1. An Introduction to Radar Systems

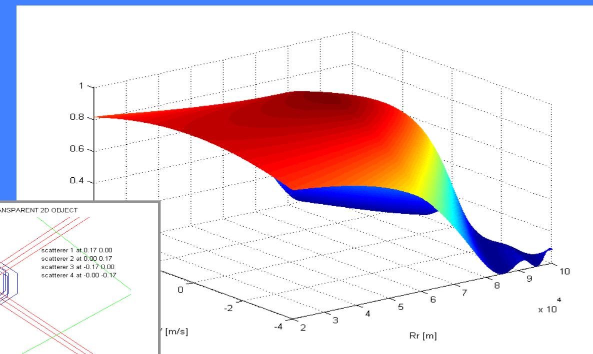
Chris Baker

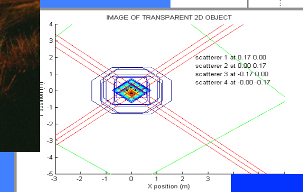
Education: Bsc Dip App Phys, PhD (1984) – All University of Hull, UK
Career: UK MoD, RSRE, DRA, DERA, QinetiQ, UCL, ANU, OSU
Research: Maritime Radar, Small target detection, Sea clutter, SAR, Imaging, Tomography, Bistatics, PBR, Multistatics, MIMO, Bio-Inspired sensing and Cognitive sensing.
Projects: RMPA, ASTOR, MSTAR plus 30 granted funded research projects
Publications: Over 200 conference and journal publications plus 7 book chapters
Service: Chair WDD 2004, RADAR 2007, Tech Chair for numerous conferences, Assoc Ed for IEEE AES and IET Radar, Sonar and Navigation
Professional: SMIEEE, Fellow IET, Fellow Eng Aus, DSAC (UK-MoD)
Prizes: IET Mountbatten Premium for best radar paper, 1991and 1994, IET Institution premium for best overall paper, 1998 IEEE International RADA2010, Best Paper

Current Research Interests

Research themes

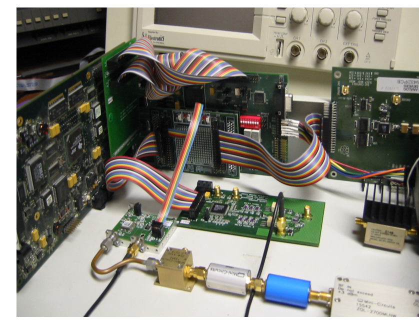
- Cognitive radar
- Target classification
- Netted and MIMO Radar
- Passive and Bistatic radar
- Imaging radar
- Radar resource management and tracking
- Narrowband radar
- Antenna arrays and Array signal processing

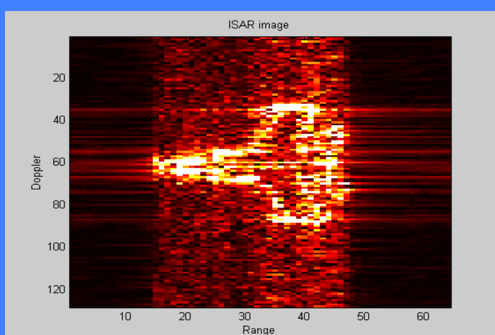


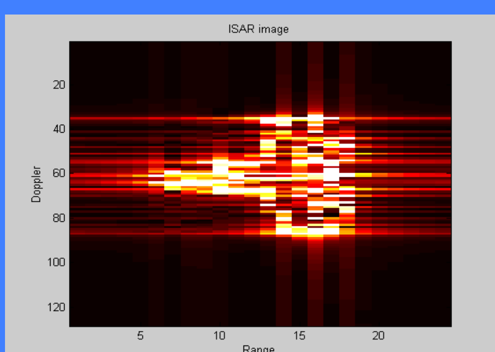


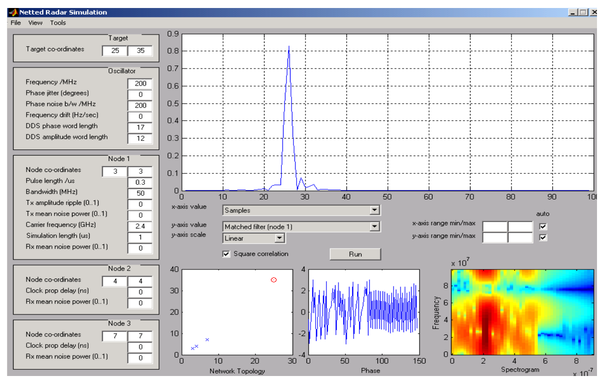
Collaboration

- AFRL
- AFOSR
- UCL, UCT
- Lockheed – Martin
- Raytheon
- Thales
- BAE
- Northrop – Grumman
- SEA



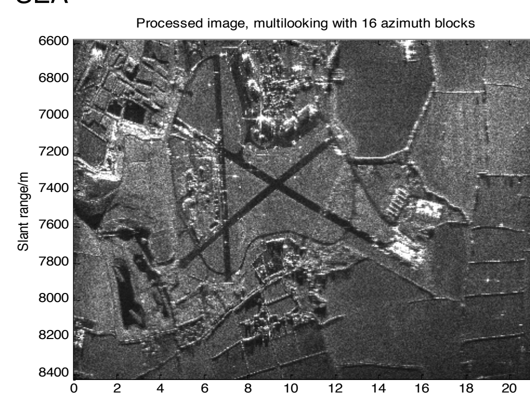






Facilities

- Radar system simulation and modelling
- Cognition Lab
- Anechoic chamber
- Radar design and construction
- Antenna design and construction
- SAR/ISAR processing



An Introduction to Radar Systems

Introduction
Radar basics
Radar equation
Noise and clutter
Displays
Receivers
Transmitters
Doppler and MTI
DPCA and STAP
FM radar
Pulse compression
Waveform diversity
Aviation radar
Secondary surveillance radar
Bistatic radar
Phased arrays
Tracking
SAR
High Resolution
Target Classification
Stealth
Emerging Trends

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Lecture notes: http://esl.eng.ohio-state.edu/~cbaker/ece5013.html

Course Objectives

To understand the principles of operation of modern radar systems

- Emphasis on physical principles
- Provide a jump off point to more detailed or specific radar sensing
- Emphasis on modern technology and signal processing methods
- New and emerging concepts

Course Textbooks

The formal course text book is:

M. A. Richards et al, ***Principles of Modern radar: Basic principles***, Scitech 2010,
ISBN: 9781891121524

and recommended supplementary reading may be found in:

Kingsley, S.P. and Quegan, S., ***Understanding Radar Systems***, McGraw-Hill, 1992
A British book, with an emphasis on concepts rather than details. Up-to-date and highly recommended. Hardback.

Stimson, G.W., ***Introduction to Airborne Radar*** (second edition), SciTech Publishing, 1998.
A well-known US book, whose first edition was published by the Hughes Aircraft Company. Treats the subject in a very conceptual manner, with lots of diagrams and pictures.

Many other textbooks have been written on many different aspects of radar. A selection of these, are as follows:

Other Textbooks

Skolnik, M.I. *Introduction to Radar Systems*, McGraw-Hill, 2003 (Third edition).
A highly-regarded introductory textbook covering the material at more than adequate depth and breadth. Available in paperback. A third edition has just been produced.

Skolnik, M.I. (ed), *Radar Handbook*
A comprehensive work. Hardback.

Levanon, N. *Radar Principles*, Wiley, 1988.
Written to accompany a university course on radar. Recommended. Hardback.

Barton, D.K., *Radars*, Artech House, 1978.
A seven-volume set of collected papers, covering (1) monopulse radar, (2) the radar equation, (3) pulse compression, (4) radar resolution and multipath effects, (5) radar clutter, (6) frequency agility and diversity and (7) CW and Doppler radar.

Nathanson, F.E. (ed.), *Radar Design Principles* (second edition), McGraw-Hill, 1991
A highly-regarded textbook with easy to understand explanations.

Woodward, P.M., *Probability and Information Theory, with Applications to Radar*, Pergamon Press, 1953; reprinted by Artech House, 1980
A classic little book which (amongst other things) introduces the concept of the ambiguity function.

Eaves, J.L. and Reedy, E.K., *Principles of Modern Radar*, Chapman & Hall, 1987.
Based on a course taught at Georgia Tech.

Swords, S., *Technical history of the beginnings of radar*, Peter Peregrinus,

1. Introduction and Historical background

James Clerk Maxwell (1831 – 1879) - predicted the existence of radio waves in his theory of electromagnetism

Hertz (1857 – 1894) confirmed by experiment that electromagnetic radio waves have the same velocity as light and can be reflected by metallic and dielectric bodies

The First Radar – Hülsmeyer, 1904

N° 13,170 **A.D. 1904**

Date of Application, 10th June, 1904—Accepted, 22nd Sept., 1904

COMPLETE SPECIFICATION.

"Hertzian-wave Projecting and Receiving Apparatus Adapted to Indicate or Give Warning of the Presence of a Metallic Body, such as a Ship or a Train, in the Line of Projection of such Waves".—

I, CHRISTIAN HÜLSMEYER of 3 Grabenstrasse, Düsseldorf, Germany, Engineer do hereby declare the nature of this invention and in what manner the same is to be performed to be particularly described and ascertained in and by the following statement:-

This invention consists, broadly, of improved apparatus for projecting electric waves in any desired direction combined with improved apparatus for receiving said waves when reflected back from any metallic body, such as a ship or a train, said receiving apparatus being adapted to put into action an audible or a visible signal and thus give warning of the presence of such metallic body in the line of projection of the waves.

My invention is based upon the property of electric waves of being reflected back towards their source on meeting a metallic body, and will be readily understood by imagining a transmitting and a receiving station such as indicated placed side by side at the same point and so arranged that waves projected from the transmitter can only actuate the receiver by being reflected from some metallic body, which, at sea, would presumably be another ship.

I have illustrated my invention in the accompanying drawing, in which:

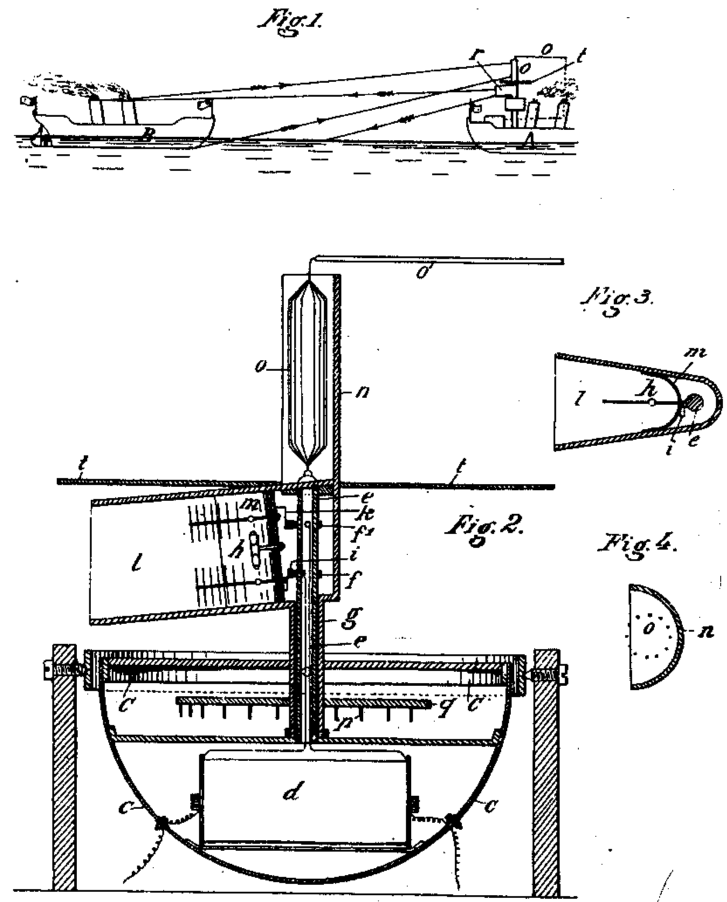
Fig. 1 is a diagrammatic view showing a ship A fitted with my apparatus, and a ship B whose presence is detected thereby.

Fig. 2 is a sectional view of the apparatus, and

Figs. 3 and 4 are sectional views of details thereof.

My apparatus comprises a transmitting and a receiving station similar to those used in wireless telegraphy, with this difference that the two stations are situated in close proximity to each other and are so arranged and constructed that they cannot directly influence one another. In view of the fact that ships are at times subject to considerable rolling, pitching and like motion, which might otherwise render the apparatus practically useless, I mount both the transmitter and receiver similarly to a compass-box, about as shown in Fig. 2, so that they are maintained by the action of gravity in an approximately vertical position. In the pivotally mounted hollow semi-sphere *c*, I also mount an induction coil *d*, the current from which actuates the transmitter. Said induction coil receives its primary current from any suitable source, for example, from accumulators, batteries, or from a dynamo generating either an alternating or a continuous current. In the case of a continuous current, I provide a suitable transformer. The secondary current of the induction coil *d* is conducted by wires through a hollow spindle *e* to two insulated rings f, f^1, fixed thereon. On said spindle *e*, I rotatably mount a sleeve or the like *g* wich carries or is integrally formed with a funnel-shaped reflector or screen *l* adapted to confine the electric waves emanating from the oscillator *h* and to assist in projecting them in any desired direction. The high tension and correspondingly insulated current from the induction coil is taken off the rings f, f^1 by means of brushes *i* and *k* and transmitted to the oscillator, immediately behind which and within the projector screen *l* a concave reflector *m* is mounted whereby

[*Price 8d.*]



The First Radar – Hülsmeyer, 1904

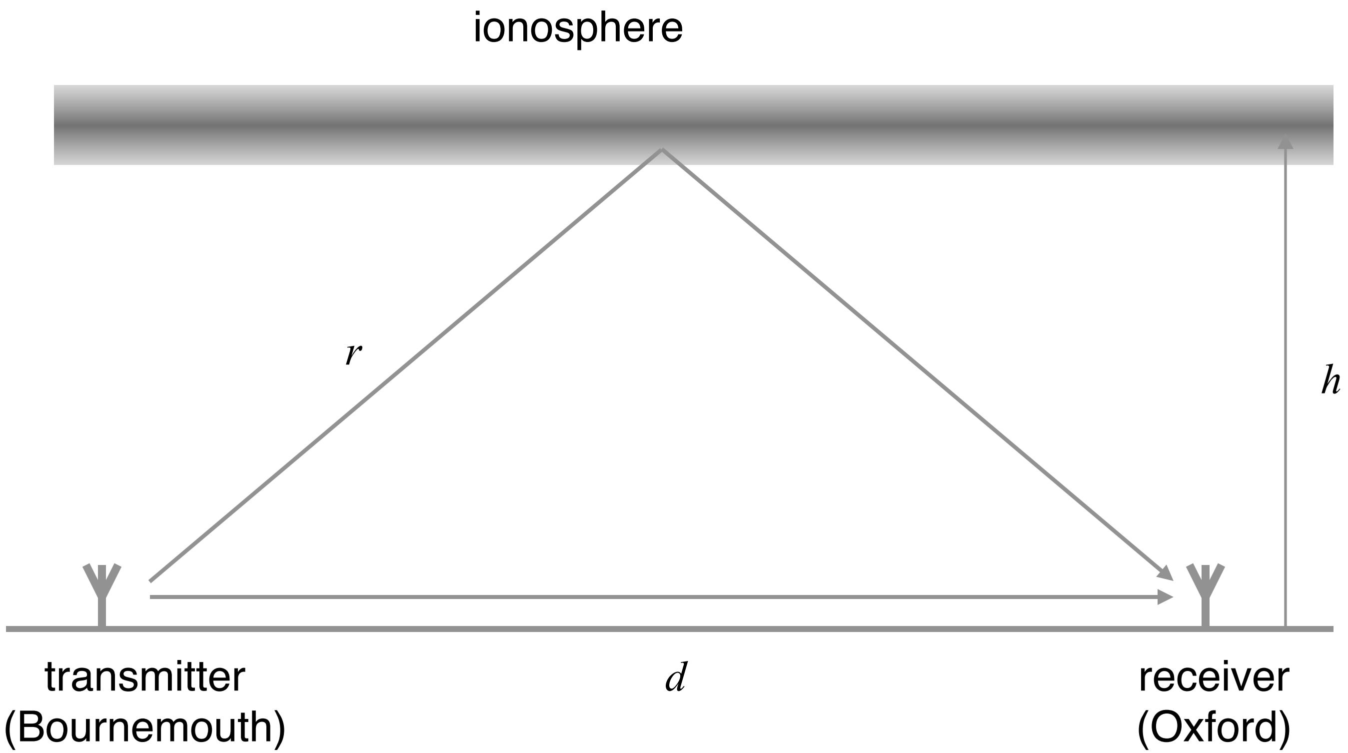
A little more history …

In the autumn of 1922, A.H. Taylor and L.C. Young of the Naval Research Laboratory in the USA demonstrated detection of a wooden ship using a CW wave-interference radar, at a wavelength of 5 m.

In December 1924, Appleton and Barnett in the UK used an FM radar technique to measure the height of the ionosphere, and the following year Breit and Tuve in the USA used a pulsed radar for the same purpose.

The first detection of aircraft using the wave-interference effect was made in 1930 by L.A. Hyland of the Naval Research Laboratory in the USA.

More history …



$$t = \frac{2r - d}{c} \qquad h = \frac{\sqrt{c^2t^2 + 2ctd}}{2}$$

Appleton, E.V. and Barnett, M.A.F., 'On some direct evidence for downward atmospheric reflection of electric rays', *Proc. Roy. Soc.,* Vol.109, pp261-641, December 1925. (experiments at end of 1924)

Acoustic Detection of Aircraft

Before the advent of radar, the only practicable means of detection of aircraft was acoustic, and a network of acoustic detectors was built in the 1920s and 1930s around the south and east coast of the UK, some of which still remain.

In calm air conditions, detection ranges of up to 25km were achievable.

Yet more history …

In 1935, Watson Watt had been asked by the UK Air Ministry to investigate the feasibility of electromagnetic 'death rays' to disable aircraft. He concluded, in an elegantly-reasoned piece, that it would not be feasible, but that detection of aircraft using radio waves should be possible. The same year he demonstrated detection of aircraft at a range of up to 8 miles in what has become known as 'the Daventry experiment', and by June 1935 he had demonstrated the pulsed radar technique to measure aircraft range.

Death Rays
(12 February 1935)

‘Suppose it is desired to produce physiological disablement in a man remaining for so long as ten minutes in the field of the beam, at a distance of 600 metres. He may be treated as composed simply of 75 kg of water. It is necessary to deliver, over his projected area of 1 sq metre (2 metres high × 1/2 metre wide) enough energy to raise his temperature by at least 2°C. Making the very unduly favourable assumptions of black body absorption, of 100% efficiency of conversion, without increased cooling by radiation and convection, the reasonable assumption of negligible absorption en route, and the unfavourable assumption of no aid from resonance in draining an area of front greater than the net projected area, it is necessary to deliver 1.5×10^4 cal/gm per minute. …..

…. It must be repeated that these figures depend on the target remaining within the field of a beam, not worse than 5° in semi-angle of divergence, i.e. within a transverse range of 100 metres at 600 metres distance, for ten minutes. The more practical assumption of one minute sends the required power up tenfold and seems to remove the whole scheme outside practicable limits.

Detection and location of aircraft by radio methods (27 February 1935)

‘Let it be assumed that the typical night-bomber is a metal-winged craft, well-bonded throughout, with a span of the order of 25 metres. The wing structure is, to a first approximation, a linear oscillator with a fundamental resonant wavelength of 50 metres and a low ohmic resistance. Suppose a ground emitting station be set up with a simple horizontal half-wave linear oscillator perpendicular to the line of approach of the craft and 18 metres above ground. Then a craft flying at a height of 6 km and at 6 km horizontal distance would be acted on by a resultant field of about 14 millivolts per metre, which would produce in the wing an oscillatory current of about 1½ milliamperes per ampere in sending aerial. The re-radiated or ‘reflected’ field returned to the vicinity of the sending aerial would be about 20 microvolts per metre per ampere in sending aerial. …..

…. If now the sender emits its energy in very brief pulse, equally spaced in time, as in the present technique of echo-sounding of the ionosphere, the distance between craft and sender may be measured directly by observation on a cathode ray oscillograph directly calibrated with a linear distance scale, the whole technique already being worked out for ionosphere work at Radio Research Station. …’

The Daventry Experiment (1935)

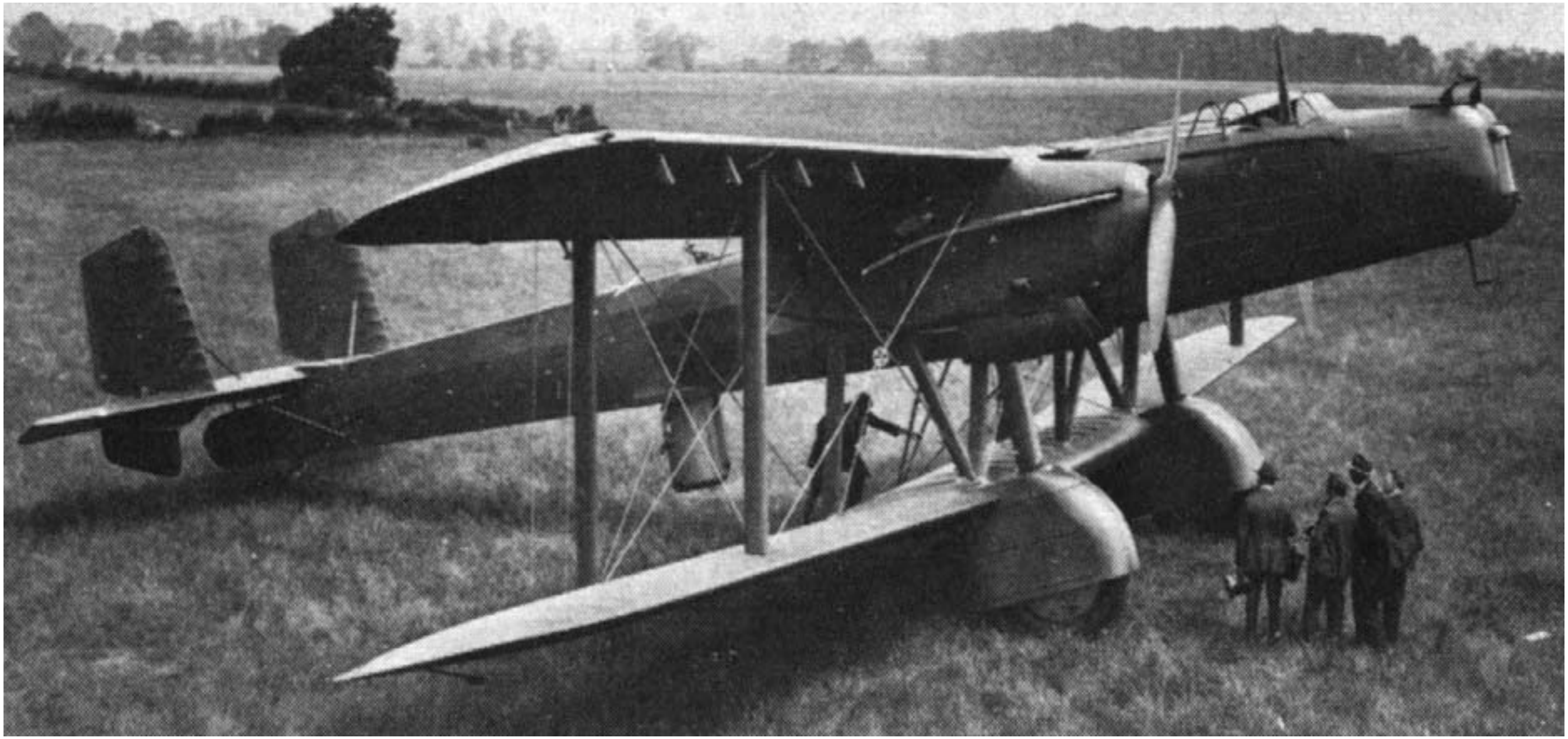
Honored guests, Watson-Watt and Hülsmeyer, at a radar conference, Frankfurt, 1953

Courtesy of A.O. Bauer, 15 January 2005, The Netherlands

After reviewing Hülsmeyer's 1904 invention, Watson-Watt stated,

I am the father of radar, whereas you are its grandfather.

The Daventry Experiment (1935)

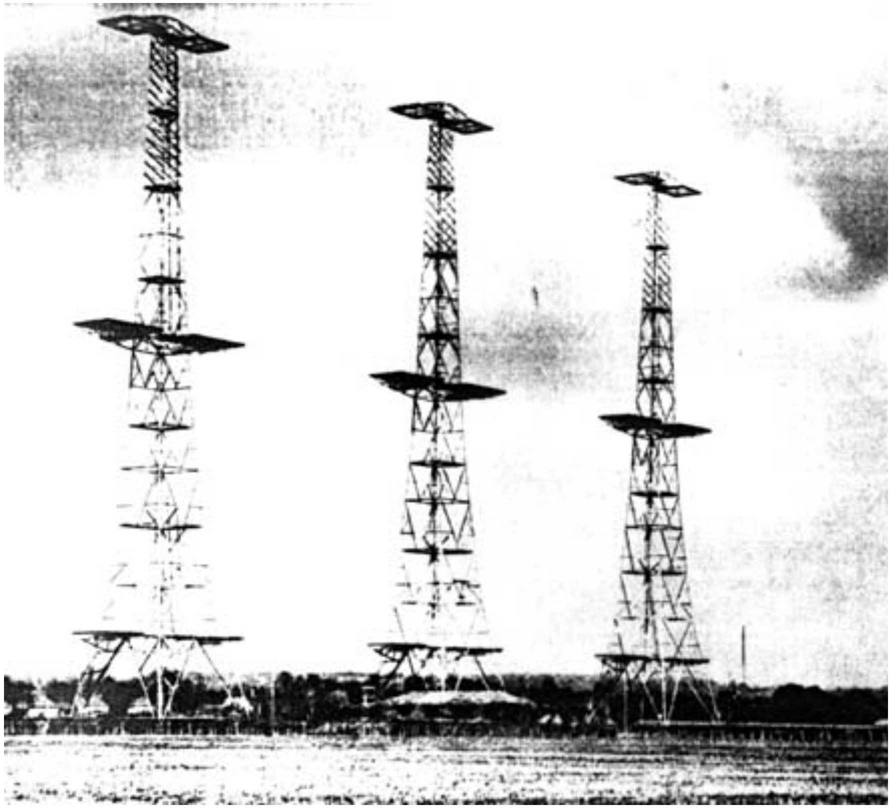


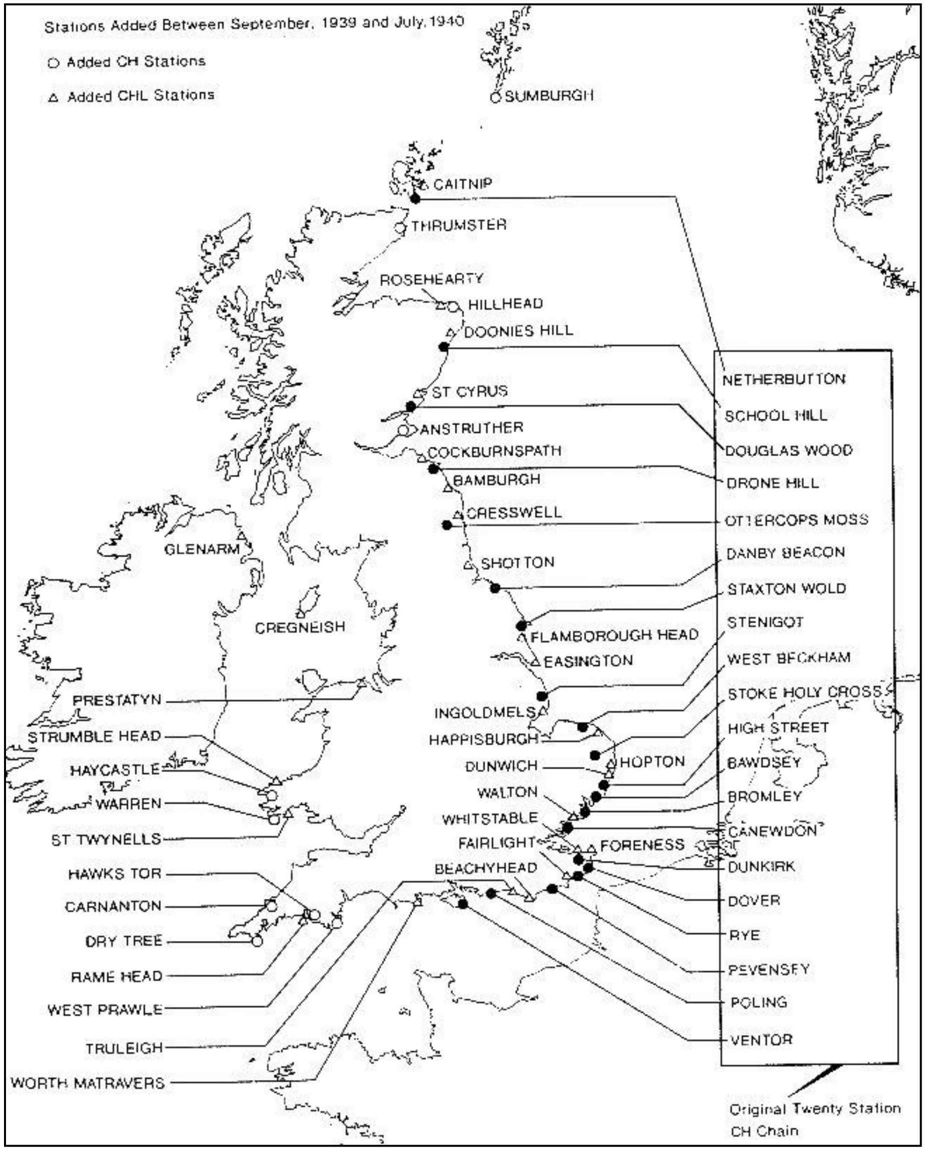
Bawdsey Manor

‘Plutôt mourir que changer’ (Rather die than change)

CHAIN HOME

CHAIN HOME





Stations Added Between September, 1939 and July, 1940
Added CH Stations
Added CHL Stations
SUMBURGH
CAITNIP
THRUMSTER
ROSEHEARTY
HILLHEAD
DOONIES HILL
ST CYRUS
ANSTRUTHER
COCKBURNSPATH
BAMBURGH
CRESSWELL
SHOTTON
GLENARM
CREGNEISH
FLAMBOROUGH HEAD
EASINGTON
PRESTATYN
INGOLDMELS
STRUMBLE HEAD
HAPPISBURGH
HOPTON
HAYCASTLE
DUNWICH
WARREN
WALTON
WHITSTABLE
ST TWYNELLS
FAIRLIGHT
FORENESS
BEACHYHEAD
HAWKS TOR
CARNANTON
DRY TREE
RAME HEAD
WEST PRAWLE
TRULEIGH
WORTH MATRAVERS
NETHERBUTTON
SCHOOL HILL
DOUGLAS WOOD
DRONE HILL
OTTERCOPS MOSS
DANBY BEACON
STAXTON WOLD
STENIGOT
WEST BECKHAM
STOKE HOLY CROSS
HIGH STREET
BAWDSEY
BROMLEY
CANEWDON
DUNKIRK
DOVER
RYE
PEVENSEY
POLING
VENTOR
Original Twenty Station CH Chain

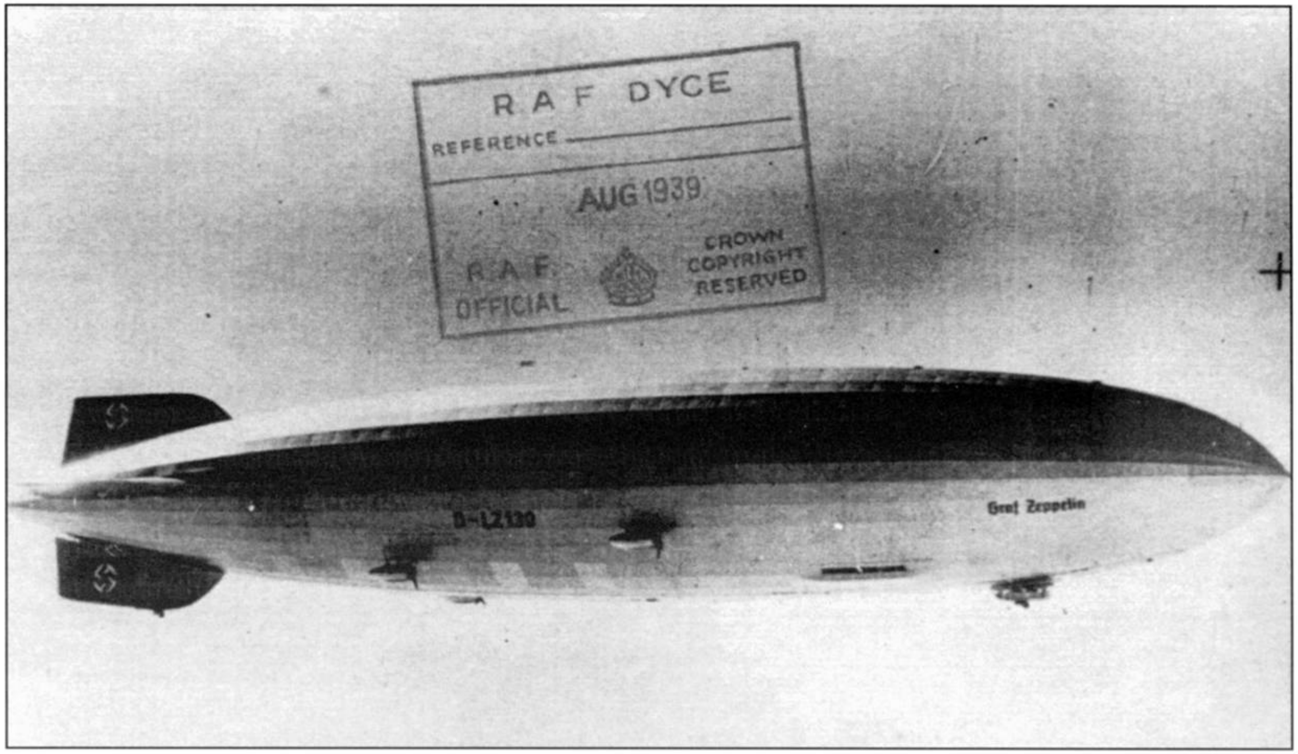
CHAIN HOME

CHAIN HOME

Radar Systems are more than just the radar

P.E. Judkins, *Making Vision into Power: Britain's Acquisition of the World's First Radar-based Integrated Air Defence System 1935 – 1941*,

Chain Home Countermeasures



A Graf Zeppelin airship (LZ-130) with signal interception equipment made an electronic intelligence-gathering mission up the North Sea on 2/3 August 1939, one month before the start of WW2 and (of course) saw the Chain Home stations and detected the Chain Home signals. But they concluded that the low frequency and the low PRF (25 Hz) must be associated with defective insulators on the National Grid, or to radionavigation or communications rather than radar - an expensive mistake.

The cavity magnetron

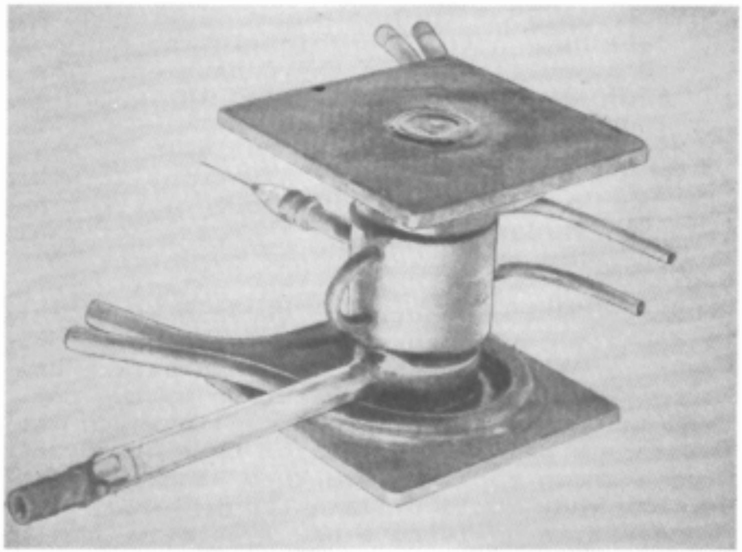
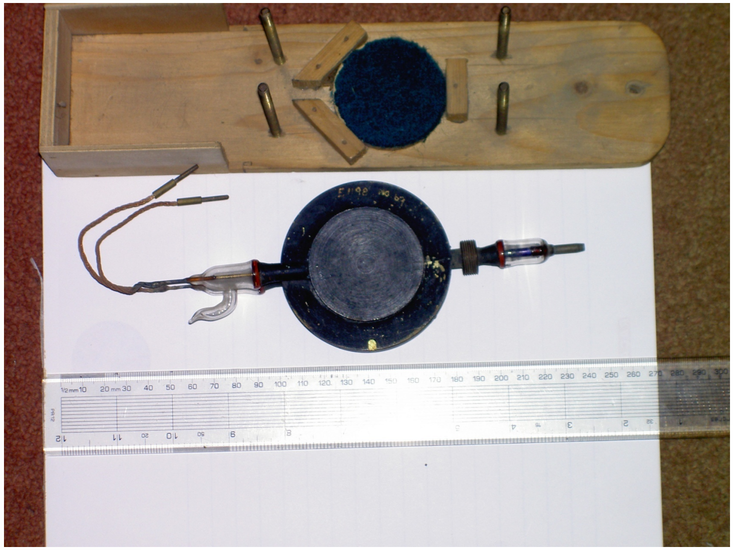
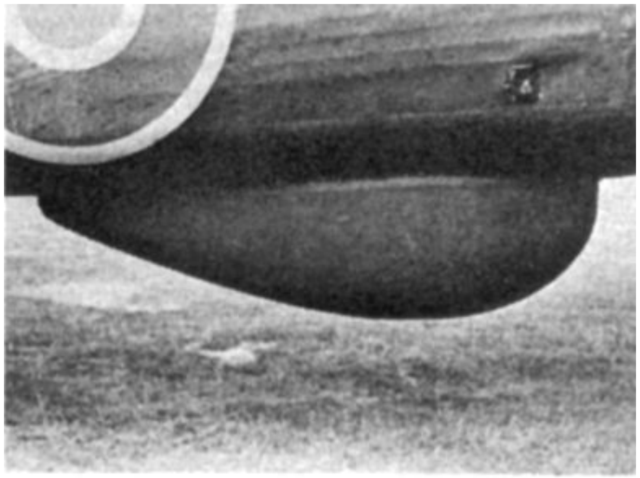


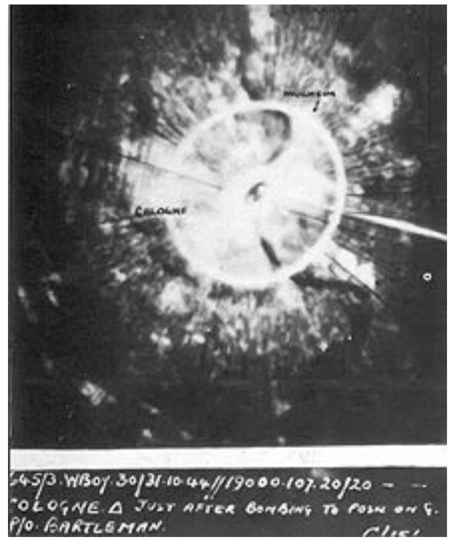
Fig. 19.7b *Anode block of first British 10cm magnetron*
GEC Journal of Research



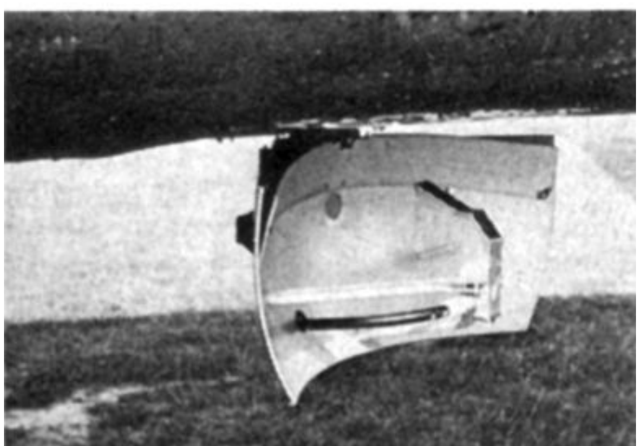
British and American Universities have a long and distinguished tradition of work in radar - the cavity magnetron was invented at the University of Birmingham in 1940.

H2S

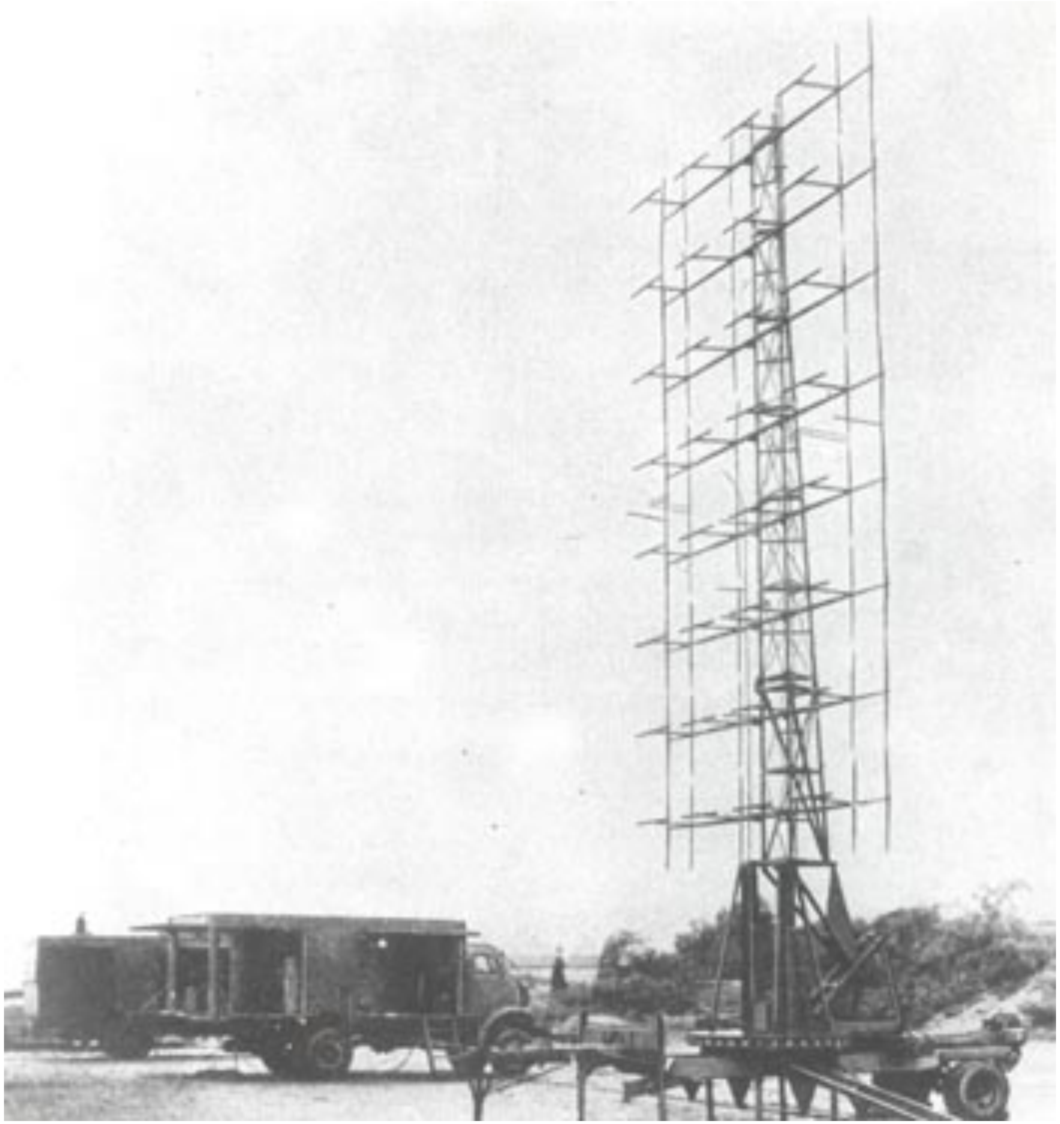



COLOGNE
JUST AFTER BOMBING
P/O. BARTLEMAN.

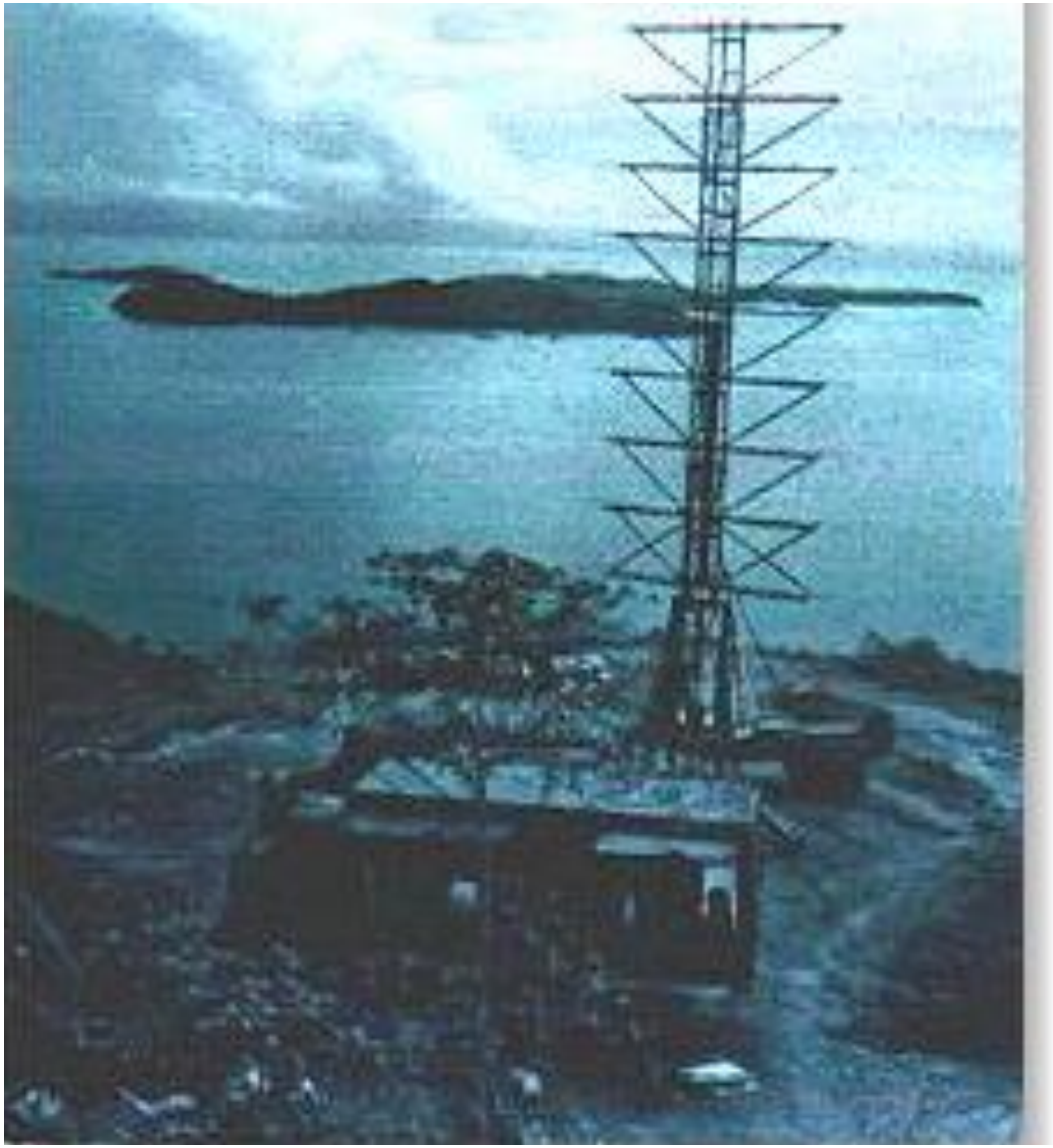

FRANKFURT.
F/L TOLCHARD.
G/82



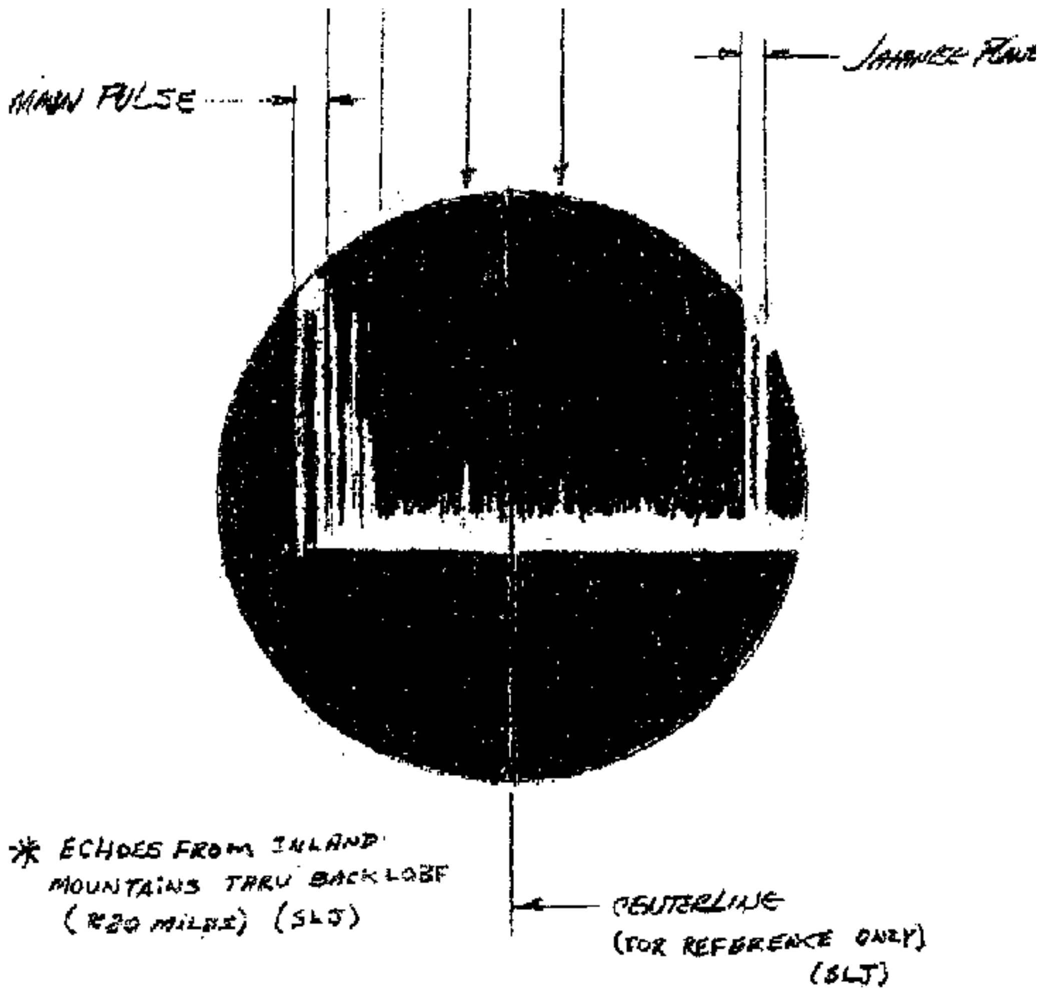
Early U.S. EW Radar: SCR-270



Early U.S. EW Radar: SCR-270



Early U.S. EW Radar: SCR-270 Pearl Harbor



Radar Screen at Opana Point 7:02AM on December 7, 1941

The name 'RADAR' (RAdio Detection And Ranging)

Copied from Louis Gebhard book on NRL 1979

UNCLASSIFIED

CLASSIFICATION CHANGED TO [illegible]
BY AUTHORITY OF Op-[illegible] Reference Authority
ON [illegible] (DATE) [illegible] Signature of Custodian

NAVY DEPARTMENT
OFFICE OF THE CHIEF OF NAVAL OPERATIONS
WASHINGTON

Op-20-Y/AB
(SC)A6/A1-1
Serial 069120
UNCLASSIFIED

Three photostats made by Comdr. [illegible] for [illegible] of "Radar" [illegible] 2/16/43.

From: Chief of Naval Operations
To : Chief of Bureau of Ships
Chief of Bureau of Aeronautics
Chief of Bureau of Ordnance
Director, Naval Research Laboratory
Chairman, General Board

Subject: Radio Detection and Ranging Equipment - Security Classification of and Approved Abbreviation for.

1. The type of radio equipment which has been developed under Special Project No. 1 and which has been referred to as "Radio Ranging Equipment", "Radio Detection Equipment", "Radio Echo Equipment", "Pulse Radio Equipment", etc., will hereafter be known as "Radio Detection and Ranging Equipment".

2. The detailed security classification of radio detection and ranging equipment is as follows:

(a) SECRET - The design of the equipment (other than the parts included in subparagraph (b)), the purpose for which the equipment is designed and the principles and methods of operation.

(b) CONFIDENTIAL - Those features which obviously cannot be kept secret, such as the design and installation of the antenna unit with its power elevating and training apparatus, the power supply for the equipment, the inter-connecting cables, and other items which do not disclose any information which is classified in subparagraph (a) as SECRET.

3. In order that radio detection and ranging equipment may be referred to in non-classified dispatches or correspondence (the contents of which do not violate the classification in paragraph 2), and also in conversation, the use of the abbreviation "RADAR" is authorized.

4. The urgency of delivery of this document is such that it will not reach the addressees in time by the next available officer courier. The originator, therefore, authorizes the transmission of this document by registered mail within the continental limits of the United States.

H. R. STARK

60834 (382)

THE WORD "RADAR"

The word "radar" was coined from "radio detection and ranging," one of the titles used by NRL for this field of work, by LCDR F.R. Furth and LCDR S.M. Tucker, who shared in responsibility for the Navy's original procurement program. LCDR Furth (later RADM Furth) and LCDR Tucker (later RADM Tucker), while on duty at the Navy Department, devised the acronym and took action to put it into effect. The above letter, dated 19 Nov. 1940, signed by ADM H.R. Stark, then the Chief of Naval Operations, made the word official. Later, both LCDR Furth and LCDR Tucker, as Captains, became directors of NRL (CAPT Furth, 1949 to 1952; CAPT Tucker, 1955 to 1956). CAPT Furth became the Chief of Naval Research as ADM Furth (1954 to 1956). The word radar quickly came into general use, although the British retained the terms "radiolocation" and "RDF" for their work in this field until 1943, when "radar" was adopted through international agreement.

THE OHIO STATE UNIVERSITY

1941-1967 TimeLine

- Invention of new model measurement techniques for antennas (Bill Everitt)
- Electro Science (then Antenna Lab) grows to 50 people by 1946 (under George Sinclair)
- Lasers and non-linear optics became an important research; “Lasers and Applications” symposium in 1962
- Time division multiple access for satellite communication demonstrated
- Concepts of wideband and frequency independent antennas introduced
- Radar Cross Section (RCS/Stealth) definition and related studies introduced, including Radome research

1941 — Antenna Laboratory is founded by W. L. Everitt. Later, his graduate student, George Sinclair, becomes the lab supervisor, and the lab grows to 50 employees.

1946 — Experimental program is moved to Tuttle Park Road.

1947 — First commercial spin-off company formed under supervisor Robert Jacques.

1948 — Professor Victor Rumsey becomes laboratory supervisor. Graduate students from this period become future leaders of ESL.

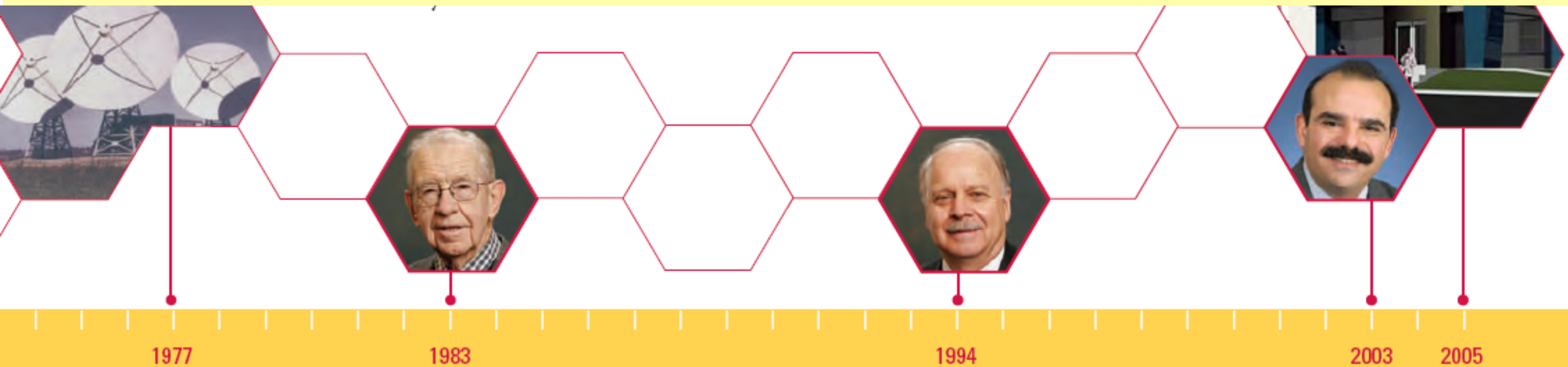
1955 — Experimental facilities moved to present location on Kinnear Road.

1964 — Addition to laboratory completed, doubling square footage.

1967 — Antenna Laboratory renamed ElectroScience Laboratory to reflect broad research programs.

1967-present

- Polarimetric imaging invented
- Uniform Theory of Diffraction invented, becoming the standard for high frequency EM analysis, leading to CAD tools that continue to define ESL's impact
- First ever integral equation solutions using modern computers---leading the way for CAD design as we know it today
- Compact Range measurement techniques invented, becoming the standard across the world
- Finite Element Methods established, and leading to the most popular CAD package in the market



1977 — ESL secures a joint service electromagnetics project (JSEP) under Director C. H. (Buck) Walter. This project (ended 1998) stands as the largest project in ESL history.

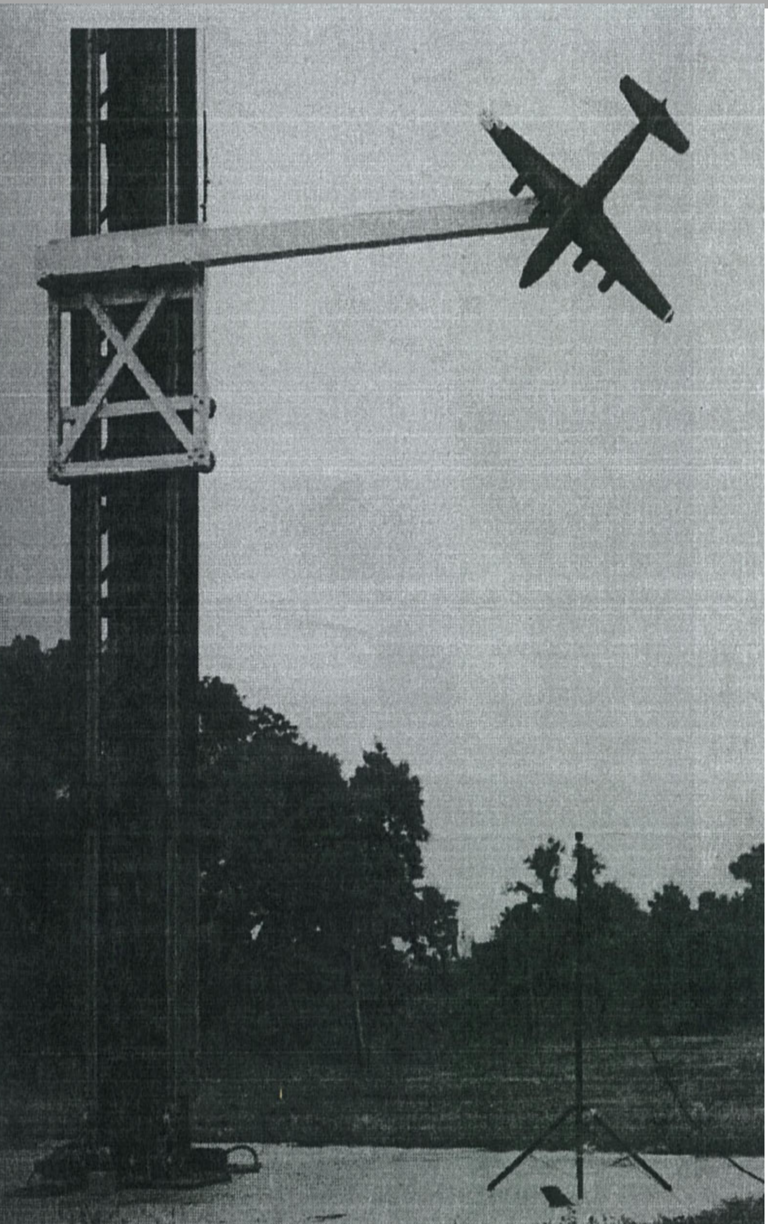
1983 — Professor Leon Peters becomes ESL director. Growth at the lab continues supported by major contracts from NASA and the Compact Range Consortium.

1994 — Professor Walter D. Burnside becomes ESL director. Significant growth takes place in industrial research causing it to reach nearly 50% of total funding.

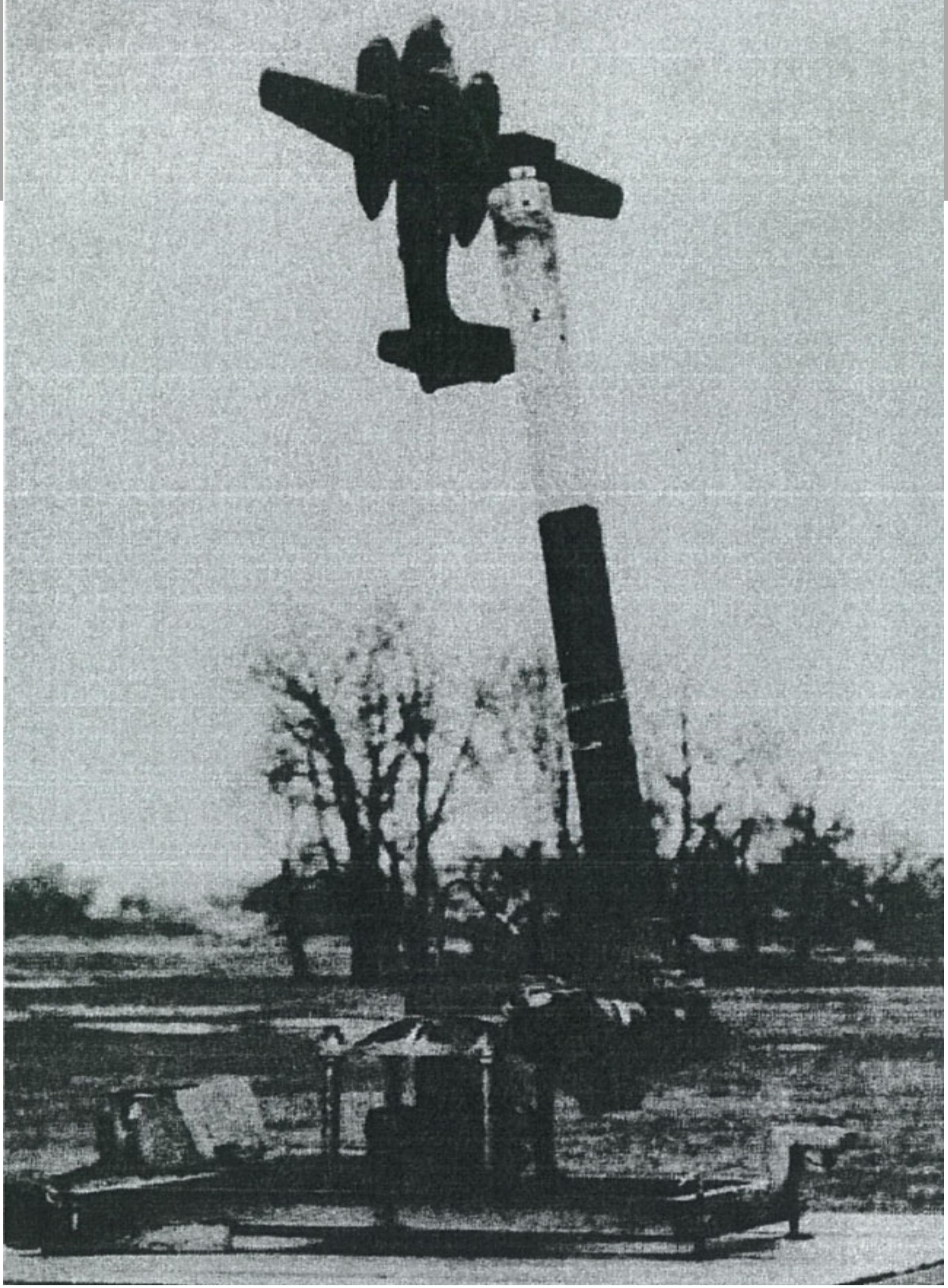
2003 — Professor John L. Volakis becomes director. ESL hosts its second IEEE Antennas and Propagation Symposium. Multidisciplinary Research Initiative (MURI) on Novel Materials for Antennas awarded.

2005 — ESL building is remodeled. College approves new ESL building financial plan.

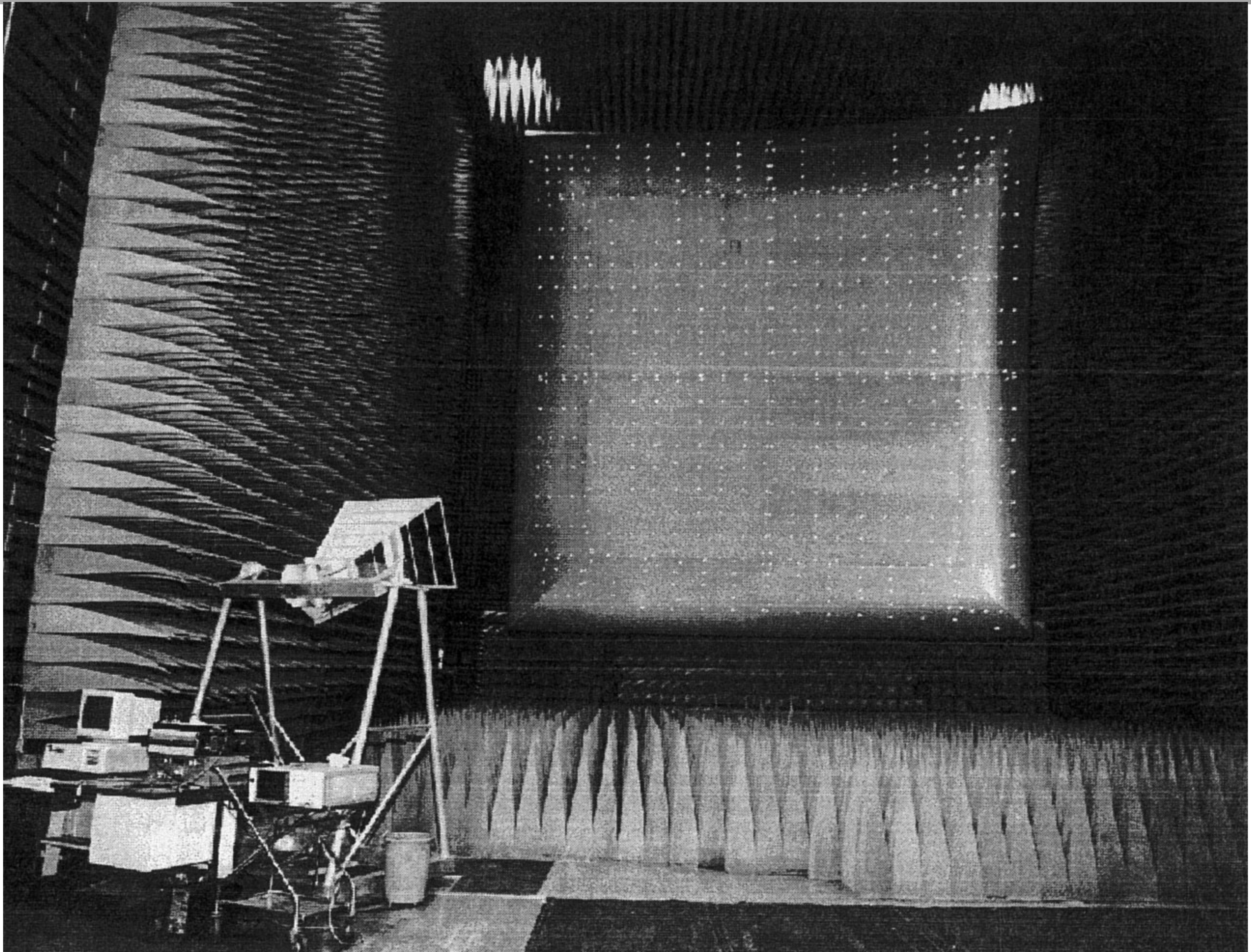
Radar Reflectivity Measurement



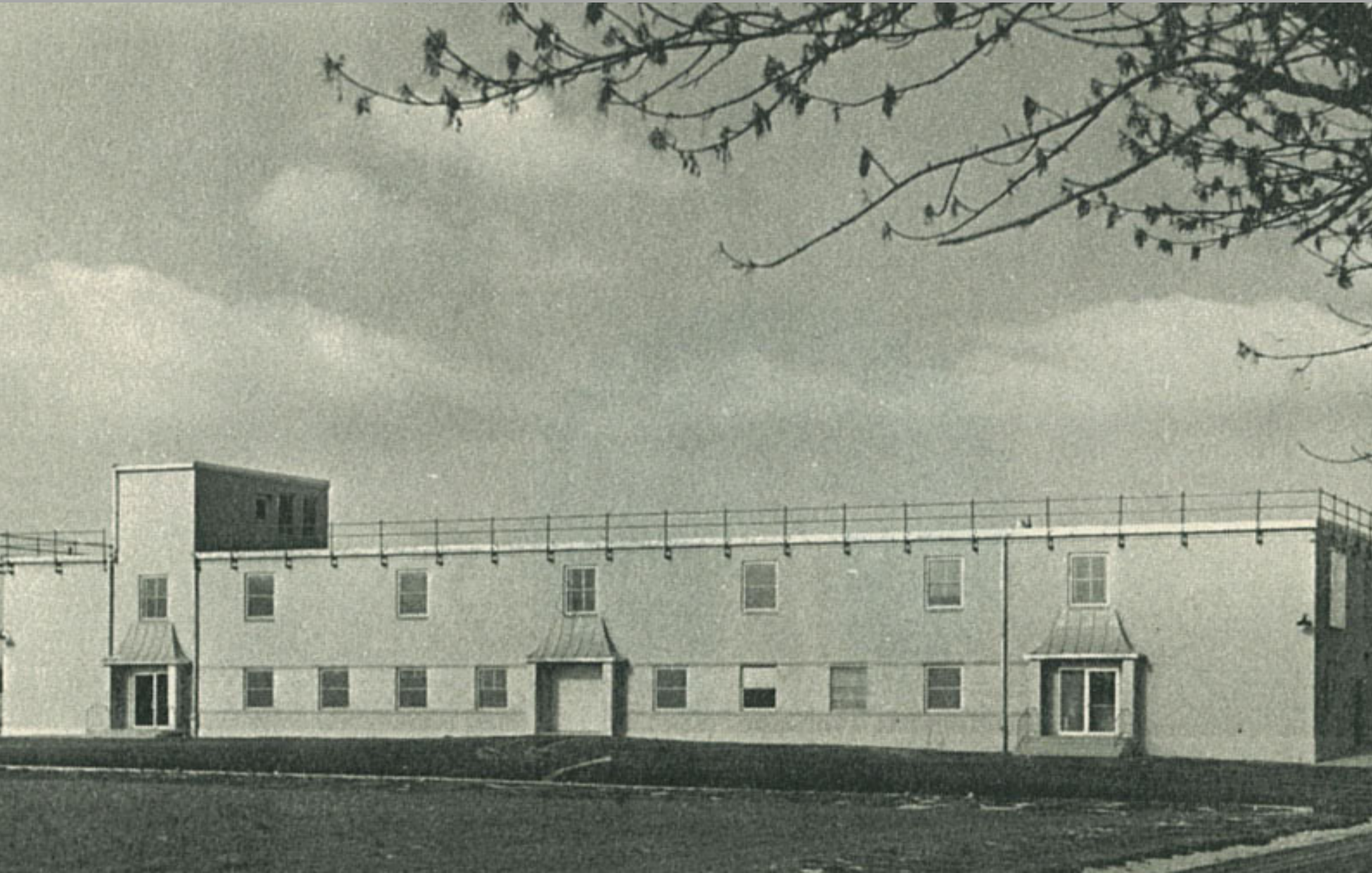
One of the first ever antenna measurements for early aircraft



Early work on the Compact Range developed at OSU-ESL by Prof. Burnside (mid to late 80s)



New Antenna Lab at Kinnear Rd. It was built with funds from the Ohio State Athletic Departmental to move the earlier Lab located at the current St. Johns Basketball arena. (the expansion to the left will occur in 1964)



Radar Facilities at OSU