VARIATIONS FROM PULSE TO PULSE IN WEATHER RADAR RETURN SIGNALS

by

LIEUTENANT COLONEL JOHN MARTIN STEIGNER
UNITED STATES AIR FORCE

A THESIS

submitted to

OREGON STATE UNIVERSITY

in partial fulfillment of
the requirements for the
degree of

MASTER OF SCIENCE

June 1962

APPROVED:

Redacted for Privacy

Chairman of Meteorology

In Charge of Major

Redacted for Privacy

Chairman of School Graduate Committee

Redacted for Privacy

Dean of Graduate School

Date thesis is presented May 18, 1962

Typed by Alura Paul

ACKNOWLEDGMENT

Many people helped make this thesis possible.

After completing one-third of my course-work in so-called "off-duty" time, the United States Air Force permitted me to absent myself for five months from normal weather-officer duty to complete the remaining two-thirds of my graduate study.

I wish to thank particularly Lt. Col. Harold A. Jacobs and my other Air Weather Service colleagues of the United States Air Force, who work at the Headquarters of the Portland Air Defense Sector. They encouraged me to complete my studies although they knew that their work on rotating shifts would increase twenty per cent during my absence. Their continuous encouragement and complaint-free attitude these past five months have been a fine example of Christian spirit and professional attitude.

Dr. Fred Decker, a Lt. Col. in USAF Reserves and head of the Atmospheric Science Branch of Oregon State University, has been patient with my ignorance of many matters which either I had lost or are new since my undergraduate work twenty-four years ago.

Sources of equipment used for this study are a sampling of how well federal, state and civilian agencies assist our universities to advance knowledge.

The United States Army Signal and Development Laboratories of Monmouth, New Jersey loaned the AN/CPS-9 radar set to Dr. Decker.

Through the generosity of the Tektronix Foundation, Dr. Decker relatively recently acquired the Tektronix Oscilloscope at a small per cent of its 1800 dollar list price.

The dollar value of the Fairchild Oscillo Camera is similar to the oscilloscope. This camera is one of numerous articles Dr. Decker has acquired at nominal cost and with much foresight from the State (Oregon) Department Finance and Administration Surplus Property Section. These items range from quonset huts to screw drivers and have a total value of thousands of dollars. All are property surplus to the Federal Government's need, but with rare exception in excellent condition.

Mr. Kenneth H. Shreeve, a Research Associate of the Atmospheric Science Branch, O.S.U., continually worked with me to get results from this equipment: radar, oscilloscope and camera. Although excellent equipment, we had no experience data to follow to obtain well-separated and clear images on film of pulses received, one each 5.4 millisecond apart. He alternately guided, lead, assisted or followed all my effort to the extent that the product wholly or in part is "our" product.

Although this thesis uses statistics very basically, I have Mr. Donald R. Jensen, Experiment Station Statistician, O.S.U., to thank for assistance. He quickly understood our problem and generously gave lucid advice.

We found that the factory-installed cathode ray tube of the oscilloscope had too long a persistence suitably to show single pulse returns for photography. We conferred frequently with Mr. William March, Staff Field Engineer of Tektronix, Portland, Oregon, concerning this persistence problem. He assisted us valuably with information and exchange tubes of increasingly shorter persistence until the problem was solved.

Quite obviously this thesis reports the combined work of several people. The effort to attain such coordination is no small part of the rich educational benefits the whole thesis experience has given me.

TABLE OF CONTENTS

LIST OF PLATES

Weather forecasts help keep our gross national product high; better forecasts could significantly raise that product. (8, p. 5)

VARIATIONS FROM PULSE TO PULSE IN WEATHER RADAR RETURN SIGNALS

CHAPTER I

INTRODUCTION

Radar of the shorter wave lengths and the atmospheric scientist have mutual targets: land, water, raindrops, cloud droplets, ice particles, snowflakes, atmospheric nuclei, regions of large index-of-refraction. The scientist uses radar to study such weather phenomena. During the early and mid-1940's weather research by radar was mostly qualitative. Phenomena were located; their extent and velocity observed and often recorded by scope photography which gave a record to analyse.

More recent and exciting, but perhaps not so well known is the use of radar for quantitative atmospheric measurements. Since the late 1940's there has been considerable research towards these ends. It continues strongly today; results show promise of valuable operational capability. Battan (2, p. 51-63, 70-73, 144) describes much of this activity and refers to many published reports which invite further study.

We are attracted by studies based upon the fact that weather radar return signals vary in signal strength, pulse to pulse. The signals analysed are those returned by weather in one discrete volume of the atmosphere, weather such as: cloud and rain (1, p. G1-G7); turbulence (4, p. 1-2); snow (6, p. 249-254; and, gustiness (9, p. 99-105), (10, p. 255-260).

These and similar studies are logical steps towards finding ways to use radar objectively to report specific weather phenomena. With such capability added to its flexible reach and continuous availability, radar could be a basic cause of a new era of weather support excellence.

Effort which could add a step towards the goal of quantitative weather radar reports is attractive. The action this thesis describes has such a step as its purpose. Pages that follow show the theory, equipment and procedures used to sense, record and analyse the relative amplitude of weather return signals.

CHAPTER II

THEORETICAL CONSIDERATIONS

The Radar Equation

The total back-scattering by weather particles may be calculated from (Battan 2, p. 25-31):

$$\bar{P}_r = \frac{\pi^5}{72}\left(\frac{P_t \theta \phi h A_p^2}{\lambda^6}\right)|K|^2 \frac{Z}{r^2} \qquad (1)^1$$

All terms within the parenthesis on the right side of the equation (1) are characteristics of the particular radar set and are constants.

The K remains constant when the back-scattering particles are the same type (i.e. either rain or snow etc) and since the refractive index of the atmosphere is essentially the same for one situation.

The r remains constant while precipitation in one discrete volume is scrutinized.

---

[1] Where:

$\bar{P}_r$, is the average power received by the radar.
P_t, is the transmitted power.
θ, is the radar beam width in the horizontal.
ϕ, is the radar beam width in the vertical.
h, is the pulse length.
A_p, is the effective aperture area of the antenna.
K, is a function of the absorption coefficient of the material involved and atmospheric index of refraction.

$Z = \sum D_i^6$, is the "radar reflectivity factor" of the precipitation per volume (D_i, the drop diameter).
λ, is the wave length of radar radiation.
r, is the distance from the radar to the target.

The variable is Z. Drop size, D, scatters radiation energy proportional to the sixth power of the drop size.

Battan (2, p. 51) says that in this equation (1) it is necessary for the average power to be a representative one in time.

Pulse Variations

In any one small volume of the atmosphere, the drops should be expected to have sufficiently similar size to return fairly constant signals during a few milliseconds. In actuality, however, constant signals do not occur even in so brief a time. Relative motions of scattering particles in range cause return power to fluctuate. This is caused by the changing phase relationship, or interference patterns, of the return power from the separate particles as they change position relative to one another.

This motion could be caused by such conditions within the volume as shear, gustiness, or turbulence, up-slope or down-slope movement, all of which are parameters significant to meteorological knowledge. Any finding, therefore, telling more about the relative motion of back-scattering particles could possibly be further used to analyse those significant meteorological parameters.

Several investigators have done considerable work to determine conditions within the volume which cause signals to exceed thresholds of amplitude which they chose arbitrarily (5, p. 68), (6, p. 254), (9, p. 105), (10, p. 260). Apparently there have been relatively few pulse-to-pulse studies of the return signal spectrograph to determine basic characteristics of the pulses such as their correlation coefficients and the time for return signals to reach independence. Battan (1, p. 51) mentions two such studies. One found that successive return signals received by 3.2 centimeter radar reached independence in twenty milliseconds; the other found that independence was reached in four milliseconds using a 1.25 centimeter radar.

Available equipment could be well used to try to learn more about variations of the return signal pulse-to-pulse.

CHAPTER III

INSTRUMENTATION

Excellent equipment was available. It consisted of three basic units, all installed and maintained by the Atmospheric Science Branch of Oregon State University: An AN/CPS-9 radar, a Tektronix oscilloscope, and a Fairchild Oscillo-Record camera.

AN/CPS-9 Radar[1]

The AN/CPS-9 radar transmits 2.5×10^5 watts at a wave length 3.2 centimeters, a pulse length of either 0.5 or 5.0 microseconds and at a pulse repetition frequency (PRF) of 931 or 186 per second from a paraboloid antenna (Plate 1, page 7) of 2.36 meters. The resulting beam width is 1.0 degree and conical. It can detect a signal at a minimum of about 1.6×10^{-13} or 1.6×10^{-14} watts.

The longer pulse length is used with the lower PRF and results in the lower minimum detectable signal of 1.6×10^{-14} watts.

The radar set is located on McCulloch Peak, 2200 feet elevation and four and three quarters miles northwest of the Oregon State University campus. From this vantage point students and research personnel use the excellent weather capabilities of the set.

---

[1] Literal meaning: Army Navy/Air Transportable, Planned Position and Range Height.

Plate 1. The AN/CPS-9 Weather Radar Antenna.

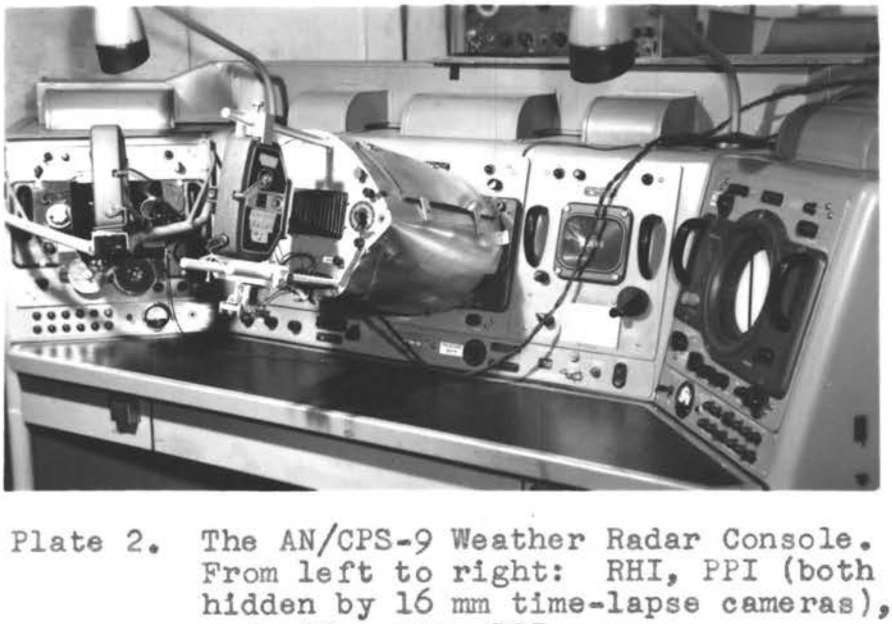

Plate 2. The AN/CPS-9 Weather Radar Console. From left to right: RHI, PPI (both hidden by 16 mm time-lapse cameras), and off-center PPI scopes.

The radar scopes (Plate 2, page 7) are two, plan-position indicators (PPI), the range-height indicator (RHI), and the R-scope. Two 16-millimeter time-lapse cameras record PPI and RHI depictions.

The long persistence of the R-scope's phosphor precludes its use to record return signals, pulse by pulse. The off-center PPI scope, therefore, is the video and trigger sweep sources for an oscilloscope with a cathode ray tube of extremely short persistence.

Tektronix Oscilloscope (Model 545-A)

The oscilloscope (Plate 3, page 9) has a range of direct-current to thirty megacycles. Its special circuits permit an accurate delay in the presentation of the sweep, as short as one microsecond after receipt of the triggering impulse. This feature permits observation of any small portion of the full range of the radar. Its cathode ray tube has these characteristics: phosphor, P16; fluorescence, violet and near ultra-violet; and persistence, less than 0.1 microsecond.

Fairchild Oscillo-Record Camera

This camera is designed specifically for recording cathode-ray oscilloscope images (Plate 4, page 9). It moves 35 mm standard, perforated film at a speed from one inch per minute to 60 inches per second or permits an

Plate 3. The Tektronix Oscilloscope (Model 545-A), type K plug-in preamplifier and P16 phosphor, cathode ray tube.

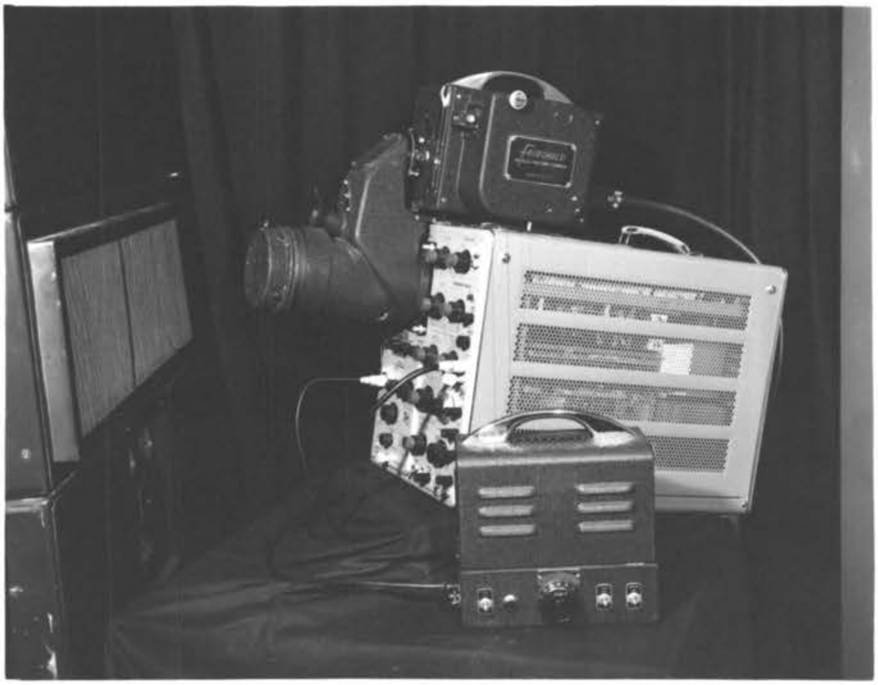

Plate 4. Fairchild Oscillo-Record Camera mounted on oscilloscope and in foreground, electronic (film transport) speed control unit.

operator to take single frame photographs.

It has a 50 mm f/1.5 Wollensak Velostigmat lens mounted in a fixed position, adjusted at the factory for correct focal distance for use with the mounts provided.

In addition its Wollensak No. 3, Rapax, Between-the-Lens Shutter permits taking still pictures of stationary patterns (moving pictures are taken with shutter open). Shutter speeds are T, B, 1, 1/2, 1/5, 1/25, 1/50, 1/100, and 1/200 of a second.

CHAPTER IV

PROCEDURES

Our effort comprised capability-development, trace-recording and trace-analysis. Relative units of time spent in these three areas were related approximately thus: capability-development, 100 units; trace-recording, one unit; and trace-analysis, 25 units.

Capability-Development

We had to develop our capability to record radar return pulses in trace-form on 35 mm film. The traces would have to be in focus sharp enough to project them and measure the amplitude of any point across the range of each trace. Plate 5, on the following page, shows such a suitable product.

The source of return signals was operational: the AN/CPS-9 radar set. The problem was to have our Tektronix Oscilloscope (really an auxiliary R-Scope, hereafter called an R-Scope) display clear pulse traces of short persistence and our camera to photograph them in succession, adequately separated.

We decided a film record which showed traces of 3.6 mm maximum amplitude would be suitable to project and measure.

A one to five ratio of useable film-size to R-Scope-

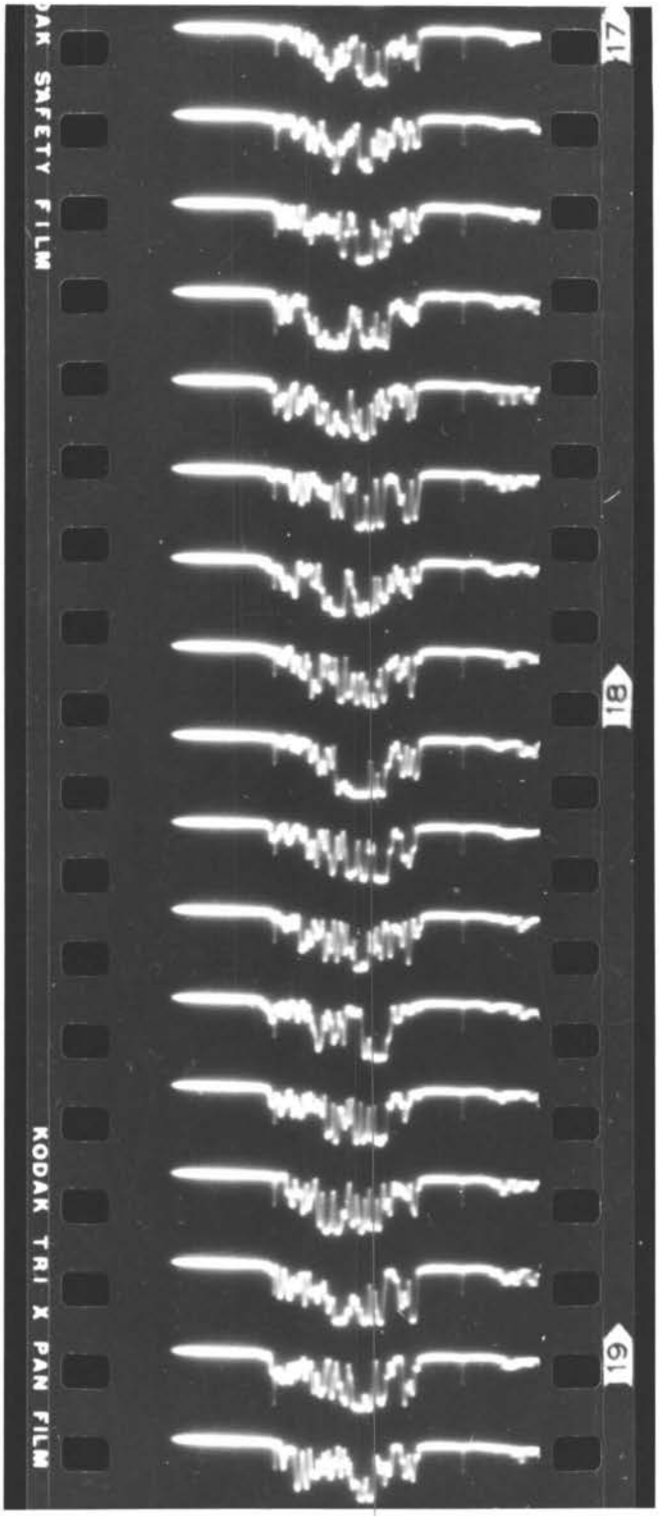

Plate 5. Trace record of weather radar return signals of 5.4 millisecond separation.

trace-size fixed an amplitude of 1.8 cm for the trace displayed by the R-Scope. It also fixed the rate of the film-transport.

The R-Scope would show traces at the same rate of the pulse return frequency of the radar: 186 pulses per second. The film, therefore, would have to be transported 38 inches per second. This would separate traces on the film by a distance sufficient to allow a maximum trace amplitude of 3.6 mm without trace-overlap. This high speed of film-transport dictated that we use the best capability of the camera lens: f/1.5.

The principal factor which decided our choice of film-type was availability. Several films are fast enough, similarly react to color wave-lengths, etc, but Kodak TRI-X PAN film was the only suitable type available with minimum delay and in 100-foot rolls. For the numerous tests made, we used it in six to twelve-foot lengths and developed it by hand. Our trace record for amplitude analysis was made on a 100-foot roll and developed commercially.

Initial tests produced blurred traces which pointed towards faulty camera focus or too long persistence of the cathode ray tube's phosphor. (The R-Scope at this time had a P-2 phosphor.) We photographed single-sweep traces at varying lens-distances; results showed a need to increase our distance by .6 inch, i.e. to move the camera .6 inch forward from its "maximum-back" position on the top of the

R-Scope cabinet. Photo definition of traces separated by the usual 5.4 milliseconds then improved slightly, but were still far from useable. Similar tests with a P-11 and P-16 phosphor followed. The P-16 phosphor tube finally gave a useable trace on film; its persistence, less than .1 microsecond, was suitable.

In this development section, I have made no mention of the R-Scope's circuitry settings simply because the circuitry had capability well within our needs and my colleague, Mr. Kenneth Shreeve, had ready skill to use its capability.

Trace-Recording

On 27 April 1962 at 1500 Greenwich Civil Time (27/1500 GCT) a front with sharp pressure discontinuity passed over the radar site. For the following twelve hours the site was under a continental polar air mass, considerably modified by its recent Pacific Ocean trajectory. Numerous towering cumulus passed within radar range and at the radar site dropped showers of predominantly rain, but occasionally grain-sized hail.

Between 27/2201 GCT and 28/0137 GCT we recorded ten runs of single pulse traces. What follows describes typical recording procedures common to all of them.

Trace-Recording

Initially to set up for all ten runs we connected the R-Scope to the radar set. With test-probe and cable we ran radar signal return information from the Off-center PPI Scope to the R-Scope: video information from the PPI's J-1 jack to the R-Scope's "Y-axis" input; master-trigger information from the PPI's J-202 jack to the R-Scope's "delayed-trigger" input jack. We had loaded the camera with film, set the lens at f/1.5, turned on the camera power supply and opened the shutter. After setting the R-Scope at a sweep speed of ten microseconds per centimeter we checked RHI and PPI weather depictions for a likely sample and chose one at 284 degrees azimuth, five to ten-mile range, tilt angle one and one-half degrees.

After setting the R-Scope for a sweep-time that would cause the center of its trace to be about seven and one-half mile range and a maximum amplitude of 1.8 cm, we slowly reduced the receiver gain of the radar set until R-Scope trace amplitudes showed predominantly less than saturated (this would give a trace-record most suitable for analysis and quite devoid of system noise).

After a final focus and intensity adjustment of the R-Scope trace, we turned on the camera motor for three seconds which exposed nine and one-half foot of film. (Plate 6, page 17, shows equipment and personnel in position to record radar return signals; Plate 5, page 12, shows a portion of film with signals recorded just as the film speed reached 38 inch/second.)

We then took supporting RHI photos on the same azimuth (Plate 7, page 18) and PPI photos at the same tilt angle (Plate 8, page 19).

Plate 6. Pulse-recording equipment and personnel in position: on the left Mr. Kenneth H. Shreeve, Research Assistant, Atmospheric Science Branch, Oregon State University; on the right, student Lt. Col. John M. Steigner, United States Air Force.

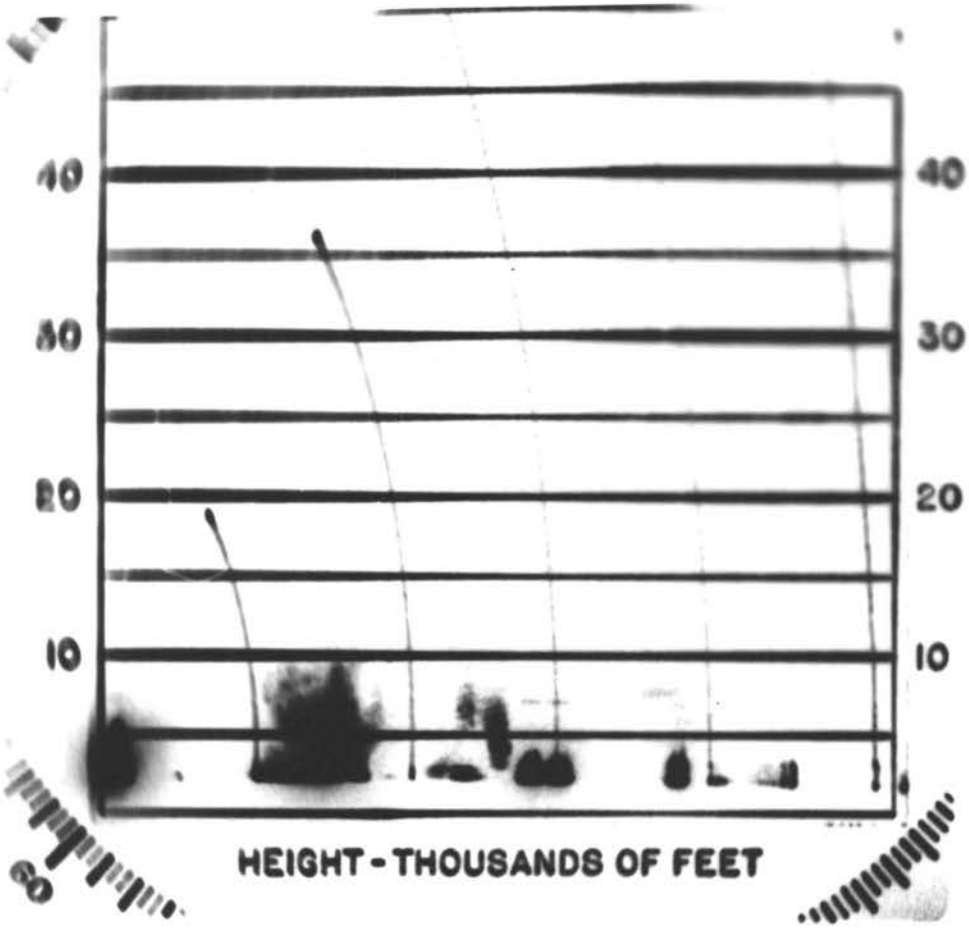

Plate 7. RHI scope depiction showing clouds between five and ten (left to right) markers at the same azimuth and within five minutes of trace record shown by Plate 5.

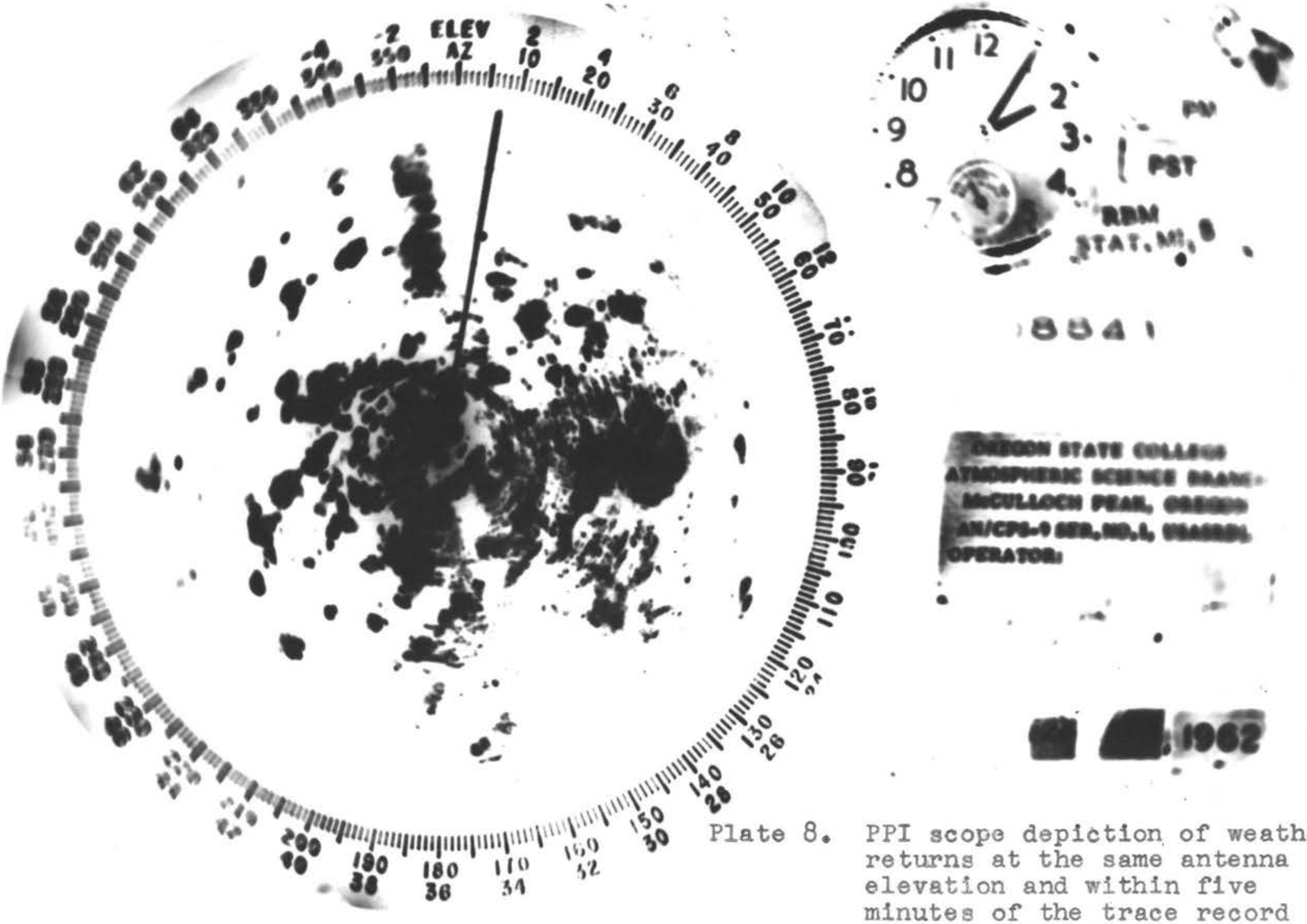

Plate 8. PPI scope depiction of weather returns at the same antenna elevation and within five minutes of the trace record shown by Plate 5.

CHAPTER V

TRACE ANALYSIS

We chose to analyse traces from Run No. 1, taken 2201 GCT, 27 April 1962. Our measurement method, observations and statistical findings follow below as do comments concerning atmospheric conditions in the sampled volume. Here first are some dimensions of that volume based upon our radar set's characteristics.

It was a discrete volume, truncated cone-shape, with its center line the "line of sight" of the radar beam and with additional dimensions of: range of mid-point, seven and one-half miles; elevation of mid-point, 3200 foot MSL; length, five miles; closer diameter, 460 foot; farther diameter, 920 foot; volume, 1.02×10^{10} cubic foot.

Atmospheric Conditions

The 28/0000 GCT Salem radiosonde indicated: instability in the volume; a wind at about 240 degrees and 25 knots; and the average temperature, 2.5 C. From 27/2230 GCT to 27/2245 GCT, intermittent hail of grain size fell at the radar site. Unfortunately the volume sampled at 27/2201 GCT was at 284 degrees azimuth; not up-wind. Nevertheless hail started to fall at the radar site at the same time it would have taken the hail-bearing cloud to be over the site after traveling from a point within three miles of our sampled volume.

Measurements

By means of a "Recordak" film reader we projected the film record of Run No. 1 (27/2201 GCT) and measured amplitude starting at the trace right opposite the film frame number 17.[1]

With the trace projected on a scaled grid (units arbitrary), we found that a vertical grid line, convenient for measuring, happened to coincide with the 6.36-mile range of successive traces. At that range we measured each trace, trace one through trace 98 (t_1-t_{98}). (See table on following page.)

The other sample was measurements made across the range of four sets of two adjacent traces, chosen at random from the same 98 traces, t_1 through t_{98}. (See table page 23.)

These measurements produced 186 observations from one atmospheric volume.

---

[1] Plate 5 shows this portion of film. It has range increasing from left to right. Two five-mile markers are easily seen; the first is at five-mile range from the radar site. The signal varies in a "down" or "minus y" direction. Each pulse is separated by 5.38 milliseconds with time increasing downward.

SUCCESSIVE TRACE AMPLITUDES, RANGE 6.36 MILES

t_1-t_{16}	t_{17}-t_{32}	t_{33}-t_{48}	t_{49}-t_{64}	t_{65}-t_{80}	t_{81}-t_{98}
38	25	40	25	24	06
25	35	25	11	21	17
25	44	26	35	20	30
48	09	27	10	31	20
35	45	27	03	12	26
24	40	30	14	44	25
39	06	09	19	28	24
06	20	36	30	31	14
19	25	40	10	11	50
10	21	16	42	18	11
33	17	10	35	31	34
15	26	06	08	15	50
44	31	44	28	15	40
50	15	33	16	08	08
30	10	35	07	13	30
14	31	40	15	15	26
					20
					24

Statistical Methods and Results

We used statistical methods to examine relationships among pulses. The relationship of specific interest to this study is the time interval required for amplitude shown by pulse traces, to become independent. Other

TRACE AMPLITUDE OF PAIRS ACROSS RANGE (mi)

Trace Number	Range										
	5.3	5.6	5.9	6.2	6.5	6.8	7.1	7.4	7.7	8.0	8.3
t_1	04	07	21	20	37	33	25	49	35	14	07
t_2	05	10	20	05	33	23	08	48	33	27	16
t_{23}	04	05	20	30	34	38	49	50	25	20	12
t_{24}	07	29	12	12	30	32	52	37	26	15	35
t_{46}	20	15	39	12	11	09	45	35	41	22	16
t_{47}	19	06	15	10	25	15	32	32	35	23	12
t_{92}	27	35	08	40	21	11	45	41	27	16	10
t_{93}	16	13	12	46	45	33	20	40	28	15	22

investigators (2, p. 52), using the same 3.2 cm wave length radar as ours, had found that the time period for pulses to reach independence was of the order of twenty milliseconds. Our analysis concerned itself with the correlation coefficient between successive pulse traces at a single point of trace-range and between adjacent pairs of pulses across their trace range.

The correlation coefficient "r" is a statistic which measures the degree of association of variables.[1] This

---

[1] The tendency for small values of one variable to be associated with small values of the other, or the tendency of small values of one variable to be associated with large values of the other.

statistic, r, varies between minus one and one, with perfect correlation at its limits and no correlation at zero (7, p. 265). Using the 186 observations measured from pulse traces we computed several correlation coefficients.

Dixon and Massey (3, p. 200) give the procedures to test hypotheses that correlations are zero at a five per cent level of significance. They point out that this test is equivalent for purposes such as ours, to testing for independence.

Using the 98 consecutive observations (shown on page 22), we obtained 49 consecutive observation-pairs by arbitrarily considering odd-numbered subscripts as one variable and even-numbered subscripts as the other variable. The resultant correlation coefficient was 0.014, which apparently does not differ significantly from zero. We concluded that on the average for those 49 pairs of observations, there is no correlation between adjacent pairs.

Each of these observations had been extracted from a pulse trace separated by 5.38 milliseconds from its adjacent pulse traces.

Our finding no correlation between pairs indicates that at the trace-range of the observation, pulses had attained independence some time before 5.38 milliseconds as compared with findings of other investigators (2, p. 52) that independence was gained in time to the order of twenty milliseconds.

In addition to considering observation-pairs adjacent in trace-time and identical in trace-range, we found the r of the first 96 of these same 98 observations separated in trace-time by 10.76, 16.14 and 21.52 milliseconds. We did this to examine the possibility that pulses of wider time separation were more highly correlated. This in turn would suggest a periodicity of pulse amplitude at or near the wider times. The correlations of these pairs were: .0303, for pairs separated by 10.76 milliseconds; .163, those separated by 16.14 milliseconds; minus 0.017, those separated by 21.52 milliseconds. None of these correlation coefficients gives evidence of dependence at a five per cent level of significance; consequently there appears to be no periodicity of pulse amplitude at or near the two, three and four pulse separations.

So far we had tested successive traces for correlation of one amplitude per trace at a fixed range. We decided to test the amplitude of some adjacent traces at several points across each trace for a five-mile range. We arbitrarily chose four pairs of adjacent traces and from each trace extracted eleven observations (shown on page 23). Then from each set of adjacent traces we paired those observations at identical ranges and used the earlier observations of each pair as the first variable and the later observation as the second variable. The correlation values we obtained again reflect independence for all but the first pair of traces: first (in time) pair, 0.789; second, 0.461; third, 0.213; and fourth 0.279.

With the one exception, 0.789, tests on the observed correlation coefficients suggest that there may be no correlation in the population, when the test is made at a five per cent level of significance.

CHAPTER VI

CONCLUSIONS

Early in this single-pulse work we named the project SPRAR, Single-Pulse Radar Returns, and have considered our work as project SPRAR-1. We implied that there will be projects SPRAR-2, SPRAR-3, etc, by various students working under the auspices of the Atmospheric Science Branch of Oregon State University.

I conclude the following concerning what SPRAR-1 accomplished:

Produced a ready capability to make a film record of return signal traces from a radar pulse of 5.0 microsecond's duration, arriving each 5.38 milliseconds.

Made three-second samplings of ten atmospheric volumes in one air mass which produced a film record of about 5500 measurable return pulses which constituted a population for statistical analysis.

Produced a ready capability to obtain observations by measuring amplitude of the film recorded traces of return pulses.

Demonstrated a statistical method to analyse these observations of amplitude, i.e., extracted 186 observations from the first consecutive 98 pulses of the 5500 measurable pulses, and arrived at findings based upon the statistic correlation coefficient.

From this small 1.8 per cent sample, extracted from one end of the total population available for sampling, found indications that independence of adjacent pulses is reached in less than 5.38 milliseconds.

Based upon the above conclusions, I recommend the following:

That SPRAR-1 be considered as not complete;

That observations be extracted throughout the 5500 return pulses already recorded;

That a program be developed for a digital computer to obtain relevant statistics concerning observations so obtained;

That resultant statistics be studied for significance and their possible functional relation to hail and rain, the back-scattering particles present in the atmospheric volumes sampled;

That results so obtained be closely examined to help decide upon the suitability, feasibility and acceptability of further SPRAR projects as a means towards ultimate improvement of weather forecasting capability.

BIBLIOGRAPHY

1. Bartnoff, S., D. Atlas, and W.H. Paulsen. Experimental statistics in cloud and rain echoes. In: Proceedings, Third Radar Weather Conference. Montreal, McGill University, 1952. G1-G7. (Abstracted in Meteorological Abstracts and Bibliography. 6 pt 2:6 G-234. 1955)

2. Battan, Louis J. Radar meteorology. 2d ed. Chicago, University of Chicago Press, 1960. 161 p.

3. Dixon, Wilfrid J. and F. J. Massey, Jr. Introduction to statistical analysis. 2d ed. New York, McGraw-Hill, 1937. 488 p.

4. Fleisher, A. The radar as a turbulence sensing probe. In: Proceedings Conference Radio Meteorology. Austin, University of Texas, 1953. p. 1-2.

5. Hilst, G. R. Analysis of the audio frequency fluctuations in radar storm echoes: a key to relative velocities of the precipitation particles. Cambridge, Massachusetts Institute of Technology, 1949. 68 p. (M.I.T. Weather Radar Research Technical Report No. 9, Part A.)

6. Hitschfeld, W. and A. S. Dennis. Fluctuations in radar echoes from snow. In: Proceedings, Fifth Weather Radar Conference. Fort Monmouth, Signal Corps Engineering Laboratory, 1955. p. 249-254.

7. Li, Jerome C. R. Introduction to statistical inference, 2d ed. Ann Arbor, Edwards Brothers, 1959. 353 p.

8. Nelsen, Richard R. and S. G. Winter, Jr. Weather information and economic decisions a preliminary report. Santa Monica, Rand Corporation, 1960. 121 p. (Research Memoranda RM-2620)

9. Rogers, Roddy R. Radar measurement of gustiness. In: Proceedings, Sixth Weather Radar Conference. Boston, American Meteorological Society, 1957. p. 99-105.

10. Rutkowski, W. and A. Fleischer. R-Meter: An instrument for measuring gustiness. In: Proceedings, Fifth Weather Radar Conference. Fort Monmouth, Signal Corps Engineering Laboratory, 1955. p. 255-260.