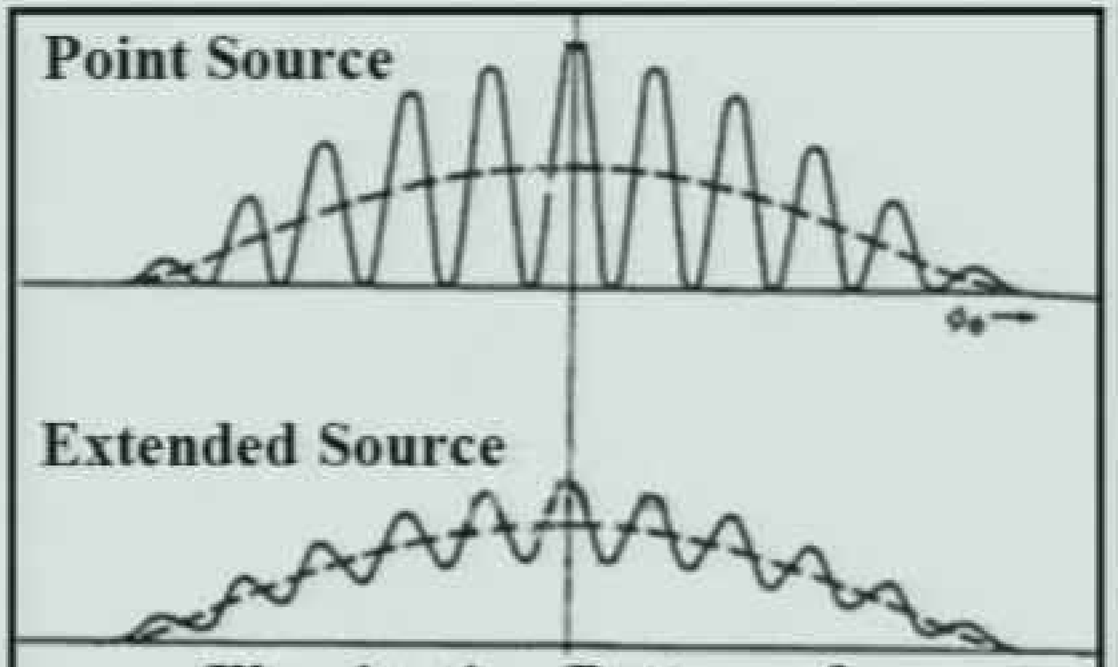
Beamforming vs. Aperture Synthesis Interferometers

- **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

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

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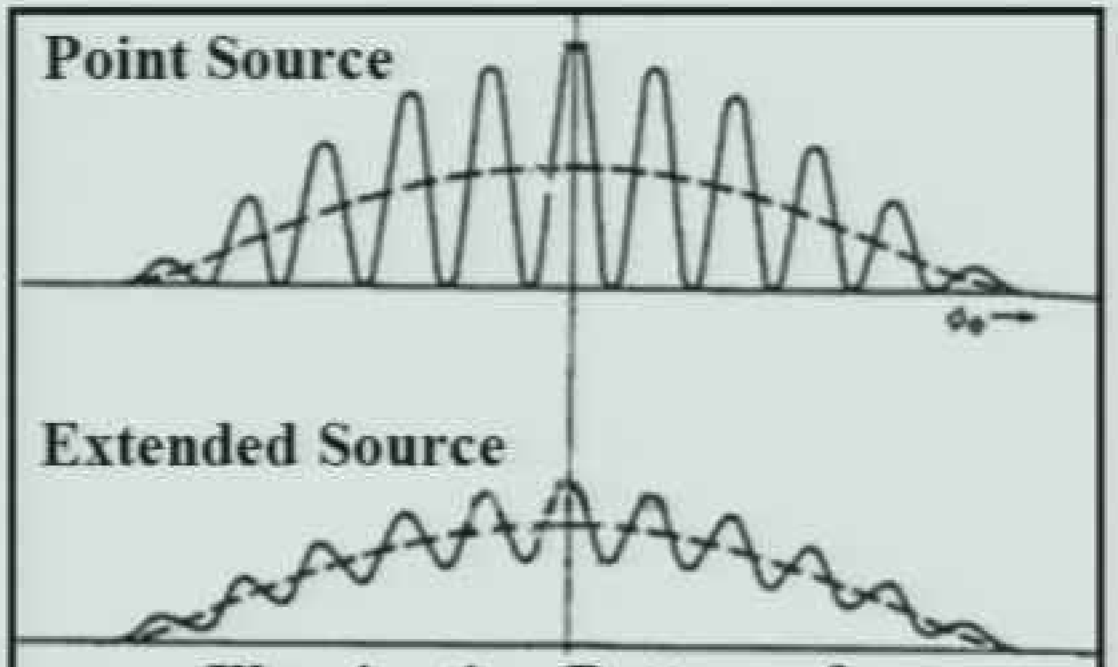

Illumination Pattern of a 2-Element Interferometer

- **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.**
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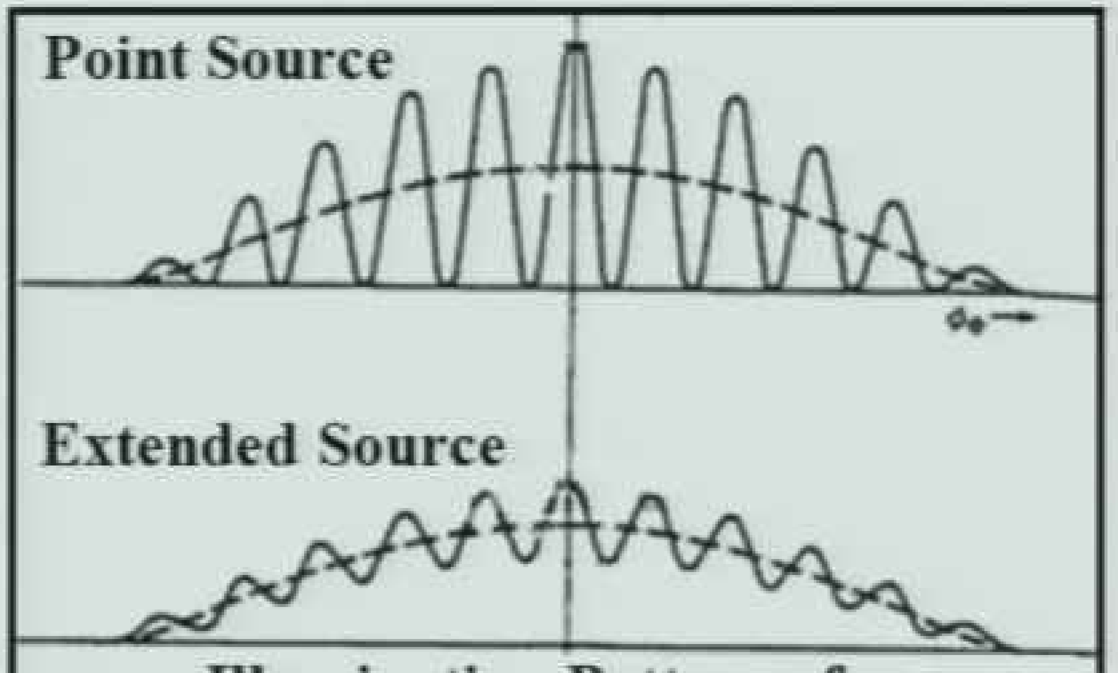

Illumination Pattern of a 2-Element Interferometer

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- **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.

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What about the First American Radio Interferometer…

Cosmic Noise

A History of Early Radio Astronomy

Woodruff T. Sullivan III

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.

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

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by Merle Tuve (Carnegie Institution of Washington)

Cosmic Noise: A History of Early Radio Astronomy,
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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 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

Nike-X Prototype *Multifunction Array Radar* (MAR-I) White Sands, NM (1964)

While researching the MAR-I (which was a 2077-element 2-D filled array designed by Bell Labs) and its role in the Colgate Paramp story (which is another oddball tale in the history of radio astronomy), I came across this book...

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

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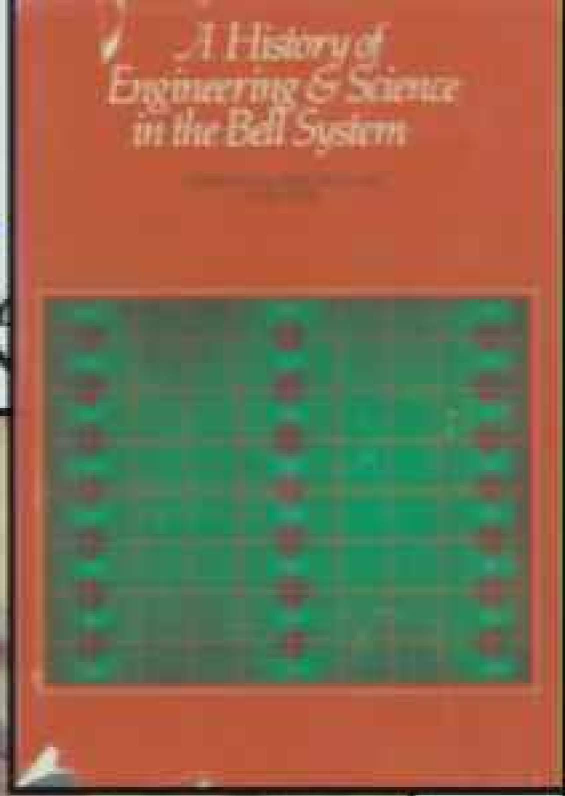

7 volumes with nearly 5,000 pages

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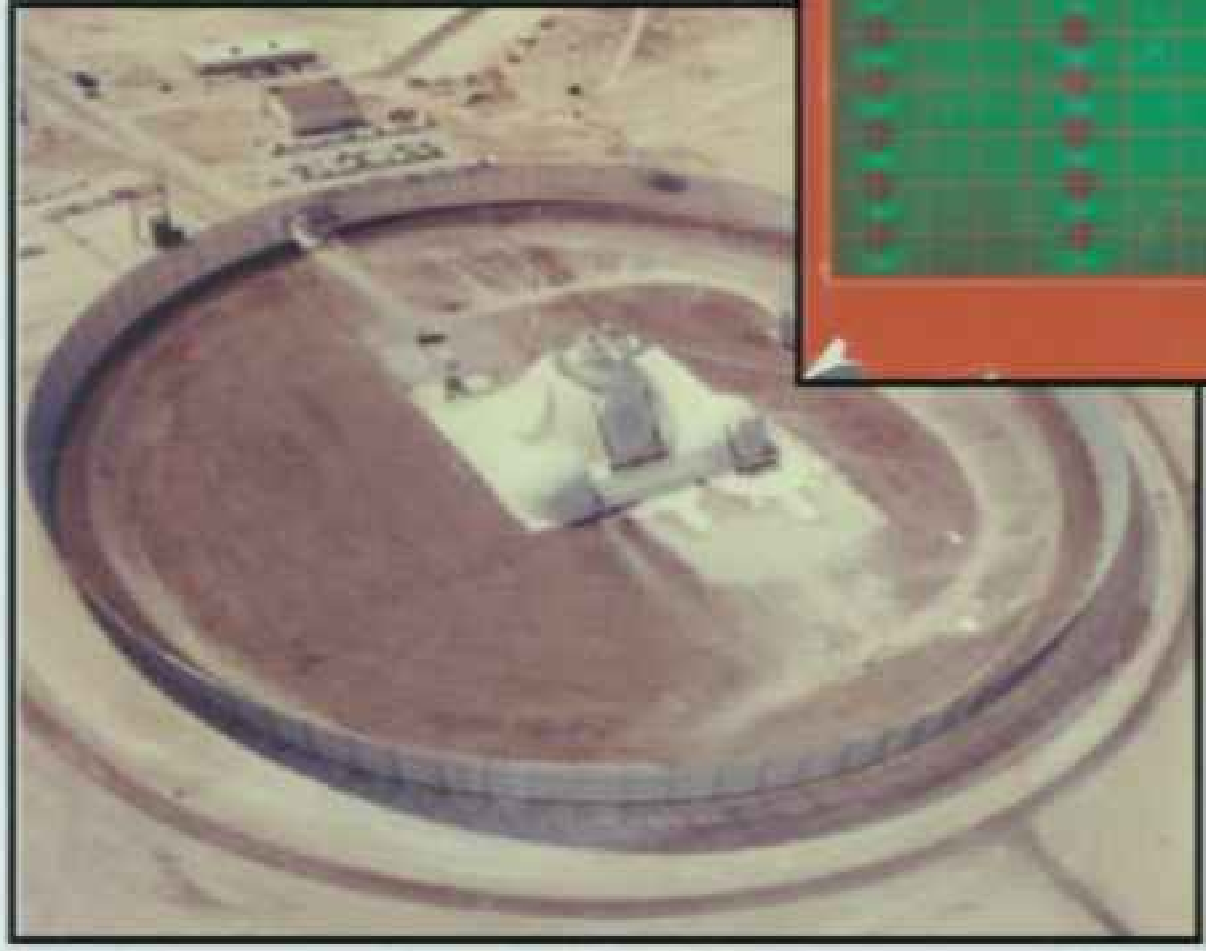

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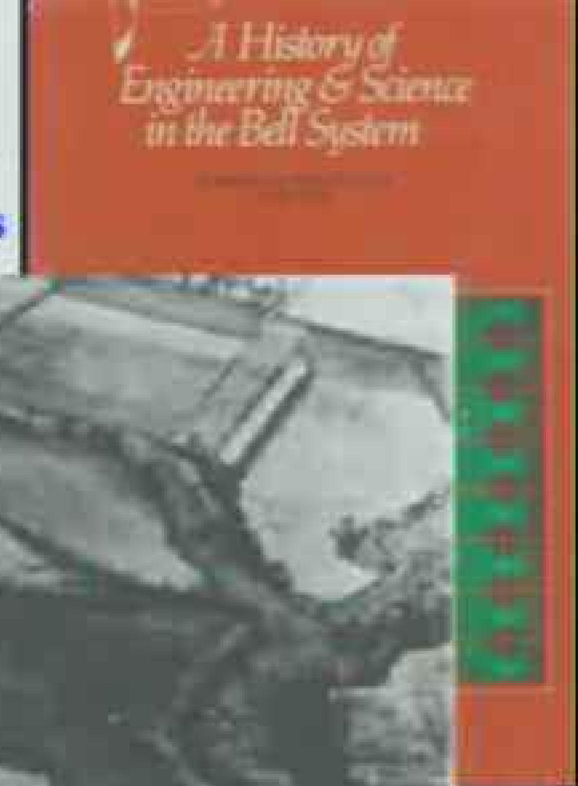

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1.5 Overcoming the Effects of Fading

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 could be steered by rotating the phase-shifter assembly. Three sets of phase shifters were placed in parallel to provide three separately steerable receiving branches. One branch served as an exploring or monitoring 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 networks before combining in the final output. The benefits of the MUSA system were a signal-to-noise improvement of 7 to 8 dB referred to one antenna alone, and a substantial improvement in audio quality, due jointly to the diversity action and a reduction of selective fading. Subsequently, a 16-element antenna was built at Manahawkin, New Jersey, for operational use.

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.

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.

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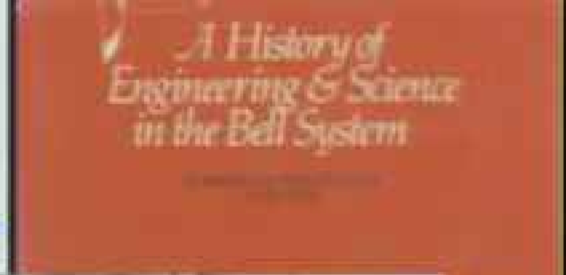

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Karl Jansky & "Star Static"

Karl Jansky with his antenna

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- **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

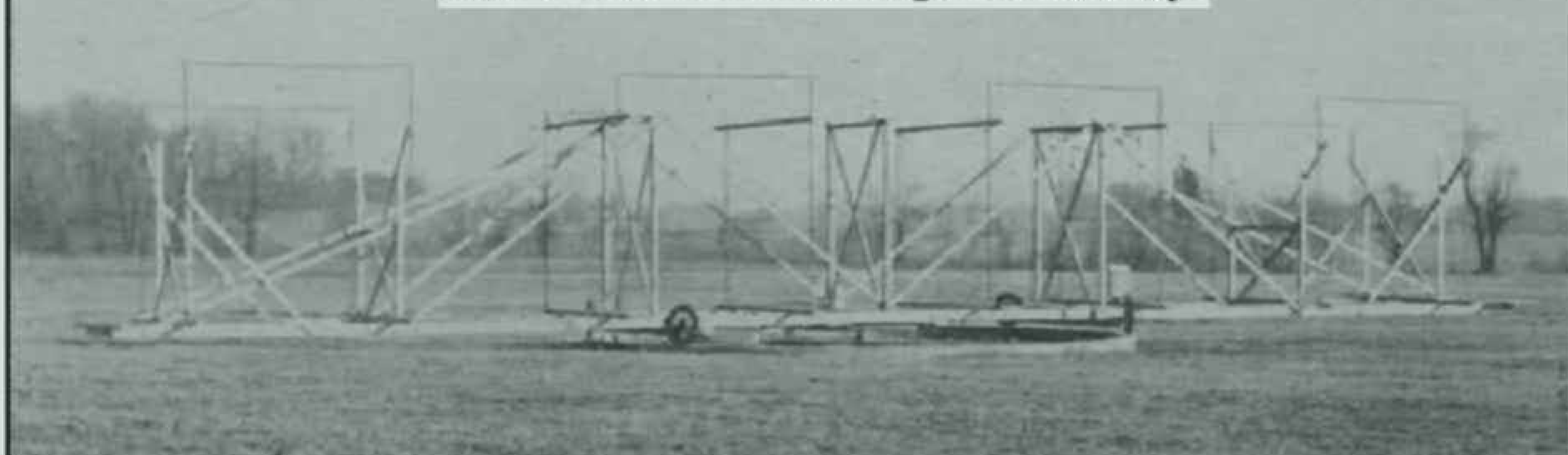

Fig. 2—Short-wave rotating antenna array.

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*

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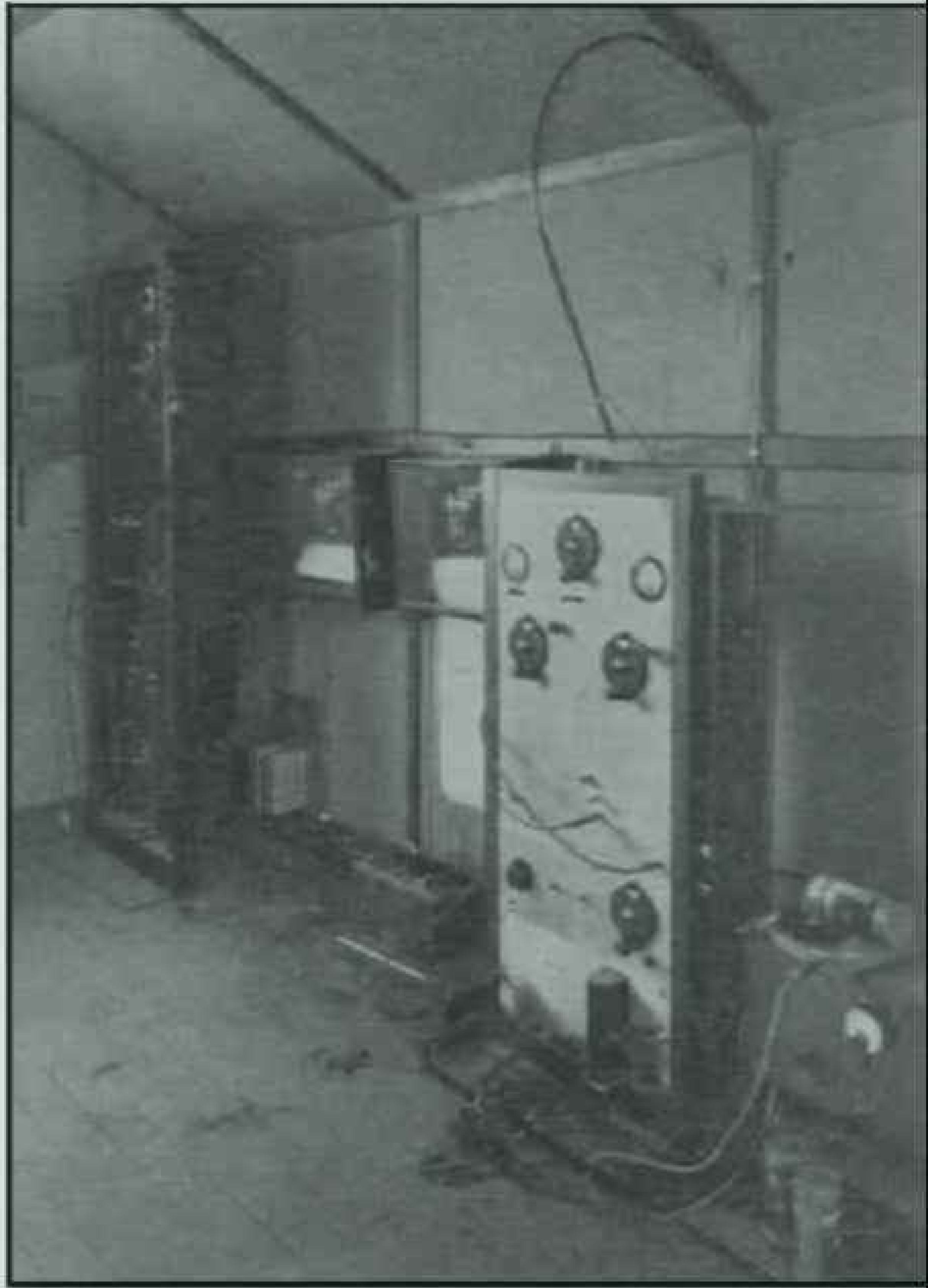

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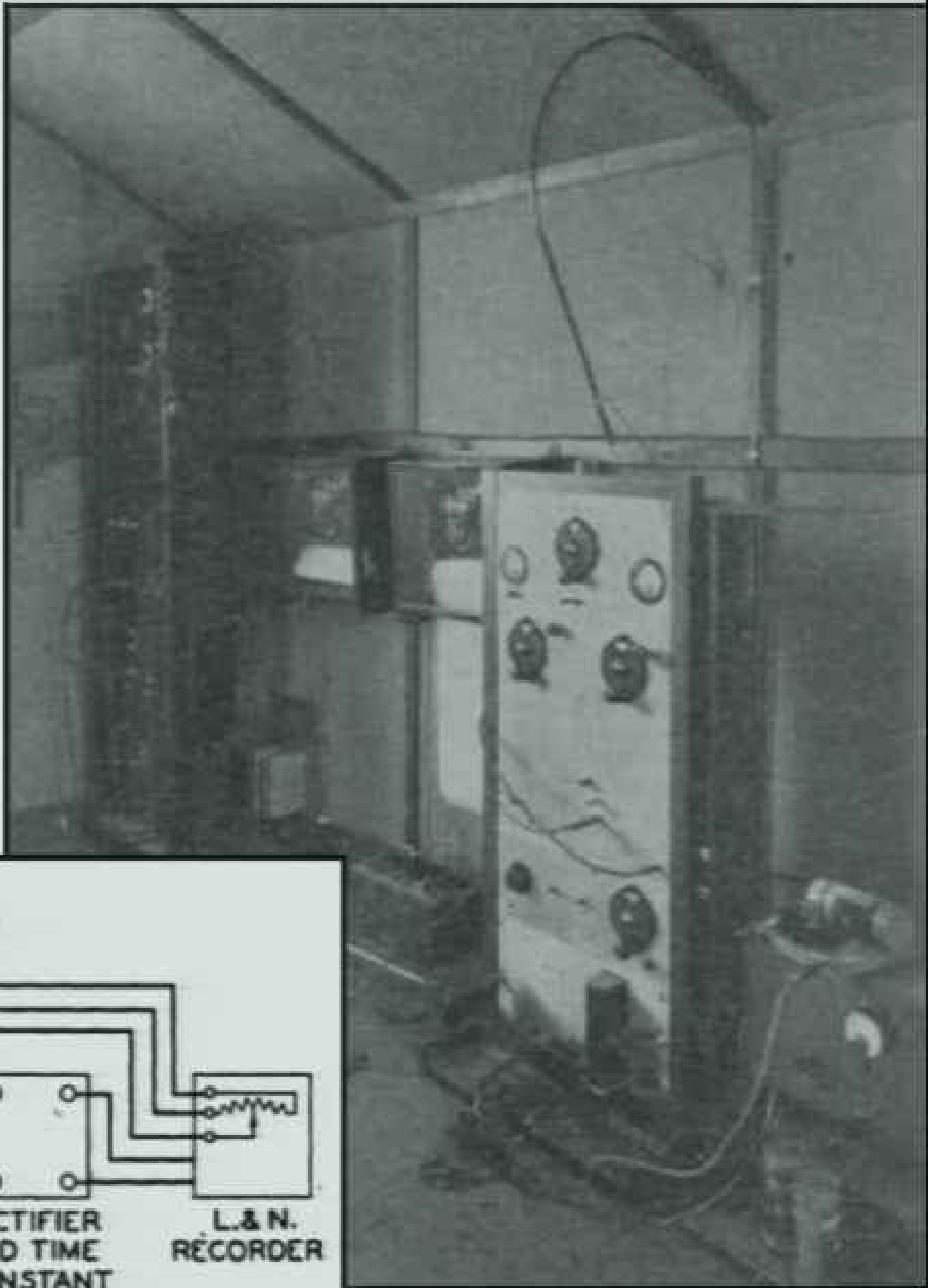

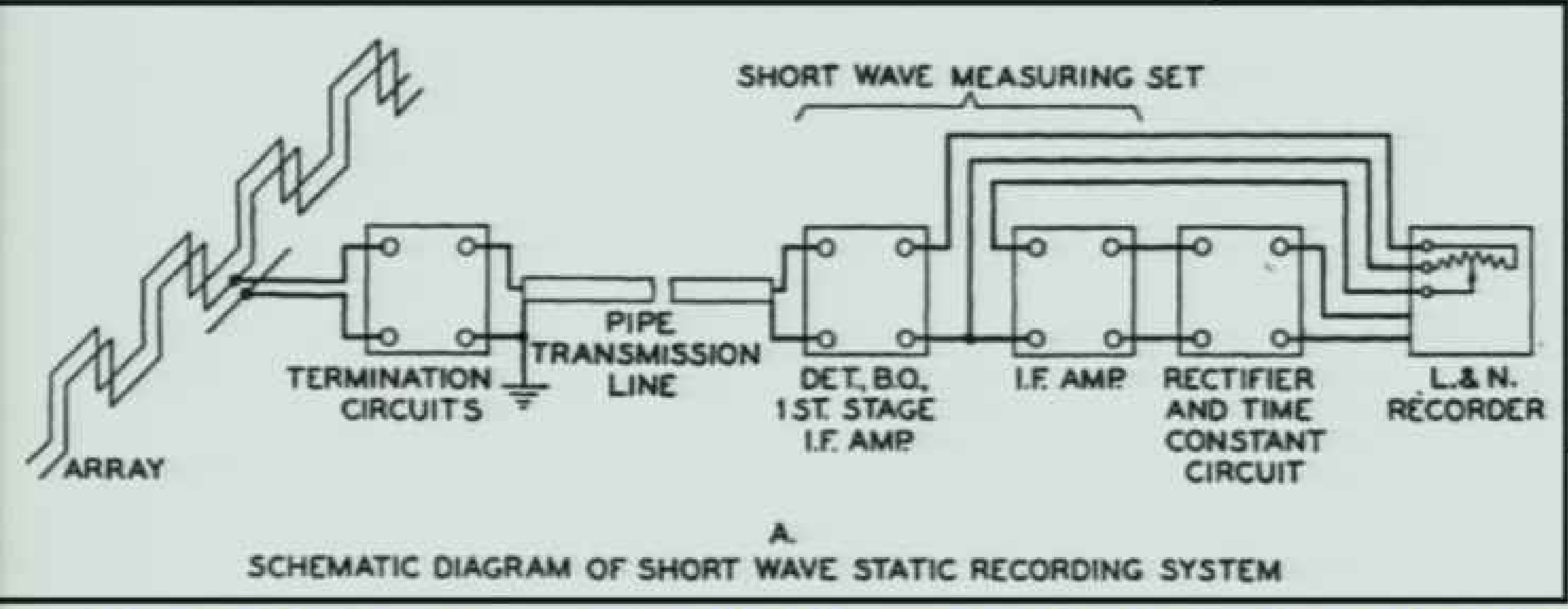

1930's "Block Diagram" (every symbol is a block)

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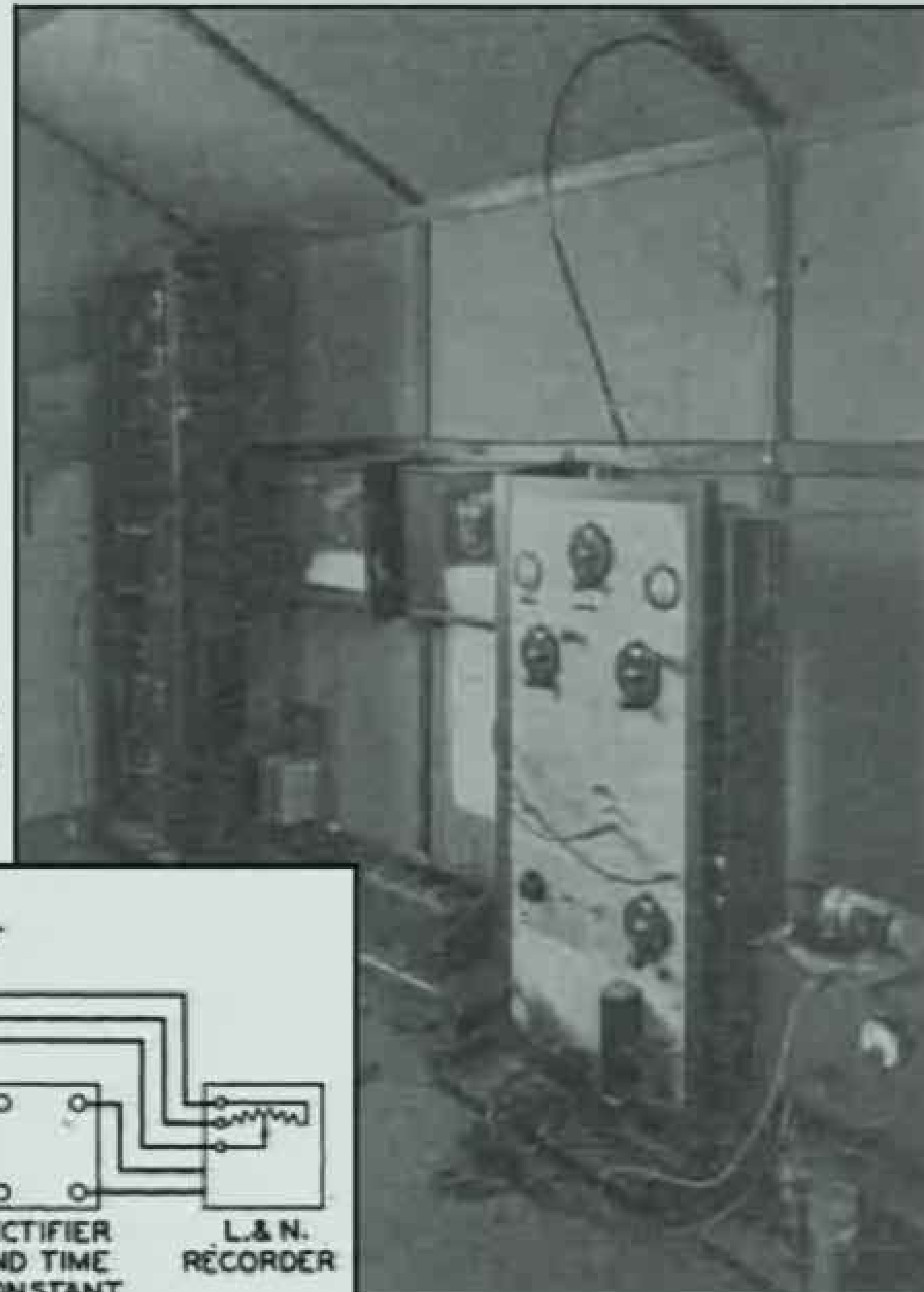

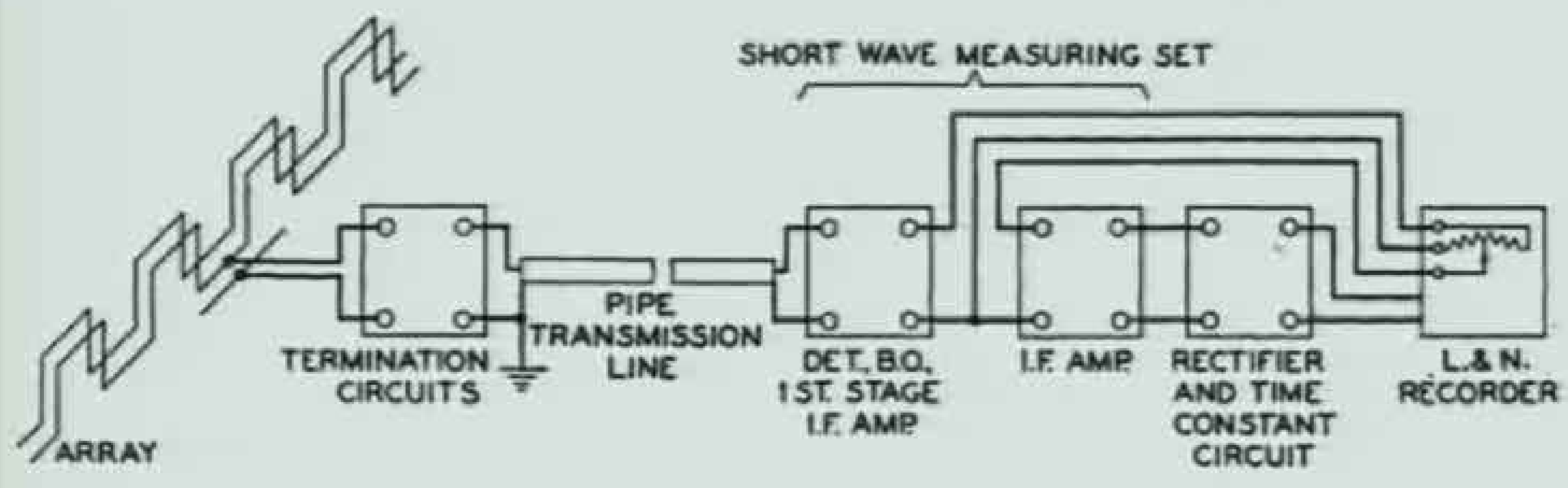

A.
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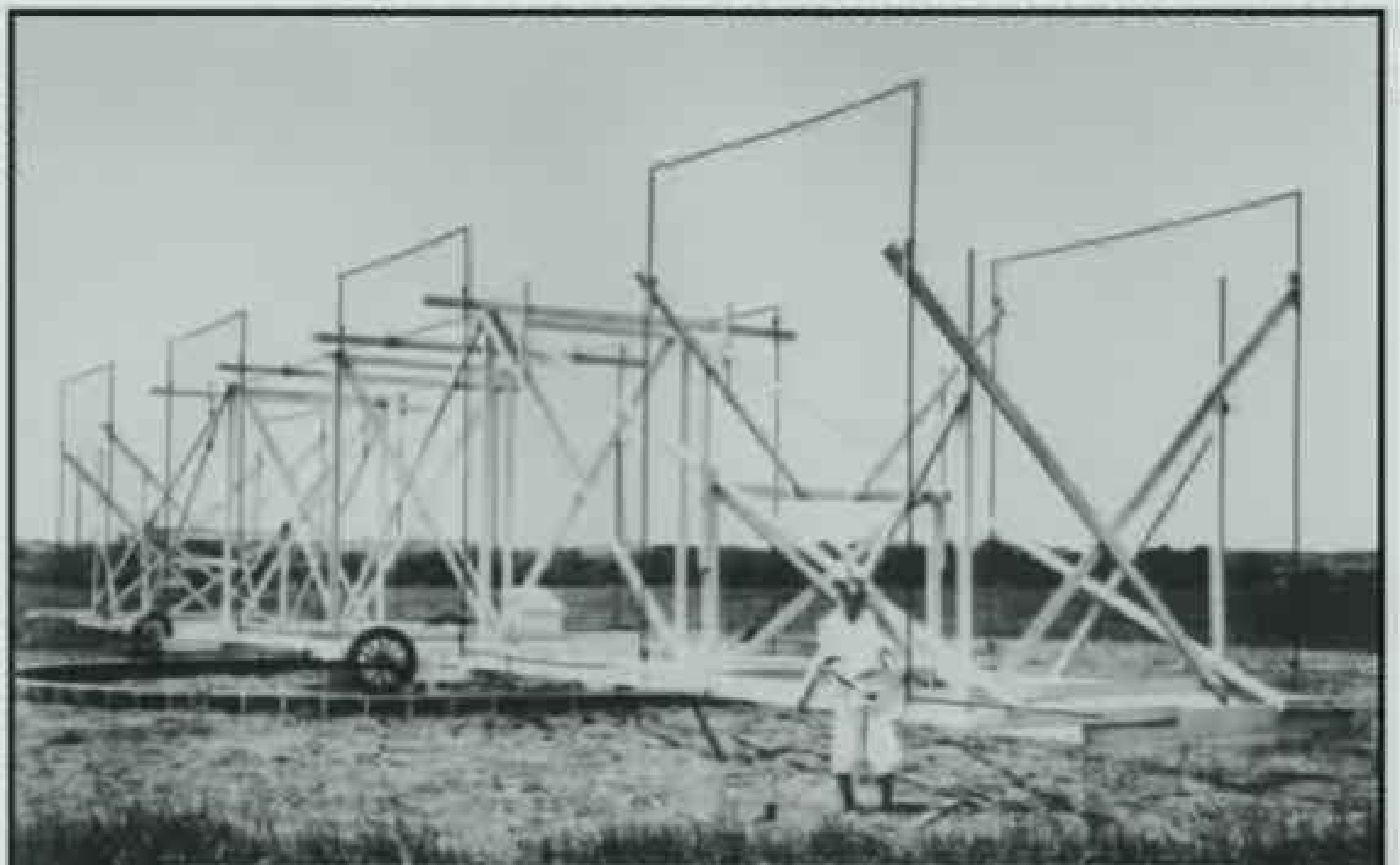

Karl Jansky & his "merry-go-round" antenna at Holmdel, NJ, in 1933

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

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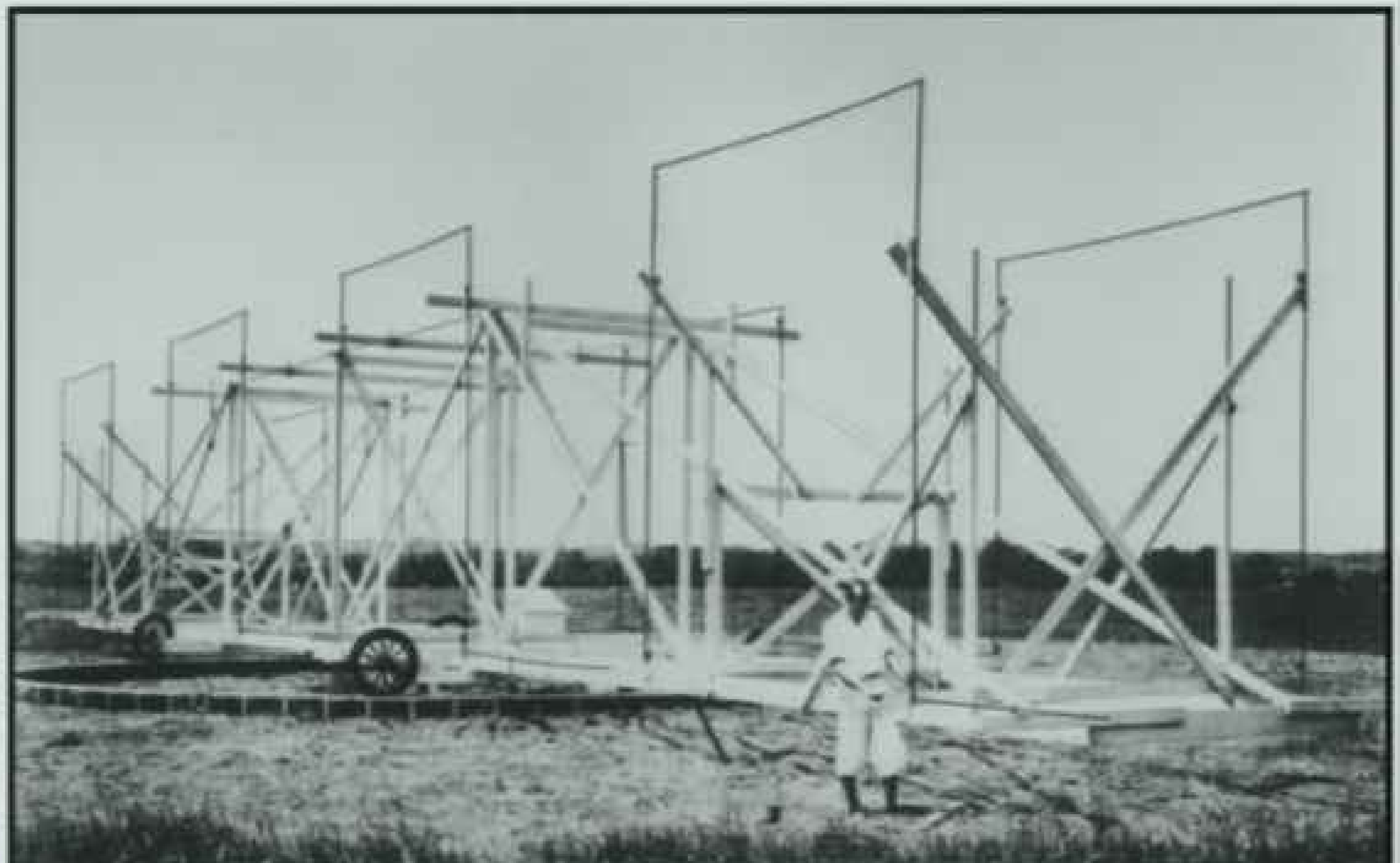

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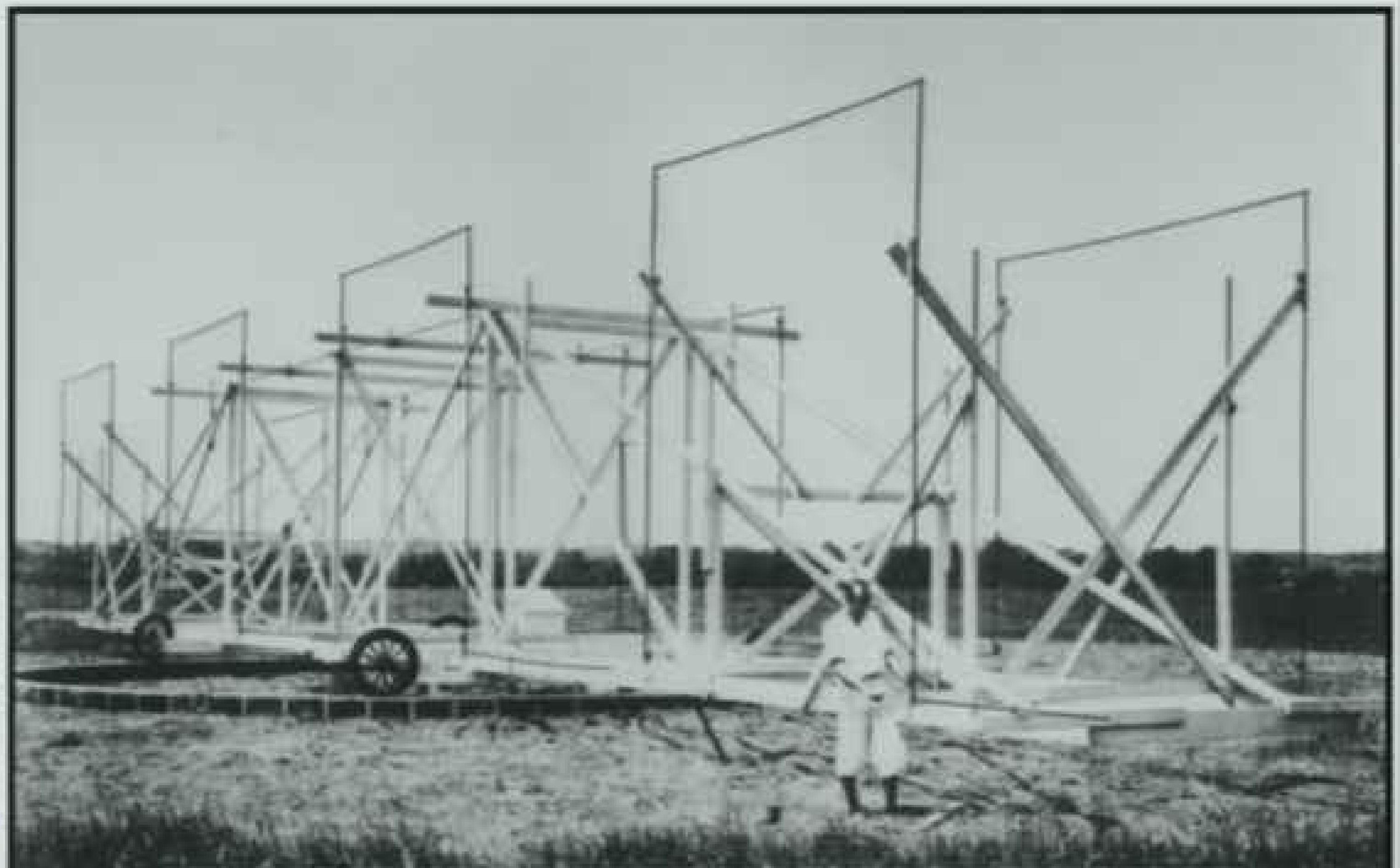

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- This is where Harald Friis entered the picture with his design of the first electronically steered phased-array.

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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.**

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- **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.**
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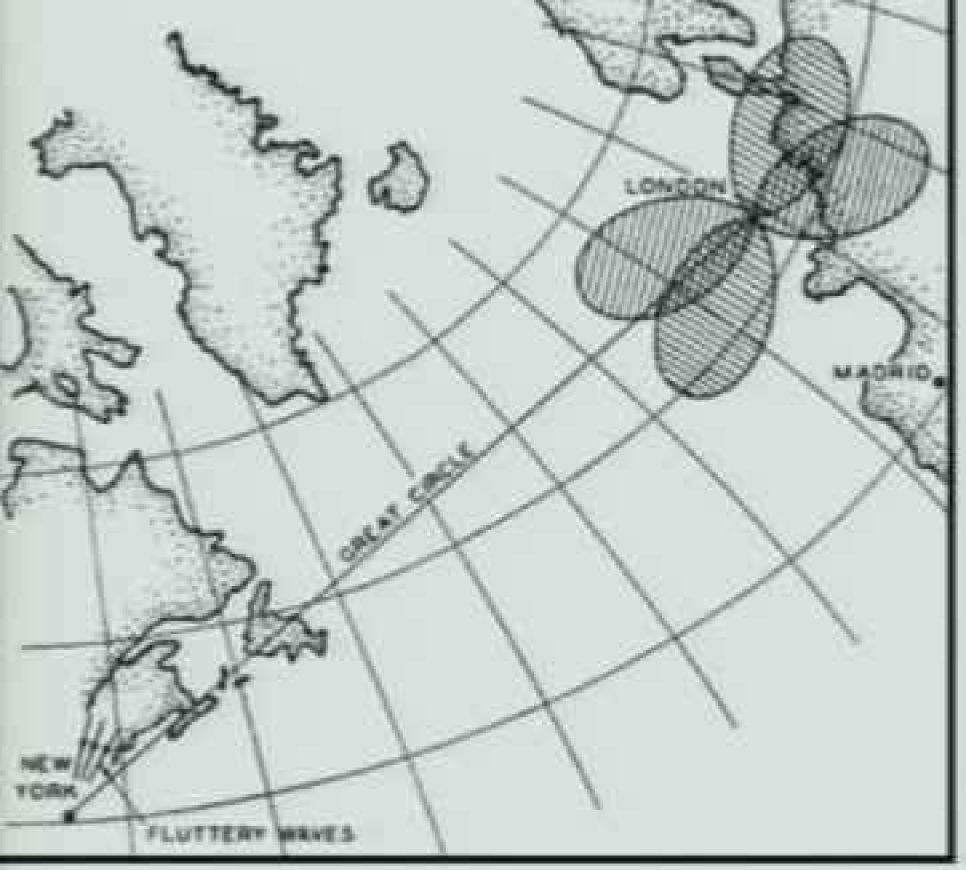
The Holmdel, NJ
Experimental MUSA



Short Wave Radio Communication & the MUSA Concept

- **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.**

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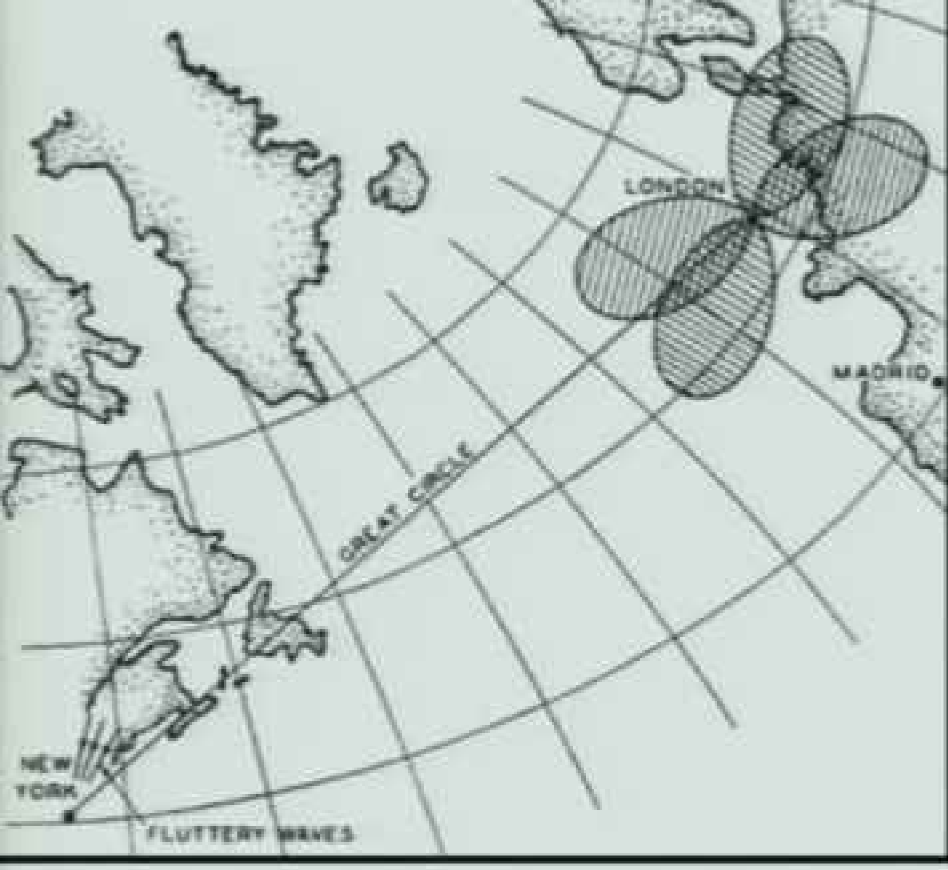

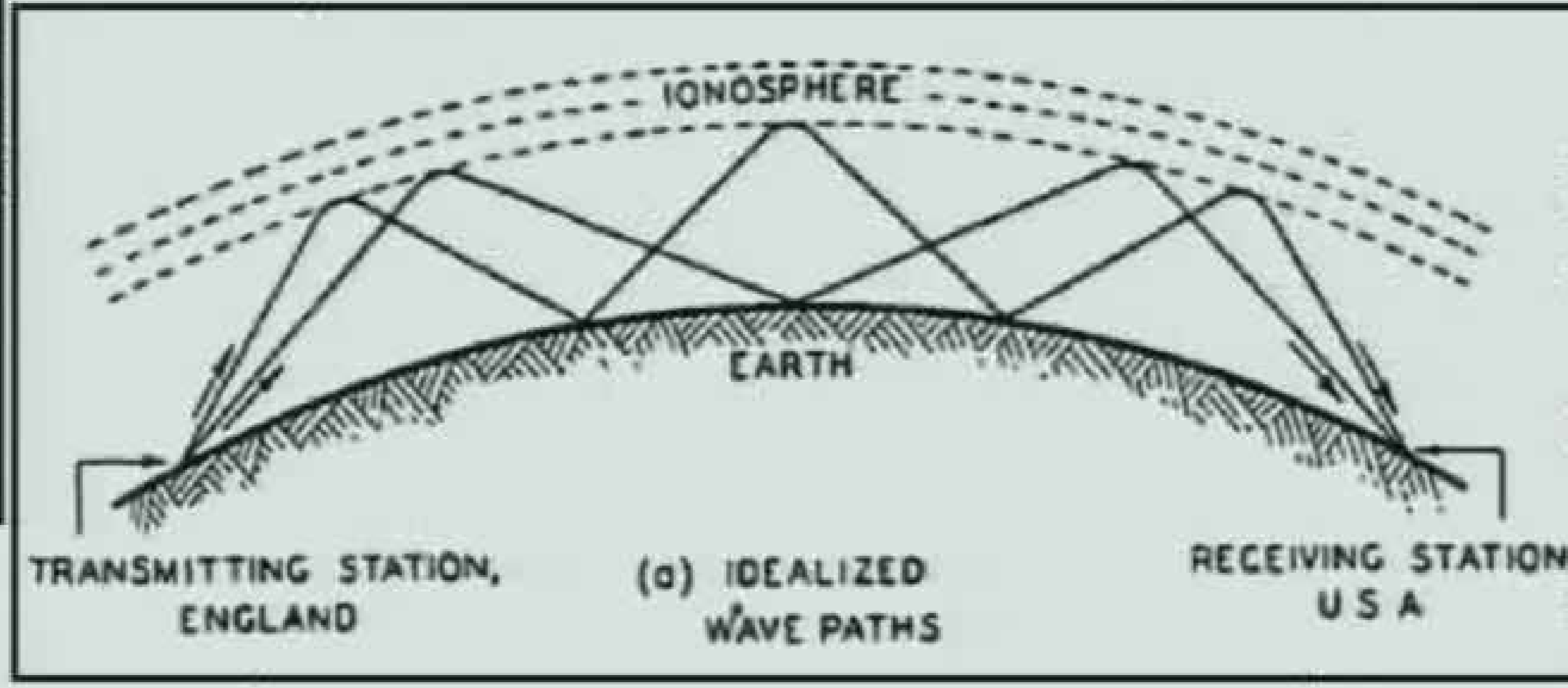

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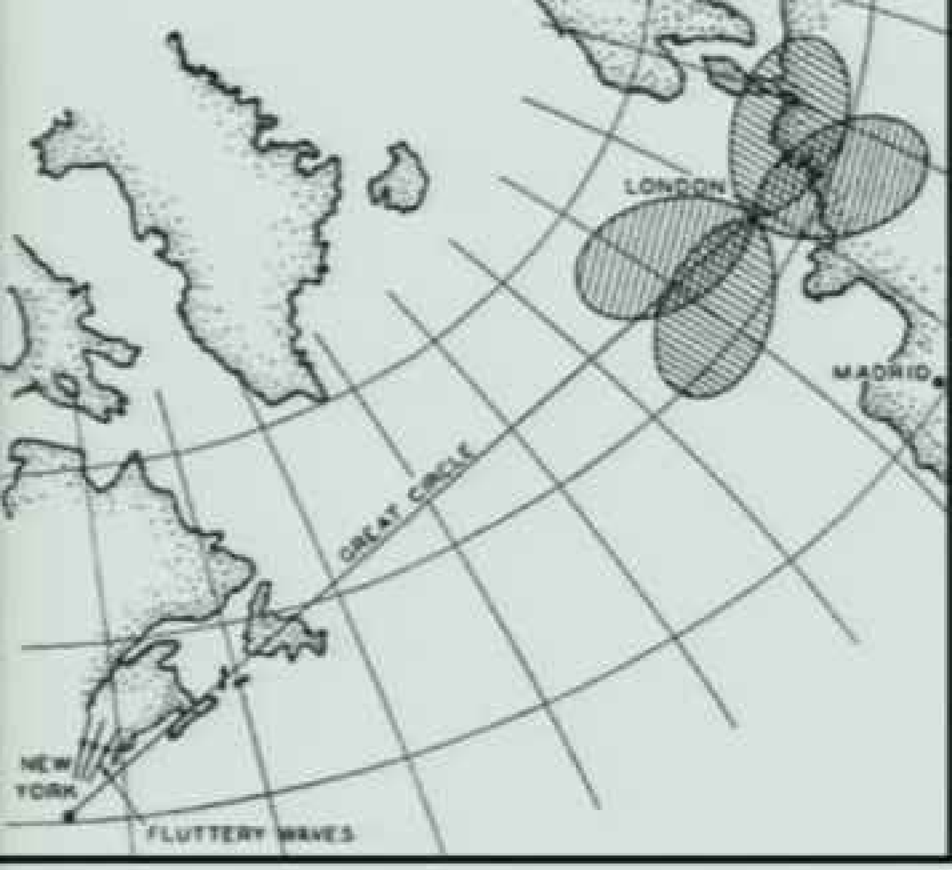

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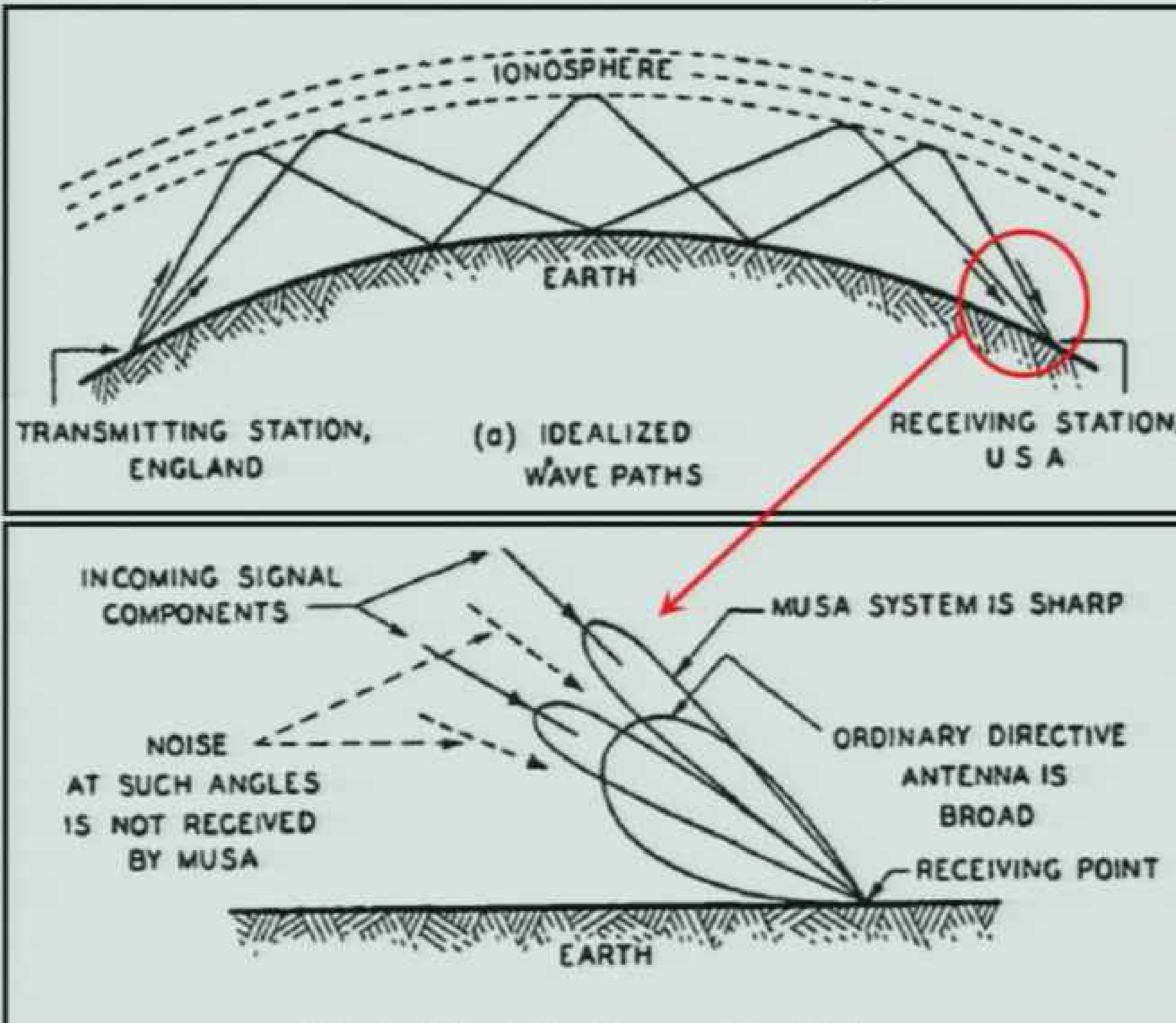

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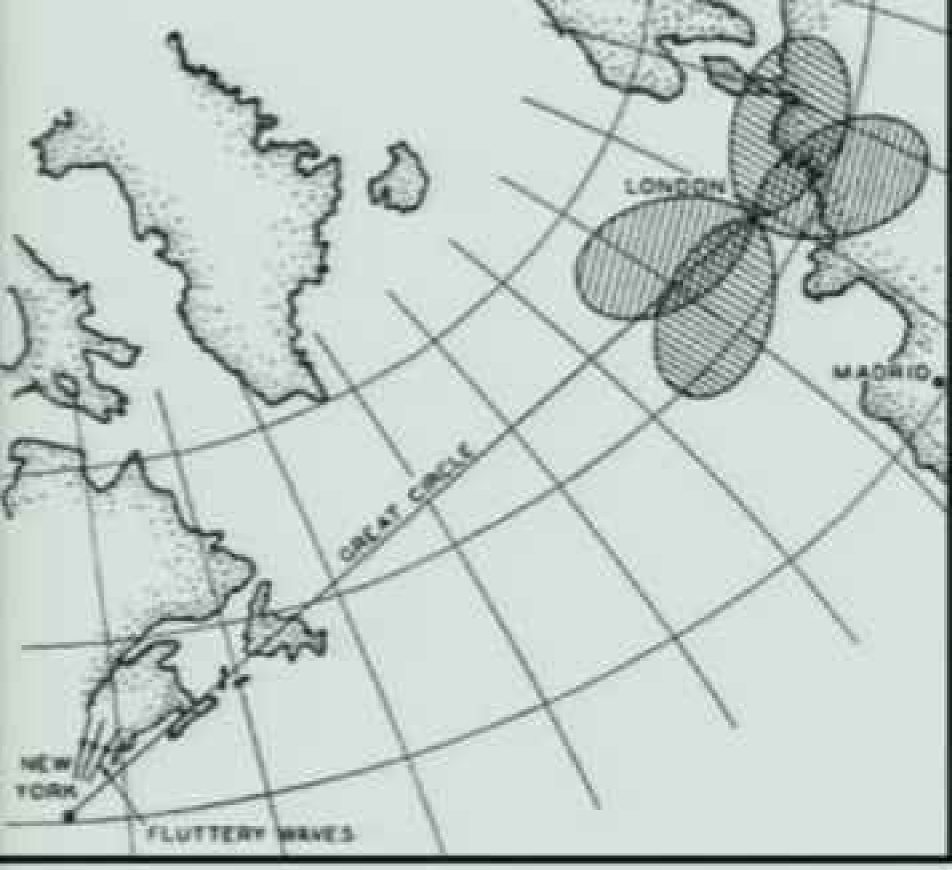

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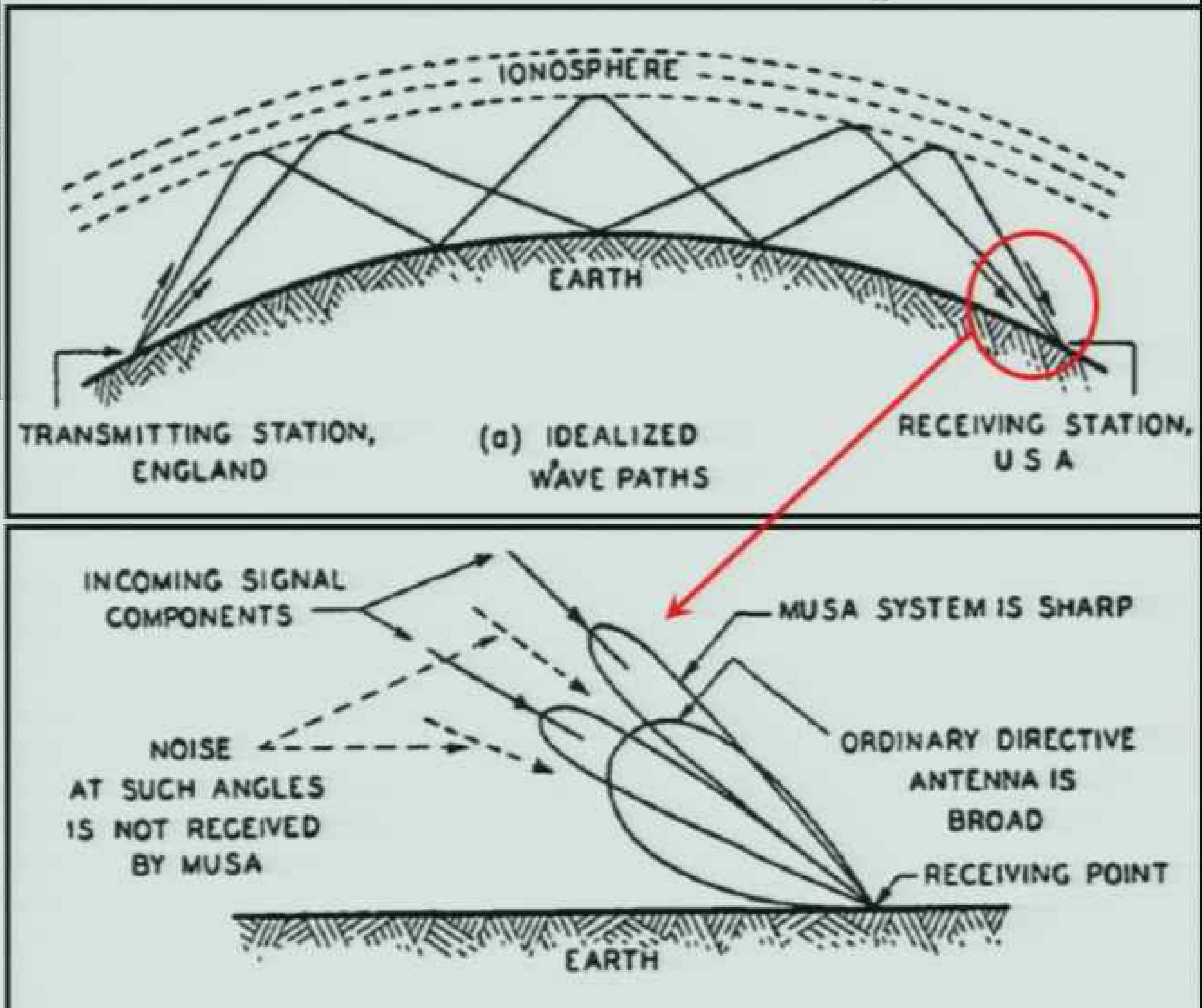

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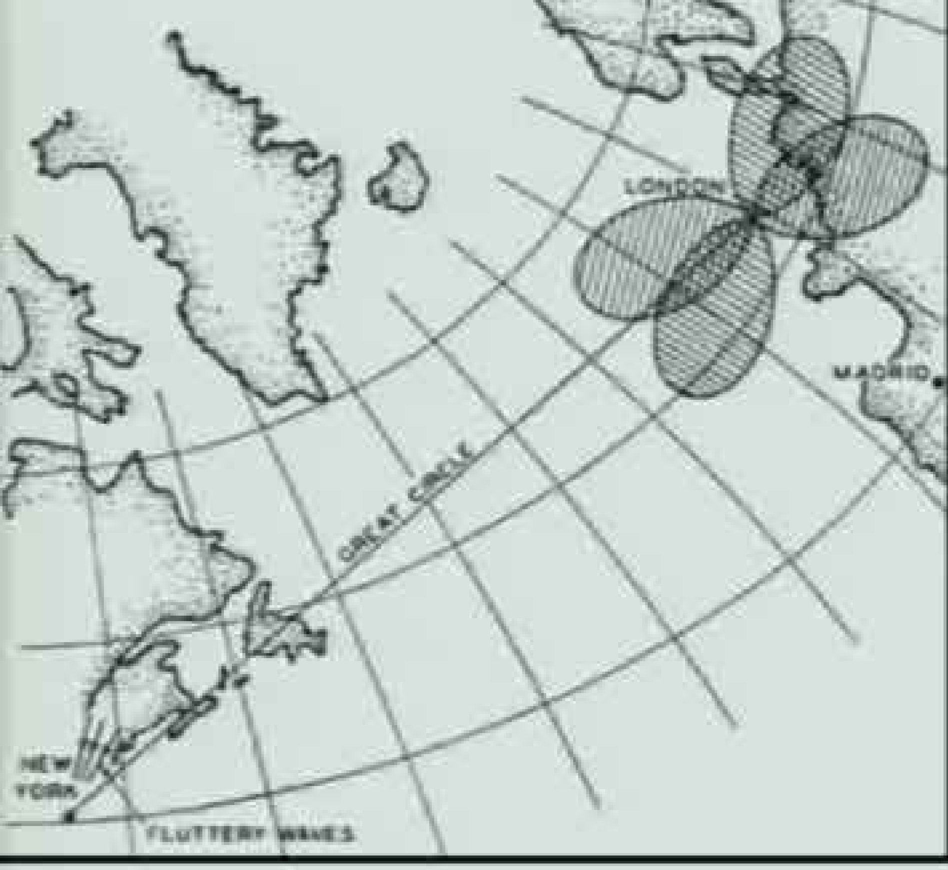

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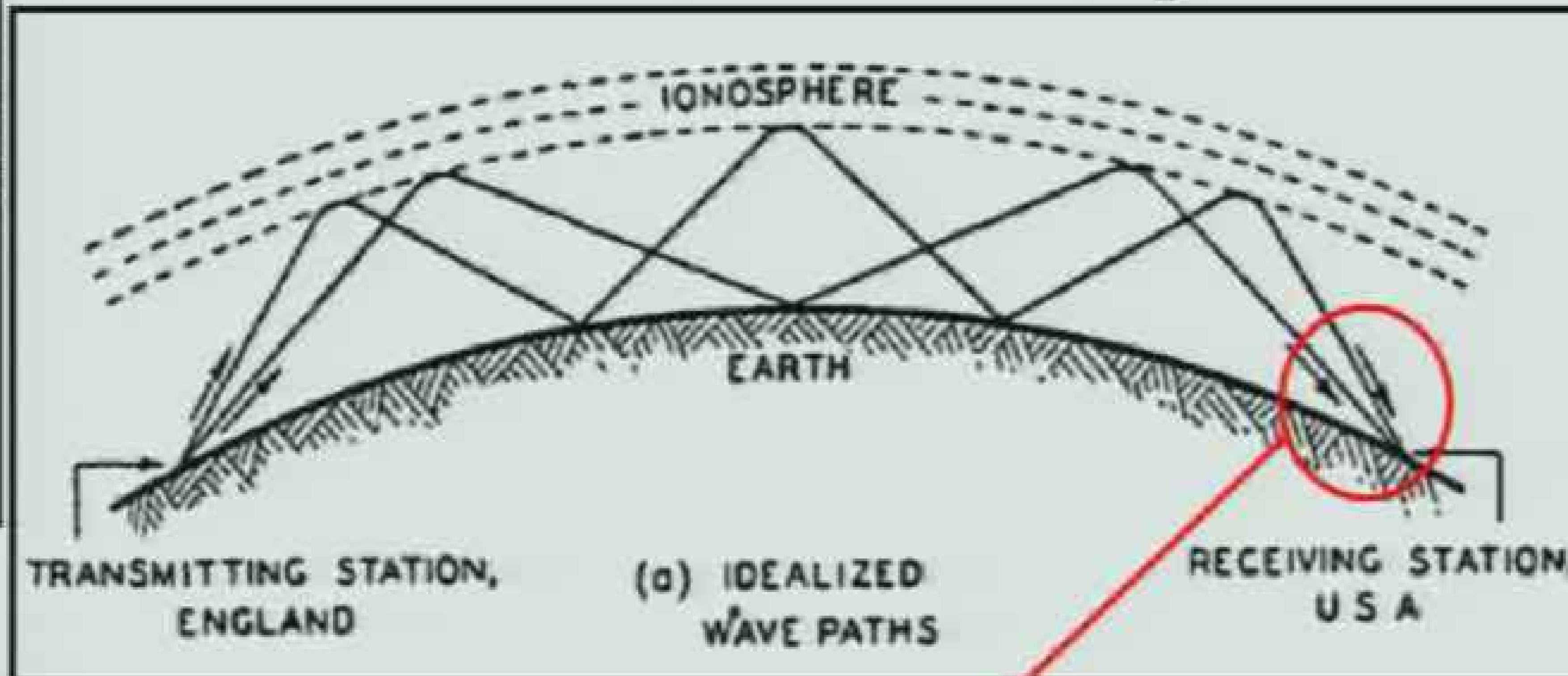

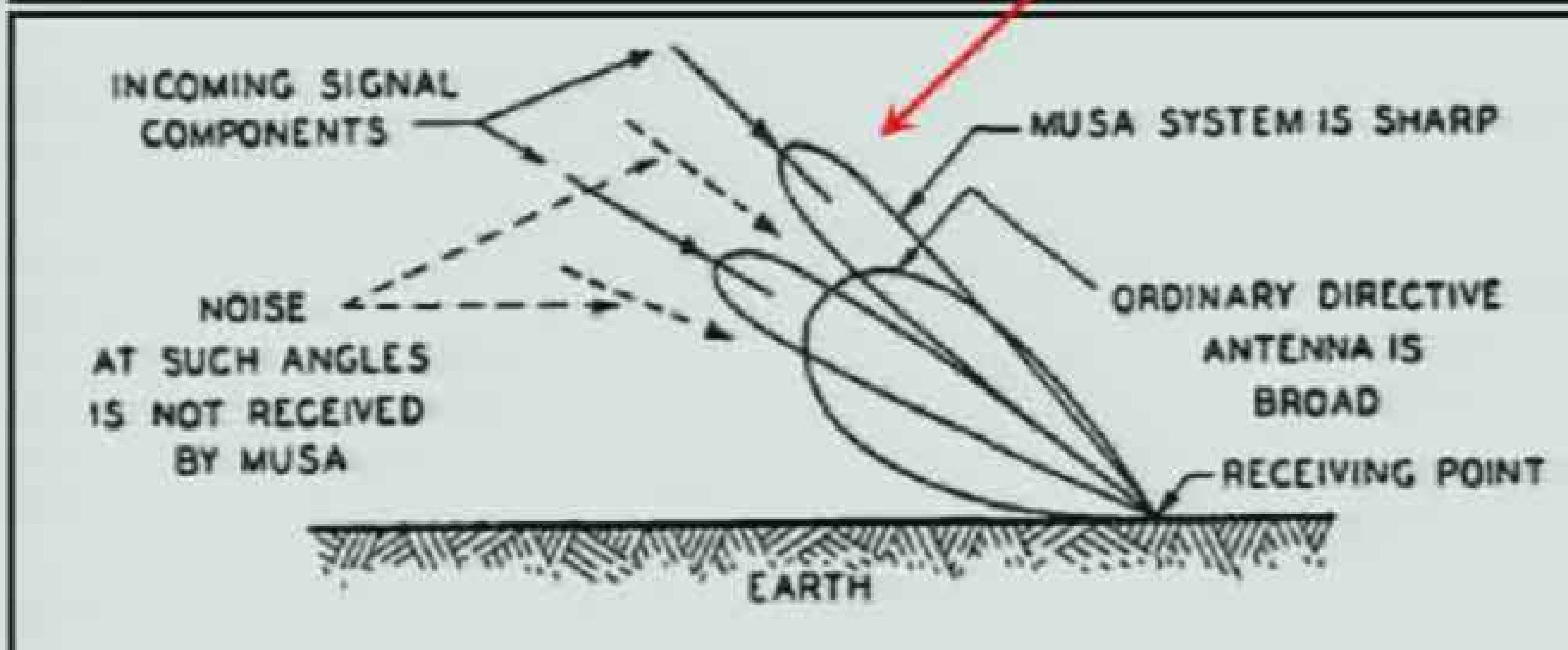

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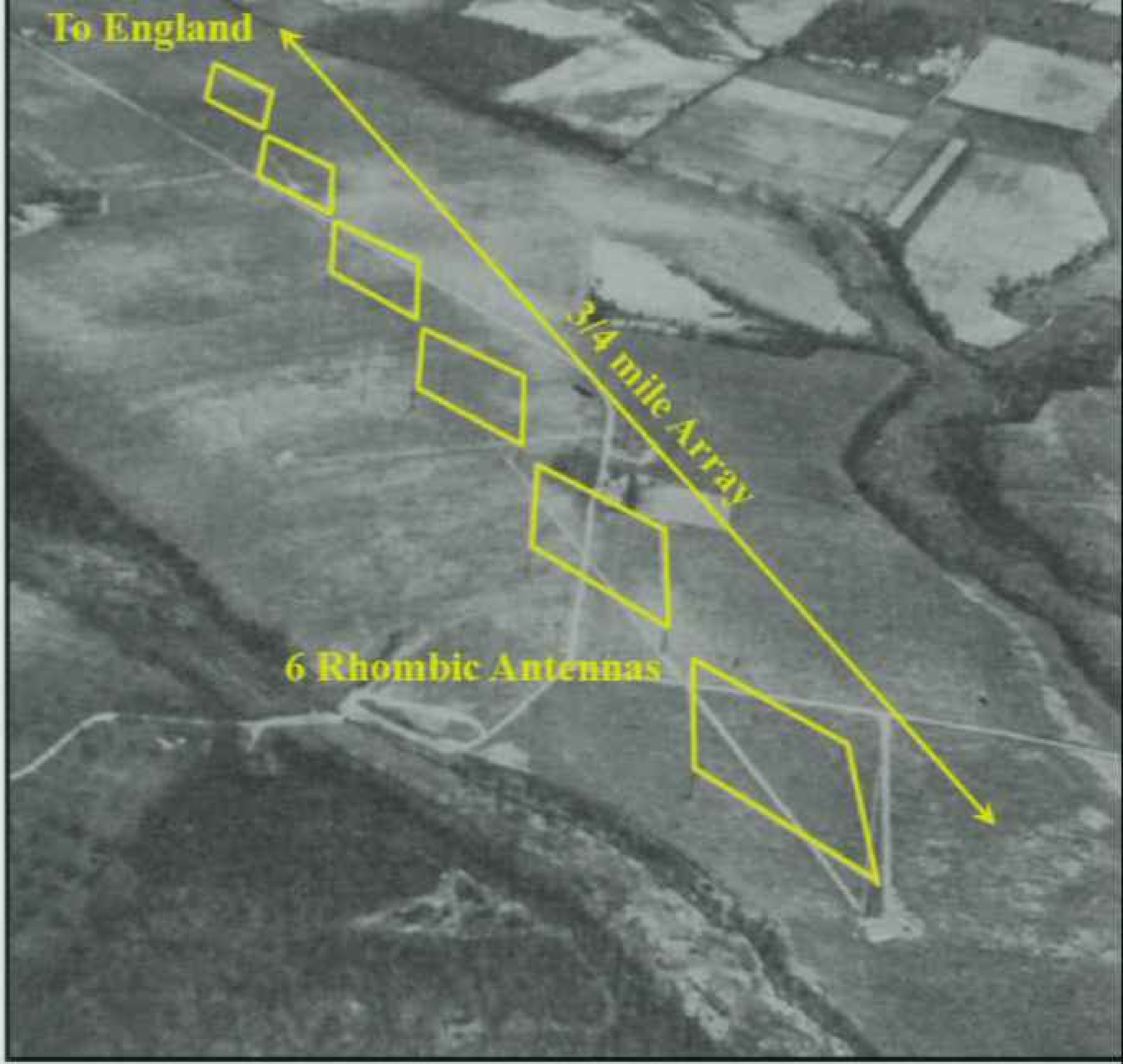

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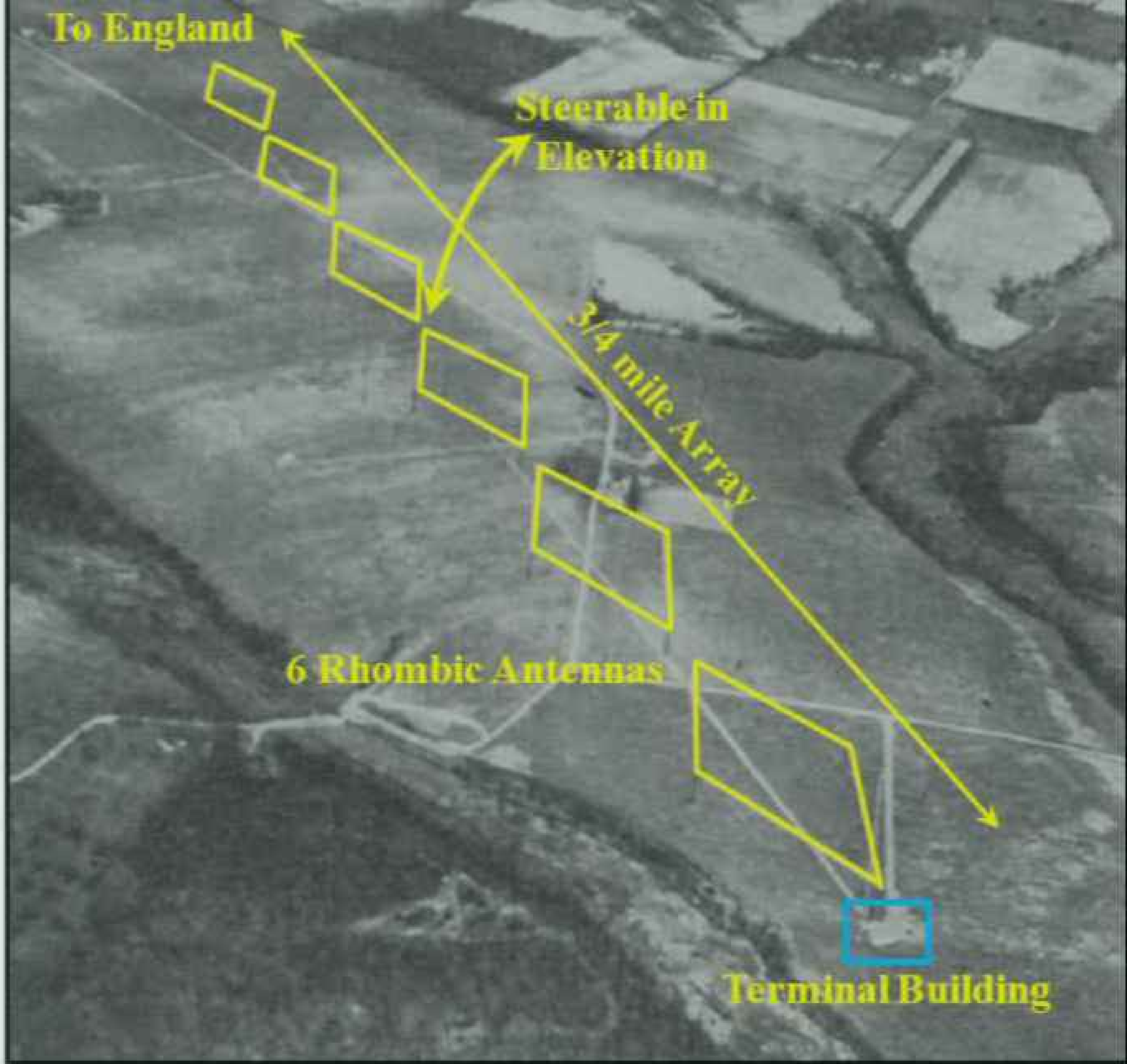

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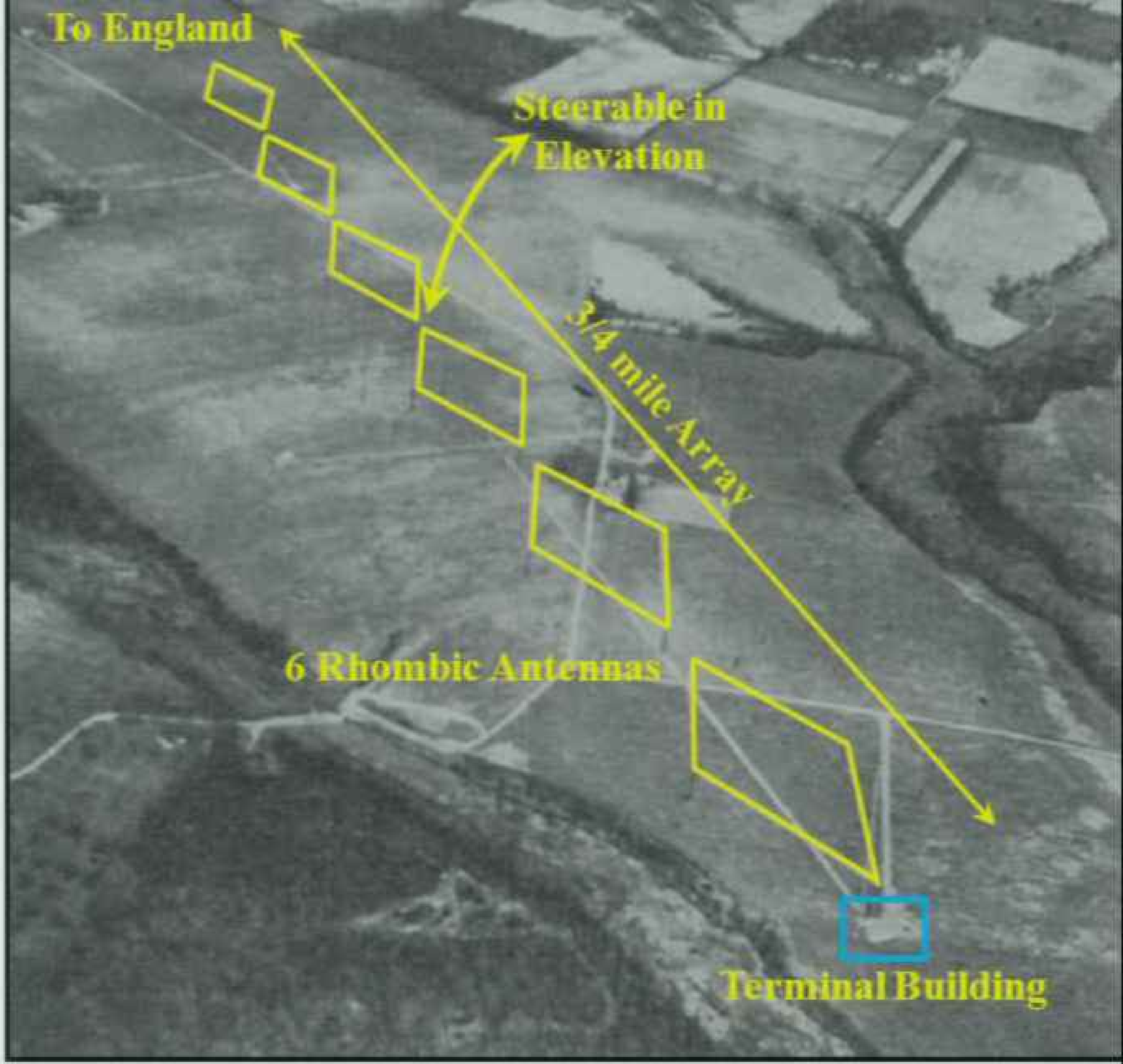

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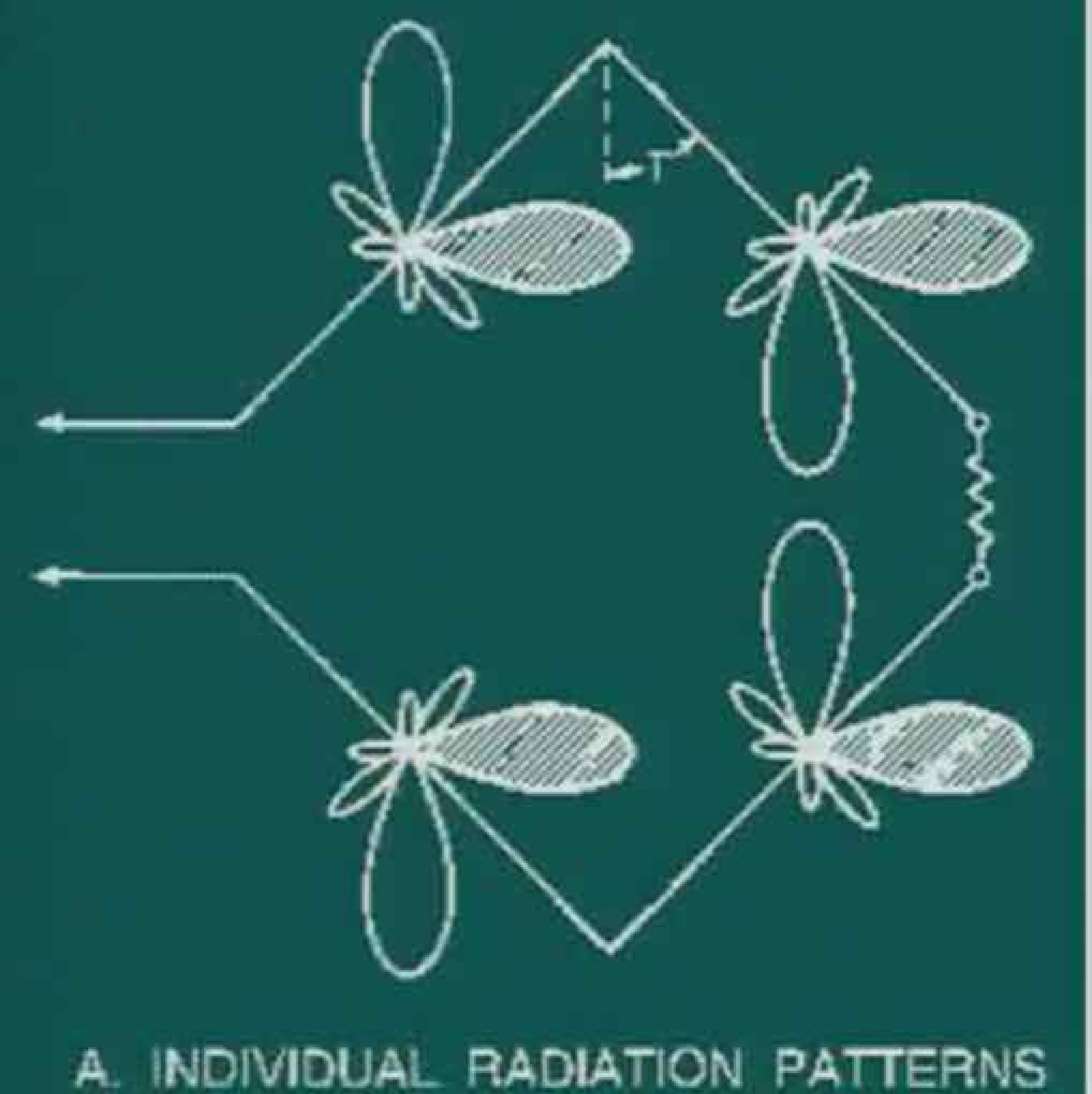

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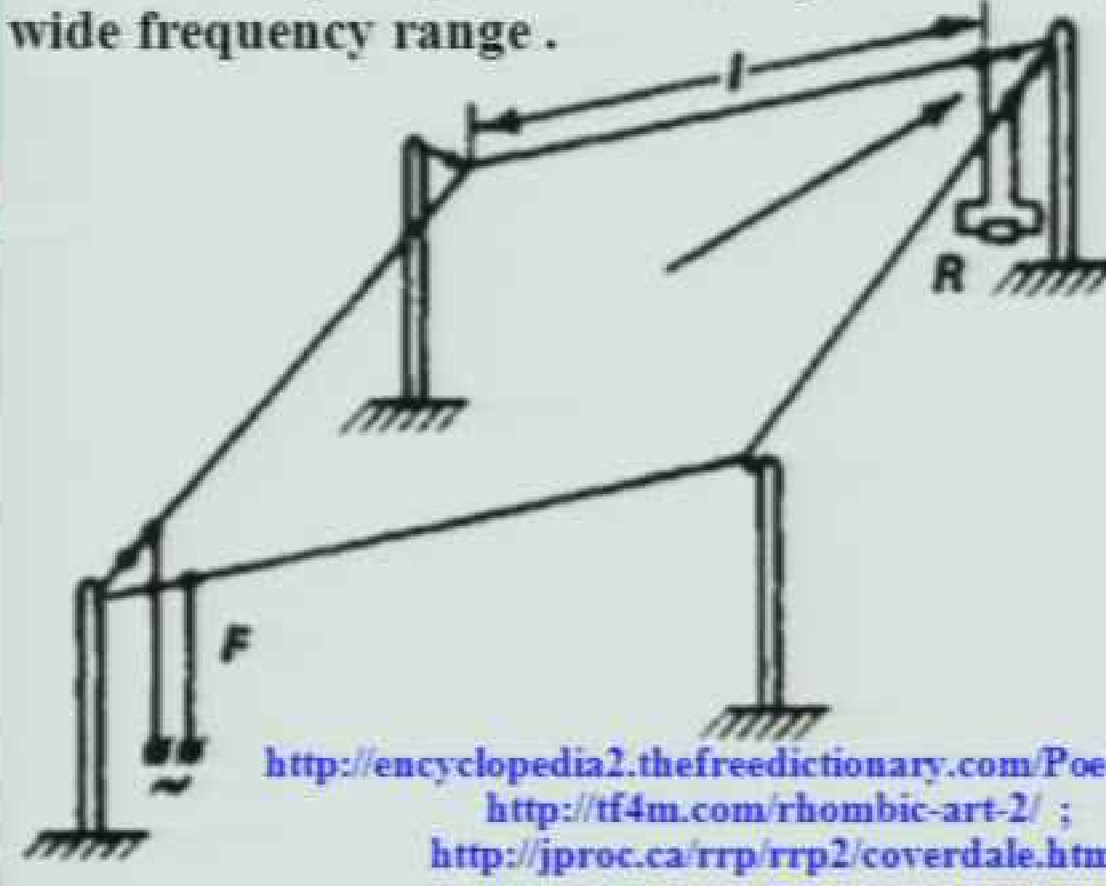
It has several advantages over other HF antennas, such as simplicity, low cost, high forward gain and wide frequency range .



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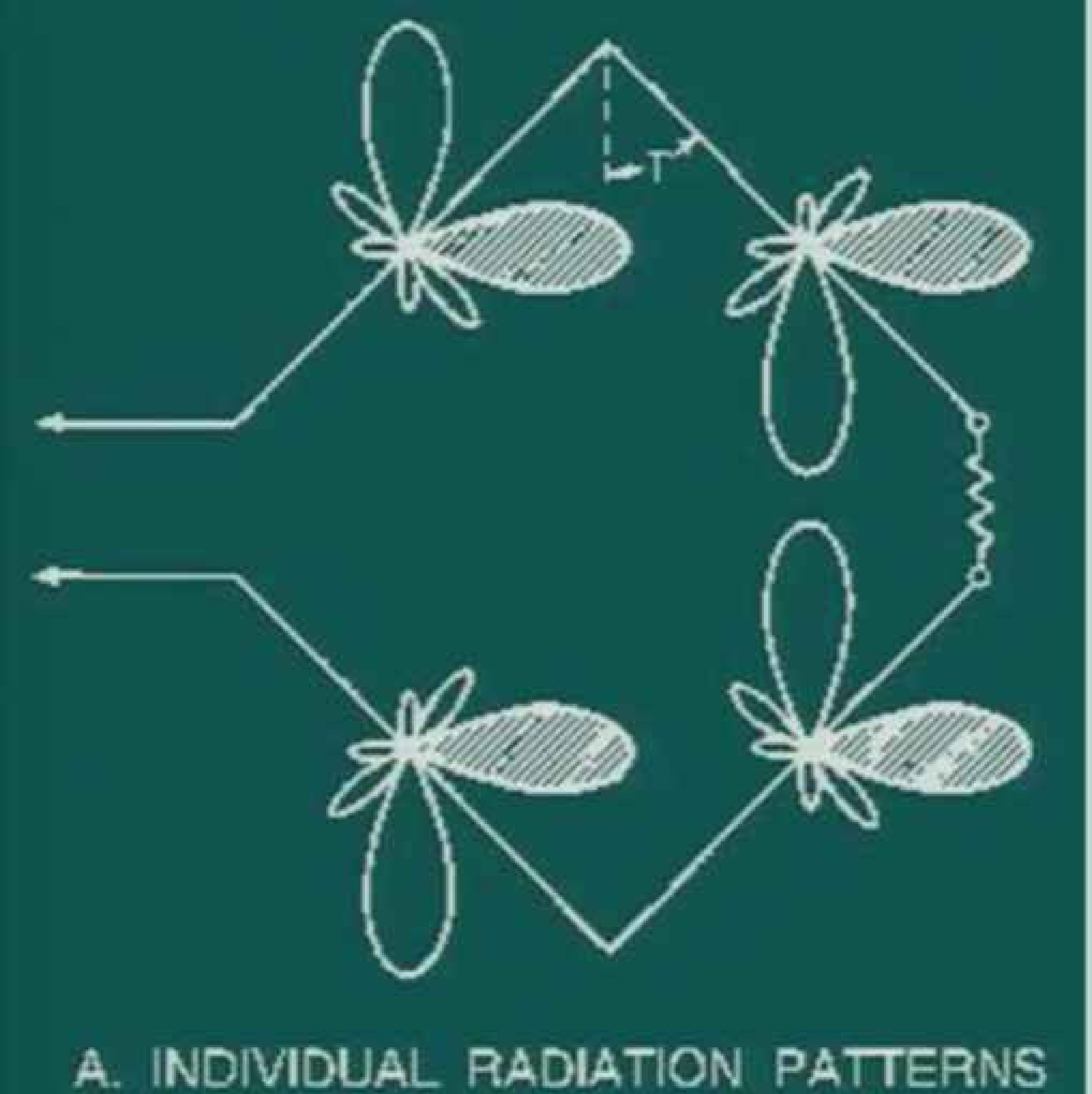

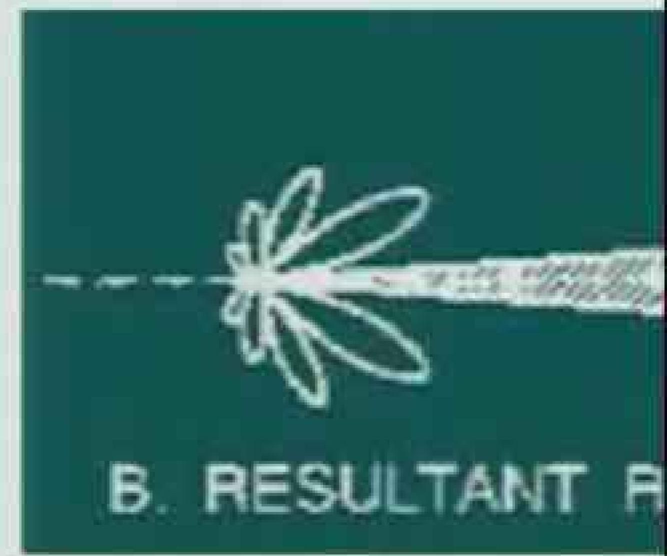

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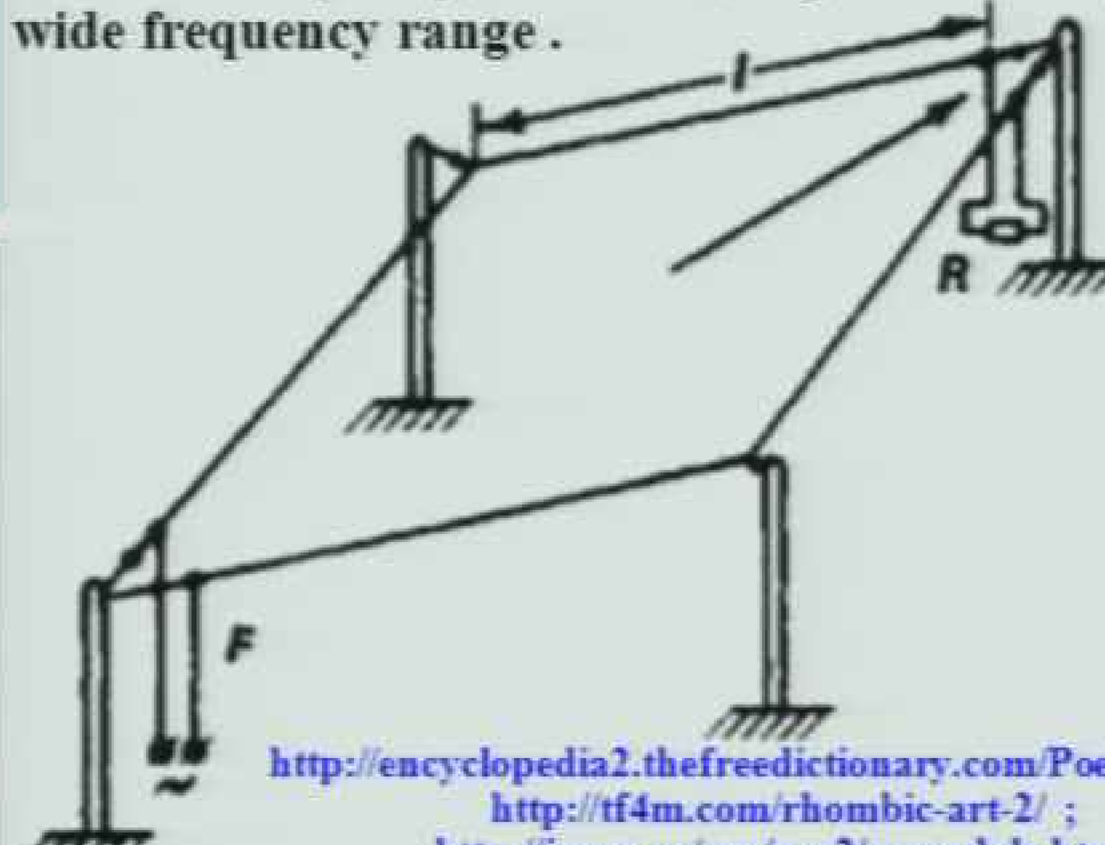

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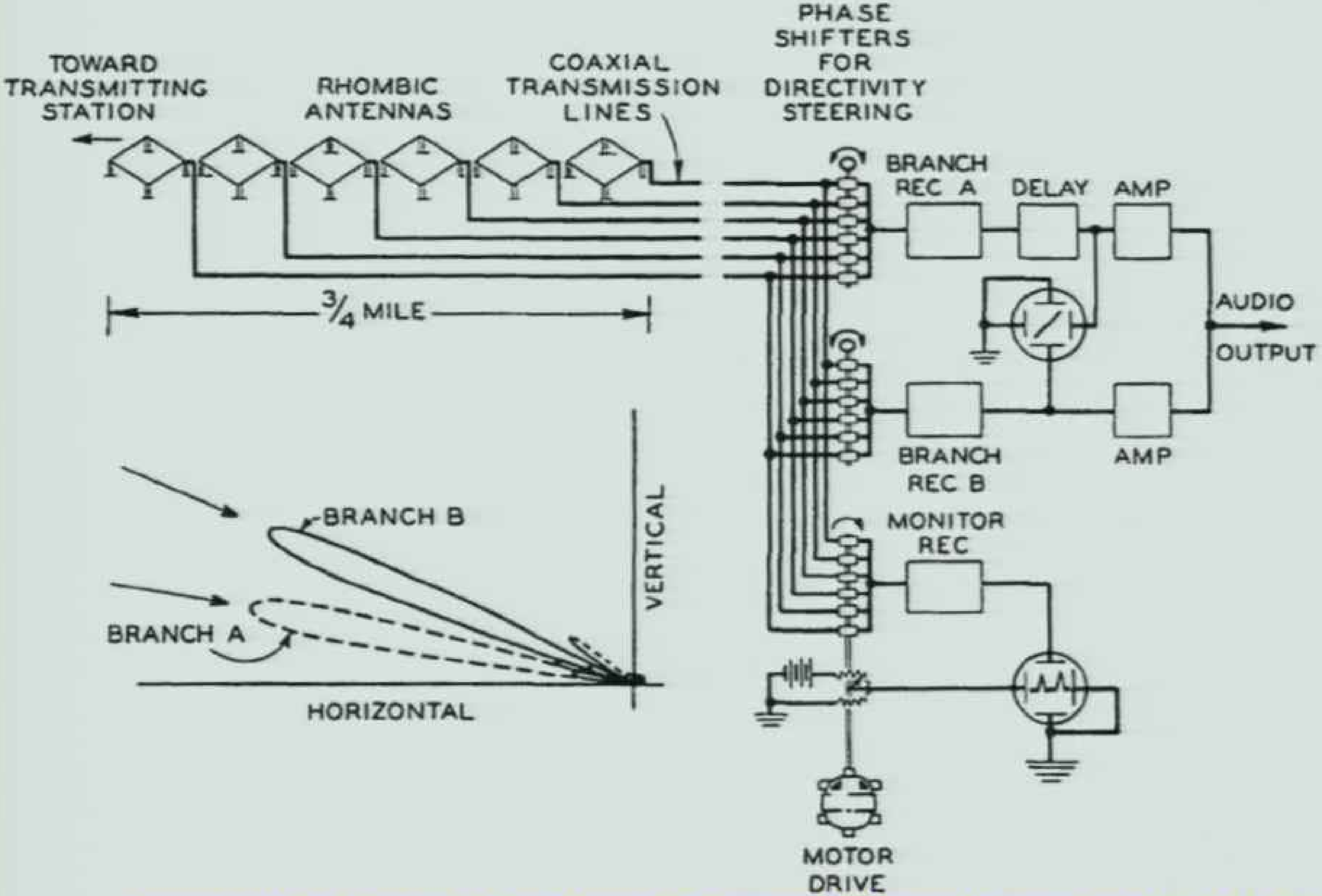
Bell Labs Experimental MUSA at Holmdel

Simplified Diagram



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

Bell Labs Experimental MUSA at Holmdel

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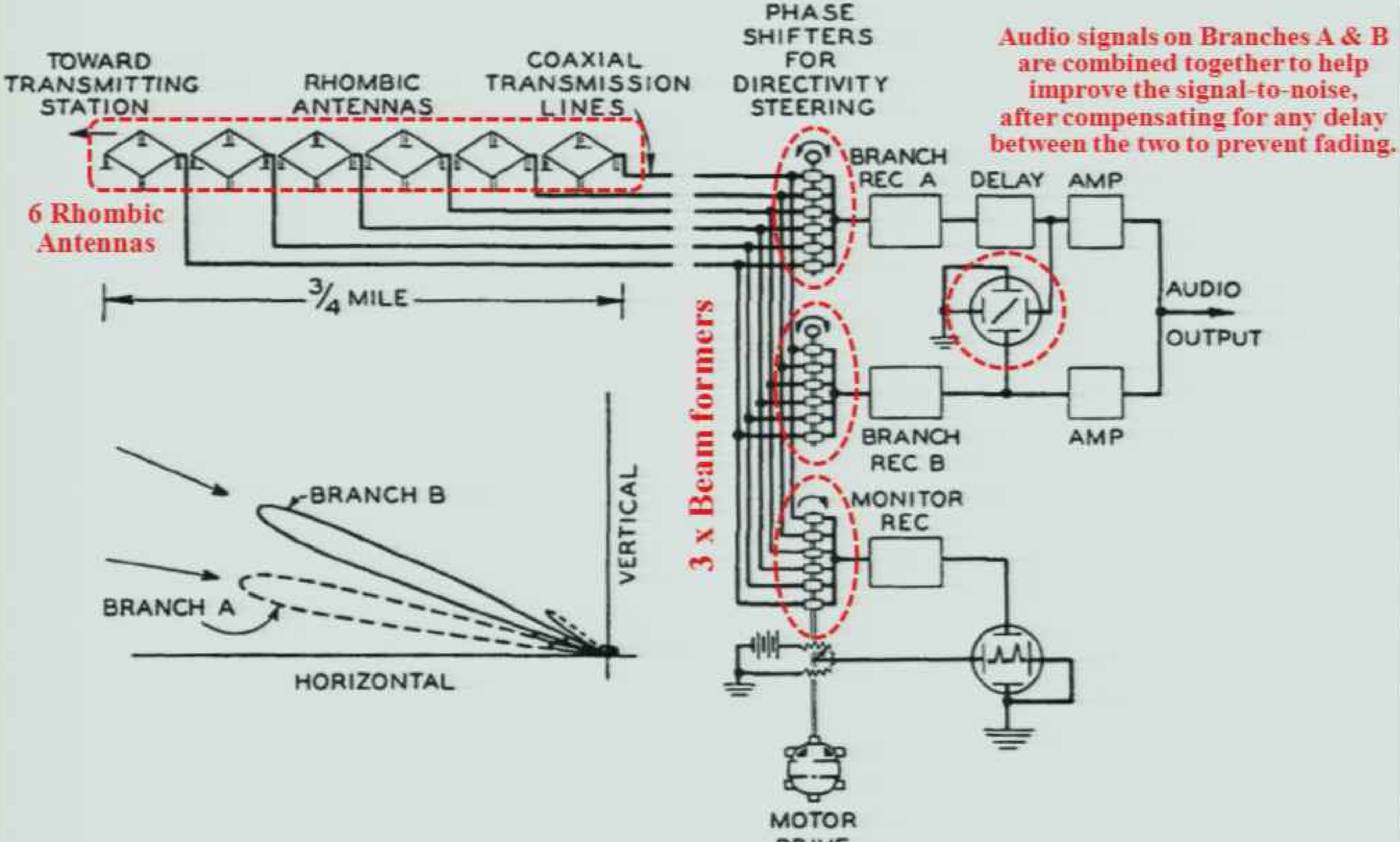

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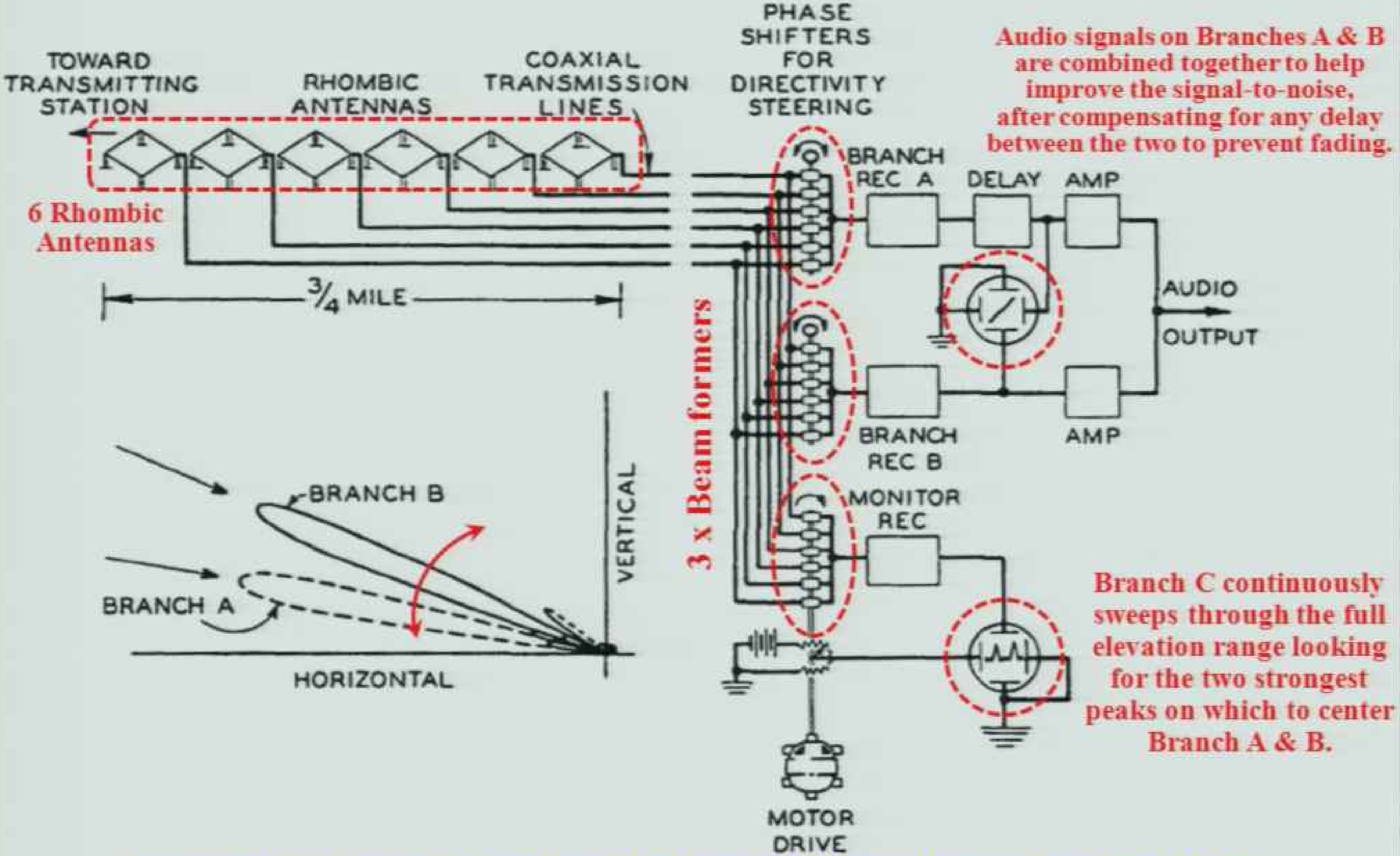

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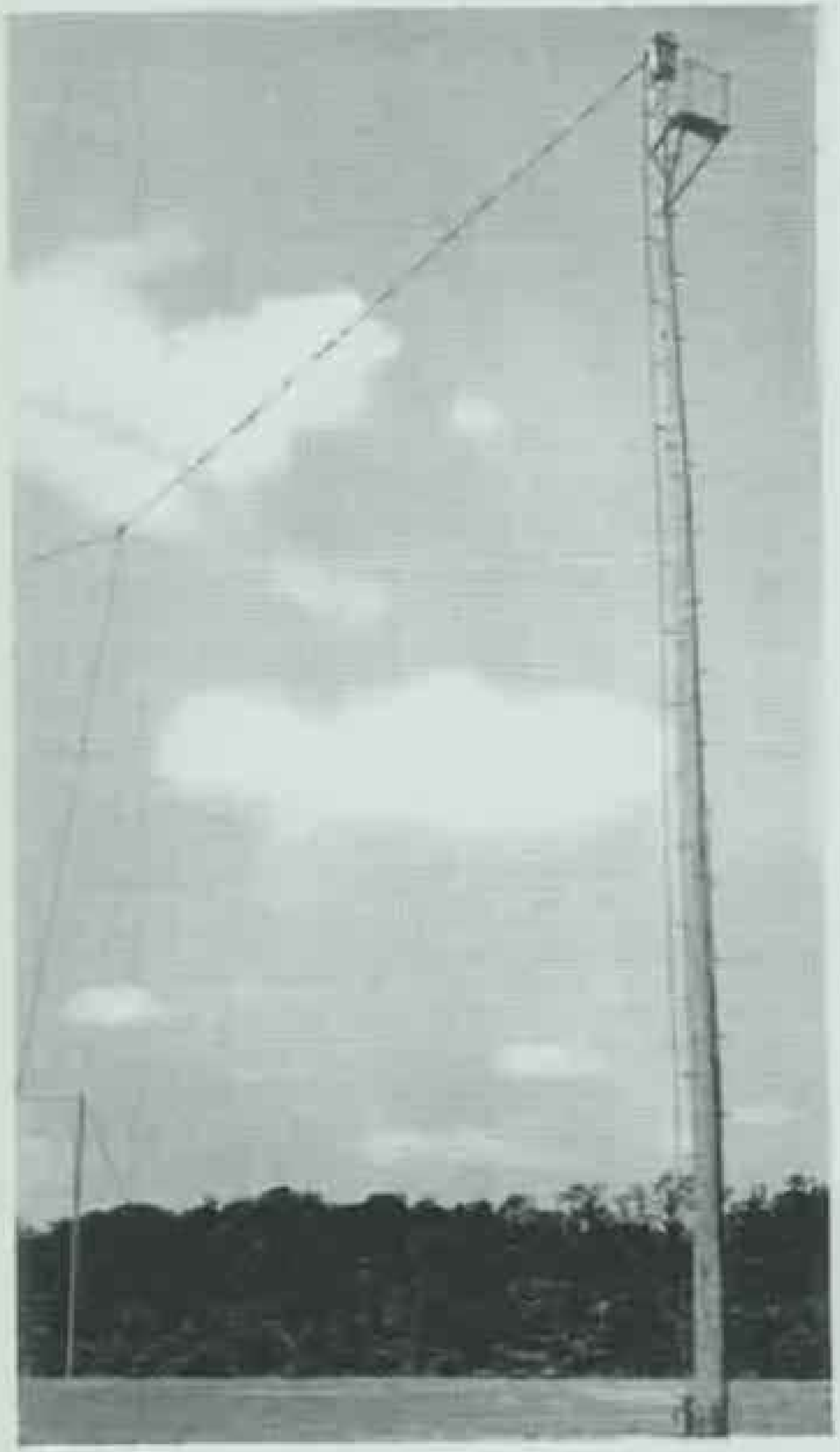


Fig. 4—At their output end each antenna is connected directly to a coupling unit, and at their termination end, the wires of each antenna are connected through three terminating resistances

MUSA from the Outside

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

MUSA from the Inside

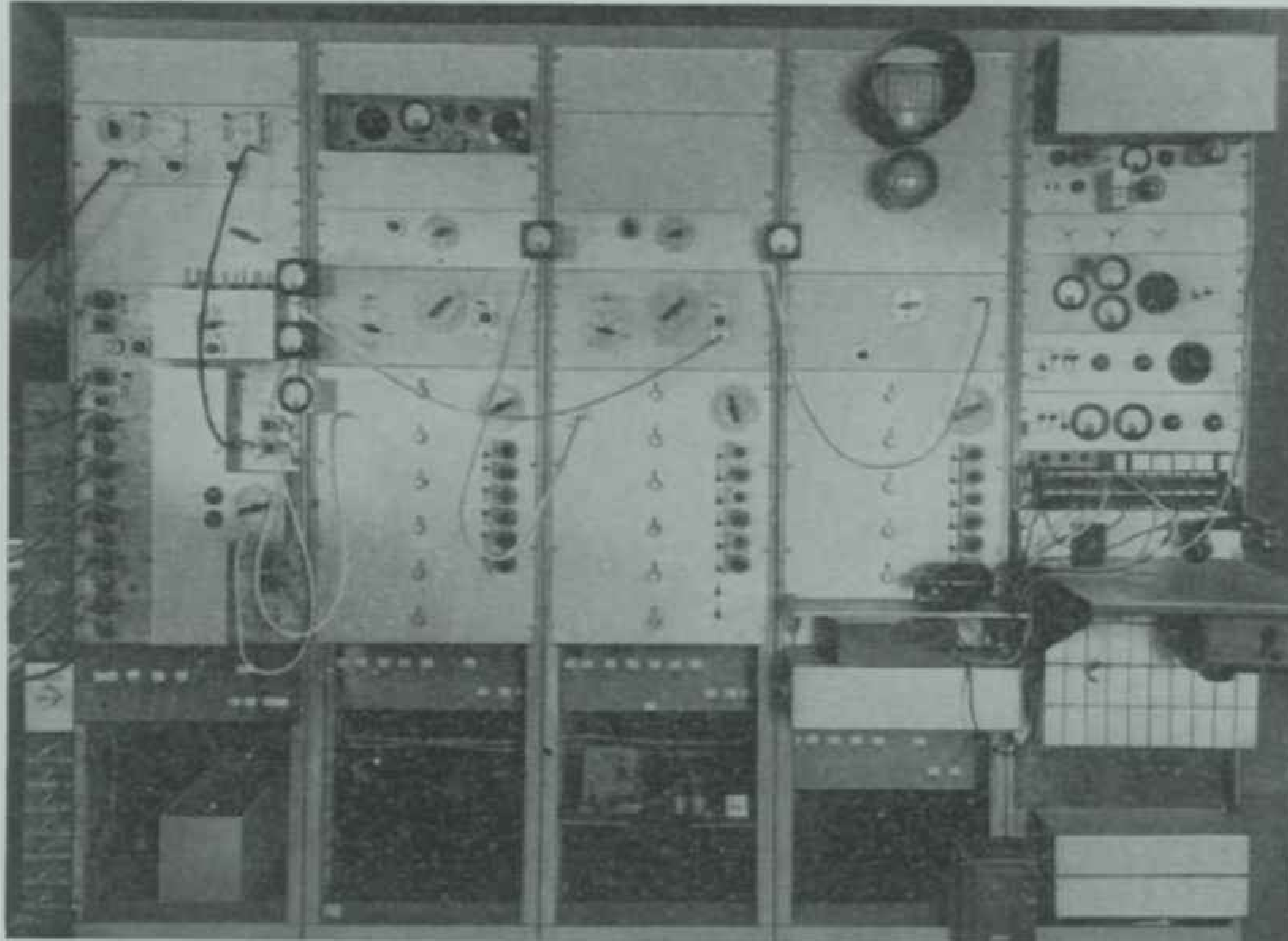
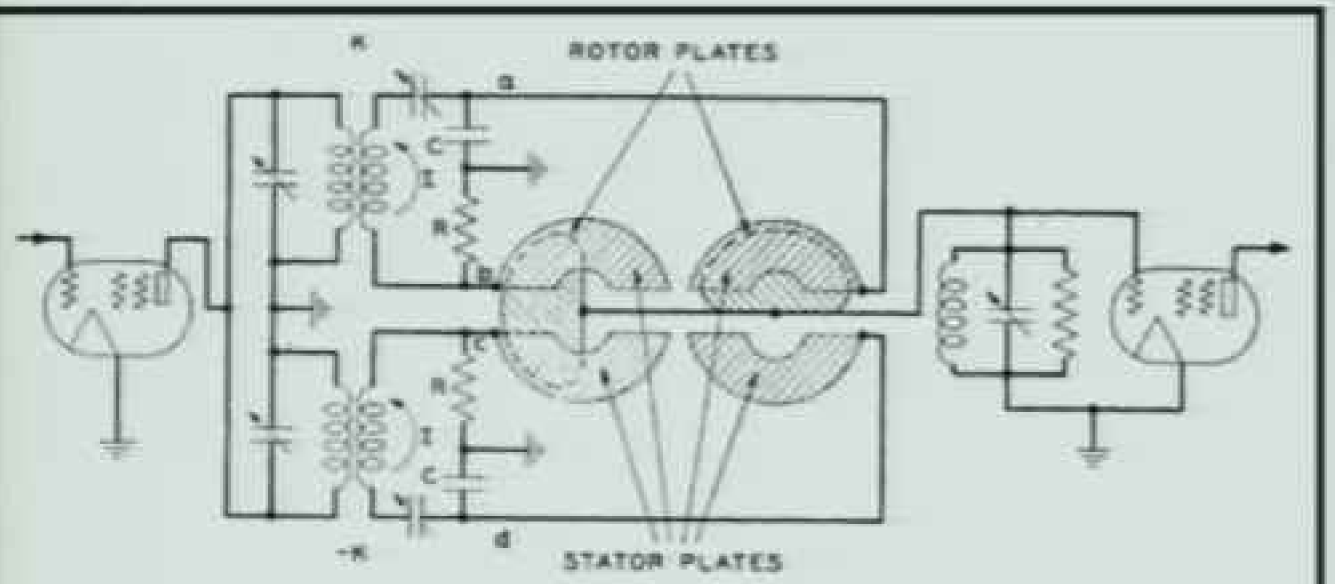


Fig. 16—Front view of the MUSA receiving equipment. The high-frequency bay is at the left and the audio-frequency bay at the right. The branch receivers are the panels directly above the phase shifting panels. The pulse receivers appear above these. At the top of the bay containing the monitoring branch 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



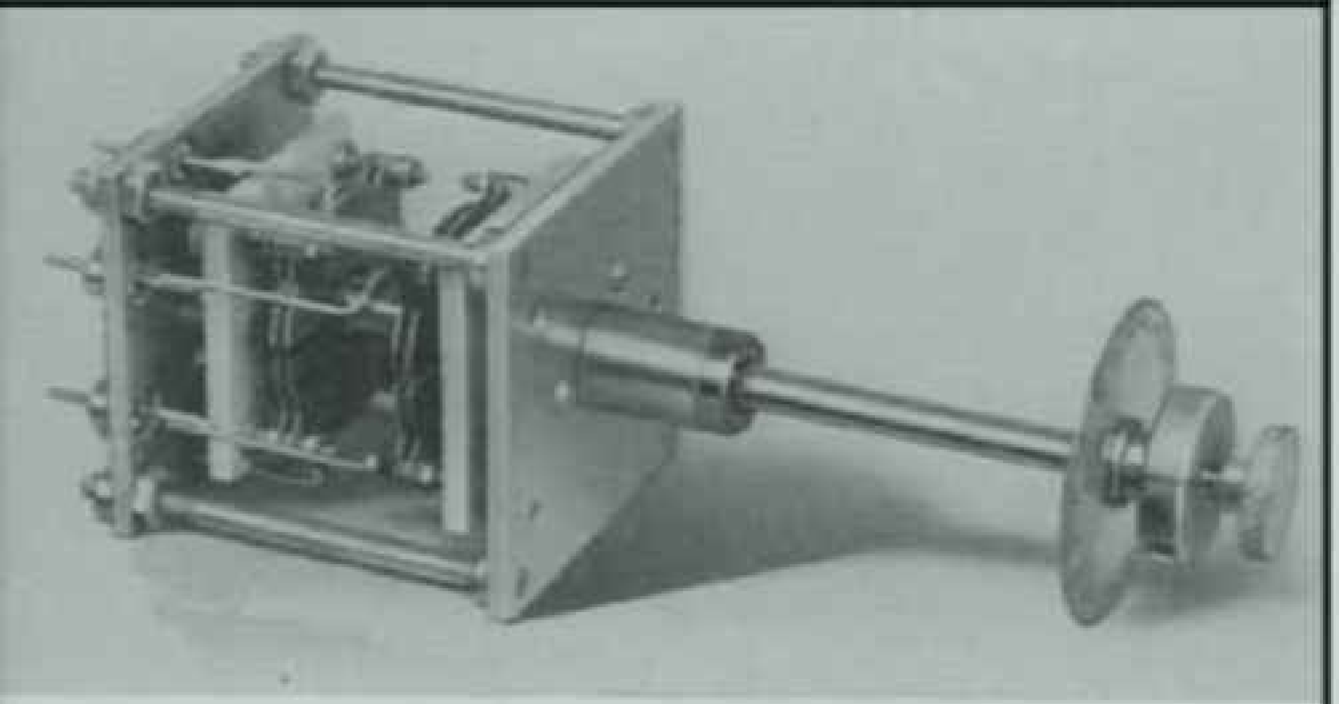


Fig. 14—The phase shifting condenser.

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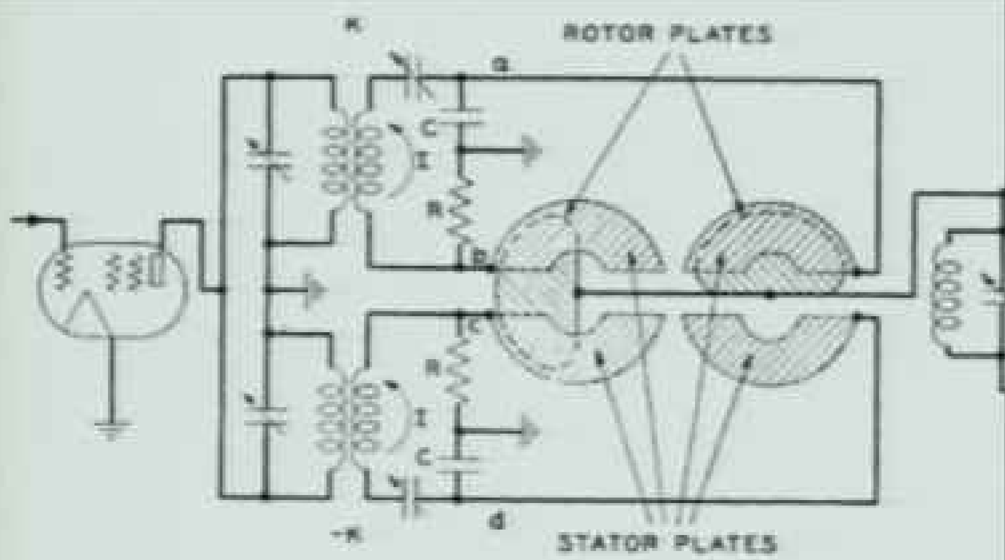

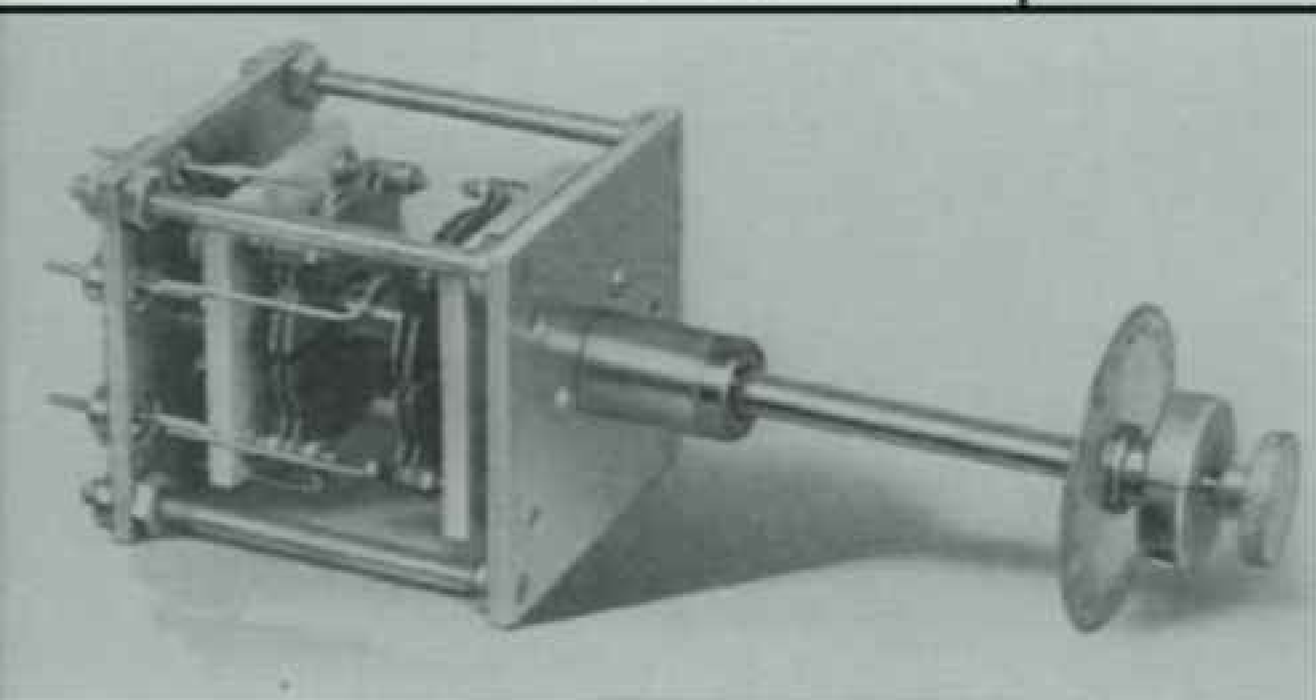

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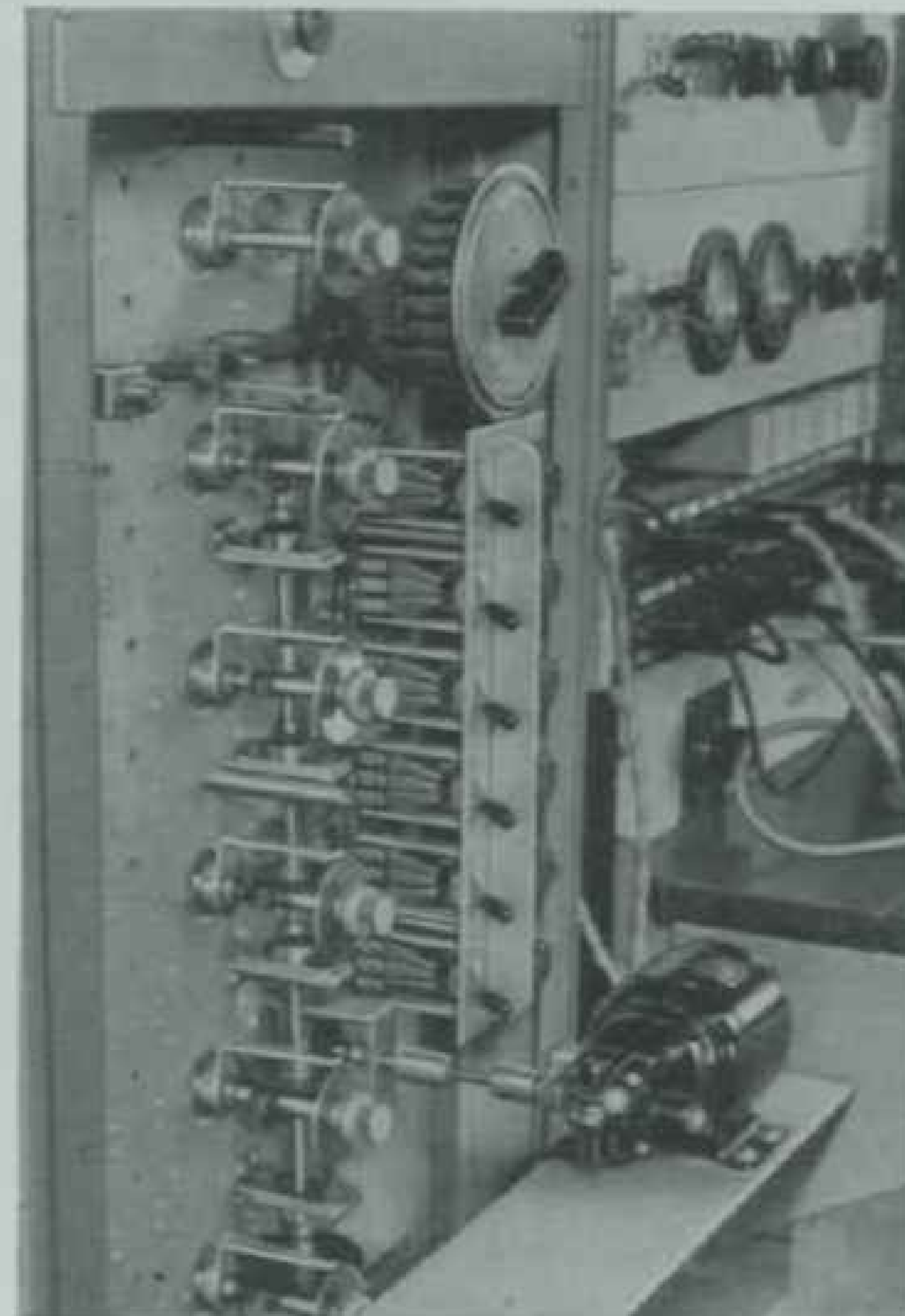

Fig. 15—Phase shifting panel of the monitoring branch. Only five of the six phase shifters are rotated for steering purposes. They are geared to the steering shaft in ratios of 1:1, 1:2, 1:3, 1:4, and 1:5.

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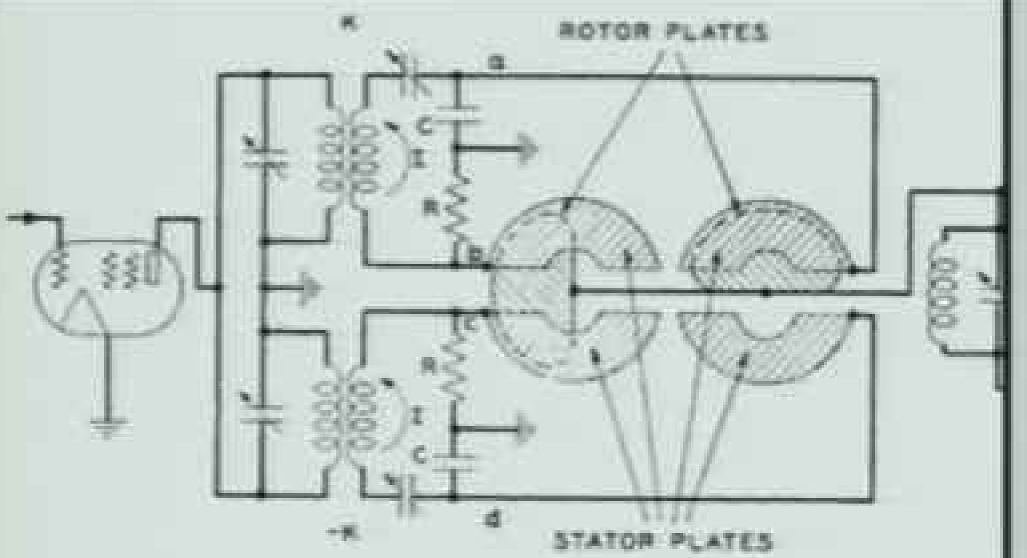

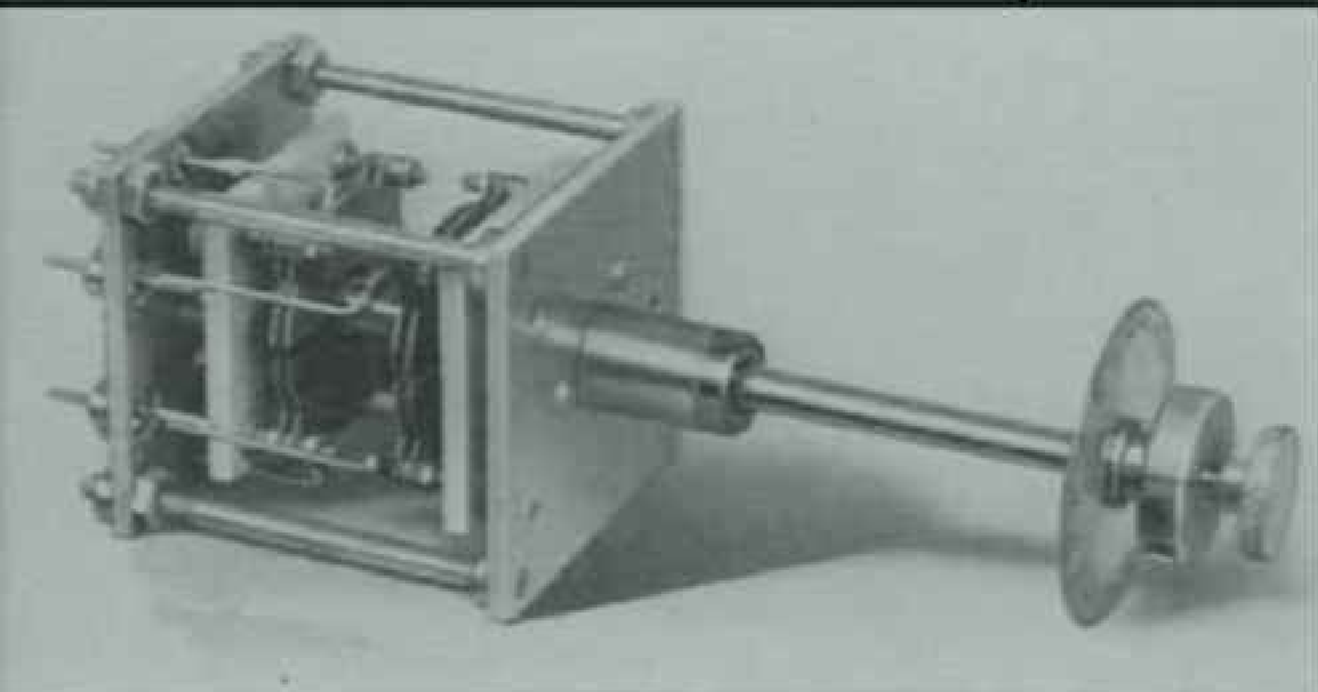

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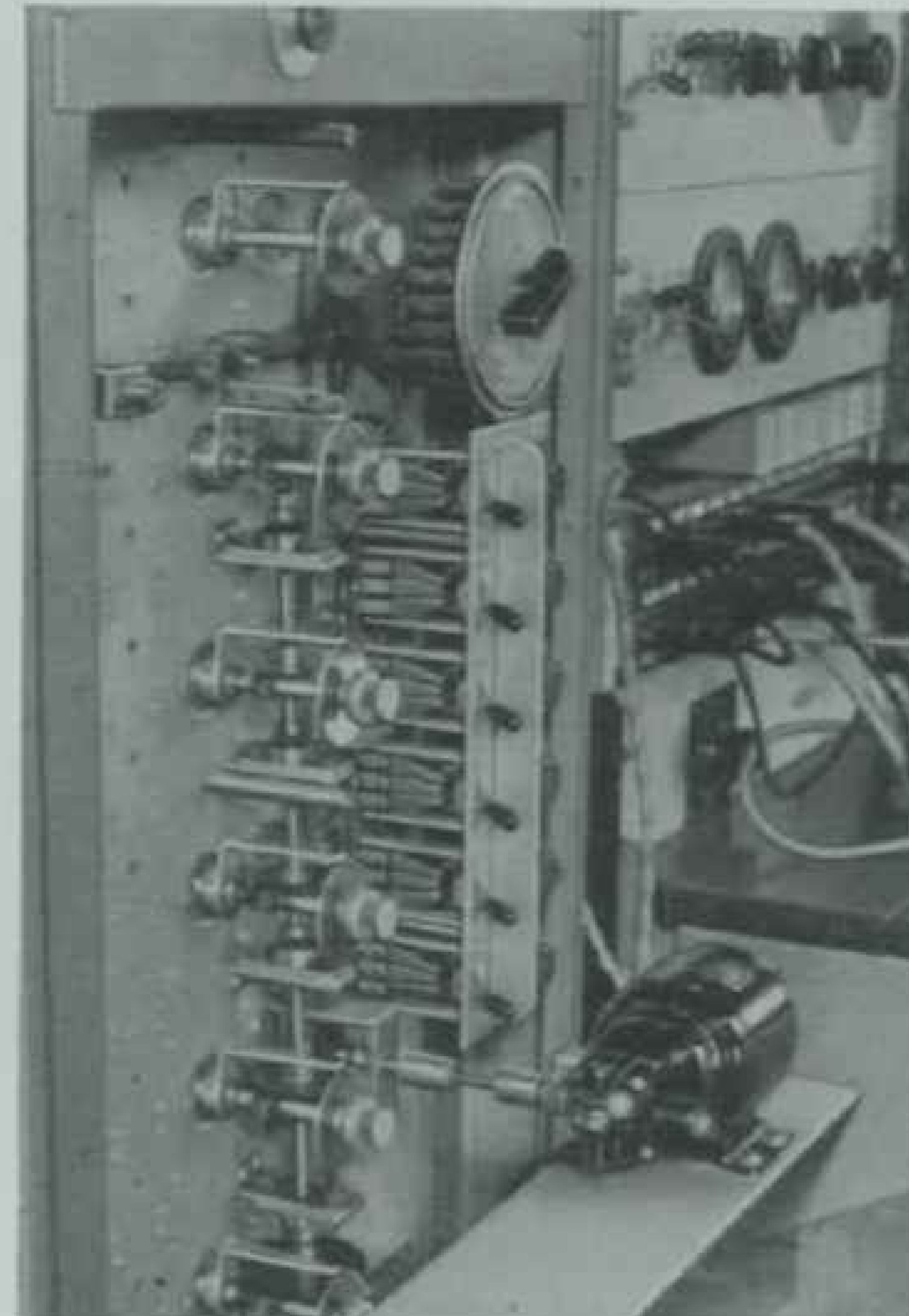

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MUSA Antenna Inputs & Rack Rear View

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.

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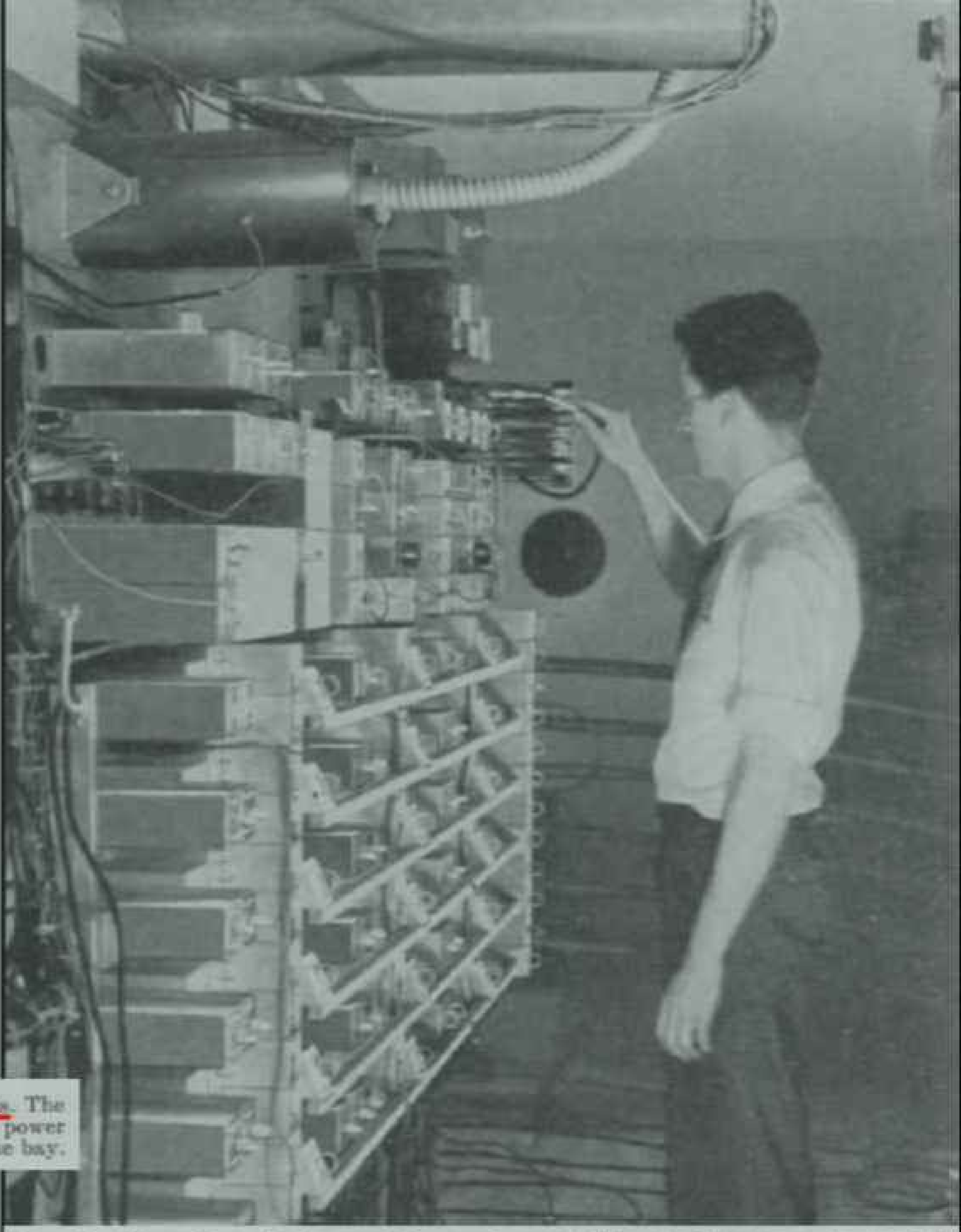

Fig. 18—Rear view of the receiving equipment. The six detector outputs feed the three branches via the square transmission lines.

A MULTIPLE UNIT STEERABLE ANTENNA FOR SHORT-WAVE RECEPTION*

Proceedings of the Institute of Radio Engineers
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(Bell Telephone Laboratories, Inc., New York City)

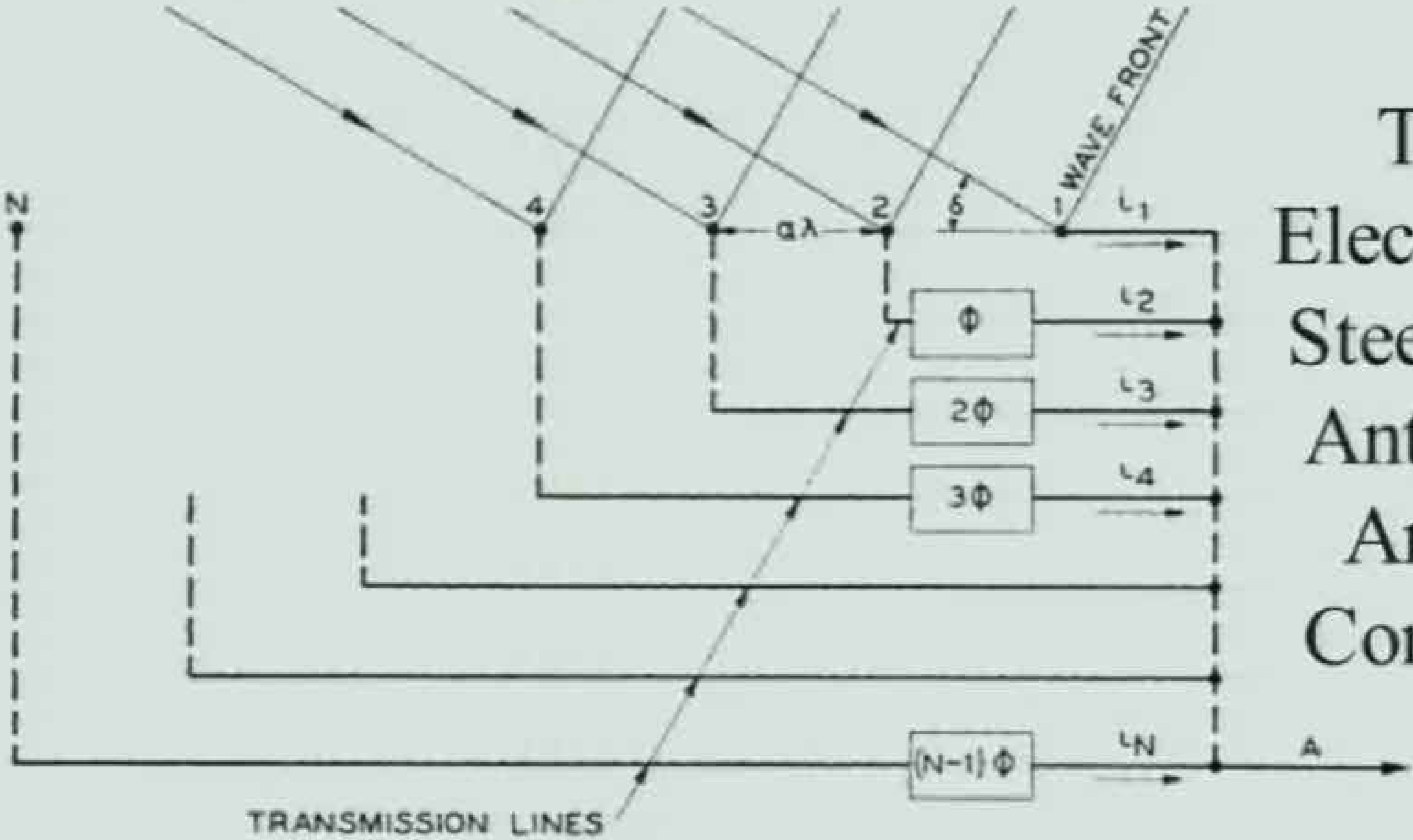

Fig. 1—A steerable antenna array using variable phase shifts ϕ, 2ϕ, 3ϕ, etc. The transmission lines indicated by broken lines are assumed to be of zero length. a is the spacing in free space wave lengths.

The Electronic Steerable Antenna Array Concept

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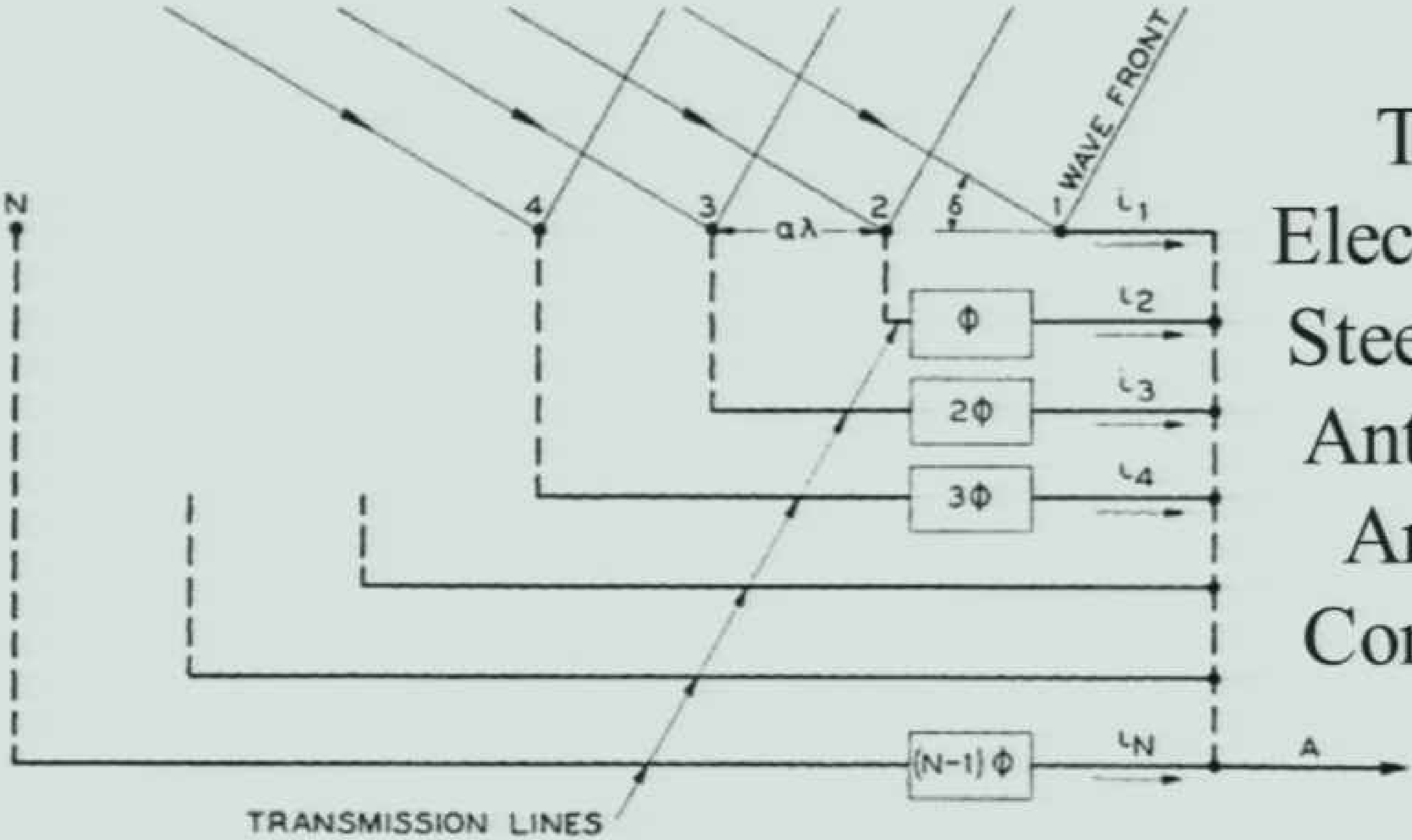

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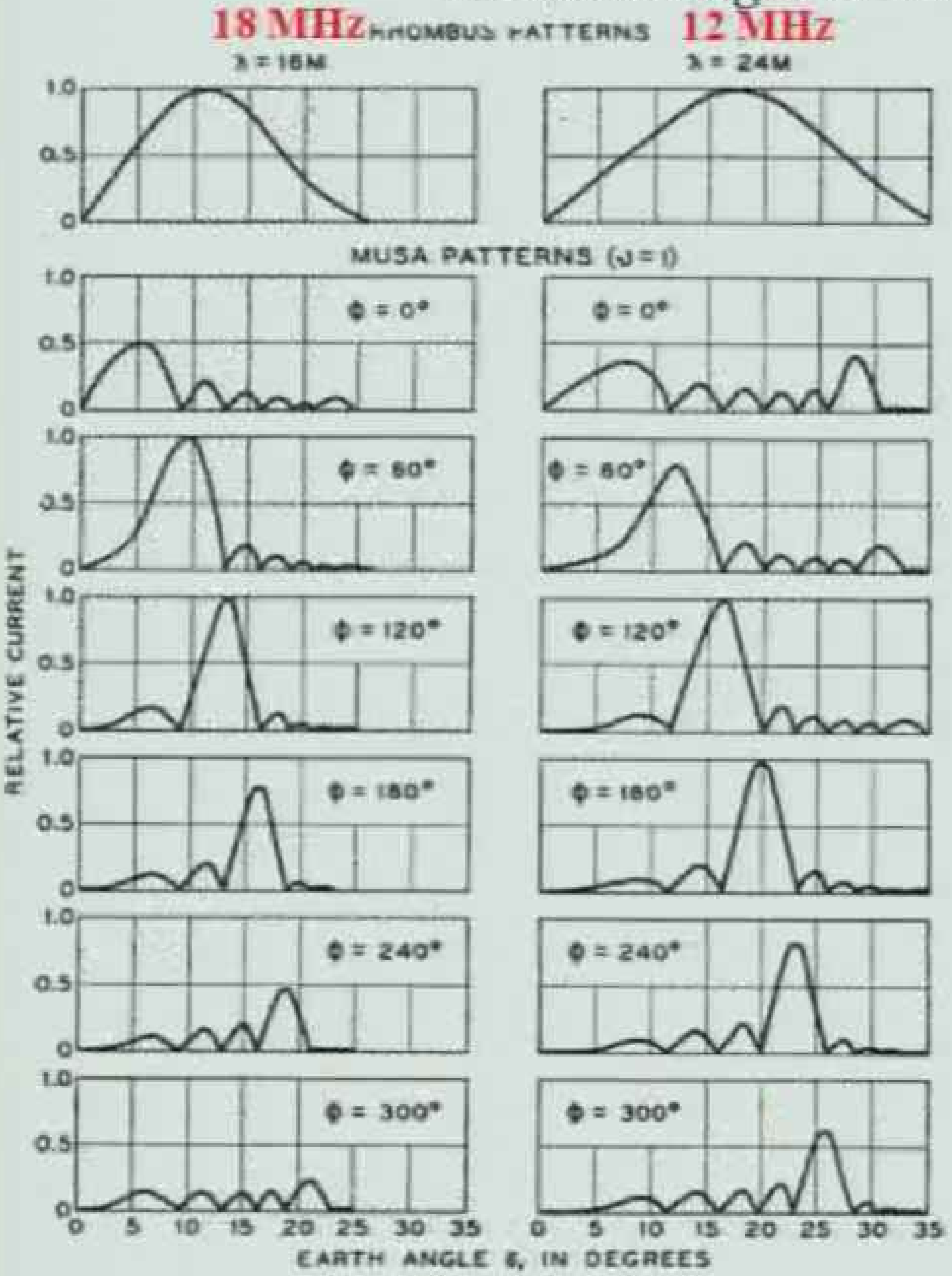
Vertical Directional Patterns of the Experimental MUSA

Elevation Angle vs. Wavelength & Phase Delay



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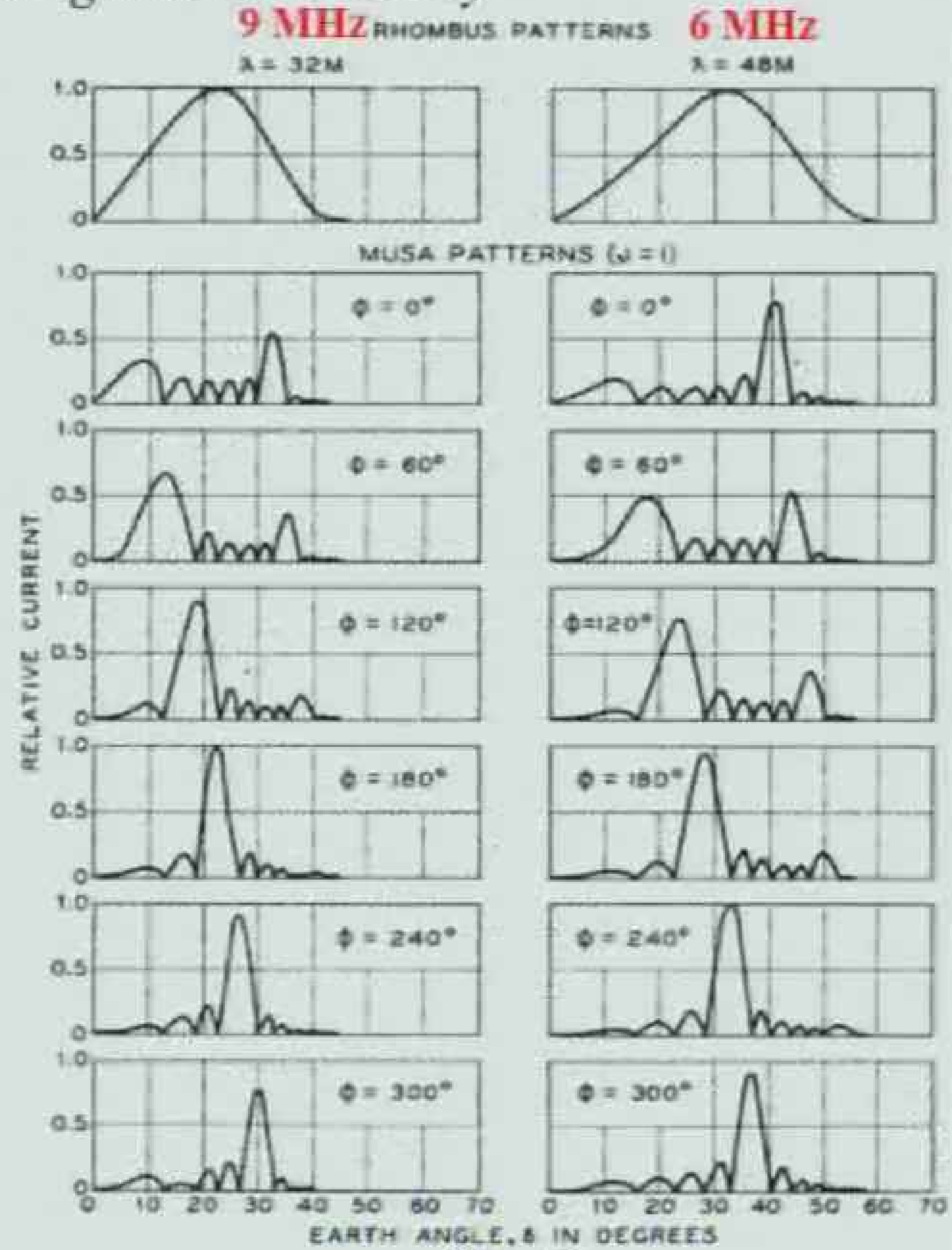

Fig. 20

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

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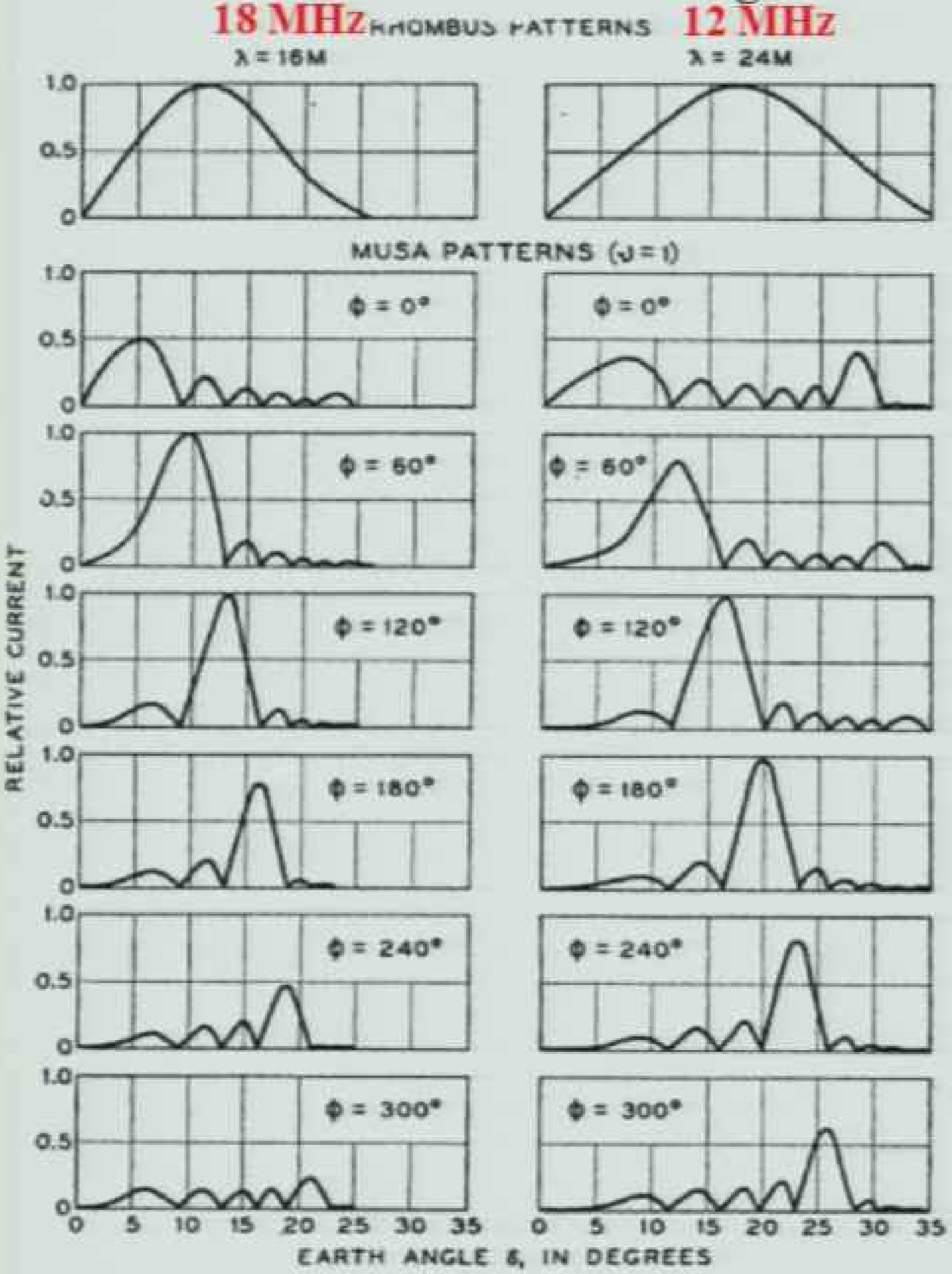

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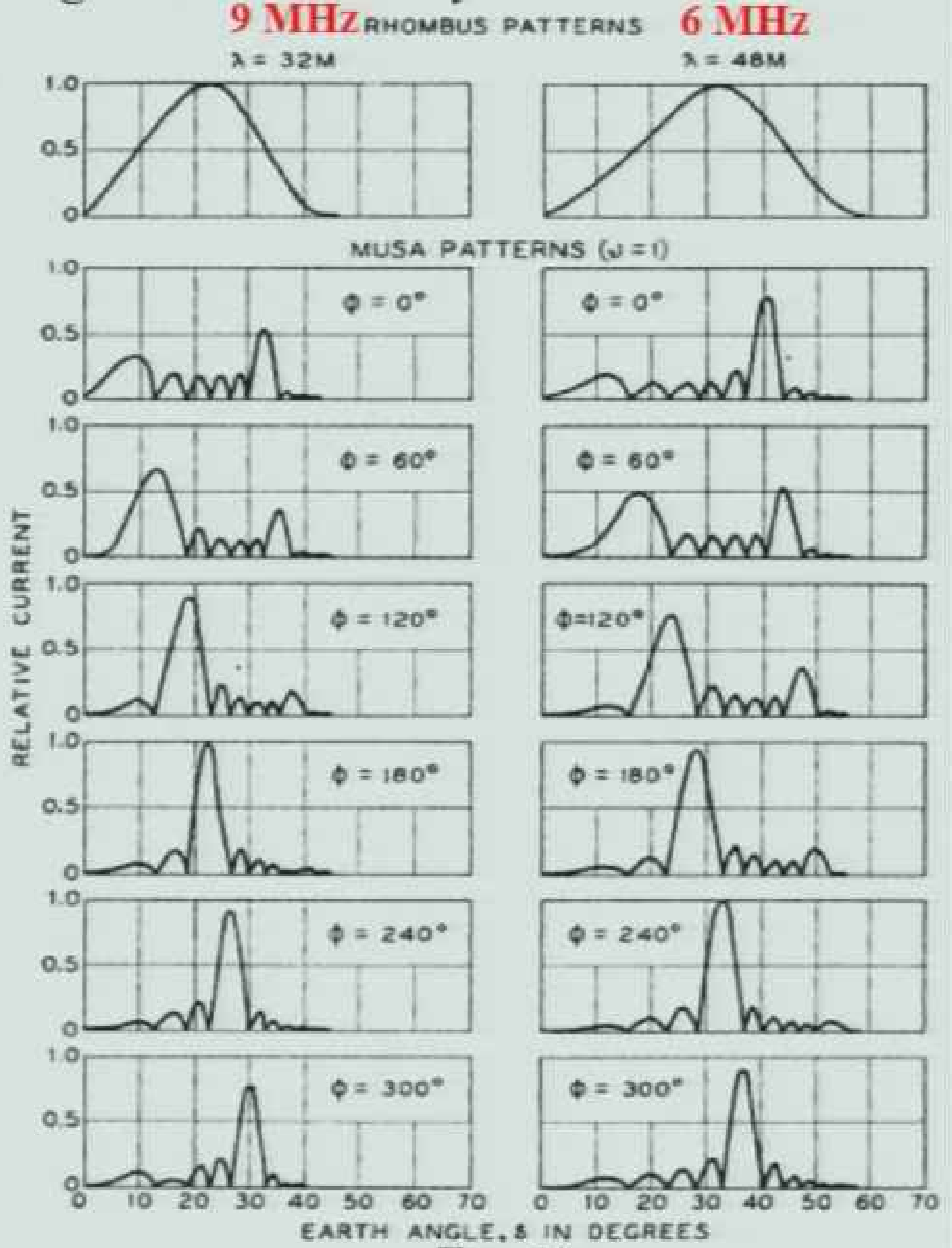

Fig. 20

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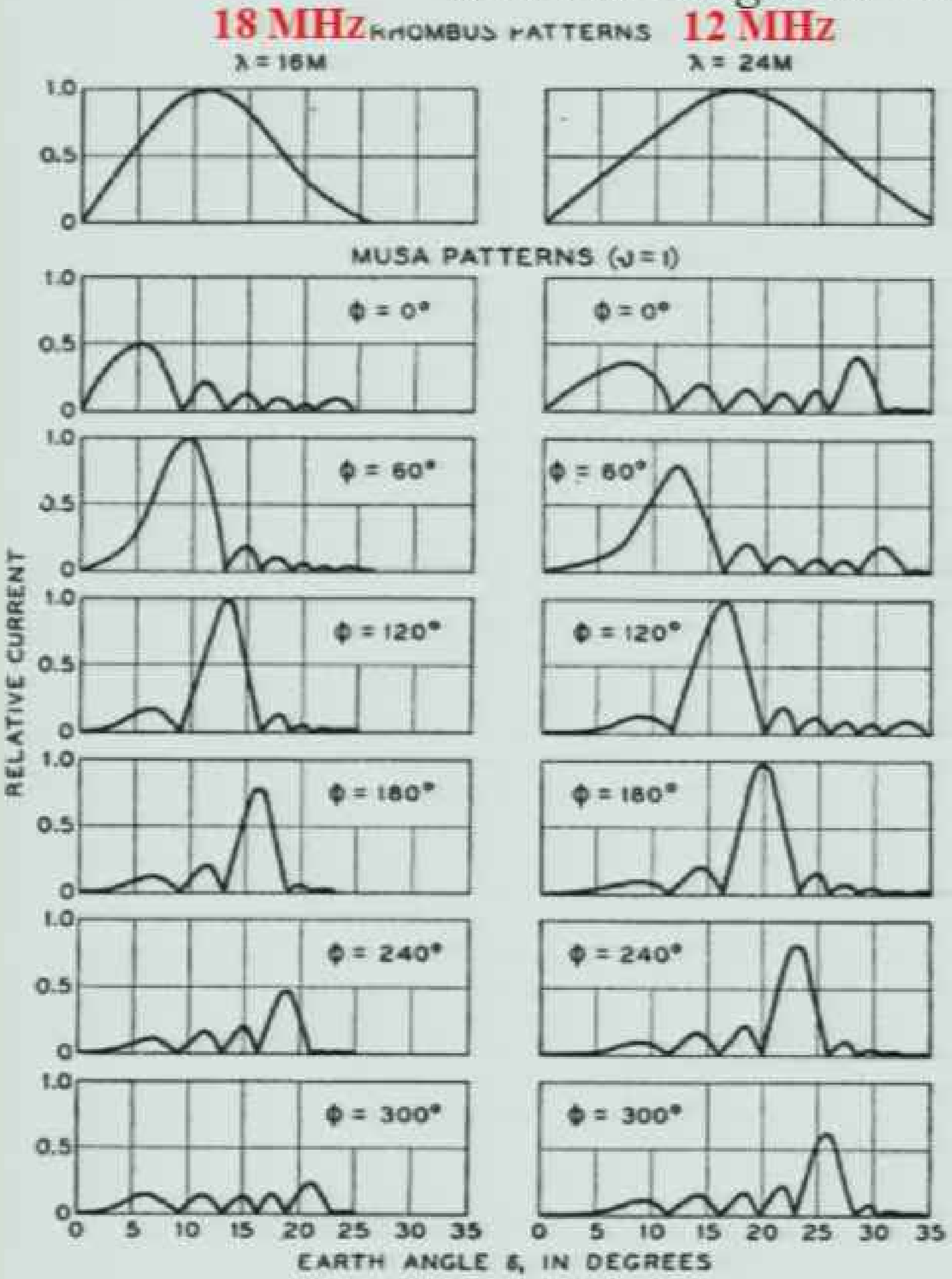

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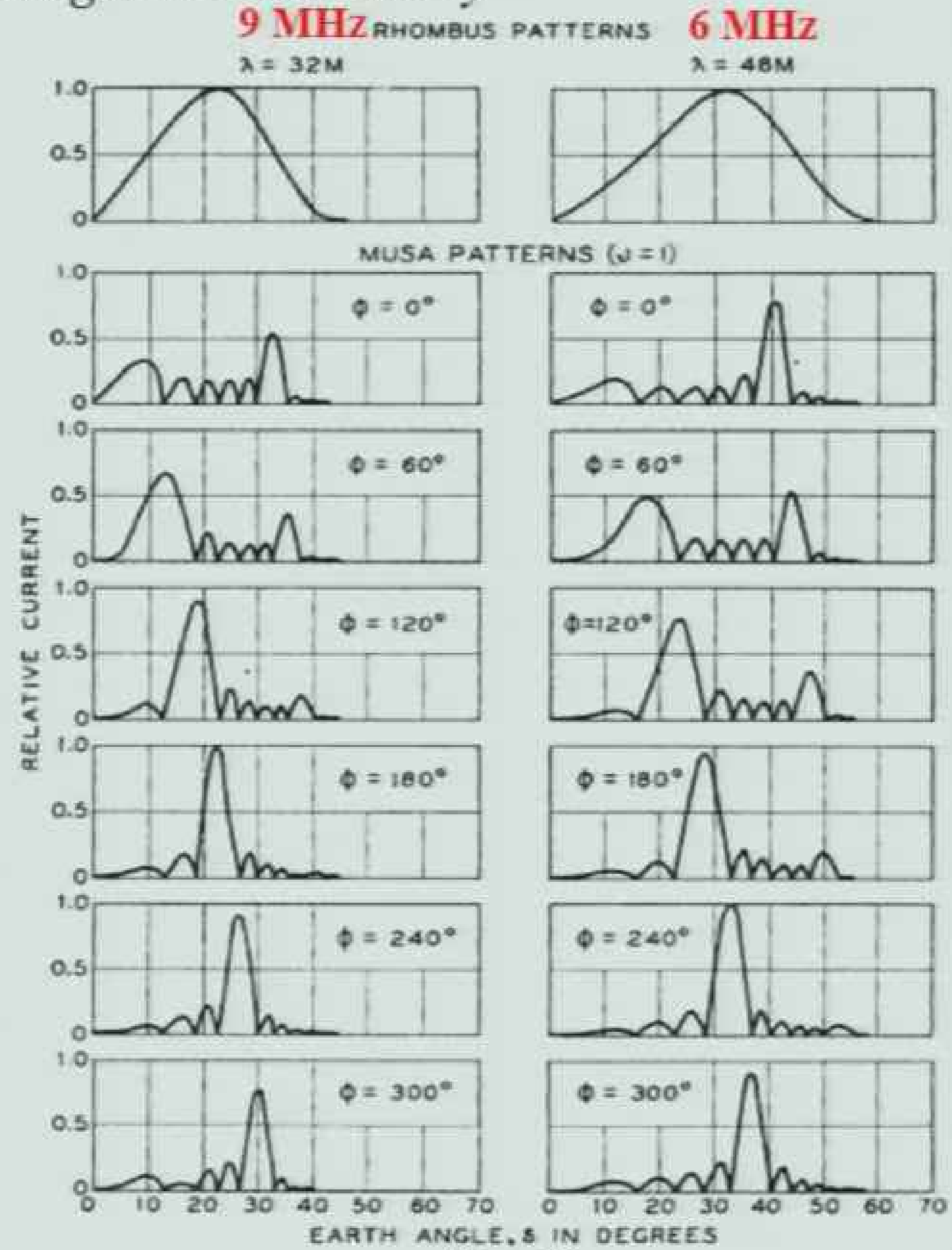

Fig. 20

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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.

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

1937

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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).

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Reference to Jansky's first paper in radio astronomy

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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		

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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…

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The Experimental MUSA and its Impact on Radio Astronomy.

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Grote Reber circa 1940.

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

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- 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.

Grote Reber circa 1940.

Reber's 1944 Radio Sky at 1.9m

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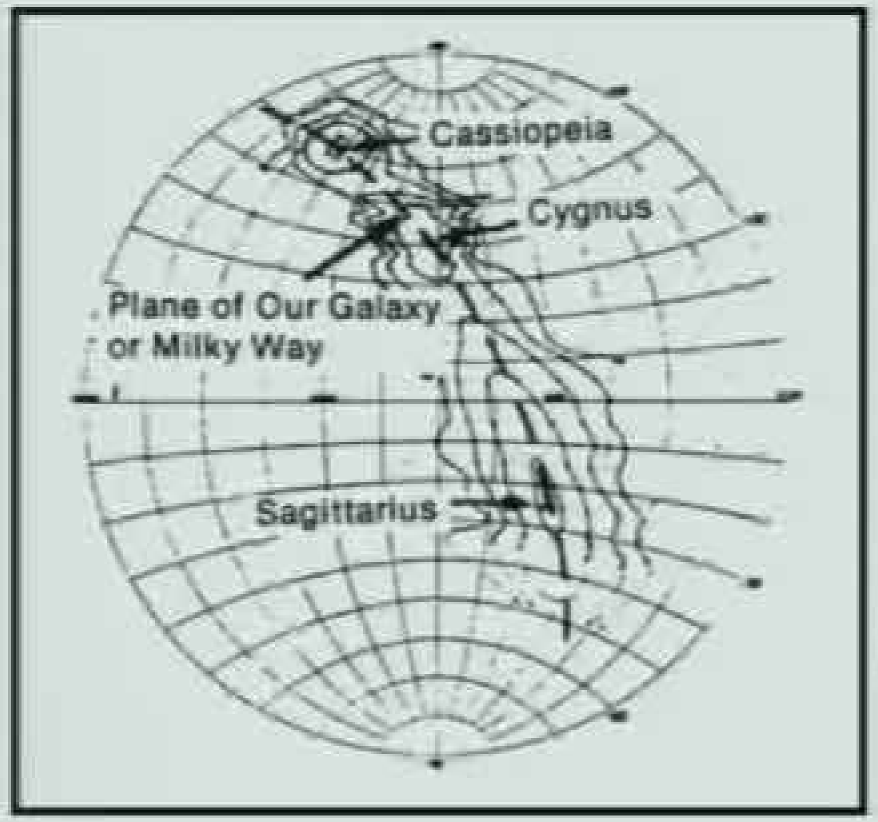
Grote Reber circa 1940.



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

Grote Reber & *Cosmic Static*

1939

- 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.
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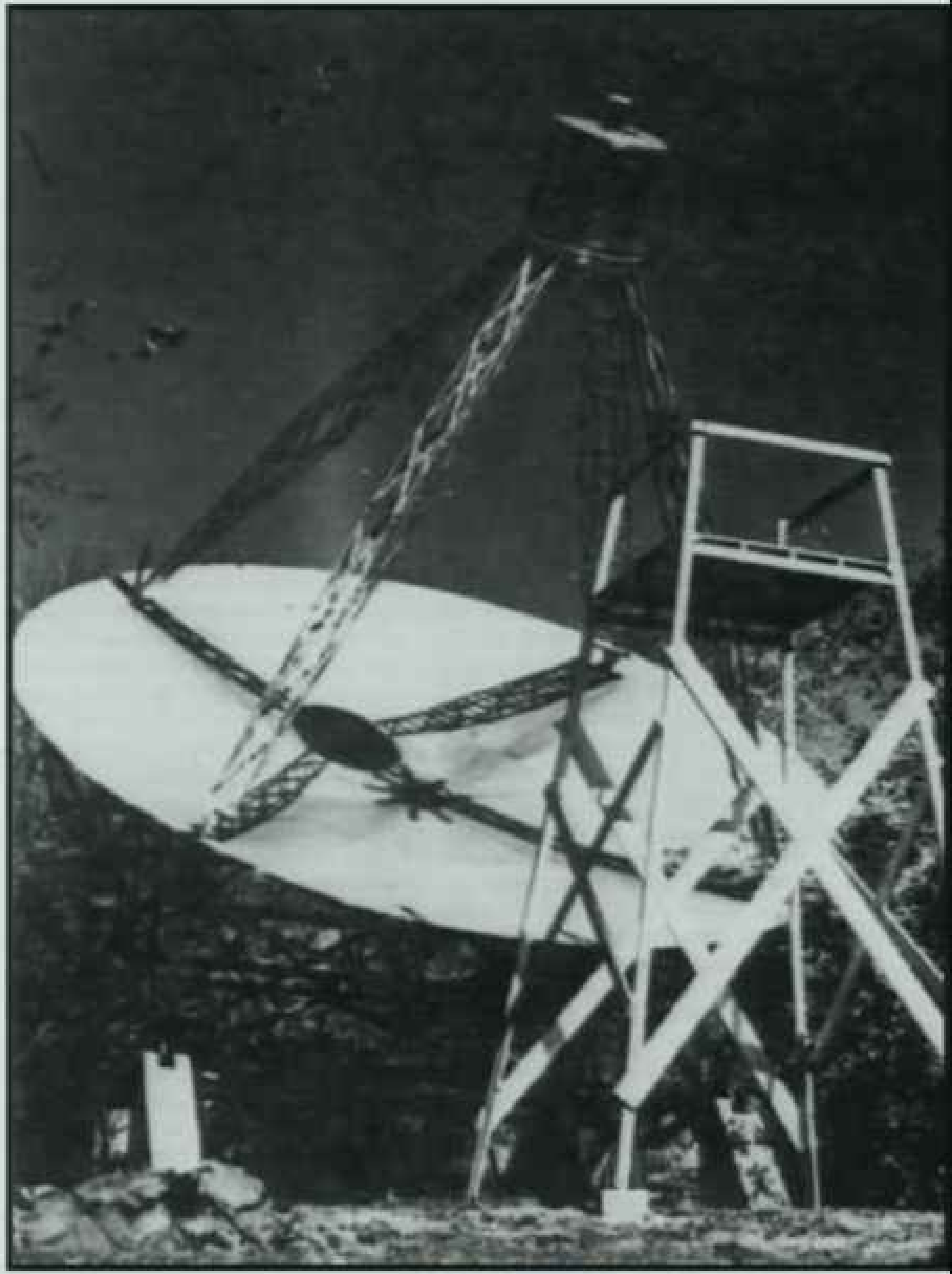

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- By 1941 he had purchased an automatic strip chart recorder.
- Reber is considered to be the *world's first radio astronomer*.

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References to the MUSA Detection in the Scientific Literature

1940a

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).

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CHARLES HARD TOWNES
Bell Telephone Laboratories, Murray Hill, N.J.
Received December 20, 1946

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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.

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[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.

Interpretation of Radio Radiation from the Milky Way,
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INTERPRETATION OF RADIO RADIATION FROM THE MILKY WAY

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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
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	160×10^{6}	1370	1370	1370
Hey, Philips, and Parsons	64×10^{6}	10,600	6000	9000
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* 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 $2T_r \times 10^{2.30} = 120{,}000°$. 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.

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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.

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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.

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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

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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_ν (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°.

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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.

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

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COMMUNICATIONS
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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.

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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=0·63/c.c. T=10,000 deg. K.	Maximum theoretical T_e assuming n=1·1/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 in 2000 at the age of 91.

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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).

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In 1973 he wrote, "*The Evolution of Radio Astronomy*" (the 1st book I ever read on the subject).
He retired in 1969 and died in 2000 at the age of 91.

REPORTS ON THE PROGRESS OF ASTRONOMY

1949

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

Freq

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.

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GALACTIC RADIATION AT RADIO FREQUENCIES 1950

III. GALACTIC STRUCTURE

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

[Manuscript received November 4, 1950]

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
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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.

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
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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.

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THE ORIGIN OF GALACTIC RADIO-FREQUENCY RADIATION

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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	$2{\cdot}4 \times 10^5$	...	...	0·161	1·34	...
Shain (17)	18·3	$2{\cdot}0 \times 10^5$	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 $1{\cdot}2 \times 10^5$ 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.

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

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.

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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
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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.

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The Distribution of Cosmic Radio Background Radiation*

1958

H. C. KO†, MEMBER, IRE

TABLE I

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Observers	Frequency (mc)	Antenna Beamwidth (deg)
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3. Higgins and Shain[3]	9.15	31° ×26°
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5. Shain and Higgins[5]	18.3	17° ×17°
6. Shain[6]	19.7	1.4°×1.4°
7. Fränz[7]	30	30° ×30°
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9. Cottony and Johler[9]	25–110	
10. Moxon[10]	40, 90, 200	35° ×70°
11. Sander[11]	60	20° ×30°
12. Hey, Parsons, and Phillips[12]	64	13° ×14°
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14. Mills[14]	85.7	0.8°×0.8°
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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.

The Distribution of Cosmic Radio Background Radiation, H.C. Ko, Proc. of the IRE, 1958
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19. Dröge and Priester[19]	200	16.8°×16.3°
20. Ko and Kraus[20]	250	1.2°×8°
21. Atanasijevic[21]	255	10° ×10°
22. McGee, Slee, and Stanley[22]	400	2° ×2°
23. Seeger, Westerhout, and van de Hulst[23]	400	2° ×2°
24. Reber[24]	480	4° ×4°
25. Piddington and Trent[25]	600	3.3°×3.3°
26. Denisse, Leroux, and Steinberg[26]	910	3.5°×3.5°
27. Westerhout[27]	1360	1.9°×2.8°

Freq

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The Distribution of Cosmic Radio Background Radiation, H.C. Ko, Proc. of the IRE, 1958
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The Distribution of Cosmic Radio Background Radiation*

1958

H. C. KO†, MEMBER, IRE

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2. Friis and Feldman[2]	US-BTL MUSA'37	9.5, 18.6	16° ×4°, 11°×3°
3. Higgins and Shain[3]		9.15	31° ×26°
4. Jansky[4]	US-BTL 1933	20.5	30° ×37°
5. Shain and Higgins[5]		18.3	17° ×17°
6. Shain[6]		19.7	1.4°×1.4°
7. Fränz[7]		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]		40, 90, 200	35° ×70°
11. Sander[11]		60	20° ×30°
12. Hey, Parsons, and Phillips[12]		64	13° ×14°
13. Baldwin[13]		81	2° ×15°
14. Mills[14]		85.7	0.8°×0.8°
15. Bolton and Westfold[15]		100	17° ×17°
16. Hanbury Brown and Hazard[16]		158.5	2° ×2°
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7. Fränz[7]	France 1942	30	30° ×30°
8. Herbstreit and Johler[8]		25–110	
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10. Moxon[10]		40, 90, 200	35° ×70°
11. Sander[11]		60	20° ×30°
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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°
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In 1956, the 25m radio telescope at Stockert, Germany, was the world's largest →

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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.

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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

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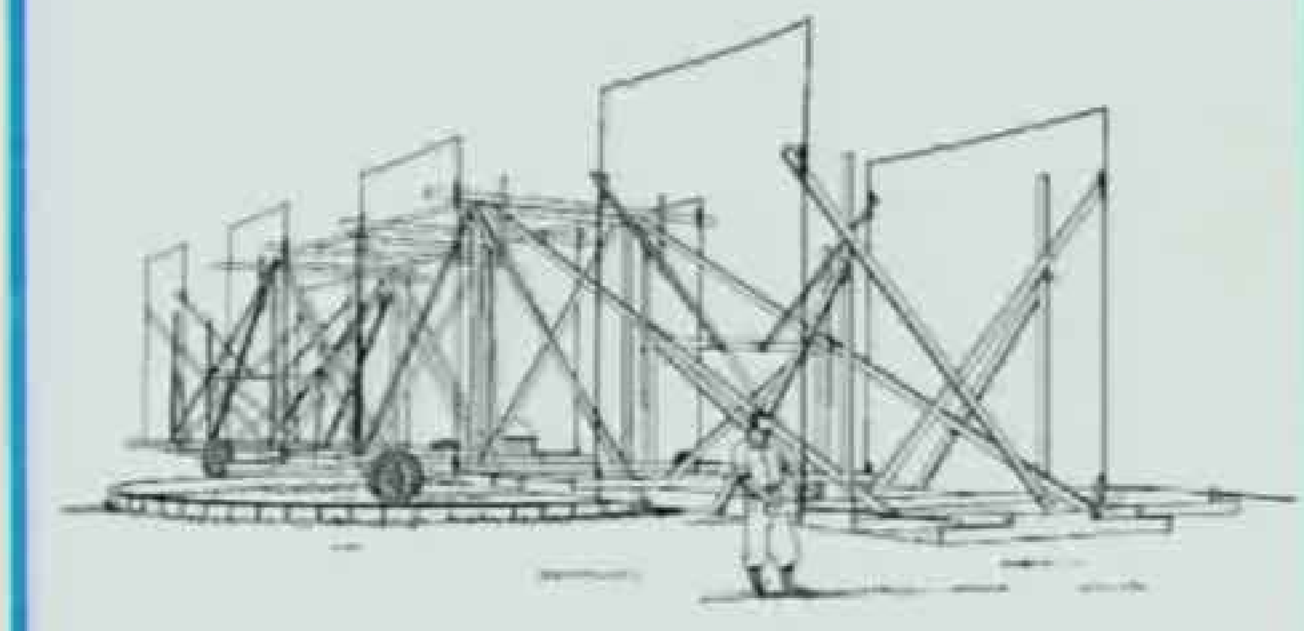
SERENDIPITOUS DISCOVERIES IN RADIO ASTRONOMY

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



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

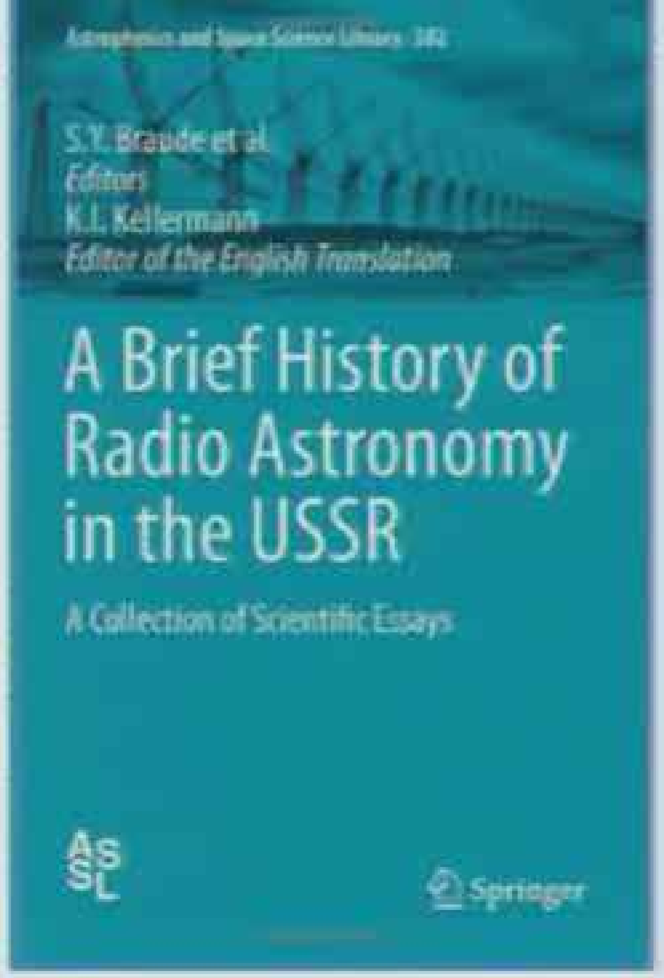
Following Karl Jansky's reports of meter-wavelength radiation from the Galaxy (Jansky 1933), only a few scattered attempts were made to confirm or extend these remarkable results (Potapenko & Folland 1936; Friis & Feldman 1937) or to understand their implication for astronomy and astrophysics (Langer 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

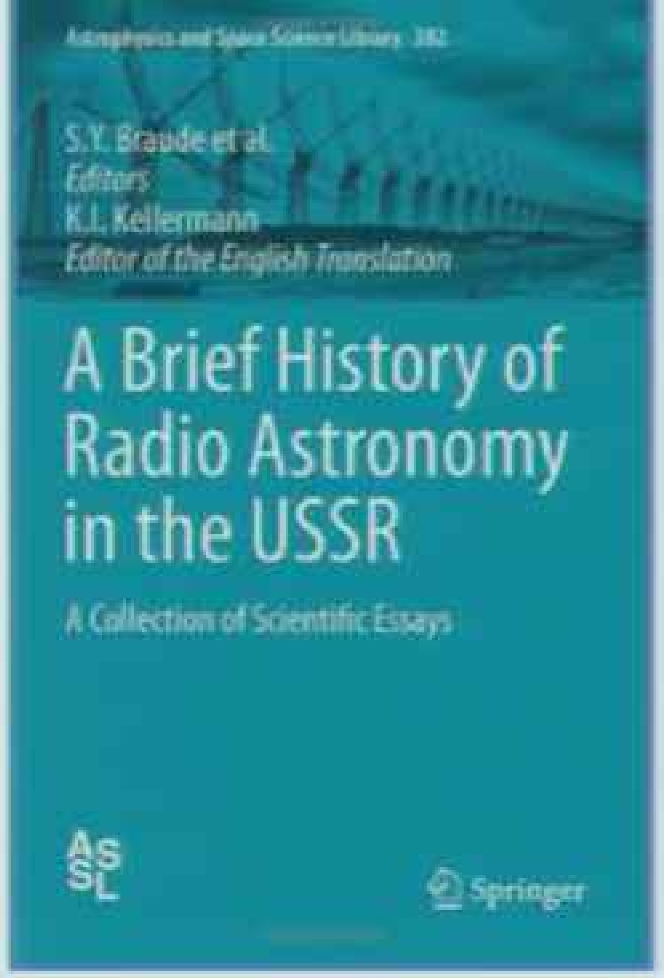
Radio astronomy research at the Institute of Radio Physics and Electronics of the Academy of Sciences of the Ukrainian SSR (IRFE) began with studies of the propagation of radio waves with various wavelengths (from Very High Frequency to medium-wave) above the interface between two media and in a plasma. 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.

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**

MUSA & the USSR

2012



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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**

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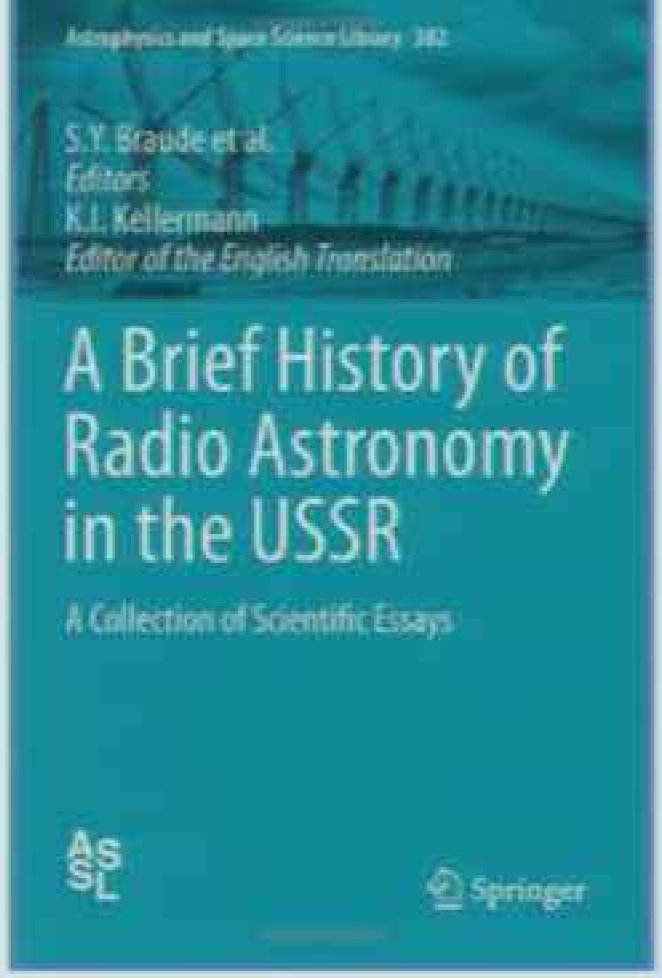

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Radio-oceonographic studies required directive antennas to radiate signals and then receive the scattered signals from particular areas of the sea surface, with the possibility of rapidly changing the direction of the antenna beam in space. In contrast 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.

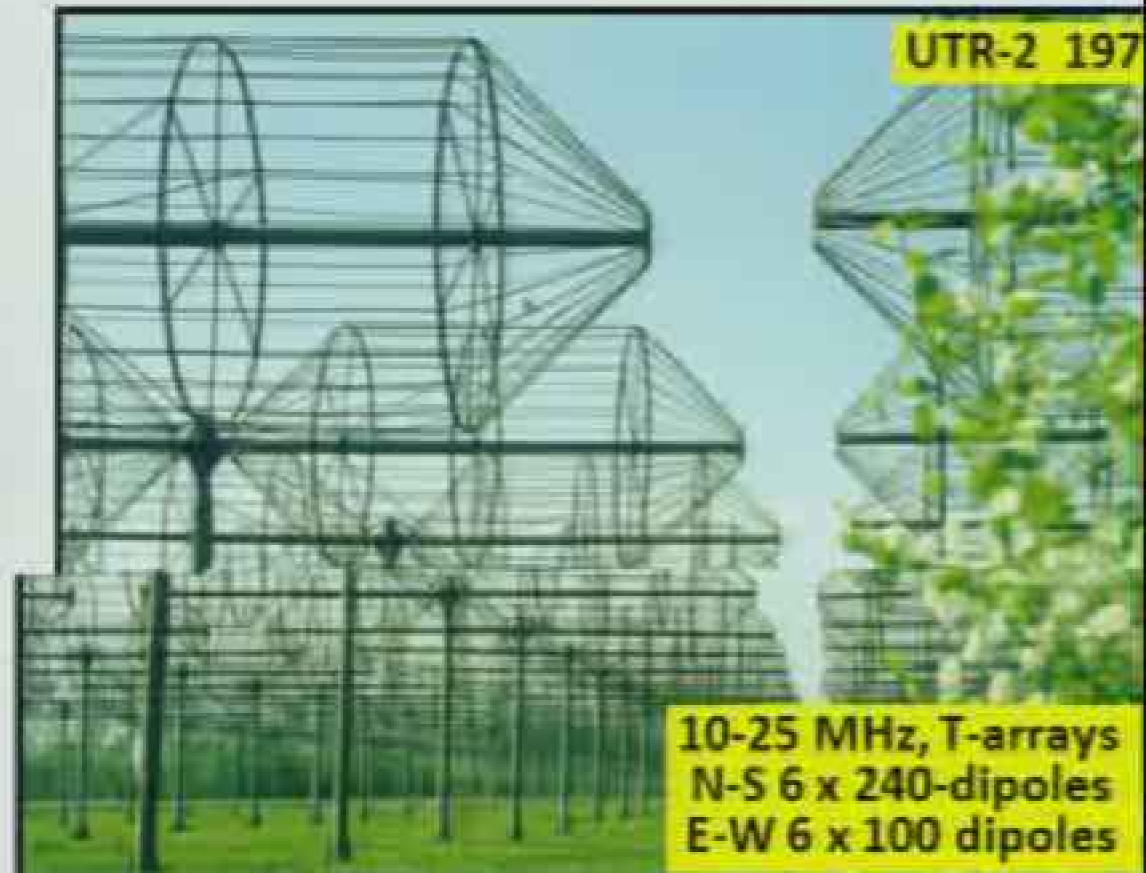
***The Development of Radio Astronomy Research at the Institute of Radio Physics and Electronics of the Academy of Sciences of the Ukrainian SSR*, S. Y. Braude & A. V. Megn, in *A Brief History of Radio Astronomy in the USSR*, Edited by S. Y. Braude et. al., Springer, 2012, p.182**

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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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.*

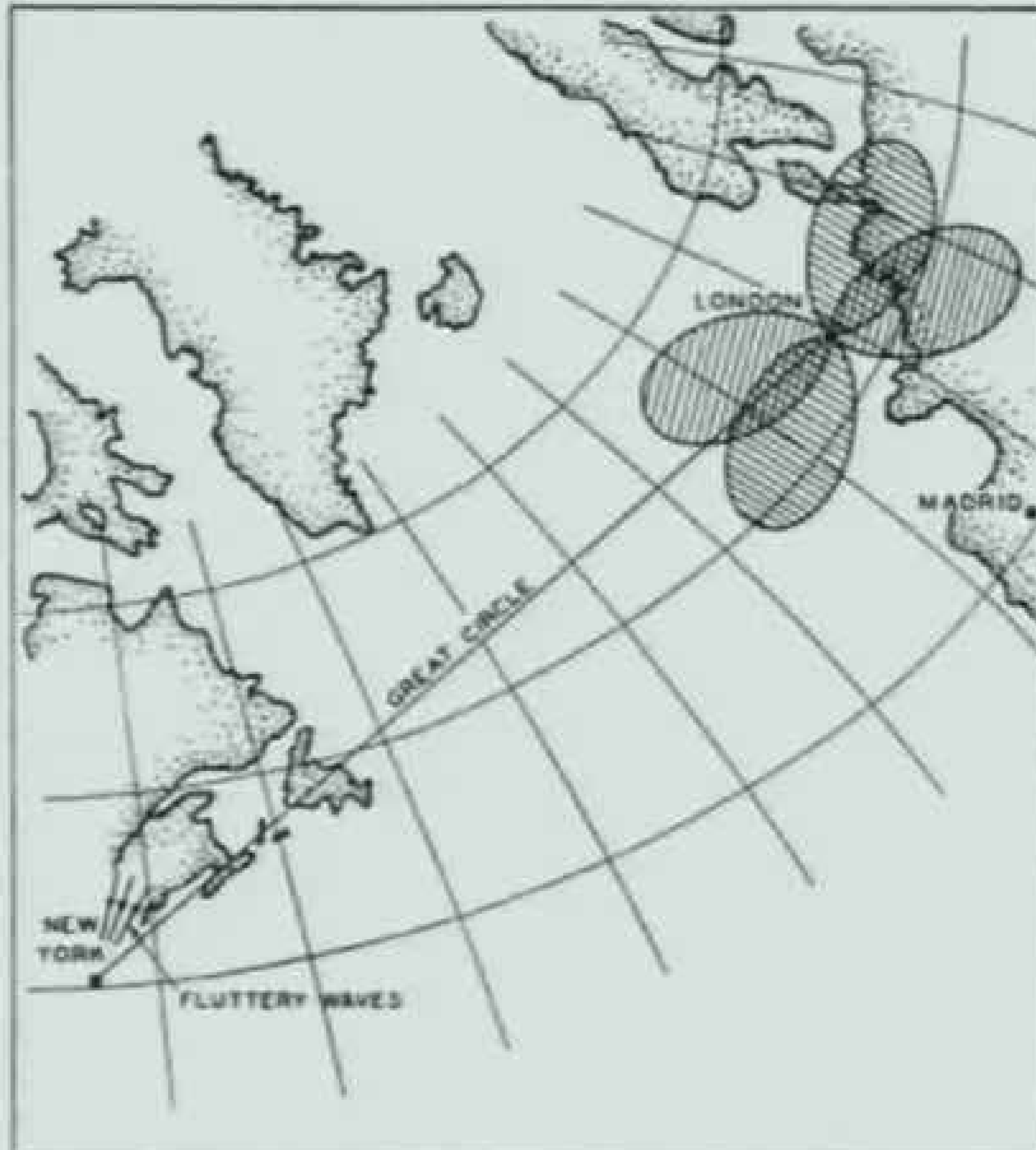

Fig. 1—Directional patterns of two British Broadcasting Corporation transmissions (9.58 and 9.51 megacycles) compared in 1936. The northerly directed antenna greatly emphasized radiation scattered from northern latitudes, and produced flutter fading.

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

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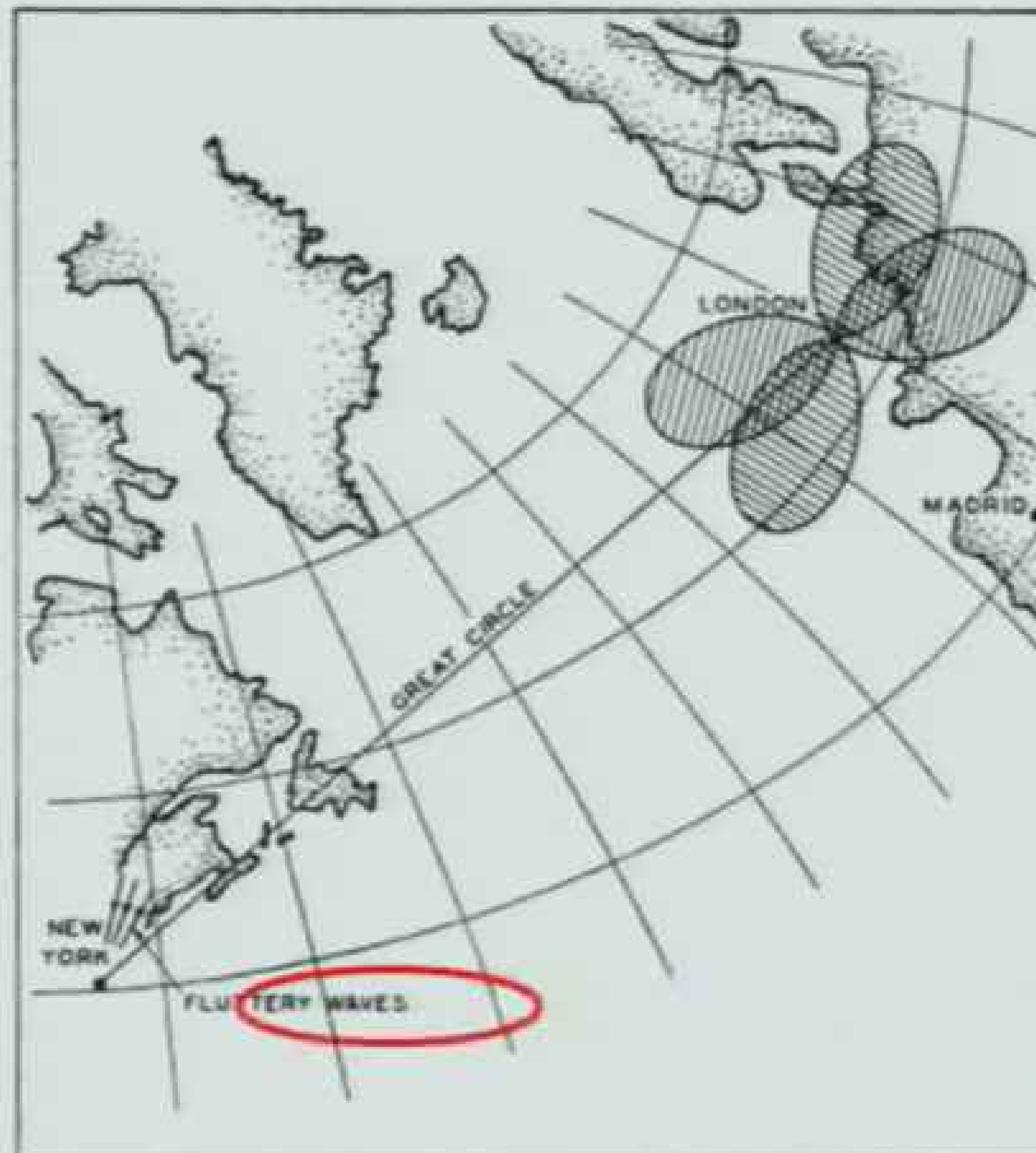

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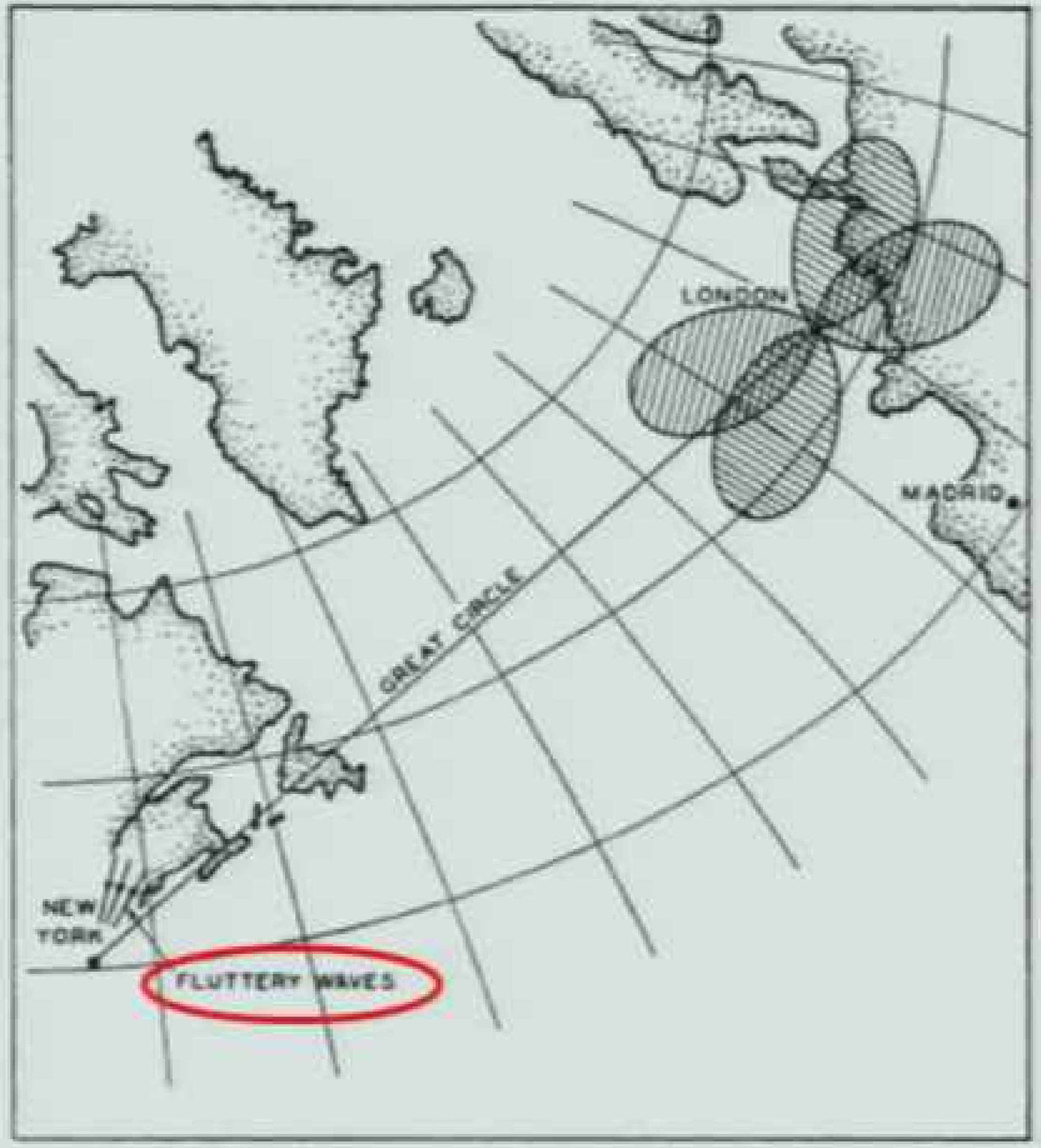

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The Broadside MUSA

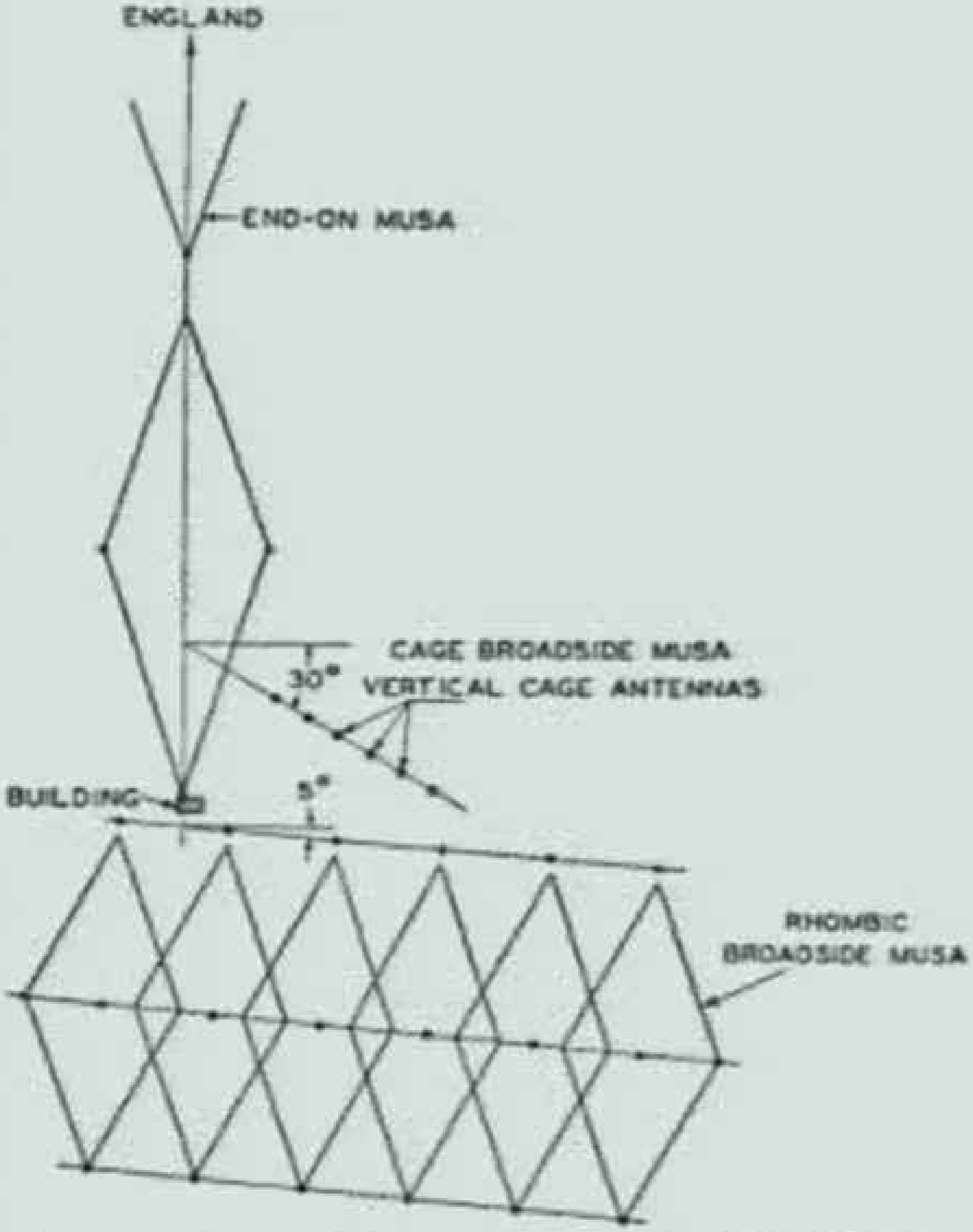

Fig. 2—Layout of steerable antennas at the Holmdel laboratory. Two of the six rhombic unit antennas of the end-on Musa are shown, in addition to the two broadside Musas, each comprising six antennas. The cage antennas are spaced 15 meters and the rhombic antennas 43 meters, center to center.

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:**

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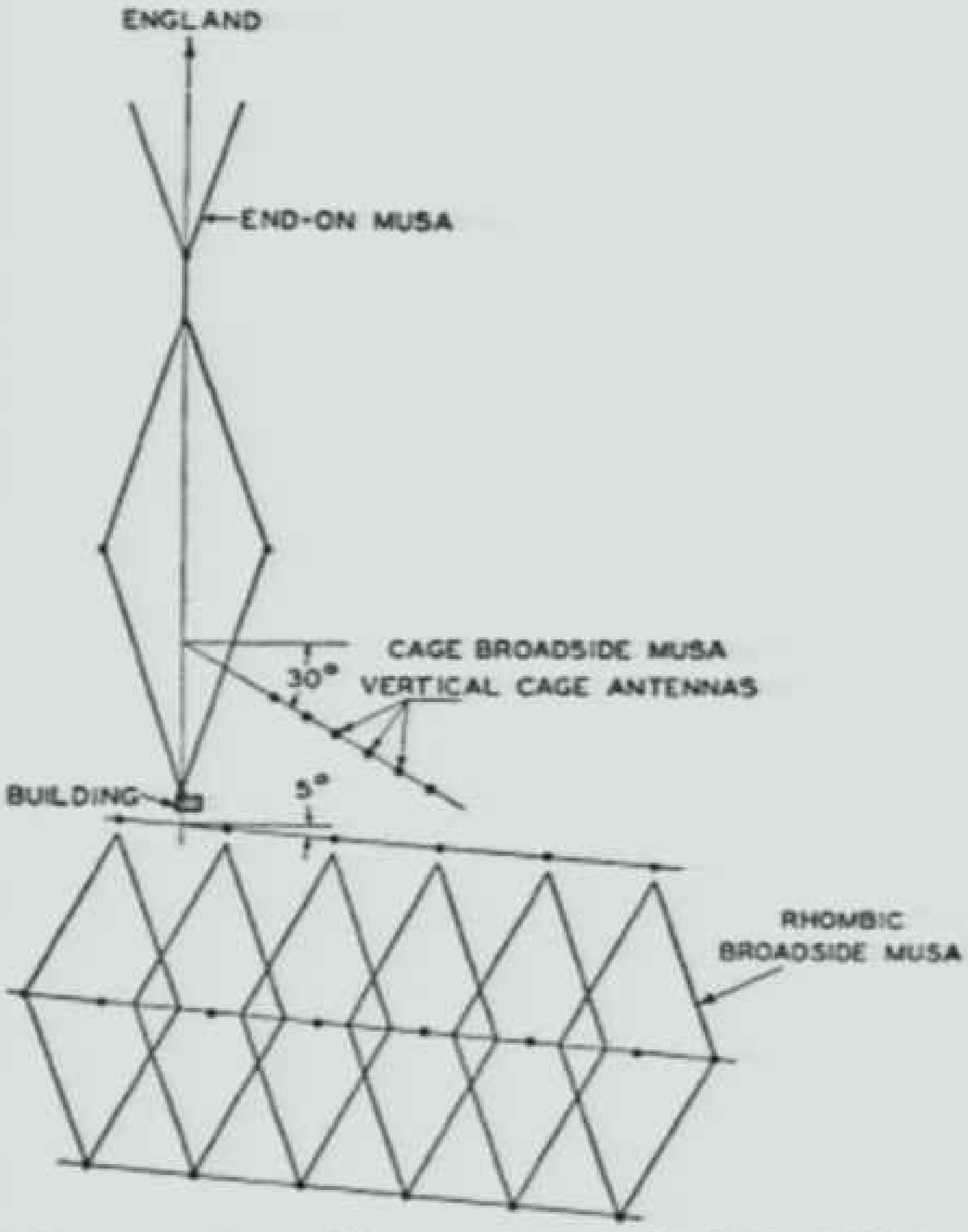

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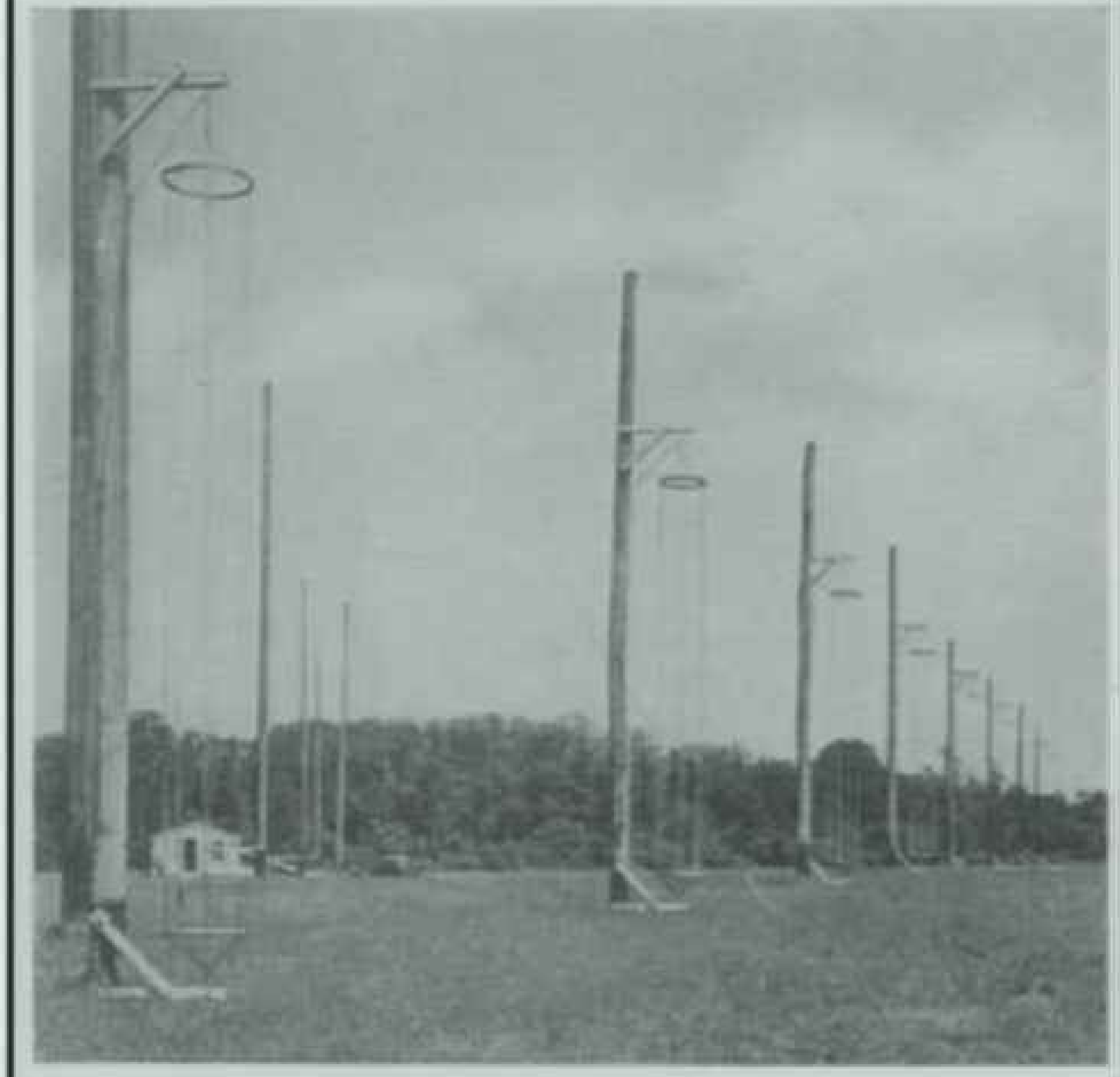

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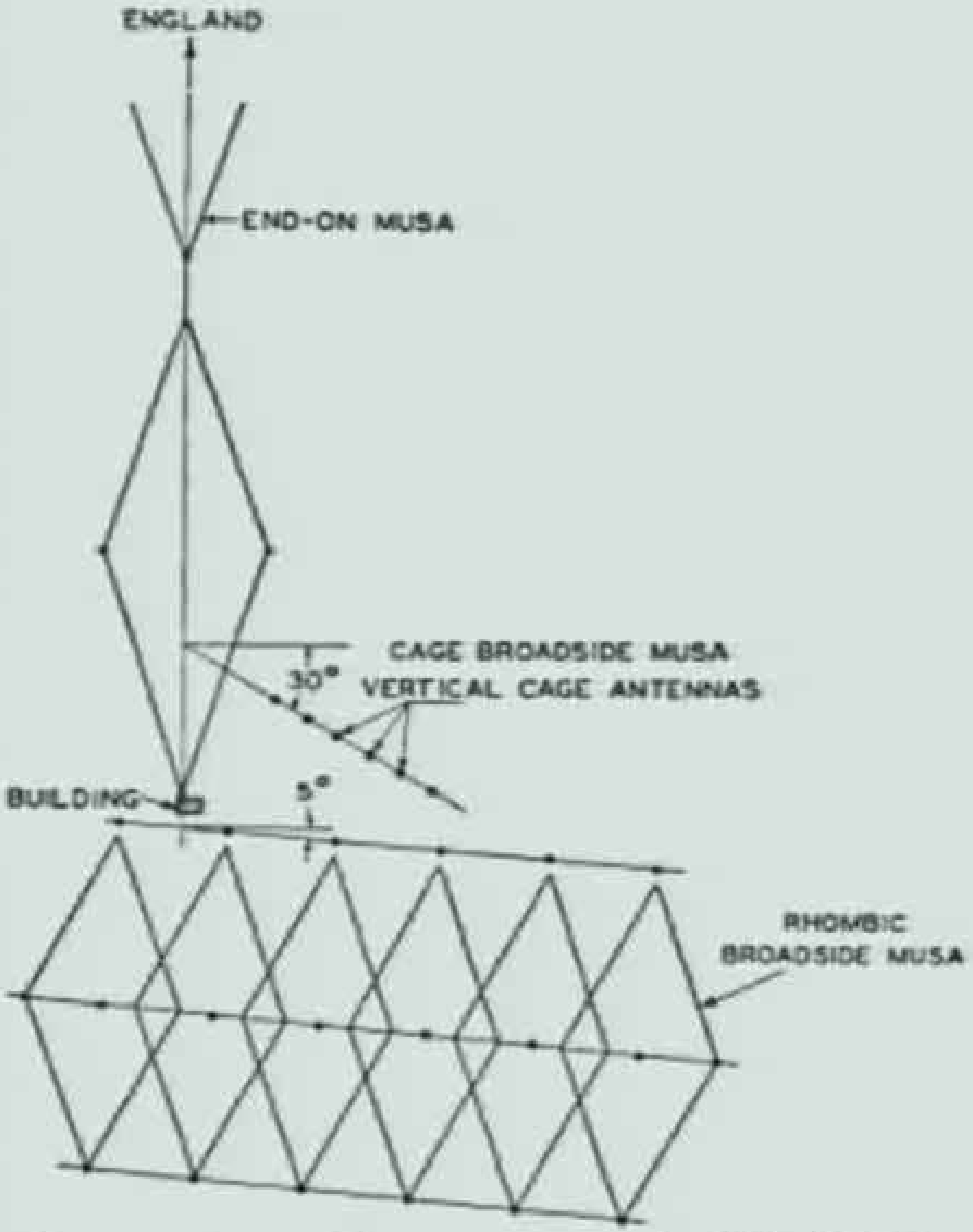

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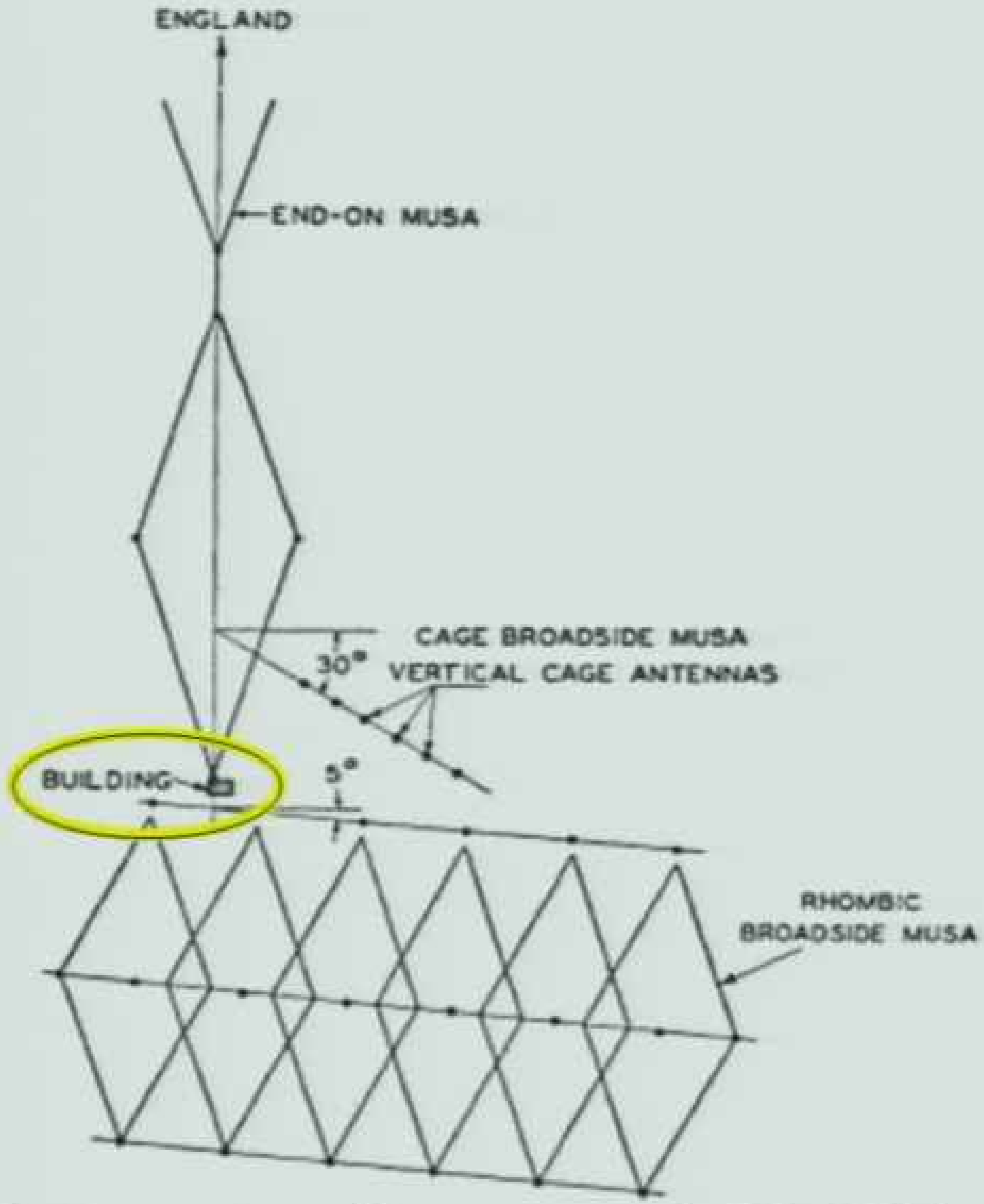

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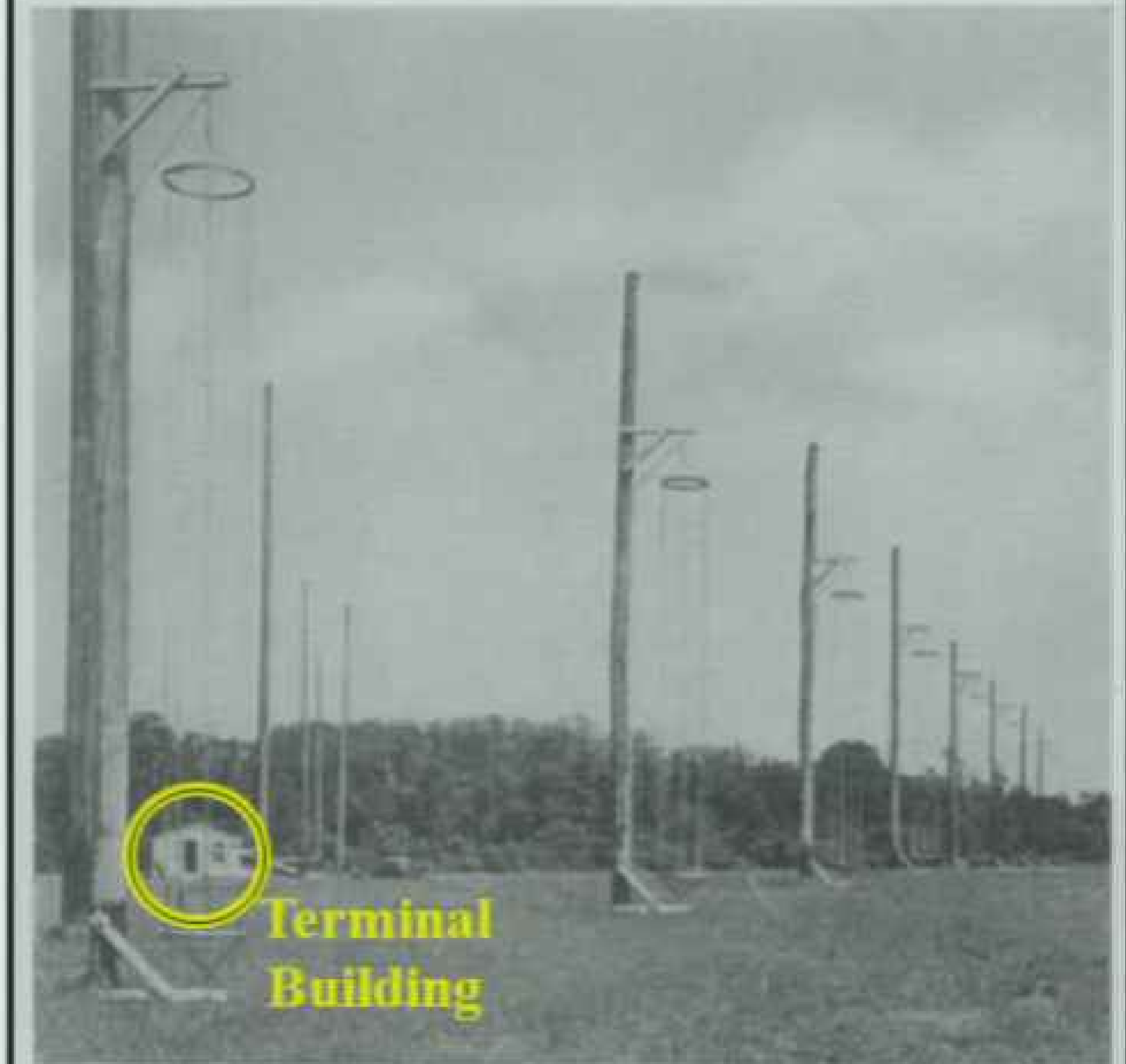

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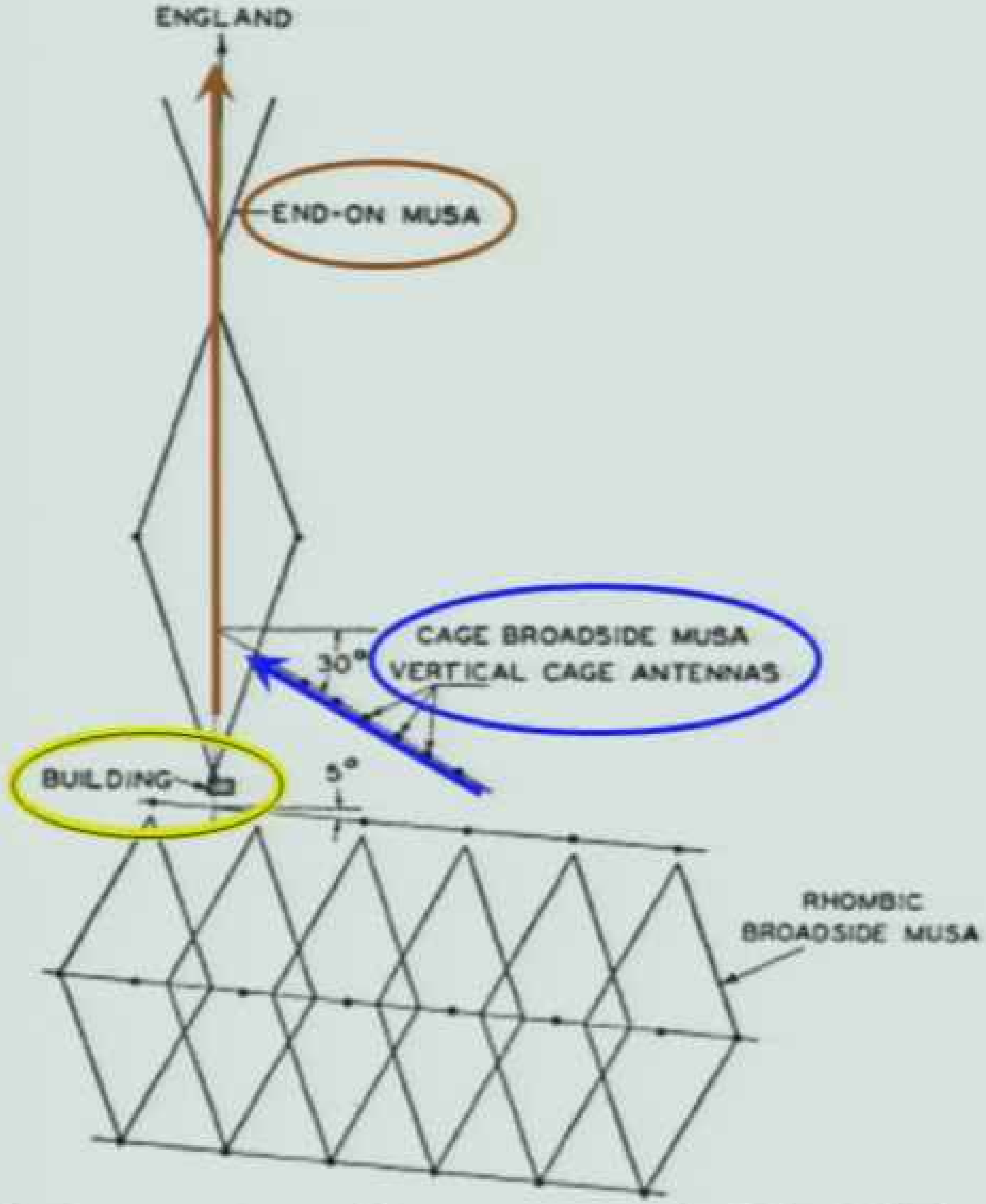

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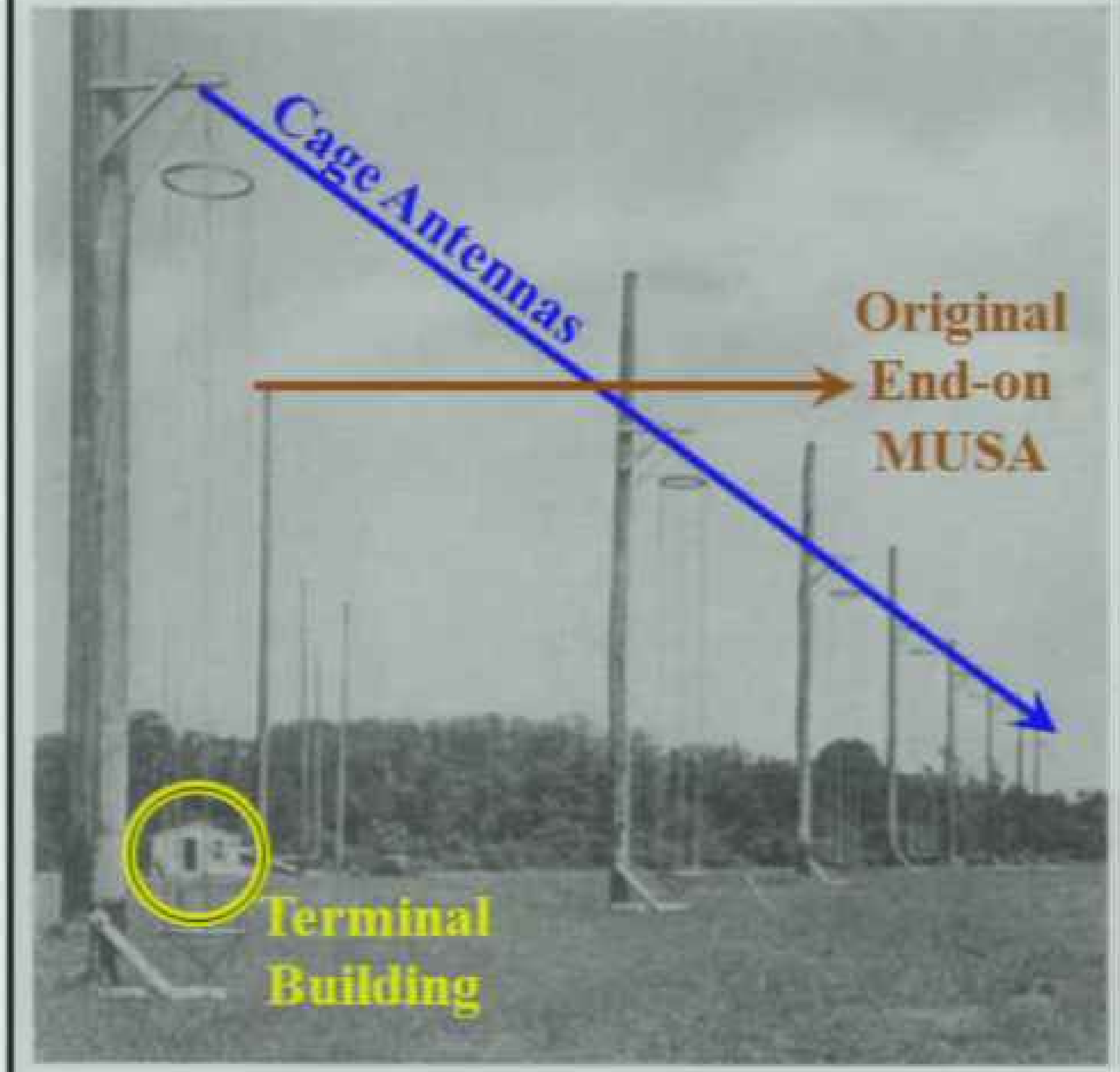

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- **The horizontally steerable MUSA used 2 different types of broadside arrays:**
  - **6 *Cage* antennas to give a wide steering range but with a broad beam**

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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.

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18 MHz

9 MHz

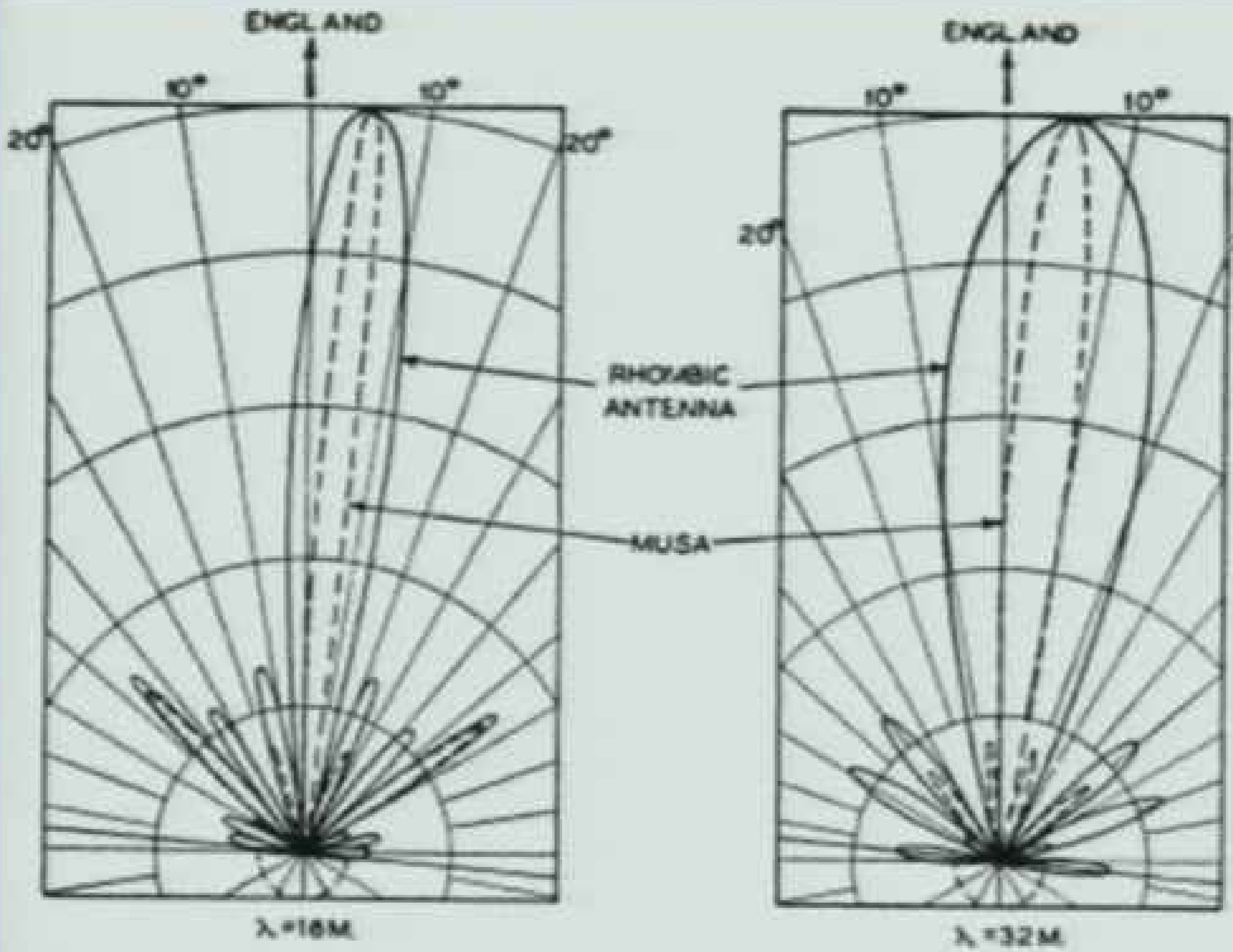

Fig. 7—Sample directional patterns of the rhombic broadside Musa. The steering range is confined to the range defined by the rhombic antenna patterns which are here shown for typical vertical angles.

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MUSA with Horizontal Steering

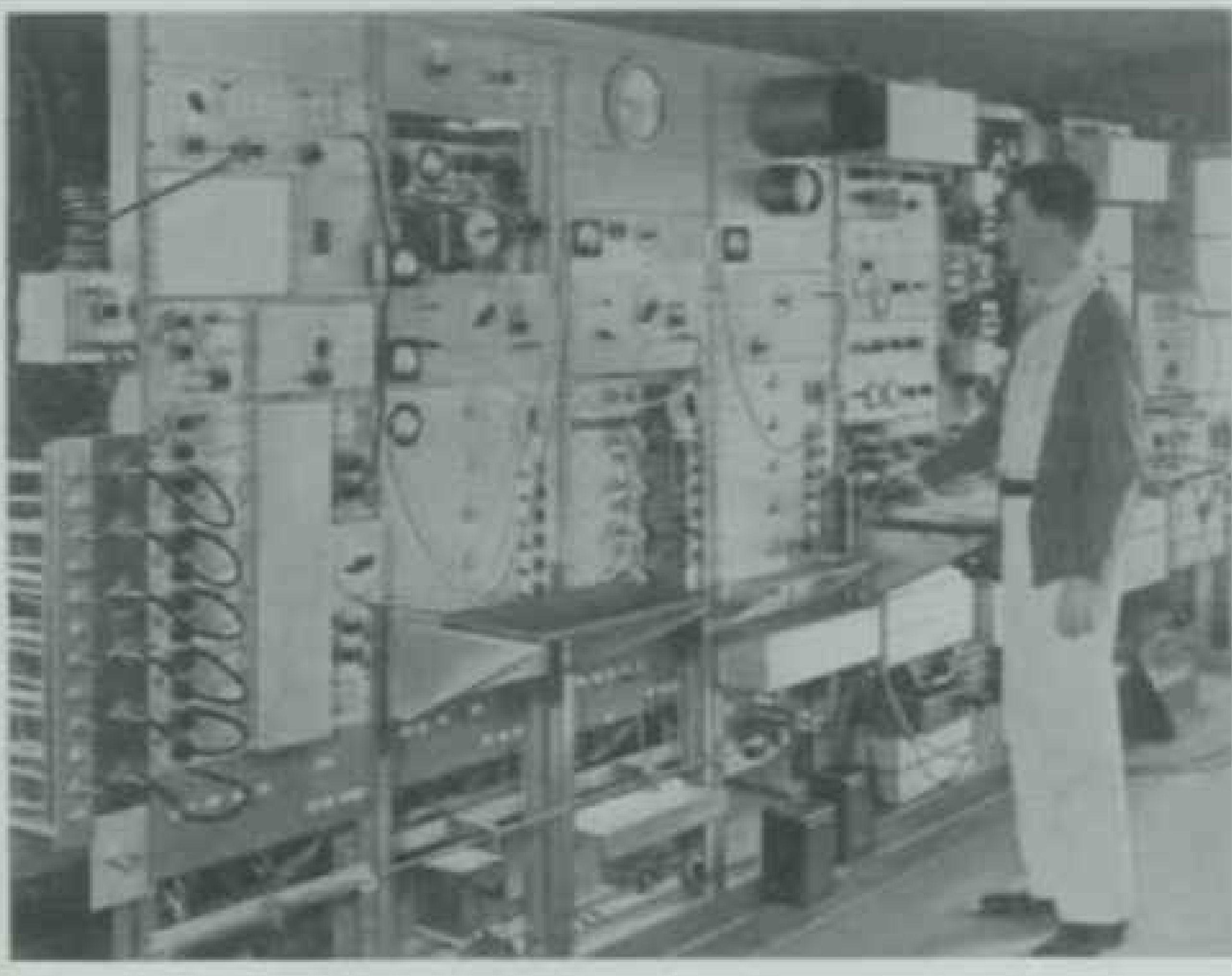

Fig. 4—View of experimental Musa receiving equipment. The three sets of transmission lines from the three Musas terminate in coaxial jacks and can be connected, one set at a time, to the receiver input circuits by means of coaxial patching cords shown at the left. Mr. Edwards, who was closely associated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

18 MHz **9 MHz**

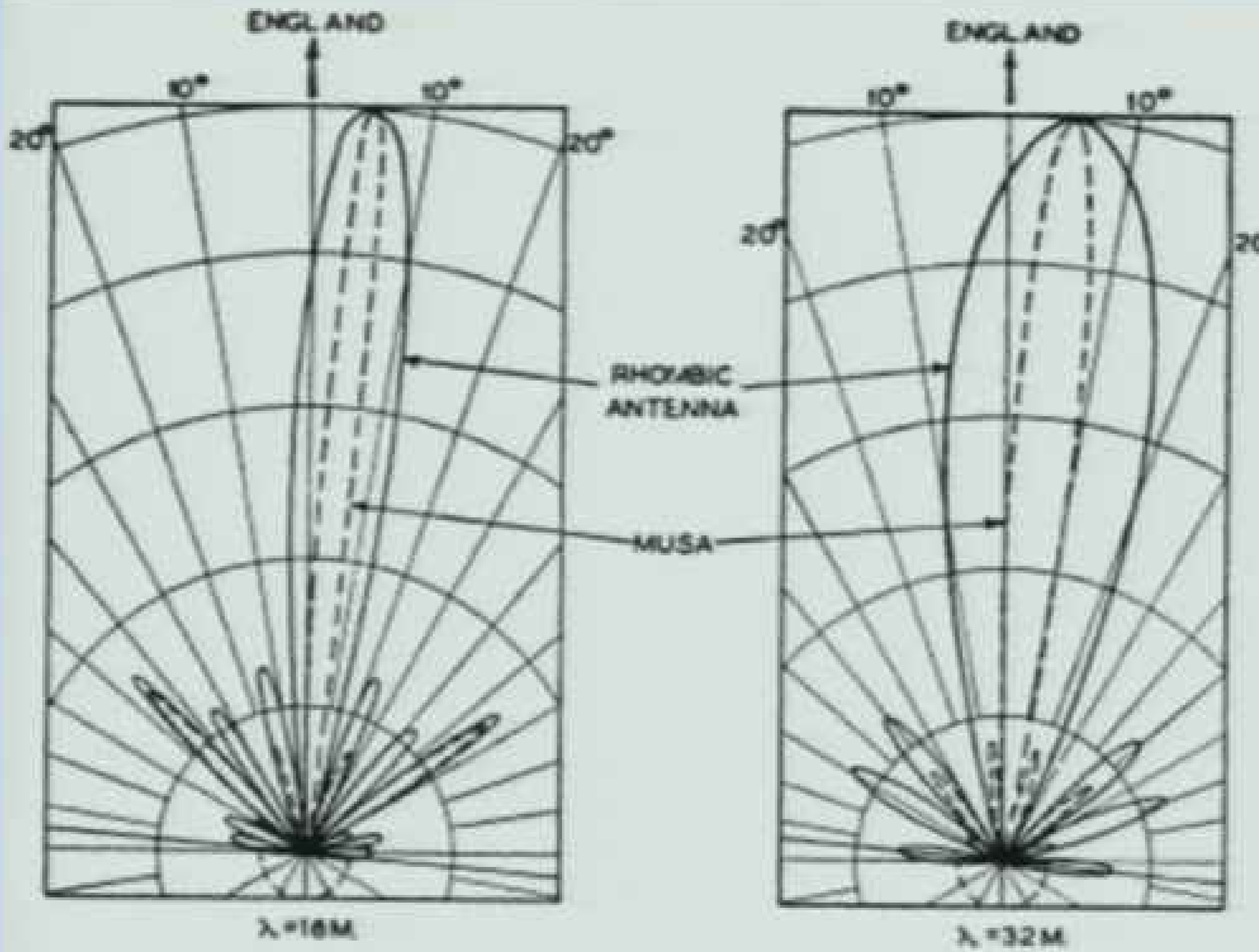

Fig. 7—Sample directional patterns of the rhombic broadside Musa. The steering range is confined to the range defined by the rhombic antenna patterns which are here shown for typical vertical angles.

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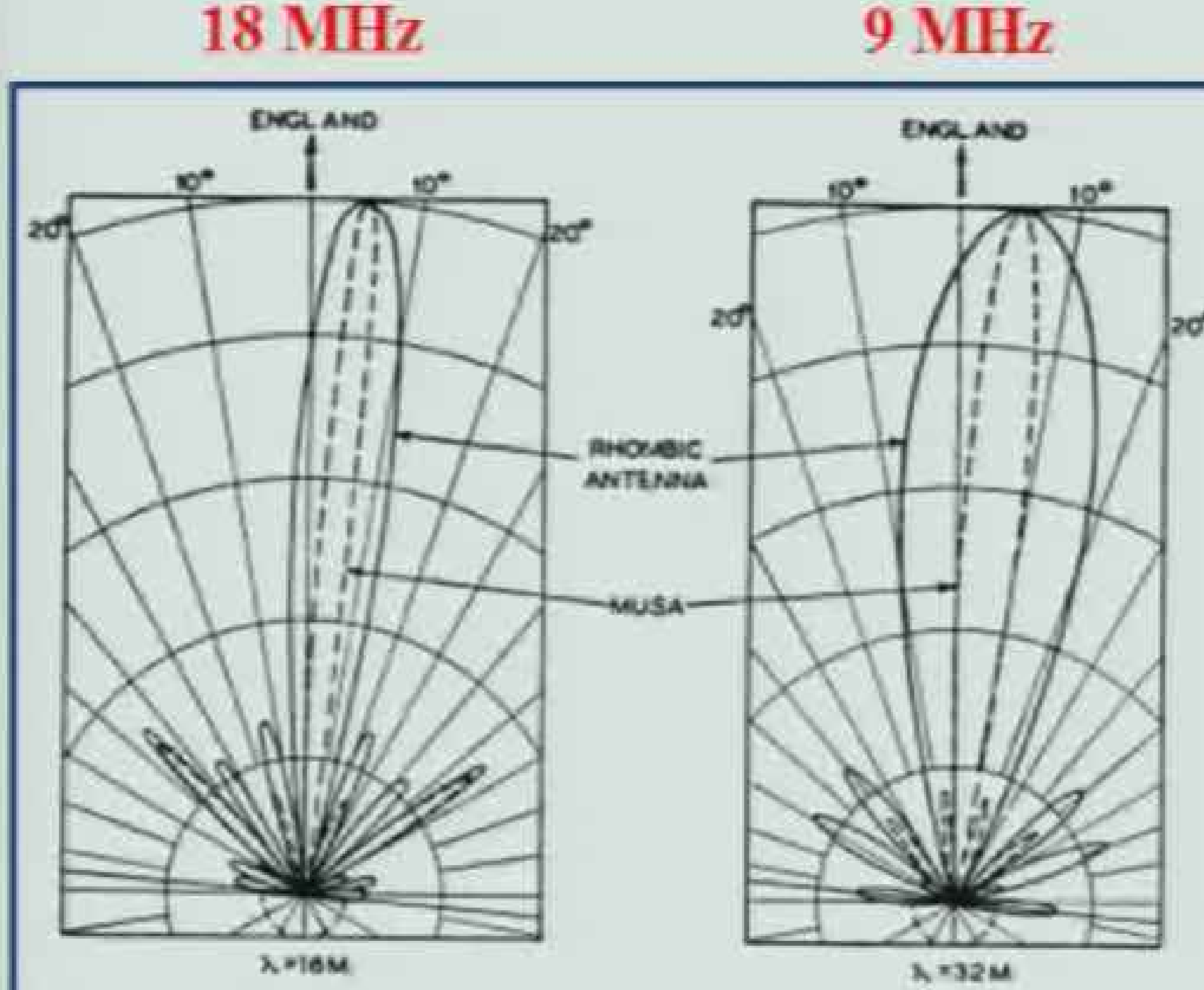

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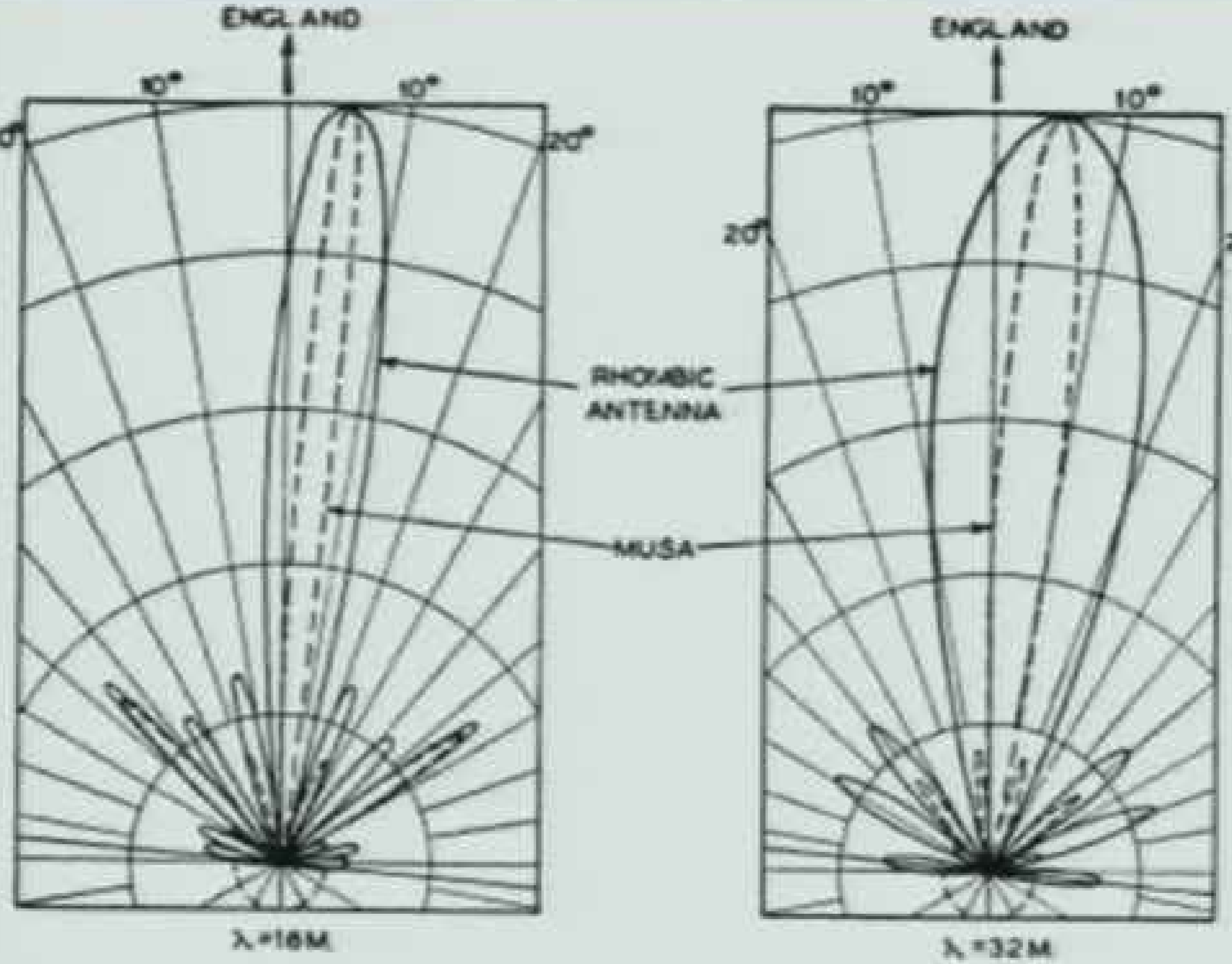

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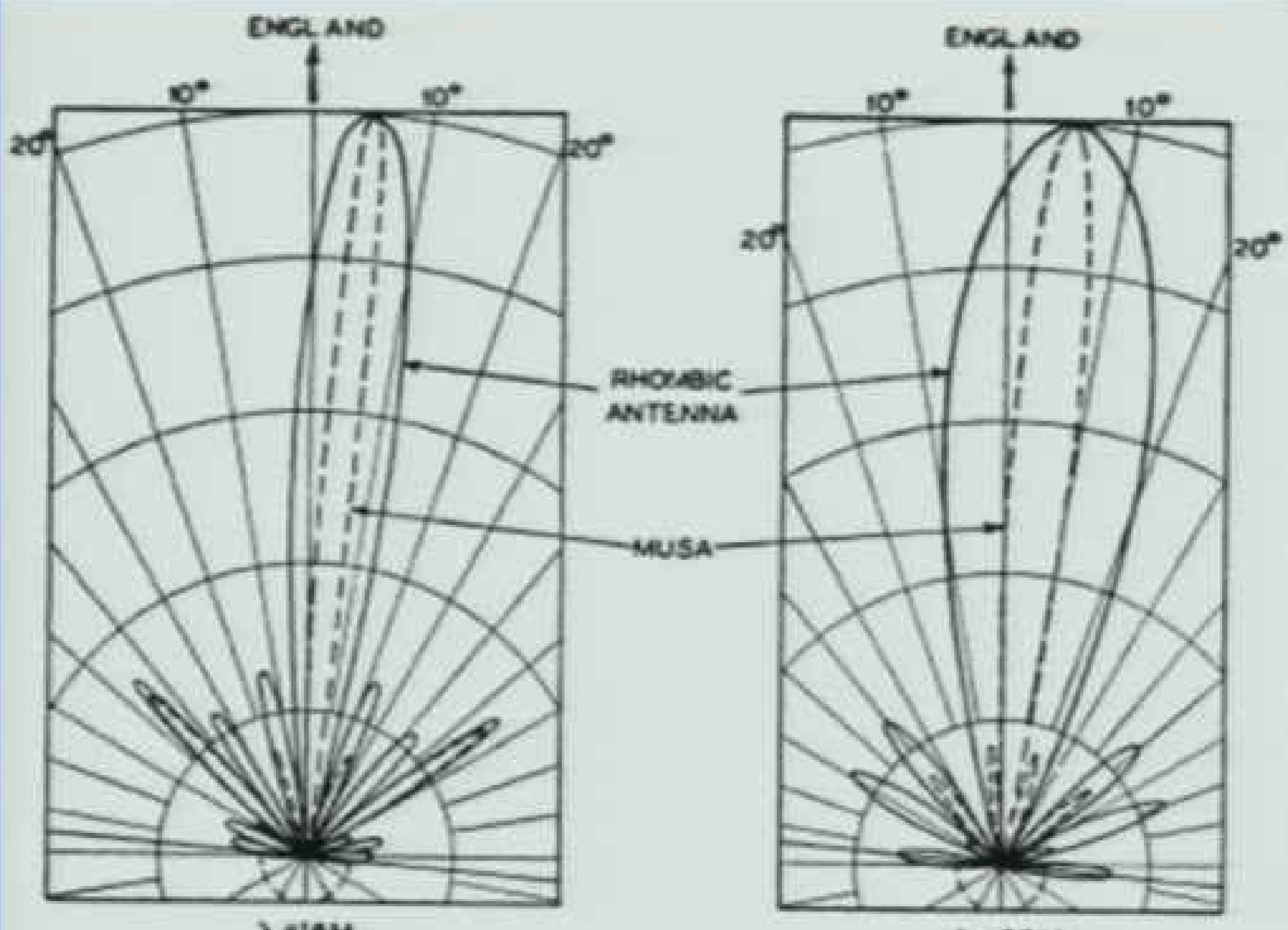

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And now for the rest of the story…

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

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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.

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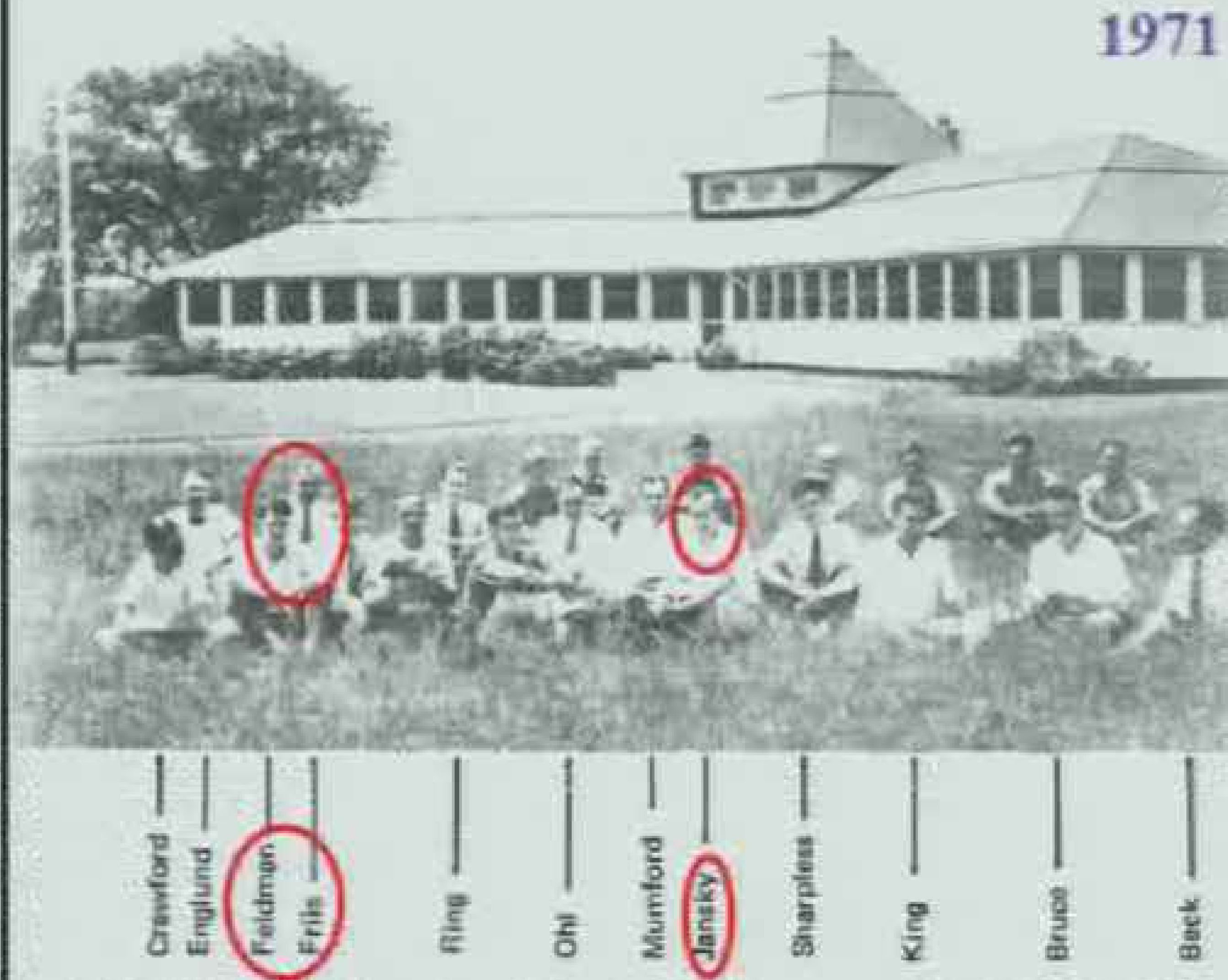
The available Johnson noise from an impedance at temperature T° Kelvin is 1.38×10^{-23} T watts per cycle of bandwidth. I defined the noise figure *NF* of a receiver as the ratio of its total output noise *N* to that part of the output noise N_j that is due to the Johnson noise in a passive input circuit at 290° Kelvin (63° Fahrenheit) or $N = NFN_j$; N_j is equal to $1.38 \times 10^{-23} \times 290$ BG $= 4 \times 10^{-21}$ BG watts where 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.



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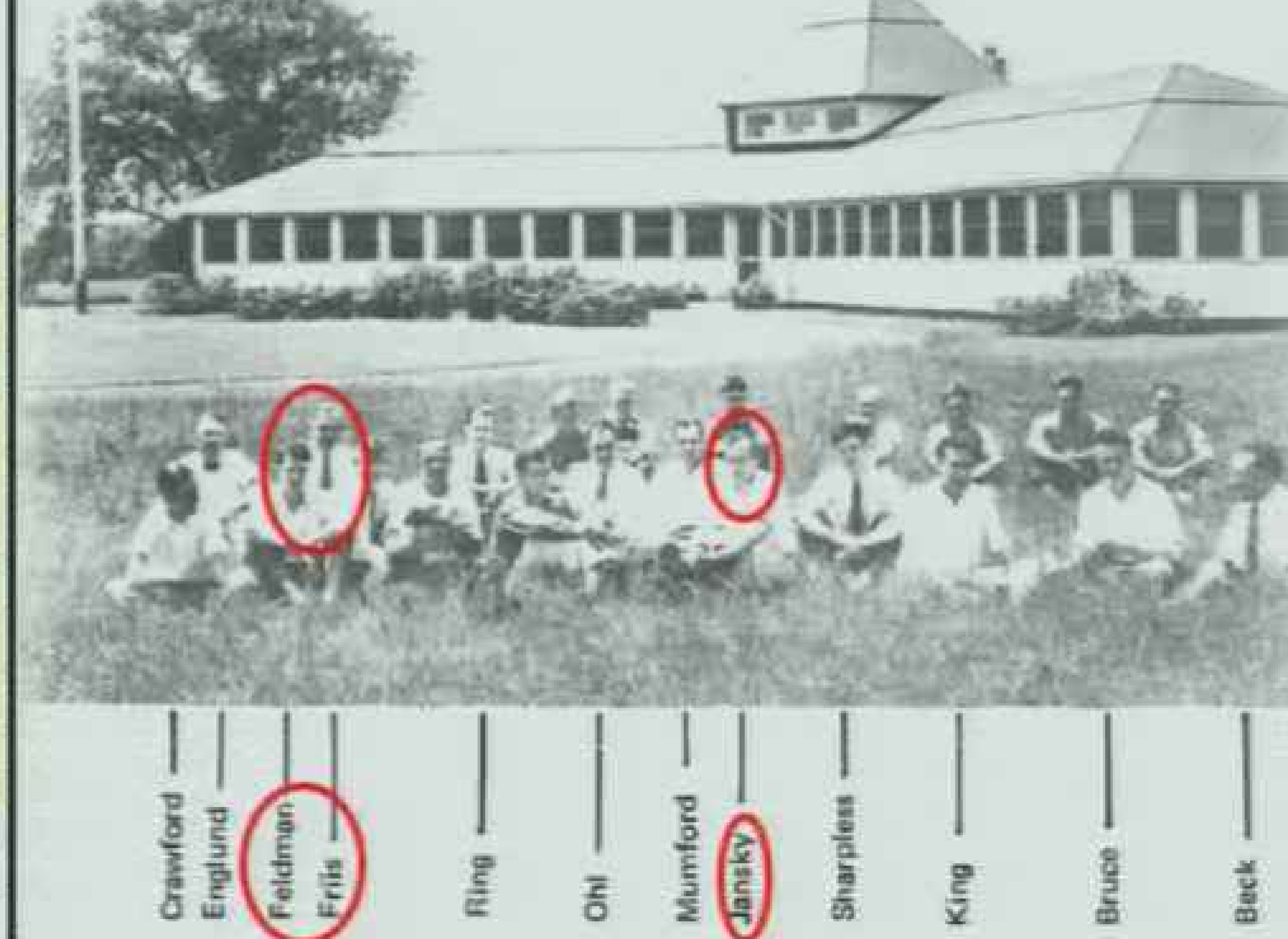

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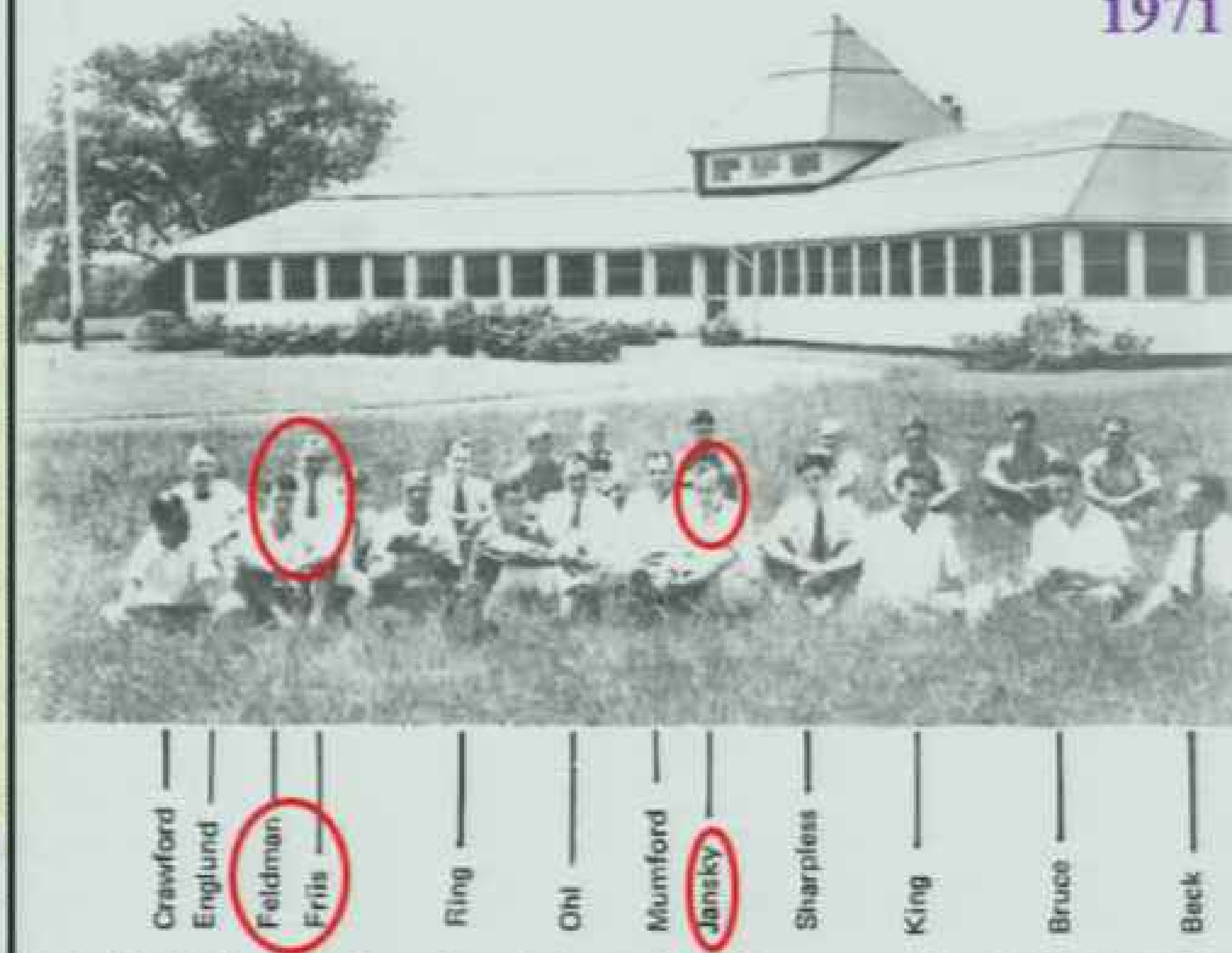

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Seventy-five Years in an Exciting World

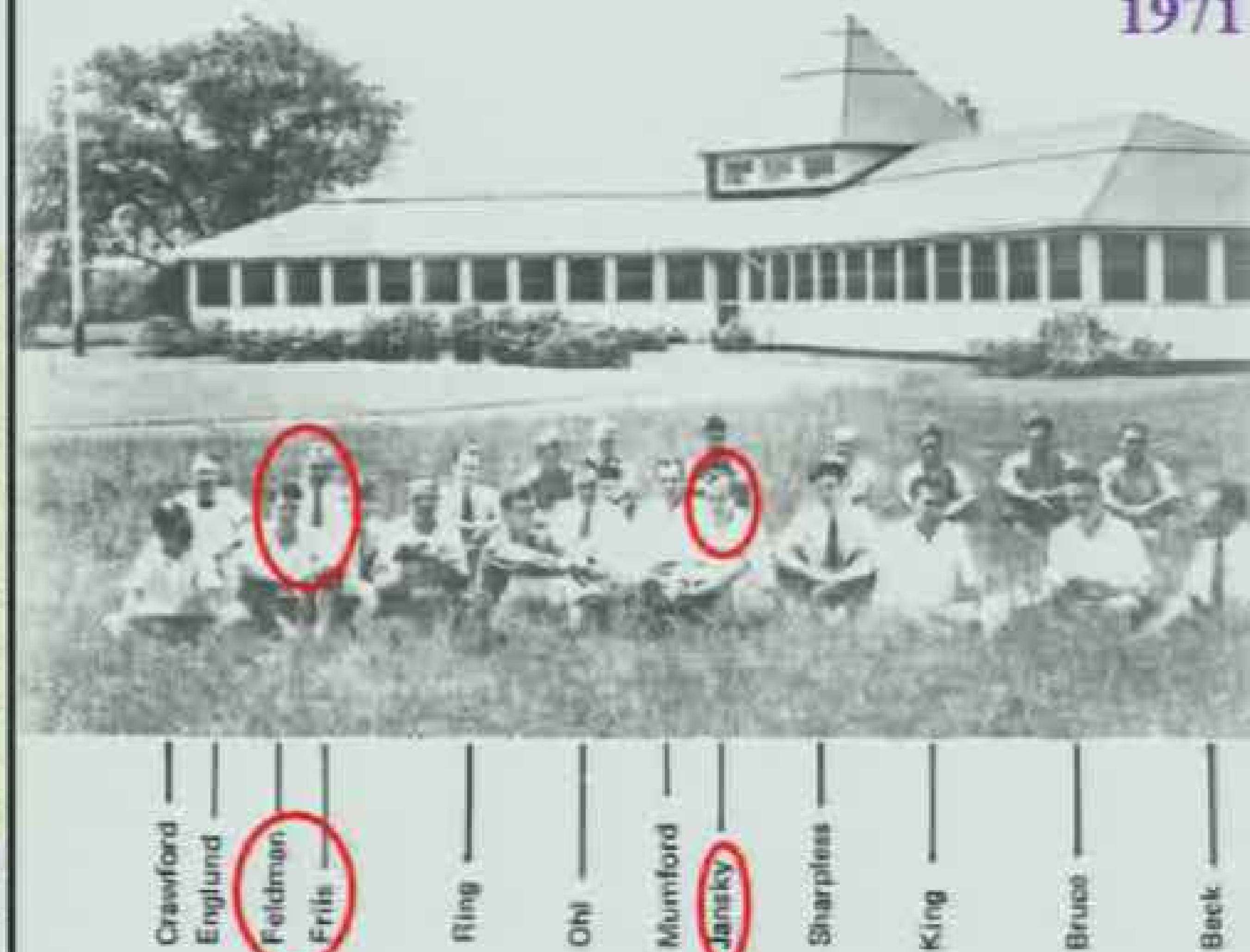
HARALD T. FRIIS

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 ... rac- tically the same wording that I had used ... mo- randum, which was transmitted ... rly nineteen forties.

Th... e
...
th...
... noise
N ... due to the Johnson
no... Kelvin (63° Fahrenheit) or N
= N ... to $1.38 \times 10^{-23} \times 290$ BG = 4×10^{-21} BG
watt... 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.

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

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

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 of said energized paths through said medium regardless of the proximity of the incoming energized paths.

2. A method of improving radio communication which comprises receiving energy from only a maximum incoming wave regardless of the number of waves incoming from the same cooperating station and changing the direction of reception in accordance with directive changes in said wave.

3. In a radio system, a plurality of unidirective antennas spaced in a plane containing a cooperating station and positioned for directive operation over the same angular range in said 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 in an array so that the major lobes of their directive characteristics are similarly pointed and include the same set or cluster of incoming wave directions, obtaining a movable directive characteristic or cone for the array, and including in the array cone at all times substantially only one of said incoming wave directions regardless of changes in said wave directions.

5. A method of obtaining sharp directivity in a radio system utilizing a plurality of directive antenna units arranged in a directive array and connected to a translation device, means for moving a directive 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.

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

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

6. A method of improving radio communication which comprises energizing a plurality of paths of different lengths between two stations, receiving the horizontally polarized components propagated along only one of the paths and the vertically polarized components propagated along only one of the paths, and combining the absorbed components.

7. A method of improving radio communication utilizing a plurality of directive units each connected to two receivers through separate phase changers, which comprises absorbing on each unit energy from the same two directions, conducting the energy received from one direction to one receiver and the energy received from the other direction to the other receiver, and combining the outputs of the receivers.

8. A method of improving radio communication 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 in an array, means for rotating the array directive characteristic for one signal, a second means for rotating the array directive characteristic for another signal, and two receivers, which comprises receiving on each unit differently directed waves of the first mentioned signal differently directed waves of the second signal, rotating the first mentioned characteristic so that its major lobe includes the direction of only one of the first mentioned waves, rotating the second mentioned characteristic so that its major lobe includes the direction of only one of the second mentioned waves, supplying the energy absorbed from the first mentioned wave to one receiver and that absorbed from the second mentioned wave to another receiver.

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.

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

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

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

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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.

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

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The early years of
RADIO ASTRONOMY

REFLECTIONS FIFTY YEARS AFTER JANSKY'S DISCOVERY

Edited by

W. T. SULLIVAN, III

Jansky & the MUSA

1935

In a 1935 Letter to his Father

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

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Edited by
W. T. SULLIVAN, III

Jansky & the MUSA

1935

In a 1935 Letter to his Father

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

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.**

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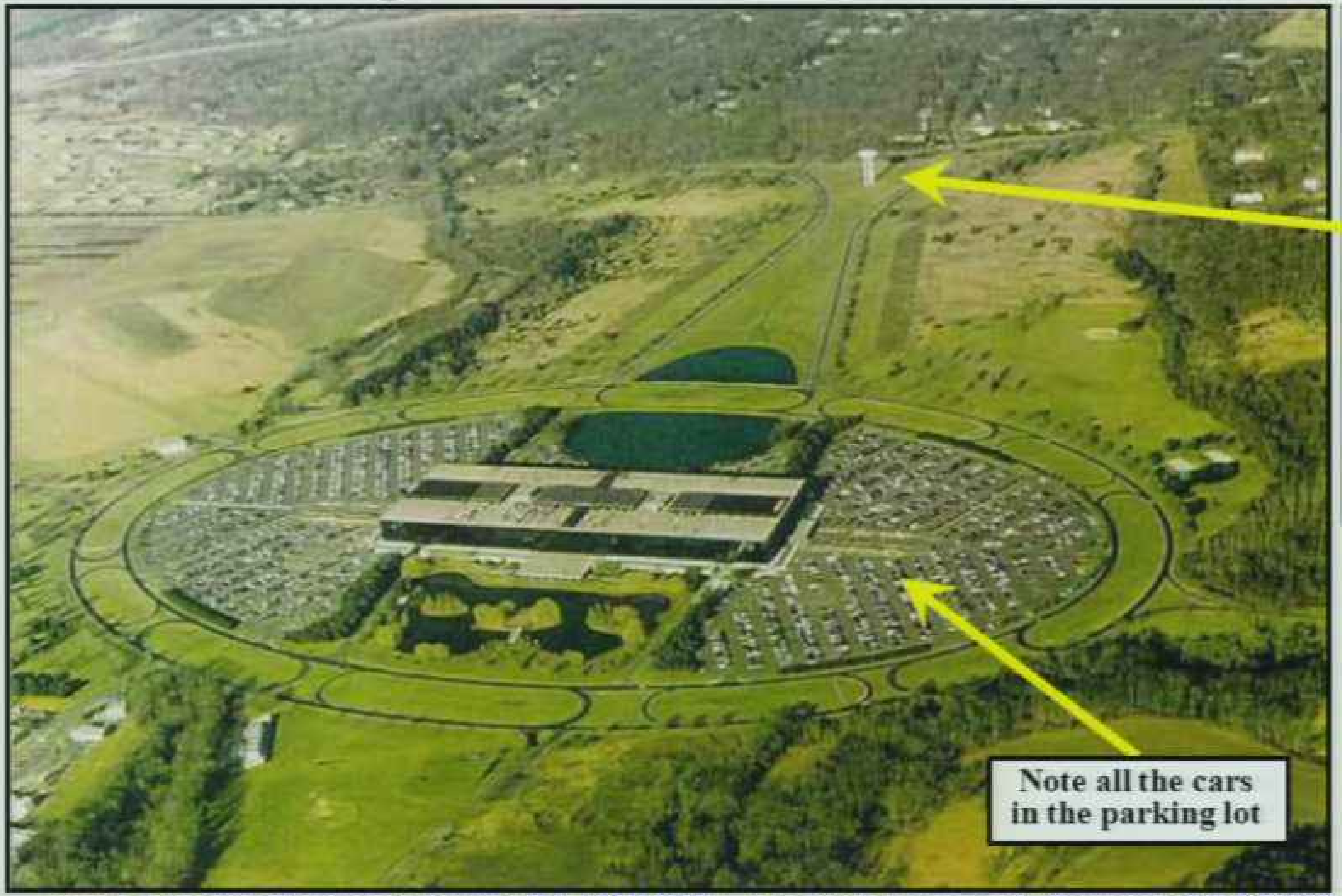

The water tower on the 472-acre complex was designed to look like a transistor, the most famous Bell Lab invention.

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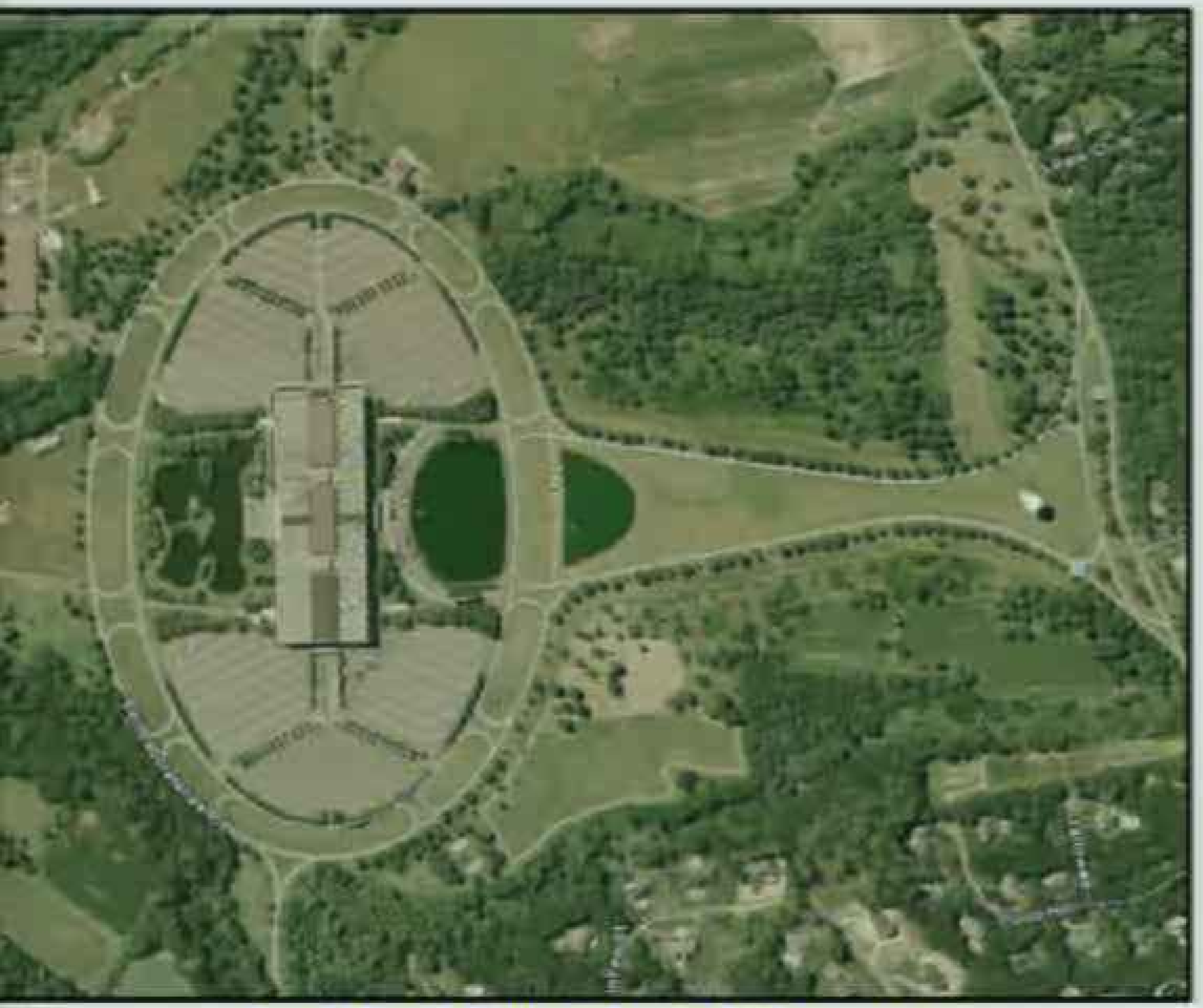
Bell Labs Holmdel Complex Today



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

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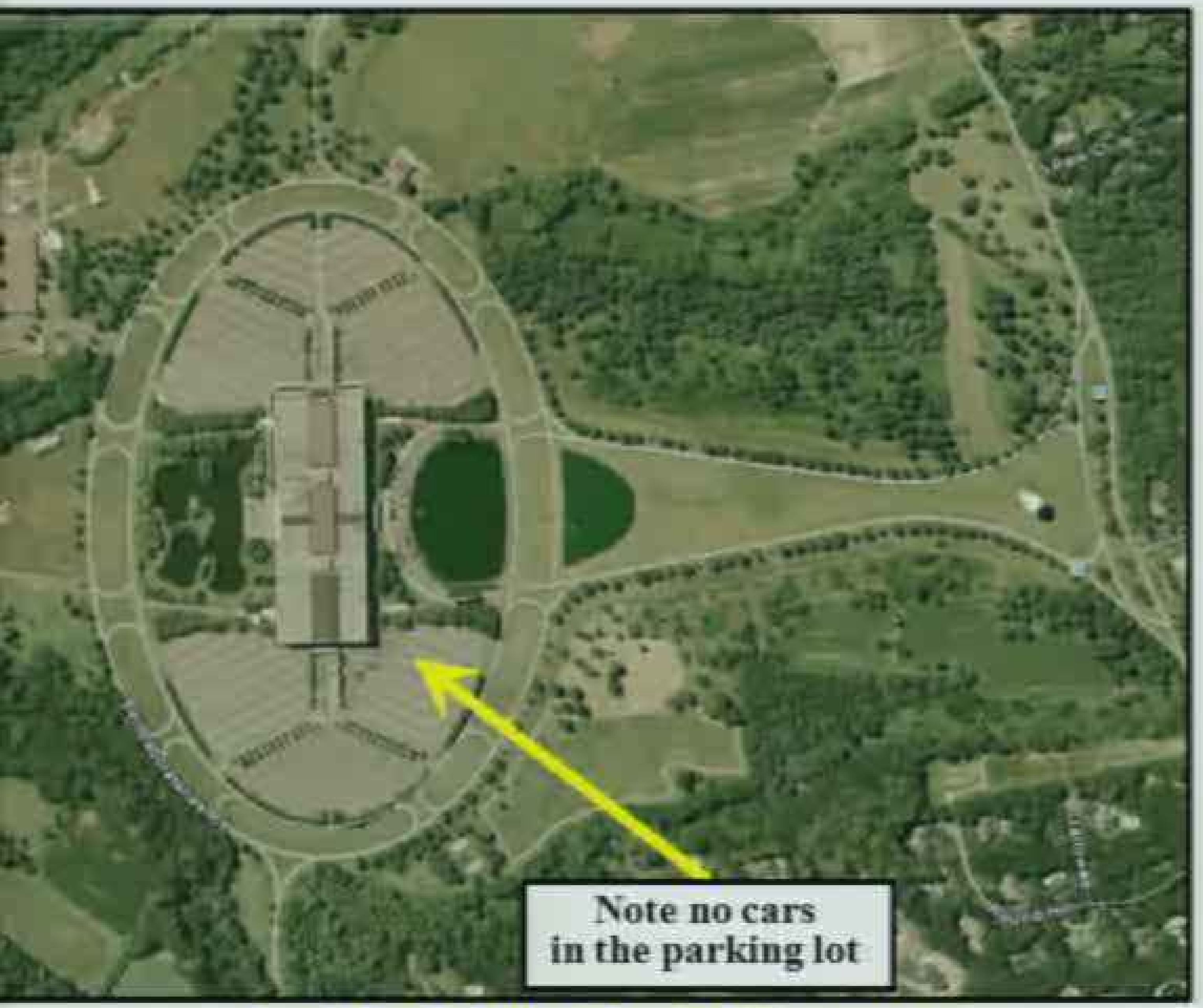

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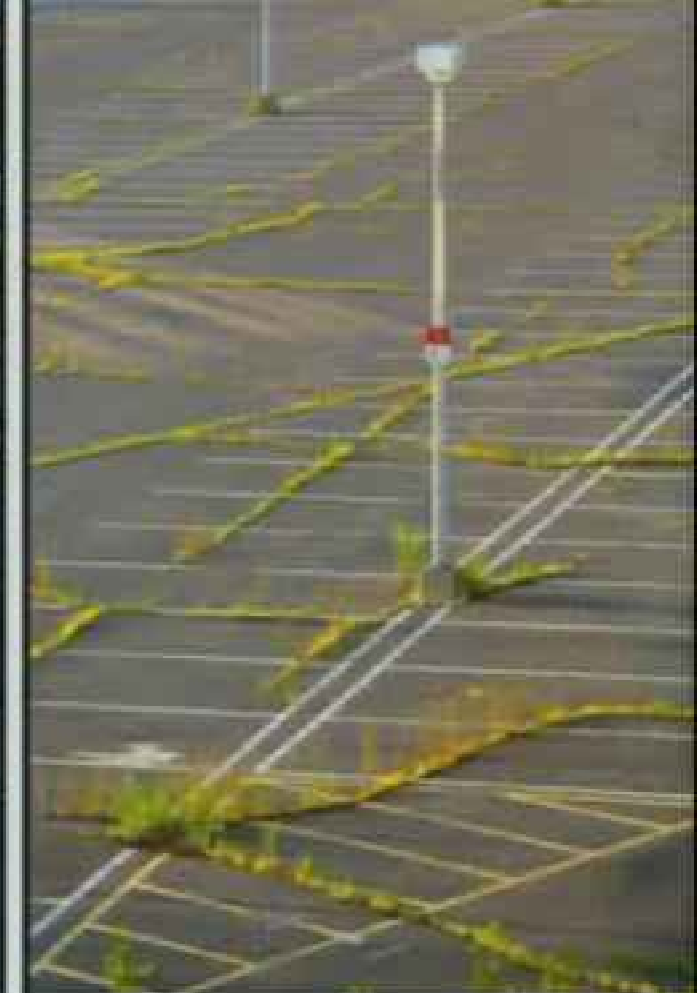

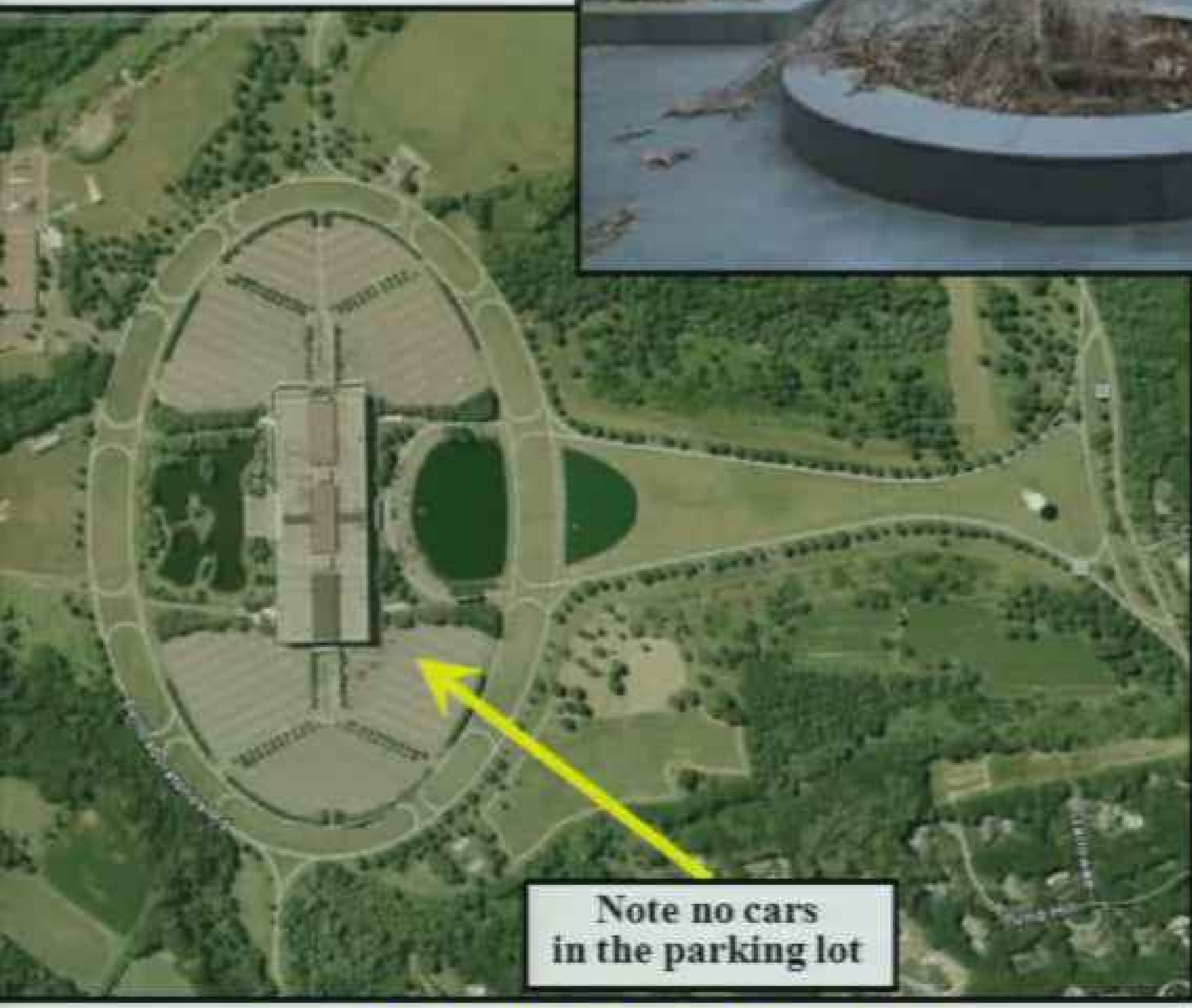

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The company eventually closed the facility in 2006 and sold it.

The world's largest lab now sits abandoned.

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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).

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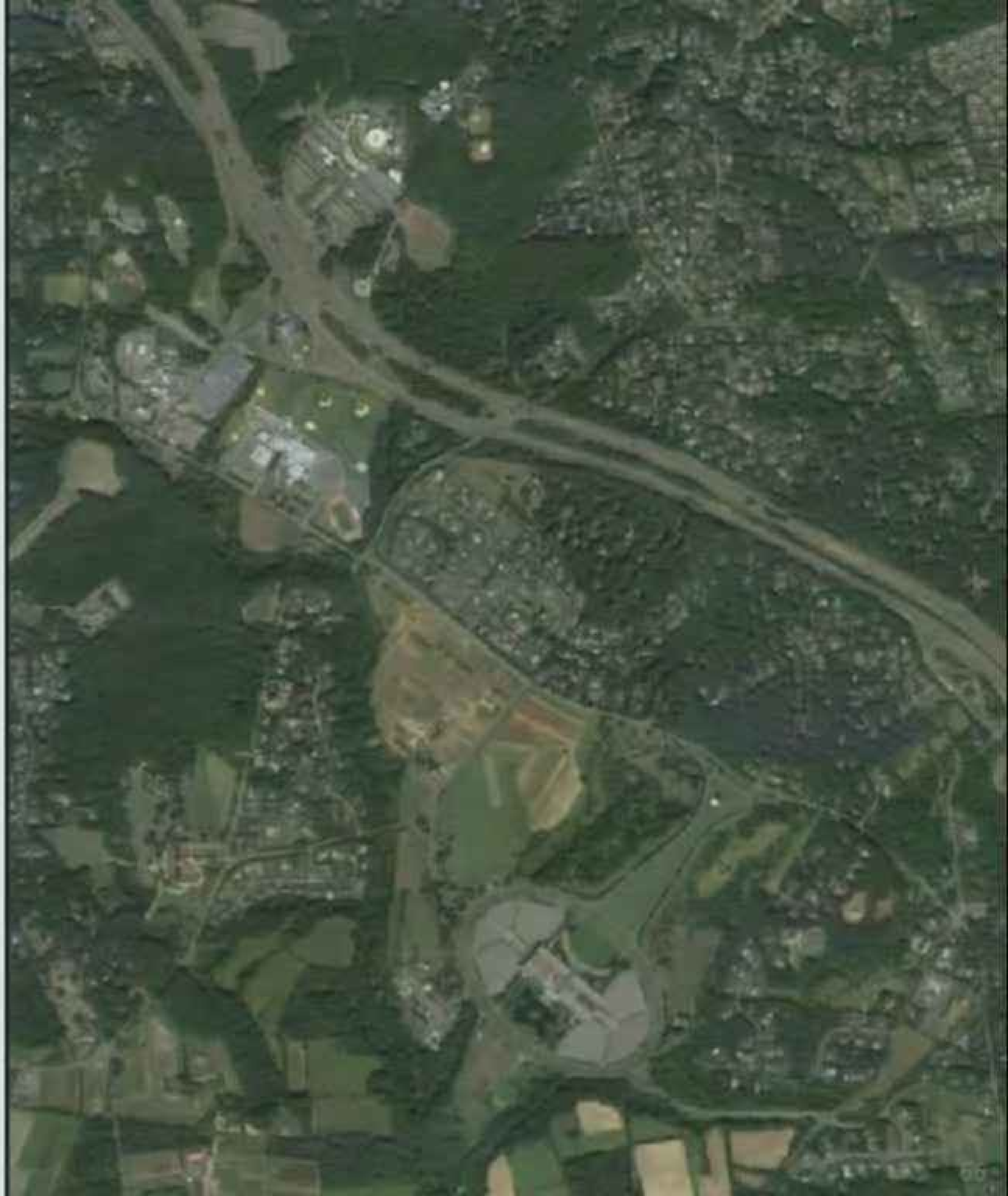

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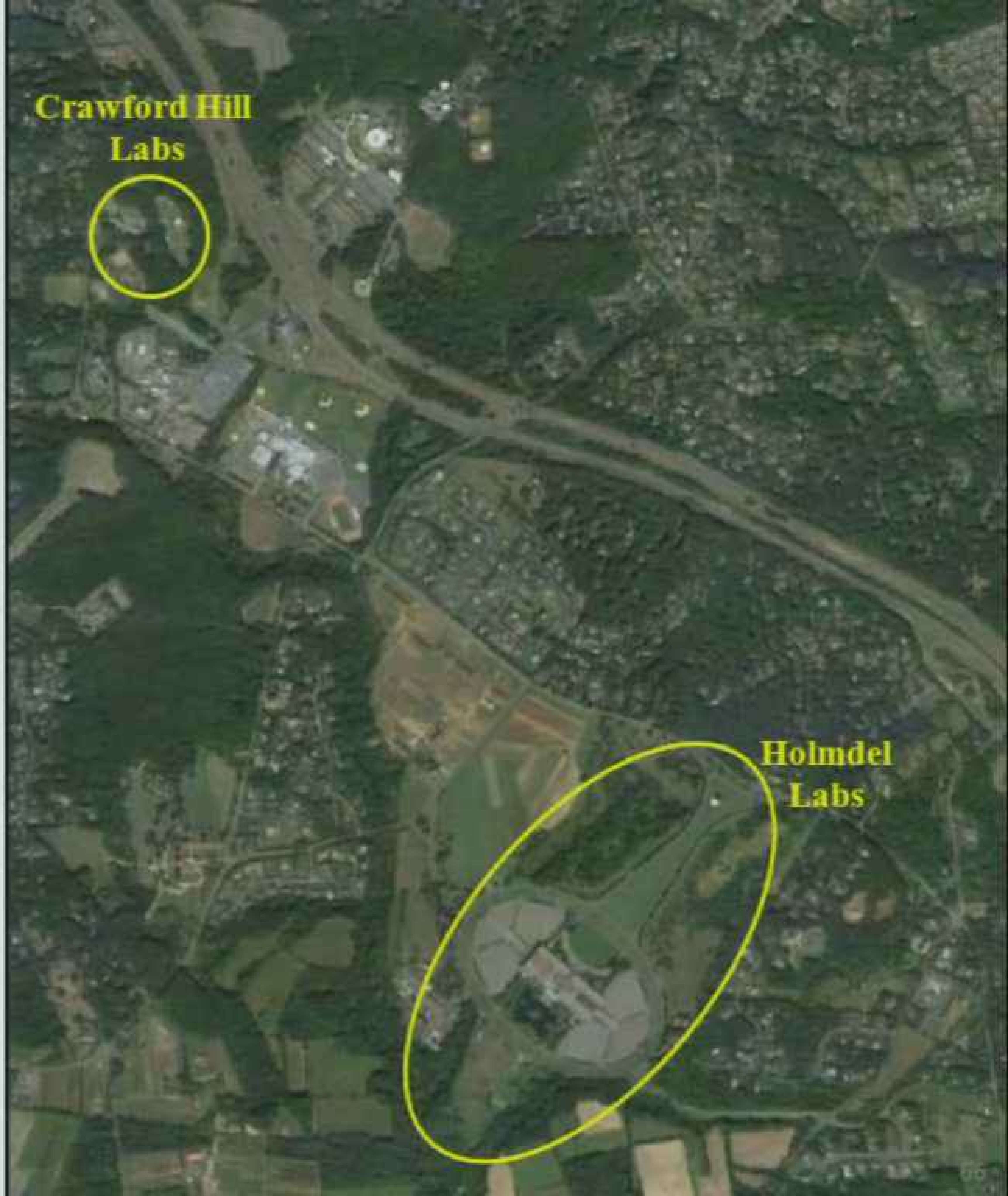

Bell's Crawford Hill Lab, Holmdel, NJ

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.

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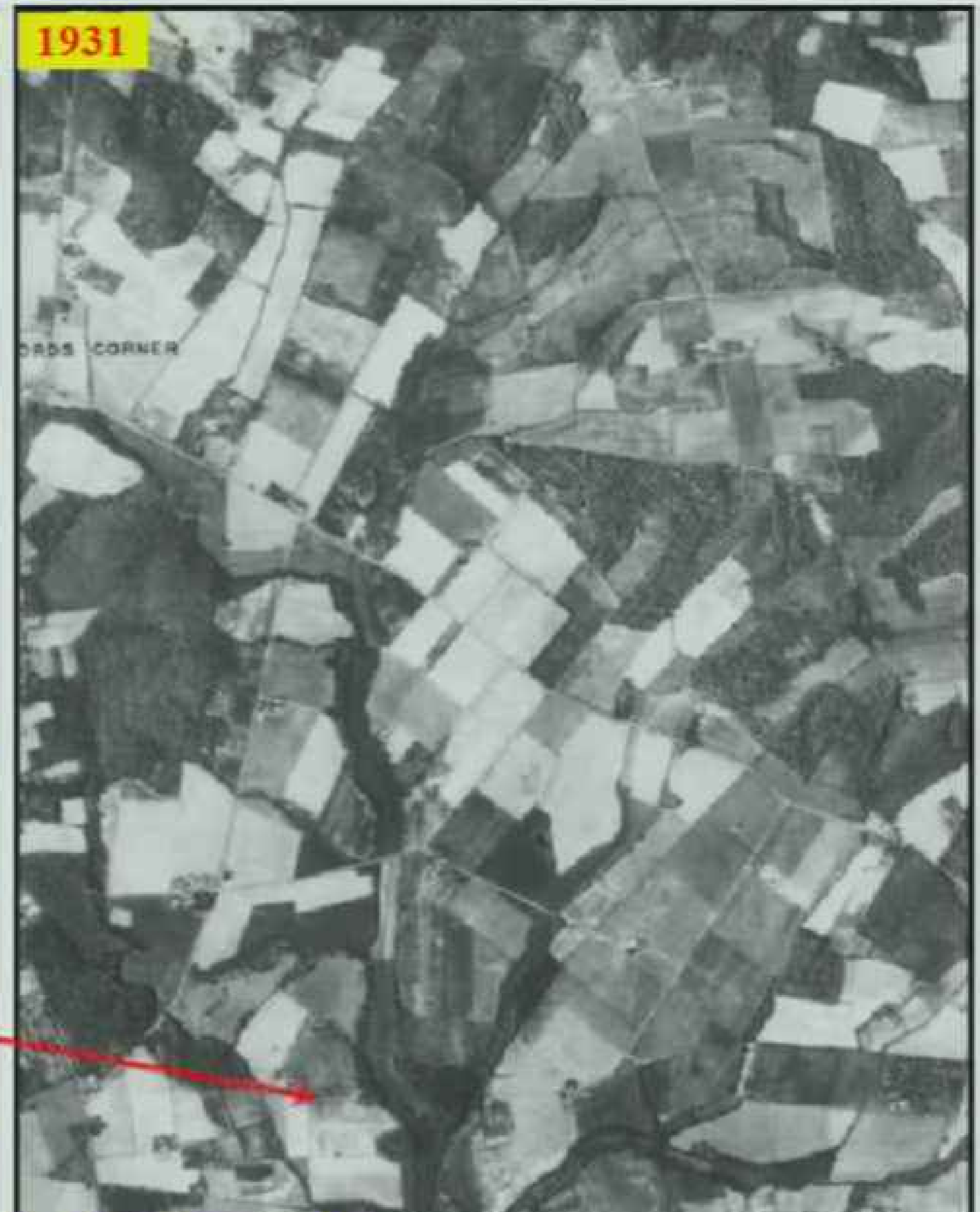

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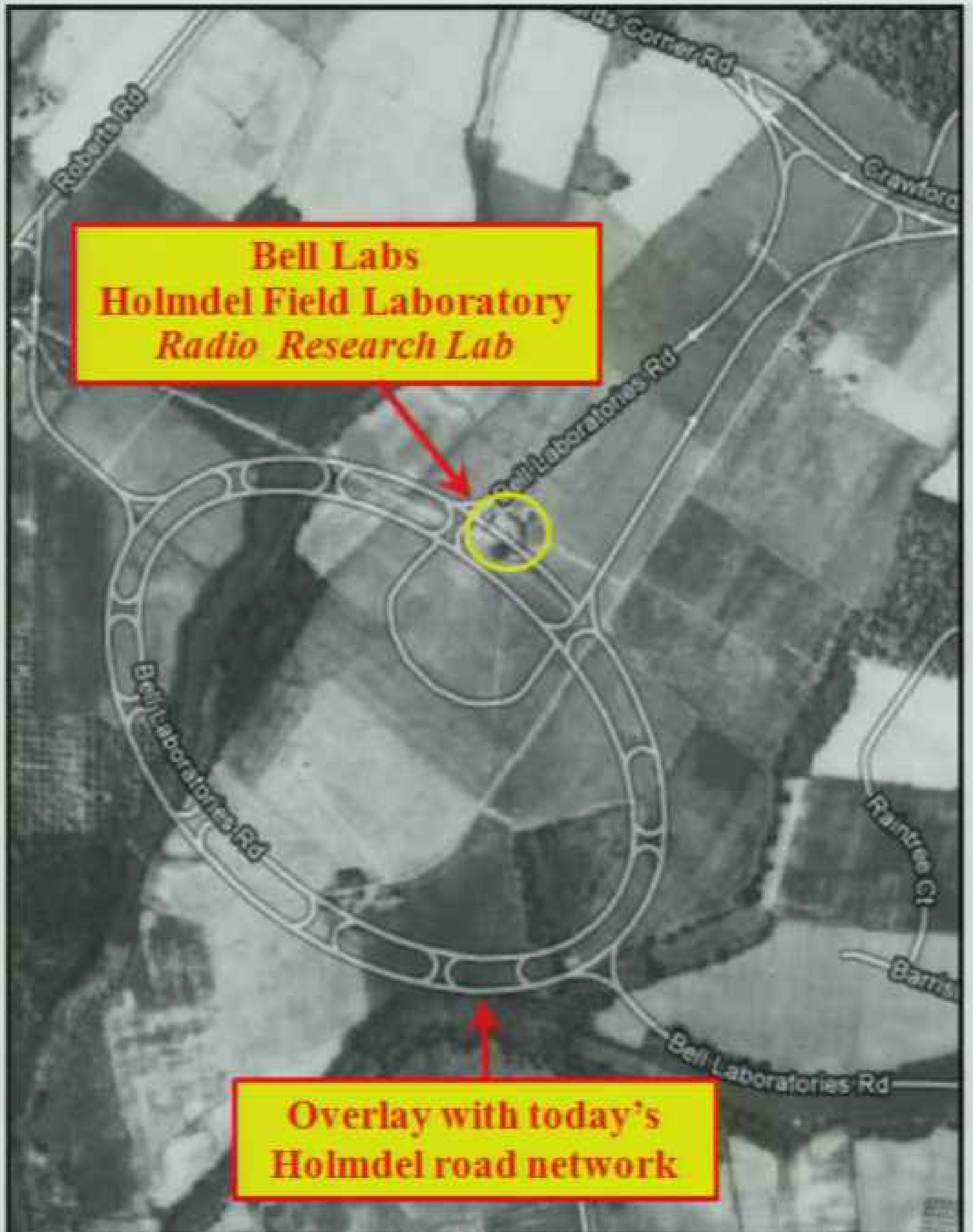

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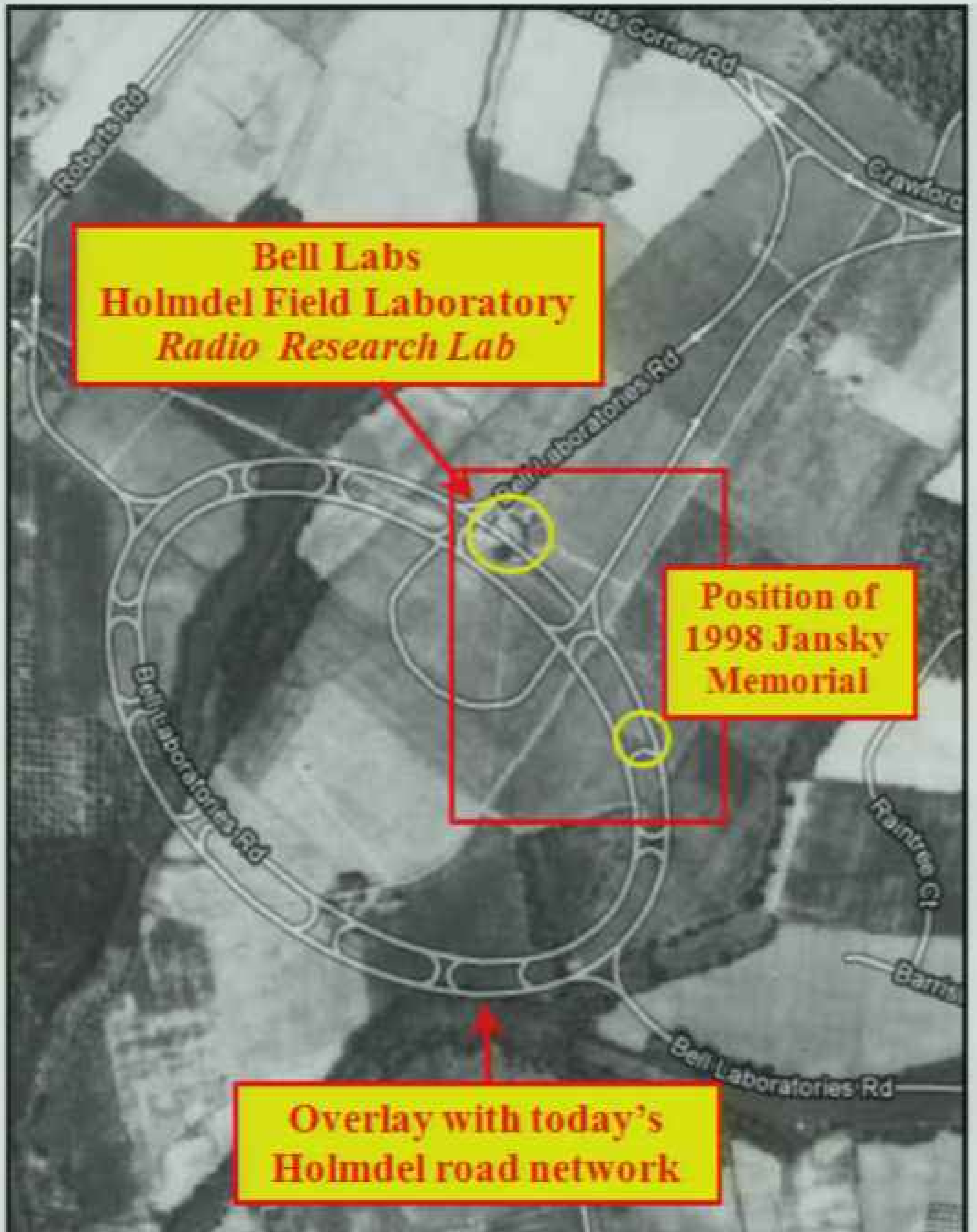

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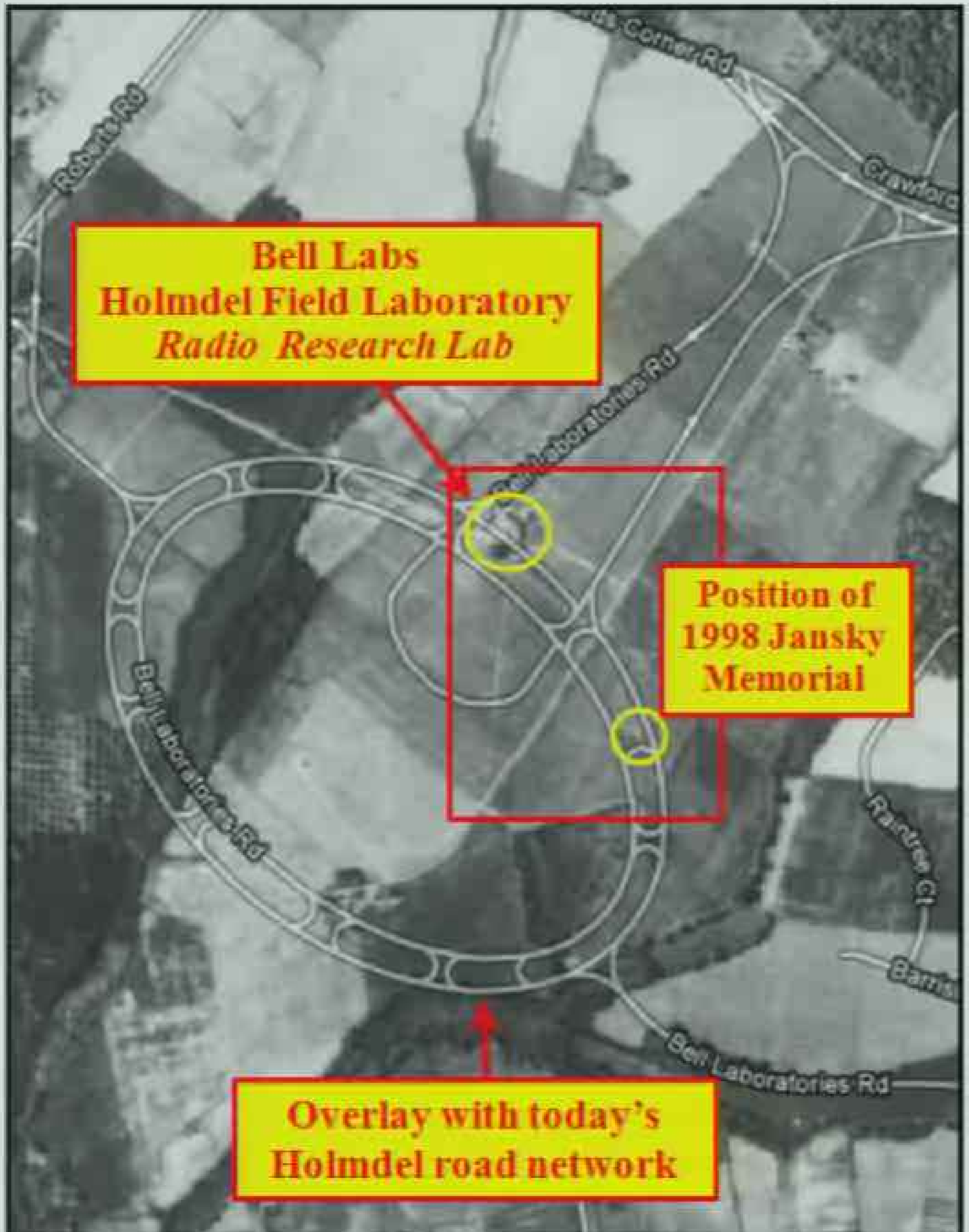

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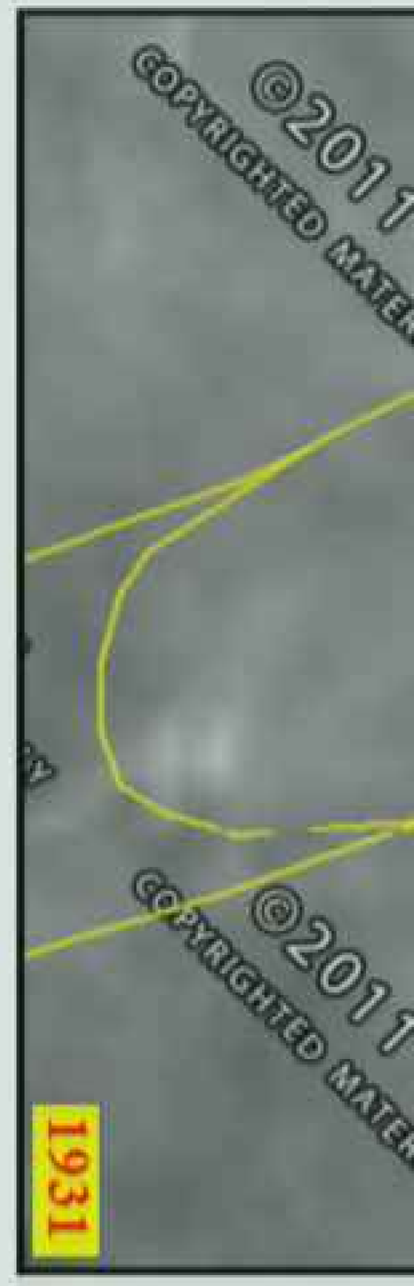

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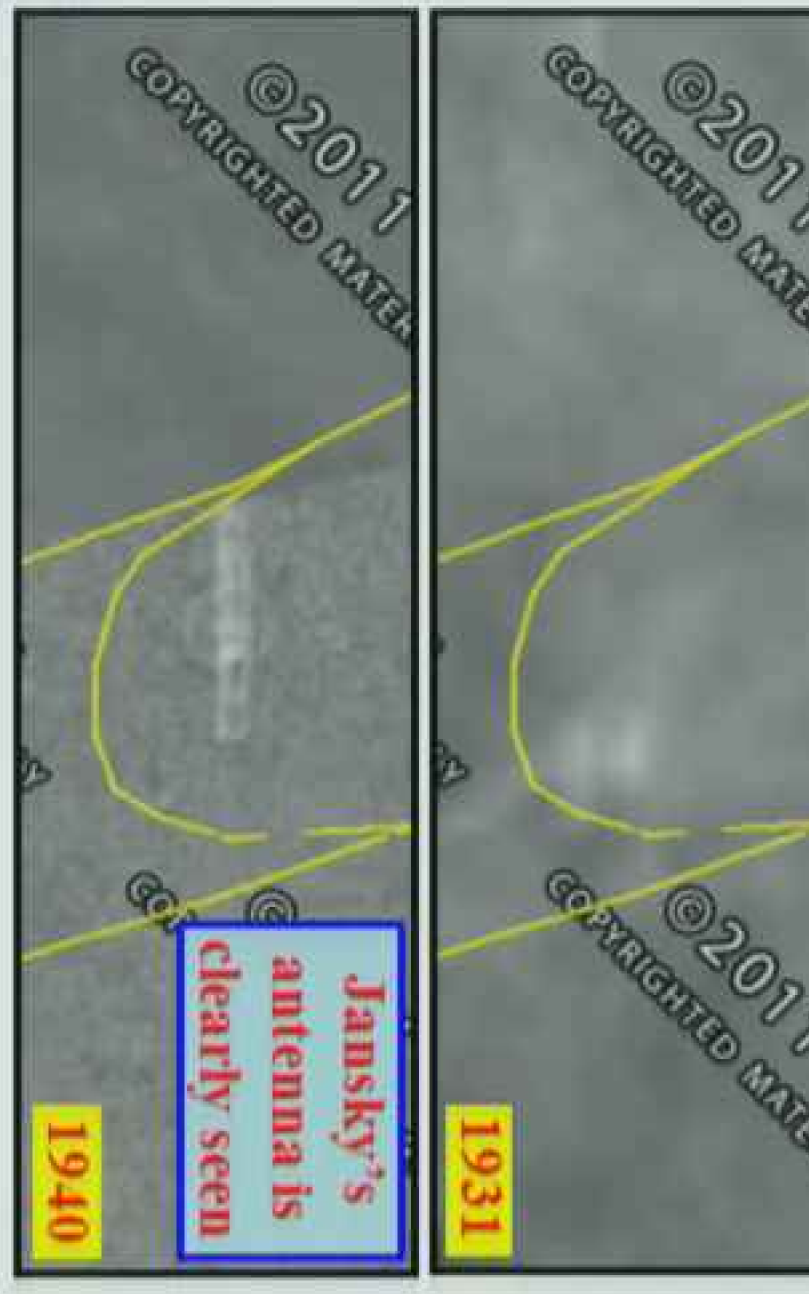

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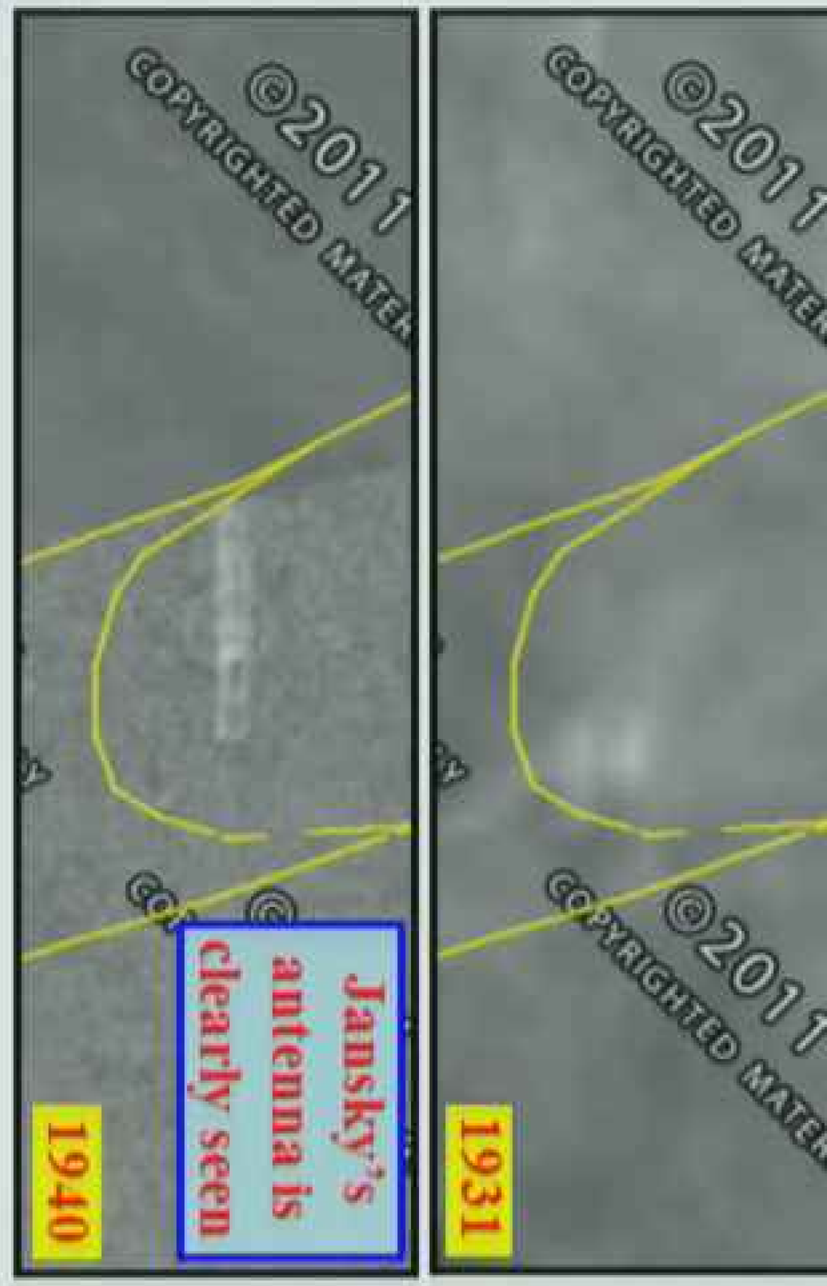

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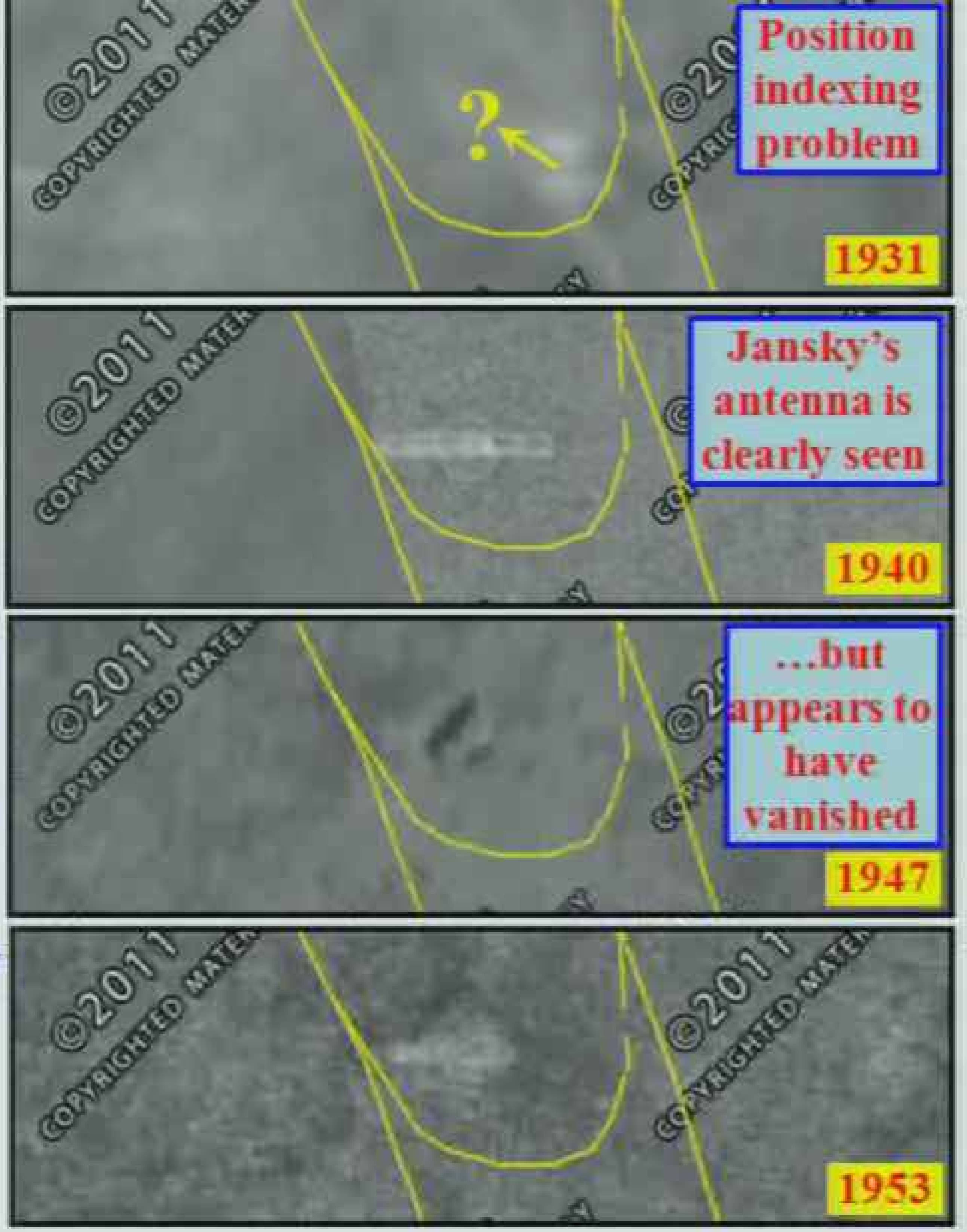

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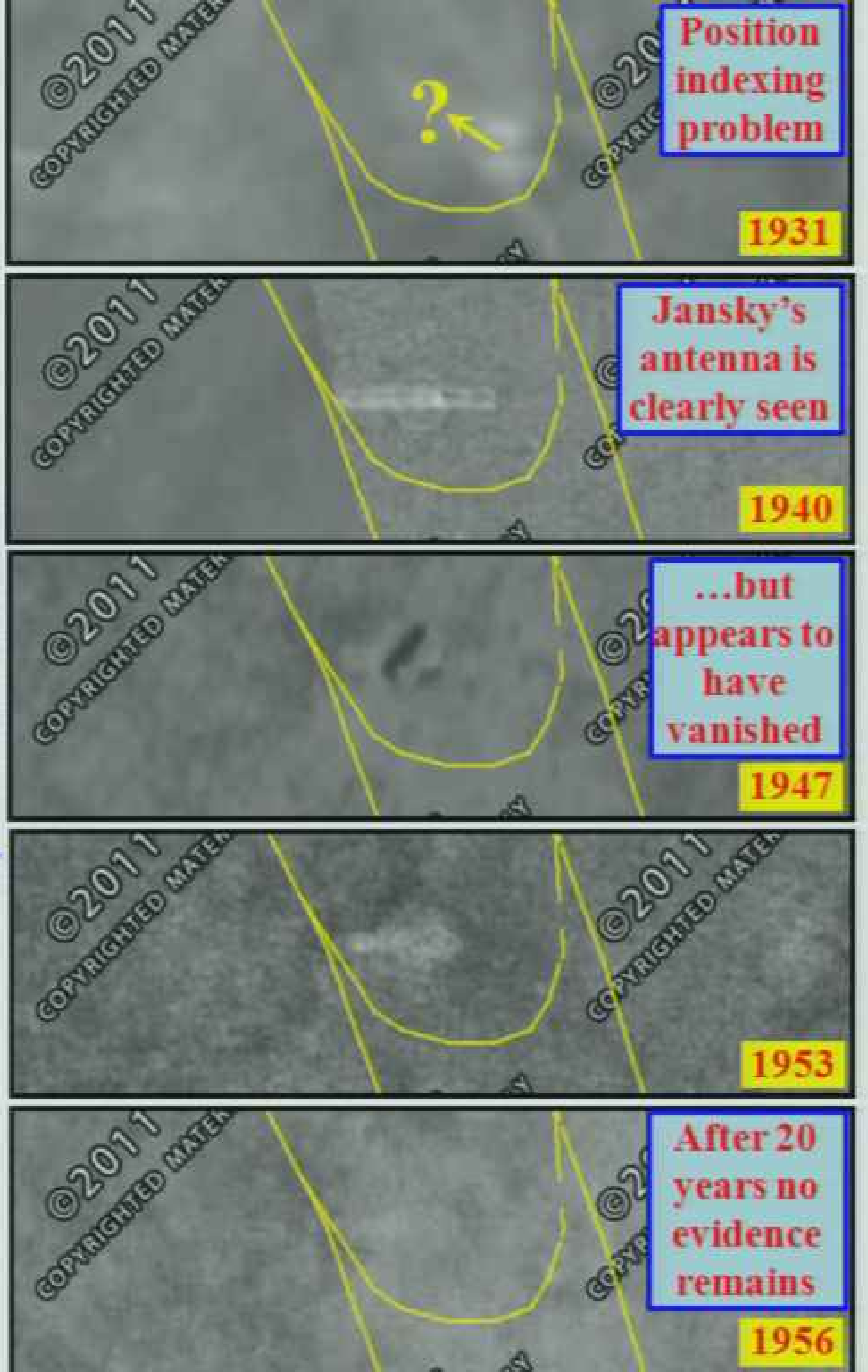

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High-altitude 1930s photo taken before MUSA built.

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

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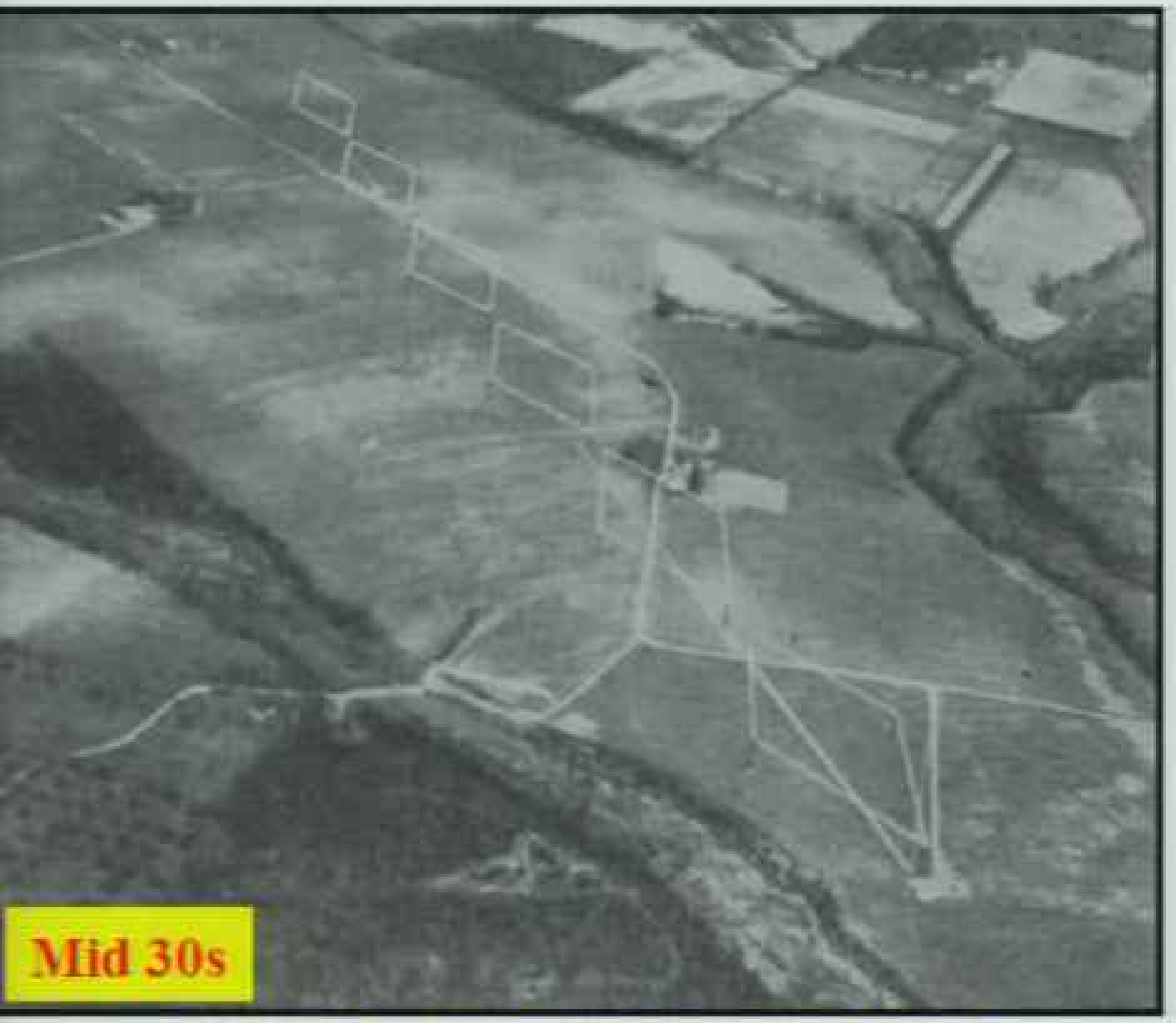

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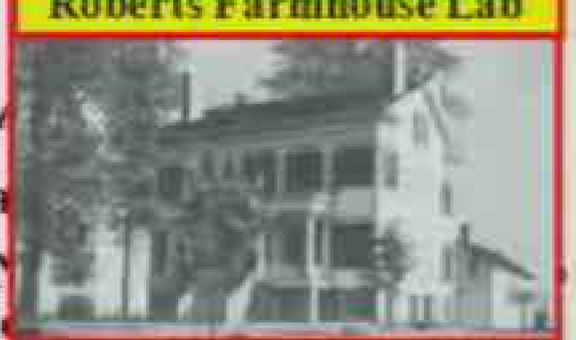

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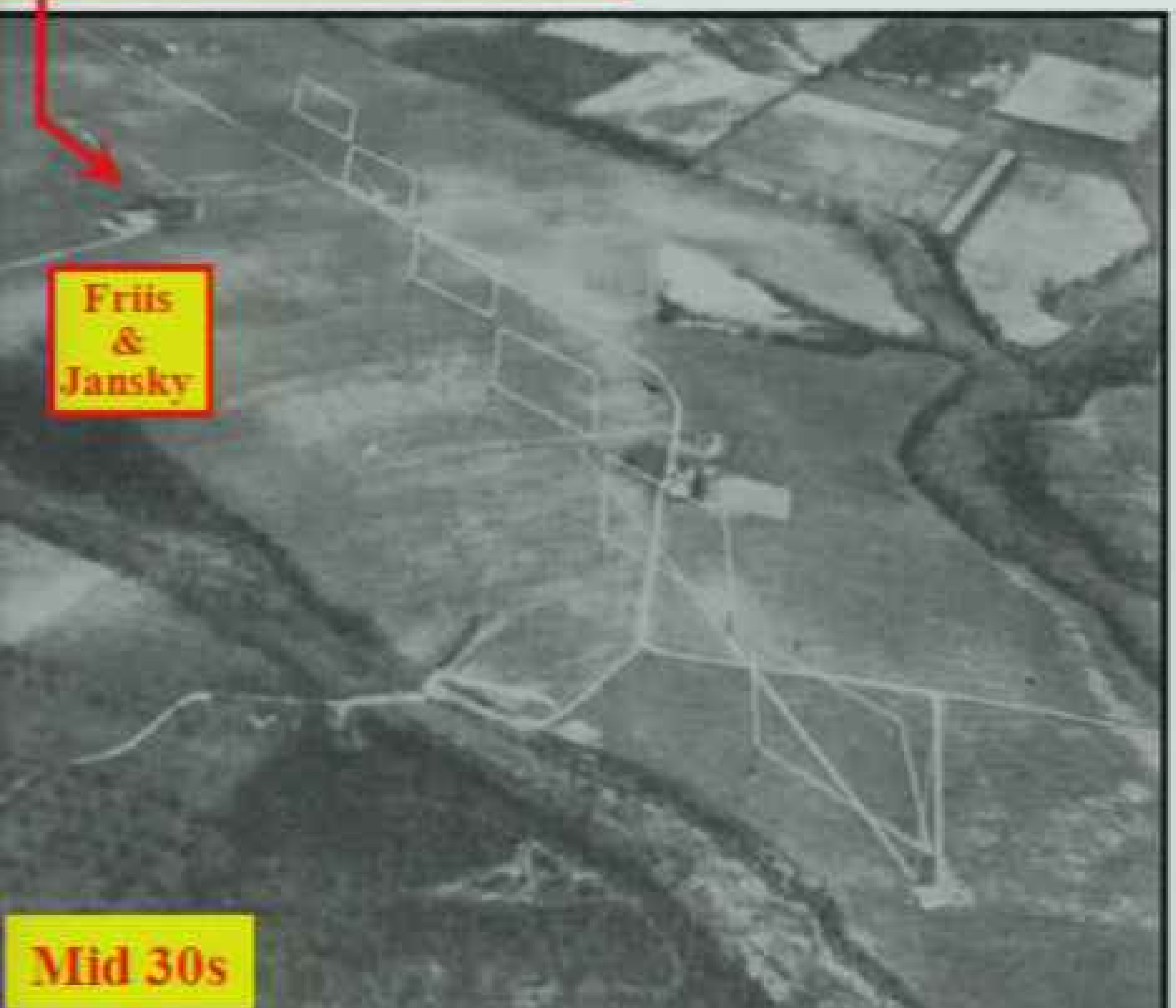

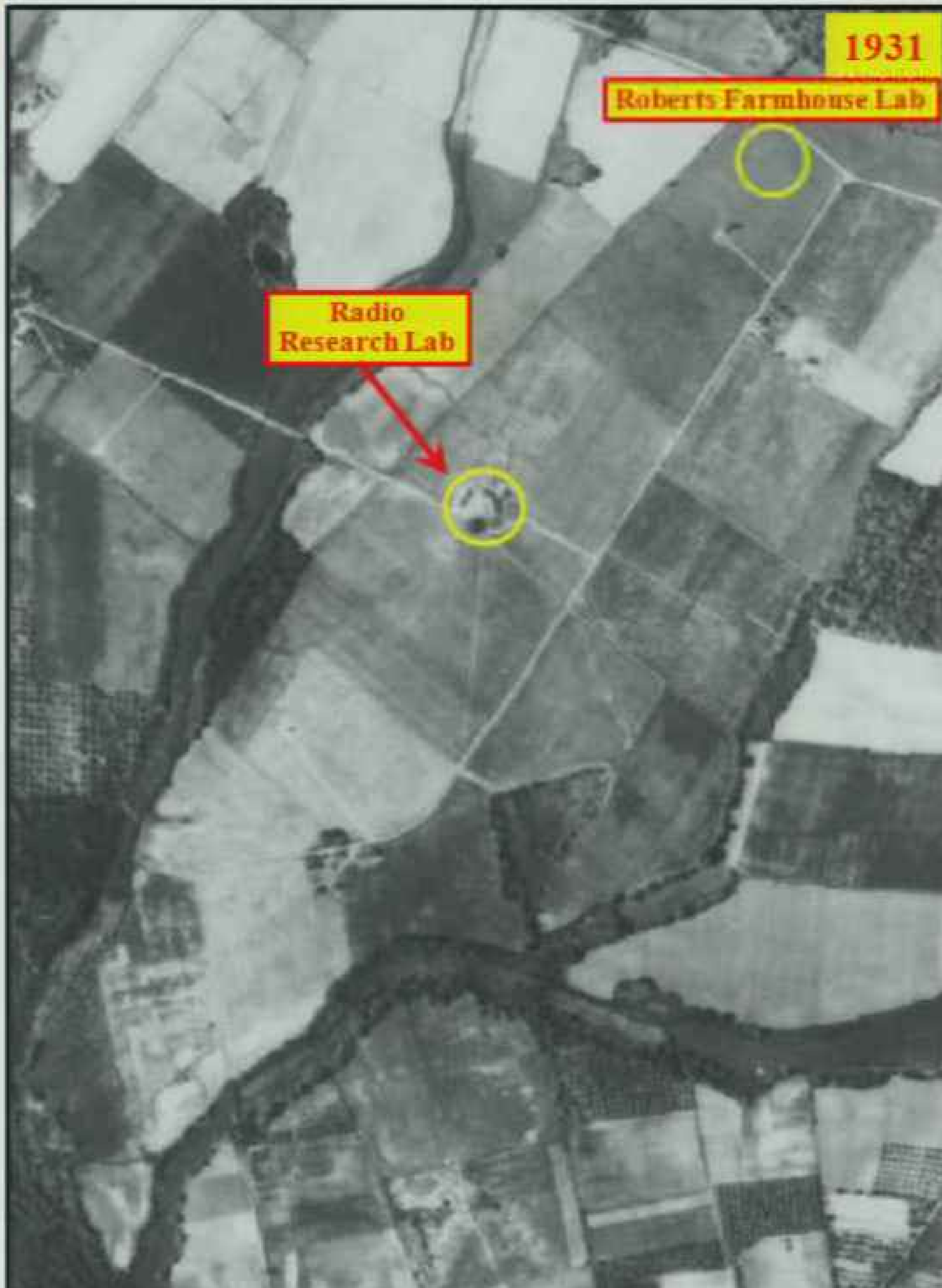

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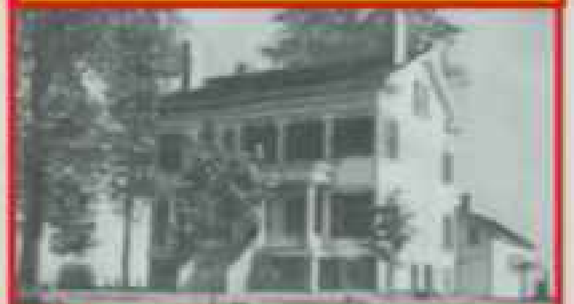

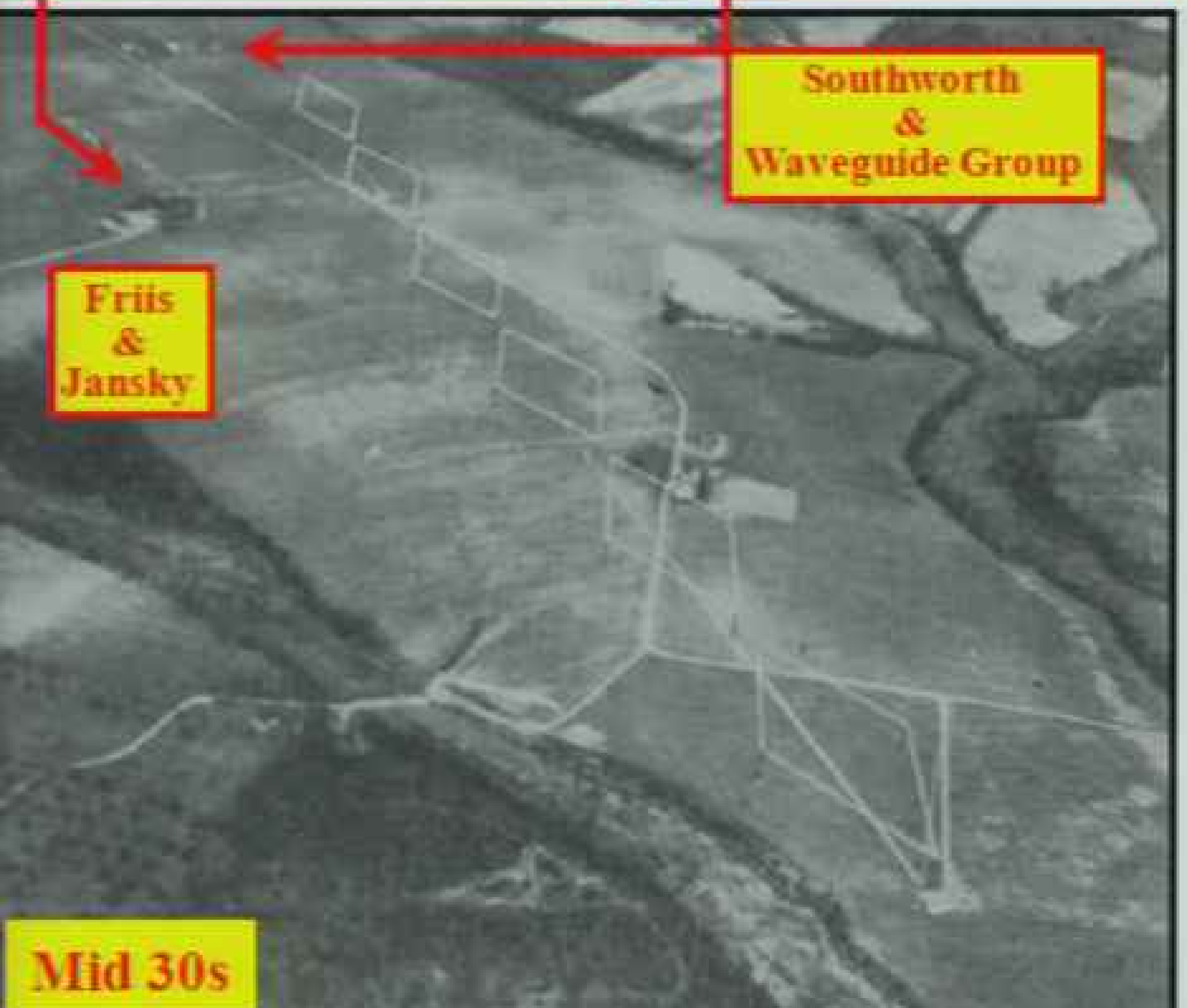

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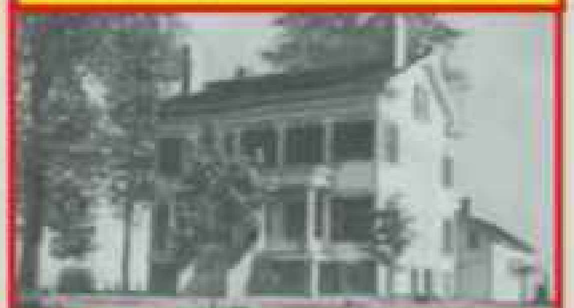

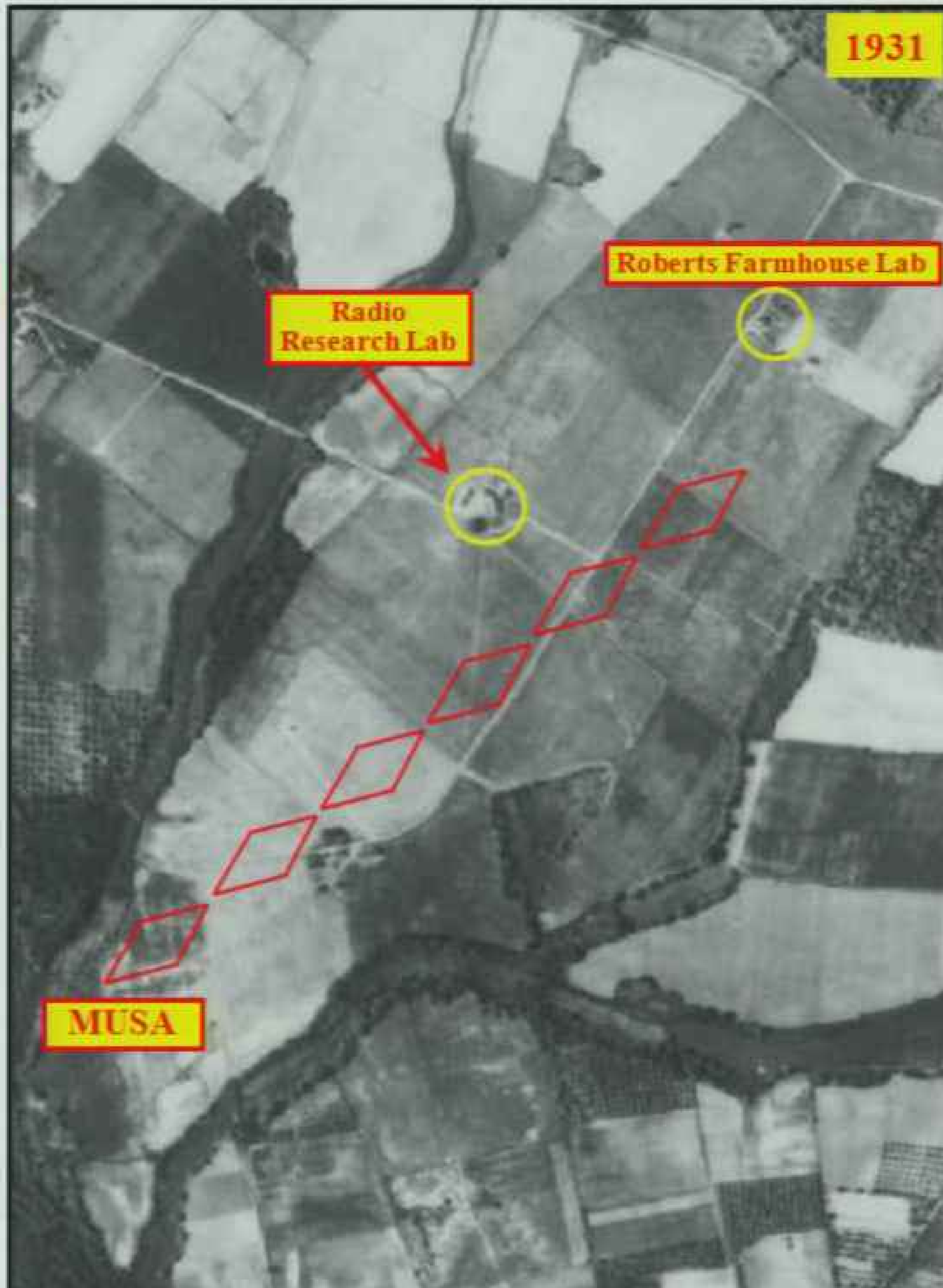

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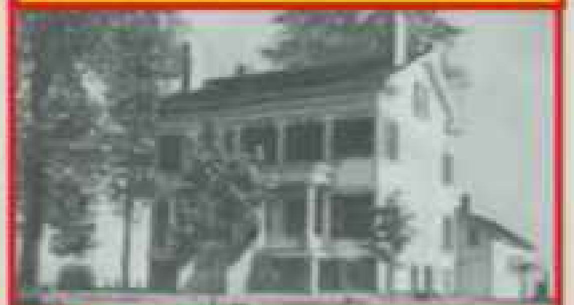

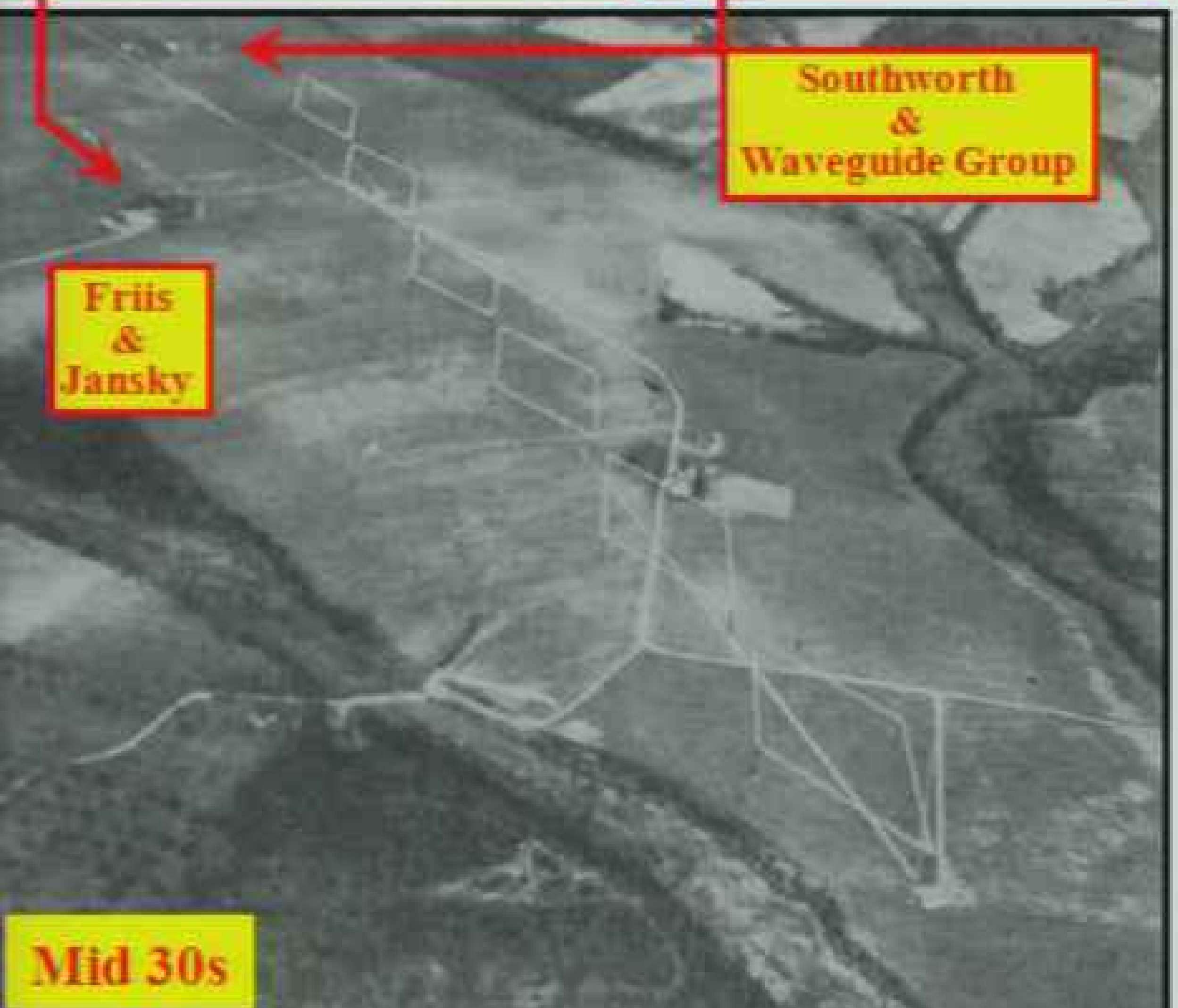

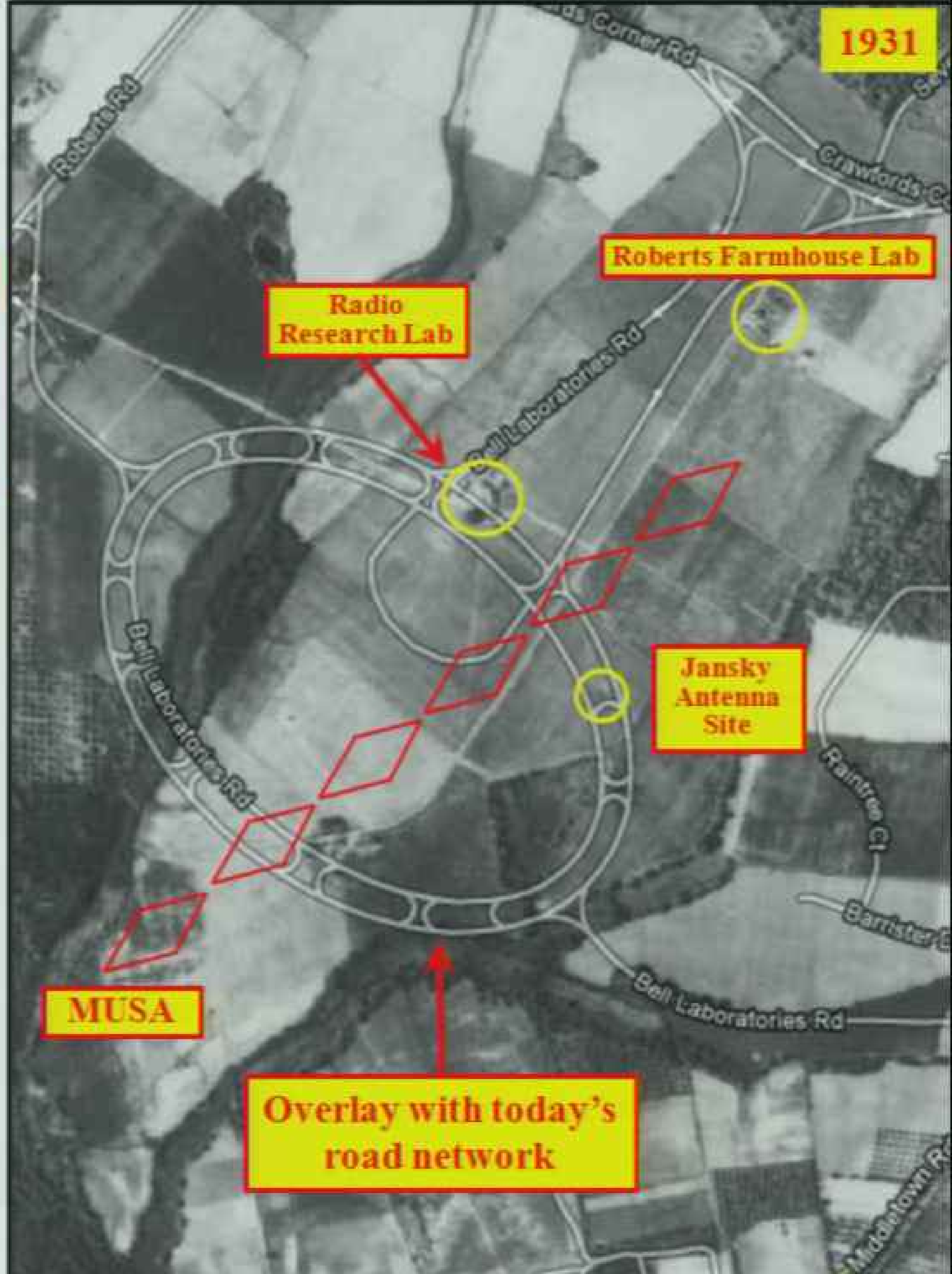

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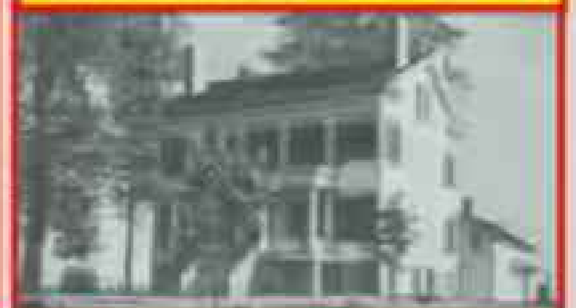

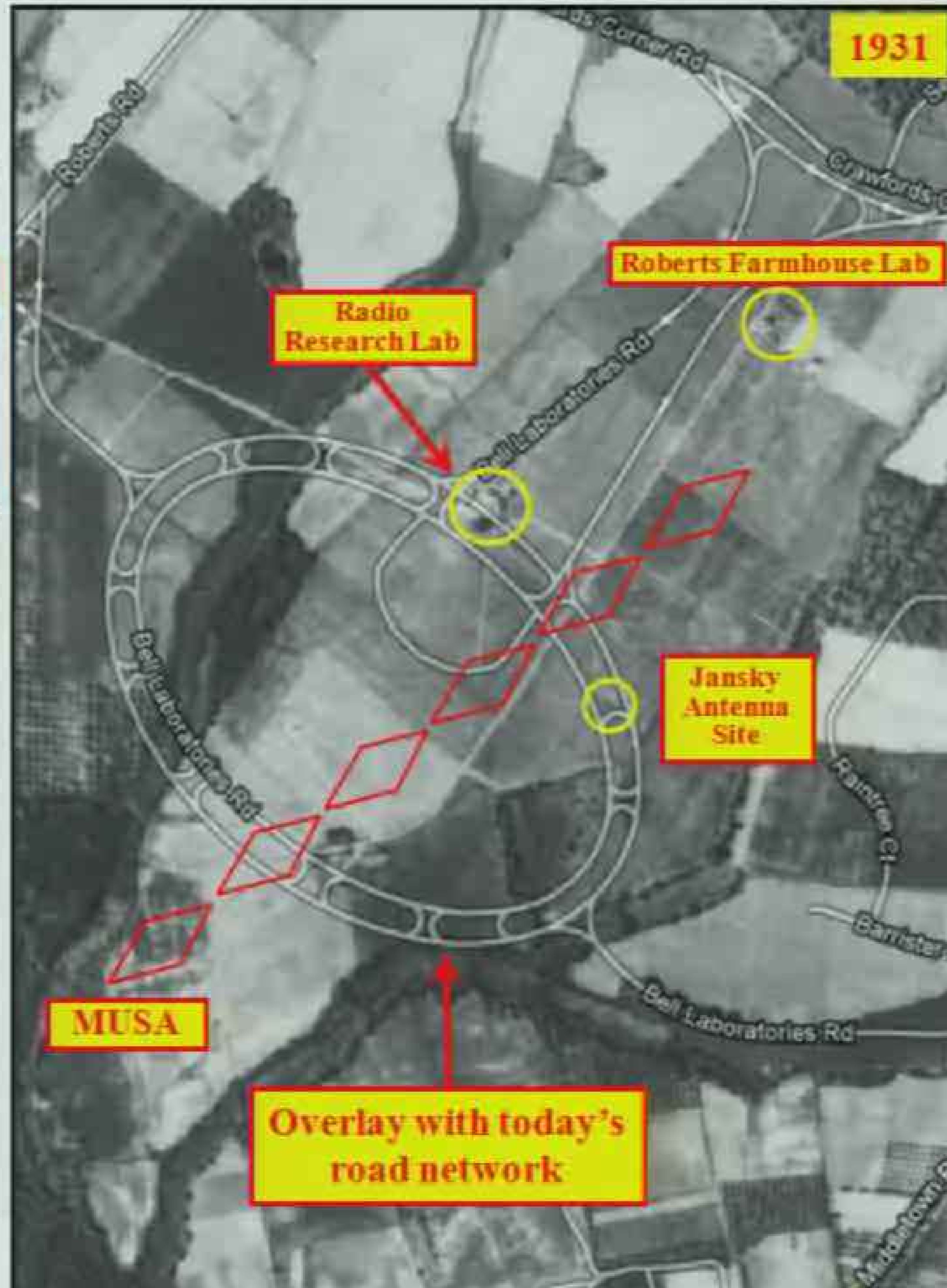

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- **The MUSA used a rather low frequency which was ideal for short-wave telephony.**
  - **But early radio telescopes did not operate all that much higher. Grote Reber's first successful observations in 1939 were at 160 MHz, the Australians were at 200 MHz, and Cambridge at 175 MHz and later at 80 MHz.**

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MUSA Legacy

The Musa Connector

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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

BELL LABORATORIES RECORD

Musa Apparatus

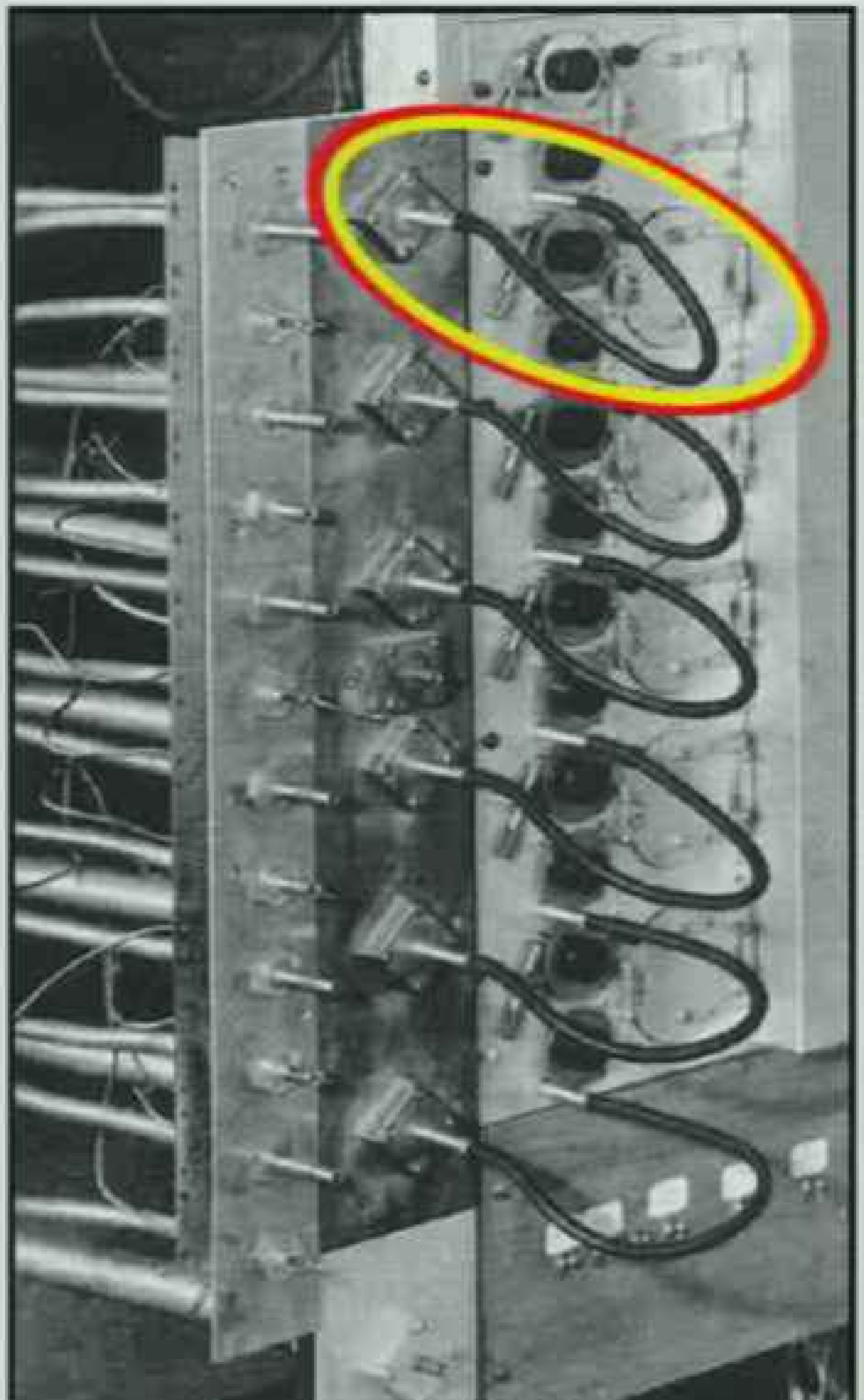
By W. M. SHARPLESS

Radio Research Department

JANUARY 1938

The MUSA Connector

Broadcast & Video Applications



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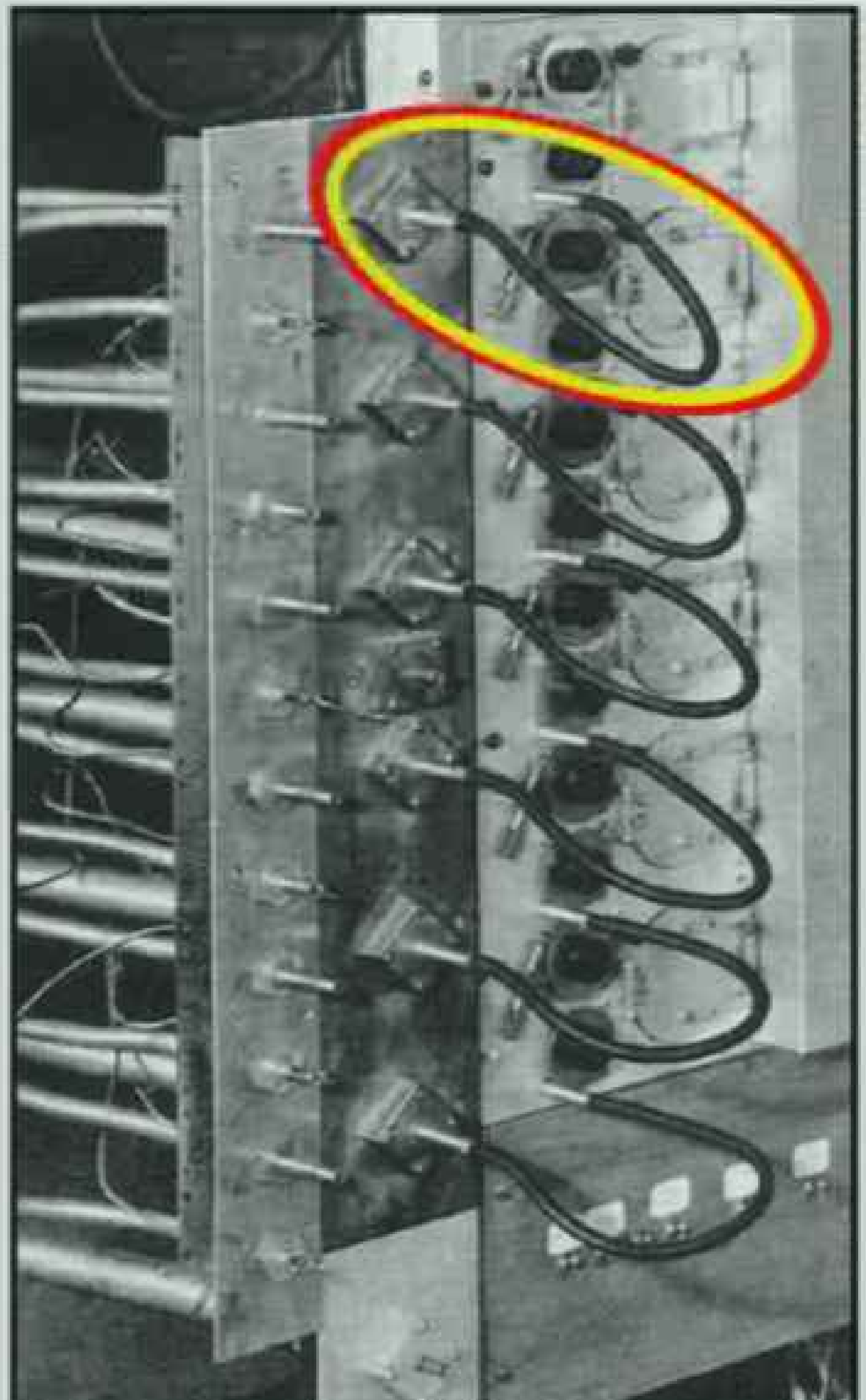

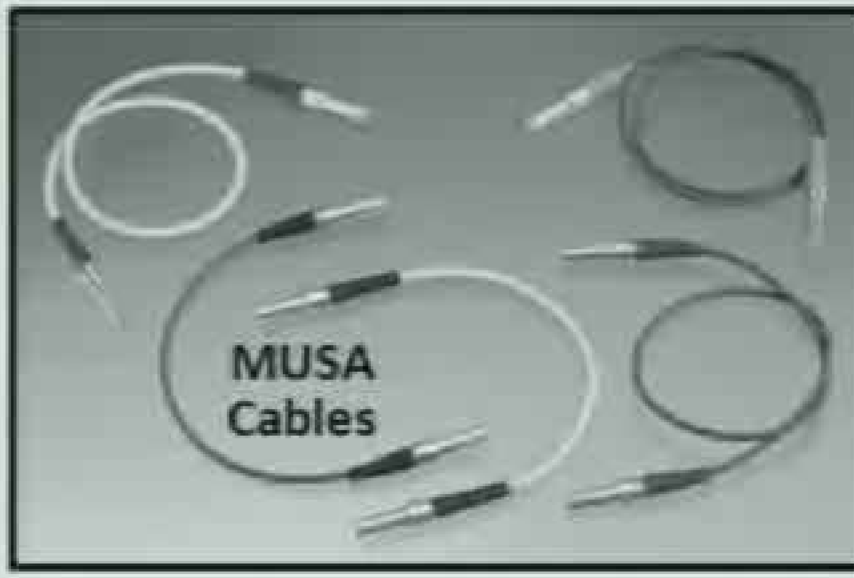

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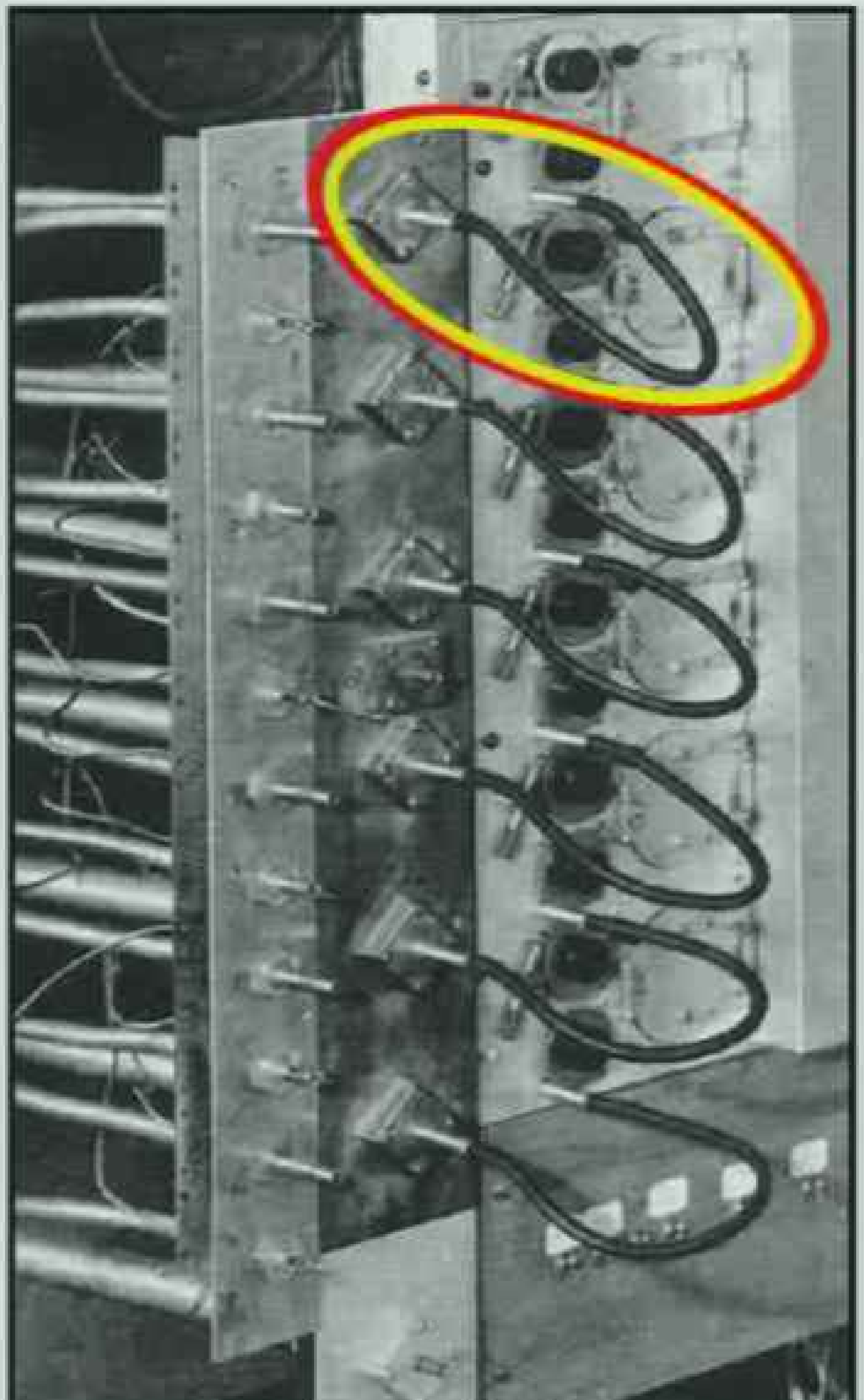

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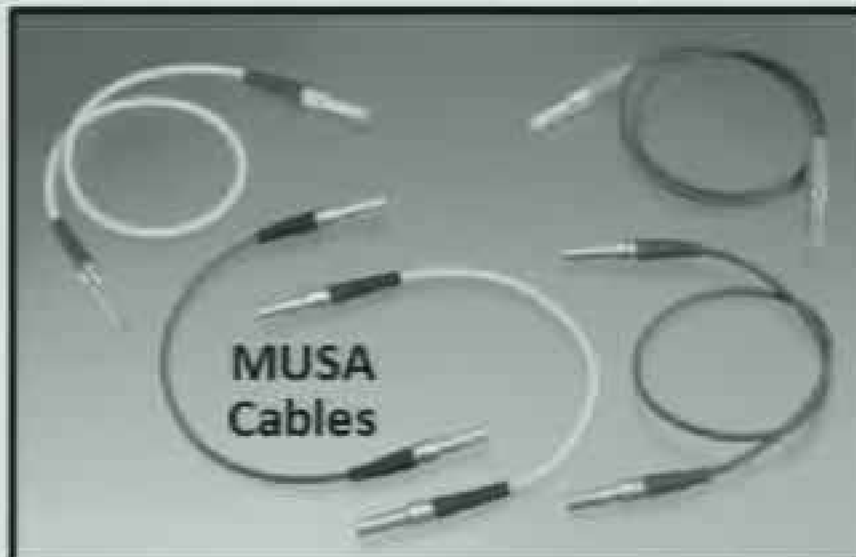

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- The Experimental MUSA's result was referenced by many of the pioneers in radio astronomy, including…
  - Jansky, Reber, Townes, Greenstein, Williamson, Hey, Bolton, Piddington, Shain, Ko, Sullivan & Kellermann
  - But surprisingly (or perhaps not) 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.

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- 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 End

Postscript:

What came after the Bell Labs Experimental MUSA ?