PATH TO NEXRAD

Doppler Radar Development at the National Severe Storms Laboratory

BY RODGER A. BROWN AND JOHN M. LEWIS

Evolution of events at the National Severe Storms Laboratory during the 1960s and 1970s played an important role in the U.S. government's decision to build the current national network of NEXRAD, or WSR-88D radars.

In 1959, 31 people lost their lives in an airplane accident over Maryland. The fuel tanks in the Viscount aircraft were struck by lightning and the resulting explosion and fire led to the fatal crash. This event, and several other aircraft accidents that were associated with severe weather, led to the creation of the National Severe Storms Project (NSSP) in 1961 with Clayton Van Thullenar as director and Chester Newton as chief scientist (Galway 1992). As part of NSSP, which was headquartered in Kansas City, Missouri, Project Rough Rider was established to fly instrumented aircraft into storms and compare the relationship of radar echo strength with aircraft-detected turbulence. This project, coordinated by J. T. Lee, lasted into the mid-1980s and was instrumental in developing important new guidelines for the safety of flight in the vicinity of thunderstorms (e.g., Kessler 1990).

In 1962, NSSP placed a research Weather Surveillance Radar-1957 (WSR-57) radar in Norman, Oklahoma, at the new field facility called the Weather Radar Laboratory. The following year a decision was made to transfer the entire NSSP operation to Norman, where it was reorganized as the National Severe Storms Laboratory (NSSL). Not only was the operation of NSSP transferred, but a larger mission was envisioned by the new U.S. Weather Bureau (USWB) chief, Robert White. This mission would include the development of more sophisticated radar processing and display systems in support of the operational needs of the USWB. Edwin Kessler was appointed the director of NSSL in mid-1963 (Fig. 1).

The early success of USWB employees David Holmes and Robert Smith in the detection of a tornado in El Dorado, Kansas, in June 1958 stimulated interest in the use of Doppler radar (Smith and Holmes 1961). These meteorologists had used a 3-cm-wavelength continuous-wave (CW) Doppler radar that had been obtained from the U.S. Navy and modified for the USWB by James Brantley at Cornell Aeronautical Laboratory (Fig. 2). Rogers (1990) has carefully reviewed the post–World War II research that led to the development of this radar and other

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DOI:10.1175/BAMS-86-10-1459

In final form 12 May 2005

Fig. 1. Kessler, soon after he became laboratory director in 1964, is shown here in a flight suit after he had completed a familiarization flight in a military aircraft used in Project Rough Rider. [NSSL photo.]

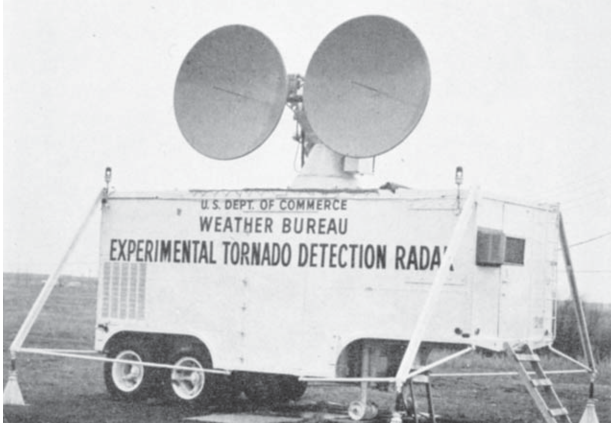

Fig. 2. USWB's continuous-wave 3-cm Doppler radar with its side-by-side transmitting and receiving antennas used for tornado studies in the southern plains during the late 1950s. The unit was converted by NSSL into a pulsed Doppler radar in 1964. [USWB photo.]

Doppler weather radars. Further, Table 1 summarizes these early efforts in Doppler radar development. The reader is referred to *Radar in Meteorology* (Atlas 1990) and the essay by Rogers and Smith (1996) for an elaboration on this history.

At the National Severe Storms Laboratory, Doppler radar work got off to a promising start with the conversion of the USWB CW Doppler radar into a 3-cm-wavelength pulsed Doppler radar. However, ensuing developments came through steps that were often fitful, where complications arose due to personnel concerns, and where there were always financial concerns. Against this backdrop, we follow the events that led to the development of a 10-cm-wavelength Doppler radar that ultimately became the prototype for the current Next Generation Weather Radar (NEXRAD), or Weather Surveillance Radar-1988 Doppler (WSR-88D) network.

KESSLER AND LHERMITTE: DOPPLER RADAR COMES TO NORMAN. Prior to his arrival at NSSL, Kessler was a research meteorologist at the Weather Radar Branch of the Air Force Cambridge Research Laboratories (AFCRL) in the Boston, Massachusetts, area (1954–61), and at the Travelers Research Center (TRC) in Hartford, Connecticut (1961–63). At AFCRL, Kessler used weather radar data to explore the kinematics of airflow and the associated water content of the air. Concurrent with his employment at AFCRL, Kessler was enrolled in the graduate meteorology program at the Massachusetts Institute of Technology (MIT). In 1957, under the guidance of Professor Henry Houghton, he received a Sc.D. degree.

Letters from the TRC files indicate that Kessler was working with Robert H. Simpson of the USWB in 1963 on issues related to weather radar. The planned role of radar in USWB operations was expressed by Bigler et al. (1962) as follows:

> Weather radar data [should] be integrated into forecasting, warning, and briefing activities, and that a system be devised to provide these data in digitized form for computer processing and as composited pictures at major airports.
>
> That research be pursued to develop techniques for integrating radar into the weather measurement systems, and for obtaining quantitative information from radar displays.

Kessler submitted a proposal to the USWB on 3 April 1963 with the intention of "collecting and processing digitized radar data and other data applicable to severe storm and tornado warning and prediction" (Kessler 1963a).

In anticipation of becoming the director of NSSL, Kessler maintained his contacts with Roger Lhermitte, a scientist and radar engineer who had

TABLE 1. Worldwide Doppler weather radar development through the mid-1960s.

Approximate year	Reference/Affiliation, country	Radar characteristics
1953	Barratt and Browne (1953) Cavendish Laboratory, United Kingdom	9.1 cm, vertically pointing, pseudo-Doppler*
1956	Brantley and Barczys (1957) Cornell Aeronautical Laboratory, United States	3.3 cm, CW, built for USWB
1956	Boyenval (1960) Royal Radar Establishment, United Kingdom	3.2 cm
1959	Lhermitte (1960) French Meteorological Office, France	3.2 cm, vertically pointing, pseudo-Doppler*
1961	Lhermitte and Atlas (1961) Air Force Cambridge Research Laboratory, United States	5.5 cm, Porcupine radar transferred from Lincoln Laboratory
1961	Tripp (1964) Cornell Aeronautical Laboratory, United States	3.2 cm
1962	Battan (1963) University of Arizona, United States	3.25 cm, vertically pointing
1963	Kodaira (1964) Meteorological Research Institute, Japan	3.2 cm, vertically pointing
1963	Gorelik et al. (1964), from Battan (1972) Central Aerological Observatory, Russia	3.2 cm
1964	Lhermitte and Kessler (1964) National Severe Storms Laboratory, United States	3.2 cm, converted USWB CW

* A pseudo-Doppler radar employs a simple technique that determines the Doppler frequency shift by comparing the frequency that is returned from a precipitation echo at a given height with that from a stationary ground target (such as a water tower) at the same horizontal distance as echo height above the radar.

pioneered the development of meteorological Doppler radar (see Table 1). A recipient of a doctoral degree in electrical engineering from the University of Paris (1954), Lhermitte was invited to visit AFCRL's Weather Radar Branch by David Atlas in 1957 (Atlas 2001). Using Lincoln Laboratory's "Porcupine" Doppler radar during that visit, the concept of the velocity–azimuth display (VAD) was born (Lhermitte and Atlas 1961); this principle is used today with WSR-88D data to produce VAD wind profiles (VWP). In 1961, Lhermitte emigrated from France to work with Atlas at AFCRL.

Although Kessler would not officially become director of NSSL until early 1964, he began to coordinate efforts to build a weather radar program at the laboratory in late 1963. In a September 1963 letter to Lhermitte, who had just recently moved to the Sperry Rand Research Center in Sudbury, Massachusetts, Kessler (1963b) writes the following:

> It seems likely that support will be found in the Weather Bureau for a contract between the Weather Bureau and Sperry Rand for your services . . . The order of priority is something like this:
>
> 1. Make the CW-Doppler operate and provide improved means of recording the Doppler data.
> 2. Improve the accuracy and reproducibility of data recording and reduction procedures used with the WSR-57.
> 3. Make the TPQ-11 operate; make its facsimile output more quantitative; provide this radar with Doppler capability.
>
> You know at this time we have a very tight budget, and this probably precludes any substantial effort to place the RCA pulsed-Doppler radar in operation. Perhaps it would be appropriate to use components from the pulsed-Doppler and other systems on our premises in the CW-Doppler and TPQ-11.

The CW Doppler radar referenced in this letter is the one that was used by Smith and Holmes, and transferred from Washington, D.C., to Oklahoma. With Kessler's commitment to developing weather radar and Lhermitte's expertise in practical and theoretical electrical engineering, it comes as little surprise that Lhermitte left Sperry Rand for NSSL in early 1964, shortly after Kessler assumed the directorship.

SUCCESS WITH 3-CM PULSED DOPPLER RADAR.

Upon arriving at NSSL, Lhermitte eagerly undertook his new challenges. He was assisted by Chief Technician Walter Watts (Fig. 3) and technicians (later engineers) Dale Sirmans and John Carter (Kessler 1990). Lhermitte exhibited intensity and passion for his work, and he expected a high level of performance from those working with him.

Sirmans, a quiet-spoken southerner, got his early training in engineering at Georgia Tech. He completed his engineering degree at the University of Oklahoma (B.S. in electrical engineering in 1968) while working for NSSP and NSSL. The self-assured Sirmans found the perfect mentor in Lhermitte (Fig. 4). As remembered by Sirmans (1997–2002), "Lhermitte was removed from day-to-day operations . . . he gave me a lot of independence, but gave advice when problems arose."

Sirmans began work on the CW radar under Lhermitte's guidance. They used many of the original components of the radar, but, because they wanted a pulsed 3-cm radar instead of the continuous-wave version, a new transmitter and receiver needed to be built. This work was completed near the end of 1964 (e.g., Lhermitte and Kessler 1964). In his oral history interviews, Sirmans (1997–2002) said that he had to pull together all of his previous education and experience in engineering to complete the job. Sirmans had completed the transmitter–receiver work while Lhermitte was away on travel. Upon Lhermitte's return, Sirmans remembers bringing him to the trailer for a demonstration:

> From a cold start, the system came up incoherent but became coherent when the phase lock loop was established, producing strikingly different signal displays when the system locked. Roger was immediately elated, he rubbed his hands together and said "We have a Doppler radar!"

Carter joined the laboratory in early 1966 while completing a B.S. degree in math and physics at Central State College in nearby Edmond, Oklahoma. Born in Oklahoma, he grew up in Wichita, Kansas, where he developed a life-long passion for electronics. Prior to and during college, he worked for the Federal Aviation Administration (FAA) in Oklahoma City, Oklahoma. There he was introduced to radar technology, through his attendance at FAA technical schools. At the laboratory Lhermitte nurtured Carter by giving him experience on a variety of projects. Carter (2003) recalls,

> I had never worked with anyone like him before. He seemed to have skills in many areas—as a scientist (foremost), a physicist, a mathematician, a very good engineer. He gave me good guidance and allowed me to work on projects I really enjoyed . . .That was a special time—inspirational.

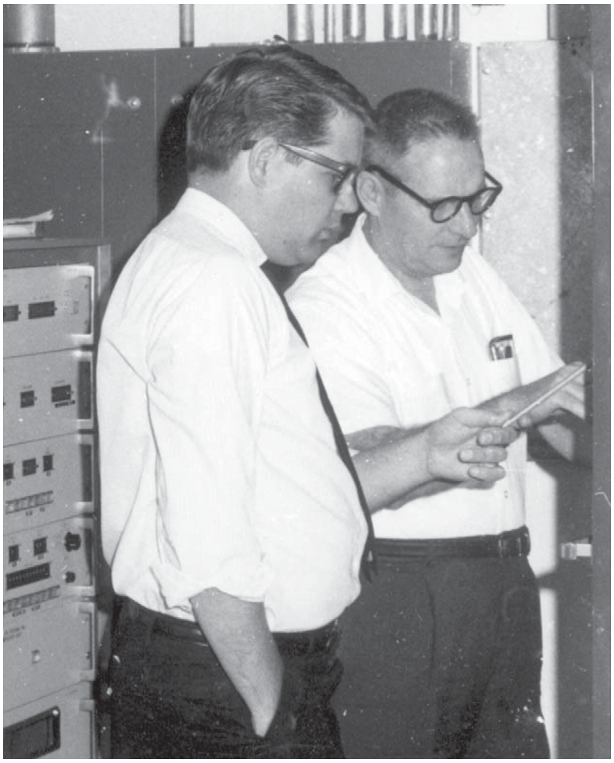

Fig. 3. Technicians (left) John Carter and (right) Walter Watts working on electronic equipment around 1968. [NSSL photo.]

Fig. 4. (left) Dale Sirmans and (right) Roger Lhermitte in Jan 1967. [Isolated by Robert Leidy from an NSSL staff photo.]

In a far-reaching and expansive paper, Lhermitte (1966a) summarizes his early work at NSSL and gives his view of the future of Doppler radar in meteorology. The first paragraph therein reads as follows:

> Conventional radar technologies have contributed significantly to the study of precipitation physics and storm dynamics. Yet many fundamental problems would be more effectively addressed if there were information on the motion of the particles inside storms not provided by conventional radars.

In this paper he discusses the following issues: the preferred wavelength for the radar, with insightful discussions of the pros and cons; the storing, processing, and displaying of Doppler radar information; and the scanning capabilities for severe storm monitoring. He concludes by stating that two types of Doppler radars are appropriate for studies of atmospheric physics: the low-powered 3-cm pulsed Doppler radar with a fixed vertical beam for studying vertical motions of the air, and the 10-cm-, or longer, wavelength pulsed Doppler radar (as cost permits) with a beamwidth of 2° or less for the three-dimensional surveillance network.

Thus, by late 1964, NSSL had a 3-cm pulsed Doppler radar. Signal processing in this radar, which was advanced for its time, analyzed one range location in real time (with a spectrum analyzer) and used analog methods to record data at 10 range locations for postanalysis (Sirmans and Carter 1968). This radar was used in a variety of studies aimed at understanding precipitation physics and clear-air radar returns (e.g., Lhermitte 1966b).

In the fall of 1966, NSSL hosted the 12th conference on radar meteorology in Norman. By that time, NSSL was well established, and its staff numbered about three dozen. That occasion provided the opportunity for the evolving capabilities of the laboratory to become more widely known.

During the following spring, the first dual-Doppler radar experiments were conducted. Cornell Aeronautical Laboratory's 3-cm pulsed Doppler radar was brought back to Oklahoma (having taken part in NSSP's 1962 spring program) to participate with NSSL's 3-cm Doppler radar in the first dual-Doppler radar experiment in the United States (e.g., Brown and Peace 1968). At the same time, another dual-Doppler radar experiment was conducted in England with radars of the Royal Radar Establishment (e.g., Browning et al. 1968).

As an undergraduate research assistant at the laboratory, Donald Burgess (2002) recounts the task of manually estimating the mean Doppler velocity from the Doppler velocity spectrum that was recorded for each range gate:

> We collected data from a storm on 29–30 April 1970. I was given the task of analyzing the velocity spectrum from 10 gates, that's all we had then. The spectra were on 35 mm film and I'd sit in front of that microfilm reader for hour after hour, doing maybe 100 spectra in a day. I got so tired I'd lose the edge—is it toward the radar or away from it? Wow, I'm glad I was young!

Burgess processed the last dataset that was collected with the 3-cm Doppler radar, which was decomissioned later in 1970.

THE IMPASSE. Just as NSSL was developing a strong expertise in Doppler radar and was getting ready to embark on a 10-cm Doppler radar program that would "more effectively" address problems of air motion inside storms, Lhermitte left NSSL in early 1967 for the Wave Propagation Laboratory (now the Environmental Technology Laboratory) in Boulder, Colorado. (Lhermitte remained in Boulder until 1970, when he moved on to the University of Miami, where he found his niche as a professor and is now a professor emeritus.) The dilemma resulting from Lhermitte's departure was formidable and the following questions arose: should the laboratory halt its activity in 10-cm Doppler radar development; should it seek a replacement for Lhermitte in the larger community; or should it continue with the home-grown team minus Lhermitte?

To assist with the decision, Kessler invited Mel Stone, who brought two other radar engineers from MIT's Lincoln Laboratory with him, to evaluate the laboratory's Doppler radar program. Their very favorable report boosted credibility for the laboratory's ongoing program and helped to guarantee the continuation of financial support, most of which came from the FAA. There remained the problem of who should head the program. As Kessler reminisced on this subject, he exhibited a nervousness that conveyed the sense of anxiety that he felt at the time. Quoting Kessler (1998),

> What do we do now? Thank goodness for [Deputy Director] Gil Kinzer. He was like a father to me. He had much experience in USWB bureaucracy and he was my stabilizing force. We decided to go ahead with our program and Dale Sirmans was put in charge. It was a tough decision because Dale talks softly and I was worried that when he presented our

> plans to Bill Hess [Director of the Environmental Research Laboratories] he wouldn't be convincing. Yet he knew weather radar and had been mentored by Roger.

During his short 3-yr stay at NSSL, Lhermitte had gotten things moving in the right direction. More importantly, people were committed to his vision and they were able to carry on after he left. As recalled by Carter (2003),

> He really was a dynamic guy with a lot of energy. I think that type of thing rubbed off on people. Everyone here had that same level of enthusiasm . . . He put us in a world-class category in Doppler radar development and that continued with all the things we did.

So, by mid-1967, Sirmans was in charge of the Doppler radar program, and plans to develop the first of NSSL's two 10-cm Doppler radars were well underway.

10-CM DOPPLER RADAR COMES TO NORMAN. In accord with Lhermitte's (1966a) advice to the larger community, the attenuation that was associated with 3-cm-wavelength radars made them unacceptable for a surveillance network. So, NSSL reaffirmed its decision to proceed with the more expensive 10-cm-wavelength Doppler radar. With the help of Kinzer and Gene Walker, a consultant from the University of Oklahoma, NSSL obtained a surplus 10-cm FPS-18 radar that had been part of the U.S. Air Force Distant Early Warning (DEW) line of radars. This radar had the basic components that were needed, including a klystron, which is the type of transmitter tube that is best suited for Doppler radars. However, the radar needed several additional components: an antenna, a pedestal, radar system control, signal processing, and a data archive (Fig. 5). The elevation axis drive was part of an old flood-control gate. Fortunately, a surplus tower was found at nearby Tinker Air Force Base. As part of a training exercise, Oklahoma Air National Guard groups dismantled the tower and reassembled it on the north research campus of the University of Oklahoma where the laboratory was located (Fig. 6). Thus, by early 1969, a 10-cm Doppler radar resided at NSSL, and was ready to be upgraded by Sirmans and his colleagues.

Fig. 5. (right) Norman 10-cm pulsed Doppler radar antenna and pedestal on an open tower with the transmitter in the building at the base (1969). (The decommissioned antenna and pedestal are now on permanent display at ground level on the same site.) The open tower was chosen as a cost-savings measure, but it proved to be unsatisfactory. So, the antenna and pedestal were subsequently moved to the permanent building shown in Fig. 6. The radar to the left of the tower was NSSP's/NSSL's WSR-57 research surveillance radar. The other two radars in the left part of the picture were used for aircraft tracking as part of Project Rough Rider. The two-story former Navy barracks building behind the three radars housed NSSP's Weather Radar Laboratory and then NSSL from 1962 through 1972. [NSSL photo.]

METEOROLOGICAL INPUT. To design the 10-cm radar's operating characteristics, meteorological information about the temporal and spatial scales of thunderstorms and tornadoes was needed. One of the principal contributors of this information was Neil Ward. He was a meteorologist's meteorologist—born and raised in Oklahoma—and was fascinated with weather from childhood; and he was an excellent operational forecaster for the USWB before joining NSSP, and then NSSL. He was especially astute about severe storms and had instituted informal scientific tornado chasing in the late 1950s as a part of weather forecasting at the Oklahoma City USWB office. He is best remembered for his tornado chamber (Fig. 7)—a hydrodynamical laboratory model that was used to simulate tornado funnels, including those with multiple vortices (Ward 1972).

Sirmans sought Ward's advice on the geomorphology of storms and tornadoes, typical scales of updrafts/downdrafts, speed of storms, etc. According to Sirmans (1997–2002), "Neil was such a nice person and easy to work with. He knew all of these details of storms and their structure. He was an immense help to me and others when it came to designing our system." Thus, as Sirmans prepared to build the 10-cm Doppler radar, he took advantage not only of the latest technology, but also of knowledge about the magnitudes and gradients of meteorological parameters that were expected to be found in severe thunderstorms.

DOPPLER RADAR AS A POTENTIAL WARNING TOOL.

When the Norman radar became operational during the middle of the 1971 spring tornado season, it was one of the few 10-cm Doppler weather radars in the world. At that time, the only type of real-time display of Doppler velocity fields within severe storms was the plan-shear indicator (PSI) display that was used on the AFCRL Porcupine radar (Armstrong and Donaldson 1969). Using output from a coherent memory filter, the PSI highlighted regions where there was a rapid change in Doppler velocity values as the radar scanned in the azimuthal direction. The PSI was well suited for displaying Doppler velocity shears within a storm, especially those associated with vortices that consist of extreme flow toward the radar next to extreme flow away from the radar. Starting in the mid-1960s, the PSI was used to document flow patterns in severe and tornadic storms in Massachusetts (e.g., Donaldson et al. 1966; Donaldson 1967; Donaldson et al. 1969).

Because the NSSL radar did not have a real-time display, time series data were recorded on seven-track, and then nine-track, magnetic tapes at a set of 16 range locations that could be stepped out on consecutive sector scans to encompass storms of interest. Researchers could not see Doppler velocity fields until days, weeks, or even months later; until NSSL had adequate computer facilities, data tapes were taken to out-of-town computers for processing. First, a fast Fourier transform had to be run to transform time series data into the Doppler velocity spectrum from which mean Doppler velocity and spectrum-width values could be computed. The data then were printed out in a rectangular "B scan" format (range versus azimuth) for analysis.

In 1970, Rodger Brown left Cornell Aeronautical Laboratory and, after a brief sojourn with Lhermitte at the Wave Propagation Laboratory in Boulder, Colorado, joined the radar team at NSSL. Shortly thereafter, Ken Crawford and Brown used the NSSL 10-cm radar to capture flow features associated with the severe storm of 23 May 1971 (Brown and Crawford 1972). A similar study was undertaken of the 2 June 1971 storm (Brown et al. 1971). The

Fig. 6. The new (surplus) Norman Doppler radar building, with the open tower, research WSR-57 radar, and NSSL building in background. The building was later painted "NOAA blue" with the radome painted white. [NSSL photo.]

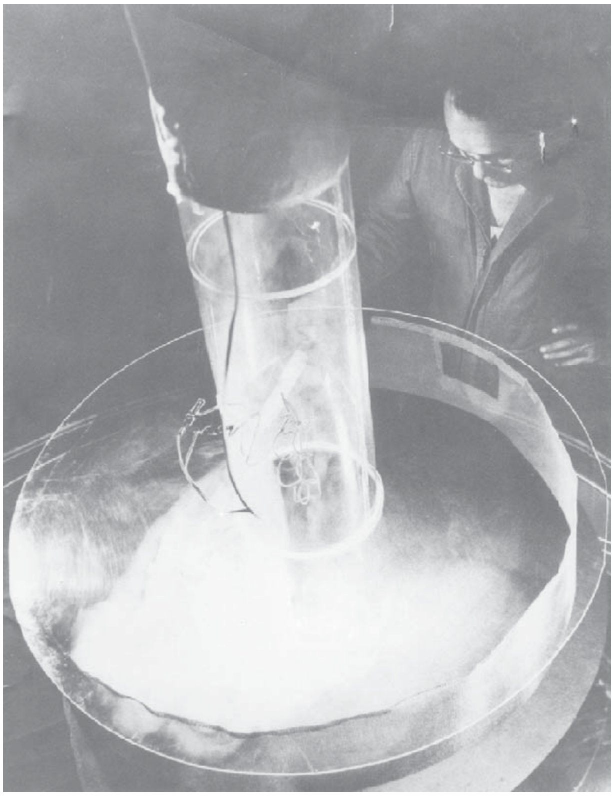

Fig. 7. Neil Ward monitoring the development of a tornado vortex in a small version of his famous tornado chamber. [Photo copyright of History of Science Collections, University of Oklahoma Libraries.]

first tornadic storm investigation was of the Davis, Oklahoma, storm on 19 April 1972 (Brown et al. 1973; Burgess 1974). However, the storm event that forever relieved any doubts about the potential value of Doppler radar as an operational warning tool was the Union City, Oklahoma, tornadic storm that occurred on 24 May 1973 (Fig. 8). In time for the 1973 severe storm season, Sirmans and Doviak (1973) developed a mean velocity processor that computed mean Doppler velocity values in real time. Doppler velocities were coarsely displayed in three shades of gray, with the three shades strobed to represent negative Doppler velocities (e.g., Sirmans et al. 1974).

The excellent Doppler radar coverage of the Union City tornado was augmented by AFCRL's PSI display that was at NSSL during the 1973 spring storm season (Brown et al. 1978; Donaldson 1978). Furthermore, the tornado intercept project teams followed the storm and obtained spectacular photography of the tornado (Fig. 8, e.g.) (Moller et al. 1974; Golden and Purcell 1978). Thus, both the timing and location of the tornado were well established. The Doppler-derived circulation known as the tornadic vortex signature (TVS) was discovered in this storm. It formed aloft at least 25 min before tornado touchdown, descended to the ground as the visible tornado formed, reached its maximum strength and maximum vertical extent when the tornado was widest, and disappeared as the tornado lifted (e.g., Brown et al. 1978). This was a dramatic indication that evolution of a TVS is linked to evolution of the associated tornado.

Fig. 8. Looking north at the Union City, OK, tornado just after it passed through the center of Union City on 24 May 1973. [Photo by NSSL storm intercept team.]

A SECOND 10-CM DOPPLER RADAR IS BUILT. While Sirmans was preparing the Norman Doppler radar for its initial data collection, Carter was at the University of Oklahoma working on an M.S. degree in electrical engineering with a National Oceanic and Atmospheric Administration (NOAA) scholarship. When he returned to the laboratory in the spring of 1972, he was unsure of his next assignment (Carter 2003). By that time Richard Doviak was head of the advanced techniques group, which included all of the engineering staff and those meteorologists working with Doppler radar data. Doviak had obtained an M.S. (1959) and Ph.D. (1963) in electrical engineering from The University of Pennsylvania and was an assistant professor there when he was hired by NSSL in the fall of 1971. Based on discussions between Doviak and Carter, and with the support of the director, it was decided that a second 10-cm Doppler radar should be built and that Carter should be in charge of the project.

The site selected for the new radar was at Cimarron Field near Yukon, Oklahoma, about 42 km northwest of Norman. As usual, donated supplies and surplus equipment, including an FPS-18 radar, had to be secured. However, as Carter (2003) recalled,

> The most money we spent on the whole project was for the pedestal. We had to go through a bidding process. As I recall, the price was under $100,000. That was really something special because that was the first thing we had ever bought that was brand new for a radar at NSSL!

As with the Norman radar, the Oklahoma Air National Guard assembled a surplus radar building and assembled the radome over the pedestal and antenna (Fig. 9). The Cimarron radar became operational in early 1974.

The Norman and Cimarron radars collected dual-Doppler data in two significant tornadic storm events that first spring and early summer—20 April 1974 (e.g., Brown et al. 1975; Ray et al. 1975; Ray 1976) and 8 June 1974 (e.g., Ray 1976; Brandes 1977; Heymsfield 1978). Armijo (1969), with financial support from NSSL, showed that the three-dimensional flow field in a storm could be synthesized from coordinated data collected by only two Doppler radars.

His derivation relied on kinematic constraints—the equation of continuity and a theoretical relationship between radar reflectivity and the terminal fall speed of precipitation. Dual-Doppler radar studies of the 1974 storms and of subsequent severe storms confirmed that the single-Doppler mesocyclone signature does, indeed, represent the presence of a mesoscale vortex. These vortices can extend vertically through an appreciable portion of the storms, and often are precursors for tornadoes.

PATH TO NEXRAD.

Because the width of a tornado typically is less than that of the radar beam, Doppler radar provides, at best, a degraded representation of the phenomenon, except for the case of a large tornado within a few kilometers of the radar (e.g., Brown et al. 1978). Beyond a range of about 100–125 km, a tornado typically is no longer detectable. The tornado's parent mesocyclone, however, is larger than the beamwidth, and serves as a detectable potential precursor for tornado formation. From mesocyclone signatures observed in Massachusetts storms, Donaldson (1970) established criteria for identifying two-dimensional circulations based on one-dimensional Doppler velocity measurements. Using those criteria, Burgess (1976) presents statistics for 37 mesocyclones that were observed on severe storm days by the Norman and Cimarron Doppler radars from 1971 through 1975. The typical mesocyclone signature has peak rotational velocities of about 25 m s^{-1} that are separated by a core diameter of about 5 km. Two-thirds of the studied mesocyclones had tornadoes associated with them, and the average lead time from the initial detection of the mesocyclone (in data analyzed after the fact) to tornado touchdown was 36 min. (Based on Doppler velocity measurements across the country during the ensuing 30 yr, it appears that only about 20% of mesocyclones have tornadoes associated with them, and typical operational lead times are 10–15 min.)

Fig. 9. Nighttime view of the radome on NSSL's Cimarron Doppler radar building being assembled by the Oklahoma Air National Guard in 1973. [NSSL photo by Charles Clark.]

The National Weather Service (NWS; formerly USWB) and U.S. Air Force's Air Weather Service (AWS), who were ready to replace their aging WSR-57 and FPS-77 radar networks, were impressed with these and other research Doppler radar findings. NWS and AWS were joined by the FAA, which was interested in the potential of Doppler radars for providing low-altitude wind shear information at airports. They jointly decided to undertake an operational experiment to determine whether the addition of Doppler capability would improve the accuracy and timeliness of severe storm and tornado warnings. The experiment was called the Joint Doppler Operational Project (JDOP), with Kenneth Wilk as the project coordinator (Staff of NSSL, AFGL, NWS, and AWS 1979). Wilk came to Norman from the Illinois State Water Survey in 1962 to manage NSSP's new Weather Radar Laboratory and continued on at NSSL as head of the group involved with the transfer of radar technology to the NWS.

Two technological advances that were developed during the late 1960s and early 1970s made it possible to display Doppler velocity data in real time for JDOP. The first was the pulse-pair processor, which was a major breakthrough that permits mean Doppler velocity and spectrum-width data to be computed from pairs of pulses and recorded in real time (e.g., Rummler 1968), instead of running a fast Fourier transform to compute the Doppler velocity spectrum, after the fact, from time series data. The mean velocity processor of Sirmans and Doviak (1973), with its coarse black-and-white display, was based on the pulse-pair concept. The second advance was the development of color monitors for displaying Doppler radar data (e.g., Jagodnik et al. 1975; Gray et al. 1975). The finer resolution provided by the use of color greatly improved the capability of observers to interpret reflectivity, mean Doppler velocity, and spectrum-width measurements in severe storms.

JDOP was conducted during the spring tornado seasons of 1977–79 using the NSSL Norman Doppler radar, with additional equipment provided by the Air Force Geophysics Laboratory (AFGL; formerly AFCRL, now the Air Force Research Laboratory). The

NWS, AWS, FAA, and NSSL participated in JDOP (Fig. 10). Results of the experiment were evaluated by comparing warnings issued by the NWS forecast office in Oklahoma City with advisories issued by the JDOP team. In general, for both severe storm and tornado warnings, there was a noticeable increase in probability of detection and a marked decrease in false alarms. Tornado warning lead time increased from –1 min, using conventional radar and spotters, to +21 min, with the addition of Doppler velocity information (Staff of NSSL, AFGL, NWS, and AWS 1979).

Based on the success of JDOP, in January 1980 the NWS, AWS, and FAA established the Joint System Program Office in Washington, D.C., to oversee the procurement of the 10-cm NEXRAD (ultimately called WSR-88D) for a national network of Doppler radars (Fig. 11). Design of the radar closely followed what had been developed for NSSL's Norman and Cimarron Doppler radars, with Sirmans playing an important role in the process. Whiton et al. (1998) provide more details about events in the radar community leading to JDOP, and follow-on events concerning NEXRAD and the FAA's Terminal Doppler Weather Radar during the 1980s and 1990s.

EPILOGUE. The driving force behind the development of NEXRAD was a coupling between research and operations. From the beginning, NSSL had a mission to link weather radar research with the needs of operational forecasters. Issues such as the advance warning of severe weather were always at the forefront of the laboratory's efforts, yet research that led to the fundamental understanding of severe storms—especially tornadic storms—was a by-product of this coupling. Without doubt, Lhermitte's vision and research strength were crucial to early Doppler radar development at NSSL. His mentorship during the period of 1964–67 sustained the effort after his departure. Much credit must also be given to Kessler for the tenacity he exhibited in the face of losing Lhermitte, and the added burden of securing funding for further development of the radar. And, finally, Sirmans, Lhermitte's protégé, accepted the responsibility of leading the team of engineers and technicians that successfully developed the 10-cm radars that became the cornerstone of NEXRAD.

FIG. 10. JDOP staff members monitoring a severe storm situation using Norman Doppler radar displays. Left to right: Don Devore (NWS), Captain Dave Bonewitz (USAF), and Don Burgess (NSSL). [NSSL photo.]

FIG. 11. (left) NSSL's research and development WSR-88D radar eclipsing the (center) older Norman Doppler radar—a foreshadowing of events to come. [Photo ©1997 Rodger Brown.]

ACKNOWLEDGMENTS. Preparation of this paper greatly benefited from oral history interviews with the following now-retired NSSL staff members: Don Burgess, John Carter, Edwin Kessler, Dale Sirmans, and Ken Wilk. Thanks to the staff of the DeGolyer Collection in History of Science at the University of Oklahoma for their help in accessing information and photographs in their archive. We appreciate Joan O'Bannon's assistance in finding and reproducing photographs from NSSL's archive. Comments on the manuscript by Doppler radar pioneers David Atlas and Roddy Rogers and by NSSL staff members Richard Doviak and J. T. Lee (retired), in addition to those listed above, are most appreciated. The two anonymous reviewers also provided very helpful comments. The early radar development that was discussed in this paper would not have been possible without the talent and dedication of the radar development and support staff who worked at various times with Roger Lhermitte, Dale Sirmans, and John Carter: Glen Anderson, Bill Bumgarner, J. T. Dooley, Larry Hennington, Jesse Jennings, Leonard Johnson, Eual Kelly, Mike Schmidt, John "Buzz" Shinn, and Walter Watts.

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