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An evaluation of the meteorological usefulness of a maser RF amplifier on an AN/MPS-34 X-band weather radar indicates that there are both advantages and disadvantages to its use. The problems associated with the maser used in this study included tuning problems, loss of gain through loss of liquid helium and from tilting too high, and instability of the gain of the maser with time. The problems encountered which are potentially common to all masers included logistics problems, loss of gain because of saturation of the maser, and sufficient additional sensitivity to the radar receiver system to allow the detection of thermal noise.

The detection of thermal noise, predicted by theory for the system used, is the most significant result of the study. Objects at a temperature of 300 K radiate thermal noise which is easily detected by the maser-equipped AN/MPS-34 while on short pulse (MDS $\leq$ -100 dbm while the noise power for the MPS-34 on short pulse from objects at 300 K exceeds -108 dbm).

The advantages of the maser for the detection of clouds, precipitation, fog, clear air turbulence, insects, and birds are investigated. Little advantage is gained by using the maser on sensitive radars for most forms of precipitation except light snow. For sensitive radars, there are definite advantages to using the maser for clouds and bird detection and to some extent for insect detection. An additional 12 db of gain doubles the maximum range of detection for point targets and increases the maximum range of detection for distributed targets four times. Fog and clear air turbulence both have such small reflectivities that the maser did not provide enough additional gain to make detection of these feasible.

Several uses of a maser for weather radar are suggested, including the study of first echoes and clouds. The addition of a maser to other wavelength radars and to radars of relatively low sensitivity are also considered.

THE METEOROLOGICAL USEFULNESS OF A MASER RF AMPLIFIER ON A HIGHLY SENSITIVE X-BAND WEATHER RADAR RECEIVER

by

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THE METEOROLOGICAL USEFULNESS OF A MASER RF AMPLIFIER ON A HIGHLY SENSITIVE X-BAND WEATHER RADAR RECEIVER

INTRODUCTION

The application of masers[1] on radar has been adopted during only relatively recent times. The possibility of amplification by emission of energy from atoms was not conceived until Weber (39) first set forth his proposal for obtaining amplification of microwave radiation through the use of crystals and gases. The following year Gordon et al. (13) in the United States and Basov and Prokhorov (4) in Russia each produced a workable microwave amplifier which used ammonia gas as the source for the amplification. Other improvements were made to the operational usefulness of masers during the following years.

Forward et al. (10) of Hughes Research Laboratories were the first to apply a maser to an X-band radar. This was a solid-state ruby maser of fixed frequency applied to an APG-51A radar modified to make both its receiver and transmitter tunable. By 1960 Hughes had developed a tunable maser which no longer required a tunable radar transmitter. This maser was first applied to the AN/CPS-9 (30, p. 4). However, the results of this experiment indicated that this maser was not useful for radar because it saturated too easily. Even with a 300 ft separation between the transmitter and its antenna and the

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[1] For a definition of various terms used in the text, refer to the Glossary in the Appendix.

receiver and its antenna, the maser was still saturated by the transmitter's output pulse.

An improved maser was later developed and applied to the AN/MPS-34 X-band radar system by Robbiani in 1964 (31, p. 1). This is the maser used in the research reported herein.

Only one other monostatic X-band radar using a maser has been used for meteorological research.[2] This is the Wallops Island satellite-tracking radar. It is not capable of continuous PPI operation, however, as it was not designed as a weather radar. Also, the maser on this radar was not used most of the time for reasons which will be discussed later.

It should be noted that there are masers capable of operating at frequencies other than X-band. Adler (1) reports the use of a maser on a radar operating at 5.5 GHz; but this, too, is not a weather radar. Also, other low noise RF amplifiers such as tunnel diodes are available which provide some of the advantages of masers, and some of these have been used on weather radars. However, a discussion of these is beyond the purpose of this paper and will not be considered further.

Prior to a discussion of the appropriate theory applicable to low noise receivers, it will be helpful to give a brief description of the purpose and use of the maser in the MPS-34 receiver system. Figure 1 is a block diagram of the basic components of a typical

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[2] Personal communication from Dr. Kenneth R. Hardy, 1966.

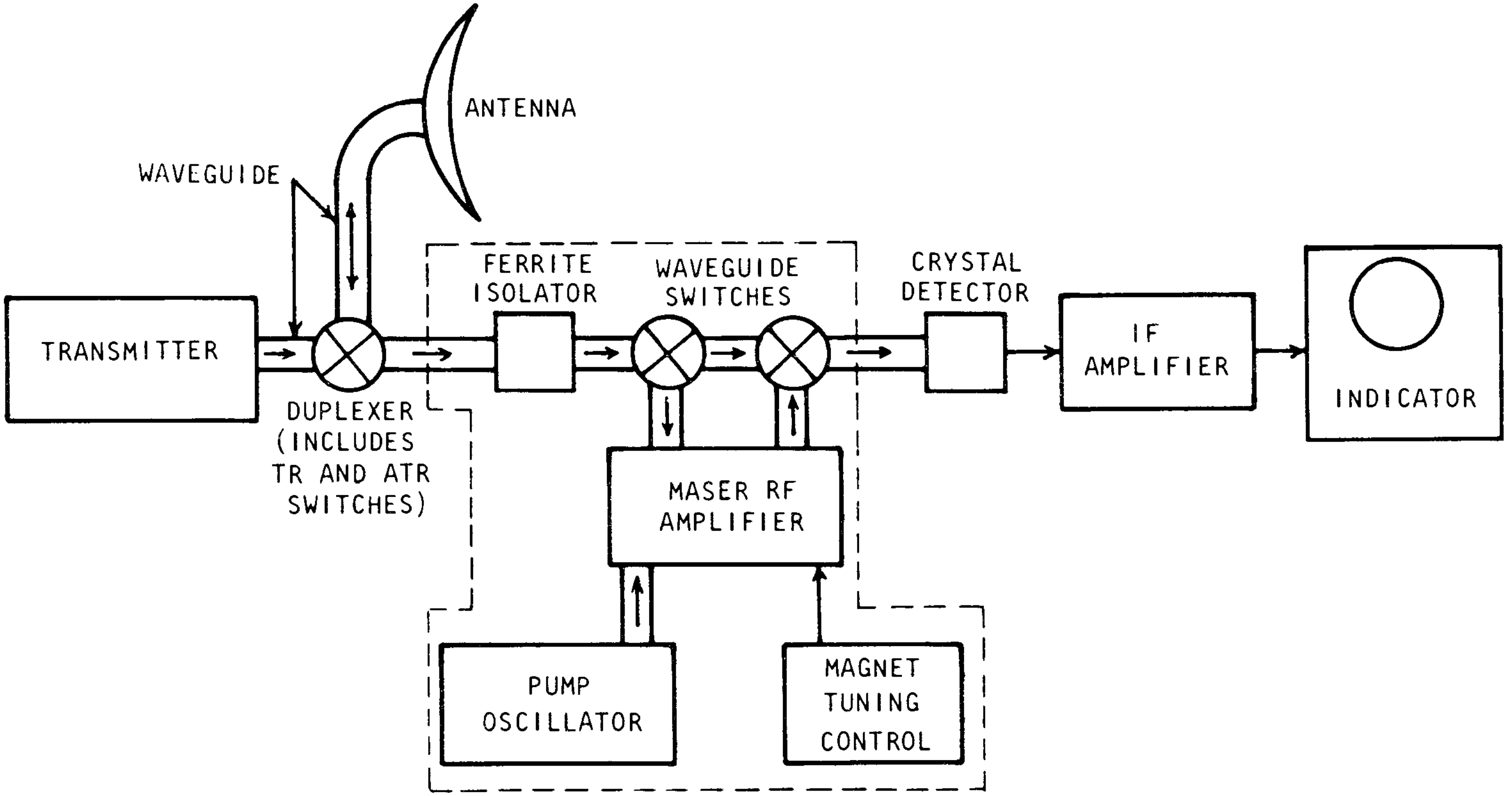

Figure 1. Simplified block diagram of the AN/MPS-34 radar showing the location of the maser and the waveguide switches.

X-band weather radar. The maser is physically inserted in the waveguide between the duplexer and the crystal detectors. A pair of waveguide switches allows the maser to be switched in or out of the system whenever desired. The additional devices are within the dashed line.

The maser operates as a low noise amplifier with a positive gain on the same frequency (RF) as the transmitter. The underlined terms are the chief advantages of the maser as will be seen shortly.

The maser is composed of a series of paramagnetic crystals (rubies) which contain several energy levels. That is, the electrons in the atoms of the crystals are capable, under certain conditions, of residing in several energy states. The energy difference between these levels is a function of the surrounding magnetic field strength. The ruby used in the maser on the MPS-34 uses three of its four inherent energy levels. These energy levels are shown schematically in Figure 2. When these crystals are in a moderate magnetic field and an RF signal of 24 GHz (from the pump oscillator) is applied, electrons leave the first energy level and enter the third, thus increasing the third level population above that of the second level (as shown in Figure 3). The difference between the second and third levels corresponds to a frequency of 9.3 GHz. Now, when a signal of 9.3 GHz is applied to the input of the maser, the electrons in energy level three return to energy level two, radiating the energy difference at 9.3 GHz in phase with the applied signal. This essentially amplifies the input signal. The electrons in the second

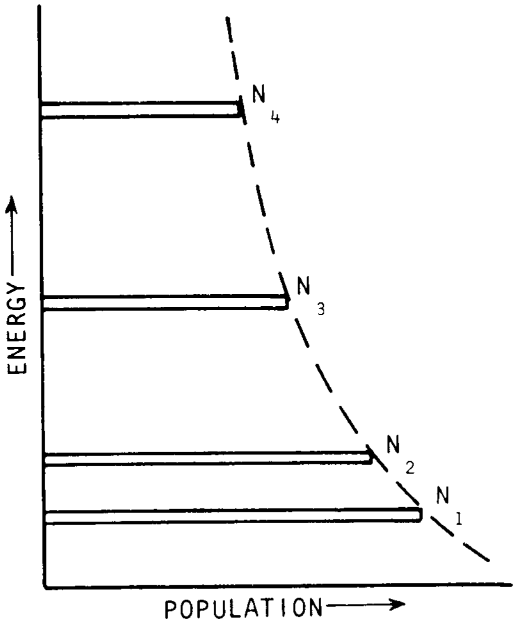

Figure 2. The energy levels of the maser in the normal state.

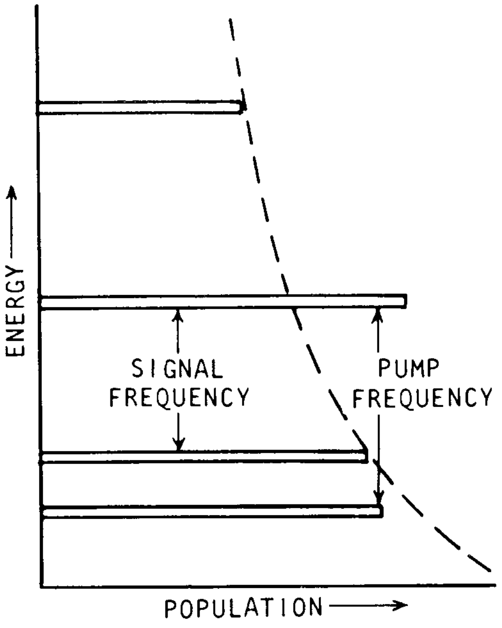

Figure 3. The energy levels of the maser when the 24 GHz pump frequency is applied to the maser.

level return to level one through natural relaxation processes. This natural relaxation process (of all levels) is slowed by maintaining the ruby crystals in liquid helium at 4.5 K.

When the input signal exceeds a certain amount, the third energy level is depopulated by the input signal faster than the pump can supply electrons to it, and, thus, the gain of the maser is reduced. The recovery time for this maser after this overpowering or "saturation" occurs is about 40 msec (31, p. 3). During saturation the maser neither amplifies nor attenuates the signal and is essentially transparent to the signal. Thus, when the same antenna is used for both transmitting and receiving as in most radars, it is imperative that the maser be adequately isolated from the powerful energy pulses of the transmitter. The ferrite isolater in Figure 1 helps to provide this isolation. Saturation problems are discussed further in a section to follow.

The purpose of the study reported herein was to evaluate the meteorological usefulness of the maser RF amplifier used on the AN/MPS-34 X-band weather radar. This study included investigating the actual and potential advantages and disadvantages of using a maser with 10 to 12 db gain during precipitation periods as well as for cloud, fog, clear air, bird, and insect detection. The data obtained were for the most part unique in that no other maser-equipped radar has yet been used in continuous PPI operations. Furthermore, time-lapse step-gain movies of the scope provided data for general cloud physics research.

Data were collected during periods of precipitation, cloudiness, and bird migration from three locations (East Central Illinois; Magdelena, New Mexico (August 1965); and Flagstaff, Arizona (July and August 1966)) over a period of one and one-half years. The capability of the maser-equipped AN/MPS-34 radar for insect, fog, and clear air turbulence detection was determined theoretically.

Perhaps the most significant result of the study was the detection of thermal noise, i.e., electromagnetic radiation radiated by any object or substance whose temperature is above absolute zero. This detection is predicted by noise theory for the system used. The magnitude of the predicted noise power and the detected noise power agree reasonably well. One of the important consequences of thermal noise detection is the variation of the minimum detectable signal of the receiver caused by temperature variations in the field of view of the radar.

Many of the results reported herein have been published as contract reports on the project to evaluate the meteorological usefulness of the maser to the Army (17, 25, 26, 27, 28, 29).

THEORY

The classical radar equation for point targets and a monostatic radar has been derived in several works on radar (5, p. 24) and is given as follows:

$$P_r = \underbrace{\frac{P_t G}{4\pi r^2}}_{a} \times \underbrace{\frac{\sigma}{4\pi r^2}}_{b} \times \underbrace{\frac{G\lambda^2}{4\pi}}_{c} = \frac{P_t G^2 \lambda^2 \sigma}{64\pi^3 r^4} , \qquad (1)$$

where P_r is the received echo power in the same units as the peak transmitted power P_t, G is the gain of the antenna (compared to an isotropic radiator), λ is the wavelength of the radiation, σ is the echoing area, and r is the range to the target. The first factor (a) gives the power density of the illuminating wave at range r and follows from the equation for the surface area of a sphere (area = $4\pi r^2$) and the definition of antenna gain. The second term (b) gives the power density of the reflected wave at the radar. The third term (c) gives the "effective receiving aperature" A_r of the antenna of the radar expressed in terms of wavelength and gain. This form of the equation is perfectly general and may be applied to any target.

For meteorological targets such as raindrops or snow flakes, however, the radar beam illuminates many targets simultaneously, i.e., all scatters in the volume V defined by the pulse length h and the vertical and horizontal beam widths of the antenna beam θ

and ϕ, given by

$$V = \pi \left(r \frac{\theta}{2}\right)\left(r \frac{\phi}{2}\right) \frac{h}{2} . \qquad (2)$$

Thus, summing the power scattered by all the particles in V, the radar equation becomes

$$\bar{P}_r = \frac{P_t G^2 \lambda^2}{512 \pi^2 r^2} (\theta \phi h) \sum_1 \sigma_i , \qquad (3)$$

where $\bar{P}_r$ is now the average power received from the sum of all the individual scatters in the volume. The factor $\sum_1 \sigma_i$ is called the radar reflectivity and designated by the Greek letter η.

If the particles illuminated by the radar beam are much smaller than the wavelength, then the Rayleigh approximation to the Mie scattering theory is applicable, and the back-scattering cross-sectional area of an individual particle (assumed spherical for most meteorological uses) is given by

$$\sigma_i = \frac{64 \pi^5}{\lambda^4} \left| \frac{m^2 - 1}{m^2 + 2} \right|^2 a_i^6 , \qquad (4)$$

where m is the complex index of refraction of water for rain or wet hail and of ice for snow or dry hail, and a_i is the drop radius. Usually the factor m^2-1/m^2+2 is replaced by the letter K. Also, the diameters of the drops are usually given rather than their radii. If these changes are made and (4) is substituted into (3) we get, after simplifying,

$$\bar{P}_r = \frac{P_t G^2 \theta \phi h \pi^3 |K|^2}{512 \lambda^2 r^2} \sum_1 D_i^6 . \qquad (5)$$

The term $\sum_1 D_i^6$ is usually termed the reflectivity factor and designated by the symbol Z. For the AN/MPS-34 radar the vertical and horizontal beam widths are equal. Hence, the final form of the radar equation for distributed targets may be written as

$$\overline{P}_r = \frac{P_t G^2 \theta^2 h \pi^3 |K|^2}{512\lambda^2} \frac{Z}{r^2} . \tag{6}$$

Equation (6) is applicable to various situations in radar meteorology when it is desired to know, for example, what the magnitude of $\overline{P}_r$ will be with a given target or what the reflectivity factor of a target is when $\overline{P}_r$ is known. In most of these uses the signal power levels are well above those which are just barely detectable by the radar receiver. However, when measurements of the <u>minimum</u> signal detectable by a radar are desired, further complications arise in the form of noise. All practical electronic devices generate noise by virtue of the random motions of electrons in conductors whose temperatures are above absolute zero. Some of the implications which may be made from the application of noise theory to radar in general and to the maser-equipped AN/MPS-34 in particular will now be considered.

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

$$dN_g = KTdf , \tag{7}$$

where K is Boltzmann's constant (1.38×10^{-23} Joules K^{-1}) and T is the absolute temperature of the resistive component of the output impedance of the signal generator. If the signal from a generator is fed into an ideal, i.e., noiseless amplifer 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 generated within the amplifier dM_o. Thus, the ratio of the output noise to output signal power dN_o/S_o is greater than the ratio of input noise to input signal power dN_g/S_g by a factor F, which is called the noise figure given as follows:

$$\frac{dN_o}{S_o} = F\,\frac{dN_g}{S_g}\ , \tag{8}$$

where the noise powers are measured in a frequency band df centered on the corresponding signal frequencies. Since $dN_o = GdN_g + dM_o$ and $S_o = GS_g$, (8) may be written by means of (7) as

$$F-1 = \frac{dM_o}{GKT_o}\,df\ , \tag{9}$$

where T_o is a reference temperature chosen to standardize the performance of the generator. Usually $T_o = 292$ K 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 (9). Using subscripts 1, 2, and 12 to represent terms from the first amplifier, the second amplifier, and the total system, respectively, we may write

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

which reduces to

$$F_{12} = F_1 + \frac{F_2 - 1}{G_1} \ . \tag{10}$$

The maser of the MPS-34 radar is the first amplifier with the normal receiver considered to be the second amplifier. Equation (10) indicates that the maser reduces the noise figure of the MPS-34 receiver system from 8 db without the maser to 1.20 db with the maser, since the noise figure of the maser is 1.06 db and its optimum gain is 20 db. The advantages of the maser become more apparent when we remember that normally the first "amplifier" of an X-band radar system is the crystal detector which might have a typical noise figure at X-band frequencies of 7 db and a gain of -5 db. Thus, if the IF amplifier has a noise figure of 2 db, the combination would have an overall noise figure of 8.3 db, over 7 db worse than the same radar with the maser described above.

The minimum signal power that is usually 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 less than the noise level, but these will be ignored in the present discussion. Solving for S_g from (8) when $dN_o = S_o$, gives

$$S_g = FKT_o df \ , \tag{11}$$

where S_g is now $\overline{P}_{r_{min}}$, the minimum detectable signal. Knowing F and df, $\overline{P}_{r_{min}}$ may be readily found.

DISADVANTAGES OF USING THE MASER

During the year and one-half of operating the maser-equipped MPS-34, several disadvantages to the maser appeared, some more serious than others. These were as follows (in approximate order of increasing seriousness): problems of increased echo detection in side lobes, logistics, tuning, loss of gain with loss of liquid helium, loss of gain from tilting too high, loss of gain because of saturation, instability of gain with time, and thermal noise detection. The ranking above is probably most applicable if the system is used as a research radar. If it were used operationally by the Army, for example, the ranking would be different. Logistic difficulties would likely be considered more serious operationally than perhaps losses due to high tilting, as high tilt angles could be avoided. Nevertheless, each of these problems will now be discussed in more detail.

Side lobe problems

One minor problem was that the radar occasionally detected targets through the side lobes which were displayed in an area of interest on the scopes. This could make echo identification difficult or at least somewhat confusing. This is usually not a problem with weather radars because the side lobes are much less sensitive than the main lobe, and the echoes of interest are usually far enough away that any echoes detected by side lobes are of no consequence during interpretation or analysis. However, when the sensitivity of the radar is increased by 10 db or more, the effects of the echoes detected by side lobes may no longer be negligible. On two occasions during this project this occurred.

First, during the New Mexico operations, the MPS-34 was used to study thunderstorm development over South Baldy, a 10,800-ft mountain located about 8 n.mi. east of the 7000-ft location of the radar. Ground return was detected from South Baldy with the antenna tilted as high as 15° to 20° although the top of South Baldy was at 5° tilt. Because of its coherent nature, however, it did not cause much confusion. In an attempt to reduce these unwanted ground return targets, a large billboard-like structure was erected between the antenna and South Baldy. This was an aluminum covered wooden structure intended to block echoes from the mountains in the direction of South Baldy. This proved unsuccessful, though, probably because it was too close to the antenna, i.e., within the transition region of the antenna. This structure made no apparent change in the ground pattern detected. For proper results, it should have been in the far field of the antenna or 940 ft or more away.

The second case was also with nearby targets. This was during the cloud detection study when the antenna was at a constant tilt of 75° (although the maser was mounted in its normal upright position for this study). Figure 4 (A through F) illustrates the magnitude of the problem. All the targets in this figure are from ground targets detected by the side- and back-lobes of the antenna during

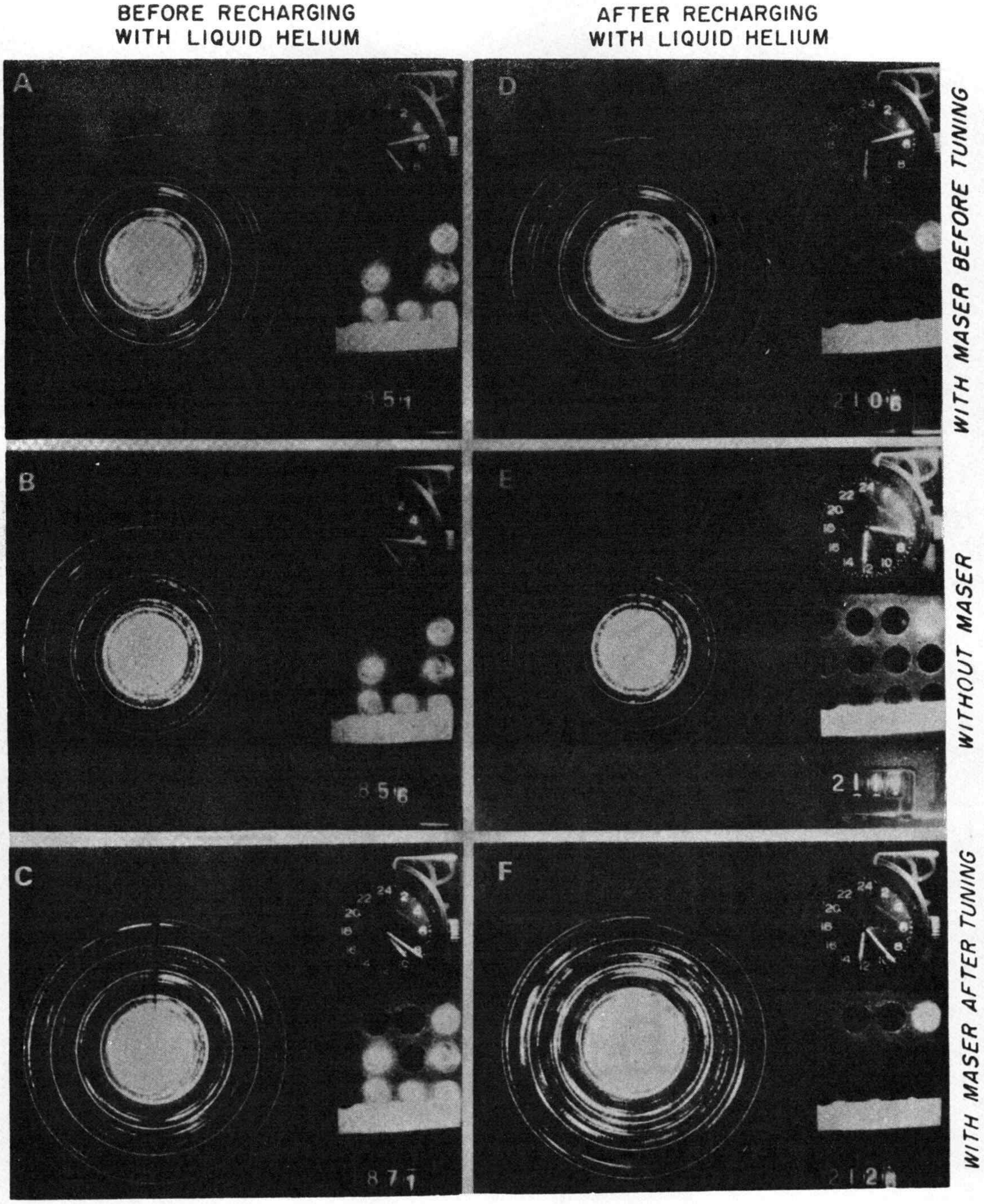

Figure 4. Variation of maser gain as indicated by variation of ground targets on 3 December 1966 at 75° tilt with 1 n.mi. range rings

cloud free periods. The range rings are 1 n.mi. apart. Perhaps this is an unfair case, though, as most weather radars are not normally used at ranges as short as 5 or 6 n.mi. Nevertheless, the ground clutter targets did make analysis difficult because they were on the same order of magnitude in reflectivity as were the clouds detected.

Logistic problems

The maser tested requires a bath of liquid helium surrounding it to maintain it at its 4.5 K operating temperature. To achieve this, the maser was generally charged with liquid nitrogen (77 K) for initial cooling. After about a half hour, this nitrogen was removed and replaced by liquid helium. Once the operating temperature was reached which required about two hours, the Dewar was capable of maintaining the helium for as much as 30 hours. Thus, for continued operation, the Dewar needed to be refilled daily with liquid helium. There were occasions when the helium boiled away in less than 24 hours. This proved especially true during the operations in both Arizona and New Mexico where the altitudes were 6000 ft to 7000 ft MSL. When this happened, it was still possible in some cases to just refill with liquid helium. On other occasions when the maser temperature exceeded that of liquid nitrogen, the charging process began with the liquid nitrogen pre-cooling.

Obtaining the liquid helium was also a problem. The radar came with a 10-liter transfer Dewar. Since some helium was lost in transferring into the maser Dewar, one filling of the transfer Dewar was never sufficient to completely fill the maser Dewar. Later a 30-liter transfer Dewar was acquired which even made it possible, with good timing, to operate over week-ends. During the Arizona and New Mexico operations the liquid helium was supplied in 100-liter Dewars. These provided sufficient helium for about one week's operations. One of the more serious problems experienced by personnel operating the Wallops Island radar was obtaining liquid helium. The helium had to come from a source many miles from their base of operations and was not always available when needed.[3]

The ideal solution to these types of problems, of course, would be to use a closed-cycle cryogenics system. This would recycle and reproduce the liquid helium needed for the maser. Unfortunately, at the time this maser was developed, none was available small enough to be added to the rotating part of the antenna pedestal. The system used on the MPS-34 (including pump klystron, power supplies, maser, and maser Dewar) weighed approximately 100 pounds. Recent developments in the field of cryogenics would now make it more feasible to mount a closed cycle system onto the antenna pedestal. This is a highly desirable feature whether the radar were to be used operationally or for research.

One other problem encountered occasionally was that all of the liquid nitrogen was not removed from the maser Dewar before the liquid helium was added. During this second step the transfer

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[3] Personal communication from Dr. David Atlas, 1967.

process would be abruptly interrupted by the liquid helium coming out of the venting port. This occurred because the nitrogen would freeze at 63 K, thus blocking the transfer tube. Thawing generally required 30 min to several hours.

One final logistic problem was the cost of operation. Liquid nitrogen is presently relatively inexpensive--about 5¢/liter. Also, ideally the nitrogen was needed only at the initial charging of the maser, and, consequently, very little nitrogen was needed. Actually, however, a charge was made for the liquid nitrogen used in the outer Dewar of the transfer Dewar (a uniform amount of about 30 liters/week). The total cost for liquid nitrogen was not too much, amounting to less than $5/week. On the other hand, liquid helium now costs over $3.50/liter. Some weeks more than 90 liters were used, which cost over $300/week. Another advantage of a closed-cycle system is that this operational expense is eliminated.

Tuning problems

Once the maser was properly charged with liquid helium it was necessary to tune the maser for peak performance. Two adjustments were provided for tuning. One was the orientation of the ruby crystals in the magnetic field, and the second was the strength of the magnetic field.

Originally it was envisioned that the orientation of the ruby crystals would not require adjustment very often. In actual practice, however, it was often necessary to reorient them at least once for each time the maser was allowed to warm. This was attributed to differential expansion caused by warming and cooling of the various metal parts which were supposed to maintain a fixed ruby orientation. Vibration might also have had some part in causing the rubies to change their orientation. When the maser was maintained at 4.2 K, changing alignment was not a serious problem.

The maser used a magnetic field strength of about 4000 gauss to provide an energy difference between the second and third energy levels equivalent to a frequency of 9.3 GHz. This strength was achieved by using a large permanent magnet of approximately this strength and a smaller tickler magnet used either of two ways. The tickler magnet could be supplied with a constant current flowing in the proper direction to give a net magnetic field strength of the proper magnitude. It could also be used to increase or decrease "permanently" the field strength of the permanent magnet by pulsing the tickler magnet one or more times with an adjustable amount of energy. Once the proper field strength was achieved, the tickler magnet would hopefully not be needed again. Unfortunately this was not the case, as the magnetic field strength changed enough that the gain of the maser also changed noticably during periods as short as one hour.

Figure 4 (A goes with C and D goes with F) illustrate this quite well. Figures 4A and 4D were taken with the maser operating but about one hour after the maser was last tuned (by adjusting the tickler current). The antenna was fixed at 75° tilt and all the targets, as was mentioned earlier, are ground targets. Figures 4C and 4F were taken several minutes after their corresponding pretuning frames, but these are now after peaking the maser gain by adjusting the tickler magnet current. Comparing A to C, at least some increase can be seen in the area covered by targets. Comparing D to F, a considerable increase is evident in the area covered by targets. The difference between F and D represents, at least qualitatively, the difference in gain that took place during a period of about one hour because of a changing magnetic field strength. Actually, this change might have taken place quite soon after the tuning. No attempt was made during this part of the study to determine how soon after tuning the sensitivity decreased.

Loss of gain through loss of liquid helium

The maser Dewar was supposedly capable of maintaining a charge of liquid helium for more than 24 hrs (9). It was equipped with two temperature sensing devices (carbon resistors) for monitoring the temperature of the maser, one located near the top and the other near the bottom of the maser. These were also useful in determining when and if a proper charge had been achieved. It was originally assumed that, if the lower temperature sensor was in liquid helium, the maser was at its optimum operating temperature. The design of the maser Dewar was such that this should have been a reasonable assumption. It was later learned, however, that near the end of a charge period, i.e., a period approaching 24 hours, the maser gain would start to decrease before the helium was completely gone from the Dewar.

Figure 4 again illustrates this. The left hand series of pictures were taken about 18 hr after the previous charge; the right hand series, about 1 hr after recharging. Figures B and E show very nearly the same amounts of echo, indicating that the overall system sensitivity without the maser has remained essentially constant in the 3 hr between pictures. Figures A and C both show at least some additional echo compared to B indicating that the maser was producing some gain. Likewise Figures D and F show more than E. The effects of loss of helium are visible only slightly if A and D are compared; Figure D seems to have at least some echo not visible on A. The greatest difference appears between C and F, and this is where the difference should be compared. The difference between C and F indicates qualitatively the amount of gain lost (with a well-tuned maser) during an 18 hr period because of a lowering of the liquid helium level in the maser Dewar.

This type of problem could very likely be eliminated more satisfactorily now through improved thermal designs. If necessary, the maser could also be refilled twice a day or more often to maintain an adequate supply of liquid helium.

Loss of gain from tilting too high

The design of the maser Dewar was supposed to make it possible to tilt the antenna and hence the Dewar through a full 90° of tilt.

This, too, proved to be impossible. It was discovered that the maser gain would abruptly decrease after titling above a certain amount. The exact point of this loss depended upon how long it had been since filling the maser Dewar with liquid helium. On the first occasion it was noticed (28 January 1966) the gain decreased at about 40° tilt. Later tests indicated higher tilts were possible shortly after charging. On 23 February 1967 the maser gain did not decrease until just over 80°. The following day, 17 hours after charging, the maser gain decreased just beyond 65° tilt. Once the gain was lost, it was necessary to re-pulse the permanent magnet of the master to achieve peak performance again.

Tilting of the antenna also caused the liquid helium to boil off faster, as it was forced to cool portions of the Dewar and maser which had become quite hot relative to 4.5 K. This might be the reason the Dewar's charge did not last as long in New Mexico and Arizona, that is, the nearby mountains at both locations forced us to use tilts as high as 45°. In Illinois the highest tilt used for most purposes was 15°.

Loss of gain because of saturation of the maser

Because of the orders of magnitude difference between the transmitted and received power levels of typical radar systems and the fact that generally the same antenna system is used for both receiving and transmitting, it is difficult to build a single device which adequately handles all the power levels encountered at the input to a normal radar receiving systems. This causes saturation problems for most masers. If the time needed for a maser to recover from saturation were a few or even a few tens of microseconds, saturation would not be a problem. However, the 40 msec recovery time for this maser (nearly 4000 miles of radar range) is much too long to allow recovery to take place. It could be resaturated 7 (long pulse) to 40 (short pulse) times in the time it would need to recover from the first saturating pulse.

Saturation of masers has been a problem since the early use of masers on radar, and at least two techniques have been used to alleviate the problem (1, 10). The maser discussed used the technique of Forward, that of inserting a ferrite isolater between the TR switch and the input of the maser. The ferrite isolator attenuates only when pulsed, and this occurs only during the time the transmitter is on. During the receive portion of the duty cycle, the isolator offers very little attenuation to the incoming microwave radiation.

The saturation level of a maser is apparently dependent upon its design and construction. The maser of Forward et al. saturated at a CW power level of -25 dbm. This maser would have worked on the radar being considered, as its average power transmitted was about +50 dbm while the total attenuation was 90 db (40 db from the ferrite isolator and about 50 db from the normal TR switch). This would have reduced the transmitter power to a level 15 db below that which saturated their maser.

The maser used for this study apparently had a saturation level of about -35 dbm. This is estimated from the fact that on one occasion (8 February 1966) a loss of 3 db occurred in going from transmitter off to short pulse (about 50 dbm average power) with an additional loss of 5 db going to long pulse (about 53 dbm average power).

Thus, for the detection of meteorological echoes it was advantageous (by 5 db) to operate on short pulse whenever possible. The losses because of saturation were very likely nearly uniform with time and could generally be taken into account quite easily. In terms of very weak echoes, however, the loss of maser gain could be critical.

Instability of gain with time

As has already been noted, the maser does not provide a constant amount of gain. In the examples given thus far, the only conclusion that could be made was that there was a certain difference in gain between two times, but when and how this difference arose was not available. Another quite interesting example of the time variation of the maser gain was evident in some of the Flagstaff, Arizona data.

During the radar operations at Flagstaff on 4 August 1966, an automatic step-tilt programmer was used which provided consistent return of the antenna to each of several tilt angles. 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 so 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. One of these assumptions is not exactly true because the transmitter was switched from short pulse to long pulse at 1400 MST. This resulted in an average abrupt drop in overall system sensitivity of 4 db. Except for this one known change, the above assumptions are reasonably approximated.

Figure 5 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 (represented by

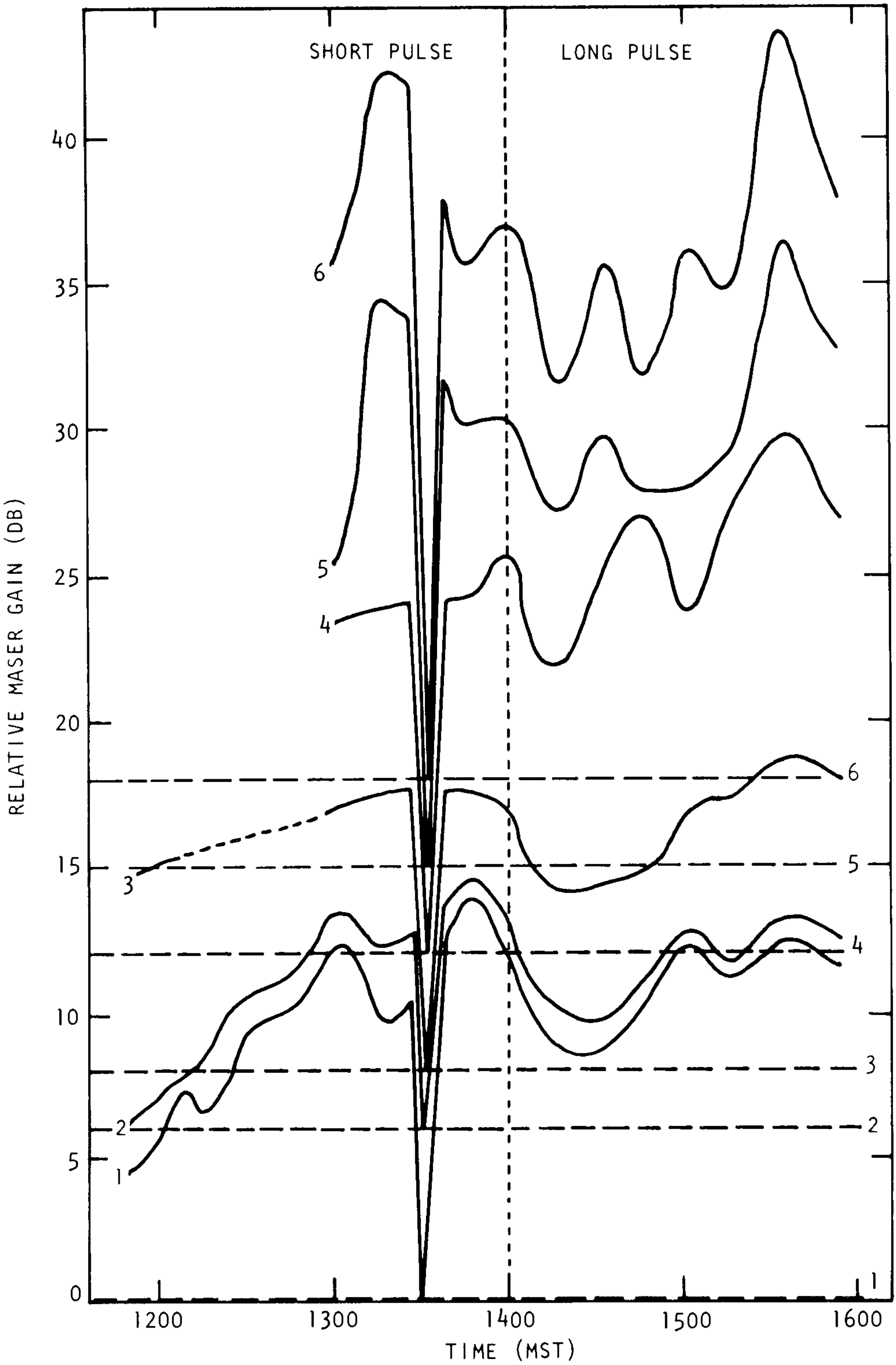

Figure 5. Time variation of maser gain at six levels of IF sensitivity on 4 August 1966 in Arizona. The numbers on each curve correspond to the dashed gain-step lines of the same number.

the straight horizontal dashed lines) with the maser switched out of the system from 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.

It should be noted here that the curves after 1400 MST were shifted upward 4 db to account for the difference in overall sensitivity between the short and long pulse measurements immediately before and after the change in pulse length. Ideally, all the measurements would have been made on either short or long pulse exclusively. An alternative would have been to switch the maser off once during the short pulse operations and once during the long pulse operations. This would have given two reference points for use in determining the gain of the maser. Since neither of these were done, the above mentioned correction should adequately account for the differences in long and short pulse operations.

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 almost exactly 12.0 db. Table 1 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 1. Time-averaged maser gain at each gain step.

Gain step	1	2	3	4	5	6
Maser gain (db)	10.4	5.6	8.5	13.2	15.4	18.8

If thermal noise limits the effective maser gain when on high sensitivity, the effective maser gain should be less on step 1 than on any of the other steps. Figure 5 does show step 1 and 2 curves close together. However, Table 3 indicates that step 1 has 4.8 db more maser gain than step 2. An explanation of this probably lies in the fact that, as mentioned earlier, some of the data points are probably somewhat in error. Specifically, the position of the step 1 base and all others as represented by the dashed lines on the figure are 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. Thus, no explanation other than a poor measurement is possible to explain the difference between the step 1 and step 2 average maser 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.

Another point to note is that the maser gain both increased and decreased during the 4 hr period. The maser was not tuned and ready for operation until 1145 MST. The initial increase in gain might have arisen through the maser slowly reaching thermal equilibrium in its Dewar.

Nevertheless, the continuous changing nature of the gain of the maser would require a continuous monitoring system for calibration purposes to insure reliable quantitative results from the data. Occasional or even frequent calibrations might help to estimate the average gain during a certain period, but these could not accurately portray the actual maser gain between measurements.

Thermal noise detection

Without the use of a low-noise RF amplifier most X-band radars are limited because of the noise power generated within the crystal detector and the IF amplifier to minimum detectable signals of about -106 dbm at best 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 (7). For an antenna directed toward objects on the earth's surface, T might be 300 K in which case dN_g is -108.4 dbm when df = 3.5 MHz (MPS-34 short pulse) and -115.0 dbm when df = 0.75 MHz (MPS-34 long pulse). These values are the noise power levels into the maser from 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 surface of the earth. 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 300 K to 238 K (-35 C) or raised to 378 K (105 C), 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 10 K (11, 38). This apparent temperature would cause a decrease in noise power of 15 db. 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. Closely related to this is the effect of the side lobes. If the first side lobe is 20 db less sensitive than the main lobe and the thermal noise from the clear sky is only 15 db less than from the earth's surface, it seems likely that the side lobes would contribute significant amounts of thermal noise when the antenna is aimed just above the horizon.

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 was discussed earlier, 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. This assumes a 3.5 MHz bandwidth. Thus, the antenna and receiver act as an X-band radiometer whether the transmitter is on or off. The amount of thermal radiation is a function of the temperature of the radiating body. Figure 6 was taken with the maser in operation and without changing the camera or scope settings. Figure 6A shows the scope as it was with the antenna at a 1^{o} angle from the horizontal. Figure 6B was taken with the antenna at 4^{o}. All echoes are of ground clutter with the San Francisco Peaks showing at 10 n.mi. to the northeast. Figure 6C was taken with an

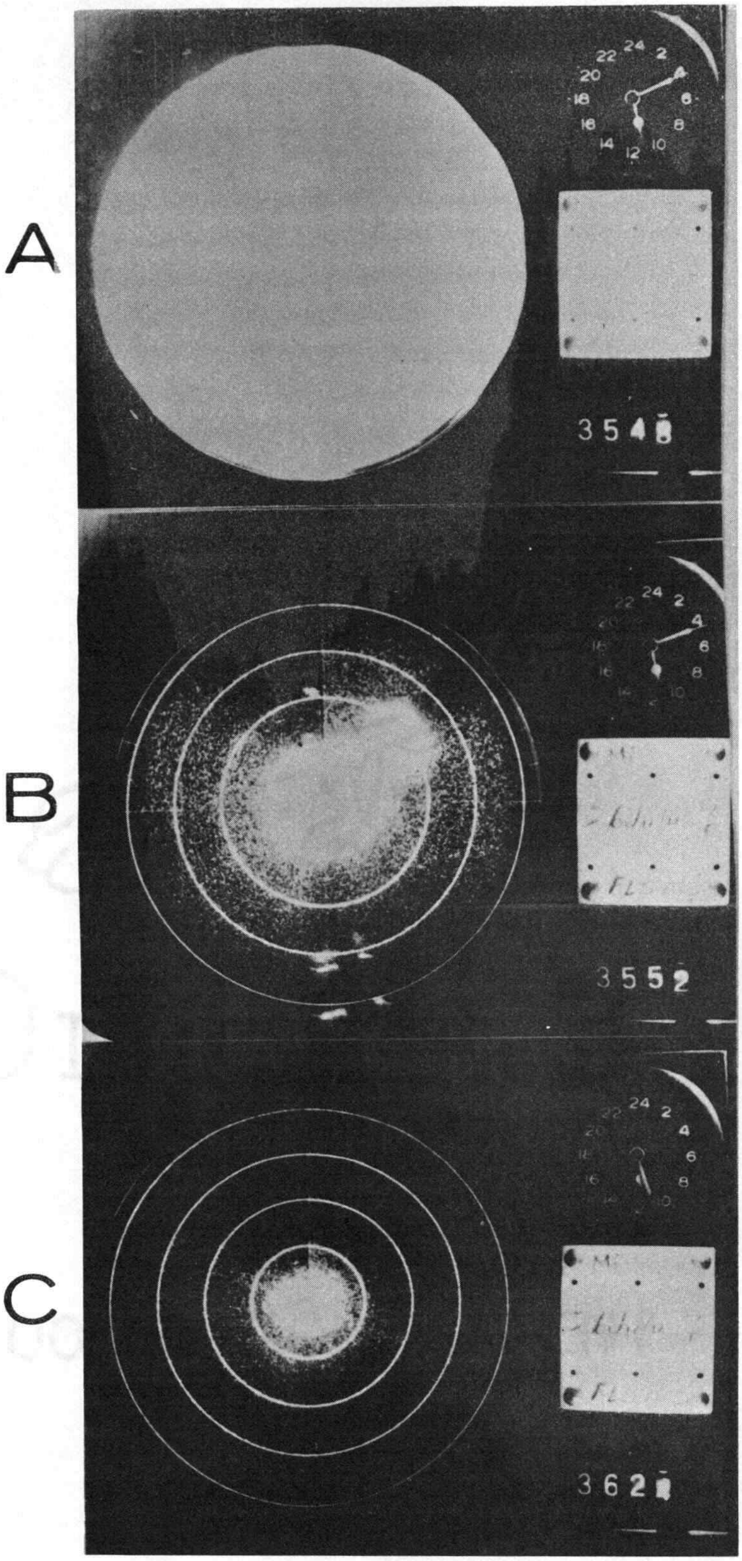

Figure 6. Thermal noise detected at tilt angles of 1°, 4°, and 11° on 26 July 1966 (5 n.mi. range rings)

antenna tilt of 11°. It will be noted that the "grass" level on the scope reduces radically as the antenna receives less and less thermal noise from the ground.

Thus, whenever the maser was operated and the radar was on short pulse, thermal noise should have been detected. Quantitative measurements of weak signals under these conditions are nearly meaningless because the minimum detectable signal changes several db as the antenna scans objects of various temperatures. If the sensitivity of the receiver is reduced, as with a step-gain control or some other device, thermal noise is no longer detected, and, hence, no longer a problem. However, the only reasonable justification for having a maser is to use it to improve the minimum detectable signal. There would be little advantage and several disadvantages to using a maser to increase the gain and then reduce the gain elsewhere just to avoid thermal noise.

ADVANTAGES OF USING THE MASER

Now that the major disadvantages of the maser have been considered, some of the advantages actually realized will be noted as well as some potential advantages obtained by using the maser for the detection of meteorological targets. The primary use intended for the maser was in the detection of echoes not detected or not easily detected by other X-band radars. Clouds are the principal meteorological source of targets in this category. Thus, the uses of a maser for cloud detection will be discussed first. Following this are the uses of a maser for other meteorological targets--precipitation, fog, and clear air turbulence. Finally the uses of a maser for detecting insects and birds will be considered.

Cloud detection

Clouds generally have radar reflectivities of such magnitudes that they are not detected by most X-band radars beyond a few miles at best. An examination will be made of what might be expected with the maser-equipped MPS-34 and what was actually detected during a study designed to detect clouds in early December 1966. In this study the antenna was aimed at 75^{o} tilt with the maser in its normal, upright position. The maser was operated with a small but continuous amount of tickler current; the maser was returned hourly.

By considering the reported reflectivities of clouds, their maximum range of detection may be determined. Ignatova et al. (16) have experimentally measured reflectivity factors from cirrus (Ci), altocumulus (Ac), altostratus (As), stratocumulus (Sc), and nimbostratus (Ns) clouds. These are listed in Table 2. The maximum range of detection for the MPS-34 for the corresponding reflectivity factors are also listed in Table 2. These are based on a receiver MDS of -113 dbm, a peak power transmitted at 84 dbm, an antenna gain of 36.2 db, and short pulse operation.

Table 2. 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	$5x10^{-3}$	0.72	$5x10^{-2}$	2.3	$5x10^{0}$	23
Ac,As	$5x10^{-4}$	0.5	$5x10^{-1}$	16	$5x10^{1}$	160
Sc	$5x10^{-3}$	1.6	$5x10^{-1}$	16	$5x10^{0}$	50
Ns	$5x10^{-1}$	16	$5x10^{1}$	160	$5x10^{2}$	500

From Table 2 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 have to operate at relatively large tilt angles, so that the slant range of the radar is small enough that these weak reflectivities are detectable. Ac and As of average reflectivity at 10,000 ft would require a tilt of at least 6° to be detected, while Ci at the same height would require a tilt of 44°.

The maximum range of detection for strong Ac, As, and Ns clouds is unreasonable because the curvature of the earth 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 ft (diameter or thickness) cease being beam-filling targets as 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 the maximum detected ranges did not seem to be limited by reflectivity. A comparison between the TPQ-11 at Chanute Air Force Base, Rantoul, Illinois, 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 $Z \propto P_r/P_t$, 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 3.

Table 3. Average reflectivity factors at 5000-ft intervals between 0620 CST on 1 December and 0020 CST on 2 December 1966

H (ft)	5,000	10,000	15,000	20,000	25,000
r (n.mi.)	0.85	1.70	2.55	3.40	4.25
$\bar{Z}$ (mm^6m^{-3})	$5.2x10^{-1}$	$3.0x10^{-1}$	$1.8x10^{-1}$	$6.2x10^{-2}$	$3.8x10^{-2}$
$\bar{Z}_{ns}$ (mm^6m^{-3})	$1.4x10^{-2}$	$4.3x10^{-2}$	$1.5x10^{-1}$	$6.0x10^{-2}$	$3.5x10^{-2}$

H - height

r - slant range

$\bar{Z}$ - average reflectivity factor

$\bar{Z}_{ns}$ - average reflectivity factor during period of no snow (1800-2400 CST, 1 December)

The decrease with height of $\bar{Z}$ 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. $\bar{Z}_{ns}$ does not show the same profile but rather has its maximum near 15,000 ft. This agrees very generally with the average height of clouds detected by the TPQ-11 for the same period. 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 mi. One additional point that should be made is that the reflectivity factors in Table 3 are averages and do not represent instantaneous profiles through individual clouds.

As a point of interest in a consideration of cloud detection with a sensitive radar, Braham (7) has detected ice crystals in cloud-free air 13,000 ft beneath cirrus uncinus clouds at 35,000 ft. He reports concentrations of 10^6 crystals/m^3. If these crystals average 100 μ in diameter, the reflectivity factor from this would be on the order of 1 mm^6m^{-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 on 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 μsec 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.

The greatest drawback to the cloud data collected by the MPS-34 in Illinois was the large number of ground clutter targets detected in the antenna's side- and back-lobes (see Figure 4). If it were not for these, a maser-equipped radar could serve double duty by detecting overhead clouds during precipitation-free periods. The potential usefulness of a maser on an X-band radar for cloud detection thus is quite good.

Precipitation detection

The detection of rain is generally not a great problem for an X-band radar with characteristics similar to or better than those of the AN/CPS-9.

Light rain (0.01 in/hr) should be detectable out as far as 156 n.mi. with the normal MPS-34 (long pulse, P_r = -106 dbm, P_t = 250 kw, assuming $Z = 200\ R^{1.6}$, where R is rain rate in mm/hr). Continuous light rain generally falls from relatively low clouds with 5,000 to 10,000 ft tops. The problem, then, for light rain detection is not so much one limited by the radar as it is one limited by the physical situation--a 0° tilt radar beam at 160 n.mi. is more than 18,000 ft above the surface (i.e., above the level of the radar, assuming standard atmospheric refraction applies). ESSA (38, p. 5-5) gives very hard rain as rain falling at a rate of more than 5 in/hr. For the same MPS-34, a beam-filling 5 in/hr rain rate would be detectable out to a distance of 23,400 n.mi.! It is obvious that a maser is not needed for heavy precipitation rates.

For strong storms with reflectivity factors on the order of 10^5 to 10^6 mm^6m^{-3} it is necessary to consider detection near the least sensitive end of the dynamic range. The closest distance at which the intensity of an echo of 10^6 mm^6m^{-3} reflectivity factor could be measured if the receiver has a dynamic range of 60 db, an MDS of -106 dbm, and a gain reduction of 60 db is 6.4 n.mi. If we add a maser with 10 db gain to the system, this minimum range for quantitative measurement increases to 20.2 n.mi. Thus, for measuring strong storm intensities close to the radar, it would be better not to have the maser on the radar.

The maser might well find application on a less sensitive, lower power radar than the MPS-34 and prove quite useful for rain detection. However, most X-band radars in use today do not need a maser to improve their rain detecting capabilities.

Generally the same conclusions hold for heavy snow as for rain. Snow also falls from clouds with tops below about 20,000 ft. This limits the range of snow detection to about 170 n.mi. The normal MPS-34 should detect heavy snow out as far as 2000 n.mi. Again this is not at all realistic because of both earth's curvature and because a 20,000 ft echo ceases to fill the beam of the MPS-34 at about 170 n.mi.

On the other hand, there might be some advantages to using the maser for light snow. The normal MPS-34 should detect light snow ($Z = 3x10^1$ mm^6m^{-3}) only out to 84 n.mi. A 10 db maser gain would increase this 3.16 times or to 265 n.mi. For snow, 265 n.mi.

is well beyond the limits of detectability because of height considerations while 84 n.mi. is not. Thus, there might be some advantage to using a maser for snow detection.

Only one case from the MPS-34 data collected during snow periods has been studied, that of 1 February 1966. In this case it was concluded that the radar with the maser was detecting all the snow within radar line of sight. The height of the beam at the maximum range of echo detected (153 n.mi. at $2/3^{\circ}$ tilt) was 30,000 ft which was also the height of the echo tops.

Since most hail storms of consequence occur in moderate or heavy rain storms, there should be little advantage to using a maser for the detection of hail storms. The maser might even introduce the disadvantage mentioned earlier of making quantitative measurements of nearby strong echoes impossible. Another potential problem is that echoes from strong storms might even exceed the -35 dbm saturation level of the maser. If hail occurred with an equivalent radar reflectivity factor of 10^{6} $mm^{6}m^{-3}$, a power level of -35 dbm would be reached if the echo came within 8.2 n.mi. (assuming long pulse operations and P_t = 83 dbm). Weaker echoes and short pulse operation reduce this range limitation somewhat.

In the discussion of precipitation detection thus far the effects of attenuation have been neglected. Since the additional gain provided by the maser could help compensate for attenuation of the radar energy by both hydrometeors and by atmospheric gases, the improvement which might be possible will now be considered.

Attenuation by gases is generally small. Water vapor attenuation at 3.2 cm wavelength over a 100 n.mi. two-way path is about 3 db based on a moist atmosphere of 10 g/kg water vapor content. Beyond 100 n.mi. the beam is probably high enough that little additional attenuation would result because of the presence of water vapor. The attenuation by oxygen at $\lambda = 3.2$ cm is about 3 db for a two-way 100 n.mi. path. Table 4 gives the average total attenuation by gases during winter and summer for two-way path lengths of 50, 100, and 150 n.mi. Also included in the table is the attenuation for clouds, assuming there are no clouds within 25 n.mi. because the beam is at low levels, and that the average liquid water content beyond 25 n.mi. is 0.1 g m^{-3} for heights up to 15,000 ft. Table 4 and the discussion of it are based on information in General Application of Meteorological Radar Sets (36, p. 27).

Gases are always absorbing and scattering the radar energy, and the amount of attenuation thus produced for a 100 n.mi. two-way path, for example, is generally within two or three decibels of the average value, even when including the effects of cloud attenuation.

Table 4. Estimated two-way atmospheric and cloud attenuation (db) for 3.2-cm wavelength radar.

	Atmospheric attenuation		
Range (n.mi.)	Winter	Summer	Cloud attenuation
50	2.2	2.9	0.8
100	3.5	4.7	2.4
150	4.2	5.6	3.6

The attenuation resulting from liquid precipitation, however, is highly variable, depending primarily on the rate of precipitation. For the sake of illustration, the empirical relationship given by Gunn and East (14, p. 539) will serve to provide some numerical examples. This relationship is

$$k_p = 7.4\text{x}10^{-3}\ R^{1.31} ,$$

where R is the rain rate in mm/hr and k_p is the attenuation because of precipitation in db/km.

Light precipitation with rates less than 10 mm/hr would produce a two-way attenuation less than 0.30 db/km of path length. Widespread areas of light precipitation are characteristic of some types of storms and could produce large total effects. A 50 n.mi. extent of 10 mm/hr rain would produce 28 db total attenuation.

On the other hand, heavy rains, while usually less extensive, produce greater attenuations per unit length. A 5 n.mi. extent of 100 mm/hr rain would result in a 58 db attenuation, again the total for two-way transmission. Thus, the effects of attenuation can be quite large and highly variable.

The added gain from the maser easily compensates for gas and cloud attenuation within most useful radar ranges. Certainly, a 10 db or greater maser gain also contributes additional information normally lost because of attenuation by precipitation, but it appears from the numerical examples that attenuation due to precipitation would often exceed this gain.

The discussion of precipitation attenuation above applies only to rain. Attenuation by snow is not as well understood and is not as easily estimated quantitatively. Gunn and East's (14, p. 536) calculations indicate that attenuation by snow is probably more than an order of magnitude less than that for liquid precipitation at the same rain (liquid water) rate. In addition, the water equivalent rain rate of snow is generally less than that for liquid forms of precipitation. Thus, except for the case of melting snowflakes, attenuation due to snow may generally be neglected without serious error.

Fog detection

No fog occurred during the period 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 (8, p. 143) summarizes the results of several researchers' reports of cloud and fog characteristics. A typical median droplet diameter might be 10 μ 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/cm^3 and a liquid water content of 0.25 g m^{-3} are probably representative.

Another set of values may be obtained. Atlas (2) 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 3×10^{-3} $mm^6 m^{-3}$ when M = 0.25 g m^{-3}.

Still a third set of values may be obtained by using $Z = N_i D_i^6$ and assuming all the fog droplets have the median droplet diameter, giving $Z = 2 \times 10^{-4}$ $mm^6 m^{-3}$. Mason (22, p. 97) quotes a medium volume diameter for sea fog of 46 μ. This would result in a Z (when the concentration is again 200 drops/cm^3) of nearly 2×10^0 $mm^6 m^{-3}$.

The variation in these values is fairly large, but they do generally agree with the Z's from stratocumulus reported by Ignatova in Table 3. The average value determined above for fog is lower than that for average Sc. Kulikova (18) reports reflectivity factors from fog as low as 1.8×10^{-6} $mm^6 m^{-3}$ with his average being 4×10^{-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 equation.)

If a value of 5×10^{-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 low 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.

Clear-air turbulence detection

A potential source of echoes during fair weather is clear-air turbulence (CAT). Atlas et al. (3) 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 10^{-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 capability of the MPS-34 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 et 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 100 ft would be required to detect weak CAT with the maser-equipped MPS-34.

Insect detection

Insects are not usually thought to be related to metorology. However, because they are detectable by radar it is worth considering the use of the maser to aid in this detection. Glover et al. (12) measured the back-scattering cross-sectional areas of a winged hawkmoth and a honey bee 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. Without a 10 db maser gain the moth would be detectable only to 2.8 n.mi. and the bee, only to 1.01 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. By tilting upward somewhat, however, the likelihood of detecting insects would be increased. With ideal conditions it is possible that large insects might be detected, but this has not been verified experimentally with the MPS-34.

Lhermite and Dooley (21), using the X-band doppler radar, were routinely able during spring, summer, and fall to make measurements of the instantaneous winds by detecting targets (concluded to be insects) carried by the wind in the clear atmosphere. Under some conditions it would be possible to determine speeds of movement of echoes from insects detected by a non-doppler radar. As just shown, however, the maximum range is quite short. Also, the analysis for speed determinations is likely too time-consuming for any use other than research where real time analyses are not generally required.

While it is theoretically possible to detect insects with the maser-equipped MPS-34, actually the problems of detection and identification would make it not appear as a very rewarding undertaking.

Bird detection

Birds were detected with the MPS-34 in two locations and the details of these cases are reported by Rinehart (24). Data were collected on 11 days in August 1965 during the New Mexico operations and on 16 May 1966 in Illinois. The primary result of the bird detection study that is of concern to an evaluation of the advantages of the maser is the maximum range of detection of birds of various sizes.

The questions to consider then are how large is the radar back-scattering cross-section of a bird and how far can a single bird be detected on the MPS-34 radar. Houghton (15) found that the best simple estimate of a cross-sectional area of a bird 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 7 shows the minimum back-scattering cross-sectional area of a target which can be detected by the normal 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 curve applies when the MPS-34 is using the maser with 10 db gain. 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 in Figure 7 are the back-scattering cross-sectional areas of a sea gull measured by Richardson et al. (23), a starling measured by Houghton (15), and the range of areas of one turkey buzzard in flight measured by LaGrone, Dean, and Walker (20).

The farthest echo detected in the one full-gain frame of data examined from 20 August 1965 was at 7.0 n.mi. This requires a back-scattering cross-sectional area of 4.5×10^{-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 possibly 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. was an evaluation of nearly 21,000 ft above MSL.

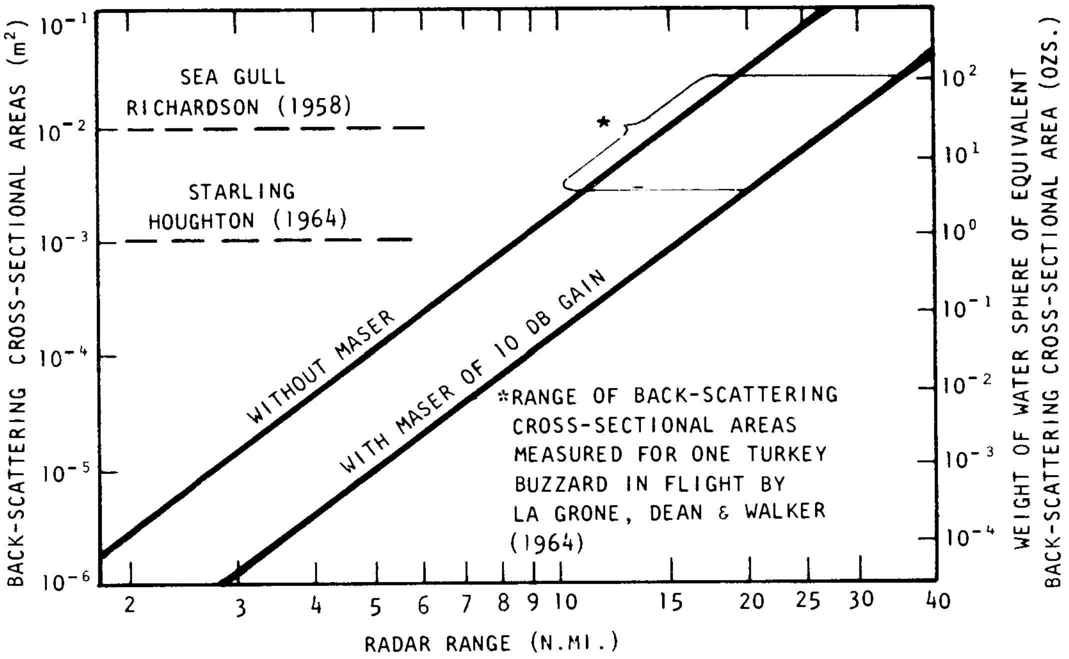

Figure 7. Radar back-scattering cross-sectional areas for targets just above the threshold of detectability for the AN/MPS-34 radar with and without the maser.

It is obvious from Figure 7 that birds should be easily detectable with the maser-equipped MPS-34 out beyond the normal limits of ground clutter interference. The fact that the MPS-34 did detect birds without the maser, indicates that a maser is not a necessity for bird detection. However, it nearly doubles the maximum range of detection, and hence could prove to be quite worthwhile under certain conditions. One of the biggest problems, however, is that of determining that the echoes are, in fact, caused by birds. This is especially true since Sutter (35), as quoted by Lack (19), says that high-flying migrating birds cannot be seen during the day, even with military optical equipment.

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

CONCLUSIONS

After studying the data collected with the maser on the AN/MPS-34 radar and the results of the investigations into the potential uses of the maser on the radar, several conclusions can be made.

(1) First of all, the maser as used on the MPS-34 is not ready for operational use. The problems of (a) maintaining proper alignment between the ruby crystals and the magnetic field, (b) maintaining the maser in the required liquid helium bath, (c) tuning and maintaining the proper magnetic field strength, (d) loss of gain through saturation of the maser, and (e) unstable maser gain combine to make it extremely difficult to operate the maser for continuous duty.

It would not be necessary to completely eliminate all of these problems to make the maser operationally useful. For instance, if the maser gain could be made stable (i.e., by making the maser magnet stable) the tuning problems would be eliminated. Then the advantages to be achieved by using the maser would be sufficient to warrant the effort needed to overcome the logistics problems. Similarly, eliminating the logistics problems by use of a closed-cycle cryogenics system might make it possible to use the time and money normally expended for charging the maser to provide a means of more frequent tuning or continuous monitoring of the overall system sensitivity; this would mean that the data could be used quantitatively with some assurance that the results would be meaningful. If the maser could be made to accept a wider range of input power levels (as might well be possible with 1968 or later technology), the problems of saturation might no longer exist; this would enable the MPS-34, for example, to operate on long pulse, thus avoiding some of the thermal noise detection and allow fuller utilization of the inherent gain.

(2) A second conclusion is that, on a sensitive radar such as the MPS-34, there is little advantage to having an additional 10 to 12 db gain for precipitation detection. Rain, snow, and hail are generally detectable without the gain of the maser to distances beyond radar line-of-sight.

(3) There is some advantage to additional gain for the detection of clouds, birds, and insects. Beam-filling distributed targets should be detected out four times farther while point targets should be detected out twice as far when 12 db additional gain is added to a radar system. However, since most X-band weather radars are not concerned with cloud detection, let alone birds or insects, these inherent advantages might not find general application in weather radar use.

(4) The two other sources of radar targets considered, fog and clear air turbulence, provide such weak echoes that adding 10 db of gain to the MPS-34 did not provide nearly enough improvement to make the detection of these phenonema at all feasible.

(5) A fifth conclusion is that the additional gain provided by the maser made it possible for the MPS-34 to detect thermal noise while operating on short pulse. This is by far the most interesting result of the study. The greatest disadvantage to having enough sensitivity to detect thermal noise is that the minimum detectable signal of the radar changes as the antenna scans objects of different temperatures. Consequently, it becomes impossible to measure accurately the signal strength of any echo which equals or just slightly exceeds the MDS of the system.

The simplest way to reduce thermal noise detection with the MPS-34 would have been to use long pulse. The narrow band width of long pulse made thermal noise power from 300 K targets only -115 dbm compared to -108 dbm for short pulse. However, as mentioned earlier, long pulse operation of the MPS-34 radar saturated the maser, resulting in a loss of over-all system sensitivity of about 5 db.

Overall, it may be concluded that the addition of a maser to the MPS-34 did increase the amount of echo detected by quite reasonable amounts. It required considerable effort to use this particular maser, but the results on some occasions seemed to justify the effort.

RECOMMENDATIONS

Several uses for a device which increases what a radar "sees" are easily envisioned. Since the maser improves the MDS of a radar (thermal noise detection excepted) the most logical use of a maser is for the detection of targets just barely detectable or just below the threshold of detectability, i.e., producing echoes too weak for detection by a given radar. One such use in cloud physics would be the study of first echoes. Another use on X-band radar would be for cloud detection. The experiences during cloud detection with the MPS-34, however, indicate that a better antenna pattern or shielding to avoid ground target detection with antenna back-lobes might be necessary to make this worthwhile. A further use would be to put a maser on some radar of another wavelength. For example, since 10 cm wavelength radars are affected much less by precipitation attenuation than 3 cm wavelength radars, the addition of a maser might increase the 10 cm radar's precipitation detection capabilities sufficiently to make it more nearly comparable to 3 cm radar. Although not strictly a meteorological use, the advantages for bird detection might well make a maser useful for studying bird migrations and related bird activities.

A good use of the maser which has not been considered yet is to use it on a less sensitive radar. There are distinct advantages to this. Many low-power, less sensitive X-band radars are not able to detect weak precipitation beyond just a few miles, although they normally have no trouble detecting moderate or strong precipitation. The gain of the maser on such a set would be quite valuable for aid in precipitation detection. In addition, the amount of gain the maser would provide is likely more on an insensitive set than on a radar like the MPS-34 or a CPS-9. The results of Table 1 indicate that as the sensitivity of the MPS-34 decreased (through gain-step reduction) the amount of gain provided by the maser increased. Thus, an insensitive receiver might be improved by 15 db or more by using the maser while the MPS-34 was only improved operationally by 8 to 12 db. There is, of course, a limit on this of about 20 db, the maximum gain of the maser. Another possible advantage is the gain-to-weight ratio of the maser system. For example, putting a maser of 15 db gain on a radar would give the same results as increasing a 50 kw transmitter to 1.6 Mw. The added weight for larger power supplies, larger transmitter, and required cooling systems for this large a transmitted power would likely exceed by one or more times the weight of a maser designed with weight as a design criteria. This, however, is only speculation.

If the meteorological targets of interest are of a type which are just barely detectable or just beyond detection with a given radar, primarily a sensitive radar in good operating condition, an integrator might provide more and better information than a maser of 10 db gain. This is certainly true if the gain of the maser is enough to make the radar detect thermal noise, as it did on the MPS-34. Integrators which are capable of detecting meteorological signals 8 or 9 db below the normal noise level of a receiver have been used on weather radars (40). Because of its random nature, thermal noise would have little or no effect on meteorological signal detection.

Finally, it would be very interesting to have available a reliable maser of constant high gain which required no charging with liquid helium and a minimum of tuning and maintenance. Perhaps such a device will become available in the future. If so, there would likely be many areas in the realm of radar meteorology in which the frontiers of knowledge might be considerably expanded through the intelligent use of such a maser.

BIBLIOGRAPHY

1. Adler, Simpson B. A maser that works in radar by avoiding saturation. Electronics 40(12):115-120. 1967.

2. Atlas, David. The estimation of cloud parameters by radar. Journal of Meteorology 11:309-317. 1954.

3. Atlas, David, Kenneth R. Hardy and Keikichi Naito. Optimizing the radar detection of clear air turbulence. Journal of Applied Meteorology 5:450-460. 1966.

4. Basov, N. G. and A. M. Prokhorov. Zhurnal Eksperimental' noǐ i Theoreticheskoi Fiziki 27:431. 1954.

5. Battan, Louis J. Radar meteorology. Chicago, University of Chicago Press, 1959. 161 p.

6. Berkowitz, Raymond S. Modern radar, analysis, evaluation, and system design. New York, John Wiley & Sons, 1965. 660 p.

7. Braham, Roscoe R., Jr. Rain physics research, April, 1965 to April, 1966. Chicago, 1966. 79 p. (University of Chicago. Department of Geophysical Sciences. Cloud Physics Laboratory. Annual report on National Science Foundation Grand NSF-GP3779)

8. Byers, Horace Robert. Elements of cloud physics. Chicago, University of Chicago Press, 1965. 191 p.

9. Description and operating instructions for X-band tunable maser. Malibu, California, Hughes Aircraft Company Research Laboratory, 1962.

10. Forward, R. L., F. E. Goodwin and J. E. Keifer. Application of a solid-state ruby maser to an X-band radar system. In: Antennas and propagation microwave theory and techniques. IRE WESCON Convention Record. Part 1. New York, Institute of Radio Engineers, 1959. p. 119-125.

11. Forward, R. L. and F. Richey. Effects of external noise on radar performance. Microwave Journal 3(12):73-80. 1960.

12. Glover, Kenneth M., Kenneth R. Hardy and Claud R. Landry. Radar characteristics of known insects in free flight. In: Proceedings of the 12th Conference on Radar Meteorology, Norman, Oklahoma, 1966. [Boston], American Meteorological Society, n.d. p. 254-258.

13. Gordon, J. P., H. J. Zeiger and C. H. Townes. Microwave molecular oscillator and new hyperfine structure in the microwave spectrum of NH_3. Physical Review 95:282. 1954.

14. Gunn, K. L. S. and T. W. R. East. The microwave properties of precipitation particles. Quarterly Journal of the Royal Meteorological Society 80:522-545. 1954.

15. Houghton, E. H. Detection, recognition and identification of birds on radar. In: World Conference on Radio Meteorology Incorporating the 11th Weather Radar Conference, Boulder, Colorado, 1964. [Boulder, U. S. National Bureau of Standards], n.d. p. 14-21.

16. Ignatova, R. V. et al. Radar echo characteristics of clouds. Leningrad. Glavnaia Geofizicheskaia Observatoriia, Trudy 173:26-33. 1965. (Translated by the American Meteorological Society for the Air Force Cambridge Research Laboratories, Jan., 1966. 11 p.)

17. Jones, D. M. A., R. E. Rinehart, E. A. Mueller and D. W. Staggs. Evaluation of the maser-equipped radar set AN/MPS-34 and Area Precipitation Measurement Indicator. Urbana, May, 1967. 47 p. (Illinois. State Water Survey. Technical Report ECOM-01257-F on Contract DA-28-043 AMC-01257(E) of the U. S. Army Electronics Command, Fort Monmouth)

18. Kulikova, G. I. et al. Possibility of radar determination of visibility of fogs. Leningrad. Glavnaia Geofizicheskaia Observatoriia, Trudy 173:71-75. 1965. (Translated by the American Meteorological Society for the Air Force Cambridge Research Laboratories, Jan., 1966. 9 p.)

19. Lack, David. The height of bird migration. British Birds 53(1):5-10. 1960.

20. LaGrone, A. H., A. P. Dean and G. B. Walker. Angles, insects, and weather. U. S. National Bureau of Standards Journal of Research, sec. D., Radio Science 68:895-901. 1964.

21. Lhermite, Roger M. and J. T. Dooly. Doppler study of the motion of clear air targets. In: Proceedings of the 12th Conference on Radar Meteorology, Norman, Oklahoma, 1966. [Boston], American Meteorological Society, n.d. p. 293-299.

22. Mason, B. J. The physics of clouds. London, Oxford University Press, 1957. 481 p.

23. Richardson, R. E. et al. Radio Observation of birds. In: Proceedings of the Seventh Weather Radar Conference of the American Meteorological Society, Miami Beach, 1958. [Boston], n.d. p. D-1 to D-8.

24. Rinehart, R. E. Radar detection of birds in New Mexico. In: Evaluation of the maser-equipped radar set AN/MPS-34 and Area Precipitation Measurement Indicator, ed. by D. M. A. Jones et al. Appendix. Urbana, May, 1967. 47 p. (Illinois. State Water Survey. Technical Report ECOM-01257-F on Contract DA-28-043 AMC-01257(E) of the U. S. Army Electronics Command, Fort Monmouth)

25. ______________ Evaluation of the maser-equipped radar set AN/MPS-34 and Area Precipitation Measurement Indicator. Urbana, Nov., 1966. 21 p. (Illinois. State Water Survey. Technical Report ECOM-01257-5 on Contract DA-28-043 AMC-01257(E) of the U. S. Army Electronics Command, Fort Monmouth)

26. Rinehart, R. E. and D. M. A. Jones. Evaluation of the maser-equipped radar set AN/MPS-34 and Area Precipitation Measurement Indicator. Urbana, July, 1965. 9 p. (Illinois. State Water Survey. Report No. 1 on Contract DA-28-043 AMC-01257(E) of the U. S. Army Electronics Laboratory, Fort Monmouth. DDC number AD 623 468)

27. ______________ Evaluation of the maser-equipped radar set AN/MPS-34 and Area Precipitation Measurement Indicator. Urbana, Oct., 1965. 14 p. (Illinois. State Water Survey. Report No. 2 on Contract DA-28-043 AMC-01257(E) of the U. S. Army Electronics Command, Fort Monmouth. DDC number AD 625 760)

28. Rinehart, R. E., D. M. A. Jones and E. A. Mueller. Evaluation of the maser-equipped radar set AN/MPS-34 and Area Precipitation Measurement Indicator. Urbana, Jan., 1966. 32 p. (Illinois. State Water Survey. Technical Report ECOM-01257-3 on Contract DA-28-043 AMC-01257(E) of the U. S. Army Electronics Command, Fort Monmouth)

29. Rinehart, R. E., E. A. Mueller, and D. W. Staggs. Evaluation of the maser-equipped radar set AN/MPS-34 and Area Precipitation Measurement Indicator. Urbana, April, 1966. 17 p. (Illinois. State Water Survey. Technical Report ECOM-01257-4 on Contract DA-28-043 AMC-01257(E) of the U. S. Army Electronics Command, Fort Monmouth)

30. Robbiani, R. L. Application of maser to nuclear/weather surveillance radar. Fort Monmouth, 1960. 13 p. (U.S. Army Electronics Laboratories. Technical Report 2151)

31. ________________ Engineering test of X-band maser for weather radar set AN/MPS-34. Fort Monmouth, 1964. 29 p. (Technical Report 2427 on DA Task 1A0-25001-A-26-03 of the U. S. Army Electronics Research and Development Laboratories. DDC number AD 602 141)

32. ________________ Increased meteorological target detection by X-band radar set AN/MPS-34 using maser preamplifier. In: World Conference on Radio Meteorology Incorporating the 11th Weather Radar Conference, Boulder, Colorado, 1964. [Boulder, U. S. National Bureau of Standards], n.d. p. 310-315.

33. ________________ High-performance weather radar. IEEE Transactions on Aerospace and Electronic Systems AES-1:185-192. 1965.

34. Siegman, A. E. Microwave solid-state masers. New York, McGraw-Hill Book Company, 1964. 583 p.

35. Sutter, E. Über die Flughohe ziehender Vogel. Der Ornithoolgische Beobachter 47:174. 1950.

36. United Aircraft Corporate Systems Center. General application of meteorological radar sets. April, 1965. 126 p. (U. S. Air Force. Air Weather Service (MATS). Technical Report 184)

37. U. S. National Aeronautics and Space Administration. Lasers and masers: a continuing bibliography, 1962/65. Washington, D. C., 1966. 127 p. (NASA SP-7009)

38. Weather radar manual, Part A (WBAN). Washington, D. C., U. S. Department of Commerce, Environmental Sciences Services Administration, 1967. 25 p.

39. Weber, J. Amplification of microwave radiation by substances not in thermal equilibrium. Transactions of the IRE, Professional Group on Electronic Devices, no. 3, June, 1953, p. 1-4.

40. Weger, Eric. Apparent sky temperatures in the microwave region. Journal of Meteorology 17:159-165. 1960.

41. Zhupakhin, K. S. The use of an integrator to increase the meteorological efficiency of a radar. Leningrad. Glavnaia Geofizicheskaia Observatoriia, Trudy 173:63-70. 1965. (Translated by the American Meteorological Society for the Air Force Cambridge Research Laboratories, 1966. 13 p. DDC number AD 630 674)

APPENDIX

GLOSSARY

A-scope: A cathode-ray display which portrays signal intensity (amplitude) and range (time) as ordinate and abscissa, respectively.

amplifier: A device which enables an input signal to control a source of power, and thus is capable of delivering at its output an enlarged reproduction of the essential characteristics of the signal.

antenna system: The waveguide, radiating element, and reflector of a radar system.

antenna gain: The gain of an antenna is the ratio of signal power at a point along the beam axis to the power that would be incident at the same point from an isotropic radiator transmitting the same total power.

bandwidth: The range of frequencies (centered on the receiver or transmitter frequency) which is passed through a device. The bandwidth is measured through the points which have 3 db less power than the frequency of maximum power (generally in units of MHz for radars).

bistatic radar: A radar system which transmits from one location and received at another location after the signal is scattered off some media.

calibration: The procedure of measuring the various powers and system losses necessary to make quantitative use of the radar data.

cavity maser: A maser which has the maser crystal in a cavity which has cavity resonances coincident with both the pump and signal frequencies of the maser crystal.

clear-air turbulence (CAT): Turbulence in the clear atmosphere not associated with cloud activity and which may be adverse to air traffic.

charging (the maser): The process of cooling the maser, initially with liquid nitrogen, and subsequently with liquid helium in preparation for operational use of the maser.

coherent signal (target): A radar echo whose phase and amplitude at a given range remain relatively constant; this type signal is returned from targets such as building, airplanes, spheres, corner reflectors, etc.

cryogenics: The study of the methods of producing very low temperature; the study of the behavior of materials and processes at cryogenic temperatures.

C-band: The band of radar frequencies between 3.9 and 6.2 GHz; the 5-cm wavelength radar band.

CW: Continuous wave; waves, the successive oscillations of which are identical under steady-state conditions.

decibel: 1/10 bel; 1 decibel = 10 $\log_{10} P_1/P_2$ where P_1 and P_2 are powers measured in the same units.

Dewar: A double-walled container (with a vacuum in the chamber between the inner and outer walls) used to hold substances whose temperatures are quite different than the ambient temperature surrounding the container.

display: The graphic presentation of the output data of any device or system.

duplexer: The device consisting of waveguide, TR and ATR tubes used to switch a single antenna between a transmitter and receiver at the appropriate time.

electromagnetic radiation: Energy propagated through space or through material media in the form of an advancing disturbance in electric and magnetic fields existing in space or in the media.

far field: The region of an antenna pattern beyond a distance of about $2D^2/\lambda$, where D is diameter of the antenna reflector and λ is wavelength; about 1000 ft for the AN/MPS-34.

ferrite isolator: The ferrite device inserted in between the maser and the TR switch designed to help prevent saturation of the maser during the transmit portion of the duty cycle.

gain: The ratio of output power from a device to the input power; gain is generally considered "gain" if the output is greater than the input and "attenuation" if the output is less than the input.

gain-bandwidth product: The product of the gain and the bandwidth of an amplifier (in units of frequency).

gas maser: A maser which uses a gas as the means of amplification.

grass: Sharp, closely spaced discontinuities in the trace of a cathode-ray tube, produced by random interference; so named because of their resemblence to blades of lawn grass on an A-scope.

IF: Intermediate frequency; the beat frequency used in heterodyne receivers, usually the difference between the received radio-frequency signal and a locally generated signal.

incoherent signal (target): A signal which has a fluctuating phase and/or amplitude; this type signal is returned from targets such as meteorological targets and sea clutter.

integrator: A device whose output is proportional to the integral of an input signal; an integrator generally reduces the effects of noise, thus increasing the signal-to-noise ratio.

isotropic radiator: A device which radiates energy equally in all directions.

K-band radar: The band of radar frequencies between 10.9 and 36 GHz; for meteorological use, the 1.86-cm wavelength band.

maser: An amplifier utilizing the principle of microwave amplification by stimulated emission of radiation; the process of amplification by means of a maser amplifier.

MDS: Minimum discernable signal; the smallest signal which can be detected (separated) from the noise level.

microwave radiation: Electromagnetic radiation with a wavelength between about 0.1 and 100 cm.

monostatic radar: A radar which transmits and receives from the same location; the received signal is back-scattered from the target.

noise: Unwanted, random signals which interfere and tend to mask the signal of interest.

PPI: Plan position indicator; a radar display which portrays position as on a map (N-S, E-W, radar in the center) and intensity by brightness of the signal.

PRF: Pulse repetition frequency; the number of transmitted pulses per unit of time (generally, pulses per second, pps).

pulse length: The length in space or duration in time of the transmitted pulse.

pump oscillator: The oscillator which supplies the energy necessary to "pump" the electrons in the ruby crystals of the maser to the excited state required for masing action.

radar: Radio detection and ranging: a method, system, or technique of using beamed, reflected, and timed electromagnetic radiation for detecting, locating, or tracking objects, for measuring altitude, etc., in any of various activities.

receiving system: That portion of a radar which receives, detects, and amplifies the very weak signals back-scattered from a target and makes them strong enough for use by the display system.

recovery time: The time required for the maser to recover from the saturated condition (about 40 msec).

RF amplifier: A device which amplifies a radio frequency signal; for the MPS-34 this is an amplifier which operates at 9.3 GHz, i.e., the maser.

RHI: Range height indicator; a radar display which portrays echo height and range as ordinate and abscissa, respectively, and intensity as brightness.

ruby maser: A solid-state maser which uses rubies (typically about 99.9% nonmagnetic aluminum oxide Al_2O_3 and only 0.1% chromium oxide Cr_2O_3, where the Cr^{3+} chrominum ion is the magnetic ion) as the media for amplification.

saturation: The condition which occurs when an input signal is so large that further increases in the input signal do not result in any increase in the output signal; for the maser, the greatest problem related to saturation is the long recovery time after saturation ceases.

S-band radar: A radar which operates in the frequency band of 1.55 to 5.2 GHz; the 10-cm wavelength radar band.

sensitivity: The characteristic of a receiver which determines how small a signal the radar is capable of detecting and displaying.

scope: A cathode-ray tube used to display the received signal in any of several standard formats.

signal-to-noise ratio: The ratio of the signal power to the noise power; for detection, a signal generally has to equal or exceed the noise power.

solid state maser: A maser which uses a solid state material for the media which provides the amplification.

temperature of an amplifier: The temperature of an amplifier is the temperature of a resistor at the input of an ideal, noiseless amplifier (with the same gain as the actual amplifier) which produces the same output power as the actual amplifier.

thermal noise: Electromagnetic radiation radiated from all substances whose temperatures are above absolute zero.

tickler magnet: The electromagnet used to increase or decrease the magnetic field strength surrounding the rubies of the maser; the tickler magnet was used to either (1) pulse the permanent magnet of the maser to the proper magnitude for optimum masing action or (2) supply a small but constant amount of additional magnetic field strength, again for optimum performance.

tickler current: The current through the tickler magnet when it was supplying a constant magnetic field strength.

transmitter: That portion of the radar which generates and transmits into the waveguide the high power, radio frequency electromagnetic radiation.

transition region: The region of an antenna within a distance of about $2D^2/\lambda$, where D is the diameter of the antenna reflector and λ is the wavelength of radiation.

tunnel diode: A semiconductor device which is capable of amplifying at radar frequencies.

TR and ATR tubes: Transmit-receive and antitransmit-receive tubes; these tubes are used to protect the receiver from the powerful transmitted pulse while still allowing one antenna to be used for both receiving and transmitting.

tuning: The procedure of adjusting various components in a system for optimum performance.

X-band radar: A radar operating in the frequency band of 5.2 to 10.9 GHz; the 3-cm wavelength radar band.