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FIVE-DIMENSIONAL WEATHER RADAR:
GREY SCALE AND CAPPI IN OPERATION, 1959-1962

STORMY WEATHER GROUP
McGILL UNIVERSITY

FINAL REPORT

APRIL 1963

Fig. 1 - Grey-scale CAPPI map at 5000 ft, showing a well-defined line of showers at 1640 EST, 20 August 1962. Range to the inner edge of test pattern is 140 statute miles. Each step up the grey scale is a factor 10 in signal power or a factor 4 in rainfall rate.

AFCRL 63-449

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GREY SCALE AND CAPPI IN OPERATION, 1959-1962

STORMY WEATHER GROUP
McGILL UNIVERSITY

Contract No. AF-19(604)-6617
Project 6672, Task 667201

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Contents

PREFACE

This Final Report is a critical summary of three years' operation of a highly automated CPS-9 and of developments and improvements made during that period.

It has always been our contention that the interests of both research and operational users are best served by a weather radar whose operation is as automatic as possible. The radar should provide a display of the precipitation pattern in the space around the radar at regular time intervals. Intensity, over a scale of about 70 db to cover the range of precipitation rates 0.1 to 1000 mm hr^{-1}, should also be indicated on each display. Since 1955 the main requirement of automatic operation, namely a routine antenna programme, has been in use on the McGill CPS-9. From this programme we have derived, in a regular time sequence, sets of constant altitude maps to provide three-dimensional coverage of the precipitation. With the addition in 1959 of circuits to display a 64-db range of signals on a stepped grey scale, we added the important dimension of intensity at no expense to the frequency of coverage.

Early in 1960 Legg had pointed out that with the modifications to the receiver circuits for grey scale we could, with very simple additions, provide a system for adding a correction for attenuation to the received signal. Legg's basic idea was developed and correction circuits were tried out in the summer of 1960.

The acquisition in 1961 of a Kelvin-Hughes Rapid Processor from the Royal Canadian Air Force allowed the automatic production of pictures for immediate use by forecasters, and thus eliminated the last item requiring manual operation, the Polaroid Land camera. Having an immediately available transparency made it possible to carry out our plans to provide the operational pictures on facsimile. The scanning for facsimile of the relatively noisy signal on the CAPPI picture provides the added benefit of areal integration, with the consequent smoothing of each grey shade and enhancement of the contrast between shades. Our first flying spot scanner was built and a facsimile system was in operation by the Fall of 1962. At the time of writing, there are improvements still to be made to the flying spot scanner, but we have achieved the fully automatic production of research and operational pictures.

K.L.S. Gunn

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PUBLICATIONS

The complete story of the modifications to the CPS-9 to provide a stepped grey scale display was written up in MW-31: The Quantitative Display of Radar Weather Patterns on a Scale of Grey, dated June 1960. A year later, a number of improvements to the grey scale display had been made and were described in MW-33: Improvements in Weather-Radar Grey Scale, dated July 1961. In addition to these two reports, a paper describing the McGill CPS-9 radar and its modifications in more general terms for the benefit of meteorologists was written in the summer of 1960 and appeared late in 1961 in Volume 34 of Beiträge Zür Physik der Atmosphäre: Wide Dynamic Range for Weather Radar, by Marshall and Gunn.

One outstanding item that has not yet been properly published is the work on electronic correction for attenuation. Another is the considerable accumulation of ideas relevant to an optimal weather radar; a short report containing some of these ideas was attached as an appendix to QSR 5 in Feb. 1961. This material should be written up for wider distribution. At the moment we can't see how to do this, but it should be done; a considerable amount of good work is involved. A short review of the electronic correction work is included here, but it did not seem wise to delay this report in order to include a more complete write-up. For this and for the facsimile developments, we have drawn up a publication plan and schedule, which follows.

PUBLICATION: FORM and DATE

ITEM	Weather Radar Conf. Proc.	Scientific Report	Paper
Electronic Correction for Attenuation	No. 9, Oct. 1962	Summer 1963	Summer 1963
Facsimile Output for Weather Radar	No. 10, Apr. 1963	Spring 1964	Summer 1964

PERSONNEL

The work summarized in this report has involved the following scientists and engineers.

J.S. Marshall	Project Director	1/6-time
K.L.S. Gunn	Physicist	1/10-time
W. Hitschfeld	Physicist	1/12-time
T.H. Legg	Engineer	Full-time (Dec 59 – Apr 60)
M. Wein	Engineer	Full-time
F.T. Barath	Engineer	Full-time (Dec 59 – Mar 61)

RADAR OPERATIONS

Antenna program

For the past three years we have used an antenna program involving a cycle consisting of 18 revolutions and lasting 3.75 minutes. There are thus 16 cycles hr^{-1}. The antenna elevates in 13 steps of 0.75°, from 0° to 9°, and in 4 steps of 1.5° thereafter to a maximum elevation of 15°. The antenna descends during the 18th revolution. This is a compromise scheme that we have used all the year round in place of a previous summer program that proceeded in 1° followed by 2° steps and a winter program that proceeded in 0.5° and 1° steps.

Displays

Routinely CAPPI maps at three heights are produced simultaneously on three displays: Main, Off-Centre and Remote. In the next antenna cycle three maps at three alternate heights are displayed. Thus, eight sets of six maps are accumulated per hour. The actual sequence of heights recorded with time on each display is as follows:

```
          6     M   O   R   M
          5   M   O   R   M              M : Main Scope
          4     O   R   M   O
Heights   3   O   R   M   O              O : Off-Centre Scope
          2     R   M   O   R
          1   R   M   O   R              R : Remote Scope

              1 2 3 4 5 6 7 8
          Time:   3.75-min cycles
```

Originally, heights 1 to 6 were at intervals of 7500 ft. When the precipitation did not reach to the upper levels, extra pictures were inserted at the lower levels. Two years ago the six heights were set to be 5, 10, 15, 20, 30 and 40 thousand feet, and left at those values throughout the summer. In the winter the upper two heights become 25 and 30 thousand feet. The Kelvin-Hughes follows the same sequence as the Remote scope.

The Main and Off-Centre scopes are each photographed by a Shackman camera equipped with a 40-mm f/2 lens. The Remote scope is photographed with a Robot camera having a 40-mm f/1.9 lens. The Shackman cameras have proved to be much less successful than the Robot. Their capacity is only about 20 ft of film, or about 15 hours of radar time.

Film loading is tricky, and over the years we have had trouble with film jamming and with the delicate film transport mechanism. The Robot, on the other hand, has a 200-ft magazine and, while the whole Robot assembly is simply a modification of a standard 35-mm camera, it has performed magnificently and almost without interruption over the past three years.

A partially-silvered mirror allows a Polaroid Land Camera to share the Main scope with a Shackman 35-mm camera. The mirror has about 12 % transmission, and the Polaroid uses the transmitted light. With Polaroid Film Type 47 (ASA 3000) and an aperture of f/4.7, we get a satisfactory grey scale Polaroid picture, with the shaping amplifier adjusted to produce an acceptable set of 7 grey shades on the 35-mm Tri-X film. The response of the Type 47 film is such that the step from background to the first grey shade is rather higher than on a positive made from the 35-mm film. This greater contrast between background and level 1 gives a better chance of seeing level 1 echoes on the high contrast "Desk-Fax" pictures received at McGill from the radar.

Test and monitoring procedures

In its new location the radar console is about 1800 ft from the antenna. To make routine use of the test set practicable we have a test antenna mounted on the roof of the building housing the console and directed at the radar antenna. It is a horn one meter long with an aperture seven wavelengths square. About 50 ft of wave guide connects the horn to the test set, which is in the same room as the console.

In measuring the transmitted power, the radar antenna is directed for a maximum meter reading. The transmitted power measurements are consistent within 1 db from day to day. The consistency provides a good indication of alignment. When alignment is achieved, a signal is transmitted from the test set to measure the receiver sensitivity. After this, the sensitivity of the first threshold in the shaping amplifier is checked and, if necessary, adjusted. For the past three years we have operated with this first threshold fixed at -96 dbm, regardless of receiver sensitivity. The receiver sensitivity is generally 4 or 5 db better than -96 dbm. The same arrangement can be used to check up to the fourth threshold, but the test set cannot supply enough power to go beyond that. The remaining thresholds are adjusted by feeding a linear ramp to the shaping amplifier and matching the spacing of the upper thresholds to the 9.6-db intervals established for the lower ones. We find that

the threshold settings do drift occasionally in the 24-hour interval between tests, but never more than 2 db. A check is made daily of the amplitudes of the seven outputs of the shaping amplifier, but they very rarely require any adjustment. These measurements indicate an encouraging stability of the receiver and shaping amplifier, and suggest that less frequent than daily measurements might be sufficient. However, we consider daily test measurements the best way to ensure that deterioration in any part of the system does not go unnoticed.

We have used the CRT cathode current as a convenient measure of CRT luminance, in particular the cathode current when the lowest level of luminance (shade 1) is displayed for the full range of 140 miles. This current is of the order of 0.05 μA. The established value for each scope is monitored and if necessary adjusted two or three times a day. On a few occasions this may have drifted by as much as 2 db, or about 1 db in negative film density ($\gamma = 0.5$). While this drift can be pretty well compensated in printing positives, it is an instability in the grey scale system that we would like to get rid of. The variations are presumably due to temperature variations affecting the display power supplies and the brightness-establishing circuits.

Experience with CPS-9 and CAPPI components

As of November 1962, the McGill CPS-9 has radiated for 35,000 hours. This represents a yearly average of 4400 hours, or a daily average of 12 hours. Actually, during three summer months of 1962 the daily average was more like 17 hours.

Our experience with magnetrons has ranged from a useful performance of 400 hours to 1700 hours. We have used all but one of the original magnetrons supplied with the radar in 1954. About two years ago we bought two replacement magnetrons for the first time. These were from Raytheon (Canada) at $600 each; Raytheon is currently charging $1100 each. These are tubes that were apparently part of the original manufacture, but which are re-tested before shipment. In the past year we bought two magnetrons from Emeltone Electronics (New York) at $275 each. They also were manufactured in the mid-1950's and come in the original sealed carton. One of these lasted 700 hours and the other is in use currently, having performed satisfactorily for 400 hours.

In 1961 we had a spate of troubles with T/R tubes. This was apparently due to several defective tubes in one shipment, and they were replaced by Bomac who supplied

them. The T/R tube currently in use has been in place for one year.

In the eight-year life of the radar we have had to replace two pieces of flexible wave guide, one outside and one inside the transmitter, and the TR/ATR cavity. The edge of the slot in the cavity was eccentric, presumably a defect in the manufacture, and pieces had chipped off at the thin edge. Some components are beginning to show notable signs of wear. Currently we are having trouble with the driving gear on the deflection coil on the Main and Off-Centre scopes. The trouble appears to be due to worn teeth on the gears.

The hydraulic system was completely replaced with a reconditioned unit from Raytheon in June 1958. The antenna response had become sluggish, and appeared to be related to metal shavings which had blocked the filters. The shavings came from the electric motor mount which had not been assembled properly by the manufacturer. The reconditioned unit operated satisfactorily until January 1963. In the intervening years we had, however, replaced the main motor bearing three times and the oil seal twice. In January 1963 the unit again gave trouble. The hydraulic system was stripped down and overhauled by a local firm (Aviation Electric). The breakdown appears to have been due to a defective low pressure relief valve, which was further aggravated by excessive leakage in the azimuth hydraulic motor. Replacing the azimuth motor with a spare and machining the relief valve plunger and seat brought the hydraulic system into satisfactory operation again.

The overhaul revealed that various parts in the hydraulic unit showed considerable wear. None of these could be replaced, however, since no parts for the unit are available "off the shelf" of the manufacturer (Vickers, Detroit). Aviation Electric are pessimistic about the remaining useful lifetime of the unit without replacement of about a dozen parts.

Staffing

For some years we had a radar technician on duty from 0900 to 2300 hours, seven days a week. Some of the technician time was occupied with the operation of the Land camera. Since the addition of the Kelvin-Hughes equipment we have operated with one technician at the radar for a standard eight-hour day during a five-day week. On Saturday and Sunday a technician is there for four morning hours. During the evening and night hours when the radar is unattended, the meteorological observer on duty one floor above drops in to change the films in the small-capacity Shackman cameras.

IMPROVEMENTS TO THE GREY SCALE DISPLAY

The modifications to the receiving circuits to permit the display of successive factors of 10 of signal power as equally discernible steps of grey were completed during the summer of 1959, so that we were recording CAPPI maps with grey scale on 35-mm film routinely beginning in the fall of 1959. During that first year of routine operation various imperfections were studied and corrected. Fig. 1 inside the front cover is typical of current CAPPI pictures incorporating the improvements discussed in this section.

CAPPI gaps

There were gaps between adjacent annular elements of the CAPPI picture due to the finite rise and fall time of the video switch gates. By delaying the triggering of the closing gate waveform, the gate was effectively lengthened and so the gap closed. We recognized that the simple method of delay that we adopted would eliminate the gaps perfectly for only one amplitude of video signal for a given adjustment of the delay. For higher signals there would be overlap. We have operated with a compromise adjustment accepting a gap of 0.5 μsec (0.05 mi) at the lowest output luminance, and an overlap giving a maximum luminance increase of a factor 1.5 for the highest signals.

Suppression of background luminance

In order to have consistent performance of a grey scale system, it is essential to maintain a fixed relationship between the luminance of the display screen and the video voltage. We began our routine operation by adjusting the cathode ray tube potentials so that in the absence of video signals, the trace was just discernible on a photograph of the display. A good measure of this condition was the cathode current drawn by the CRT, and this current was adjusted to a standard value with zero signal.

The presence of a detectable luminance with no signal, however, is undesirable for two reasons. (1) One cannot integrate the total light output from the screen and use it as a measure of the total amount of precipitation because of the large contribution from the background. (2) The background luminance constitutes an eighth grey shade, and so limits the dynamic range available for the seven signal levels.
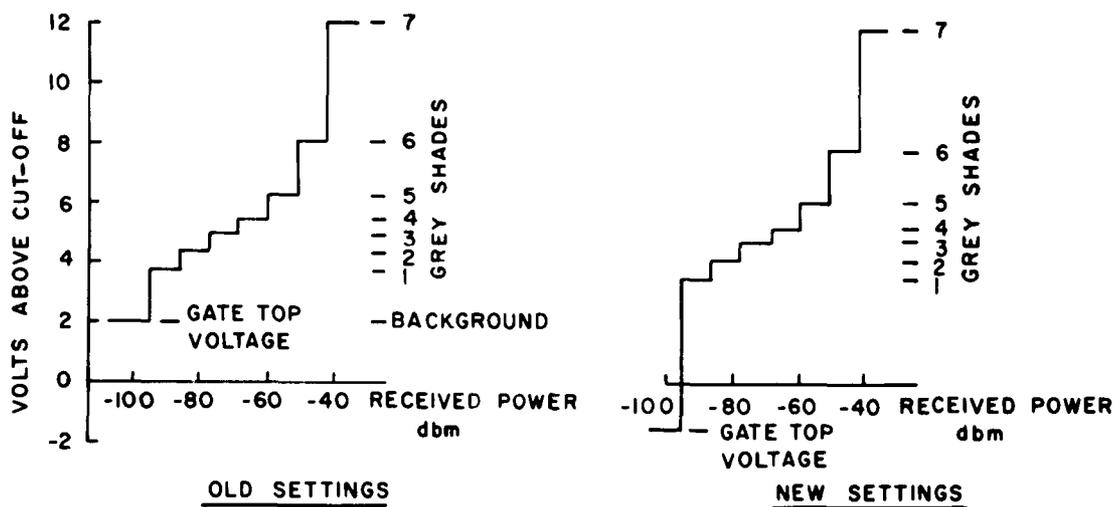
Fig. 2 — Voltages applied to the CRT before (left) and after (right) background
suppression

After studying possible ways of suppressing luminance in the no-signal areas, we chose to do it by lowering the gate provided by the video switch below the CRT cut-off voltage. The shaping amplifier is then adjusted so that the amplitudes corresponding to the seven shades of grey are higher by the amount by which the gate top was depressed (Fig. 2).

With the background luminance suppressed, a new scheme had to be adopted to provide a reference for the grey scale. This consisted of turning on threshold 1 of the shaping amplifier for the full 140-mile range, and measuring the cathode current corresponding to this luminance. Since the shaping amplifier is common to all the displays, the measurement of the shade 1 cathode current on one display involves interrupting the picture on the other two displays.

We have not actually done any integration of the light from the display tube that the background suppression now permits. Instead, we have been integrating on an A-scope display. Thus, the principal benefit we have derived from the background suppression is the extended dynamic range.

Improvements to the test pattern

With a grey scale display it is necessary to have some form of test pattern appearing regularly on the film record to keep track of any changes in the characteristics of the circuits, the CRT or the film and its processing. Early in the grey scale development we abandoned the bull's-eye pattern that used up a whole frame. We settled on a peripheral pattern with each picture, occupying the range interval 140 to 160 miles. The first peripheral pattern was produced by applying a rising then falling wave form to the input of the shaping amplifier, successively triggering the seven threshold circuits. The waveform came from the sinusoidal azimuth synchro. Its slope varied widely and produced variable test patterns from frame to frame. The various shades were of unequal lengths, with generally long periods of shades 1 and 7. Too large a strip of the brightest shade 7 constituted a real distraction from the much smaller patches of echo on the map itself.

Consideration of these deficiencies led to a new peripheral test pattern incorporating the following improvements. The shades of grey were made consistently the same extent in azimuth. This was done by providing a voltage linear with time or with azimuth, from a new test pattern generator. Allowing 10 degrees of azimuth per shade gave a test pattern occupying 70 degrees. It seemed reasonable, therefore, to put four such test patterns with each picture. The new test pattern with 10-degree segments of each shade also served to monitor the settings of the thresholds of the shaping amplifier. Since these thresholds are designed to be equal steps, any departure from equal lengths of the various shades would indicate a need for adjustment of the threshold settings.

Non-uniformities on the display

In the early grey scale pictures we found undesirable radial streaks at several azimuths, each covering several degrees in azimuth. When we changed from 16-mm to 35-mm film we also detected for the first time a fine scale pattern of spoking on all bearings.

The radial streaks were found to be due to various microswitches that had been mounted on the deflection coil drives of the displays. These microswitches were used to trigger various components of the CAPPI system, and were slowing down the rotation of the trace at every contact. Upon release, the rotation rate would speed up and hunt for a few cycles before again reaching synchronism. To remove these defects we built an

auxiliary azimuth device. It is a slave servo system consisting of a servo motor, a control transformer, and a servo amplifier. A 10-inch shaft rotating at synchronous antenna speed carries five aluminum discs, each 4" in diameter. Smaller, 1-inch disks protruding from the edge of the larger ones act as cams to trigger microswitches mounted nearby. Once the activation of the various CAPPI elements and cameras had been removed from the display synchro systems to this new device, the radial streaks disappeared. The device has proved completely successful over the two years that it has been in use.

Regarding the spoking, the trace is brightened approximately every half degree in azimuth. By sweeping a Land camera across the tube face to produce separate images of each trace, we discovered that the traces were all of the same intensity, but that there was a 60-cycle modulation of the position of the traces. Approximately every third trace is where it should be with the intermediate two displaced. Further tests using swept photographs established that the displacement modulation is not due to a rotational vibration of the deflection coils, since the effect is the same whether or not there is power in the servo system. Over a period of about a year, we made more refined measurements of both the amplitude of the trace displacement and the magnetic fields near the display tubes. At various times we also tried experiments with various added shields. While these activities provided us with further information about the spoking problem, we have not yet eliminated it from the displays. A summary of our measurements of the amplitude of the modulation and of the magnetic field near the neck of the various display tubes follows.

Display	Modulation Amplitude	Magnetic Field
Main	0.04 mm	0.02 gauss
Off Centre	0 08 mm	0.02 gauss
Remote	0.35 mm	1.3 gauss
Kelvin-Hughes	0.1 mm	0.01 to 0.05 gauss
Alberta Decca Type 41	0.15 mm, with no magnetic shield 0.10 mm, with magnetic shield	--- ---

There is probably more than one source of this 60-cycle effect on each display. The stronger field and greater modulation on the Remote display may well be due to the relatively close location (compared to the other scopes) of the power supplies. There is also an exhaust fan on the Remote not present on the other scopes.

We are impressed with the ubiquity of this problem. Every scope photograph having a reasonable resolution shows spoking. It is presumably not too important to many radar users. But with a stepped grey scale display, the contrast between shades is degraded, and meaningful density measurements on the film record are difficult to make, particularly in the middle greys.

Correction for variable line spacing

We recognized early in the development of our grey scale displays that some means of compensating for the brightness variation on the radially swept display would be necessary.

Various forms of electronic correction were considered. Only one of these would be possible with the stepped grey scale system; namely, to suppress the sweep for various distances from the centre. Thus, while all the traces would appear at the edge of the display, only half would appear for one half the radius etc. We have never got around to trying a system of electronic correction such as this, because optical correction by means of a variable density filter seemed to be a simpler and cheaper way to achieve a uniform luminance across the display.

We managed to make enough of these filters for our own displays using 'Kodalith Autoscreen' film. We found the film difficult to work with; its characteristics were not identical from occasion to occasion and in trying to produce a number of the filters for other users the wastage and time consumed was large. In the last few months, however, we have got a photo-engraving firm to produce a master negative from which positives, with a characteristic very nearly the required one, can be produced consistently. These correction filters are discussed in somewhat more detail in a paper by Gunn submitted to the Tenth Weather Radar Conference.

CRT: Rectangular Raster
Hewlett-Packard Lab Oscilloscope

OBJECTIVE LENS: to image
raster on film

CONDENSER LENS: to take light
uniformly from any part of film
frame to photomultiplier

PHOTOMULTIPLIER: Type 5819

SHAPING AMPLIFIER: also
serving as stepped modulator

600-OHM LINE

MARKING AMPLIFIER

5" ALDEN RECORDER

SYNC
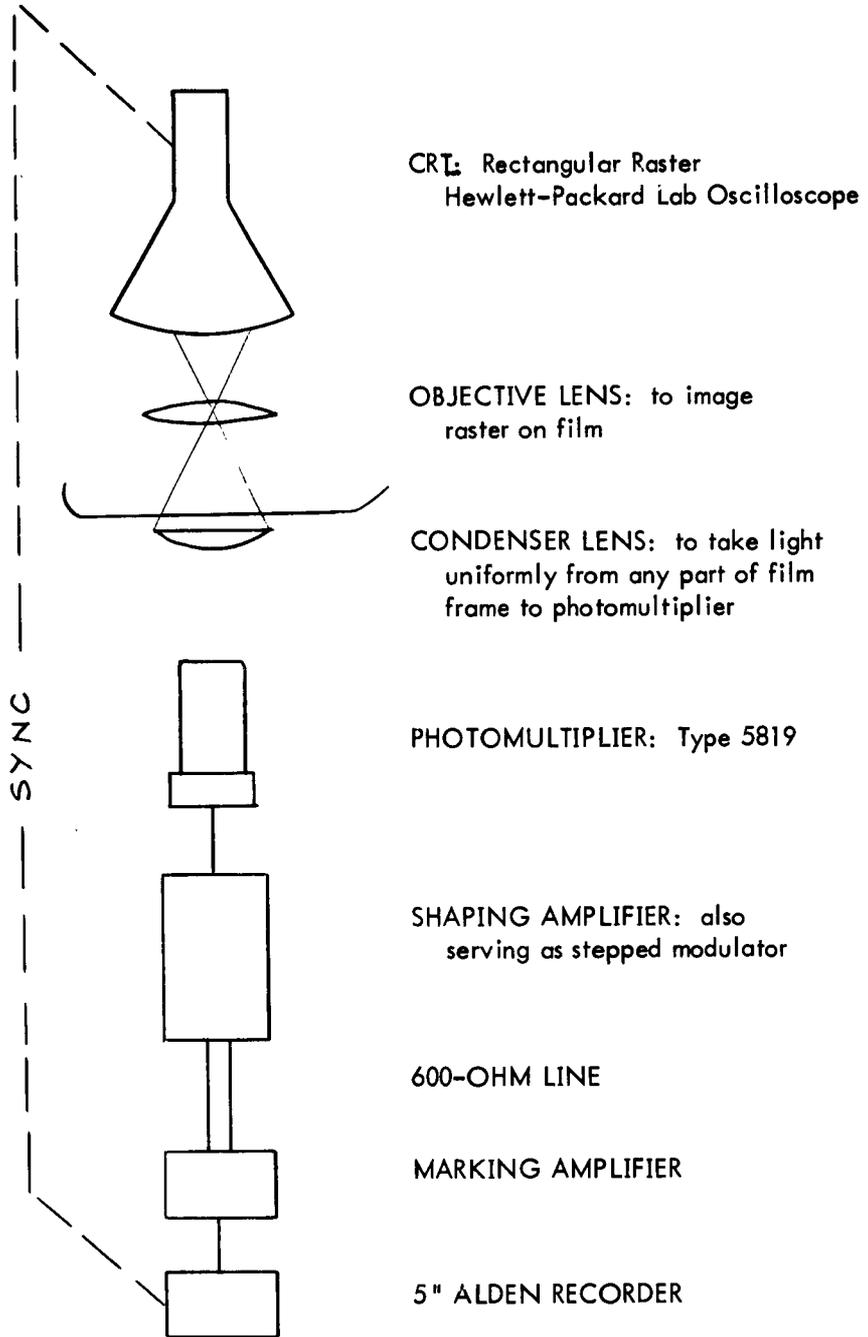
Fig. 3

WEATHER RADAR MAPS ON FACSIMILE

Since 1959, grey scale pictures for immediate use have been taken with a Polaroid Land Camera. For many years we have pointed out the virtues of operational pictures on facsimile paper. Facsimile is a most economical form of bright display. Pictures can be provided at a low cost at several outlets in the neighbourhood of the radar. At each of these outlets the user has a semi-permanent record, providing him with a history of the past few hours. The scanning of a transparency for facsimile transmission also provides an opportunity for areal averaging before introduction of the stepped grey scale, resulting in pictures with sharper contours and an enhancement of the contrast between intensity levels. With pictures on facsimile, of course there is no longer a camera operator required, and the whole radar system becomes automatic.

Late in the summer of 1961, we obtained the Kelvin-Hughes Rapid Processor on loan from the Royal Canadian Air Force, and so were in a position to add a facsimile display to our system. Earlier that summer we had begun to put together components for a facsimile system. In order to have a facsimile signal that could be passed over a narrow bandwidth line, our first requirement was a slow speed flying spot scanner. We found no such scanners available on the market nor under development and so we proceeded to make our own. Our plan was to build a prototype model which would eventually be used to scan old film records to provide pictures with greater areal integration. In building the prototype we would gain experience toward an eventual system incorporating the Kelvin-Hughes Processor. The optical system of the projector in the processor would be used in reverse. The flying spot would be imaged by the objective lens on the film in the projector gate. A photomultiplier mounted in the position of the bulb would pick up the light modulated by the film.

A block diagram of the prototype system is shown in Fig. 3. A Hewlett-Packard Oscilloscope (Model 130B) with a CRT having a P-11 phosphor is used as the scanner. The optical system consists of a 75-mm Schneider enlarger lens wedded to the gate and condenser system of a 35-mm projector. The shaping amplifier actually serves more than one function: in addition to modulating the carrier, its shaping and stepping facilities provide a set of seven equally-spaced voltages on a linear scale to be fed to the marking amplifier. The

5-inch Alden recorder used in this system had been acquired some years ago. It was supplied by Alden with a non-standard drive system to provide a helix rate of 12 revolutions per second.

We have been impressed with the number of unforeseen difficulties that arose in bringing together these various components into a stable and practical system. As might be expected, great care is needed in aligning the components of the optical system in order to have uniform response across the field. What we did not expect was the large number of limitations presented by the Hewlett-Packard scope. The original 5-inch CRT supplied for this scope has several defects when used as a scanner. At the right and left of a 3-inch wide rectangular raster there was a fall-off of 3 to 4 db in brightness. The coarse grain of the CRT introduces noise which offsets the smoothing effects of areal integration. We then acquired a CRT with a fine-grain phosphor. It also had a fall-off in intensity at the edges, and while the fall-off was smaller (about 1.5 db) it was non-symmetrical. We decided to compensate for this fall-off by means of a continuous-tone filter placed immediately behind the film in the gate. (Since it is behind the film, scattering in the continuous-tone emulsion will not effect resolution.) The worst feature of this particular scope is the halo accompanying its spot. The phosphor around the spot is actually excited within a circle about 30 times the spot diameter. The contribution from this halo amounts to about 30% of the light reaching the photomultiplier. While this does provide striking areal integration, the accompanying loss of resolution is more than can be tolerated.

The high voltage supply of the Hewlett-Packard scope was not stable and resulted in a slow and random drifting in the spot brightness over a range of 2 or 3 db. We abandoned the built-in high voltage supply and bought an external stabilized one, and this drift was eliminated. The sweep circuits of the Hewlett-Packard were found to have an inherent hold-off, which resulted in a maximum possible duty cycle of the order of 0.7. This meant either a modification to the 360° helix of the recorder, or new sweep circuits. We built new sweep circuits. We have thus ended up using only the deflection amplifiers of the original Hewlett-Packard scope.

The Alden recorder performed adequately, but the backlash in the special gear system was a source of some trouble. Also, we found that dirt collected on the helix and

produced vertical streaking of the pictures. The real limitation of the Alden equipment for use with a grey scale system is the limited dynamic range (6 to 7 db in reflection density) of the Alden paper.

In September 1962 we proceeded to build up a facsimile system to work with the Kelvin-Hughes processor. In order to have a working system providing operational pictures as quickly as possible, we decided to use the Hewlett-Packard scanner. We realised that its limitations were such that we would want to replace it as soon as a new scanner could be built but in the meantime it would provide operational pictures in short order. For a recorder we had decided some months before to use an 11-inch Muirhead machine (D611F). Two of these had arrived after some delay at the end of August, 1962. We liked the wider dynamic range of the Muirhead paper and the greater precision in the drive system compared to the Alden. With the slower helix speed of this instrument (2 rev/sec), the bandwidth of ordinary telephone lines would be sufficient to transmit the sharp boundaries between shades. We could thus put the stepped modulator at the transmitting end of the telephone line, and so save one set of modulation and demodulation that would have been necessary if the thresholding had been done at the receiver end, as we had planned. The slower writing speed (100 lines per inch) results in a 4.5-inch advance of the paper during the 225-second antenna cycle. We decided that an efficient way of using these parameters was to provide two pictures side by side on the 11-inch facsimile paper, the first containing echo of shades 0, 1, 2, 3, 4 and the second with shades 0, 4, 5, 6, 7. The gating of the signal to present pictures in these two forms was fairly straight-forward. A sweep generator was built to scan the negative twice during each facsimile trace. We derived a trigger to synchronize the scanner by means of an optical system. A mirror mounted on the helix shaft reflected light from a pilot lamp onto a silicon photo diode once per revolution.

By the middle of October 1962 we were able to supply operational pictures with this system on a routine basis. However, yet another shortcoming of the Hewlett-Packard Oscilloscope for our purposes prevented the successful display of the side-by-side pictures. The deflection preamplifiers had an instability with a period of a minute or so, which caused a shift in the trace position and therefore a distortion in the display picture. When used with internal sweep, the stages causing the instability were not in use. Rather than spend further
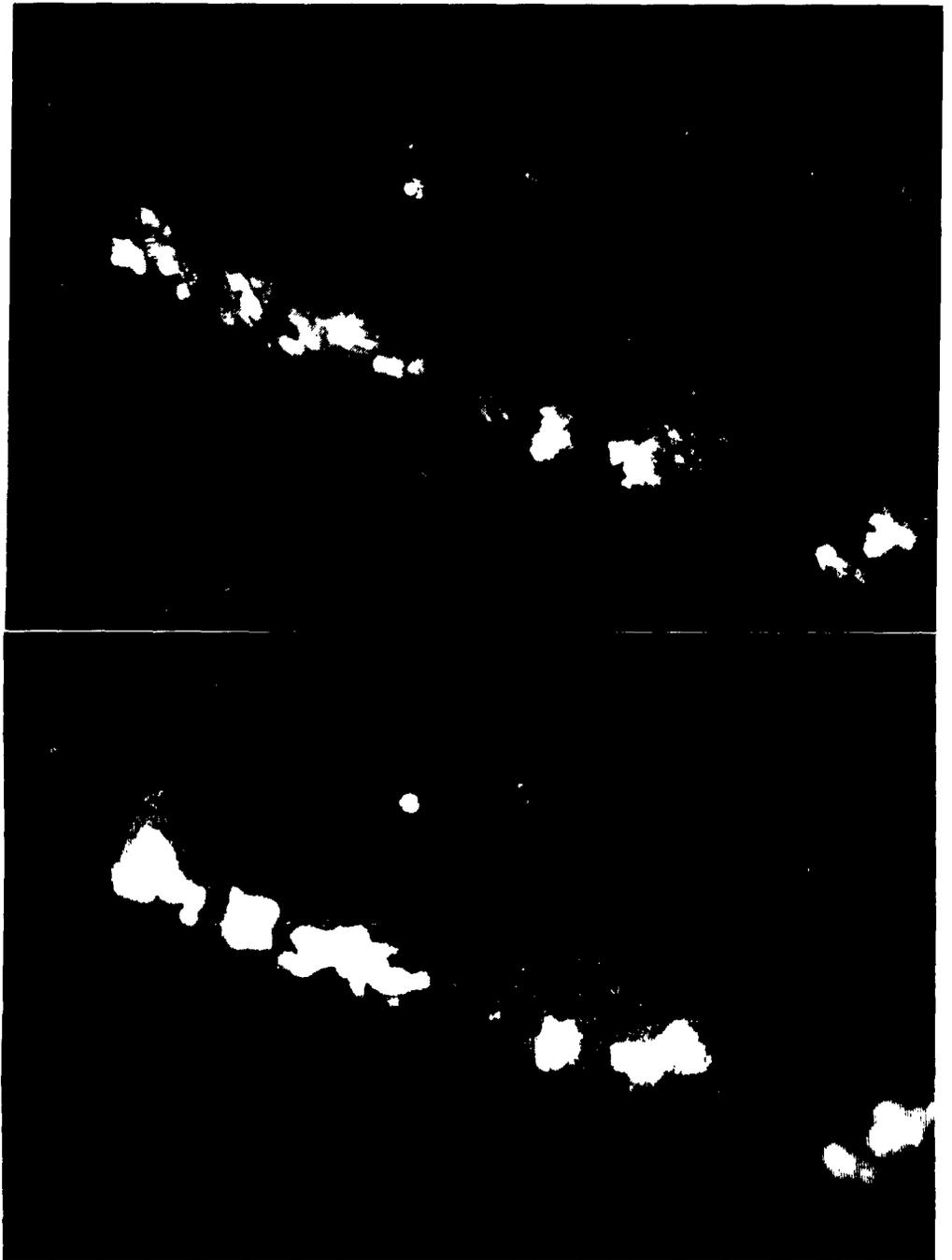
time on this latest problem with the scanner, we decided to operate with a single picture and the internal sweep.

Regarding the Muirhead recorder, the dynamic range of the paper has lived up to expectations. We have found that blade wear is a greater problem than we expected. We are scanning negatives from the Kelvin-Hughes, and so the display on paper consists of a circular black picture surrounded by white paper. The high-contrast boundary, which occurs as an identical pattern each cycle, produces a sharp discontinuity in the wear of the writing blade. Its useful life is only about 8 hours under these conditions, instead of the rated 24 hours. We plan to modify the format to display an inscribed rectangle, and so avoid the high-contrast step from black to white at the edge of the picture. To reduce the overall wear we shall probably have to reverse the present grey scale so as to display black echoes on a white background.

As soon as the system described above was operational, we proceeded to prepare a magnetically deflected high-resolution CRT as a replacement for the original scanner. This CRT unit was the display from a second Kelvin-Hughes processor that was included in the equipment on loan from the RCAF. Before inserting this CRT as the scanner we used it as an intensity-modulated display which we could photograph to provide an archival record on film (rather than on the short-lived facsimile paper). An example is shown in the lower half of Fig.4, with the corresponding position of the original CAPPI in the upper half. The smoothing of each intensity level and the sharpness of the boundaries is striking. The relatively large spot and its halo have produced the striking smoothing at the cost of a considerable loss in resolution. In this example, a positive transparency was scanned: the loss of resolution shows in the disappearance of small peninsulas of no echo, and in the enlargement of small echo areas.

At the time of writing, the new scanner is being mated to the Kelvin-Hughes equipment. This means that it will no longer be available for use as a brightness-modulated display. We are planning to acquire somehow a unit of similar quality so that we can count on having archival records of the areally-integrated pictures.
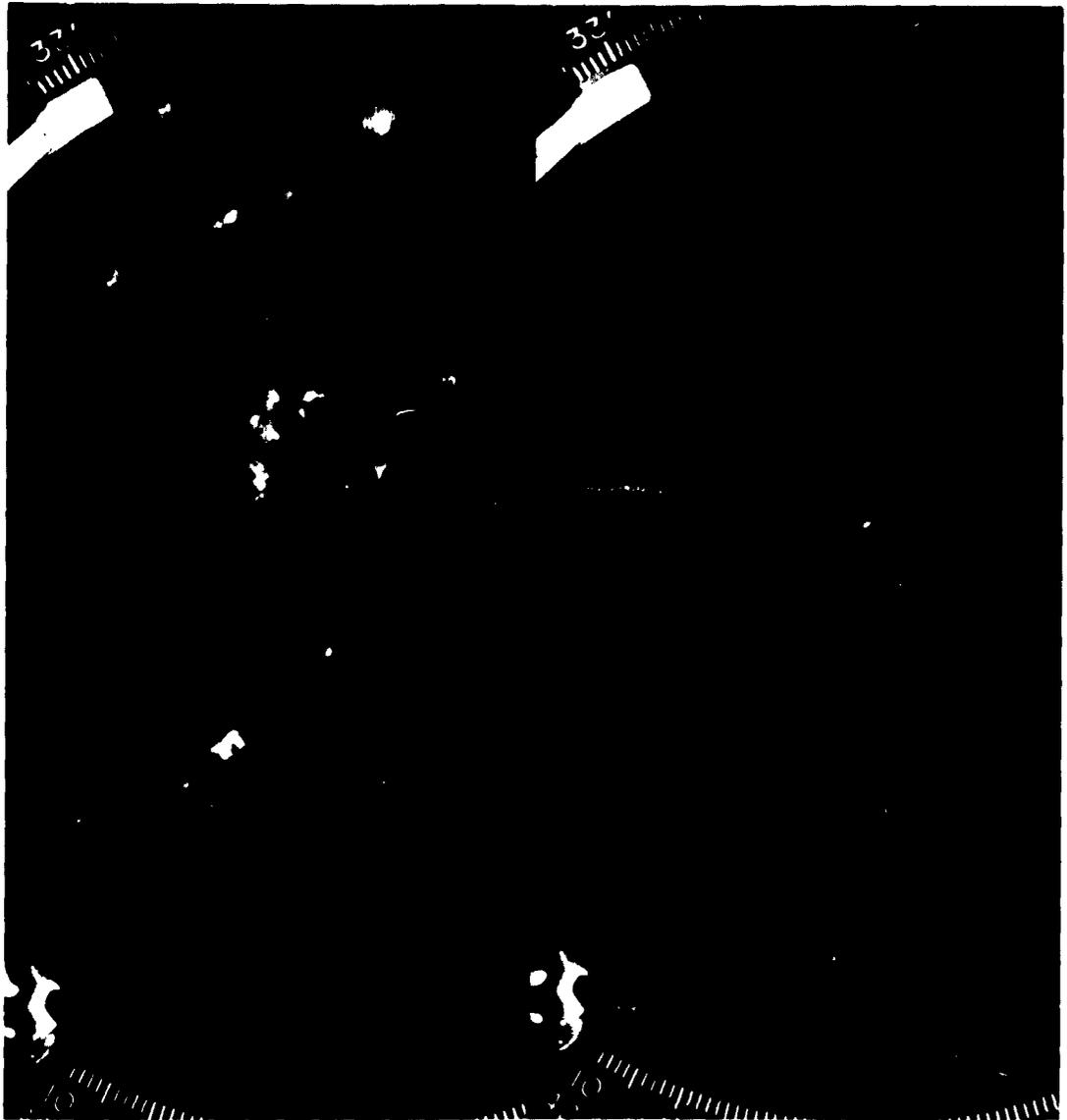
Fig. 5 - CAPPI pictures at 15,000 ft, 9 September 1960, corrected for attenuation (left) and uncorrected (right). The high intensity cores in the corrected picture are enhanced and recognizable. The radial shadows cast by the intense cells persist in the corrected picture because echo attenuated below detectability cannot of course be recovered.

ELECTRONIC CORRECTION FOR ATTENUATION

The value of a grey scale display of signals over a wide dynamic range is seriously limited by attenuation at the 3.2-cm wavelength of the CPS-9. The poor correlation between signal intensities on the display and raingauges in the Montreal area during the first summer of grey scale operation led us into a study of attenuation and of the possibilities of useful correction for it. We made a statistical study of the limitations of attenuation, using synthetic storms taken from one summer's raingauge records. This work was reported in Scientific Report MW-32: Weather Radar Attenuation Estimates from Raingauge Statistics, under another contract (AF-19(604)-2065).

At the same time that the statistical study was being made, we were proceeding with the assembly of circuit components for an electronic correction system at the radar. The system had been suggested by Legg in MW-31 and consisted in deriving continuously a correction from the received signal and adding the correction to the signal before it was displayed by means of a feedback loop. Since we had inserted a logarithmic receiver to extend the dynamic range, adding the correcting voltages to its output is just what is required since that is equivalent to multiplying the signals at the input of the receiver by a correcting factor.

Hitschfeld and Bordan had shown in 1954 that a correction for attenuation is critically dependent on the absolute calibration of the radar. A small underestimate of the radar sensitivity would lead to an infinite value of the "corrected" rainfall rate. Legg suggested that this critical condition leading to infinite signal could be used to place a lower limit on the absolute sensitivity of the radar. A reasonable correction could be obtained without knowing the absolute sensitivity of the radar.

It was these notions that were put into practice by Wein in the spring and summer of 1960. A description of his work was contained in a paper presented at the Ninth Weather Radar Conference, which is included here as an Appendix. A sample set of corrected pictures is shown in Fig. 5. As Wein points out in his paper, a limitation of the correction method is the requirement for the high degree of stability of the radar and of the correcting circuits. A stability to better than 1 db is required, although the sensitivity need not be known with this precision. There is a similar requirement on consistency of the relationship between back-scatter (Z) and attenuation (A), or in other words on the

consistency of drop size distributions in nature. It is this consistency on which the
reliable performance of an attenuation correction system depends ultimately. A measure
of this consistency is indicated by Fig. 6, where the quantity $(ZR)^{0.5}$ to which attenua-
tion is proportional, has been plotted for data from many storms on many occasions. A
considerable number of the data depart by more than 1 db from an average locus. Data
for a single storm are likely to show less scatter and so offer more hope that one setting
of the correction circuits would do for the duration of that storm.
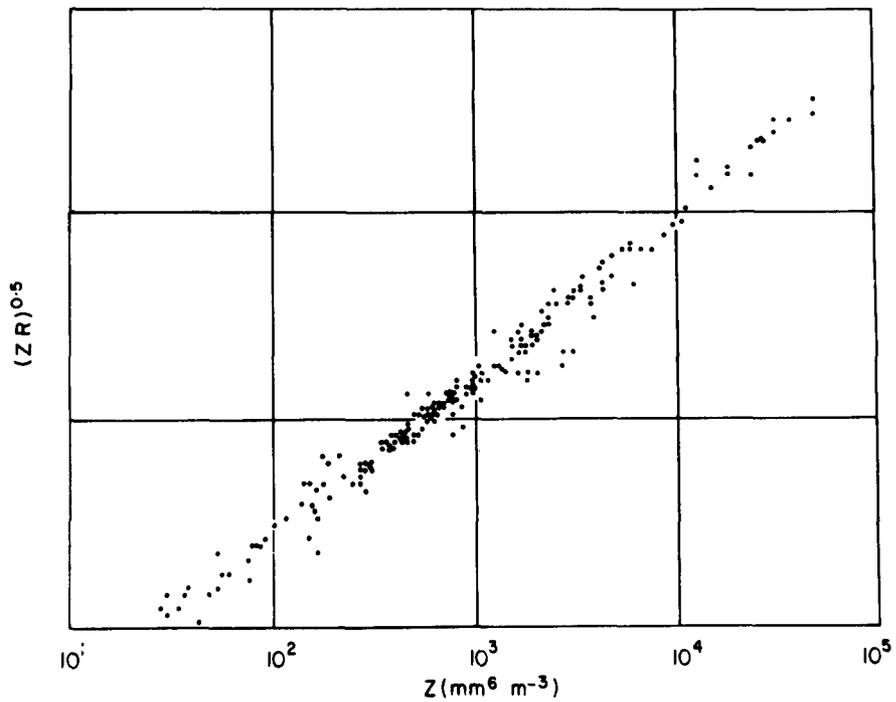
Fig. 6

APPENDIX

THE ELECTRONIC CORRECTION FOR ATTENUATION
OF 3.2-CM RADAR SIGNALS FROM RAIN

THE ELECTRONIC CORRECTION FOR ATTENUATION
OF 3.2-CM RADAR SIGNALS FROM RAIN

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ABSTRACT

Radar signals at 3.2 cm have been corrected electronically for attenuation by the rain before being displayed on a scale of grey.   The correction is computed by integration of the signals in a feed-back loop.   The use of logarithmic and antilogarithmic devices makes it possible to apply the proper power law relationships between back-scatter and attenuation.   Corrected grey scale CAPPI records have been obtained.   The signal from heavy cores is enhanced although the total area on the display remains that of the original attenuated signal.   Reliable performance of the correction system depends on the consistency of the distribution of raindrops in nature, or in other words, on the consistency of the relationship between back-scatter (Z) and attenuation (A).   The uncertainty in this relationship is the ultimate limitation in the practical application of any correction for attenuation.

1.   INTRODUCTION

Rain attenuation at a wavelength of 3.2 cm substantially distorts the observed pattern of a rainstorm, affecting the usefulness of a radar at this wavelength as a tool in making quantitative measurements, Atlas and Banks (1). In spite of the distortion, the observed patterns contain enough information about the storm to suggest investigating possible methods of correcting for the attenuation.   One of the difficulties in a correction procedure is the necessity for accurate knowledge of the radar sensitivity.   This was pointed out by Hitschfeld and Bordan (2) in their analysis of errors inherent in the radar measurement of rainfall at attenuating wavelengths.   Additionally, there may be a lack of consistency in the Z-A relationship.

The attenuation between the radar and any point in space is related to the intervening precipitation.   Hence the amount of correction to be applied to signals received from that point is derived from the intervening echo pattern. If the radar calibration is in error or the assumed Z-A relationship is not valid due to changes in the drop size distribution, the derived correction is in error.   It turns out, however, that the error in the correction is a rapidly increasing function of the calibration error.   The requirements on a precise calibration are especially stringent when the error is in the direction of under-estimating radar performance.   In this case a calibration error of as little as 1 db could lead to infinite corrections.   A comparable discrepancy in the Z-A relationship could lead to the same result.

By Spring 1960 circuitry had been incorporated into the McGill CPS-9 Radar to display the precipitation echoes on a scale of grey.   With relatively few additional components an electronic correction system was set up and the corrected signals were then displayed as before.   Trials were carried out during Summer 1960 and sets of comparison photographs were produced showing the precipitation patterns before and after correction

2. THEORY

Attenuation of the signal, in decibels, due to intervening precipitation is defined by

$$\text{ATTENUATION} = 10 \log P/P_r \tag{1}$$

where P_r is the received power and P is the power that would be received in the absence of attenuation. We define the "apparent reflectivity" (Z_a) as it would be measured by radar through intervening precipitation. Since $P/P_r = Z/Z_a$,

$$\text{ATTENUATION} = 10 \log Z/Z_a = k \int_0^r Z^\alpha dr \tag{2}$$

where k is an attenuation constant, equal to the number of decibels of attenuation in two-way propagation through one mile of precipitation of unit reflectivity. At the wavelength of 3.2 cm, k is approximately 0.00326 and α is 0.81.

In order to illustrate the general process of correction, let us consider a hypothetical storm as shown in Fig. 1, as a plot of Z against range. The broken line, labelled Z_a, represents the apparent reflectivity as it would be indicated by an ideally calibrated 3.2-cm radar and a perfect Z-A correlation. One can calculate the Z_a-curve from the Z-curve using equation 2. The curve Z_a' in Fig. 2 is a plot against range of reflectivity as it would be observed on a 3.2-cm radar whose calibration is in error. The shape of the Z_a' curve is identical to the Z_a curve in the diagram above, but it suffers a vertical shift equal to the calibration error. One can attempt to reconstruct the Z profile from the Z_a' profile. Suppose the curve labelled Z' is the corrected profile so obtained. The particular Z' curve that is obtained depends on the radar calibration, i.e. on the vertical position of the Z_a' curve in Fig. 2. As the Z_a' curve is shifted up or down a family of the Z' profiles is generated, one of which is shown in the figure. The equation describing the correction process gives Z' in terms of Z_a' and is essentially equation (18) of Hitschfeld and Bordan (2).

$$Z' = Z_a' / [1 - \frac{\alpha k}{B} \int_0^r Z_a'^\alpha dr]^{\frac{1}{\alpha}} \tag{3}$$

Inspection of this equation reveals that the denominator becomes small at attenuation values of just a few decibels. Therefore the expression is sensitive to errors in the measured reflectivity. In the case illustrated a calibration error of 0.8 db has led to infinite correction. This narrow margin of stability is the chief problem of any correction method.
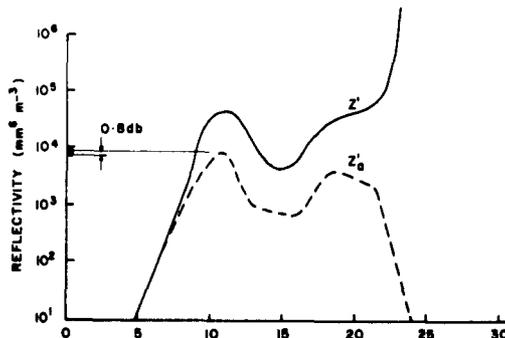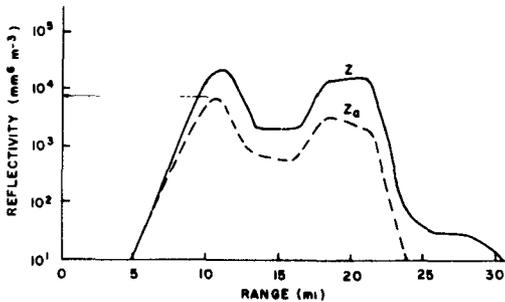
Fig. 1 (Above) Hypothetical storm profile (solid) and attenuated profile (dashed).

Fig. 2 (Below) Same profile as measured on a 3.2-cm radar (dashed) and corrected profile (solid).

3. THE CORRECTION SYSTEM

The part of the receiver system required for displaying precipitation patterns on a scale of grey is shown in the upper half of Fig. 3. The logarithmic receiver, followed by a gain control, then by an antilogarithmic amplifier, establishes a desired power law between the output and input signals. A low power law enables one to "compress" the wide dynamic range, required at the input, into the smaller dynamic range of a cathode-ray tube display. We have been using the system with an additional feature whereby the signals are quantized in the antilog amplifier. The output signals are in the form of seven discrete amplitudes and these are displayed as seven steps in CRT luminance. The correction system is shown in the lower part of Fig. 3. (It has turned out to be similar in many respects to a correction system developed by Kodaira (3).) A feedback loop is inserted between the log receiver and the display power law control. In the feedback loop a running correction is derived and added to the signal: because of the logarithmic form of the signal, this addition represents a factor correcting for attenuation. The required power law of 0.81 is established by a control in the feedback loop. The signal in the antilog form is integrated in range to 140 miles (a delay of 10 miles is included to prevent integration of ground clutter close to the radar). The zero-signal switch breaks the loop, whenever there is no detectable signal appearing ahead of the adder.

The output of the logarithmic receiver (V_1) is proportional to the logarithm of the apparent reflectivity (Z_a')

$$V_1 = F \ln Z_a'/Z_m' \tag{4}$$

where Z_m' is the reflectivity which at 100 miles is assumed to correspond to the least detectable signal on the particular radar. It is understood that circuits are provided in the radar which correct for the inverse square law dependance on range. The (') on Z_a implies that it may be in error because of an error in the calibration constant Z_m'. The following equation, giving the corrected reflectivity Z' in terms of the apparent reflectivity Z_a', can be derived

$$Z' = Z_a'/[1 - \frac{\alpha C}{F Z_m'^\alpha B}\int_o^r Z_a'^\alpha dr]^{\frac{1}{\alpha}} \tag{5}$$

The steps in the derivation leading to this equation are outlined briefly in Fig. 3. Equation 5 is equivalent to equation 3, and by comparison we can write $C/F Z_m'^\alpha = k$. The value of the parameter C is determined by the setting of the calibration control. If we assume the standard Z-A relationship to hold at all times then for each value of C, a corresponding radar calibration constant (Z_m) is implied and a corrected reflectivity Z' results as shown in Fig. 2. If we used the true calibration constant Z_m by an ideal choice of C, then the true reflectivity pattern would be recovered.
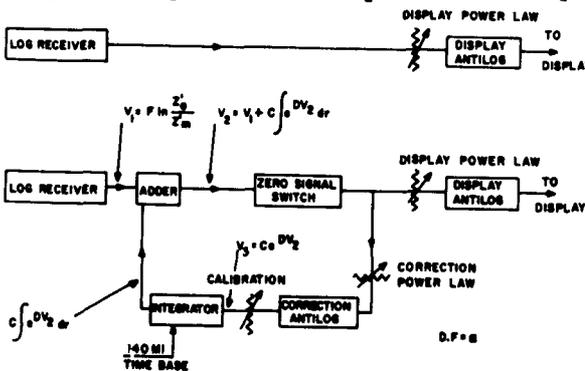
Fig. 3. Display system with correction circuitry (below), and original system (above).

Statistical estimates of attenuation in the Montreal region indicate that half the storms with rainfall rate exceeding 10 mm hr^{-1} cause a maximum attenuation greater than 10 db, while 82% cause at least 4 db, over a 120-mile path, Hamilton and Marshall (4). As a useful range we have assumed the maximum attenuation to lie between 4 and 20 db, with 10 db as the most likely value. On the basis of the meteorological conditions as well as by inspecting the uncorrected grey scale display, the operator must decide whether the storm is intense enough to contain high rainfall rates and hence cause appreciable attenuation. Once the decision to proceed is made the system is brought into adjustment in the following way. The most intense target is chosen and the antenna is pointed at it. The calibration control is turned up from the position giving zero correction until the correction at the chosen target is 10 db, consistent with the assumption. We have constructed an error diagram in the form of a plot of the error in Z' vs true attenuation with lines of constant applied correction. With the aid of this diagram it is possible to estimate the performance of the correction system. If the maximum attenuation is between the expected limits, the error in Z will be between -10 and +8 db. The error in Z' can be expected to be maximum at the most intense target echo and should be less everywhere else. If a more intense echo later appears within the range of the radar it may cause saturation if we have been over-correcting, requiring readjustment of the calibration control. The choice of 10 db applied correction is a compromise so that worthwhile improvement is made without the danger of persistent saturation.

4. RESULTS

The corrected signals were displayed in the form of CAPPI grey scale photographs and compared to corresponding uncorrected pictures. No examples are included in this report because of the difficulty of reproducing half-tone pictures adequately. In the corrected pictures the total area of the precipitation remains unchanged; this is inherent to all correction methods, of course. Echoes observed on a 3.2-cm radar are often characterized by radial shadows cast by intense cells closer to the radar. These shadows are not affected by correction, because once the signal is attenuated down to noise the information cannot be recovered. The intense cells causing the attenuation are increased in intensity and are more readily identifiable. It is improbable that this correction can be made fully automatic: an operator's judgment is needed to set the calibration control, and in our experience this needs to be done at least every half hour because of fluctuations in the receiver and the transmitter, and of course because of variations in the Z-A relationship. These may be due to abnormal drop size distribution in a particular cell. Furthermore, returns from each pulse are treated individually while ideally an average of independent returns should be taken before the signals enter the correction loop.

5. REFERENCES

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