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TECHNICAL REPORT ECOM-01257-F

EVALUATION OF THE MASER-EQUIPPED RADAR SET AN/MPS-34 AND AREA PRECIPITATION MEASUREMENT INDICATOR

FINAL REPORT

by

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EVALUATION OF THE MASER-EQUIPPED RADAR SET AN/MPS-34 AND AREA PRECIPITATION MEASUREMENT INDICATOR

Report No. 6

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FINAL REPORT

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Fort Monmouth, New Jersey 07703

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PURPOSE

The purpose of this contract is to evaluate the capability of the maser-equipped radar set AN/MPS-34 and the Area Precipitation Measurement Indicator (APMI) to operate as a highly sensitive meteorological sensing device and as a system for rapidly measuring, integrating, and displaying areal precipitation; determine what meteorological phenomena not detectable by other radar may now be detected, measured, and displayed by this equipment; and determine the general utility of these units for Army meteorological purposes.

ABSTRACT

The engineering and design problems of the Area Precipitation Measurement Indicator (APMI) are discussed. Recommendations are made for improving the video processing, integration, and display systems for the second generation APMI. Analog and digital integrators are compared for processing considerations. The merits of polar and rectangular coordinates are discussed in terms of presentation schemes. It is suggested that some form of built-in calibration capability be included in any future device of this type. Also included are some general considerations for later designs of radar data processors.

After discussing the theory of low-noise amplifiers, the problems inherent in the detection of thermal noise by a radar and the difficulties in making quantitative measurements from the data are illustrated. Engineering problems encountered during the contract period and methods of correcting them are described. The lack of stability of the maser gain makes quantitative measurements nearly impossible. One study indicated that the maser gain varied as much as 8 db/30 minutes, whereas another study showed that even hourly retuning of the. maser magnet was too infrequent to maintain optimum maser gain.

The use of the maser on the AN/MPS-34 was evaluated for the detection of birds, insects, thin lines, clear-air turbulence, clouds, fog, rain, and snow. Clear-air turbulence cannot be detected with the present system. It is very unlikely that insects or fog would be detected with the system except under very unusual situations. Birds should be detectable out to a few tens of miles depending on their size. Rain and snow within line-of-sight of the radar should be detectable to near the. 450-mile range capability of the radar scope.

Recommendations are made for improvements in the maser to make it usable as a meteorological tool by the field Army.

PART I. AREA PRECIPITATION MEASUREMENT INDICATOR

INTRODUCTION

Upon delivery, it was originally intended to operate the Area Precipitation Measurement Indicator (APMI) and to compare the results with amounts of rain as determined from the East Central Illinois raingage network. This original intent was never successfully accomplished. Initially, a greater part of the effort was directed toward the maser amplifier of the radar. It was felt that this was a more beneficial and desirable task than to implement the APMI. Nonetheless, considerable effort was expended on the APMI.

Early work required a means of recording the- output of the APMI for later data analysis. A 16-mm camera was mounted to photograph the memory scope.. Circuits were designed which permitted data to be gathered on one azimuthal scan, and photographed on the following scan. The integrator was then reset and the cycle repeated. The additional logic along with the camera control relay introduced much noise into the, integrator circuitry. Some, but not all of this, was eliminated by better bypassing of the power supplies and additional isolation of some of the more critical logic boards of the integrator.

The system was plagued throughout the project by many malfunctions within the integrator. W. G. Stone of U. S. Army visited the APMI installation and aided in trouble shooting on four occasions during this contract. In June 1966, Edward Silha, a senior in electrical engineering with excellent capabilities in digital logical design, was assigned to trouble shoot the entire APMI system. After a time, it became apparent that there were a number of difficulties which have been in existence from the initial implementation of this instrument. It is our belief that this instrument could never have functioned as originally intended. Thus, the data which were gathered early in the project are now thought to be improper. As an example, in the Third Quarterly Report, the large false alarm rate of 20 percent was attributed in large part to the peak detection processing of the radar video. It is now felt that more importantly, the high false alarm rate was due to failure of the buffer memory to be cleared under some conditions. It. also is easily determined that the second revolution increase in squares filled must have been a result of this error in the logic of the original design. Thus with reference to Figure 1 of the Third Quarterly, it is felt that this error of failure to clear accounted for most, if not all, of the false alarm rate in levels 1 through 6 . The false alarm rate of level 10 is more likely an error of the print inhibit circuit for normal zeros from memory. It might at first appear that such an error should be detected more easily; but, in all fairness to both the original contractor, evaluation personnel at U. S. Army, and the present contractor, such a subtle difficulty of failure to clear a register is difficult to assess in view of the statistical and highly variable nature of both the weather signal from the radar and the sensitivity of the APMI to induced noise. Indeed, it would appear that without very careful analysis of the logic and without careful consideration of details, this problem would have remained unrecognized for a much longer period.

DISCUSSION OF CIRCUIT MALFUNCTIONS

The most noticeable hardware malfunction was the operation of the 2N398 neon driver transistors. More than 30 of these transistors were found to be defective after the first application of power. The initial power installation was poorly regulated and probably accounts for this failure. Although most of them were electrically defective, about 20 percent of the defective 2N398 transistors had broken base leads. This happened only on the 2N398 transistors, and the break occurred only on the base lead at the body of the transistors. The defects were strictly electrical in other types of transistors. Since only about 20 transistors were defective, other than the 2N398's, the cause would seem to be aging or possible voltage surges from the power supplies.

One major circuit is particularly troublesome. This is the 931.2 kHz clock. The clock operates at room temperature but does not operate reliably at lower or higher temperatures. Either the clock design or the crystal is deficient, for the transistors and diodes have greater frequency capabilities.

Locating the other defective devices was complicated by the random characteristics of the timing logic. It was difficult to observe some wave-forms because of the asynchronous timing. The asynchronous timing made it difficult to determine if the randomness was due to a defective device or incorrect logic.

An example of this randomness was in the generation of the 2/5, 4/5, and 1-mile clock pulses. An unnecessary flip-flop and two unnecessary "AND" circuits were used to start the 1/5-mile clock. This caused the start of the 1/5-mile clock to be delayed anywhere from 1 to 5 microseconds. Since the 1/5-mile clock is counted to provide the 2/5, 4/5, and 1-mile pulses, this random starting affected the other counts. The reset for the counter that produced the 1-mile pulses extended beyond the start time of the 1/5-mile clock causing the reset and count pulses to be applied to the counter at the same time. Since the pulses are of equal amplitude, this caused uncertainty in the first 1-mile pulse. Further, since asynchronous timing with respect to the radar PRF was adopted by the designers, an uncertainty of $\pm 1\mu s$ is to be expected in all of these timing pulses with respect to the radar transmitter.

Failure to provide logic to disable the 2/5- and 4/5-mile pulse generators at the end of the store and print cycles added further uncertainty to the timing. The total uncertainty was about 15 microseconds, which may significantly affect data collection when the desired cell size is small, and makes the observation of wave-forms difficult and trouble-shooting nearly impossible. .

As in the timing logic, the APMI as a whole contains much excess hardware. Some circuits use unnecessary circuitry to perform logical functions that could be performed with fewer components. This excess hardware is not used to speed up operations, but is a result of using unsimplified Boolean functions. In fact the equipment is thereby slower than it would be and less reliable because of the added circuits.

The circuit used to reset at the end of an azimuthal revolution contained two unnecessary inverters and one unnecessary flip-flop. The entire circuit consisted of 1 comparator, 5 inverters, and 3 flip-flops; or 13 active devices. Four of these were not needed. The shaft angle encoder outputs (sin Ø, cos Ø) could have been used for reset applications, thereby precluding the need for the pot, comparator, and associated circuits.

A minor problem occurred within the intensity alarm circuit. The intensity alarm comes on when intensity level flip-flop #10 is set. For small targets it would be easy to set this flip-flop without noticing the alarm, because the flip-flop is reset for the next range increment and the alarm is turned off.

As time permitted all the logic mentioned above was corrected, except for the intensity alarm and the removal of some of the excess circuitry. The main timing uncertainty has been reduced to one microsecond. Some of the excess circuits were removed where a major overhaul was not required. The intensity alarm has not been altered. However, a simple solution would be to count the number of saturated targets, set the alarm at some minimum number, and require the operator to reset the alarm after triggering it. This is only a minor problem.

The most important logical error found so far was in the memory timing. Part of the malfunctioning in the memory timing may have been caused by the circuits slowing down with age. The adder reset pulse (during integration) is originated simultaneously with the load sync and memory register strobes. At times this would cause the adder to reset before the information had been transferred to the memory. This was easily corrected by delaying the added reset.

The other part of the problem was that, if the information in the memory (during the store cycle) had been printed or was dimension data, the information in the temporary buffer was not cleared. During the next integration cycle more information was added to that already in the buffer. This would cause overflow and complete destruction of any intelligible interpretation of the data in that buffer cell. This clearing problem also apparently produced the high false alarm rate mentioned earlier. This design error was corrected by skipping the print cycle during data collection and then print on the second revolution collecting no data during printing.

The corrections were made with the idea of not changing the. original philosophy or design of the APMI. The implementation of a machine designed to perform the same function as the APMI, but with better efficiency would, seem to be preferable.

RECOMMENDATIONS

Basically, the APMI is composed of two general parts. These are radar video processing and integration and the data display. In practice there is an interrelation between these parts. A large number of alternative schemes of accomplishing the functions of these parts have been investigated but only the. more promising are discussed.

Radar Video Processing and Integration

The present APMI performs the-integrations,by two methods. Integration in range is accomplished by passing the video through a simple low-pass RC circuit. The time constant of this circuit is adjustable from 0 to 10 ps. After this analog integration is performed, the maximum value during the range interval is converted to a digital form of 10 levels. These digitized values are then averaged at a given range for 8 or 16 radar sweeps by digital techniques. The averaged value is then reported to 11 levels (10 non-zero levels plus a blank for no echo).

Maximum Signal

Two major drawbacks to this system have been recognized. One of the drawbacks is that use of the maximum signal during an analog range interval biases the results unduly. This effect has been discussed in the Fourth Quarterly Report. It was shown that the expected error of 8 independent samples is about 4 db. This value would seem to be intolerable for most applications. Furthermore, the amount of expected error varies significantly with the range interval, the pulse length, and the time constant of the low-pass filter. The intended purpose of the peak measurement on an individual scan was to prevent missing a small intense echo because of averaging over a larger portion of no echo. In the final instrument a greater chance of missing the intense echo is allowed by the technique of scan conversion (i.e., only 1 integration of possibly 50 is used as output). It may well be that Army applications require knowledge of the most intense area rather than the average area. If this is so, it is recommended that the integration cells be smaller and the report be made on the highest valued integration cell within the larger reporting cell.

Truncation Error

The other major drawback to the present system is the truncation error that occurs because the number of reporting levels of intensity is equal to the number of integrating levels. This is compounded by lack of any round-off in the averaging circuit.

The truncation error can be most easily described by an example. Suppose that 15 sweeps are converted to level 1 and one sweep by virture of the statistical properties of the signal is too small to convert to level 1„ Without round-off, the present system would provide a 0 output even though 1 would be a much better estimate. This portion of the problem could be improved by providing round-off of the averaged digital signal. The problem is deeper, however, than this. Suppose that round-off is incorporated and a signal whose average is just above the lowest level (level 1) occurs. Approximately one-half of the time the individual sweeps will convert to level 0. During an integration series of 16 sweeps there will frequently be 9 or more times that the individual sweeps convert to levels below 1. Thus the sum of the 16 sweeps will be less than 8, so that averaging, even with round-off, can result in the report of a no-signal condition. This condition would exist about 10 percent of the time, and errors of the order of 3 db may be expected. The solution to this problem is to provide integration levels below the first reporting level. If the levels were separated by 5 db or more, one non-reporting level would be sufficient.

The same problem exists on the high end of the levels but is of less importance since the highest report level would be outputted regardless of the error in quantizing.

Integration Technique

The present integration system depends primarily on digital techniques to perform the major integration. The amount of integration performed by virtue of the low-pass filter (even with 10 µs time constant) is limited. Furthermore, a portion of the filtered information is destroyed by choosing the maximum level during the range interval.

Analog Integrators. A number of completely analog integrators have recently been constructed by various groups. A consideration of these devices for incorporation into a future version of the APMI is recommended. Analog integrators in general have the advantage of being able to process a large amount of data while retaining all of the inherent resolution of the radar.

Two of the better analog integrating devices are the quartz delay line integrator developed by the Massachusetts Institute of Technology (Kodaira, 1957) and the contiguous interval pulse integrator developed by Arthur D. Little, Inc. and the National Severe Storms Laboratory (Lhermitte and Kessler, 1965). The first system is, a frequency modulated quartz delay line integrator which would appear to be useful for this type of a device. This integrator should be capable of about 1 db precision which, when followed by some form of digitizer with 5-db. intervals, should yield a satisfactory digital output. The quartz delay line has a major disadvantage in that it is not easily incorporated as an addition to a radar but must instead synchronize the radar from the integrator. This appears to be a very serious disadvantage for Army usage.

The second system has recently been used successfully by R. Lhermitte of N.S.S.L. and C. B. Moore of.A.D.L. This system uses a series of simple pulse integrators which operate on contiguous range intervals. Each pulse channel integrates over a given range and for a time determined by the design, which could be of the order of one beam width in azimuth. From this device there would be continuous (in time) information available from the previous radar sweeps, This data could be sampled in any orderly manner for digitizing and digital display. This system does not require that the radar be synchronized to the integrator and could be used with different radars. The circuitry required is not as complex as that of the quartz delay line, and calibration techniques, could be more easily implemented. A block diagram of this device is shown in Figure 1. Another advantage of this integrator is the separation of the timing for data collection and data processing. It is recommended that separate timing be used during data collection and data processing.

The use of separate timing would allow more processing time on the collected data than is now possible. The gates, d_i, would be controlled by the range timing circuits and would be on.from the time the range increment starts until it ends. The gates, a_i, would gate the contents of pulse integrators, X_i, to the analog to digital converter. Meanwhile d_i-1 would reset X_i-1. The a_i's would be controlled by the data processing timing.

Digital Integrators. To fully implement a digital integration of all of the . radar data available appears to require the largest amount of circuitry of the integration schemes considered. In general, it will probably be necessary to reduce the amount of data by some means before practical digital techniques can be applied. In the present APMI, the prior processing is such that only one measurement in each range interval is digitized and used in the, average. Thus, basically, digital integration is used in azimuth and analog integration in range. Considering the rapidity with which data may come from the radar (approximately 2 mHz rate)., it seems that sophisticated circuitry would be necessary to digitize and sum at this rate. Thus it is recommended that the integration in range should be performed by analog methods. This range integration should proceed in more logical manner than the present peak detection process. The digital integration should have at least one more quantizing level than reporting level. It should also be such that round-off of the averages is performed.. However, use of analog integration prior to digital integration ,is recommended over an all-digital technique.

Summary of Integration Techniques. The recommendation for the integrator section of the new APMI is that a contiguous range interval pulse integrator with not less than 1 mile range resolution and 2 beam width azimuth resolution be. adopted. By processing from this resolution output, any coarser resolution can be obtained, and, at least in central Illinois, the higher core values of intensity should be available when required. Coupled with this analog integrator there should be a moderate-sized digital integrator. This integrator would allow the averaging of the 1 mile by 2 beam width analog cell to the larger 4- to 10-mile cell. It should be noted that in this system the digital rate need not be nearly as high as in a fully digital system since sampling of the analog gates can proceed at a rate determined by the processing unit (within reason no information iS lost). For the larger squares a true average could be obtained or, alternatively, the highest value of any of the individual cells. The digitized output could be stored in memory for display or for multiple PRF averaging.

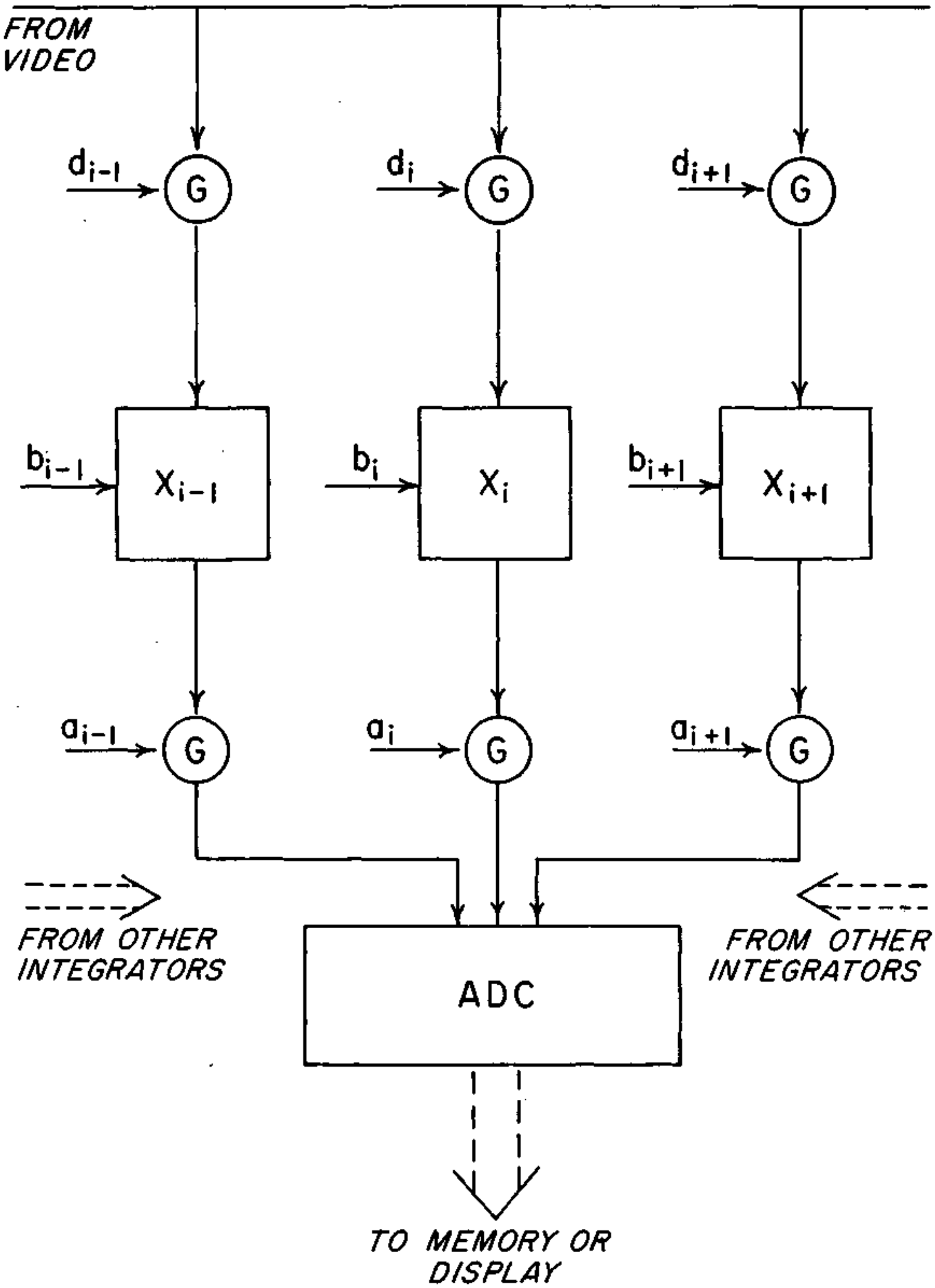


FIGURE 1. BLOCK DIAGRAM OF PROPOSED CONTIGUOUS RANGE ANALOG INTEGRATOR

By separating the collection timing from the processing timing, the amount of hardware needed to realize a specific design is reduced, and more time is available to process the data and make discriminations concerning them. Data manipulation would be independent of range instead of being restricted by the shortest range.

Because of the change of coordinates, some areas will have more than one value calculated for them. Rather than discard the accumulated information, a more sensible operation would be to average the new data with the data already stored, or alternatively, the maximum intensity could be selected, if required. This assumes a separate print cycle revolution. Integrate and store could be accomplished on even azimuthal revolutions, and print on odd revolutions. Interlaced printing could be achieved simultaneously by lagging printing operations for 90° of antenna rotation.

If print and integrate-store are going to be accomplished together, the 90° print lag allows more time for data manipulation because the integrate-store operation does not have to test for a printed word. This system appears to be the most advantageous and is recommended for future design.

Presentation Schemes

The existing APMI presentation is difficult - to interpret as no markers are visible to orient an operator. If this system is used again, across should be placed at the center of the array and at a few other selected positions.

The integration cell size should be indicated somewhere within easy access to the operator. The present cell size is determined by the setting of three switches, and a conversion table is necessary to determine cell size.

Polar Coordinate Systems. Because the polar coordinate scheme of data display is capable of presenting more of the information available from the radar, it is a more natural representation of the radar display. Thus more information at closer ranges, which have higher information density, can be displayed. It seems that generally there is more information available at closer ranges than could be profitably used in operations.

The simplest and most straightforward implementation of a polar technique is to assign for each reporting cell a fixed angular extent and range extent. The number of cells in such a scheme as a function of range extent and angular extent can be determined by reference to Figure 2. In order to have high range and azimuth resolution a very large number of cells are required. The advantage of such a scheme is that the number of radar volumes (or independent measurements) in each cell is identical. For ease of statistical interpretation if nothing else, this is a decided advantage. To some extent this scheme also represents the ultimate in the information which a common scanning radar is capable of achieving. This is true because the inherent resolution accuracy of a radar degrades with range in such a way as to maintain the angular accuracy independent of range. Thus the radar is capable of resolving in azimuth two targets at closer ranges more easily than the same two targets at greater ranges.

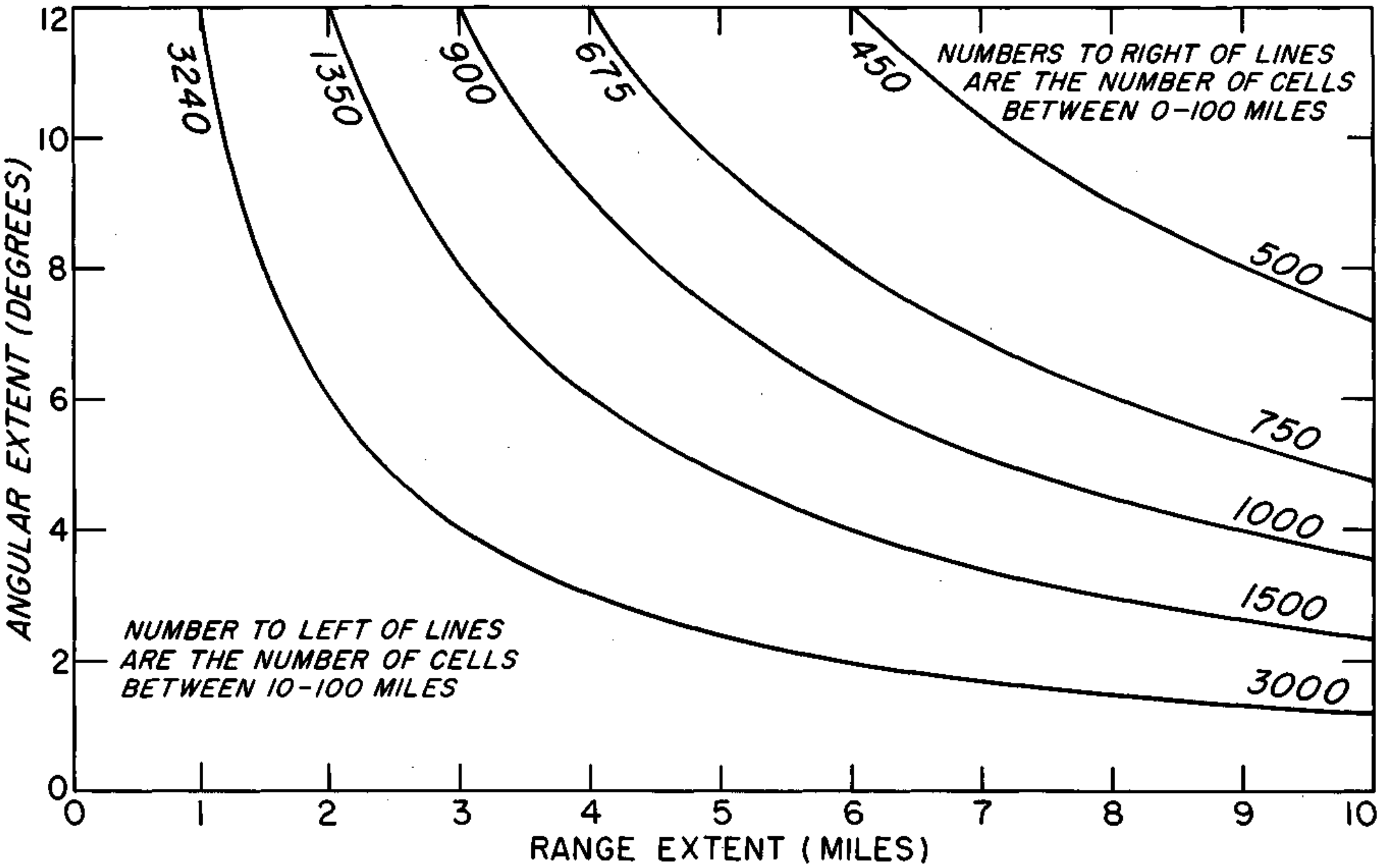


FIGURE 2. NUMBER OF CELLS REQUIRED FOR POLAR COORDINATE SYSTEM

It might be noted in passing that the data acquisition rate for this means of processing is constant. It was probably for this reason that the original APMI performs its integration in polar coordinates and then transforms to rectangular coordinates for readout. For practical circuit processing rates, this technique of polar integration will have to be considered even if rectangular output is desirable. Because of the difficulty in operator interpretation, polar coordinate expanded displays are not easily handled. Thus, if there were only one sector of interest, some expansion schemes would be such that a straight line of echoes would appear curved. At least two expansion techniques might be envisioned. A B-scope presentation such as in the present APMI could be used. This would have distortion. Secondly a presentation similar to an offset PPI might be used. If some form of electrical printing is used, the second method would not introduce distortion, but expansions would be limited to a factor of 2. An offset PPI type with the center completely removed from the printing area is possible and would remove the factor of 2 restriction.

Table 1 summarizes the advantages and disadvantages of polar coordinate techniques.

Table 1. Summary of Polar Coordinate Techniques

Advantages	Disadvantages
The same number of samples in each cell.	The size of the cell varies with range.
Data processing rate is constant.	Number of cells required to produce desired resolution at long ranges is high.
Information available is maximum possible from radar.	Expansion of scale is more difficult but may not be necessary as often.
Somewhat easier to incorporate analog integration in range.	

Rectangular Coordinate Systems. A rectangular coordinate system for presentation of information appears to be desirable for operational purpose. This system is more compatible with most outputting devices. It would be easily presented on teletype printers, electrostatic printers, and/or character displays such as the one the present APMI. Interpretation of positional information from location within the display can be easily made by an operator and easily relayed to a remote facility by manual or automatic means. Enlargement or expansion of an area of interest can easily be performed and the resulting display still easily interpreted. It should be noted that the present APMI expanded scale is not truly a rectangular coordinate system, but it should be so in future design.

The major disadvantage of this system is the added difficulty of processing the inherently polar radar information. This processing must degrade the radar resolution at short ranges to fit the size of the box. The technique used in the present system is considered to be inadequate and misleading. In the present system a polar coordinate cell is formed such that the subtended angle is equivalent to the antenna rotation during 8 or 16 sweeps. The range cell is equal to the size of the side of the rectangular reporting cell. On the 9th or 17th sweep after an integration cycle has commenced, the polar coordinates of the integration cell are converted to rectangular coordinates. If the rectangular cell determined by the conversion is unfilled, the results of the integration are loaded into memory. If, however, a previous integration has been loaded, the new one is discarded. Using this technique at 20 miles with antenna rotation of 5 RPM on short pulse and a 5-mile-square reporting cell, there will be 55 polar cells which will be discarded regardless of their value. At 90 miles, there are still 11 cells which are discarded. On long pulse, the discarded values are slightly less than one-half as many. The result of this technique is that the echoes within the first half or less of each square are the only echoes which contribute to the report on the square. The first half in this statement refers to the portion first covered by the radar in scanning. This difficulty has been evident in some of the data obtained by the APMI and should be avoided in future designs. One easily implemented refinement would be to reload the memory with the largest of the two polar integrations rather than always to lead with the first. If the philosophy of the intended use dictates knowing the maximum intensity within a reporting cell, this technique is preferred.

A second solution would be to add the results digitally and also remember the number going into each cell. An average could then be determined for each cell and reported. This requires considerably more hardware. The memory would have to be expanded by at least 6 bits for each reporting cell and provision made for true division (i.e., not division by powers of two).

Other schemes not requiring such sophistication should be more profitable. One such scheme would provide that at short ranges only every fourth radar sweep would be used in the polar integration. At medium ranges perhaps every other sweep could be used and at long ranges, every sweep. Secondly, it is recommended that 16 sweeps be used in the integration section under all conditions. There seems to be no necessity to switch the integration times from 16 to 8 when transferring to long pulse operation. There is the possibility that different averaging techniques might alleviate the difficulty.

To perform the averaging requires much more instrumentation in rectangular-coordinates than in polar coordinates. On paper at least, every sweep which passes through an area could be gated into a digitizer and a value obtained and added to the sum for this box. Highly sophisticated addressing circuitry would be involved as well as very fast processing of information since the data rate could be at least twice as high as the polar technique. Again, at least 6 bits more memory for each cell would be required, and true division would be necessary for interpretation. It appears that the rectangular system would not easily be adaptable to any form of analog averaging.

Table 2 shows the advantages and disadvantages of a rectangular integrating scheme.

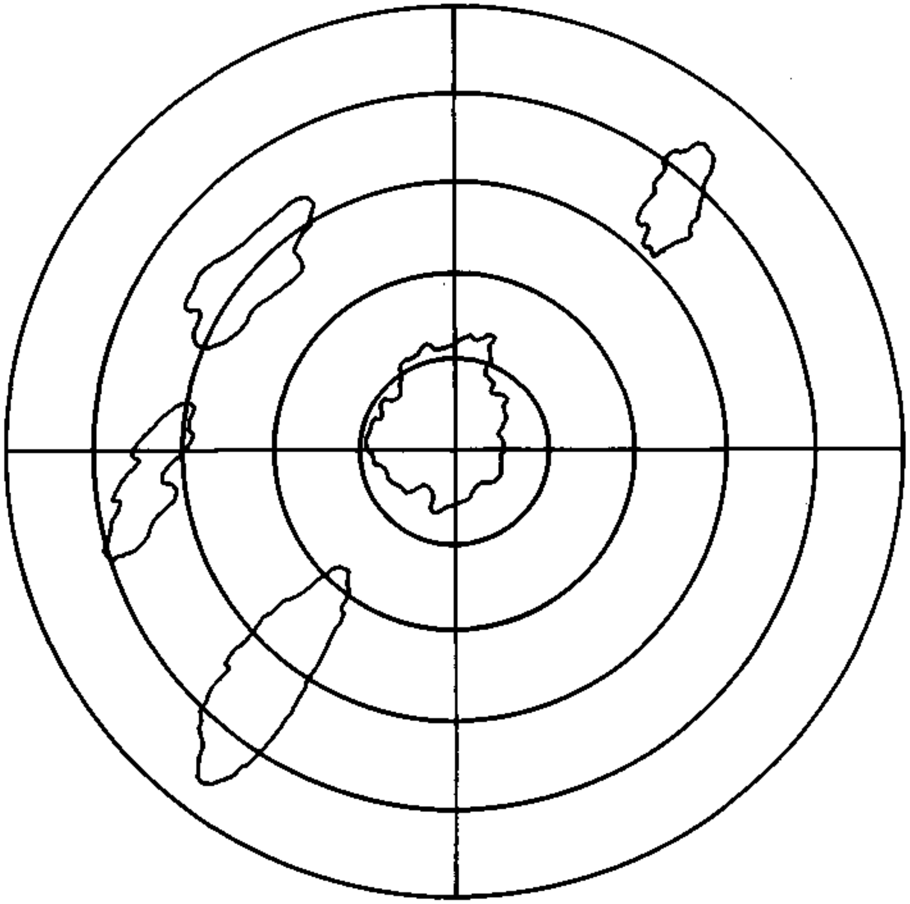
Table 2. Summary of Rectangular Coordinate Techniques

Advantages	Disadvantages
The cell is the same size at all ranges, producing ease of interpretation.	Inherent resolution at short ranges destroyed.
Expansion of an area of interest is easily performed and produces no distortion.	Integration in rectangular coordinates requires more. sophisticated and greater amount of circuitry.
Number of cells required for a given resolution at long ranges is smaller.	Analog integration very difficult, if not impossible.
Easy to adapt for transmission.	

Non-Mapped Presentation. A scheme for presentation of digitized data has been envisioned which, unlike the proceeding types, does not present a map-like structure. It is proposed that an orderly listing of the azimuth, range, and intensity of targets be presented next to a standard non-digitized radar display. In use, an operator could glance at the standard PPI and form a general impression of the rain areas. If there were rain in an area of interest, the precise values of intensity could be determined by reference to the. continually updated side display.

Figure 3 is an example of one such display that is under consideration. One of the advantages of this system is that the operator has less difficulty in rejecting ground return and anomalous propagation. In addition, if cell areas are large, a glance at the PPI yields qualitative information as to the extent of precipitation within the integration cell. Frequently characteristics of the echo (such as hooks or sharp breaks in lines) could also be seen on the PPI which would provide the operator with additional information as to the severity of the storm. Under this scheme the integrator section would provide primarily intensity values which are extremely difficult to obtain directly from a PPI.

The PPI would provide the ability to utilize all of the radar resolution; therefore, the number of integrating cells could be reduced. Information on intensity indicated in this form could be transmitted very efficiently to remote locations. At remote locations the information could be displayed in a rectangular map-oriented style or printed in the same form as before. Regardless of the presentation scheme finally adopted, the side presentation of the radar PPI would be advantageous.



STANDARD PPI DISPLAY
WITH 10 MILE RANGE RINGS

INTEGRATOR INTENSITIES

NORTH WEST			NORTH EAST		
INT	AZ	RANGE	INT	AZ	RANGE
3	272	32	3	040	39
3	300	30			
4	308	31			
3	320	32			

SOUTH WEST			SOUTH EAST		
INT	AZ	RANGE	INT	AZ	RANGE
3	220	20			
4	220	30			
3	220	42			
5	265	36			

FIGURE 3. PROPOSED DISPLAY OF COMBINED RADAR AND INTEGRATOR OUTPUTS

Calibration

One of the major difficulties of the present APMI has been calibration of the equipment. Ideally, the calibration should be performed with a signal source which has the same statistical characteristics as the weather echo. In the present system, all attempts at calibration using a signal generator at the radar frequency have resulted in large uncertainties of the power levels. As the signal generator power is increased through several decibels, the integrator output slowly changes from one level to the, next. This is apparently the result of noise superimposed on the signal. When calibration is performed using a 30 Mc signal generator, these effects are not as noticeable. However, the calibration of the system requires that at least one level be calibrated with respect to power at the antenna terminals in order to include the performance of the receiver. It is recommended that future systems be constructed with some means of internal calibration.

Internal operation of the integrator should be checked by allowing the operator to force a digital number in the early stages of processing. This feature would be most beneficial in trouble shooting the equipment. If possible with the type of integration adopted, it would be preferable to have the integrator fed with a sequence of different digits. A better estimate of the performance of the averaging circuits could then be made.

For calibration purposes, a noise signal generator operating at the IF frequency should be provided. If possible, the power spectra of this generator should match the spectra of weather echoes. This generator output should be variable, of known amplitude, and capable of amplitude modulation. As an alternative to this generator, a noise generator capable of producing the noise spectra of the video output of the IF strip could be used. Since considerably higher power would be required, it is doubtful that this would be advisable. Absolute calibration through the radar remains a problem, even with these additions, A statistical scheme of calibration in which the level might be described as that point where one half of the time the higher level is converted and one half the time the lower level is converted is proposed as the best solution.

It may be that a more precise integrating scheme will eliminate some of the difficulties found with the present APMI. In particular, the uncertainty of range interval (unsynchronized master clock) of ± 1/5 mile plus the peak detection process may be accounting for a portion of the uncertainty in determination.

Finally, a strong plea is made for incorporation of checking features for as many of the sub-assemblies as possible. Unless the reliability of the equipment can be increased by several orders of magnitude, individual circuit check features are indispensable.

Other Considerations for Future Design

Detailed recommendations for the design of the next radar processing device depends upon the usage planned for the device. Obviously, the device is intended to remove as much arbitrariness in scope interpretation as possible, but somewhat different goals may be desired. It seems that there are at least two major applications of weather-radar in the Army, One of these is determining the amount of precipitation over areas of various sizes. The other major requirement is determining where and how hard rain is falling at present and where it is likely to be later. The radar also would be useful in mesometeorological investigations of wind shift lines, gusty damaging winds, extreme rainfall gradients, and other phenomena.

Precipitation Amount. Determining the precipitation amount requires the storage and addition of the data over an earlier time period. If rain amounts during the previous 6 hours are desired, the device must be capable of much larger storage than would be necessary for determining amounts during shorter time intervals. This ability to integrate or sum the amounts for prior time can be called amount integration in order to separate it from the more fundamentally required signal integration discussed in other sections.

The frequency of sampling for amount integration necessary for a given accuracy is a function of the type of rainfall and the areal resolution required. Rainfall statistics suggest that sampling of rain rates once every 5 minutes should be adequate for areas on the order of 5 miles on a side. If larger areas are considered sufficient, longer time periods should be adequate. If smaller areas are necessary, more rapid sampling is required.

In the amount integration section, some means of changing the signal levels to equivalent rainfall rates must be provided. As was pointed out in Quarterly Reports 3 and 4, the level positions must be set so that the average can be interpreted in an appropriate manner. Likewise for the amount integration, the levels must be established in a systematic manner. Since rainfall rate is not linearly related to average power, the sequence of power levels will be different from the sequence of rate levels. Ideally, there may be many more quantizing levels of rate than original power levels. This occurs since there is more inherent accuracy in the average of 16 power levels than in any individual level. For the amount integration, a quantizing interval of at least 5 bits and probably 6 bits would be advisable. The additional bits would be available from the digital summing before the division takes place. If 3 bit digitizing takes place initially and addition over 16 sweeps takes place, 7 bit registers are required. Thus, the use of 6 bits for the amount integration does not require further refinement or enlargement of the basic integration system.

Conversion of the power level to a rate should be flexible enough to allow operator insertion of different R-Z relationships for best accuracy. Operation of the integrator should be such that the time between samples used for amount integration can be variable.. The amount integrator should be capable of determining the time between samples and sensing whether the. radar is operating in an appropriate mode when a sample is required. In an operating situation it would seem likely that, during a 6-hour interval, there will be other requirements that the radar must fulfill. Thus, the amount integrator should sound an alarm when it requires data and then wait until the radar is made available. When available, an additional integrating scan should be performed, and the time interval from the preceding sample should be compensated for.

The output of the amount integrator may be fed to the output facility of the intensity integrator for display; or, since it is basically a slowly changing datum, output could easily be accomplished on teletype. Storage areas or cell sizes of the amount integrator may be coarser than the intensity integrator cells which would allow for a saving in amount integrator storage facility.

Present and Future Rainfall Rate Determination. For all aircraft operation problems as well as other operations, little past information is necessary. At most, the presentation of the intensity integrator output 15 to 30 minutes earlier would be required for time extrapolation. If forecasting is required, some past information must be available to the operator. If teletype or electrostatic printers are used, past information is easily available. If the choice falls on a character generator and memory scope display, some means of preserving past information must be added. The best way would be to have two buffer memories of capacity nearly equal to that of the intensity integrator memory and a programmer to cycle information into the buffers as desired. The buffer memories could then be recalled on command of the operator. It would seem that the operator might profitably use the radar PPI or a remote PPI for this requirement.

Although it is not necessarily a part of Army tactical requirements, a permanent record of the intensity integrator is desirable. Such records are indispensable in testing and proving the usefulness of the device and might be useful tactically in certain combat areas.

The Superimposed Display. One of the more elegant displays that might be considered is one in which the integrator output numbers are superimposed on a PPI presentation of the radar video. Using this display, the operator could see all the resolution of the radar as well as the intensities of the echoes at one glance. A switch which would allow the operator to display intensity numbers above the switch amount should be provided.. For instance, on some occasions the switch might be set so that only levels above 5 would be displayed. One glance might be sufficient for the operator to determine the location of the most intense (5) echo and how widespread this intensity is.

The superposition of these displays could be made either by using a two color tube or by optically superimposing two display tubes with different color filters for each tube. A display such as this would seem to provide the operator with all of the information (except Doppler velocities) available from a radar on one display and should be easily interpretable.

PART II. THE MASER-EQUIPPED AN/MPS-34 RADAR

INTRODUCTION

The purpose of this investigation was to determine the utility of an X-band weather radar such as the AN/MPS-34 with improved receiver sensitivity in the detection and measurement of echoes peculiar to weather and to determine what additional information could be obtained with the higher receiver sensitivity. It was hoped that a number of discontinuities known to exist in the atmosphere, but not detected by a normal weather radar, could be studied with the maser-equipped AN/MPS-34. Most of the phenomena to be studied were available for analysis; however, some phenomena such as the less common severe weather (tornadoes, large hail, etc.) were not present on operating days in the three states, Illinois, New Mexico, and Arizona, where the radar was operated.

HIGH GAIN AMPLIFIERS

The use of a maser on the. AN/MPS-34 results in an increase of gain to such an extent that different philosophies are required in interpretation of the data. The theory of low-noise amplifiers is applicable to the AN/MPS-34 maser system. Robbiani (1960, 1964) has discussed this theory as it applies to the maser-equipped AN/MPS-34.

The available noise power, dN_g, from a signal generator within a narrow frequency interval, df, is

$$dN_g = KTdf \qquad (1)$$

where K is Boltzmann's constant (1.38×10^{-23} joules per degree Kelvin) and T is the temperature of the resistive component of the signal generator's output impedance. If the signal from a generator is fed into an ideal amplifier with gain, G, the only noise at the output terminals is that due to the amplification of the input noise. The noise at the output of a practical amplifier is the result of the amplified input noise plus the additional noise, dM_O, generated within the amplifier. Thus, the ratio of the output noise to the output signal power, dN_O/S_O, is greater than the ratio of input noise to input signal power, dNg/Sg, by a factor F which is called the noise figure and is expressed as follows:

$$\frac{dN_o}{S_o} = F \frac{dN_g}{S_g} \qquad (2)$$

where the noise powers are measured in a frequency band, df, centered on the corresponding signal frequencies. Since $dN_0 = GdN_g + dM_0$ and $S_0 = GS_g$, equation (1) may be substituted into equation (2) and rearranged to give

$$F - 1 = \frac{dM_o}{GKT_o df} \qquad (3)$$

where T_0 is a reference temperature chosen to standardize the performance of the generator. Usually T_0 = 292K as this is a reasonable approximation to the ambient temperature at which measurements are made.

When two amplifiers are put in series, the overall noise figure of the combination may be derived from the noise figures of each section. The overall output noise power is again composed of two parts, the input noise amplified by the gain of the second plus the additional noise generated in the second amplifier. The second part may be derived from equation (3). Using subscripts 1, 2, and 12 to represent terms from the first amplifier, the second amplifier, and the total system respectively; we may write

$$dN_{o_{12}} = G_2 dN_{o_1} + (F_2 - 1)G_2 KT_o df$$

which reduces to

$$F_{12} = F_1 + \frac{F_2 - 1}{G_1} \qquad (4)$$

The maser of the AN/MPS-34 radar is the first amplifier, and the normal receiver is considered to be the second amplifier. Equation (4) indicates that the maser reduces the noise figure of the, AN/MPS-34 receiver system from 8 db without the maser to 1.14 db with the maser, assuming the maser's noise figure to be 1.06 db and it's optimum gain to be 20 db.

The minimum signal power detectable by a human observer from an A-scope presentation is one which has a magnitude equal to the noise power present on the A-scope. (Integration techniques make it possible to detect signals with magnitudes much less than the noise level, but these will be ignored in the present discussion.) Solving for S_g from equation (2) when $dN_0 = S_0$, gives $Sg = FKT_0 df$, where S_g is now P_{min}, the minimum detectable signal. Knowing F and df, P_{min} may be found readily.

Without the use of a low-noise rf amplifier most radars are limited because of the noise power generated within the crystal detector and the IF amplifier to minimum detectable signals of, at best, about -106 dbm as in the case of the MPS-34 without maser. Because the maser itself generates little noise, the limitation with a maser-equipped radar becomes that imposed by the magnitude of the noise power introduced into the maser from the antenna. If the signal generator mentioned earlier is an antenna, then the maximum possible noise power at the input of a radar is that given by equation (1). For an antenna directed toward objects on the earth's surface, T might be 300 K in which case dN is -108.4 dbm when df = 3.5mHz (MPS-34 short pulse) and -115.0 dbm when df = 0.75mHz (MPS-34 long pulse). These values are the noise power levels into the maser from the thermal radiation at X-band wavelengths. Pointing the antenna at the sky, with or without a meteorological target in view, gives a considerably lower apparent temperature than the ambient air or ground temperature.

Several things might be noted from the above discussion. First, the minimum detectable signal is dependent on the temperature (and, hence, the noise power) of the objects in the antenna beam pattern. There will be little variation in the thermal noise level when the antenna is aimed near the earth's surface. To produce a 1 db change in the thermal noise power detected by the antenna, the temperature of the radiating object would have to be lowered from 300K to 238K (-35C) or raised to 378K (105C), either of which is unusual at the earth's surface. On the other hand, when the antenna is pointed at the clear sky, the apparent temperature sensed by the antenna is probably less than 70K. This apparent temperature would cause a decrease in noise power of 6.3 db. Lawson and Uhlenbeek (1950) suggest that for 3-cm wavelength radar and a zenith-directed antenna, the antenna temperature ought to be "extremely small." This occurs because the radiation from the atmosphere must equal the partial absorption of the black-body radiation in the atmosphere. Since gases in the atmosphere attenuate 3-cm wavelength radiation only very slightly, the atmosphere can, thus, radiate only slightly and, hence, contribute little to the apparent antenna temperature.

A second point to note is the dependence of the effective noise power input to a radar on the band width of the receiver. From the standpoint of avoiding detection of thermal noise, the maser-equipped MPS-34 ideally should have been operated on long pulse exclusively. However, a loss of sensitivity on long pulse, which will be discussed later, made it advantageous to operate on short pulse for echoes within 75 miles.

A third feature is the fact that an X-band radar receiver with a minimum detectable signal (MDS) of -109 dbm or better has a sensitivity sufficient to detect the random noise generated from attenuating objects at normal temperatures within its antenna pattern. Thus, the antenna and receiver act as an X-band radiometer. This is true whether the transmitter is on or off. The amount of thermal radiation is a function of the temperature of the radiating body. Figures 4 and 5 were taken with the maser in operation and without changing the camera or scope settings. Figure 4a shows the scope as it was illuminated with the antenna at a 1° angle from the horizontal. Figure 4b was taken with the antenna at t°. All echoes are of ground clutter with the San Francisco Peaks showing at 10 n. mi. to the northeast. Figure 4c was taken with an antenna tilt of 11°. It will be noted that the "grass" level on the scope reduces radically as the antenna receives less and less signal from the ground.

Figure 5a, taken on 27 July 1966 at full maser gain shows precipitation on the scope to the east at 10 miles. The antenna was at the 1° tilt angle, and

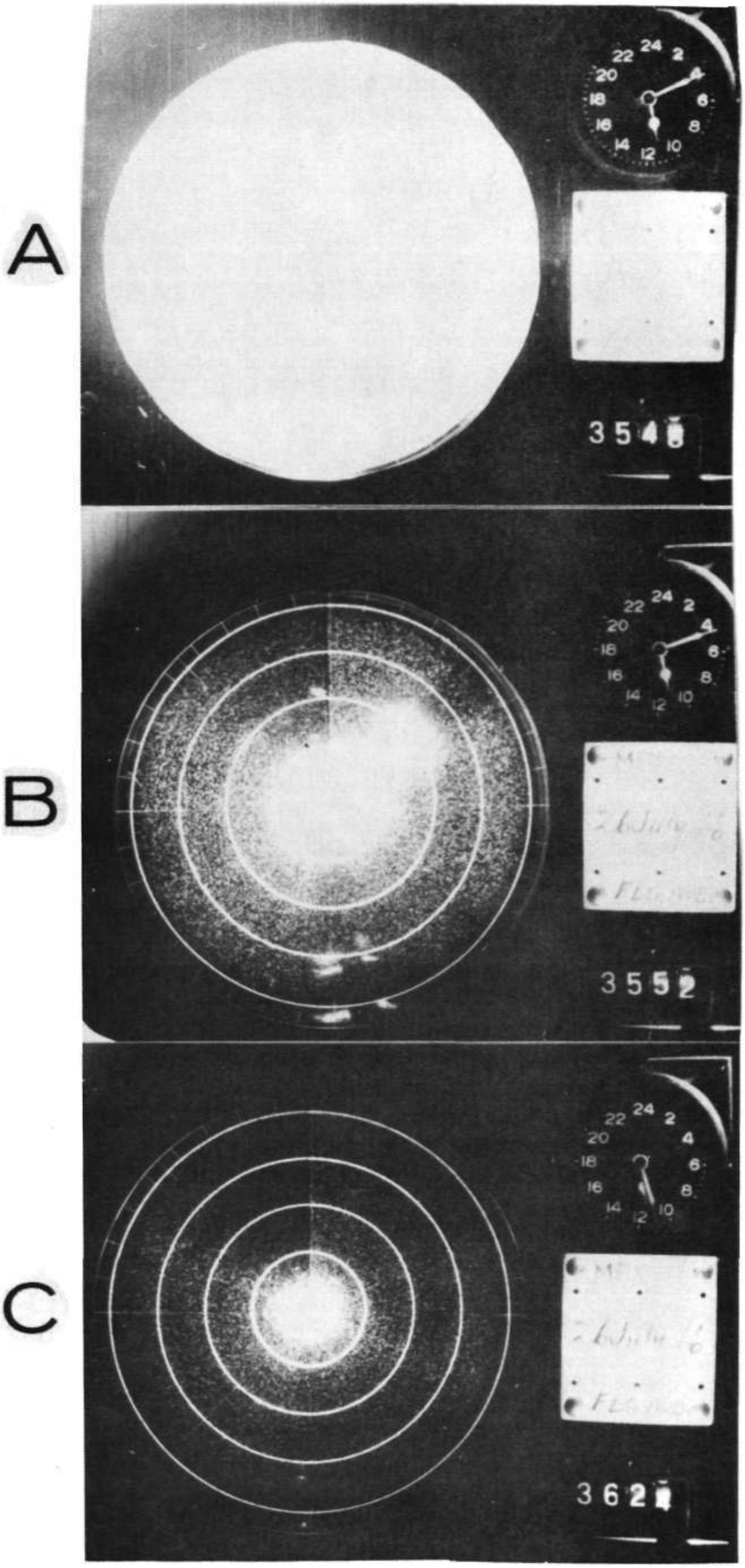


FIGURE 4. THERMAL NOISE DETECTED AT TILT ANGLES OF 1°, 4°, AND 11° ON 26 JULY 1966 (5 N.MI. RANGE RINGS)

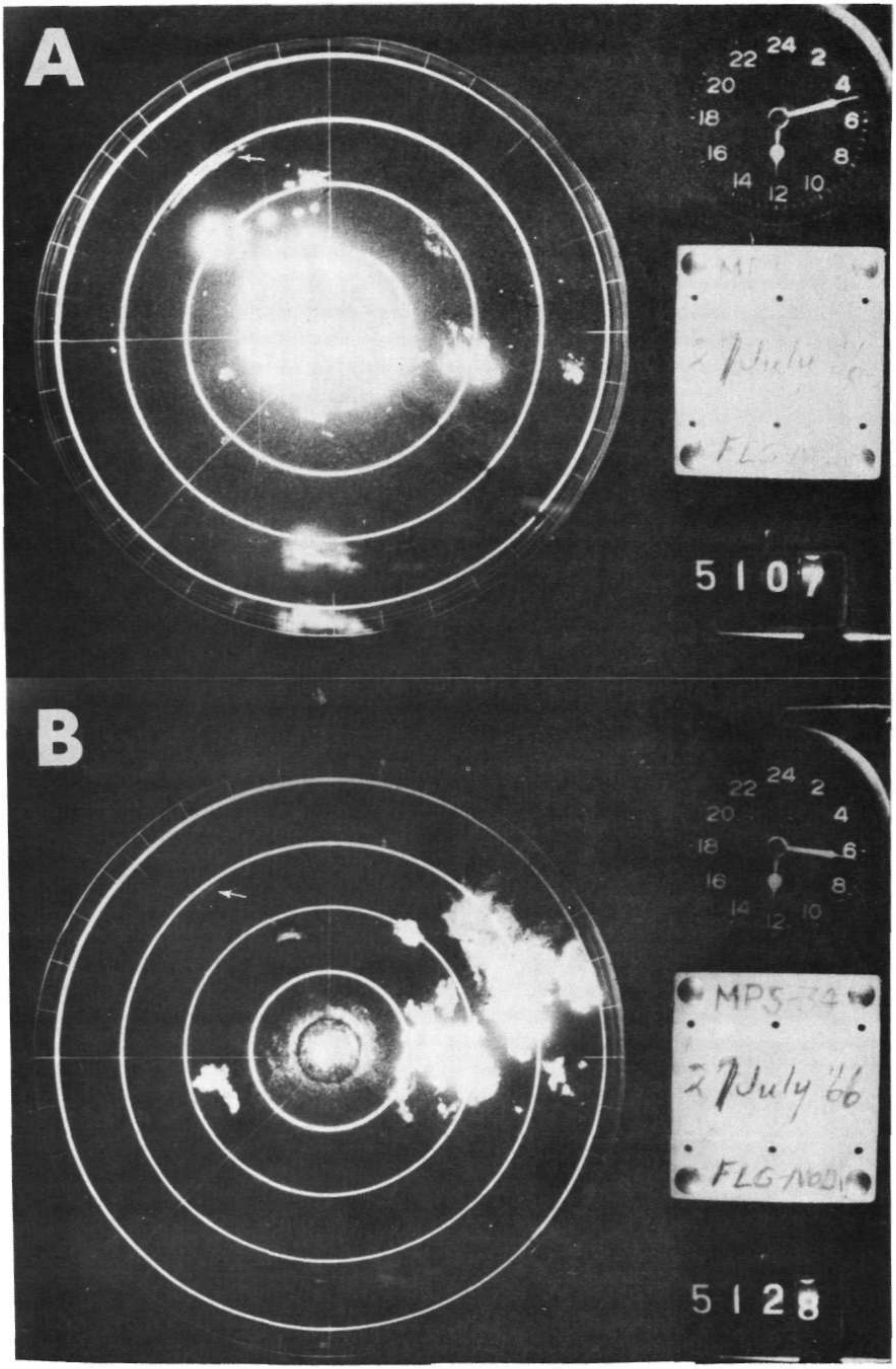


FIGURE 5. THERMAL NOISE DETECTION DURING A PERIOD OF PRECIPITATION DETECTION ON 27 JULY 1966 IN ARIZONA (5 N.MI. RANGE RINGS)

its beam was intercepted by surface objects. The black radial streak at 130° azimuth was caused by the camera switching. Thermal noise is visible on the, scope in Figure 5a although noise was taken into account when the scope was adjusted. It seems reasonable to believe that when the main antenna lobe is intercepted by precipitation the noise radiated by the rain would be detected by the receiver. However, this noise should only be detected when the antenna, is directed at the rain and should not appear when the antenna is directed toward the transparent sky. Since the noise radiation is random in time, the display of noise on the scope will appear at all ranges of the noisy azimuth and not just at the range of the radiating source. Figure 5b taken at 11° tilt does not show that noise is being detected from the rain since there is no difference in the grass level in the rain and no-rain directions. The answer probably lies in the fact that, although this is 3-cm radiation and precipitation does attenuate the signal, the amount of attenuation and, therefore, the amount of thermal radiation is insufficient to permit its detection by the maser-equipped AN/MPS-34 radar. The rain detected at the 11° tilt is not seen on the 1° tilt because of the attenuation of the signal by nearby surface objects on the lower tilt angle.

A test signal appears on both photographs in the northwest quadrant at approximately 58 miles (white arrows). The signal is stronger at the 1° tilt since the test horn was fixed in elevation with respect to the antenna and less signal was received by the antenna at the 11° tilt angle.

EQUIPMENT AND OPERATIONAL PROBLEMS

Throughput the contract a number of problems were encountered which limited the collection of data. Many of these were due to equipment failures, lack of helium as needed, and instability in components. These are discussed in the following.paragraphs.

The equipment was received on 10 May 1965. Power was provided originally at 220v., 60-cycle, single phase, 3 wire. However, these requirements were found to be in error due to a misunderstanding and a power source of 120/208v., 60-cycle, 3 phase, 4 wire had to be procured for the radar site. This new power requirement was fulfilled on 2 June 1965. The Atmospheric Sciences Laboratory of USAECOM had returned the maser amplifier to Hughes Research Laboratories for reconditioning and it was received at the radar site on 24 May 1965. Shipping damages necessitated a visit by James Kiefer, a Hughes Research Laboratory representative, to align the magnet before the maser-amplifier would give acceptable gain. The waveguide, access tube, and fill tube of the maser. were bent severely and attempts to straighten them were never completely successful. As a result, the complete maser assembly is subjected to horizontal stresses when the flange box is attached to the maser dewar. This misalignment contributed to a gasket problem. After the magnet was aligned by the factory representative, the maser gave a net gain of 8-10 db when installed on the radar in comparison to the 14–16 db gain realized in the test setup used for alignment.

At the start of operations, a 10-liter helium dewar, which came with the. maser, was used for transporting liquid helium from the Physics Building to the radar site. Experience proved that 12-14 liters of liquid helium were needed, to initially charge the maser. If delays were encountered in getting a refill, the original helium would be lost without collecting data. This problem was solved, by receiving permission to procure a 30-liter dewar for helium transport and storage. A troublesome problem encountered early in the research period was the inability to maintain a satisfactory seal between the flange box of the maser and the maser dewar. Various types of silicone gasket materials were used but failed to maintain a seal for more than 2 or 3 transfer operations. This poor seal prevented efficient removal of the liquid nitrogen used in the maser dewar for pre-cooling the. system. A satisfactory solution of this gasket problem was obtained by using Teflon gaskets.

On 30 July 1965 the radar and maser amplifier were transferred to Magdalena, New Mexico, where data were collected for a cooperative field project on thunderstorm electrification supported by funds from contract Nonr-815(03). While on the field project, the maser magnet was aligned by project personnel, and an automatic vertical scan which permitted photographing of an RHI scope was improvised.

After the radar's return from Magdalena, New Mexico, it was discovered that the K-Band pump klystrons had been misplaced. Two months of operation time were lost before they were recovered from a mislabeled and misplaced salvage box. At this time the magnet again required alignment.

During the initial operation in June 1965, it was noted that the transmitter activation decreased the maser amplifier gain by 5-8 db if the isolater was not operating. In contrast to prior operations, this loss of gain was observed throughout the experiment, and the pulsed isolater had to be used in all operations to protect the maser from the magnetron pulse. Because of an inadequate heat sink, failure of zener diodes in the pulser power supply occurred on several occasions. For lack of a ready source of zener diodes, VR tubes were substituted for several of the zener's and the pulser operated with a hybrid power supply.

During June 1966 an experiment, with two inexpensive wide-mouth vacuum flasks, proved that by immersing the smaller flask containing the maser and liquid helium into the larger flask containing liquid nitrogen the maser's temperature would drop to the required 4.2°K necessary for the alignment of the magnet; The removal of the maser from the open mouth flasks did not misalign the magnet and it could then be locked without disturbing its alignment. In addition to saving many liters of liquid helium, this new procedure speeded up the alignment process by several days.

It was noted that the tilting of the -antenna 38° for only a few minutes would cause the maser to lose a large percentage of its gain. After the return to its normal operating position, the trimming current would then need adjusting. Also, as time elapsed after the charging of the maser dewar; the resistance of the trimming coil increased, resulting in an improper trimming current from the. constant voltage power supply. Since this power supply could be modified to a remote sensing voltage-controlled unit, a suitable resistor was placed in series with the trimming coil, and the voltage across it was sensed to give a constant current supply for the trimming coil. After this constant current source was provided, the antenna could be tilted to 45° without causing a gain loss. However, larger tilt angles were not possible without a loss of gain, and it is assumed that tilting caused a rise in the maser's temperature.

On 20 June 1966 the maser-radar van was transported to Chanute Air Force Base for a road inspection before departing on 30 June 1966 for Flagstaff, Arizona, to be a part of field project AMC-02376(E). After completion of the project it was returned to the University of Illinois Airport on 29 August 1966.

The AN/MPS-34 radar was operated during the field project in the Flagstaff, Arizona, area for a total of 41 hours, 18 minutes. The first day of operation was 21 July 1966 when the equipment was operated without maser as a test of the status of the basic radar. The maser amplifier was operational for 24 hours and 4 minutes of the project time.. The remaining 17 hours, 14 minutes of operation without the maser amplifier were prompted by the desire for a better understanding of the distribution of radar echoes in the Flagstaff area in support of the ESSA-USAECOM Cloud Physics Project. The AN/MPS-34 radar was the only radar equipped for continuous scope photography on the project. The maser amplifier was not used during these operations because of the lack of liquid helium. Helium was not available because of delays in the trucking of the supply dewars from the Torrance, California, reduction plant.

The maser amplifier has been used with the AN/MPS-34 radar for field trips during the summers of 1965 and 1966. Each of those field trips involved the use of the maser at relatively high altitudes, approximately 7,000 feet. On both occasions it was found that the maser dewar failed to hold a charge of liquid helium over a 24-hr period, whereas the. dewar held a charge for 24 hours rather easily at the lower elevation (750 feet) in Illinois. On an average the maser would begin to warm after approximately 12 hours at the higher altitude. A literature search for a cause for this boiling off of the liquid helium at an accelerated rate revealed no reason for the phenomenon. Yet, the observation was made for both the New Mexico and the Arizona projects and must be considered as an operational fact.

The fact that the dewar would not hold a liquid helium charge for a period longer than 12 hours while at the higher altitude necessitated the complete recharging of the dewar each operating morning with the attendant charging-time delay. Thus, the radar could not be used for the collection of meteorological data until the charging had been completed, usually between 1000 LS.T and 1200 LST. Usually, detectable clouds had formed within radar range before operations could begin.

During the Arizona field trip, Junction Box 3400 became wet and, as a result, upon the radar's return all the terminal boards and connectors in this box had to be replaced.

The antenna was tilted close to the zenith in order to study the detection of clouds by the radar. In order to avoid the loss of gain experienced previously when the antenna was tilted to extreme angles, the maser was remounted such that the maser dewar was in a vertical position when the antenna was at a tilt angle of 85 degrees. While tilted vertically, the clouds associated with several different weather situations were observed as they passed over the radar.

With the exceptions of a noisy and unstable receiver and of the moisture problem in Junction Box 3400, the troubles encountered with the non-maser portion of the radar system were standard malfunctions normally expected in radar operations.

Antenna Gain

One other problem was experienced with the, standard AN/MPS-34 radar system that did not involve the maser, but is commonly encountered in production radars. This was the relatively poor antenna gain determined by measurement as compared to the gain of 45 db quoted by the manufacturer for the AN/MPS-34. On 26 August 1965 in New Mexico a 10-in aluminum sphere was flown to measure the antenna gain. The measured value was 36.2 db, nearly 9 db below the rated value. Perhaps some of this difference may be attributed to different techniques of measuring. Nevertheless, the difference found is quite large, especially since the antenna gain is squared in the radar equation. An improvement in antenna gain of only half the difference between the measured and rated values would increase the overall capability of the AN/MPS-34 by an amount nearly the same as the additional gain produced by the maser, but without the detection of thermal noise and the engineering and analysis problems associated with the maser.

Maser Gain Stability

One question about the data obtained with the maser-equipped AN/MPS-34 involves the stability of maser-produced gain. Examples of two cases in which the maser gain is known to have varied will illustrate this problem.

During the radar operations at Flagstaff on 4 August 1966, an automatic step-tilt programmer which provided consistent return of the antenna to each of the several tilt angles was used. This provided some good ground targets on the 4.4° tilt angle which, along with the receiver step-gain control, was used to monitor the overall system sensitivity.

Data taken at this constant tilt angle during a four-hour period were used to indicate the variability in overall system sensitivity. If the various system parameters remain constant with time, the area detected from a ground target (San Francisco Peaks at about 10 mi, range NE, in this case) at a given receiver IF gain setting, should also remain constant with time. Similarly, if the area detected from a ground target is the same at various times, the overall sensitivity should also be the same. An analysis of the data was made such that the time variation of the overall system sensitivity was determined. If the assumptions are made that the transmitter output, the tilt angle, the normal portion of the receiver, the atmospheric refraction, and the antenna thermal noise were all constant during the period, then the variation in overall sensitivity can be entirely attributed to variations in the maser gain.

Figure 6 illustrates the variation of the maser gain with time as determined from the above analysis. The curves are lines of constant overall system sensitivity referenced to the sensitivity of the radar at each of the first six gain steps (the straight dashed lines) with the maser switched out of the system (1329 - 1333 MST). Since each curve represents a constant value of overall system sensitivity, the curves may be interpreted as the change (in db) in the IF amplifier sensitivity necessary to exactly compensate the uncontrolled variations in maser gain. Comparing any given curve at any time with the dashed line of the corresponding gain step indicates the magnitude of maser gain at that time and at that level of IF sensitivity. The fact that the peaks and dips do not always occur at the same time may in part be due to fluctuations in the equipment during data collection; the overall trends, however, are quite apparent in the curves. The average maser. gain of all gain steps just before and just after switching the. maser off relative to the no-maser data is 11.8 db. The time-integrated maser gain, again averaged for all gain steps, is slightly over 9.5 db. Table 3 lists the time-averaged maser gain at each of the six gain steps obtained by integrating the area between corresponding curves and gain step lines for each step.

Table 3. Time-Averaged Maser Gain
at each Gain Step

Gain step	1	2	3	4	5	6
Maser gain (db)	8;5	3.5	5.9	10.5	12.7	16.0

If, as is now believed, the maser limits the signal by thermal noise detection at full gain, step 1 should exceed step 2 in overall sensitivity by less than the 6 db difference in their gain settings. Figure 6 does show step 1 and 2 curves close together. However, Table 3 indicates that step 1 has 5 db more maser gain than step 2. An explanation for this probably lies in the fact that, as mentioned - earlier, some of the data points are probably somewhat in error. Specifically, the step 1 (and all others for that matter) curve position on the figure is based on the single data point obtained with the maser off. Had this point been in error the entire curve would have been shifted up or down accordingly. This would have changed the overall maser gain derived from the curve. Also, the point on the. step 2 curve which indicates a negative gain (while all other steps have 2-1/2 to 13 db positive gain at the same time) might also have appeared more correct had the . single no-maser data point been different, Thus, no explanation other than a poor measurement of area on either step 1 or step 2 with no maser operative is possible , to explain the step 1 and step 2 maser average gains. On the other hand, it is reasonable to expect higher effective maser gains on the less sensitive steps. This is evidenced in steps 4, 5, and 6 and is an indication of how much more effective a maser would be for a less sensitive radar..

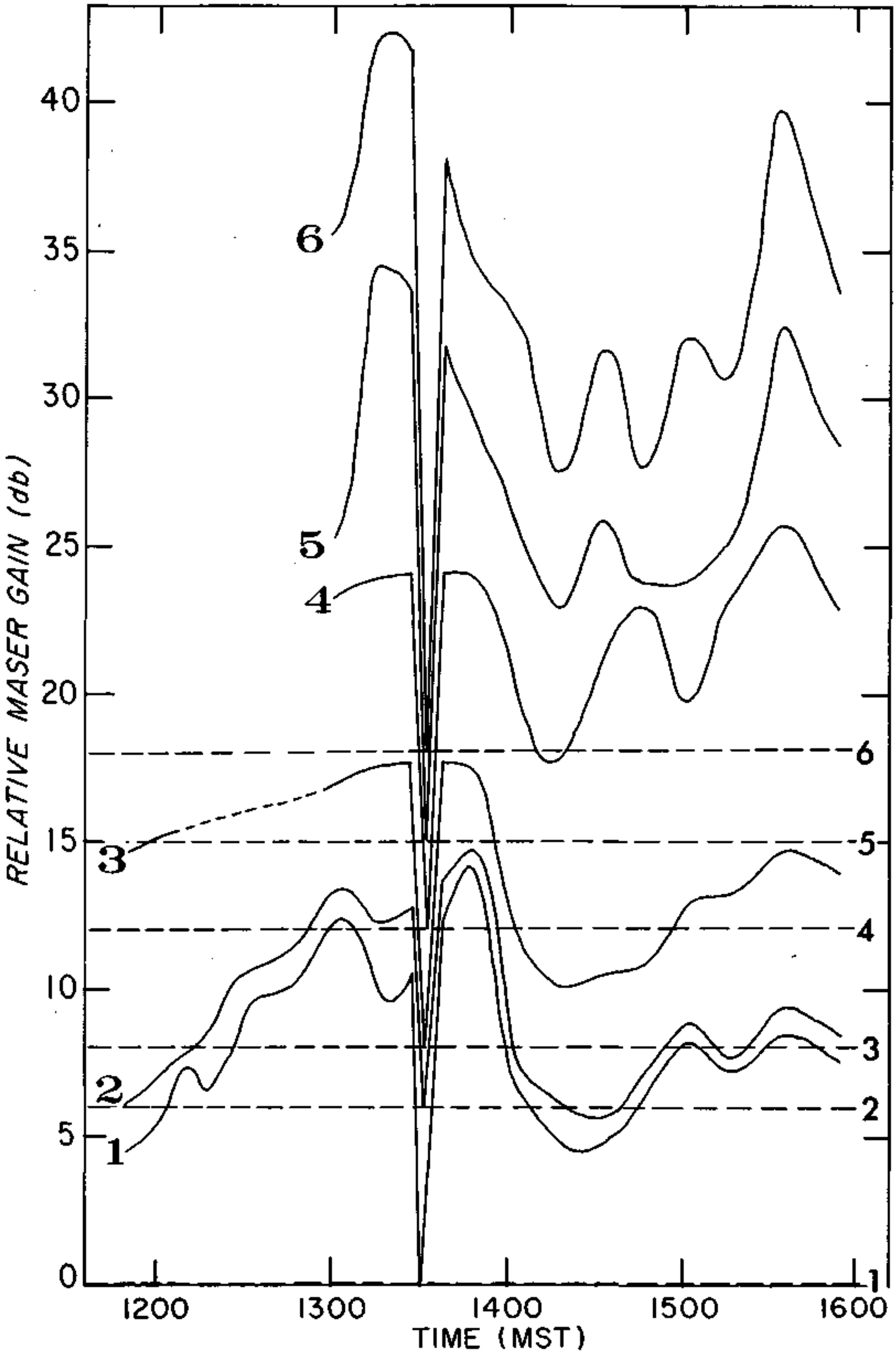


FIGURE 6. TIME VARIATION OF MASER GAIN AT SIX LEVELS OF IF SENSITIVITY ON 4 AUGUST 1966 IN ARIZONA. THE NUMBERS ON EACH CURVE CORRESPOND TO THE DASHED GAIN-STEP LINES OF THE SAME NUMBER

Another less quantitative example of maser gain variation may be presented from the cloud detection study on 31 November through 3 December 1966. During this period the radar was operated at a constant tilt angle of 75° on 6 n. mi. range with as many as nine receiver gain steps. On 3 December the maser was switched out of the system once each hour for several minutes and was also tuned for maximum gain by adjusting the maser magnet tickler current. Figures 7a, 7b, 7c, and 7d, 7e, and 7f are two sets of three photographs each taken to illustrate the changes in the maser gain during operations. The first photograph of each set is with the maser operating just before switching to normal receiver, the second is without the maser in the system, and the third is with the maser back on after adjusting the magnet tickler current. The first set of three is just before recharging the maser dewar with liquid helium (about 18 hours after the previous change), and the second set is about one hour after charging.

There appears to be little difference in the number and intensity of echoes on Figures 7b and 7e, indicating that the overall system sensitivity without the maser is approximately the same at each of these times. Comparing Figure 7a and 7c shows little difference, except that Figure 7c has slightly more echo than Figure 7a. Both Figures 7a and 7c seem to have more echo than Figure 7b, indicating that the maser was producing some gain.

The difference between the before-tuning and after-tuning photographs of the second set is quite apparent. The fact that the third photograph of the set has considerably more echo than the first indicates that, assuming the maser was properly tuned after the charging session, the maser gain did not maintain its maximum gain but degraded during the hour to some lower value of gain. The difference between 7c and 7f is attributed to better cooling after the filling. Apparently, even though there was liquid helium in the dewar before filling, the temperature of some of the rubies was higher because of the lower liquid level.

One conclusion that may be drawn from the foregoing discussion is that the maser, while producing sizeable increases in the echoes detected, does not maintain a constant gain; rather, it varies with time by quite sizeable amounts. The maser gain in the Flagstaff example both increased and decreased with a net increase during this observation time. The illustrations from the Illinois data showed the more expected variation, that of a decrease during each period. In order to make any meaningful quantitative measurements from the data at least one of the following would be required: 1) much more frequent measurements of receiver sensitivity, 2) a system for monitoring the receiver sensitivity continually, or 3) a maser whose gain is constant over longer periods of time than the maser presently on the AN/MPS-34. The first is probably unsuitable for any operations other than for research. The second, while possible for some modes of operation, was not possible for all modes of operation with the. test equipment that was available. The third alternative is certainly the most desirable to achieve even if improved calibration techniques are used.

Summation of Engineering Problems

Basically, the operation of the maser radar was plagued with an unstable maser amplifier and by the installation of "laboratory-engineered" equipment in a "field" system.

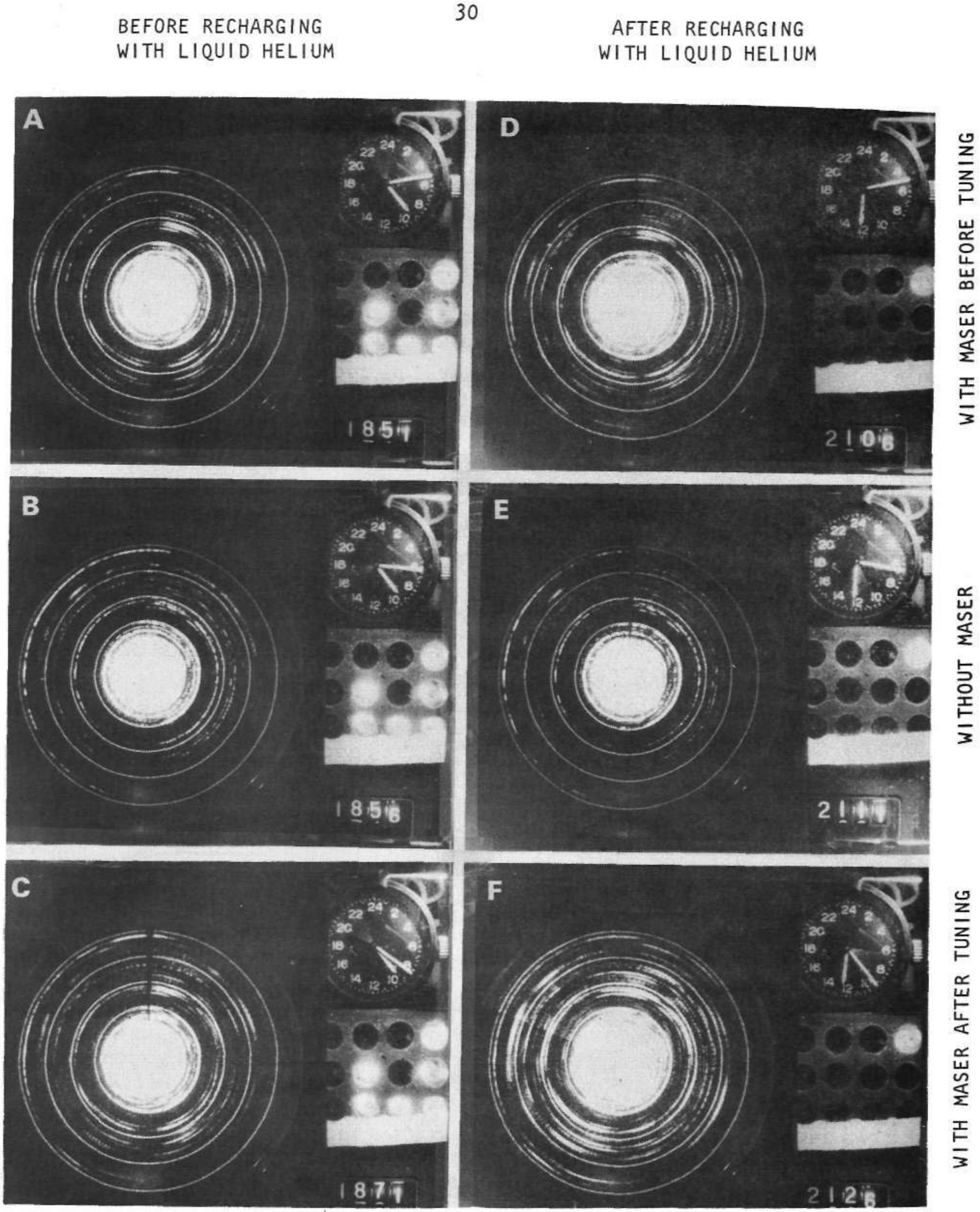


FIGURE 7. VARIATION OF MASER GAIN AS INDICATED BY VARIATION OF GROUND TARGETS ON 3 DECEMBER 1966 AT 75° TILT WITH 1 N.MI. RANGE RINGS

1. The unstable maser seemed to be associated with three problems:

a) The desired operating point (as fixed by the magnetron frequency) was at a magnetic field strength greater than the magnet was capable of providing. While it could be pulsed to the correct point, this was not a stable point and the strength began decreasing immediately. As a result, the only stable operating mode was to use the magnet at its highest stable magnetic field strength and add the required magnetic field by a trimming current through the electromagnet. This trimming current added heat to the system and caused a more rapid loss of liquid helium.

b) The maser magnet and rubies would not stay oriented with respect to each other for maximum gain. The reason that the magnet became misaligned is not understood, but it is assumed that thermal cycling caused the locking mechanism to loosen. After 1 or 2 weeks of operation, the magnet required alignment. When the maser was disassembled, the screw which locks the magnet in its angular position was found loose.

c) The dewar is a single fluid type. To quote the instruction manual (Anon., 1962): "The helium cavity and the dewar neck form a re-entrant type of cavity in which the wall temperature is essentially constant throughout. As a result, the liquid does not contact 'hot' areas within the dewar with subsequent boil-off regardless of the position of the dewar. This feature, plus the single-fluid type dewar, allows the maser to operate in any position," Unfortunately, this description proved highly inaccurate. If the antenna was not tilted, the maser dewar would, as stated, hold a charge for at least 24 hours in which the bottom sensor remained in liquid helium. However, tilting of the antenna which tilted the maser dewar warmed the maser sufficiently to cause it to lose its net gain, and from the violent boiling-off of helium gas, it was apparent that the liquid helium was contracting "hot" spots. Furthermore, it was observed that there was a temperature gradient between the top and bottom temperature sensors. This gradient was observed to start almost immediately, after the charging of the maser dewar and to increase somewhat proportionally to time elapsed and to the amount of tilting,

2. The maser installation was undoubtedly a temporary one and several problems occurred due to inadequate weatherproofing of the maser components,

3. Under certain weather conditions missing waveguide windows and waveguide switches that were not weatherproofed permitted condensate to form in the waveguide, necessitating disassembly and drying of waveguide components. Also, the formation of condensate on the flange block of the maser during cryogenic transfer was a continual problem. Under high humidity conditions, this would result in wet cable connections. After a few cooling cycles, the maser mica used in the waveguide windows cracked and allowed condensate to form inside the waveguide.

4. The box containing the pump klystron power supply and controls leaked, causing a few pump klystron power supply failures. In this case, small problems became quite time-consuming because the components were packed away in inaccessible packages, subjected to uncontrolled humidity, and cycled through extreme temperature

ranges. This equipment might operate satisfactorily in a "test bench" setup but it needs more reliability engineered . into its sub-units before it is suitable for a prolonged field operation,,

5. The maser amplifier is a very interesting addition to a weather radar and should be investigated completely using a stable maser, preferably with a closed cryogenic cooling system. Experience indicates that integration techniques are necessary to utilize the tremendous gain available from a maser amplifier. If film and scope integration are to be utilized as a recording method, the scope and photographic techniques will require rigid standardization. Also, the receiver performance should be checked by the measurement of the noise figure of the receiver. A visual observation of the MDS is much too subjective to achieve a true performance check of a high gain receiver that is operating in the region of limiting antenna thermal noise.

Radar Comparison

A comparison of two approximately equivalent radars is given in Figures 8a-8d. Figure 8a shows the AN/MPS-34 with the maser as depicted on 80 nautical mile range PPI. It will be noted that there was anomalous propagation of ground clutter to the west-southwest to the edge of the scope. Precipitation echoes are scattered to the east and in a line to the west-northwest as well as a group of echoes centered approximately 30 miles west of the station. Figure 8b also shows the AN/MPS-34 radar 2 minutes later, but on the 200 mile range. It will be noted that there are additional precipitation echoes in all quadrants. In addition there is interference evident from the AN/CPS-9 radar 1/4 mile to the north. The comparable pictures from the AN/CPS-9 radar are shown as Figures 8c and 8d. Obviously, the AN/CPS-9 has much less sensitivity and has detected much less echo at all ranges even though it is mounted approximately 35 feet higher than the AN/MPS-34. The
* AN/CPS-9 was operating at a power ratio of,-163 db while the AN/MPS-34 was operating with a power ratio of -194 db including 6 db maser gain. This is a difference of 31 db for the two radar sets. Both radars were operating on long pulse. This is the only example available for comparison since the CPS-9 was not being operated routinely during this contract period.

Fair Weather Conditions

During the operation of the maser radar a search was made for echoes of an unusual nature or from unusual sources in both the real-time operations and after the fact in the time-lapse movie data. Two types of echoes of an unusual nature have been found and the reason for failing to detect others was investigated.

Bird Detection. Echoes which were deduced to be birds were detected both, in New Mexico during the 1965 operations and on 16 May 1966 in Illinois. These are reported in Quarterly Reports 3 and 5 and in the paper on bird detection presented at the Twelfth Weather Radar Conference. Since this paper is not in the Proceedings of the Conference, it has been included as Appendix I of this report. It summarizes the results of birds detected from New Mexico and Illinois. The New Mexico results were obtained without the use of the maser. The use of a maser

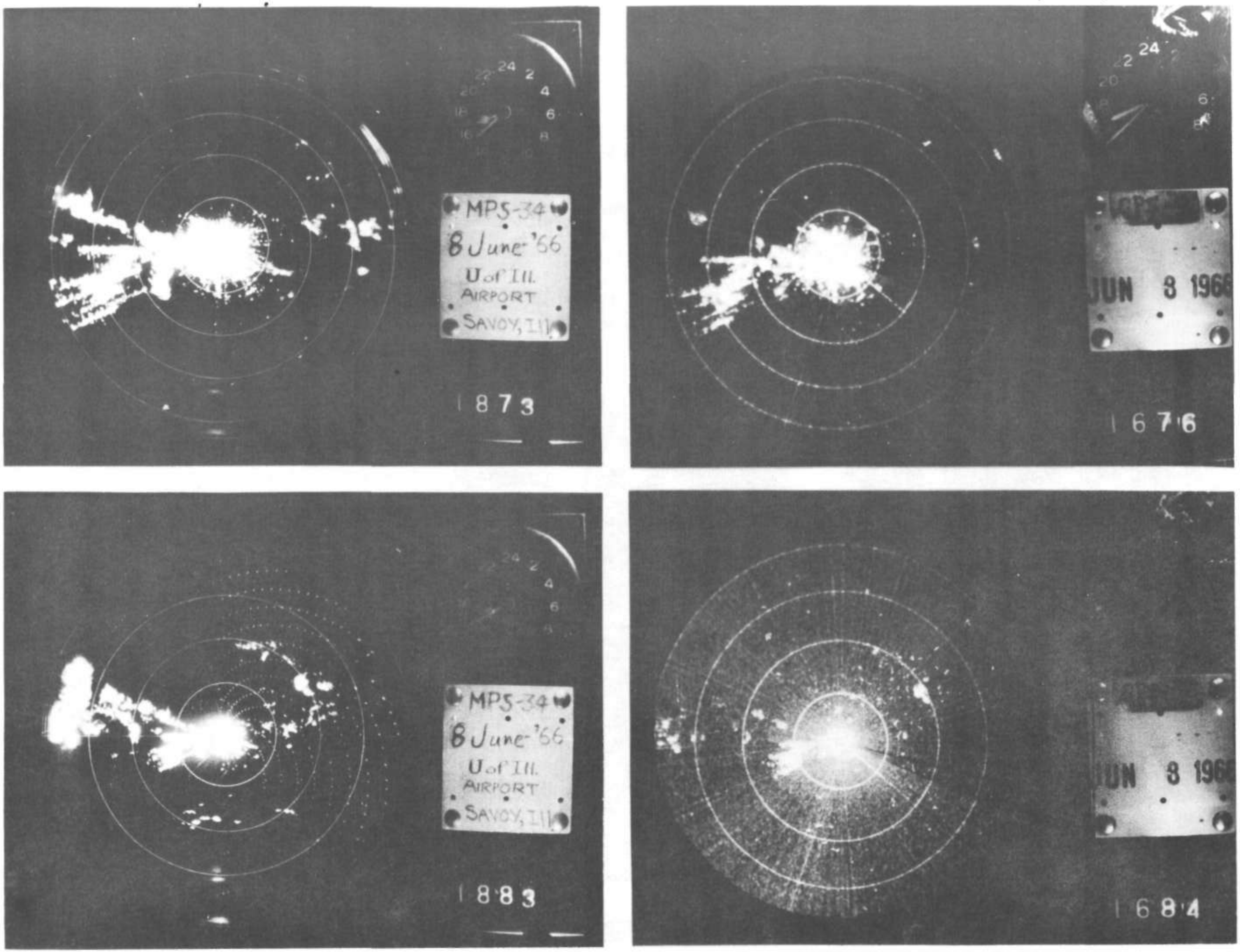


FIGURE 8. COMPARISON OF AM/CPS-9 AND MASER-EQUIPPED AN/MPS-34 ON 8 JUNE 1966 IN ILLINOIS (20 N.MI. RANGE RINGS)

with 12 db gain should have increased the maximum range of detection of these point targets by a factor of two. Thus, birds with weights on the order of 1. ounce would have been detectable with the maser to 18,n. mi. during the New Mexico operations. Larger birds, of course, would be seen somewhat farther. Birds of 1 pound weight should be detectable to ranges of about 25 n, mi.

Thin Line Detection. A second type of unusual echo was detected during the Flagstaff operations. This was a single thin line which passed directly over the radar about 1440 MST on 2 August 1966, The thin line resulted from the cold outflow of a large cumulonimbus echo about 10 miles east of the radar. Although it originated in a precipitating system, it produced no apparent rainfall in its passage over the radar and is thus included as a fair-weather anomaly.

The thin line had an average length of 9 n. mi., an average width of 3/4 n. mi., a maximum height of 6500 ft. above the radar, and traveled at an average speed just over 8 knots. It reached its peak speed of 15 to 18 knots just as it passed over the radar and was at its largest dimensions (14 n, mi. length and 2 n. mi. width) about 8 minutes later. The winds at the radar site increased during the thin line's passage from an average of 5 knots to an average during passage of about 12 knots with a peak gust of 23 knots. The temperature dropped 6F while the humidity rose from 28 percent to 42 percent during its passage.

The echo from the thin line was incoherent in nature and had characteristics similar to those from precipitation echoes. It produced echoes which showed up with 24 db attenuation in the receiver gain control, so it would have been easily detectable without the maser at the close ranges encountered. Based on echo strength alone, it could have been detectable at ranges beyond 400 n. mi. The actual maximum range would probably be something less than 100 n. mi. because of earth's curvature. It probably would be even less because the line ceases to be a beam-filling target vertically at 60 n. mi. and, if aligned with a radial orientation, it ceases to be a beam-filling target horizontally at 40 n. mi. (for average width). In addition, if it were beyond 20 n. mi. the VE repeater would have been operated on a scope range longer than the 20 n.,mi. range used, the; echo would be smaller on the scope, and its characteristic shape would be much less evident.

Insect Detection. Angel-type echoes due to insects were not known to have contributed any echoes during the period of this contract. Glover et al. (1966) give the back-scattering cross-sectional areas of a winged hawkmoth and a honey bee measured in flight. The back-scattering cross-sectional area for the moth averaged near 1 cm^2 with a maximum of about 10 cm^2 while that for the bee averaged near 10^{-3} cm^2. With the MPS-34 radar having an MDS of -113 dbm, the moth should on the average be detectable to a range of 9 n. mi., while the bee should be detectable to only 1.8 n. mi., Under normal operating conditions of low tilt angle and scope ranges, generally 25 miles or longer, it is very unlikely that any insects would be observed in the data or on the scope. With ideal conditions it is possible that large insects might be detected, but this has not been verified experimentally with the MPS-34.

Clear-Air Turbulence; A fourth potential source of echoes during fair weather is clear-air turbulence (CAT). Atlas et al. (1966) have investigated experimentally and theoretically the reflectivity produced by CAT. They found that for 3-cm wavelength radars, the reflectivities from severe, moderate, and weak CAT are 10^{-15}cm^{-1}, 10^{-16}cm^{-1}, and l0^{-17}cm^{-1}, respectively. The minimum detectable reflectivity for the MPS-34 is about 6.5×10^{-12}cm^{-1} when the MDS is -112 db and the distance is 10 n. mi. This is a difference of 38, 48, and 58 db, respectively, between the MPS-34's capability and the signal from severe, moderate, and weak CAT. Thus, based on theory, the MPS-34 will not detect CAT. It is interesting to note that while Atlas el al. were able to detect CAT on one occasion with their 10-cm and 72-cm radars, their 3-cm radar lacked 6 db of being capable of detecting severe CAT. An antenna with a diameter greater than 10G ft. would be required to detect weak CAT with the maser-equipped MPS-SU,

Vertically-Pointing Radar. One of the desired aims was to test the maser-amplified AN/MPS-34 for its ability to detect clouds not detected by other radar sets. Chanute Air Force Base has in operation an AN/TPQ-11 radar designed for cloud base and top detection operating at a wavelength of 0.86 cm. This radar was in operation from 0700 CST until 2300 CST of each day of data collection with the AN/MPS-34 radar. Thus, there is a simultaneous record with breaks for the two radars from 1700 CST on 30 November 1966 until 3 December 1966 at 1030 CST. The TPQ-11 was removed from service at 1030 CST on 3 December because there were no clouds to observe. The MPS-34 radar was out of service for two periods, once each day, for the refilling of liquid helium in the maser dewar.

The weather included the passage of a cyclone south of the two stations with the data collected from the time that altocumulus clouds were overhead through a period of light snow to the clearing of the sky in the continental arctic air mass.

The MPS-34 antenna was fixed to rotate with the vertical axis 15° from the zenith so that a cone of 15° radius was sampled. This configuration permits the sampling of more clouds than would be sampled by a zenith-pointing radar. Rearrangement of the waveguide connections was necessary to permit the mounting of the maser dewar in an upright position with the antenna at this high angle to avoid a loss of maser gain and excess use of the liquid helium as noted elsewhere in this report.

It was quickly noted that the side lobe return of surface echoes seriously interfered with the determination of cloud echo returns to a height of nearly 30,000 feet. This ground clutter made the detection of cloud echoes extremely difficult.

The Chanute TPQ-11 is located approximately 15 miles NNE of the MPS-34- radar limiting the correspondence to be expected between the two radars since it is not likely that exactly the same configuration of clouds would be present over the two radars at the same time. The corresponenee and detection turned out to be quite good since echoes were observed on the MPS-34 at the same times and to the same heights as were detected on the TPQ-11. However, as noted above, in most cases the same heights were masked by the ground clutter on the MPS-34. Figure 9 is a graphical illustration of the echoes as observed by the two radars. It will be noted that the TPQ-11 appears to have detected as many clouds as did the MPS-34. In one instance a cloud was detected by the MPS-34, but not by the TPQ-11;

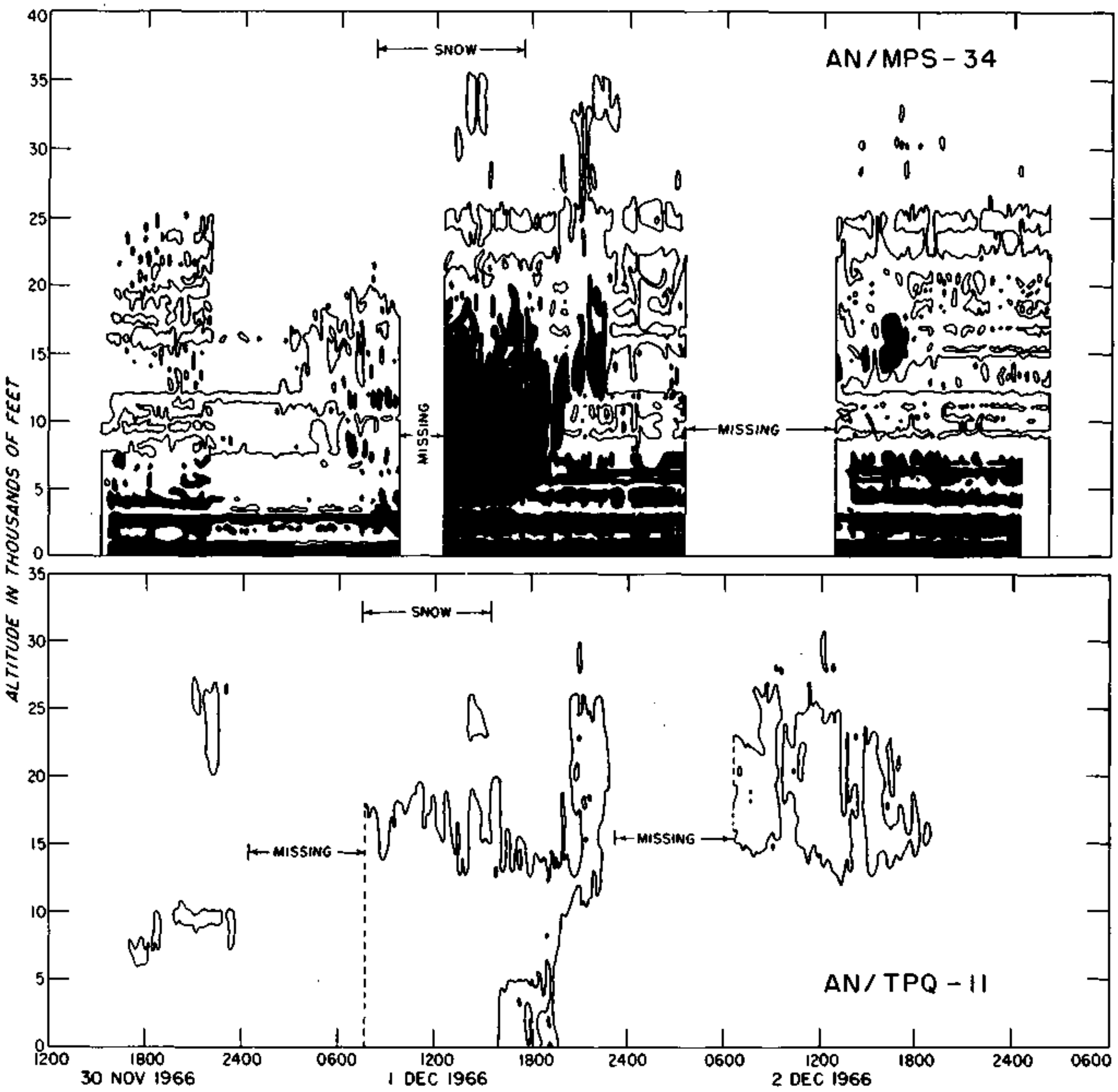


FIGURE 9. COMPARISON OF CLOUD DETECTION BY THE AN/MPS-34 AND AN/TPQ-11 RADARS

this appears to have been a cirrus cloud occurring during the time the snow was reaching the surface on 1 December 1966. It seems possible that the 0.86 cm radiation was attenuated by this precipitation, whereas the 3.2 cm radiation was not.

The depiction of the echoes received by the MPS-34 radar, as shown in Figure 9, not only shows the maximum detectable signal as the maximum outline of the echoes, but also shows the echo observed on stepped-gain at approximately 11 db reduction from maximum sensitivity. This gain reduction should correspond approximately to the difference in gain between the MPS-34 radar without the maser and the radar with the maser.

Of gravest concern is the fact that the cloud echoes are obscured by the side lobe ground clutter when the maser is in best operating condition, as evidenced by the echoes observed after 1200 C on 2 December 1966. From the broadening of the echoes before 1900 C, it could be assumed that clouds were being detected, but a clean indication of cloud boundaries cannot be found because of the ground clutter which should be the only echoes present at the end of the time illustrated in the figure at 0200 C of 3 December 1966. This assumes that there were no bird or insect targets during this collection period since the temperature at the surface was between 8° and 20°F which should be too cold for insects. If present, most migratory birds would have been seeking shelter from the cold. In private conversations with Frank Bellrose of the Illinois State Natural History Survey, it was determined that there was the possibility that geese and ducks were migrating on November 30 through the 3rd of December of 1966. However, geese would not have been flying over 2,000 feet above the surface and ducks would not have been flying above 5,000 feet. There is a species of goose, the snowgoose, which has been known to fly as high as 25,000 feet on rare occasions; however, these geese were known to have migrated much earlier than November 30 since their nesting grounds are much farther north and freeze much sooner than November 30. Since these echoes were continuous in time between 5,000 and 25,000 ft. indicated, it is not thought that they were due to birds or insects.

By considering the reported reflectivities of clouds, their maximum range of detection may be determined. Ignatova et al.,(1966) have experimentally measured reflectivity factors from cirrus (Ci), altocumulus (Ac), altostratus (As), stratocumulus (So), and nimbostratus (Ns) clouds. These are listed in Table 4. The maximum range of detection for the corresponding reflectivity factors are also listed in Table 4. These are based on a receiver MDS of -113 dbm, a peak power transmitter of 84 dbm, an antenna gain of 36.2 db, and short pulse operation.

From Table 4 it would appear that the maser-equipped MPS-34 should easily detect all nimbostratus clouds; in fact, there is little question about the detectability of any precipitating cloud system. Altocumulus, altostratus, and stratocumulus clouds of average reflectivities should be detectable fairly easily much of the time. However, for these and cirrus clouds to be generally detected, the radar would need to be operated at relatively large tilt angles. Ac and As of average reflectivity at 10,000 feet would require a tilt of at least 6° to be detected, while Ci at the same height would require a tilt of 44°.

Table 4. Radar reflectivity factor and corresponding maximum range of detection for various cloud types

	Minimum Z		Average Z		Maximum Z	
Cloud Type	Z (mm^6 m^{-3})	$r_{max.}$ (n mi)	Z (mm^6 m^{-3})	$r_{max.}$ (n mi)	Z (mm^6 m^{-3})	$r_{max.}$ (n mi)
Ci	5×10^{-3}	0.72	5×10^{-2}	2.3	5×10^{0}	23
Ac, As	5×10^{-4}	0.5	5×10^{-1}	16	5×10^{1}	160
Sc	5×10^{-3}	1.6	5×10^{-1}	16	5×10^{0}	50
Ns	5×10^{-1}	16	5×10^{1}	160	5×10^{2}	500

The maximum range of detection for strong Ac, As, and Ns clouds is unreasonable because earth's curvature and beam filling again combine to limit the useful range of detection. The practical limit is about 100 n. mi. for Ns of 7,000-ft. tops. Ac and As with maximum dimensions of 5,000 feet (diameter or thickness) cease being beam-filling targets at distances greater than 57 n, mi. and are therefore less likely to be detected beyond this distance.

Now, how do these values of Z and r_{max} compare with the clouds detected in December 1966? First, the values of r_{max} are not really comparable because r_{max} did not seem to be limited by reflectivity. The comparison between the TPQ-11 and the MPS-34 indicated that the MPS-34 was very likely seeing all the clouds that were there. There is also an uncertainty in the reflectivity factor calculations caused by uncertainties in measuring P_r and P_t. However, since $Z \alpha \frac{P_r}{P_t}$, errors common to P_r and P_t cancel such that this uncertainty might not affect the results. With this in mind, the reflectivity factors that were found are given in Table 5.

The decrease with height of $\overline{Z}$ may be explained by the fact that snow was falling some of the time during the period. This would increase the reflectivity of the lower levels more than the upper levels because the snow crystals and flakes grow during their descent, thus increasing the reflectivity near the ground, $\overline{Z}_{Ns}$ does not show the same profile but rather has its maximum near 15,000 feet. This agrees very generally with the average height of clouds detected by the TPQ-11 for the same period as illustrated in Figure 9. It should be noted that, although this period is classified as a no-snow period, there was some very light snow occasionally.. However, visibility was always at least 10 miles. One additional point that should be made is that the reflectivity factors in Table 5 are averages and do not represent instantaneous profiles through individual clouds.

Table 5. Average reflectivity factors at 5000-ft intervals between 0620 CST on 1 December and 0020 CST on 2 December 1966

H	5,000	10,000	15,000	20,000	25,000
r	0.85	1.70	2.55	3.40	4.25
$\overline{Z}$	5.2×10^{-1}	3.0×10^{-1}	1.8×10^{-1}	6.2×10^{-2}	3.8×10^{-2}
$\overline{Z}_{Ns}$	1.4×10^{-2}	4.3×10^{-2}	1.5×10^{-1}	6.0×10^{-2}	3.5×10^{-2}

H = Height (ft)
r = Slant range (n, mi.)
$\overline{Z}$ = Average reflectivity factor (mm^6m^{-3})
$\overline{Z}_{Ns}$ = Average reflectivity factor (mm^6m^{-3}) during period of no snow (1800-2400 CST)

As a point of interest in a consideration of cloud detection with a sensitive radar, Braham (1966) has detected ice crystals in cloud-free air 13,000 feet beneath cirrus uncinus clouds at 35,000 feet. He reports concentrations of 10^6 crystals/m3. If these crystals average 100µ in diameter, the reflectivity factor from this would be on the order of 1 mm^6 m^{-3} and would have been easily detectable by the MPS-34 as it operated during the cloud study. Of course, the crystals could also have been detected and displayed by the TPQ-11.

There was one observation during the cloud study which perhaps indicates something about the capability of the MPS-34 in a "clear-air" situation. At 0130 CST, 2 December 1966 while tuning the maser atop the radar, a weak, fluctuating signal was observed on the A-scope at approximately 3 n. mi. (32 microseconds after the transmitted pulse). This signal was quite different from the ground clutter display at the same time. Careful observation of the sky revealed a very thin layer of cloud passing in front of the moon. It was not visible as an obscuration of the stars but only as it passed over the face of the moon. This was rather surprising in that to all casual appearances it was a clear sky with distinct shadows cast by objects in the moonlight. An attempt was made to find this echo later in the time-lapse movie data, but it was not detectable. Also, later visual observations with special emphasis on looking for similar clouds near the moon revealed none. Apparently, the cloud (and echo) observed was transient above the radar, not lasting until the tuning could be completed and the recording camera turned on.

Experience gained during this cloud echo detection experiment indicates the need for tuning the magnet tickler current for maximum signal at least once each hour. This was performed for the data collected from 1245 C of 2 December until the end of the data run, but only occasionally was this performed prior to this time. It will be seen on Figure 9 that the data collected on 30 November does not have the extent of echo with height indicated on 2 December. The performance check on the system made after 0930 C of 1 December noted that the maser gain was less than one. In other words, the radar would have been performing better had the maser not been in the system. Experience also showed that magnet tickler current had to be substantially increased during the time of operation., This continued until the amount of heat being added to the magnet caused the maser to deteriorate in performance as well as boiling off an excessive amount of liquid helium. It is our understanding that the maser magnet was not always this unstable before receipt of the equipment by the Water Survey.

Fog. No fog occurred during the periods of operation of the MPS-34, so that no experimental determination of the advantages of using the maser for fog detection can be made. However, consideration of reported characteristics of fogs may be used to give some indication of what results might be obtained when it is used for fog detection.

Byers (1965) summarizes the results of several researchers' reports of cloud and fog characteristics. A typical median droplet diameter might be 10μ for the fogs reported. Droplet concentrations and liquid water contents for the fogs were not given but those for non-precipitating stratus clouds were. A concentration of 200 drops/cm3 and a liquid water content of 0.25 g m^{-3} are probably representative.

Atlas (1954) reports the following equation for calculating radar reflectivity factor Z ($mm^6\ m^{-3}$) from clouds when the liquid water content M ($mg\ m^{-3}$) is known: $Z = 4.8 \times 10^{-8} M^{2.0}$. This results in a reflectivity factor of $3 \times 10^{-3}\ mm^6\ m^{-3}$.

Using $Z = \Sigma N_i D_i^6$ and assuming all the fog droplets have the median droplet diameter, $Z = 2 \times 10^{-4}\ mm^6\ m^{-3}$. Mason (1957) quotes a median volume diameter for sea fog of 46u. This would result in a Z (when the concentration is again 200 drops/cm^3) of nearly $2 \times 10^0\ mm^6\ m^{-3}$.

The variation in these values is fairly large, but they do generally agree with the Z's from stratocumulus reported by Ignatova in Table 4. The average value determined above for fog is lower than that for average Sc. Kulikova (1965) reports reflectivity factors from fog as low as $1.8 \times 10^{-7}\ mm^6\ m^{-3}$ with his average being $4 \times 10^{-4}\ mm^6\ m^{-3}$. (Kulikova, however, defines Z as

$$Z = \Sigma N_i r_i^6 \left[\frac{m^2 - 1}{m^2 + 2} \right]^2$$

as opposed to the conventional definition of $Z = \Sigma N_i D_i^6$. His values should be about 69 times smaller than those calculated from the same drop-size spectra using the latter equations.)

If a value of $5 \times 10^{-3}\ mm^6\ m^{-3}$ is used for the reflectivity factor for fog, the maximum range of detection would be 1.6 n. mi. (as for weak Sc clouds). The sea fog reported should be detectable to 31 n. mi.

It appears unlikely that the MPS-34 would be useful for fog detection for two reasons. First, the reflectivities from fog are generally so low that it should not be detectable to very great distances. Second, by definition fog is at the ground. In east central Illinois, ground clutter is a problem at all tilt angles to ranges from 5 to 25 n, mi. Elsewhere the extent of interference might be less, but the effects are still likely to be appreciable in most cases.

Precipitating Weather Systems

Attenuation Effects . The only opportunity for the measurement of precipitation attenuation occurred with dry snow which has so little attenuation as to be impossible to measure with the instrumentation available on this contract. Whereas attenuation blocking by heavy thundershowers has been observed on the AN/CPS-9 in Illinois, it was not observed on the few occasions of thundershowers when the maser radar was operated in Illinois. Many more thundershowers were observed in Arizona and New Mexico, but on no occasion was attenuation observed qualitatively. This is not to say that attenuation does not effect the maser radar, but that attenuation did not have the dramatic effect sometimes observed on less sensitive 3-cm wavelength radars.

Lightning. The time-lapse movies of the PPI available from the observation of thunderstorms in Illinois, New Mexico, and Arizona were reviewed for possible lightning detection as it has been observed on the PPI scopes of longer wavelength radars. No lightning was observed. No attempt was made to detect lightning by the method suggested by Ligda (1950), i.e., by aiming the antenna toward a lightning-producing storm and looking for lightning-produced radiation on the A-R scope.

Severe Local Storms. No severe local storms; such as, large hail or tornadoes occurred on operational days of the radar.

Snow Detection. As reported in Quarterly Report No. 5 under this contract, data were collected on the detection capability of the maser radar during a period of widespread moderate to heavy snow. Little information has been given in the literature on the response of a radar to snow. Langille and Thain (1951) first . reported an experiment to correlate the signal power returned from falling snow to the accumulation of snow on the ground. He found that snowflake measurements resulted in the same Z-R relationship for snow that Marshall et al. (1948) had found for continuous rains, $Z = 200R^{1.6}$.

Lillesaeter (1965) investigated the attenuation of visible light by falling snow and rain. The attenuation by snow appeared to be proportional to the rate of snowfall and, obviously, with distance. For dry snow the attenuation was approximately 18 db km^{-1} per mmw hr^{-1} where mmw is the water equivalent in millimeters of the melted snow. Of greater importance to this investigation was the finding that the visual range varies inversely as the rainfall rate, and is 1 km when R is 1 mmw hr^{-1} with the constant of proportionality being 1. Although these figures are a factor 2 from those used in Quarterly Report No. 5, the difference is very slight. The major lack of correlation is found in the cases of echo-no precipitation and no echo-precipitation.

On the same dates the snow accumulation on the East Central Illinois Network was measured in the 25 weighing-bucket gages in operation. This accumulation was related to the reflectivities as measured by the maser radar. A correlation coefficient of 0.18 was found. The poor correlation was caused by two factors not related to the radar; these are the inability of the gages to properly measure snowfall and the very small range of snowfall rates measured which magnifies the differences observed.

Conclusions

The maser amplifier has been found to perform as the theory for low-noise amplifiers predicts when used as an RF amplifier with the AN/MPS-34 weather radar. The maser was found to add from 10 to 13 db additional gain to the radar receiver under optimum operating conditions. The maser can be most effectively used with a radar which has less normal receiver gain than has the AN/MPS-34 since the added sensitivity causes the radar to display the thermal noise available at low antenna angles. However, for specialized studies which may not require that the antenna be scanning the horizon, the additional gain is realized and could be very useful. For those specialized studies such as the detection of cloud boundaries and thermal bubbles, additional gain would be desirable.

It was found that the present maser was unstable for field use, partly because of damage sustained in shipment and partly because of the instability of the maser magnet. In addition, it was found that the stability of the alignment of the maser rubies was poor, probably because of the alternate contraction and expansion of the metal as the maser was allowed to warm and cool again.

The fact that the maser-equipped MPS-34 does detect thermal noise from warm, attenuating objects scanned by the antenna raises the possibility that this property may be adapted to a system for determining the amount of attenuation occurring at 3-cm wavelength from precipitation. Thus, with the amount of attenuation measured by the radar acting as a radiometer, an attenuation correction could be applied to the incoming radar signal with considerable confidence that the correction would be appropriate. The amount of noise received by a radiometer is a function of the attenuation of the radiating object and the temperature of the object. The temperature of the raindrops will be the wet-bulb temperature of the ambient air. This will vary from 273°K to approximately 290°K, a percentage change of less than 4 if an average value of 280°K is chosen. The Dicke (1946) radiometer is suggested as a useful system.

The appropriate equations are

$$G = KT\Delta f$$

and

$$T = t(1-e^{-a})$$

where G is the noise receiver by the antenna, in watts, K is the Boltzmann constant (1.38×10^{-23} joules K^{-1}), T is the effective temperature in °K sensed by the antenna, f is the bandwidth of the receiver, t is the wet-bulb temperature of the rain in °K, and a is the attenuation in nepers. The attenuation, a is equal to $\alpha \ell$ where α is the absorption coefficient and ℓ is the length into the absorbing medium. Point to point attenuation is indeterminate; thus, only the total attenuation over the radar ray path will be known.

The noise power received by the antenna is found by eliminating T from the two equations,

$$G = Kt(1-e^{-a})\Delta f.$$

In this expression all quantities are known or measurable except a. Since the signal from the maser, in the Dicke radiometer, is referenced to a constant attenuation, some instability in the maser can be tolerated.

SUMMARY

The present APMI and maser system for increased radar sensitivity are not ready for field use. A number of recommendations are made to improve the quantizing of the radar weather signals. The increased sensitivity of a radar is desirable for certain meteorological applications if the operating logistics can be simplified. The study suggests that precipitation attenuation at 3-cm wavelengths might be resolved through measurement of the thermal noise from precipitation. Specific details were given in the body of the report.

APMI

The Area Precipitation Measurement Indicator (APMI) was found to have a number of circuit errors which probably made it incapable of performing as intended. One of these was noise introduced by coincident pulses permitted by the asynchronous timing. Many of the transistors were found to be mechanically broken or electrically inoperative.. A means of photographing the display scope with a 16-mm camera was devised. Data were collected using this system for one storm. These storm data were used to evaluate the operation of the APMI. The data are believed to be unreliable for correlation with rainfall intensity. Modifications were made to the circuitry where major changes were not required. These modifications were made with the idea of retaining the basic philosophy for the design of the APMI.

It is recommended that integration in the APMI should be accomplished with a contiguous range interval pulse integrator with not less than 1-mile range resolution and 2-beam width azimuth resolution. The advantages and disadvantages of analog and digital integration are given with the indication that analog integration is somewhat preferable. It is recommended that the operator should have some indication of the position of the radar on his digitized display scope plus several reference points to indicate azimuth and range. These references could be electronic crosses. The merits of polar coordinate and rectangular coordinate display systems are discussed. Both systems have several desirable characteristics and no specific recommendation is made as to which system is preferable. It is proposed that an orderly listing of the azimuth, range, and intensity of targets be presented next to a standard non-digitized radar display. This would have the advantage of presenting the operator with the information available from a standard PPI or RHI in all its detail with a ready reference nearby to help him interpret the data.

Recommendations are made for means of calibrating the APMI, both for total radar APMI system calibration and for internal checks of the APMI.

With a look to the future, recommendations are made for the inclusion of a number of useful additions to the APMI. These are a means of integrating the instantaneous APMI output to obtain precipitation amounts over various time periods, a means of retaining earlier APMI display data for reference so that the operator may make decisions as to future movement, and a superimposed display of both the PPI and the intensity information. A switch should be provided so that the operator may select the intensity level to be displayed.

MASER

The maser-equipped AN/MPS-34 radar has been used for the detection of echoes from various sources in Illinois, New Mexico, and Arizona. The availability of a high-gain amplifier such as the maser results in unique problems involving the detection of thermal noise radiated by external objects into the radar antenna. This thermal noise problem is discussed with reference to its effect upon the detectability of weather echoes.

The operational problems involved in keeping the maser in tune and at a constant high-gain are discussed. It was found that the maser dewar is not capable of keeping the maser rubies at 4.2K at tilt angles above 45°, thus limiting the usefulness of the radar in detecting phenomena above this tilt angle.

It was found that the stability of the maser gain was highly variable, failing to remain constant from one hour to the next. This is thought to have been caused by an unstable maser magnet. It also was found that the alignment of the maser rubies was unstable and required frequent adjustment. This was probably due to the thermal expansion and contraction of the equipment in cycling from liquid helium to atmospheric temperatures.

The detection of echoes of birds in New Mexico and a thin-line phenomenon in Arizona are discussed. The possibility of detecting insects and clear-air turbulence is reviewed and found that the gain, even with the maser amplifier, is insufficient for this purpose.

The radar antenna was pointed at an angle of 75° from the horizontal, and the maser amplifier was remounted to permit it to continue to operate efficiently for the detection of clouds over the radar. The echoes from the MPS-34 were compared with the echoes observed by an AN/TPQ-11 radar at Chanute Air Force Base, It was found that the detection capabilities of the two radars were quite comparable with a possibility that the MPS-34 was somewhat more sensitive. However, side-lobe suppression on the MPS-34 is insufficient to eliminate the detection of ground clutter within 5 miles of the radar site. Since this range corresponds to an altitude of 35,000 feet, the effectiveness of the MPS-34 as a cloud detection device is severely limited.

Although no fog was observed by the radar, it was determined that light fog should be detectable to approximately 1.5 n. mi. and heavy fog, to 31 n. mi. However, in central Illinois these distances are essentially within the ground clutter pattern of the radar and would, therefore, severely restrict the use of the radar as a fog detector.

Quantitative measurement of attenuation effect was made in a dry snow which should have essentially no attenuation at this wavelength. Other effects such as the inability of precipitation gages to properly measure snow overshadowed any attenuation effect which might have been present. During one wintertime data collection period, the. ability of the maser-equipped radar to detect snow at various ranges was measured. It was found that the detection of snow was a strong function of the range between the radar and the observed point. This is thought to be caused more by the lack of sufficient height of the storm clouds rather than by the ability of the radar to detect the precipitation. There was one attempt to correlate the radar echo from snow with the snow falling in the gages of the East Central Illinois Raingage Network. It was found that there was a very poor correlation, probably because the raingages are very inefficient snow gage devices.

The possibility that the detection of thermal noise from precipitation might be used as a means of determining the amount of attenuation in precipitation at 3-cm wavelength is discussed. This seems to be an accurate and unique method for correcting for the partial loss of signal by the 3-cm radar and could resolve most of the criticism of the use of 3-cm radar in quantitative precipitation measurements.

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APPENDIX

RADAR DETECTION OF BIRDS IN NEW MEXICO

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1. INTRODUCTION

Birds have been observed on radars by several researchers, and reports of these are found in the literature of the past few years (see, for example, Richardson et ale, 1958). This paper reports the detection of relatively large numbers of echoes which are concluded to be bird echoes during a field project near Magdalena, New Mexico, with an AN/MPS-34 X-band radar. The radar was equipped with a maser RF amplifier which, however, was not used for the collection of most of the data used in this study.

When the echoes were first observed on the scope their source was not readily determined. Nothing unusual was within view of the observers. It was not until viewing the time-lapse radar movies that the motions of the targets were measured and their apparent cause determined. The radar was generally operated near 15° tilt to avoid ground clutter detection from mountains in the area. The resulting absence of nearby ground clutter echoes made it possible to detect the birds much more easily than when the radar is used at the more common lower tilt angles. Although bird echoes were detected 11 days during the 16 days of New Mexico operation, the results reported herein are from 14, 20, and 30 August 1965. Most of the data for this paper were extracted from the operations on 20 August.

2. SIZE

The echoes generally appeared on the film as point targets. The theoretical minimum radial extent a target can have on short pulse (0.5/sec) is 246 feet. From one frame of film, 201 echoes were traced as close to their apparent size as possible, and the average echo diameter was determined to be about 360 feet. The difference between the observed-target size and the point-target size can be attributed to the inaccuracy of tracing the echoes (which averaged just 1.1 mm on the tracings), the tendency of the CRT to expand the size of saturated targets, and the likelihood that some of the echoes were really not point targets but rather were the result of two or more birds flying in adjacent sampling volumes. However, the average size does not vary markedly from the size a point target should have.

3. DENSITY

The areal distribution of the bird echoes has some interesting features. Among these is the seemingly large number of echoes observed. Tracings of echoes on three consecutive step-gain frames produced 658, 330, and 201 echoes per frame, respectively. These numbers are not the total number of echoes on the frames, but only those which could be distinguished individually from the ground clutter and from each other. Echo densities were determined as shown in Figure 1 by dividing the area of the scope into rings 1 n. mi. in extent and counting the echoes within each ring. The decrease in density with range is probably primarily a function of $1/R^4$ although there is an inseparable dependence on height because the data were taken at 15° tilt. If the areal density curve of Figure 1 for gain step 1 were extrapolated back to the interval between the radar and 1 n. mi., over 40 echoes/n. $mi.^2$ would be indicated, which would be the equivalent of one bird per 16 acres. However, because of the narrow beam width of the MPS-34 only a small volume of the atmosphere was being sampled. The volumetric densities corrected for the effects of the volume of the beam are also shown in Figure 1. In clear weather during the daytime most birds fly below 5000 feet (Lack, 1960). Thus, by extrapolating the gain step 1 line for the volumetric density back to the minimum range and integrating the curve below 1 n. mi., the average volumetric density was 1670 echoes/n. $mi.^3$, or the equivalent of 2.6 birds per acre if all landed.

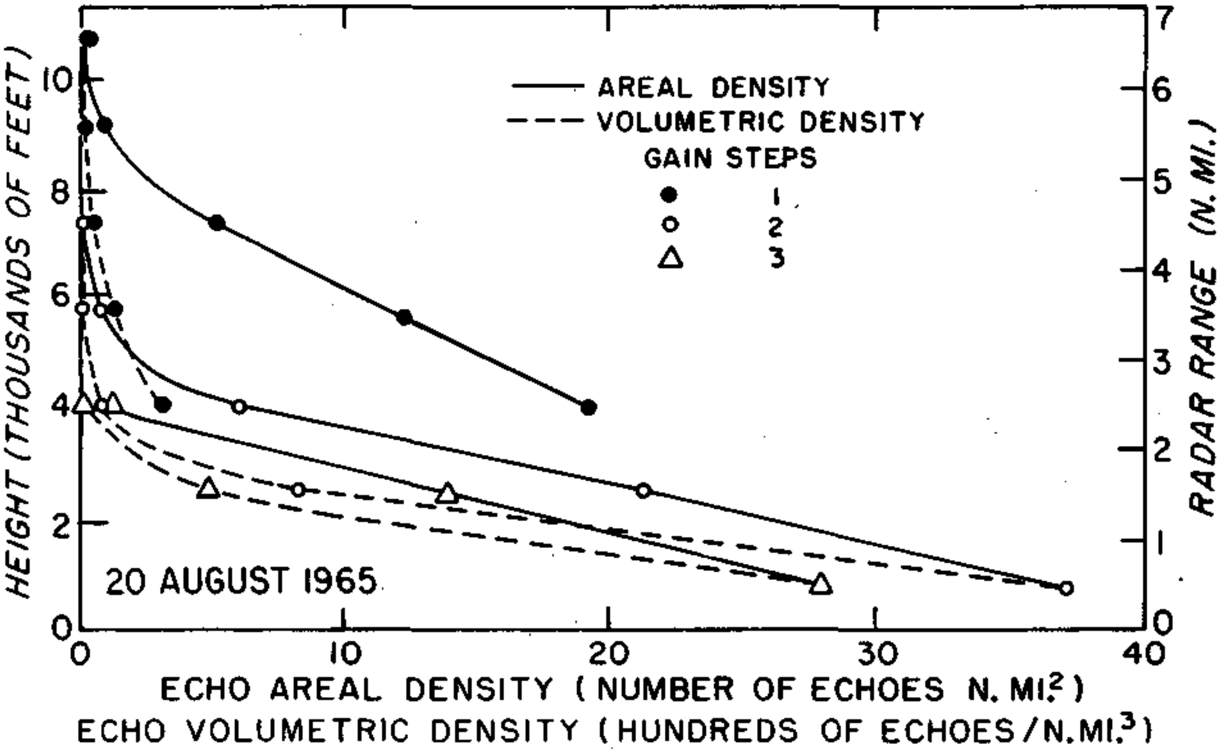

Figure 1. Areal and volumetric distributions of bird echoes.

4. BACK-SCATTERING CROSS-SECTIONAL AREAS

Also considered were the questions of how large the radar back-scattering cross-section of a bird is and how far a single bird can be detected on the MPS-34 radar. Houghton (1961) found that the best simple estimate of a bird's cross-sectional area can be made by determining the back-scattering cross-section of a sphere of water whose mass is equal to that of the bird being considered. Because the back-scattering cross-section from a bird depends on its orientation relative to the axis of the radar beam, this method is only approximate.

Figure 2 shows the minimum back-scattering cross-sectional area of a target which can be detected by the MPS-34. This area is plotted against range (using values of P_r = -103 dbm, P_t = 85.3 dbm, and antenna gain = 36.2 db). The right-hand ordinate gives the weight of a water sphere having a back-scattering cross-sectional area equal to that indicated on the left-hand ordinate. Also plotted on Figure 2 are the back-scattering cross-sectional areas of a sea gull measured by Richardson et al. (1958), a starling measured by Houghton (1964), and the range of areas of one turkey buzzard in flight measured by LaGrone, Dean, and Walker (1964).

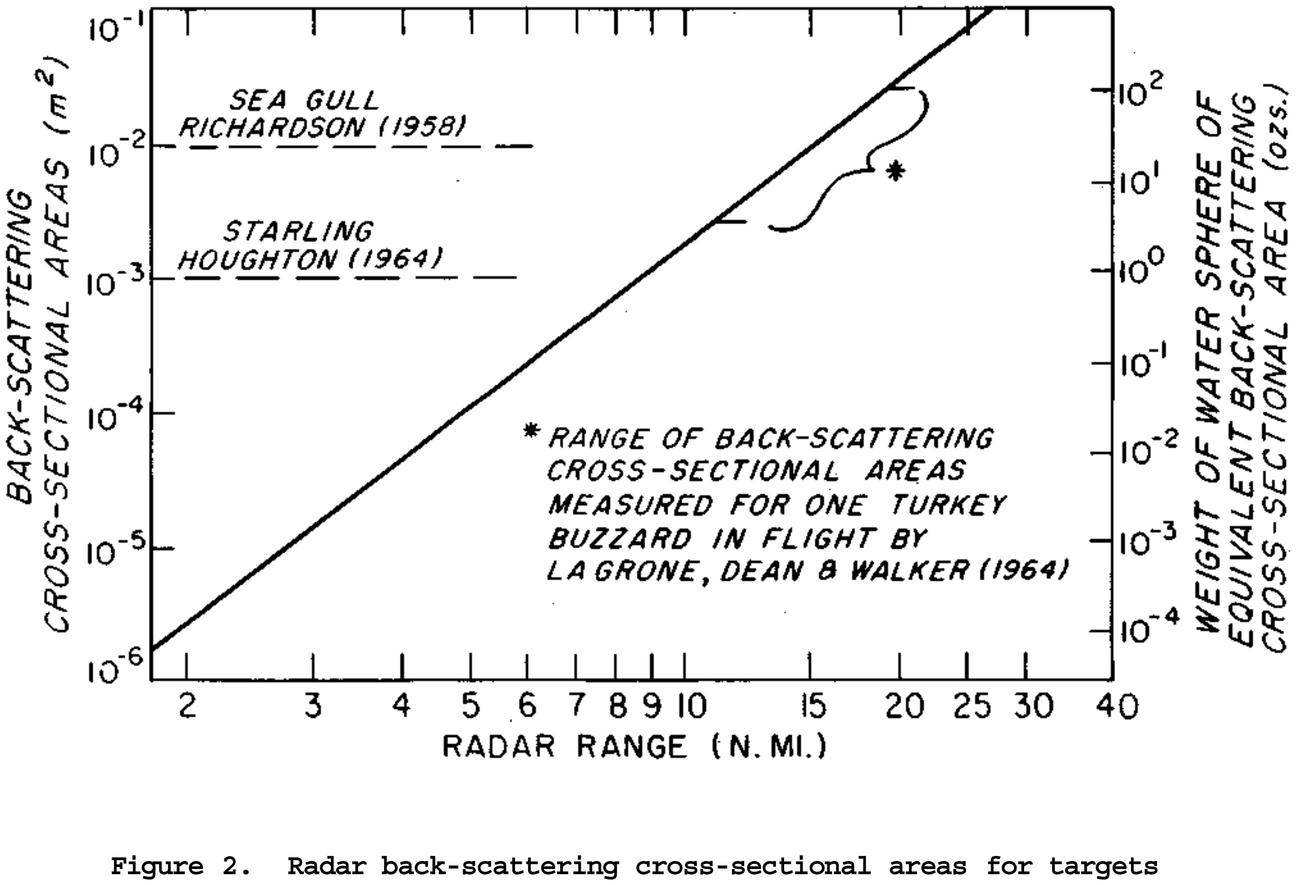

Figure 2. Radar back-scattering cross-sectional areas for targets just detectable by the AN/MPS-34 radar (P_r = -103 dbm, P_t = 85.3 dbm).

The farthest echo detected in the one full-gain frame of data on 20 August 1965 was at 7.0 n. mi. This requires a back-scattering cross-sectional area of 4.6×10^{-4} m^2, and could be attributed to a bird with an approximate weight of 0.27 oz. Frank Bellrose, Aquatic Waterfowl Specialist with the Illinois Natural History Survey, stated after reviewing the radar data that the birds which would have been migrating over New Mexico in August were probably warblers, thrushes, other small birds of this size range, and some shore birds such as sandpipers. Birds of the first group weigh from 1/2 to 1 oz. and should have been detectable at ranges up to 8.7 n. mi. The disagreement is not too great, especially when it is borne in mind that this represents only one frame of full-gain data and that 8.7 n. mi. is an elevation of nearly 21,000 ft above MSL.

5. HEIGHTS

Although Lack (1960) reports that most of the birds he detected with radar flew below 5000 ft, he also has detected some birds at heights up to 21,000 ft without attempting to find exceptional cases. Thus, the maximum height of 15,000 ft above terrain detected by the MPS-34 in New Mexico is within reason even when adding the 7000-ft ground elevation. Radio contact with another radar crew on South Baldy at the time of detection on 20 August 1965 indicated that their radar was detecting echoes at about 3000 ft above Baldy's 10,800-ft elevation, or nearly the same elevation as those being detected by the MPS-34 at that time. It is interesting to note that the highest birds detected by Lack were presumed to be warblers, chats, and fly catchers, some of the smaller migrating birds.

6. SPEEDS AND DIRECTIONS

Houghton (1964) gives a range of speeds for several kinds of birds. These speeds ranged from 14 to 44 knots, the average being 28 knots. Speeds and directions were determined for a number of bird echoes on 14, 20, and 30 August. Table 1 gives the range of speeds, the average speeds, the average vector velocities, the uniformity of direction of travel, and the number of echoes tracked. These are categorized by day and by quadrant on 20 August. Because of the difficulties of tracking the echoes, only those which lasted for six frames (1 minute) or longer are presented.

The range of speeds (5 to 70 knots) is reasonable. Certainly, an average speed of 25 knots is reasonable. The average velocity is the average speed and direction of all echoes, determined by taking the vector sum of the individual velocities and averaging them. An estimate of the degree of uniformity of direction of travel was obtained by taking the ratio of the average vector speed to the average speed (expressed in percent); the larger the vector speed compared with the average speed, the more uniform the directions of travel of the echoes composing these averages. The fact that the uniformities are fairly large could indicate the birds were migrating in similar directions; the increase in average daily uniformity could indicate that the migration toward the south-southwest was also increasing. The wind was another cause of the uniformity of travel direction of the echoes. The winds for 14, 20, and 30 August averaged 7.2 mps from the west-southwest, 4.0 mph from the north-northwest, and 5.3 mph from the west, respectively, at the top of South Baldy. These winds agree in a very general manner with the echo directions indicated in Table 1.

7. DISCUSSION

One question yet exists. If there were no actual visual observations of the birds for correlation with the radar echoes, can it still be safely concluded that birds indeed cause the echoes described herein?

On 16 May 1966 we were advised that there would be a relatively large night time migration of small birds over Illinois. Consequently, the radar was operated specifically to detect the passage of these birds and did, in fact, detect up to 1.5 times as many echoes as on 20 August 1965 in New Mexico. However, the radar operator could not visually observe any birds outside and was unable to detect them on the radar scope. At the same time 75 birds were sighted at various heights by Bellrose (private communication) while flying in a single engine airplane near the radar site. At the only height with data from both sources, 2500 ft, Bellrose sighted three birds or a volumetric density of 3.8×10^3 birds/mi^3 while the radar detected 9.2×10^2 echoes/mi^3, a factor of 4 difference. About half the total number of birds sighted appeared to be flying alone while the other half were in loose cells of at least two or three. The agreement between radar and optical observations is probably within a factor of 2.

Thus, the failure to observe the birds in New Mexico should not be considered a serious problem, especially since Sutter (1950), as quoted by Lack (1960), says that high-flying migrating birds cannot be seen during the day, even with military optical equipment.

8. CONCLUSIONS

Radar can be a very useful tool for the detection and tracking of migrating birds and should continue to provide both new and supplemental information on

Table. 1. Range of Speeds, Average Speeds, and Average Vector Velocities for Bird Echoes Observed on 14, 20, and 30 August 1965 in New Mexico

Date (August 1965)	Quadrant (degrees azimuth)	Range of Speed (knots)		Average speed (knots)	Average speed (knots)	Velocity heading (degrees)	Direction uniformity (percent)	Number tracked
		low	high					
14	all	6	33	21	13	354	62	17
20	0-90	12	53	30	26	182	87	18
	90-180	5	59	21	19	178	91	10
	180-270	8	70	24	21	172	87	24
	270-360	8	68	22	18	264	82	17
	all	5	70	25	21	165	84	69
30	all	15	47	28	24	136	86	19
Extremes, averages, or totals		5	70	24.8	15.2	156	61	105

the migrating habits of birds of all sizes. Since many bird migrations are triggered or at least related to various atmospheric phenomena, a better understanding of these migrations should lead to some new insights into meteorology.

9. ACKNOWLEDGMENTS

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13. ABSTRACT

The engineering and design problems of the Area Precipitation Measurement Indicator (APMI) are discussed. Recommendations are made for improving the video processing, integration, and display systems for the second generation APMI. Analog and digital integrators are compared for processing considerations. The merits of polar and rectangular coordinates are discussed in terms of presentation schemes. It is suggested that some form of built-in calibration capability be included in any future device of this type. Also included are some general considerations for later designs of radar data processors.

After discussing the theory of low noise amplifiers, the problems inherent in the detection of thermal noise by a radar and the difficulties in making quantitative measurements from the data are illustrated. Engineering problems encountered during the contract period and methods of correcting them are described. The lack of stability of the maser gain makes quantitative measurements nearly impossible. One study indicated that the maser gain varied as much as 8 db/30 minutes while another study showed that even hourly retuning of the maser magnet was too infrequent to maintain optimum maser gain.

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