

AN IMPROVED GATE SYSTEM FOR THE MADRE RADAR

[UNCLASSIFIED TITLE]

G. K. Jensen

Radar Techniques Branch
Radar Division

December 6, 1960



U. S. NAVAL RESEARCH LABORATORY
Washington, D.C.

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ABSTRACT

The Madre radar system achieves a high signal sensitivity and high range-rate resolution through the full use of crosscorrelation and storage techniques. It is thus well suited both for detecting long-range aircraft and for distinguishing among any such aircraft which differ only slightly in radial velocity.

To maintain nearly the same system sensitivity for Madre when used against rapidly accelerating targets, such as missiles, it is proposed that a set of acceleration gates be added. This will in no way alter the system's present capabilities against conventional aircraft. The modification will be accomplished by a curve-matching or fitting process. A large number of different built-in functions will be compared sequentially for the best match with the accelerating target signal.

Information-processing systems have also been proposed for the display of target data.

PROBLEM STATUS

This is an interim report on one phase of this problem; work is continuing on this and other phases.

AUTHORIZATION

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PROPOSED ACCELERATION GATE SYSTEM FOR THE IMPROVEMENT OF THE MADRE RADAR

INTRODUCTION

At the time the Madre radar was conceived, the main threats to our defenses were the manned bomber and the air-breathing missile. Thus the characteristics of the system were generally tailored to optimize the detection of this type of target. Below-the-horizon detection at great distances was envisioned by use of a one-hop ionospheric-propagation path. Through the use of crosscorrelation and storage techniques, great sensitivity to small changes in range rate was achieved, at some sacrifice in the accuracy of range information.

Recently there have been significant advances in the military sciences which have greatly increased the defense requirements. Now, one of our most urgent defense problems is the early detection of the incoming long-range missile. From the detection standpoint, the characteristics of the missile differ radically from those of the bomber. Higher accelerations and higher terminal velocities are primary differences. Also, the time available for detection (for an ionospheric radar) has been shortened to only the missile travel time from launching pad to the F-layer ionosphere.

Calculations on a computer are in progress to determine the actual acceleration characteristics that may be expected from all types of missiles. These curves are being used in further studies to determine the capability of the present Madre system in detecting a ballistic missile during the powered portion of its flight from launching pad to full cutoff.

It should be noted that Madre is admirably suited to enhancing the detectability of aircraft targets which have velocity changes of less than 5 knots in the 20 seconds required to fill the drum storage, or a corresponding acceleration less than 0.4 ft/sec^2 , assuming an operating frequency in the upper end of the band. On the other hand, preliminary results from the computer indicate that as long as the radar receiver site is not close to, or in, the plane of the missile's orbit, detection is possible over about a one-minute period with a loss of system sensitivity of 10 db or less. Above that which is realizable with a nonaccelerating target. Thus the present Madre would have during this entire time interval an overall system gain of 23 or more db instead of the maximum of 33 db. During portions of this time, the system degradation would be even less. It should be pointed out further that in operational use, since at least two radars would guard a given sector of space, detection may be possible by at least one such radar in all cases.

Enough detection failures would occur, however, to make it desirable to enhance the capabilities of the present system against accelerating targets, while maintaining its present capability against slower targets. It is evident that a system of acceleration gates must be devised comparable in number and sensitivity with the existing range-rate or velocity-gate system.

DESCRIPTION OF THE PRESENT MADRE RADAR SYSTEM

The Madre radar is a phase-coherent pulse-doppler system with the added sophistication of a pulse-sampling technique, and a magnetic-drum storage together with cross-correlation, which achieves a large gain in system sensitivity. A more complete description of the present system is available.*

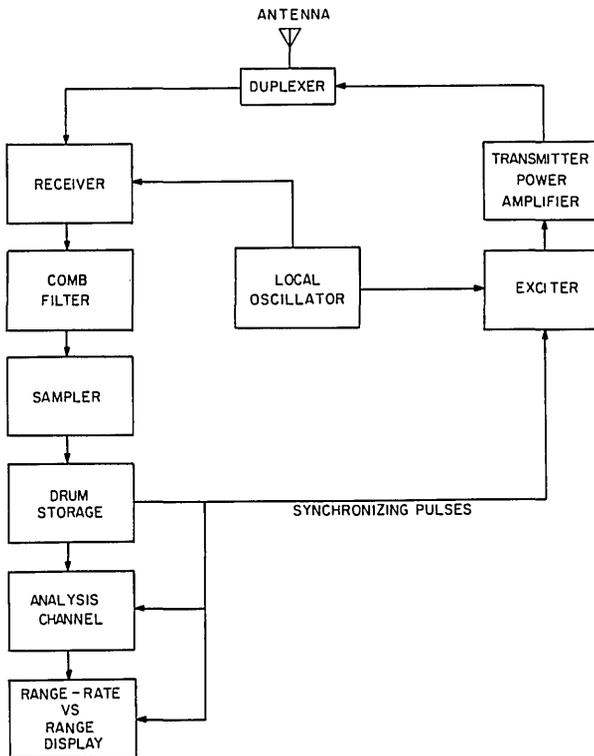


Fig. 1 - Simplified block diagram of the Madre radar

A simplified block diagram of the system is shown on Fig. 1. A pulse repetition rate of 180 cps is used which is obtained from a separate synchronizing track on the drum. This limits the highest unambiguous signal doppler frequency at the receiver output to 90 cps. The lower limit of the doppler frequency range, about 5.0 cps, is set by the necessity of rejecting backscatter (which exists below 4.0 cps) with a comb rejection filter. After the doppler signal is separated from the backscatter, it is amplitude-sampled with a very narrow sampling pulse in each of the 23 range gates in the pulse-repetition period, and the amplitude information is stored on a track around the drum in 23 corresponding range gates. Each succeeding pulse-repetition period is similarly sampled, and the samples are stored next to the first in each range gate. This process continues until at the end of 20 seconds 3600 samples have been laid side by side in each of the 23 range gates on the track around the circumference of the drum. At this point the storage has been filled, and from then on the oldest information is erased and the newest written in its place.

*F. E. Wyman and E. N. Zettle, "Magnetic Drum Storage Crosscorrelation Radar," NRL Report 5023 (Secret Report, Unclassified Title), Nov. 14, 1957.

Readout of the 3600 samples stored in each of the 23 range gates is accomplished in one revolution of the drum, or 1/180 second. This results in a compression of time by a factor of 82800, which permits the analysis of all range and range-rate gates in no more than the 20 seconds required to fill the storage. Because of the time compression, the original doppler frequencies (5 to 90 cps) are multiplied to 0.4 to 7.5 Mc. The original signal bandwidth of 4 kc (or 2 kc when foldover is considered) is in effect multiplied by this same ratio, so that if an output-signal bandwidth of 2 kc were also used, which it is, the equivalent narrow-banding would be equal to the ratio. In terms of the original signal bandwidth, the effective output bandwidth is 1/20 cps, which allows recovery of signals many db below the noise level.

Analysis of the output of the storage is accomplished by sweeping the center frequency of the output filter from the low to the high end of the doppler band at a rate of one bandwidth per drum revolution. All 23 range gates are examined for signals for a particular doppler frequency or range rate for a given drum revolution. On successive drum revolutions, all range gates are likewise examined for each increasingly higher range rate. In actual practice, the filter is not tuned over the doppler band, but the same result is obtained by heterodyning with a variable local oscillator. The filter output is presented as intensity modulation on a two-coordinate display with range rate forming the ordinate axis and range the abscissa. With a 2-kc filter bandwidth, 3500 range-rate gates would be formed in sweeping out the doppler band, which would take 20 seconds to complete. Twenty seconds was considered an excessive length of time for the range-rate sweep. It was reduced to about two seconds by utilizing a combination of predetection and postdetection narrow-banding while maintaining the same output bandwidth, instead of all predetection bandwidth narrowing. A limited amount of postdetection bandwidth narrowing can be tolerated without an appreciable loss in system sensitivity. The predetection bandwidth was widened to 30 kc while the output postdetection bandwidth was maintained at 2 kc. Range-rate resolution was decreased as a consequence, because the target signals in a range gate now are only required to remain confined to within a 30-kc bandwidth instead of a 2-kc bandwidth. Allowing for some overlap, there will now be 320 range-rate gates formed, which will require only about two seconds to sweep out.

Two analysis channels are actually used; the second has a predetection bandwidth of 8 kc to provide for a greater range-rate resolution if desired. The 30-kc channel provides a five-knot resolution, and the 8-kc channel about one-knot resolution at the upper end of the operating-frequency band. Since 20 seconds was required to fill the storage, this means that in the case of the 30-kc channel, the target must vary less than five knots in velocity in this period, or less than 0.25 knot per second, or 0.4 ft/sec² if no loss in system sensitivity is to be accepted. These figures reveal the difficulty. A range-rate resolution of 0.4 ft/sec is very useful for detection of aircraft but is a disadvantage which will result in loss of system sensitivity when detection of missiles with potentially high acceleration is attempted.

REQUIREMENTS OF THE ACCELERATION-GATE SYSTEM

The benefits of an acceleration-gate system will be more evident when the loss in system sensitivity that occurs when attempting to detect a missile with an extremely high radial acceleration of say 100 ft/sec² is considered. This could occur when the radar observer is in the plane of the missile trajectory. Targets whose accelerations exceed the 0.4 ft/sec² resolution of the system are ones whose doppler frequencies vary more than one predetection output-filter bandwidth (30 kc) in 20 seconds. In the above example, the doppler frequency will sweep over more than 200 range-rate gates, on an average, thus

dividing the signal energy by a like ratio, which results in a loss of 23 db in system sensitivity. Obviously, if the original system sensitivity is to be retained, some means must be devised to keep the doppler signal within the 30-kc bandwidth of the analysis filter. This can be accomplished by modulating the local-oscillator frequency feeding the analysis channel with a time-varying function which is just the reverse of the time variation of the doppler frequency coming from the drum storage, so as to effect a cancellation of this variation. If the match between the local-oscillator modulation and that of the doppler signal is sufficiently close, then the resultant signal will remain in the analysis filter for the full time, or 240 μ sec the width of one range gate, and a full-amplitude output signal will be available for display.

To be certain that doppler signals are all detected with equal sensitivity, a number of factors must be considered. When a practical application of the radar is considered, it is evident that missiles would probably be launched over a wide spread of azimuth angles and ranges with respect to the radar site and for any particular trajectory will present continuously changing radial accelerations and velocities. Therefore, a corresponding spread in radial accelerations as well as ranges can be expected. This means that a single modulating function is insufficient to assure detection of all doppler signals, but that a large number of different functions will very likely have to be provided and tried before an acceptable match is found – that is, one in which full signal buildup is achieved in the analysis filter. The trying of successive modulation functions will effectively establish a series of acceleration gates.

Matching of functions is complicated by the fact that the target, in the majority of cases, will be moving steadily through the range gate in which it appears. Since the modulating function can be only one range gate in duration, the doppler signal must be nearly centered in the range gate for an acceptable match. This requires that all of the functions be tried more frequently than every integration period of 20 seconds. Matching will also be complicated by the fact that the initial range-rate or doppler frequencies of the targets will differ considerably, which requires that a full-rate gate system be retained.

Addition of an acceleration-gate system to the radar introduces yet another problem: the time required to examine all range, range-rate, and acceleration gates for targets. The addition of acceleration gates to the radar in effect adds a third dimension to the information flowing from the system. In the present system, range and range-rate information is displayed on an x-y coordinate scheme, as previously mentioned. It takes 20 seconds to fill the system storage completely and two seconds for the analysis equipment to examine each range and range-rate gate combination for targets. If it is desired, and if it were possible in the present system (which it is not) to examine each range and range-rate gate combination for targets having a particular acceleration, another two seconds would be required, and an additional two seconds for each additional acceleration gate. If 300 acceleration gates are required, the total analysis time will add to 600 seconds before repeating, which is completely unacceptable because of the length of time and because the signal may persist in the storage for no longer than 20 seconds. What is required is to find a method of signal analysis that uses no more time to examine the information in three coordinates than the original system takes in two coordinates.

PROPOSED ACCELERATION-GATE SYSTEM

Present two-coordinate analysis time can be shortened from two seconds to 5.5 millisecc by paralleling the analysis channel so that a separate channel is available for each range-rate gate (236 channels are required for a 30-kc spacing). For each drum revolution (5.5 millisecc), all 23 range gates will be examined for targets at all range rates

simultaneously. This means that in only two seconds, 360 different acceleration gates can be examined; hence time has now been provided for a large number of acceleration gates. The number 360 is arbitrary; it may be scaled either up or down. The number of acceleration gates actually required in a radar at a given site will be determined by many factors, such as azimuth-angle coverage, range coverage, number of different missile types expected, negative and/or positive radial accelerations, etc. Also, as the system is visualized, the circuits and thus the functions which establish the acceleration gates can be mounted on small plug-in boards which can readily be changed to allow for a still greater flexibility. The next problem is one of devising an electronic system which will establish these acceleration gates.

Since the existing bandwidth of the analysis channel (30 kc) is to be preserved, the problem becomes one of compensating for the frequency modulation of the doppler signal as seen at the output of storage. The frequency deviation due to acceleration may be far greater than one bandwidth in the 20 seconds of storage. To confine the doppler signal to the analysis bandwidth, the excessive frequency deviation must be cancelled out. This can be accomplished by modulating the doppler signal with a function having characteristics negative to the existing modulation, as previously mentioned. This process, which might be labeled "curve matching," will establish one acceleration gate.

It is fortunate that the paralleled analysis channels necessary to acquire time for the acceleration gates are available, because they are also necessary in the curve-matching system. A single sweeping oscillator signal was used in the single analysis channel to read out all range-rate gates in the original system as shown in Fig. 2. The predetection and postdetection filters are also shown. When the analysis channels are paralleled, a fixed local-oscillator frequency is necessary for each channel, with each frequency differing from the adjacent frequency by one bandwidth, or 30 kc. They occupy the band from 13.4 to 20.5 Mc. A block diagram of the curve-matching system is depicted on Fig. 3. If the local-oscillator spectrum is unmodulated, then all range and range-rate gates will be read out in 5.5 millisecc for all nonaccelerating targets (accelerations less than 0.4 ft/sec^2). The first acceleration gate can be established in the next 5.5 millisecc by modulating all of the local-oscillator signals simultaneously with the same function. This function must be repeated for each of the 23 range gates once around the drum. At this point all range and range-rate gate combinations will have been examined for targets having this acceleration. Likewise, the remaining 358 acceleration gates may be successively examined by successively switching functions into the modulator, for matching targets in the two seconds, at which time the entire cycle is repeated.

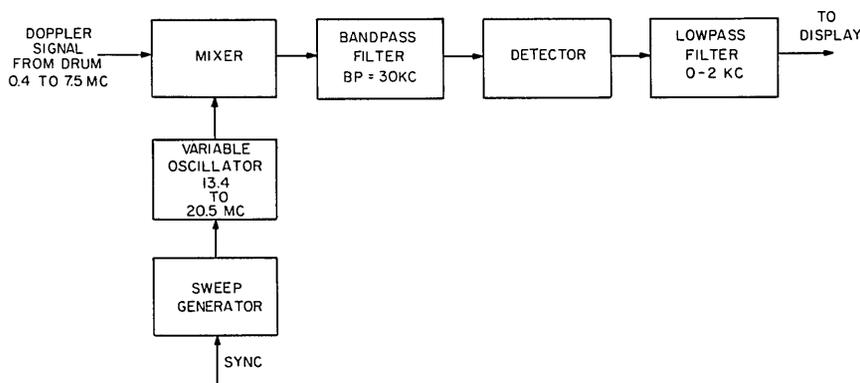


Fig. 2 - Original analysis channel

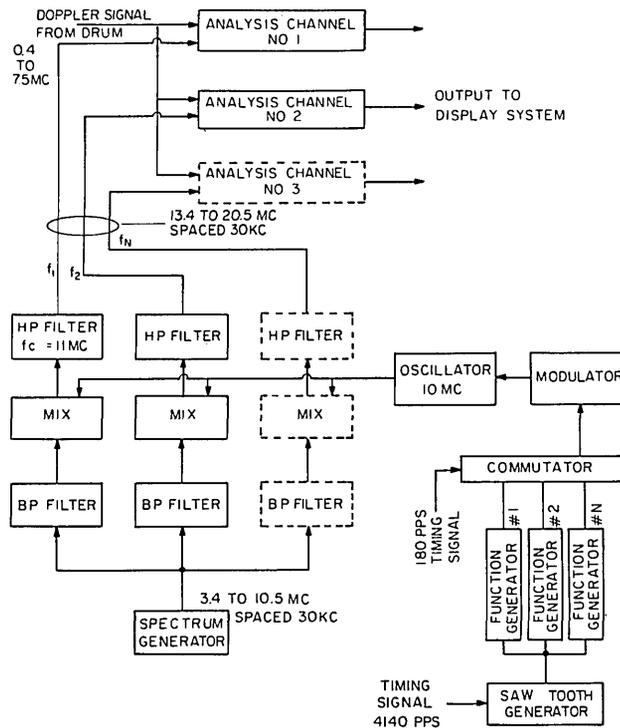


Fig. 3 - Proposed acceleration gate system

Reference to Fig. 3 shows that the spectrum generator, 10-Mc oscillator, modulator, commutation, function generators, and sawtooth sweep are common to all the paralleled channels. Each function generator might be simply a potentiometer which modified the slope of the input sawtooth waveform that is also supplied as input to all of the other function generators, or, if necessary, it might be a crystal-diode network allowing a non-linear voltage-time function to be obtained. One function generator is required for each of the 360 acceleration gates. An alternate method of switching functions that does not require the electronic commutator proposed in Fig. 3 has also been devised.

The problem of the target not having a specific initial range rate when curve matching has been resolved by paralleling of analysis channels. Regardless of what the initial range rate of the accelerating target is, it will fall in one of the range-rate channels or gates and will thus be detected. The problem of matching a target moving steadily through the range gate has also been resolved by repeating the matching of all 360 curves every two seconds. Since missiles, even under unfavorable conditions, for the greater part of their flight from pad to ionosphere will take more than 20 seconds to pass through a range gate, at least ten opportunities will be available every 20 seconds to try matching each of the 360 acceleration curves. Hence, at least one of these tries in each case should be sufficiently well matched in the range axis to fall into a range-rate gate or an analysis channel with slight loss of system sensitivity, thus producing detection.

Multiple targets, as such, pose no problem to this system, because all combinations of range, range rate, and acceleration are examined for targets every two seconds. It takes an Atlas missile 270 seconds to reach the F2 ionosphere; thus there may be as many

as 13 twenty-second integration periods available for detection of this type missile, assuming optimum ray-path geometry.

Another type of multiple target situation can become a problem. It is the masking effect strong near-range targets may have on much weaker far-range targets. The problem arises from the fact that the unambiguous range of the Madre radar is 450 naut mi, which means that there will be four foldovers for ranges out to 1800 naut mi and the consequent masking of one range-gate and range-rate-gate combination in each foldover by a strong target in the first range interval. The situation is further complicated by the fact that the acceleration-gate system will tend to spread the strong target signal over a number of range-rate gates and acceleration gates due to the modulation of the variable oscillator in accordance with the acceleration functions.

The solution to this problem could be either the elimination of the strong near target or attenuating its amplitude. It is likely that operational Madre radars will be sited where, for the most part, there will be few near-range targets. Secondly, it is possible electronically to attenuate, but not eliminate, the amplitude of the near-range target; detection of these targets may still be desirable. This can be accomplished with a signal-cancelling system located between the drum output and the input to the acceleration-gate system. It is desirable to reduce the number of masked range, range-rate, and acceleration gates to a minimum. Since the range and range rate of the strong near target will be known, the cancelling operation can be timed and performed to occur only during the correct range gate and range-rate gate. However, to cancel the correct range-rate gate, or the fewest, including the correct gate, requires that only a portion of the doppler band be used for the cancelling process. The band can be divided into portions with a series of bandpass filters. Ideally the number of filters should be large, allowing each to be only one range-rate gate in width. As a practical matter a compromise of about ten would probably be satisfactory.

INFORMATION PROCESSING

The rate of information outflow from the proposed acceleration-gate system is high, because all combinations of 23 range gates, 236 range-rate gates, and 360 accelerations gates are searched for targets every two seconds. This information may be further processed for purposes of visual display and digitalized for purposes of computing true target parameters.

Any visual presentation of the above information must contend with the fact that the information now contains three variables instead of two, as previously. Since it is convenient to display only two variables on one display, it is necessary to select appropriate pairs of the variables. For example, acceleration vs range might be displayed, along with a second display of range rate vs range. If desired, acceleration vs range rate may also be displayed.

Acceleration vs range is the simplest pair to process and apply to a cathode-ray tube. A raster scan can be formed by sweeping the electron beam horizontally, corresponding to range, in synchronization with rotation of the drum and in the vertical, corresponding to acceleration, in synchronization with the commutation cycle of the acceleration-function switch. Figure 4 shows the raster scan and the electronics associated with the display. Target location can be indicated by intensity-modulating the control grid of the crt to form a bright spot at the proper coordinates, of the display. The modulating signal will be obtained from the output of all 236 analysis channels, which are paralleled after a suitable threshold detector. Paralleling the output of the range-rate channels destroys range-rate information which is necessary to eliminate the third variable. Sacrifice of

information inevitably exacts a penalty which in this case is the inability to separate targets of like accelerations but different range-rates. However, this information is present in the second display, where each range-rate gate is shown separately and the presence of multiple targets will be evident. The second display also has a limitation which is resolved by the first display.

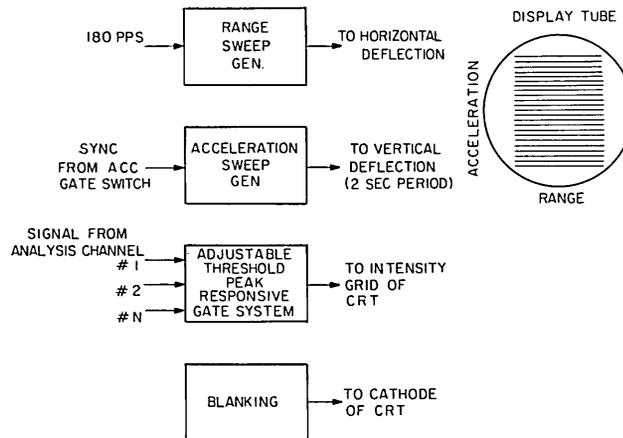


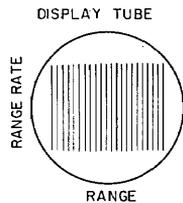
Fig. 4 - Proposed acceleration-vs-range display system

Display of range-rate-vs-range information is more difficult for several reasons. . . One is that range-rate information appears simultaneously at the outputs of all the 236 separate range-rate channels, one for each of the range-rate gates. Because the range-rate information does appear simultaneously, it cannot be applied directly to the cathode-ray-tube display but must be converted to a sequential form. Conversion to sequential form can be accomplished by an electronic commutation system which examines the output of each range-rate channel in sequence for target signals. If full use is to be made of all the range and range-rate information, the examination cycle must be completed during the time of each range gate. Preferably, at least two full cycles should be completed in the 240- μ sec period of each range gate to insure detection of the nonrectangular target pulses.

These requirements dictate the type of raster scan which must be employed on the range-rate-vs-range display. If range rate is presented along the y coordinate and range along the x coordinate, then the raster scan will appear as shown on Fig. 5. A block diagram of the required electronics is also shown. The signal will, as before, be applied to the intensity grid of the cathode-ray tube. Hence, when a target signal appears at the output of one of the range-rate channels, its presence will be detected in the corresponding portion of the examination cycle, and it will then, through synchronization of sweeps and examination cycle, also be presented on the display of the proper range and range-rate coordinates.

In considering the overall problem of displaying target information, it is most desirable to minimize any degradation of signal-to-noise ratio where further processing of the signal is required between the final system narrowbanding and the display crt. Where the outputs

of many separate channels¹ must be combined, this can be accomplished in one of two ways to avoid accepting most of the loss in signal-to-noise ratio which would otherwise be suffered if the channel outputs were added linearly. One method is to commutate between the channels as shown on Fig. 5 for the range-rate-vs-range display. Little if any loss in signal-to-noise ratio need arise in the commutating process itself. The second method is to provide a threshold detector at the output of each channel and then combine as indicated on Fig. 4. Here there will be a loss of signal-to-noise ratio which is determined by the selected level of the threshold detector and the desired false-alarm rate. This loss is not peculiar to this system but is common to all systems which provide control of false-alarm rate.



There is no reason why the acceleration-range display system of Fig. 4 could not have employed signal commutation or have used the signal output of the electronic commutator of Fig. 5. For experimental purposes this is the preferable method, because it allows control of the threshold level at the display and little, if any, degradation of signal-to-noise ratio ahead of the actual display.

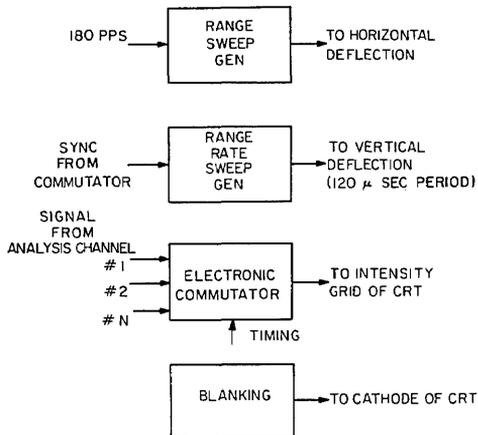


Fig. 5 - Proposed range-rate-vs-range display system

The possibility of degrading the signal-to-noise ratio at the display crt itself should also be considered. In this system three-dimensional information has been collapsed to two dimensions for purposes of visual display. As a consequence the noise of the unwanted dimension can build up brightness of the display screen over the two-second readout cycle and considerably reduce the signal-to-noise ratio, because a long-persistence crt is required. The manner in which the buildup occurs can be illustrated by reference to Fig. 5, the range-rate-vs-range display. Here all range-rate gates and all range gates are examined for targets every 1/180 second for one acceleration gate, and any resulting detections are displayed on one complete raster of sweeps on the display crt. This process and the sweeps are repeated for each succeeding acceleration

gate on through the 360 acceleration gates, which takes 2.0 seconds. It will be noted that the sweeps repeat and lay one on top of one another, hence the possibility of noise addition or buildup.

The problem here is one of not letting one sweep or element fall on a previous sweep or element until all accelerations gates have been read out. This system has only 23 range gates and 236 range-rate gates, and since a high-resolution crt can provide on the order of 2000 lines or elements each way across its face, there are sufficient surplus elements to allow the above requirement to be met. This can be accomplished by shifting each sweep a line or element width in the appropriate direction each time and repeating the cycle every 360 sweeps.

With the elements separated, the minimum loss in signal-to-noise ratio should result, and the sweep-shifting operation can be arranged so as not to introduce any ambiguity in the display. This operation should be incorporated into all display systems.

Another problem that must be considered when dealing with missile targets is that under unfavorable situations a signal may exist for no longer than about 20 seconds. This is sufficient to fill the storage, but since information older than 20 seconds is steadily erased there will be only 20 seconds available for analysis and detection of the target. Even though the signal is completely analyzed ten times in the 20 seconds, only one or two of the ten analyses may produce a detection, if the target is moving rapidly through the range gate. Thus it is evident that if the target produces only one blip and no more it would be most desirable to employ a display with a very long persistence. Devices such as the visual-readout storage tubes seem very suitable for this application. Actually this device is also desirable for the first display for the same reason.

ALTERNATE DESIGN OF THE ACCELERATION-GATE SYSTEM

The design of the acceleration-gate system may be based on another approach. Instead of multiple or parallel analyzing channels being used, one for each range-rate gate, the multiple channels may be arranged to provide acceleration information, one channel being required for each acceleration gate. The change of the channel from a range-rate gate to an acceleration gate is accomplished by replacing the fixed-frequency local-oscillator signal that was sequentially modulated with a series of functions corresponding to different accelerations with a local-oscillator signal that sweeps in frequency over a band corresponding to all the range-rate gates and which is continuously modulated with a function representing a single acceleration. Figure 6 shows a simplified block diagram of the local-oscillator portion of this system. It will be noted that this system requires 360 channels instead of only 236.

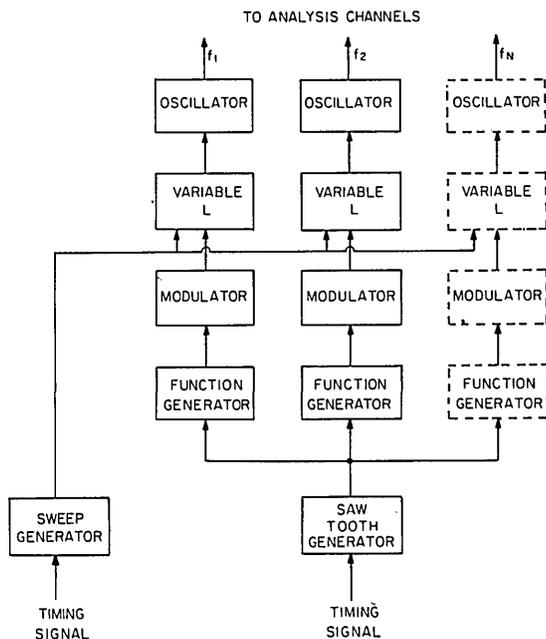


Fig. 6 - Local-oscillator generator for the alternate acceleration-gate system

CONCLUSION

On the basis of the initial considerations, as discussed in this proposal, it appears entirely feasible to extend the use of the Madre radar to the detection of high-speed missiles possessing high acceleration rates, yet retain virtually all of the signal-enhancement properties of the present system. The proposed acceleration-gate system will provide 360 acceleration gates, 236 range-rate gates, and 23 range gates and will in no way alter the radar system's present capabilities against conventional aircraft.

* * *

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