# Industrial Radar for Hurricane Tracking

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An explanation seems in order as to why an industrial corporation manufacturing chemicals has apparently invaded the province of the U. S. Weather Bureau in tracking tropical storms. The facts are that the program is not in competition with the Weather Bureau, but in cooperation with it; and it was undertaken in order to facilitate chemical manufacture. A hurricane need come no closer than a hundred miles to cause thousands of dollars' loss to the Dow Plants. The vulnerability of the site on the Texas Gulf Coast and the nature of some of its operations require that plant shutdown be started about twelve hours before the occurrence of hurricane winds.

A hurricane is an area disturbance consisting of circular winds about a calm center or eye. Apparently most such storms originate in the tropics, but they travel far and may strike coastal areas anywhere in the Tropical or Temperate Zones. Those in the Northern Hemisphere always rotate counterclockwise, while those in the Southern Hemisphere rotate clockwise as viewed from above. Hurricanes are usually dangerous over a diameter of 100 miles or more, with the worst winds near the center. The calm area at the center may be several miles in diameter, and barometric pressure may be as low as 27 in. In addition to the very severe circular winds, which may exceed 100 mph, the whole disturbance moves as though it were a giant top spinning and sliding at the same time. This "forward" or sliding motion, which it is sought to follow or predict, usually ranges from 4 to 15 mph. However, the storm may stay in one spot for half a day or double back on its past track.

A single storm may have a life as long as two weeks, during which it traverses thousands of miles of ocean. Once the cycle is started, energy is poured into the storm continuously in the form of warm moist air. This causes heavy rains as it spirals in toward the center and the resulting pressure drop provides impetus for continued winds and more rain. The storm usually dissipates soon after hitting land areas, but these hurricanes cause much damage and loss of life on the Gulf and Atlantic coasts. They are invariably accompanied by extremely high tides and usually by torrential rains.

The inhabitants of inland areas may have difficulty in comprehending the destruction of a hurricane, considering that the 125-mile-an-hour winds are only a fraction as great as those of a Great Plains twister. The explanation is in the large area covered and the high water. Tides of 16 ft have been experienced along the Gulf Coast, and 40-ft storm tides are not unusual in some areas. Add to this the fact that many coastal communities are 4–8 ft above sea level and it becomes apparent that cyclone cellars are of no value.

What property of a hurricane allows it to be detected by means of radar? During the war it was discovered that aircraft could hide in heavy rainstorms and avoid detection by some types of radar because the rain gave a radar indication of the same type as an airplane, but over a wide area. The indication was not changed by the presence of an aircraft in the rain area. Later it was found that hurricanes presented a distinct picture on these radar sets because of the rain which almost invariably accompanies them. Fig. 1 shows a typical picture of the radar presentation of a hurricane on a plan position indicator. The picture is equivalent to a map or plan view of the area with the radar located at the convergence of the radial lines. These lines and the range circles form a polar coordinate reference system used to locate targets accurately with respect to the radar.

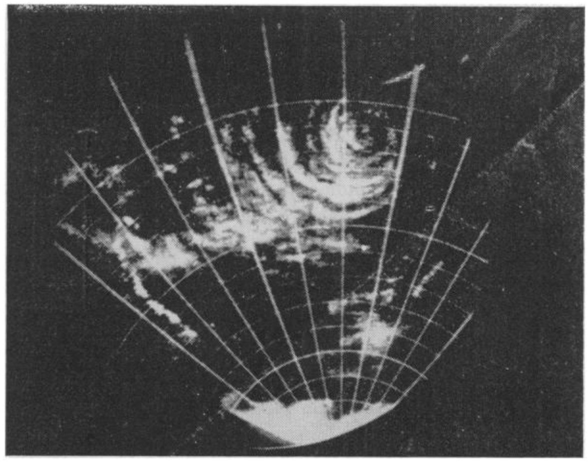

FIG. 1.

The irregular white areas represent radar reflections fom the bands of heavy rains. Radar returns of this type have been found to result from hurricanes in all parts of the world, and have never been observed from any other cause. The picture shown was made from the 'scope of a 10-cm Army radar during the 1945 hurricane which went up the Florida peninsula.

The timing device of a pulsed radar set controls the entire set—transmitter, receiver, and the presentation device. Powerful pulses of radio energy are generated by the transmitter and radiated in a highly directional beam. The receiver antenna and the receiver pick up the returned echo (if any) and send the notice of arrival to the presentation device, which measures the time required for the signal to echo from any target and gives a visual indication of this time. Usually the size and intensity of the echo and its azimuth bearing from the radar are also shown.

A single such pulse will give an indication of all the echo-producing objects in the path of the radio beam. However, since it may be desired to sweep the antenna rapidly through the complete 360° of rotation and scan the complete area covered by the radar, provisions must be made to send out rapidly recurring pulses. Thus the timer is designed to wait only the minimum time required for the reception of an echo from the maximum expected range before repeating the cycle. In the event the antenna is not rotated, recurring echo pulses are indicated in the same position on the indicator and are integrated by the persistence of the phosphor on the cathode ray tube to give a more distinct indication.

Practical radar sets usually have numerous additional blocks which perform auxiliary functions. Most sets have only one antenna, which functions alternately for the transmitter and the receiver through the use of an automatic switch. Power servo systems permit the operator to point the antenna in any desired direction by fingertip controls. Other devices may provide the automatic frequency control.

Radar for general use or search usually is equipped with a type of presentation known as the Plan Position Indicator, or PPI. In this unit, time is measured by the radial distance which a spot moves from the center of the cathode ray tube. Direction in which the spot moves is made to coincide with the direction in which the antenna is pointing. The spot starts from the center at the time the radio wave is sent out, and moves from the center outward at constant speed. Reception of an echo is made to brighten the spot momentarily. Since travel time is proportional to the distance to the echo-producing object, and time also is proportional to the radial distance the spot has moved on the indicator, this gives a bright spot for each echo-producing object in its map or plan aspect with reference to the radar set. Distance and angles may be scaled directly on this presentation.

The factors affecting radio propagation and the question of what causes a radio reflection or echo have been studied in great detail in connection with the wartime radar program. In general, any conductor of electricity or any insulator with properties greatly different from the atmosphere may cause a radio reflection. The reflection is usually diffuse, comparable to light reflected from a rough surface. To produce a strong echo, the object must be of a size comparable to or larger than a half wavelength of the radio wave. However, much smaller objects, such as drops of water, cause some reflection; and if there are enough of these objects in a given area, an echo will be received. Calculations show that the energy returned from a drop of water varies as the sixth power of the ratio of drop diameter to wavelength (*2*)

Practically, this means that 3000-megacycle or 10-cm radar sets will "see" rain, while 100- or 500-megacycle sets will not. Radar operating on 10,000 megacycles or 3 cm will indicate the presence of light rain or fog. Water drops of a minimum diameter of about 1.2 mm are indicated by 10-cm radar. Another point which should be emphasized is that an object need not be opaque to radio waves in order to produce an echo. An object may produce a radio echo and still transmit a large percentage of the signal. At times as many as three rainstorms in a row radially from a radar have been seen on the radar 'scope.

Radio energy of wavelengths commonly used in radar work travels essentially in straight lines, just as light does, and diminishes as the square of the distance from the source. Under normal atmospheric conditions there is a slight bending in the vertical plane which extends the radar horizon slightly beyond the optical horizon. To be "seen" by a radar set with its antenna at 25-ft elevations, an object at a range of 100 miles must have an elevation of about 4,000 ft, while at 300 miles an object must be about 40,000 ft high.[1] Thus, it is seen that there is a definite limit to the range that may be attained, even though a very large amount of power is used. Meterologists are in general agreement that the central core of a hurricane may rise to 50,000 ft but the maximum height at which water drops are present is probably somewhat less. Because of these considerations, it appears that no radar of present design located on the ground will be able to detect a hurricane at ranges much in excess of 300 miles. Occasionally radar targets are detected at ranges far beyond the optical horizon. This is caused by anomalous atmospheric conditions, creating a duct or layer through which radio waves are led around the earth's curvature. Unfortunately this phenomenon cannot be relied upon to extend radar coverage.

When it was decided to install a radar set for the purpose of tracking storms, the question of the most suitable type arose. The Weather Bureau recommended the SCR-584 or 784, since these sets are designed for about 3000 megacycles (10 cm) and have adequate power. A trailer-mounted SCR-784 was purchased and certain necessary modifications were made with the assistance of Weather Bureau personnel. The installation was made under terms of an agreement whereby all data obtained with the radar would be sent directly to the Weather Bureau and would be released to the public only through that agency. The set was located about two miles from the open Gulf on land about 18 ft above sea level, with a clear view seaward.

The SCR-784 has a very short pulse width or length of time during which energy is transmitted, and relatively short design range. This does not imply a lack of power, but rather a short listening period between transmitted pulses. The peak power of the set during the 0.8-microsecond transmitted pulse is 250 kw, or five times that of the most powerful commercial broadcast station. Modification of the set for the weather work began with a slowing of the pulse repetition frequency to give more listening time between transmitted pulses. Additional multivibrator stages were added to the timing circuits to give a frequency of 188 pulses per sec, which permits reception of echoes from objects 300 miles distant. Then the presentation unit was modified to cause the cathode ray spot to sweep more slowly, corresponding to the time required to receive echoes from the longer range. Multiple ranges of 100, 200, and 300 miles were provided, with a selector switch to choose among them.

This completed the necessary modifications, but several others were made in the interest of improved efficiency. A larger parabolic antenna reflector was installed in order to focus the radio waves into a sharper beam and thus give a higher concentration of energy and improved ability to resolve contiguous targets into separate pictures rather than merging them into a solid pattern.

The slowing of the pulse repetition frequency previ-

[1] $R = 1.43\ (\sqrt{H_1} + \sqrt{H_2})$ Where $R$ is range in miles and $H_1$ and $H_2$ are heights of radar and target in feet.

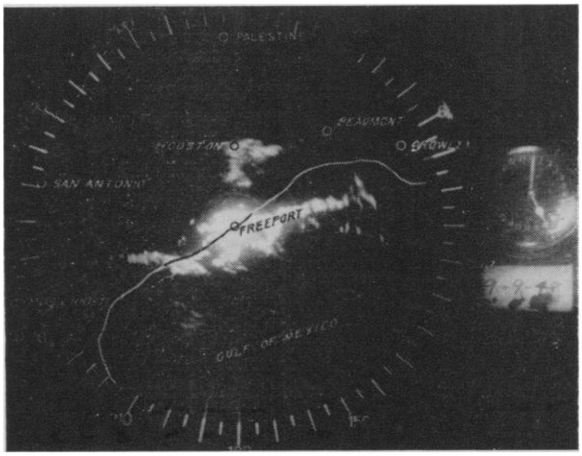


FIG. 2.

ously mentioned resulted in a reduction in the average energy transmitted by the station, since each pulse contains a definite energy and the number per second was reduced. In order to increase this average energy output, the pulse width was increased from the original 0.8 microsecond to 1.6 microsecond. In general, average power is unimportant so long as peak power is maintained, but a pulse of longer duration improves the signal from a diffuse object or one with depth, such as a rainstorm. This greater pulse width gives poorer resolution in range, but it is still more than adequate. The angular resolution of the modified equipment is of the order of two degrees, which means that at a range of 100 miles isolated objects less than four miles apart will have their echoes merged. This difference between angular and range resolution causes point targets to produce elongated pictures with the long axis tangent to range circles.

Other modifications included installation of a new preamplifier and a larger PPI tube. Camera equipment was arranged to permit rapid photographing of the screen

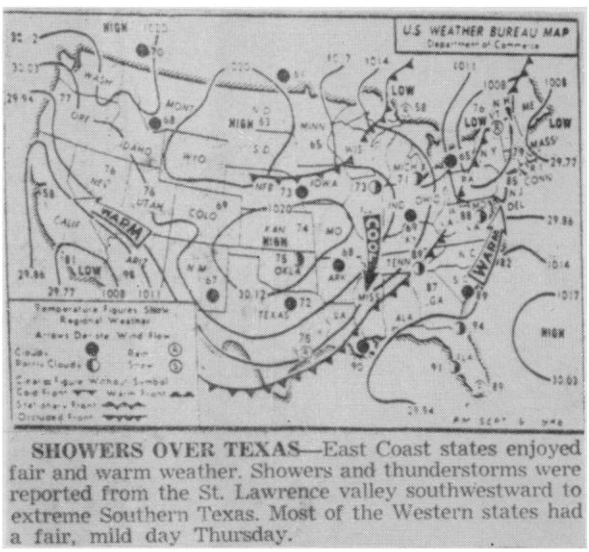


FIG. 3.

with convenient means for identifying each picture as to date and hour. An automatic camera was also provided, to take a picture every minute. When projected as a movie film, the record of this camera should be very interesting.

After the equipment was installed and modified, many observations were made to test the range and accuracy. Thunderstorms and isolated rains were observed and telephone calls were placed to verify the actual weather at the points where rain was indicated. Agreement was surprisingly good. Some cases of disagreement were apparently caused by rain in the upper atmosphere which evaporated before striking the ground. Results were consistent enough to show that rain will always be indicated. Many storms have been observed at ranges greater than 200 miles, at least one at 240 miles being verified. Echoes from 280 miles have been observed. Several times the radar screen has presented a picture of a line squall that agreed very closely with a front indicated on the official weather maps. Figs. 2 and 3 indicate one case of this type. Geographical features were dubbed in to orient the 'scope photograph better. This picture also illustrates a case of the radio waves' penetrating 80 miles of solid rain and still retaining power to produce an echo from rain 100 miles distant.

A program was set up for daily observations during the hurricane season—from the middle of June to the first of November. In the event that a tropical storm is known to be approaching, the equipment is manned continuously. A weather consultant is on hand to interpret the results and direct the experimental program. Experience during the war indicates that considerable information about a hurricane may be revealed by one observation on the radar screen. The center or eye of the storm is usually well defined as a clear area completely or partially surrounded by heavy rain. Even before the main part of the storm comes within range, the squall line associated with it may provide some information. These squalls may be from 40 to 100 miles from the center and they are thought to run at right angles to the line of progress of the storm. It is also generally acknowledged that rains are heaviest in the right front quadrant of the moving storm—this is based on storms in the Northern Hemisphere, which always have counterclockwise rotation as viewed from above. In a storm moving radially, that is, approaching the radar, the movement should be apparent from observations taken 15 min apart. This contemplates a speed of four mph and a range resolution of the radar of one mile.

As an experimental program, efforts will be made to obtain a vertical profile of the hurricane core by taking successive photographs as the angle of antenna elevation is increased. If this is successful at all, it will probably be at rather short ranges, since the angular resolution is hardly adequate for this.

Fortunately, the hurricane data obtained thus far with this equipment has been of a negative nature. That is, the first hurricane season and a portion of the second have elapsed with no hurricanes having presented themselves for observation. This does not dampen enthusiasm for the program in any way, the range and reliability of the equipment having been proved on rainstorms. It must be acknowledged that the hurricane which struck New Orleans on September 3, 1948, passed within 300 miles of the radar. No indication of a hurricane or even of rain was obtained during its course. However, this particular disturbance barely qualified as a hurricane, the highest wind velocity being 70 mph. Undoubtedly it did not reach the altitude required for radar observation at this extreme range.

## Cosmic Ray Instrumentation

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Cosmic ray work is a subject rich in examples of advances in instrumentation leading to great discoveries in pure science. Cosmic ray research started, in fact, as instrument research, as the investigation of the leakage of electricity through the air in electrometers. Coulomb (1785) can be considered its founder. His career exemplifies the mutually beneficial interaction between basic research and instrument development. He first determined the law of torsional elasticity, the way in which the elastic constant depends on the radius and length of the cylinder. He then used this knowledge in the construction of a torsion balance of unheard of sensitivity. With this instrument, which could measure forces down to 0.005 dynes, he discovered the inverse-square law of force between electric charges. He then made a more sensitive torsion balance, readable to 0.001 dyne, with which he was able to prove, long before Faraday's ice pail, that there is no electricity on the inner surface of a conductor in equilibrium. Like everyone who has experimented with static electricity, Coulomb observed the apparently inexorable leakage of charge. He, however, studied it quantitatively, and resolved it into leakage along the supports and a leakage through the air. He planned a careful study of the dependence of the rate of leakage on the nature of the gas, its density, and its humidity, but had to postpone the project for lack of "instruments to measure exactly the purity of each gas and its humidity." Had Coulomb carried out this program, he would have been well into the physics of ionization chambers.

More than a hundred years later, in 1900, it was found that the conductivity of the air is due to continual ionization, and C. T. R. Wilson, in 1901, published the bold speculation that this ionization is due at least partly to an extremely penetrating radiation from outside the earth. In 1912-13, Hess and Kolhoerster obtained convincing evidence that there is an ionizing radiation coming down from on high, and by 1926 the scientific world was on the whole convinced of the existence of cosmic rays.

An outstanding example of an ionization chamber now in use for the continuous recording of cosmic ray intensity is the so-called Carnegie Model C, designed by Compton, Wollan, and Bennett in 1934. In this instrument the cosmic ray ionization in a 19.3-l sphere of purified argon compressed to 50 atmospheres is balanced against the ionization in a small chamber due to the beta rays from a uranium source of adjustable position. The collecting electrode, common to the large chamber, whose wall is at +250 v, and to the balancing chamber, whose other electrode is at −250 v, is connected to a Lindemann electrometer, the position of whose needle is recorded photographically through a microscope. The use of balancing makes the readings largely independent of voltage and temperature variations. With its 10.7-cm lead shield around it, this instrument has an average cosmic ray current at sea level of about $2 \times 10^{-13}$ amperes, corresponding to about 15 fast particles per sec. About once a day there is a "burst," corresponding to the simultaneous passage of more than 500 fast particles.

An extremely useful wartime development in ionization chamber technique is the use of electron collection coupled with fast amplifiers. The leaders in the application of this technique to cosmic ray problems have been Rossi, Bridge, and Williams, who have thereby made important advances in our knowledge of high energy nuclear interactions. It is possible to rid argon of electronegative impurities, so that the electrons formed in the ionization process are collected free rather than attached. Their drift velocity in the direction of the applied field is on the order of 1000 times greater than those of the massive ions. Under appropriate conditions of field geometry and gas filling, a fraction of the total pulse height exceeding 90% is attained in a few microseconds. This makes possible the use of ion chambers in relatively fast coincidence with other chambers and counter tubes. Furthermore, the same workers, together with Hazen, have shown how the shape of the ionization pulse, as photographed on a fast cathode ray oscillograph sweep, gives information on the initial spatial distribution of ions, so making it possible to distinguish between bursts due to many fast particles spread through the chamber and bursts due to "stars" of a few heavily ionizing particles.

The ionization chamber is merely the most venerable of the many instruments now used in cosmic ray research, each of which has been responsible for tremendous advances. The instruments of cosmic ray research are the instruments of nuclear physics, just as, for example, the instruments of conventional astronomy are those of optics.

The most striking feature of cosmic ray nuclear physics is the low intensities with which one has to deal. In the Carnegie Model C ionization chamber that I mentioned the flux of penetrating particles through a sphere 33.2 cm in diam is only about 15 per sec at sea level in high latitudes. The increases in intensity at very high altitude do not exceed several hundred times; it is sometimes necessary, on the other hand, to go below ground or water, where the intensities are decreased by similar factors. A second feature of cosmic rays is their heterogeneity in composition, energy, and direction. This means that as a rule the more clean-cut in design an experiment is, the longer will it take to obtain statistically significant data. A third peculiarity of cosmic