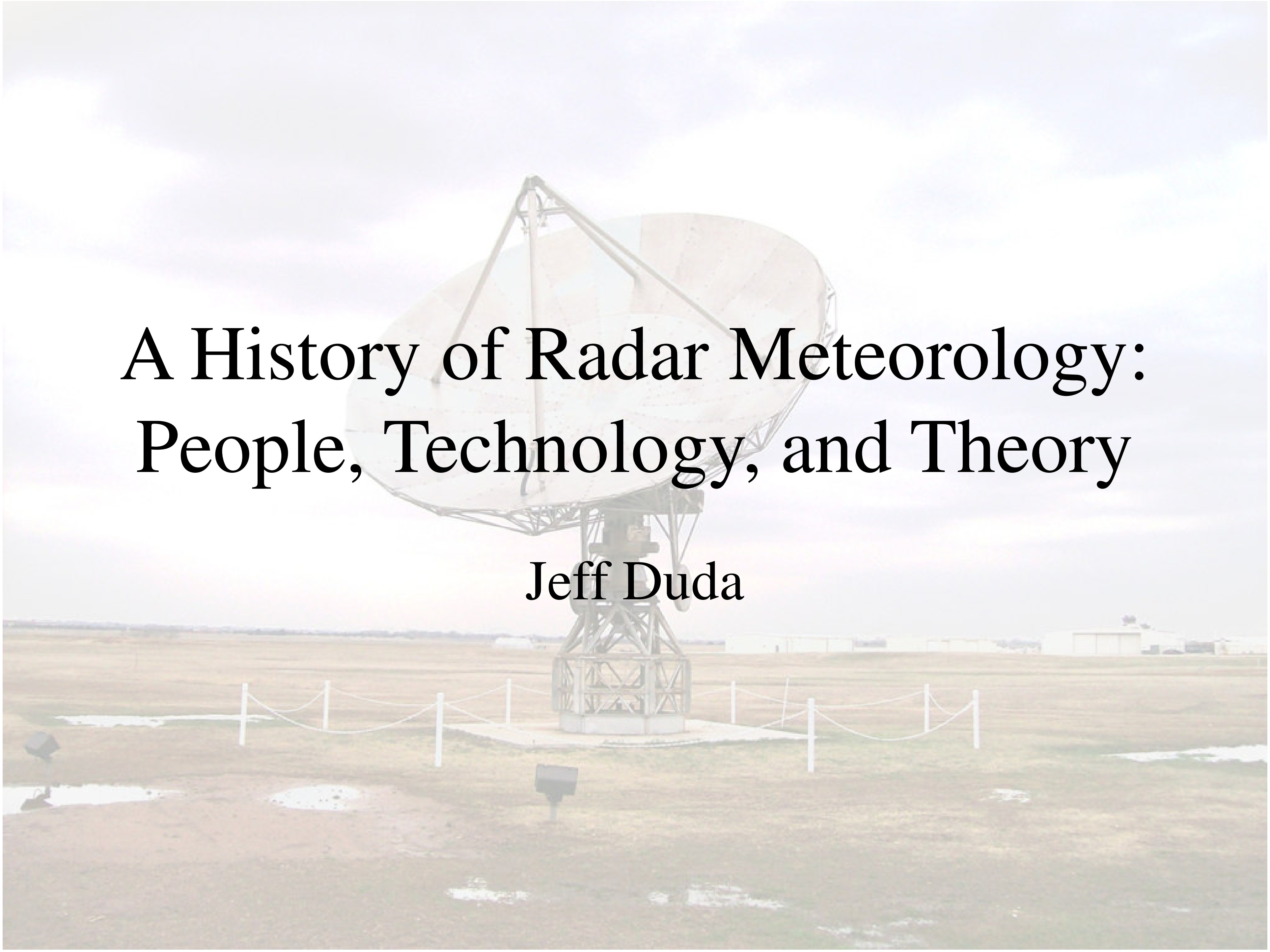
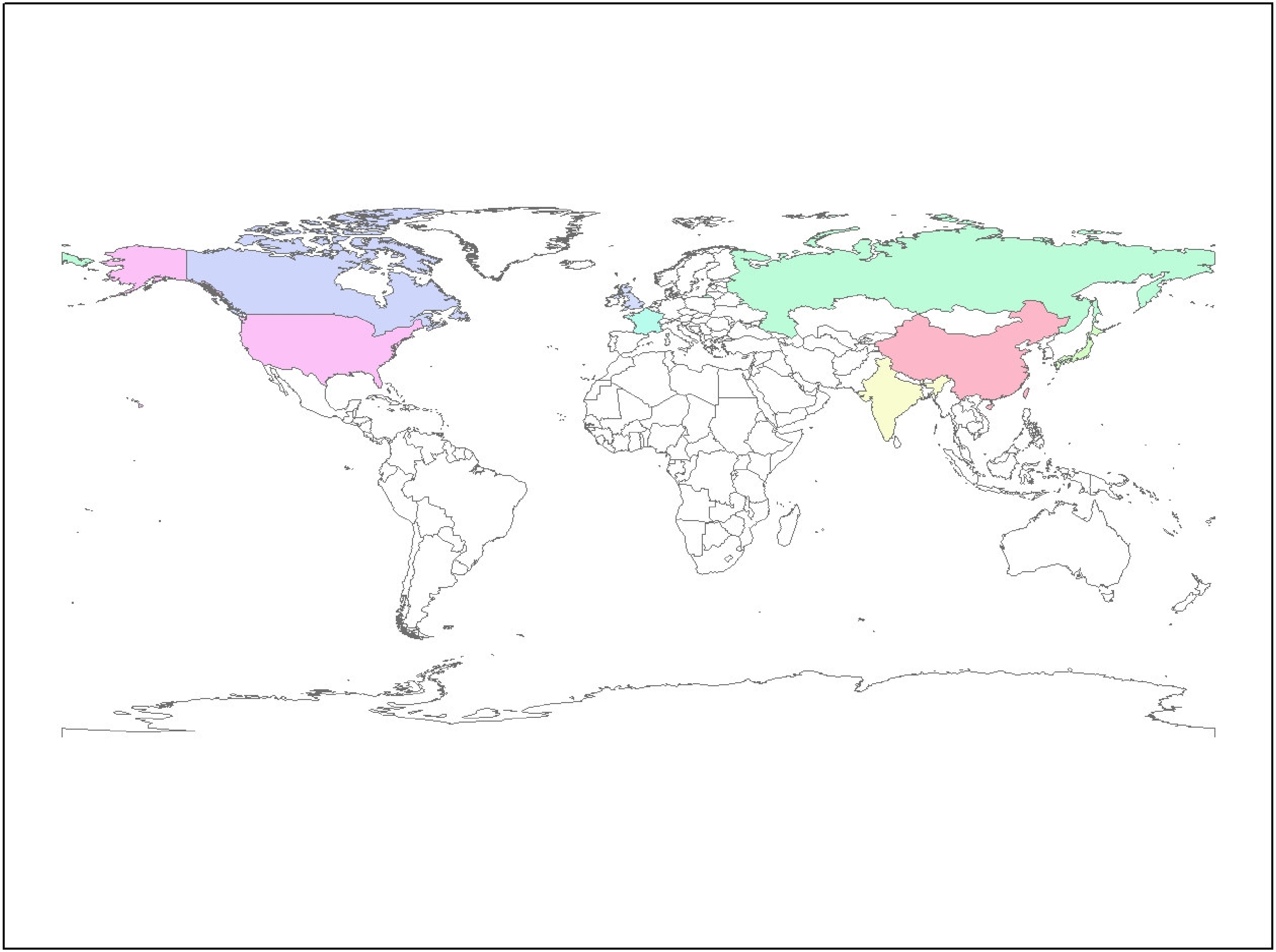


A History of Radar Meteorology: People, Technology, and Theory

Jeff Duda

Overview

- Will cover the period from just before World War II through about 1980
  - Pre-WWII
  - WWII
  - 1940s post-WWII
  - 1950s
  - 1960s
  - 1970s



Pre-World War II

- Concept of using radio waves established starting in the very early 1900s (Tesla)
- U.S. Navy (among others) tried using CW radio waves as a "trip beam" to detect presence of ships
- First measurements of ionosphere height made in 1924 and 1925
  - E. V. Appleton and M. A. F. Barnett of Britain on 11 December 1924
  - Merle A. Tuve (Johns Hopkins) and Gregory Breit (Carnegie Inst.) in July 1925
    - First that used pulsed energy instead of CW

Pre-World War II

- Robert Alexander Watson Watt
- "Death Ray" against Germans
- Assignment given to Arnold F. "Skip" Wilkins:
  - "Please calculate the amount of radio frequency power which should be radiated to raise the temperature of eight pints of water from 98°F to 105°F at a distance of 5 km and a height of 1 km."
  - Not feasible with current power production

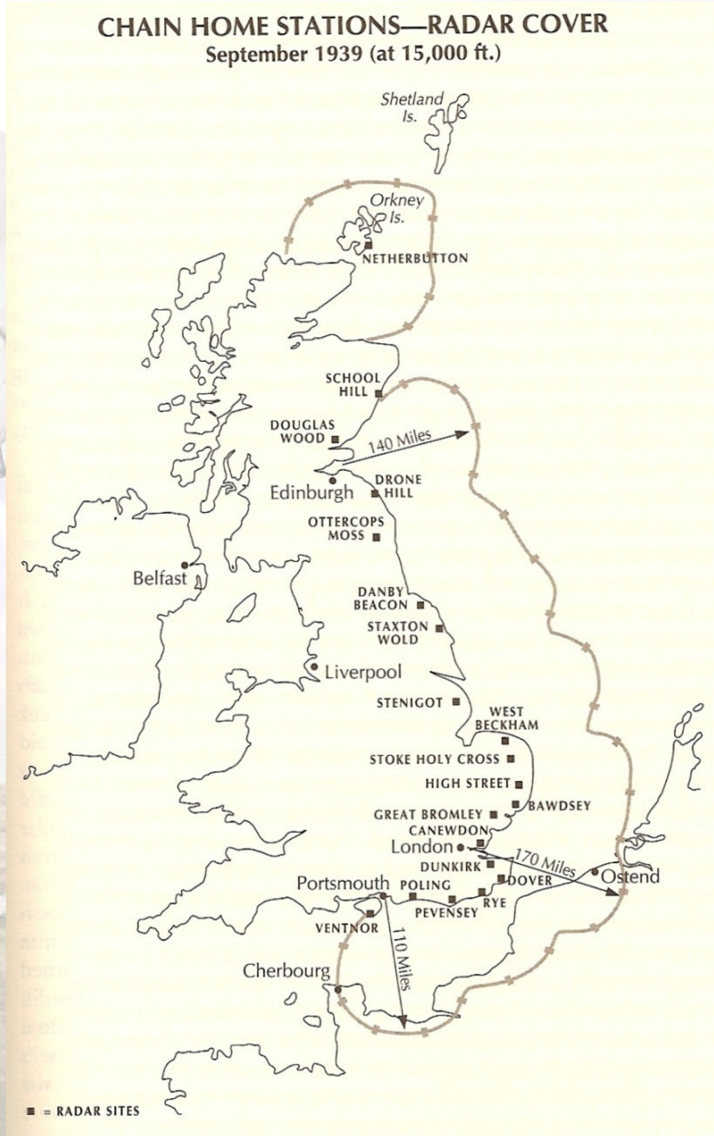
Watson Watt

Pre-World War II

- Watson Watt and Wilkins pondered whether radio waves could be used merely to detect aircraft
- Memo drafted by Watson Watt on February 12, 1935: “Detection of Aircraft by Radio Methods”
  - Memo earned Watson Watt the title of “the father of radar”
  - Term “RADAR” officially coined as an acronym by U.S. Navy Lt. Cmdr. Samuel M. Tucker and F. R. Furth in November 1940
- The Daventry experiment
  - February 26, 1935
  - First recorded detection of aircraft by radio waves
  - Began the full-speed-ahead development of radar for use in the coming war

Pre-World War II

- Orford village
  - First site for radar development (spring 1935)
  - Watson Watt recruited Welsh physicist Eddie Bowen among three others to develop radar
  - Slowly but surely improved the technology
    - Reduced wavelength and maximum range from hundreds of meters and units of miles to under 1 m and up to 100 miles within one year
- Bawdsey Manor (mid-1936)
  - More "official" (main lab) first site for research and development
  - Development of the Chain Home defense system
  - Bowen: "get these things into fighter planes!"



Sources: Swords, "The Beginnings of Radar," p. 296, and Bowen, Radar Days, p. 27.

World War II

- Big development: cavity magnetron
  - Capable of increasing power output tenfold plus
    - 30 – 40 W → 400 W at ~10 cm
  - Invented by John Randall and Henry Boot at the University of Birmingham on February 21, 1940
  - Opened the door wide for significant development

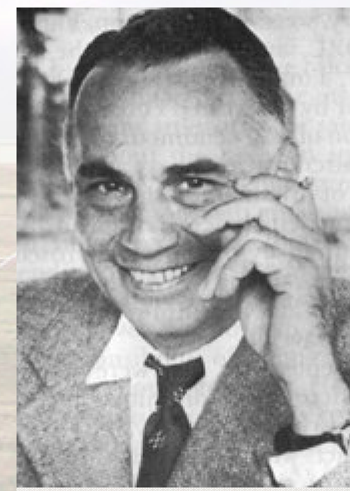
CAVITY MAGNETRON (IEEE)

World War II

- Problem: British taking a lot of abuse from German Luftwaffe bombing missions, can't develop the technology on their own
- Solution: ask the Americans for help
- The Tizard Mission (August – October 1940)
  - Aka, "The British Technical and Scientific Mission to the United States"
  - Secret mission across the Atlantic on the *Duchess of Richmond* to Nova Scotia first
  - Eddie Bowen among the leaders
  - British hoped to trade one secret for another, but after being unable to reach an agreement with the Americans, Churchill was okay with just sharing the secret for free
  - First tests showed the cavity magnetron could output 10 – 15 kW at ~10 cm!

World War II

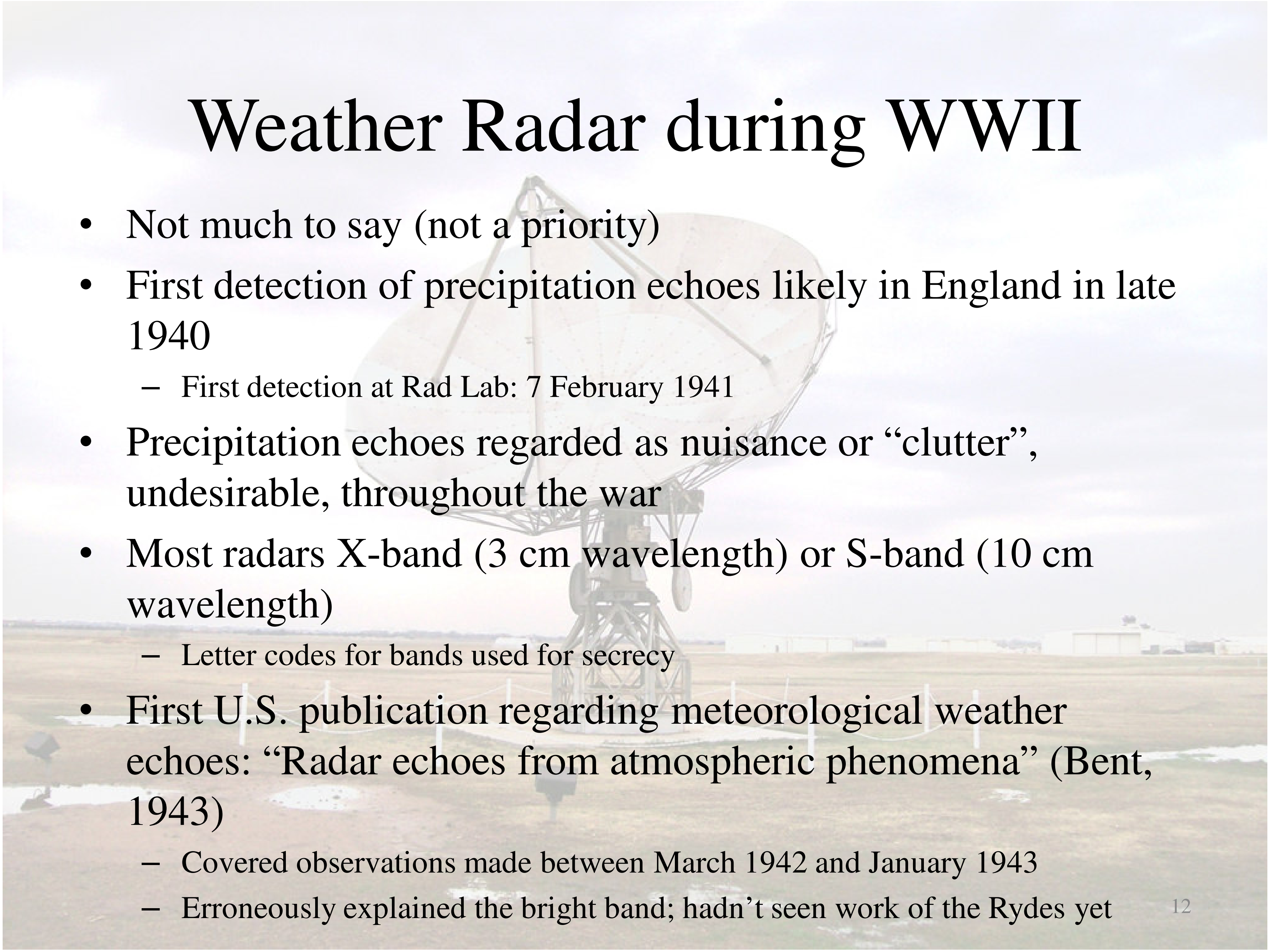
- With help from Alfred Loomis and Vannevar Bush, funding for full-scale development in America began in October 1940
  - Initial budget for first year: $455,000
  - After much argument, location was chosen: MIT
    - Secrecy (who would suspect something so significant being developed at a university?)
    - Initially named Microwave Laboratory → Radiation Laboratory to allay suspicion (common practice for the development of radar during the war)
  - Some initial scientists/researchers: Eddie “Taffy” Bowen, Ernest O. Lawrence, Isidor Isaac Rabi, Lee A. Dubridge (oversaw the “Rad Lab” for the first few years)
  - “The” place to be for radar development in America during the war



Alfred Loomis

World War II

- Radar continues to be developed slowly but surely, now mainly at the Rad Lab and Telecommunications Research Establishment
- Radar gave Allied powers big advantage
  – U-boats: sneaky “b---ards” hung out along the east coast of N. America and west coast of Europe, frequently sinking battleships, destroyers, and carriers
  – After Air-to-Sea-Vessel (ASV) detection developed and put into airborne fighters, one-third of all U-boats shot down between March-June 1943
  – Unfortunately, a Pathfinder (bomber) carrying the radar technology was shot down over Holland on 2 February 1943; the Germans reverse engineered the technology; almost overnight, all German U-boats, as well as other vehicles, had microwave detecting technology
    - The *Rotterdam-Gerät*
  – Centimeter radar was considered the technology that gave the Allies the edge in winning the Battle of the Atlantic, and arguably, the war



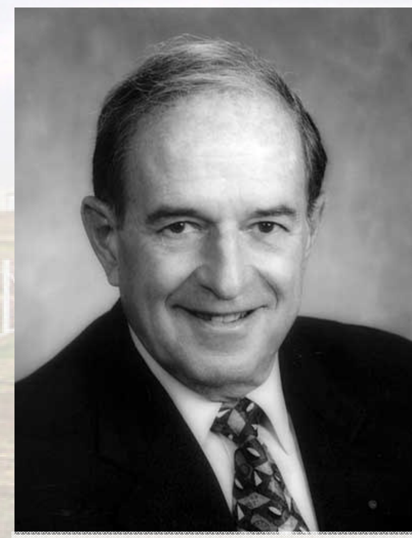
Weather Radar during WWII

- Not much to say (not a priority)
- First detection of precipitation echoes likely in England in late 1940
  - First detection at Rad Lab: 7 February 1941
- Precipitation echoes regarded as nuisance or “clutter”, undesirable, throughout the war
- Most radars X-band (3 cm wavelength) or S-band (10 cm wavelength)
  - Letter codes for bands used for secrecy
- First U.S. publication regarding meteorological weather echoes: “Radar echoes from atmospheric phenomena” (Bent, 1943)
  - Covered observations made between March 1942 and January 1943
  - Erroneously explained the bright band; hadn’t seen work of the Rydes yet

1940s post-WWII

- Secrecy no longer important
- Weather Radar Research Project at MIT: 15 February 1946
  - Initial project director: Alan Bemis
- U.S. Air Force All Weather Flying Division: project AW-MET-8 formed in December 1945
  - David Atlas among the first to lead
- Project Stormy Weather in Canada: 1943
  - AKA the “Stormy Weather Group” after 1950 at McGill University
  - First led by J. Stewart Marshall

Alan Bemis



Dave Atlas

1940s post-WWII

- John Walter Ryde (and wife Dorothy)
  - Ryde (1941); Ryde and Ryde (1944); Ryde (1946)
  - Developed the theory of scattering and attenuation of microwaves
    - "The attenuation and radar echoes produced at centimetre wavelengths by various meteorological phenomena"; not published until after WWII
    - Computed backscatter cross sections by hand
    - Used the works of Rayleigh (1871), Mie (1908), and Gans (1912)
    - Years ahead of their time; disbelieved or ignored by peers for awhile
  - Also computed early Z-R relationships using DSDs from Lenard (1904), Humphreys (1929), and Laws and Parsons (1943)

1940s post-WWII

- J. Stewart Marshall
  - Met Walter Palmer while working in Ottawa
- Stormy Weather Group focused on precipitation and cloud microphysics
- Investigation of Z – R relationships
  - Wexler and Swingle (1947): “Radar storm detection”
  - Marshall et al. (1947): “Measurement of rainfall by radar”
  - Marshall and Palmer (1948): “The distribution of raindrops with size”
- Marshall and Palmer (1948) seminal work in the field

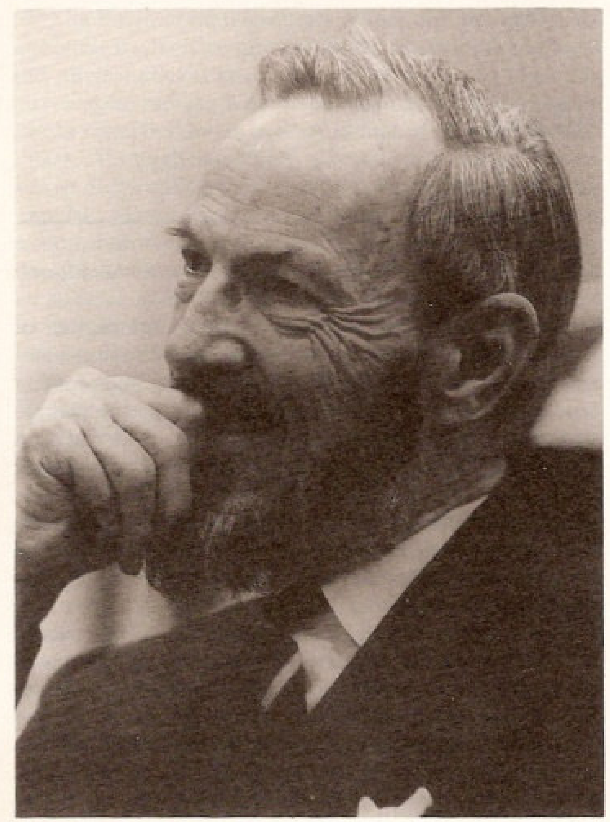


Fig. 1 J. Stewart Marshall (in 1979), founder and Director of

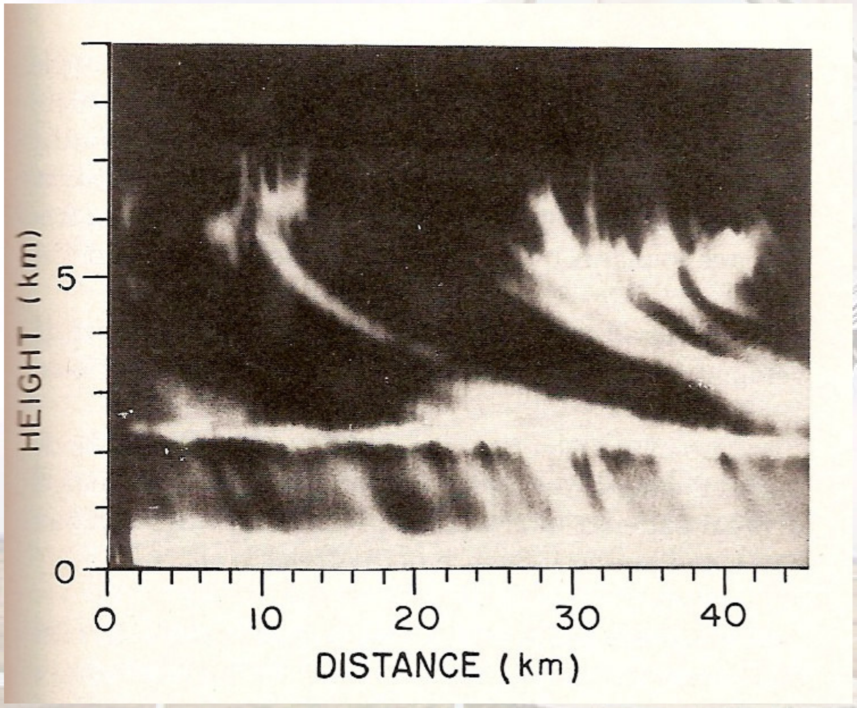
1940s post-WWII

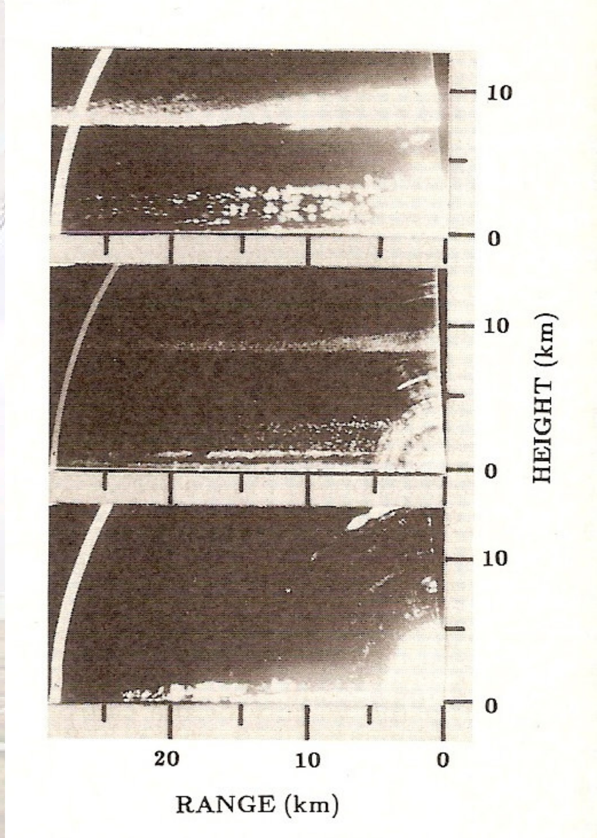
- More on Marshall-Palmer distribution and Z – R relationships
  - $Z = 200*R^{1.6}$ (Marshall and Palmer 1948)
  - "It may be possible therefore to determine with useful accuracy the intensity of rainfall at a point quite distant (say 100 km) by the radar echo from that point."
  - Many other researchers suspicious of their computations due to simplicity
  - Other papers like Twomey (1953), Imai et al. (1955), Atlas and Chmela (1957), and Fujiwara (1960, 1965) derived other relationships in which reflectivity for a given rain rate differed by up to 38%, but they also remarked that there were physical explanations for the differences; could choose a relationship based on physical explanation and for a particular situation

1940s post-WWII

- Bright bands
  - Bob Cunningham (MIT), Hooper and Kippax and Ian Browne (England), Tibbles and Guy Eon (Canada) among first to investigate “bright bands” occurring near the freezing line
    - Cunningham and Eon (separately) flew through the bright band in the mid to late 1940s
- Angel echoes
  - Colwell and Friend (1936, 1939), Watson Watt, P. Syam and I.N. Bhar (India) among the first to investigate echoes from the clear atmosphere (angel echoes)
    - Hypothesized that refractive index gradients were the cause (corroborated by Atlas et al. (1953) and Atlas (1960))
  - Baldwin (summers of 1943 and 1944) detected “dot” angel echoes at shorter wavelengths
  - Crawford (1949): angel echoes from birds and insects
  - Plank (1956): “Type I angels” from longer wavelengths (refractive index), “Type II angels” dots at shorter wavelengths
  - More on this later

Bright bands and angel echoes





1940s post-WWII

- AN/CPS-9: first radar designed specifically for meteorological use
- Thunderstorm Project (Florida and Ohio, 1946 and 1947)
  - First multiagency field experiment for thunderstorm study and that relied so heavily on radar for research
- Iso-echo contouring technique developed by Atlas, 1947
  - Suppresses higher reflectivity values making gradients easier to see
- 14 March 1947: first Weather Radar Conference held at MIT
  - Over 90 attendees from various agencies
- Operational radar meteorology forming
  - Weather Bureau obtained 25 AN/APS-2 radars, modified them, and renamed them WSR-1s, 1As, 3s, and 4s
    - First was commissioned at Washington D.C. on 12 March 1947
    - Part of the Basic Weather Radar Network, established in 1946

1940s post-WWII
other notes

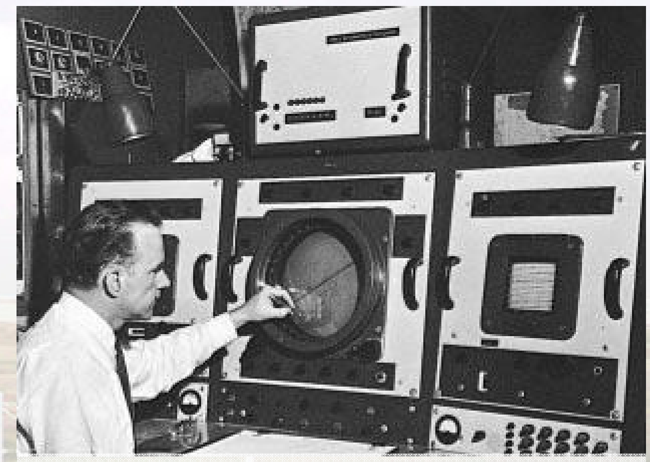
- Shipley (1941) uses the word “cell” to relate lightning activity from thunderstorms
- Workman and Reynolds (1949) thought “cells” on radar might actually represent fundamental units of electrification and precipitation in thunderstorms

1950s

- Improving technology
  - Pulse integrator
    - Used to get quantitative reflectivity measurements
  - Sweep integrator
    - Developed by Nobuhiko Kodaira of Japan
    - Enabled display of signals in 2D and 13 intensity levels
  - R-meter
    - Developed by Walter Rutkowski
    - Measures spectral width of a signal
    - Rod R. Rogers used R-meter to try to separate components of spectrum width, unsuccessful
  - CAPPI (constant altitude plan position indicator)
    - PPI was in use during WWII
  - FASE (fast azimuth slow elevation)
    - Scanning strategy improved display of radar data

1950s

- U.S. operational radar networks underway
  - 1954 & 1955: several hurricanes struck the U.S. Atlantic coast
    - No radar to detect them
  - Weather Bureau appeals to Congress and gets funded in 1956, buys 31 radars which will become WSR-57s
    - Built by Raytheon
    - Had radomes (most previous radars didn’t, none of previous operational radars did)
    - 14 placed ~200 nmi apart along the coast
    - First operational WSR-57 installed in Miami in June 1959
    - 11 placed in the Midwest for storm detection
    - Network will continue to expand through the 1960s



WSR-57 console

1950s

Advances in meteorology due to radar

- "Mesoscale" meteorology
  - Myron Ligda, 1951: many meteorological echoes of a size not observed before (between synoptic and storm/micro scale); I'll call them "mesoscale"
- Mesoscale meteorology would not exist today if it weren't for radar!

Radar has had profound impacts on many phases of meteorology, including aviation forecasting, cloud physics, and the theory of precipitation formation, but its impact on mesoscale meteorology may prove to be the most important. In fact, one can argue that mesoscale meteorology did not exist prior to the advent of radar.

Despite the careful work by members of the Norwegian school and others, it was never possible to tie precipitation patterns to synoptic-scale cyclones and fronts in a completely satisfactory way. Although precipitation is associated in a general way with fronts and cyclones, it is generally spotty and the patterns vary from one synoptic-scale system to the next.

Radar proved to be the ideal equipment to observe precipitation patterns. Early radar work showed the broad, diffuse echoes associated with warm fronts and the discrete, intense cells that accompany some cold fronts. It also showed amazing variations: some intense thunderstorms near warm fronts, bands of convective cells in the

Excerpt from *Radar in Meteorology*, Chapter 13, page 107

1950s

More advances

- Investigation of polarization diversity
  - Reginald Newell, Spiros Geotis, and Aaron Fleisher (MIT) studied variable polarization of a 3-cm radar
    - Investigated measurement of orientation and shape of falling particles using both linearly and circularly polarized waves
  - Atlas et al. (1953) used circular and linear depolarization ratios to distinguish hydrometeor shapes
  - Early thoughts: falling hailstones had a horizontal orientation like raindrops, and thus indistinguishable
  - Research of polarization diversity dwindled during the 1960s, so little work was done on this after the 1950s; it picked back up starting in the late 1960s, though

1950s

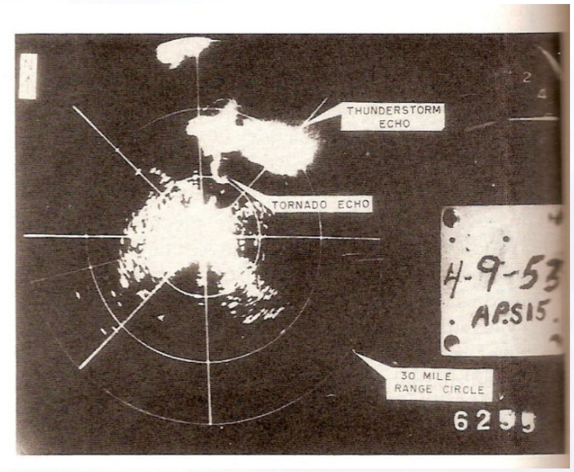
More advances

- Stormy Weather Group investigates hail (Alberta Hail Studies Project – ALHAS)
  - Designed to stop hail from falling to protect farmers from losing their crops
  - Spotter network of farmers reported hail
  - Decca type-41 storm radar pointed vertically to measure hail
  - Never able to stop hail operationally (some experimentation was loosely successful), but discovered many interesting facts relating probability of hail to cloud top height: cloud tops that penetrated the tropopause much more likely to produce large hail
  - Results of this study agreed with those from similar studies in New England and Texas with differences in actual range of cloud top height for hail occurrence
  - Variable polarization data from this study showed hailstones to have a random orientation

1950s

More advances

- Storm detection and measurement
  - First hook echo discovery on a tornadic storm on 9 April 1953 in Illinois
  - Garrett and Tice (1957) and Bigler (1958) identified BWERs in tornadic storms
  - Nolen (1959) found that ¾ of tornadoes studied formed within a reflectivity pattern with a wave in a line and called it a line-echo wave pattern (LEWP)
  - Wokingham, England storm of 9 July 1959 passed very close to the radar in southeast England
    - New observations obtained – storm did not change cloud top height or mass character for one hour, echo-free vault region (Keith Browning)
    - Last storm to pass through southeast England for years
  - 11 September 1954: Hurricane Edna observed by multiple radars
    - FPS-4 (3 cm) first to get a vertical cross section through the eye of a hurricane



1950s

More advances

- Advent of Doppler radar
  - Ian Browne and Peter Barratt (Cambridge) first to demonstrate the use of Doppler techniques to calculate motion
    - 27 May 1953: vertical motion measured in a rain shower
      - Doppler spectrum consistent with 2 m/s downdraft
      - Paper reporting this (Barrat and Browne, 1953) not published or publicized at conferences for a few years
  - James Brantley and Barczys got that work published and presented
    - Brantley and Barczys (1957): CW Doppler measurements of weather echoes
  - Brantley convinced Vaughn Rockney that this could be used for tornado detection; applied for grant
    - 92 m/s winds measured by radar in tornado in El Dorado, KS on 10 June 1958
  - Thus began the Doppler era

Jim Brantley, summer 1955. (Photo courtesy of Walter

1950s

- Texas Tornado Warning Network
  - Kicked off on 24 June 1953, but took 6 years to bring the network up to full strength, at which time 17 radars were in use
  - Volunteer spotter networks
  - Used modified APS-2F (WSR-1,-1A,-3,-4)
  - Texas A&M University managed the funds and arranged for the modifications
- 5 April 1956: Bryan and College Station, TX tornado
  - Tornadic “hook” signature detected by APS-2F radar at Texas A&M Univ. at 2:00 PM
    - Ironically, not part of the Texas Tornado Warning Network
  - At 2:45 PM, Texas A&M meteorologists told Bryan PD that tornado would touch down in 30 minutes
    - Actual damage started at 3:09 PM
- Bigler (1956): A note on the successful identification and tracking of a tornado by radar. *Weatherwise*

1950s
Other notes

- 3rd Conference on Radar Meteorology held at McGill University in 1952
  - First suggestion of using “preprints” made by Marshall
- 6th Conference on Radar Meteorology held at MIT in March 1957
  - “More data!” they wanted
- *Radar Meteorology*, 1959, Louis Battan
  - First textbook on radar meteorology
  - Translated into Chinese for use by students and meteorologists in China until they were able to obtain their own research radars in the 1960s
- Bergeron process becomes better defined and better understood
  - 1930s: ice crystals grow at expense of liquid water
  - 1940s: observations show rain from clouds not exceeding the freezing level
    - Coalescence process for precipitation growth first suggested
  - 1950s: agreement that Bergeron process and coalescence compete for precip growth

“More Data!”

Louis Battan

THEME SONG OF THE SIXTH WEATHER RADAR CONFERENCE

(lyrics by Aaron Fleisher)

More data, more data
Right now and not later.
Our storms are distressing,
Our problems are pressing.
We can brook no delay
For theorists to play.
  Let us repair
  To the principle sublime
  Measure everything, everywhere
    All the time.

For data are solid,
Though dull and though stolid,
Consider their aptness
Their matter-of-factness.
Theory is confusion,
A snare and delusion,
  A dastardly dare,
  A culpable crime,
  Measure everything, everywhere
    All the time.

No need to be weary
Of the mysteries of theory.
We have only to look
At the data we took,
Immediately inspired,
Grasp the answers required.
  What are so rare
  As reason and rhyme.
  Measure everything, everywhere
    All the time.

More data, more data,
From pole to equator
We'll gain our salvation
Through mass mensuration.
Thence flows our might,
Our sweetness, our light.
  Our spirits full fair
  Our souls sublime;
  Measuring everything, everywhere
    All the time.

L'Envoi

And it shall come to pass, even in our days,
That ignorance shall vanish and doubt disappear
Then shall men survey with tranquil gaze
The ordered elements shorn of all fear.

Thus to omniscience shall we climb
Measuring everything, everywhere, all the time.

1960s

- Further improving technology
  - Sweep generator modified (Donat Hoegl) to get more pulses to measure a volume (1962)
    - Effectively increased the resolution of radar images
    - Mario Schaffner digitized sweep integrator in 1966
  - Storm Radar Data Processor – (1960) – David Atlas
    - Enabled processing and displaying of radar data in real time; digital display
    - Beginnings of digital radar meteorology in the 1960s
  - RAYSPAN frequency analyzer
    - Used to construct the first vertical wind profile using the Velocity-Azimuth Display technique (27 May 1961)
  - Coherent Memory Filter → Plan Shear Indicator
    - Developed by Graham Armstrong in 1966
    - Used to display Doppler velocity data on a PPI
  - Calibrated Echo Intensity Control (CEICON), 1966
    - Enabled control of reflectivity levels by inserting various degrees of attenuation into radar software
  - Video Integrator and Processor, 1968
    - Allowed radar to average instantaneous backscattered power from targets, thus automating and standardizing measurements
    - Allowed display of six values of reflectivity based on rain rates

1960s

- Radar equation updated
  - Initial work by Rydes assumed target was small compared to radar volume (single targets like planes)
  - Meteorological targets fill volume
  - Result: much higher predicted values of reflectivity compared to experimental values obtained

The radar equation in meteorology

By J. R. PROBERT-JONES

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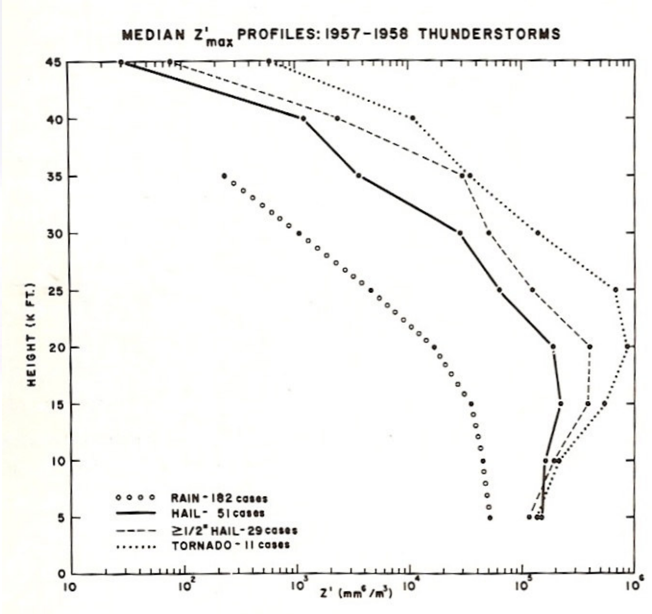
(Manuscript received 29 January 1962; in revised form 18 June 1962)

SUMMARY

While meteorologists can obtain much useful information by using radar in a qualitative manner, great benefit can be derived by obtaining quantitative measurements. However, these measurements have been found, in general, to be below values calculated from radar theory by a factor of between two and five, and there has been no satisfactory explanation for this discrepancy. In this paper, the radar equation for a meteorological target is derived, particular attention being devoted to the effect of the shape of the main lobe of the beam, and of the radiation outside it. It is shown that previous theoretical expressions for both the gain and the echoing volume have been too large, and hence that previous equations overestimated the received power. The present equation gives good agreement with all the experimental data.

1960s

- More advances in storm detection and structure
  - Walter Hitschfield discovers splitting storms in 1960; splitting storms further investigated by Browning, Donaldson, and Hammond
    - Tornadic storm near Wichita Falls, TX on 4 April 1964 observed by NSSL radar to move to the left of, and faster than, the mean wind vector! Another one seen on 23 April!
    - Storm relative winds for right and left movers formed a mirror image
  - Geary, OK storm of 1961 well documented to have weak echo regions
    - First to be identified as a supercell
  - Donaldson (1961): different types of storms have different vertical profiles of reflectivity
    - Only rain: decreasing reflectivity with height
    - Tornadic: pronounced maximum aloft, decreasing from there
  - First detection of mesocyclone on radar using PSI by Donaldson on 9 August 1968



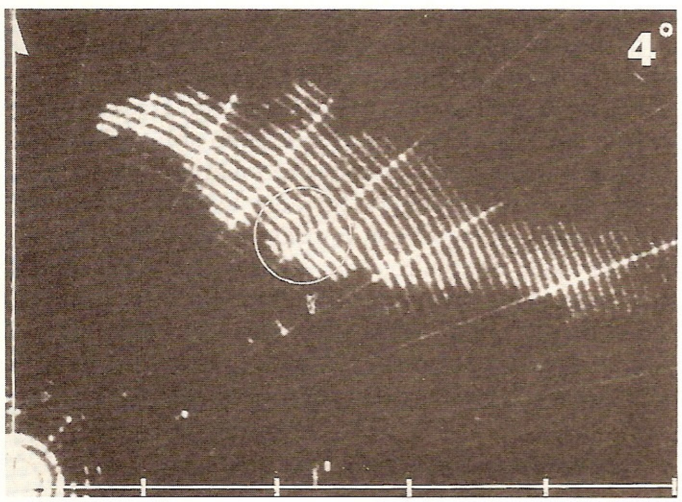


Fig. 5 PSI (plan shear indicator) photograph of the Marblehead, Massachusetts storm of 9 August 1968. The inscribed circle encloses a characteristic pattern indicating a mesoscale cyclonic vortex at an altitude of 2 km. This is the first observation of a mesocyclone by Doppler radar. (From Donaldson, 1970.)

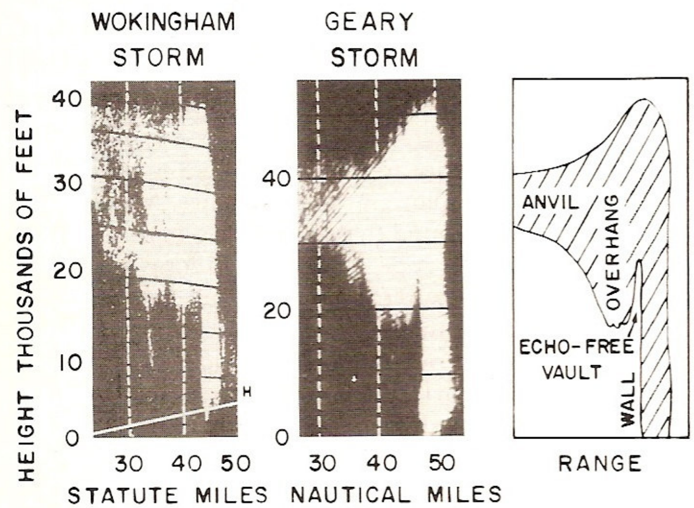


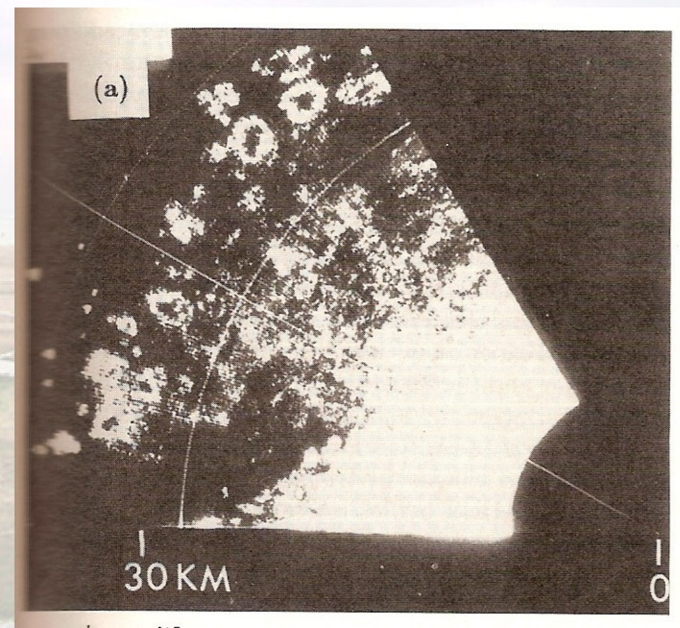
Fig. 1 RHI photographs illustrating the similarity of the echo structure of the Wokingham and Geary storms during their most intense phases, with a sketch illustrating the key features. Storm motion in both photographs is from right to left. (From Browning and Donaldson, 1963.)

1960s

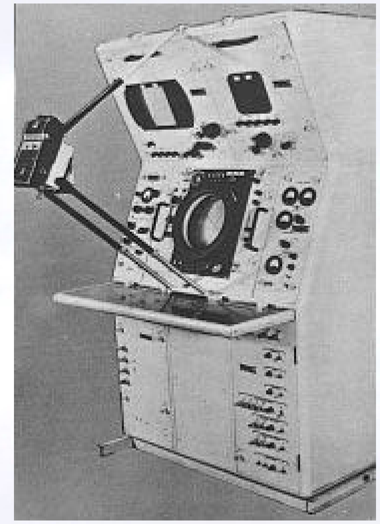
- Further development of Doppler radar
  - Atlas (1963) suggested playing with PRF to be able to measure high velocities (requires high PRF) and measure echoes at distant ranges (requires low PRF)
    - "Doppler dilemma", problem had been recognized in the late 1950s; technology was lagging substantially behind theory and practice
  - Dual-Doppler wind measurements
    - First made on 2 May 1967 in a rain shower in England (Peace and Brown, 1968)
    - Used one radar pointing vertically and another displaced horizontally looking horizontally into the same area
  - Rummler (1968) developed the pulse pair technique to obtain mean and variance computations of Doppler velocities
    - First applied in 1972

1960s

- More research on clear air echoes
  - Wallops Island, VA research (Atlas)
    - Started in 1964
    - First observation of tropopause on radar
    - Battan (1973) concluded that clear air echoes at wavelengths of 3 cm or less due to insects or birds and those at 10 cm or longer due to refractive index fluxuations (not necessarily tight gradients)
  - Hardy and Ottersten (1969) showed donut shaped clear air echoes due to boundaries of dry convective thermals



1960s



FPS-77 console

- Operational networks expanding
  - Air Weather Service replaces FPS-68 with FPS-77 radar
    - C-band to compromise between X and S bands
    - First installed in March 1966; most installed by 1969
    - Poor/no training, maintenance early on
  - 14 more WSR-57s obtained by Weather Bureau in 1966-1967 to fill holes in coverage east of the Rockies
    - Up to 1966 all radars located near Weather Bureau/NWS offices; some of the new 14 weren't; were placed in places to optimize coverage

1970s

- Technology improvements
  - Movement of radar systems to computer based; digitizing
    - Increased storage capacity dramatically from magnetic tape method
  - Color radar displays
    - First invented by Ken Glover of Air Force Geophysics Lab and colleagues at Raytheon in 1974
  - VIL technique invented by Greene and Clark (1971)
  - Display techniques
    - HARPI, PPHI, AZLOR, ADA

1970s

- Storm detection using Doppler radar
  - Michael Krauss first unequivocal observation of a tornado on radar on 9 August 1972 (Brookline, MA)
    - “unequivocal” because it was sighted by NWS employees and an MIT student at the same time it was being observed on radar
  - Union City, OK tornado of 24 May 1973 observed by chasers and radar
    - Close enough to radar site to resolve what would later be called a “tornado vortex signature” by Brown and Lemon (1976)
- Dual-Doppler radar network established
  - One at NSSL in 1971, the other at Cimarron Field, OK in 1973

1970s
Operational networks upgrading

- Enterprise Electronics Corporation developed a new brand of S- and C-band radars
  - First went to a TV station in Tampa, FL in 1969 (WSR-74S)
  - NWS got funded to buy 66 in 1976 to replace aging WSR-57s; called them WSR-74Cs
    - Would buy 16 more between 1981 and 1985 – the last purchase made before NEXRAD
    - Some WSR-57s survived until upgraded to WSR-88Ds
- NWS conducted D/RADEX from 1971 – 1976
  - Tested digitizing of radar output for meteorology and hydrology
  - 5 WSR-57s used
  - Idea tested: gradually increase antenna tilt to get a volume scan

1970s
Operational networks upgrading

- Joint Doppler Operational Project (JDOP): 1977 – 1979
  - Battan (1976) and Atlas (1976) wrote reviews on Doppler radar to present to U.S. government
  - NWS and NSSL declare plans to upgrade operational network to Doppler capability with or without DOD
  - As much an operational experiment as it was a research experiment
  - Success led immediately to the creation of the NEXRAD network
- Severe Environmental Storms and Mesoscale Experiment (Project SESAME): spring 1979
  - Conducted in the southern plains states
  - Data aided JDOP
    - 10 April 1979 Witchita Falls, TX tornado invisible to a 5-cm radar due to attenuation, but plainly visible to a 10-cm radar in a similar position
    - Convinced project investigators to use 10-cm radar instead of 5-cm radar
- Successful studies of clear-air echoes in the 1970s led to the requirement that NEXRAD radars be capable of detecting these echoes, especially in the boundary layer and also being able to obtain Doppler velocities

1970s

- More studies of clear air echoes
  - Browning et al. (1972, 1973) studied Kelvin-Helmholtz waves in atmosphere

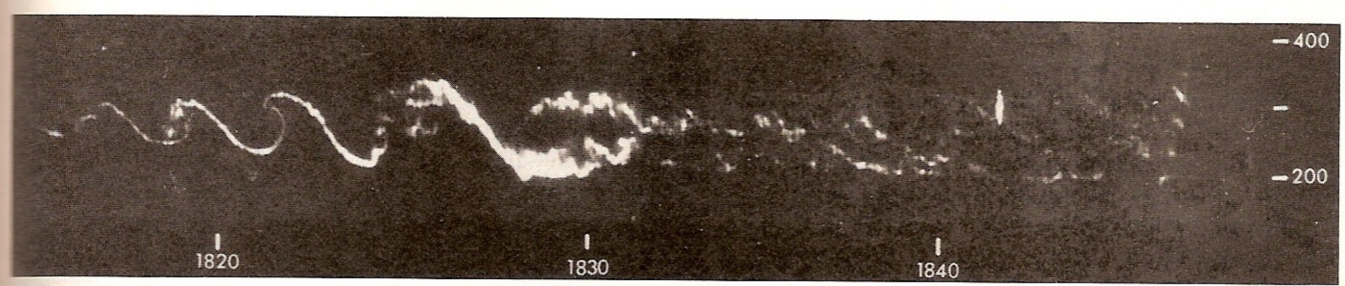
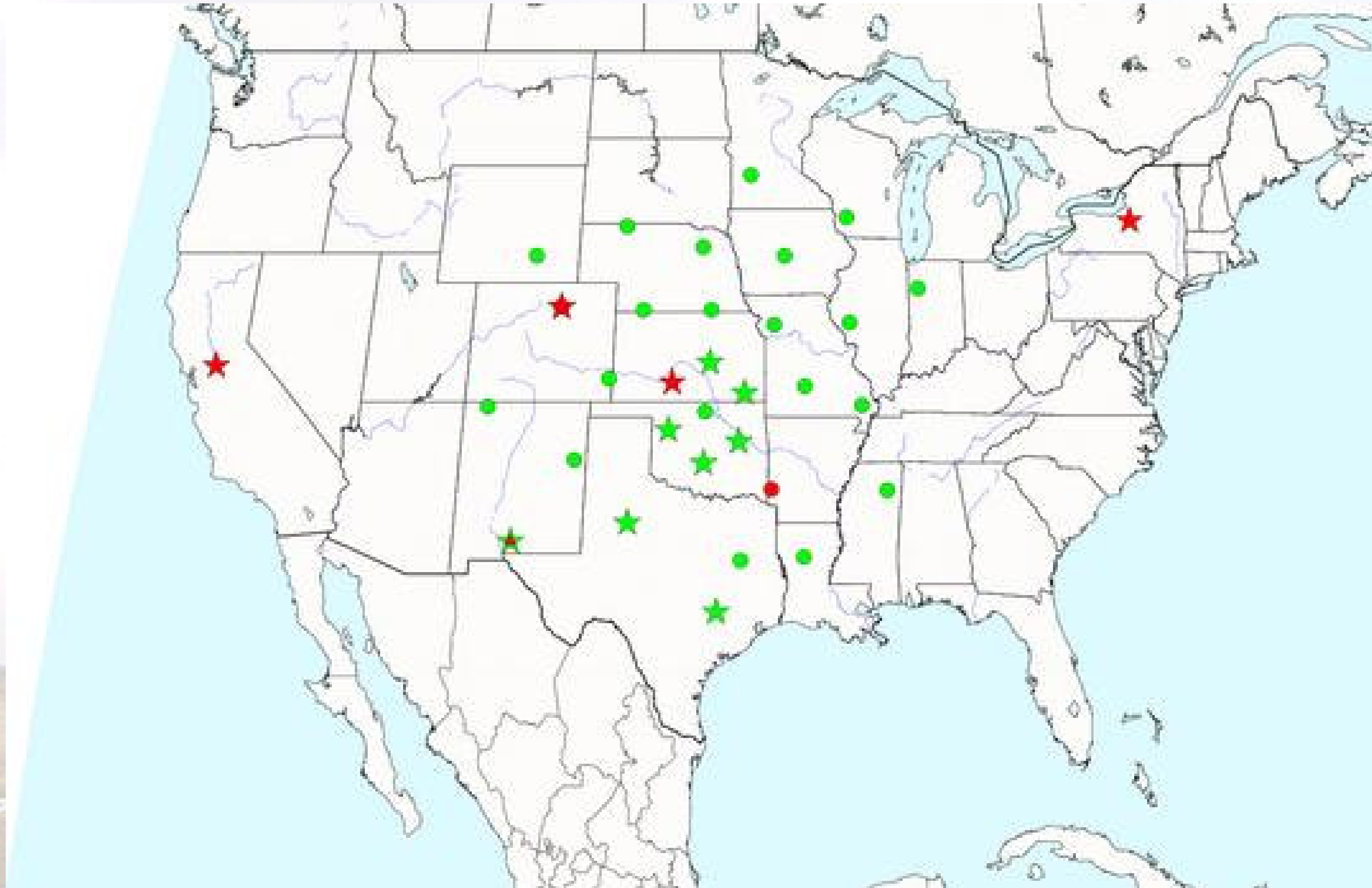


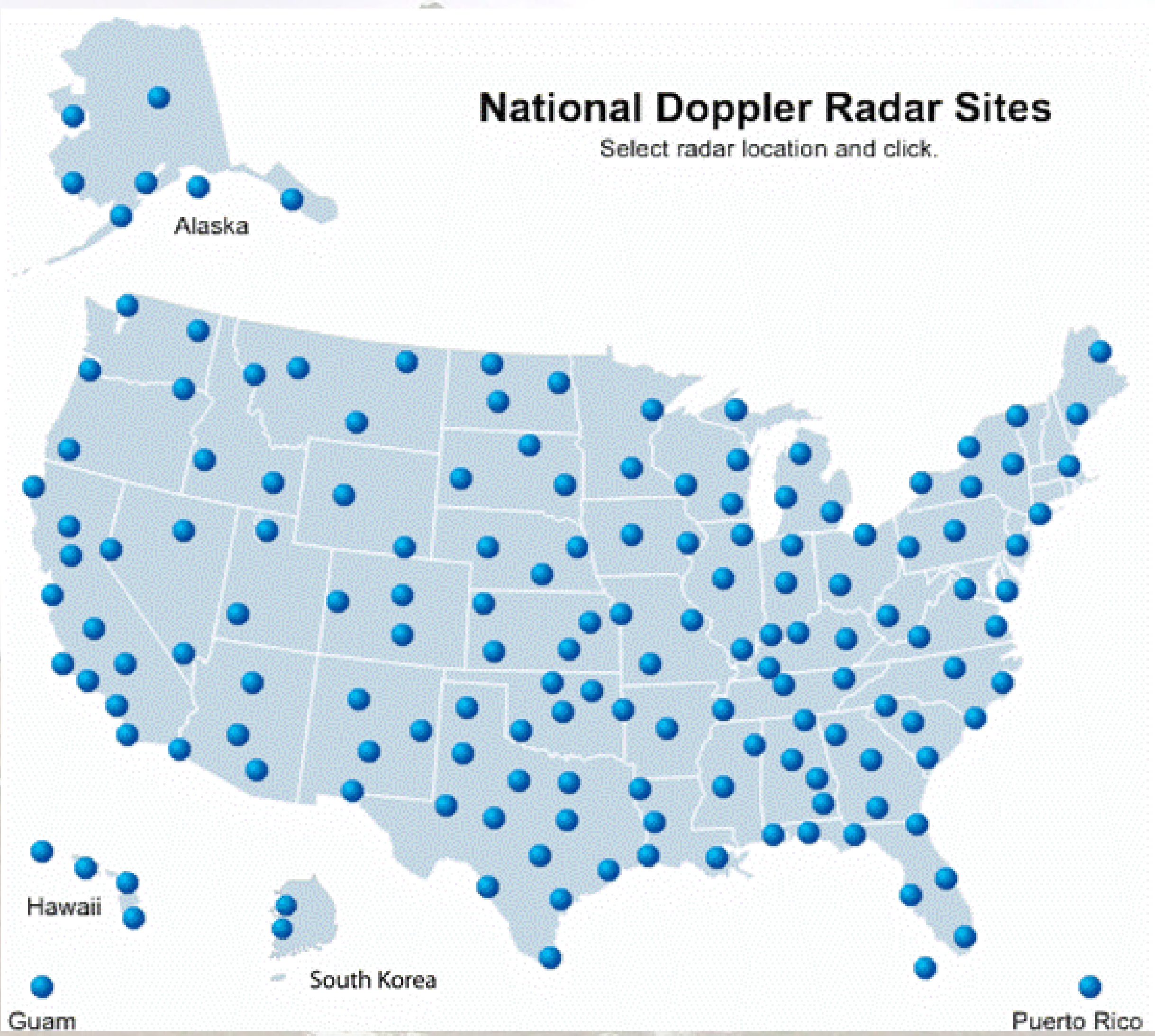
Fig. 4.3 The FM–CW time–height observation of Kelvin–Helmholtz shearing instability made with a vertically pointing, 10-cm wavelength FM–CW radar located near San Diego, California on 6 August 1969. The times are PST and the height scale is in meters. The sequence, from left to right, shows the growth of a billow, its breaking, and subsequent decay. (From Gossard et al., 1970.)

- Ben Balsley, Warner Ecklund, and David Carter (NOAA Aeronomy Lab) showed use of VHF/UHF radars to determine atmospheric winds
  - Ecklund et al. (1979) used Platteville, CO radar to measure winds in 1978
  - Work like this led to the establishment of the Colorado Wind Profiling Network, and then the NOAA Profiler Network

NOAA Profiler Network



NEXRAD Network today



References

Atlas, D., and Coauthors, 1990: *Radar in Meteorology*. Amer. Meteor. Soc., 806 pp.

Buderi, R., 1996: *The Invention that Changed the World*. Simon and Schuster, 575 pp.

Doviak, R. J., and D. S. Zrnić, 1993: *Doppler Radar and Weather Observations.* 2^{nd} Ed., Academic Press, 562 pp.

Probert-Jones, J. R., 1962: The radar equation in meteorology. 551.501.Sl : 551.508.S5 : 621.396.91

Whiddington, R., 1962: John Walter Ryde. 1898 – 1961. *Bio. Mem. Fellows Roy. Soc.*, **8**, 105 –117.

Whiton, R. C., P. L. Smith, S. G. Bigler, K. E. Wilk, and A. C. Harbuck, 1998a: History of operational use of weather radar by U.S. weather services, Part I: The pre-NEXRAD era. *Wea. Forecasting*, **13**, 219 – 243.

—, —, —, —, 1998b: History of operational use of weather radar by U.S. weather services, Part II: Development of operational Doppler weather radars. *Wea. Forecasting*, **13**, 244 – 252.

The end