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THE APPLICABILITY OF SUPERCONDUCTING ELECTRONICS TO RADAR SYSTE--ETC(U)
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The Applicability of Superconducting Electronics to Radar Systems.

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Radar Division

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Steady progress has been made in both theory and technology of superconductive electronics, but there has been little application to operational electronic systems. This paper, which was prepared for presentation at the 1976 Navy Summer Study on Superconductive Electronics, reviews those applications that might be of interest to radar. These applications include low-noise receivers, stable RF sources, MTI, synthetic aperture radar, and other areas of signal processing. Also included is a brief discussion of some of the potential problems associated with the use of such devices in a

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practical radar. Although there are areas of possible radar application of superconductive electronic devices, the burden of using cryogenics operationally as well as the availability of other competing electronic devices make it appear unlikely that superconducting electronics will find significant application in radar in the near future.

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THE APPLICABILITY OF SUPERCONDUCTING
ELECTRONICS TO RADAR SYSTEMS*

1. Introduction

This paper reviews the potential applications of superconductive electronics to radar, and provides an assessment as to where such devices might have some utility for improving the performance or capabilities of radar. The point of view is that of the radar systems designer, rather than the superconductive-electronics expert. The claims, promises, and hopes of those working in superconductive electronics will be assumed as valid, and will be taken as the basis for this review and evaluation. Thus the various applications of potential interest to radar will be examined and opinions offered of their possible utility to radar systems.

The types of applications that will be considered here are low-noise receivers, stable and noise-free RF sources, digital signal processing, as well as several miscellaneous applications. Some mention will also be made of the practical limitations imposed on the use of cryogenics in operational systems.

It is appropriate to review the possible utility of superconductive electronics for radar since there has recently been much basic work done in the physics of this phenomenon, as well as a number of efforts to demonstrate applications.[1,2] It would seem beneficial to now set priorities for those areas of superconductive electronics that might lead to some useful application. This paper makes no attempt to assess priorities of work in superconductive electronics. It does, however, consider applications where these devices might be of interest to radar and where they seem to be of little or no current interest.

As far as the author is aware, there are no superconductive electronic devices in operational radars nor is anyone currently experimenting with them in developmental radars. There has been a small effort in the past to apply low-noise masers with superconducting magnets to radar, but this did not find its way into routine application because the benefits

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*An oral version of this report was presented at the "Navy Summer Study on Superconductive Electronics," U.S. Naval Postgraduate School, Monterey, CA, August 2, 1976.[11]

did not balance the limitations.[3] The fact that there is no current application of superconductive electronics in radar, and that there have been no serious proposals, is probably an indication that the potential utility of superconducting electronics as currently understood will not have a major impact on radar in the near future. Of course, it might also mean that the radar system designer has not yet heard the full story on superconductivity. (By way of contrast, it can be pointed out that devices which have had major impact on radar in the past have been the high power klystron amplifier, solid-state devices, digital computer technology, and the phased-array antenna.)

There is always a danger that the potential of any new device will not be understood by the system engineers that can benefit from its use, and therefore it might not be employed. The system engineer usually learns to accomplish the required task as best he can with the resources he has at hand. When a new capability comes on the scene he might not recognize how it could be of benefit to him. A "requirement" for it might not exist if it never occurred to the designer that there is a possibility of his being able to achieve it. Thus, the system engineer might be cool to such claims as a potential frequency stability of 1 part in 10^{15}, or a pulse compression ratio of 10^9, or an analog-to-digital converter with 10 GHz bandwidth since these are far removed from what he is accustomed to. He can understand better the promise of a new device that will give him his usual frequency stability or pulse compression ratio more efficiently, at less cost or in a smaller package. On the other hand, it is probably easier for the researcher to recognize where the fruits of his work might have application than for the systems engineer to understand what part of the vast amount of basic research can be used in his engineering applications. Therefore, all those doing basic and applied work in superconducting electronics should be encouraged to not hesitate to suggest where their work could be of interest for satisfying current needs and for achieving new capabilities.

2. Radar and Superconductive Electronics

Radar is an electromagnetic device for the detection and location of targets by means of scattered energy. It determines the distance (range) to the target and the two angular coordinates (azimuth and elevation). From the doppler frequency shift the range-rate, or relative velocity, of the target can be determined. The doppler frequency shift is employed in MTI (moving target indication) and pulse doppler radars for separating the desired moving targets from the undesired stationary clutter background due to the land or sea. Radar can also measure the size of a target, its profile in the range dimension (as indicated by the major scattering centers), its two dimensional (range and angle) image or map, its shape, and internal motions as might be due to surface vibrations or engine modulations.

A simple block diagram of a radar system is shown in Fig. 1. The parts of the radar that might be potential candidates for superconductive electronics (SCE) are shown with light shading. Listed below the major

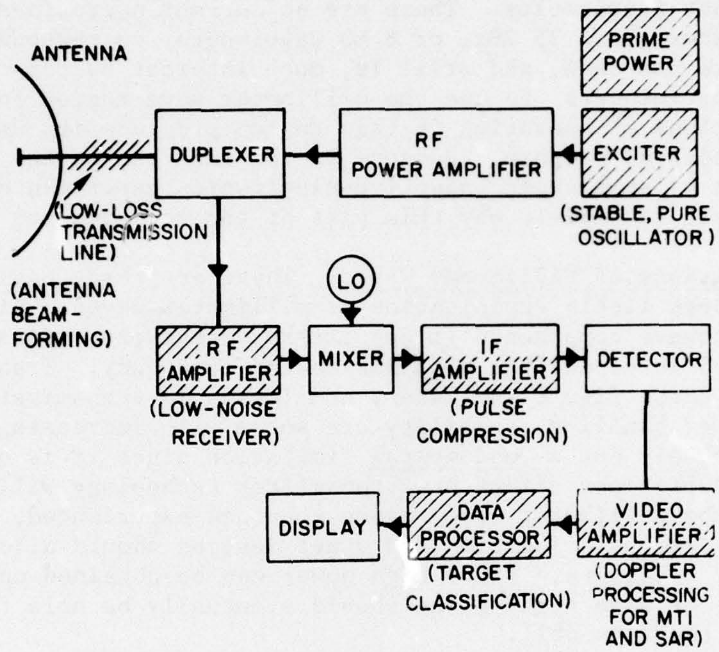

Fig. 1 — Simple radar block diagram, with the possible areas of application for superconducting electronics shown by the shaded blocks

boxes defining the radar system are the potential areas of application identified as being of possible interest to radar. The half-shading of the IF and video amplifiers signifies that SCE is only of interest for the signal processing aspects of these boxes and not the amplification.

Long-range surveillance radars are found at the lower microwave frequencies, while information-gathering and tracking radars are found at the higher frequencies. There are no current operational applications of radar above 35 GHz, or 8 mm wavelength, corresponding to K_a band. There has been, and still is, much interest by component developers and experimenters to use the millimeter wave region for radar, but the limitations of operating in this region preclude its use for other than some special purpose. Because of the interest in the millimeter wave region by some superconductive-electronics experimenters, it might be well to explain why this part of the spectrum has seen little use.

Limitations of Millimeter Waves. There are three basic reasons why there has been little exploitation of millimeter waves. First, conventional microwave components (transmitters, receivers, transmission lines) are degraded in capability with increasing frequency. Transmitter power decreases, noise figure increases, and losses in transmission lines as well as power handling capability are worse with increasing frequency. This is probably not a fundamental limitation since it is quite likely that with sufficient effort new transmitter technology will allow higher powers in the millimeter wave region than now experienced, and the superconductive Josephson junction and other devices should allow lower noise figures for receivers. Since high power can be obtained on either side of the millimeter wave region, one should eventually be able to achieve high power there as well.

The second factor that limits the capability of millimeter wave radar has to do with the physical size of the antenna aperture. Some claim that the reduced aperture size for a given beamwidth is an advantage of millimeter wave operation. It may be advantageous in certain applications, but it also can be a serious disadvantage. The smaller collecting aperture means less sensitivity for the radar system. Since the capability of a radar depends on the product of its antenna aperture times the average power, any reduction in antenna aperture has to be made up by a corresponding increase in average power. This then is a more fundamental limitation in restricting the utility of millimeter wave radar than is the current lack of suitable equipment.

The third limitation to operation in the millimeter wave region is the high absorption losses in propagating through the earth's atmosphere. The normal attenuation of millimeter wave energy in a clear atmosphere severely limits the range, and hence the utility, of radar in this part of the spectrum. The attenuation in rain further aggravates the problem so that it is not likely that frequencies significantly greater than K_a band will see any major radar application. If radar is used in space, outside the attenuating atmosphere, it is likely that millimeter waves will be an interesting candidate if the requisite technology is available. Even if millimeter waves prove attractive for radar applications outside the atmosphere, the likelihood of it being used in large quantities is small.

The emphasis on millimeter waves in the above is made since some superconductive devices operate in this region and appear to offer merit over more conventional microwave devices that operate at millimeter waves. The potential use of superconductive devices for achieving sensitive receivers in this frequency region is encouraging, but the millimeter wave applications of radar can not be looked to with confidence for strong justification of the support of superconductive electronics, even though it is likely that there could be some limited application of radar there in the future.

In the next several sections, some of the superconductive devices of possible interest to radar will be examined. The emphasis will be on the needs of the radar system designer rather than on the current or likely status of the superconductive electronics technology.

Low-Noise Receivers

Josephson junctions used as parametric amplifiers have demonstrated noise temperatures of $15^{0}K$ at X band.[4] Superconducting devices, however, must compete with other cryogenic devices for low-noise-temperature receivers. The traveling-wave maser, for example, is capable of an effective noise temperature of $10^{0}K$, the lowest of any microwave amplifier.[3] Such devices have been demonstrated in experimental radar with a closed-cycle liquid-helium refrigerator. Although cryogenic devices are capable of very low noise temperatures, there has been almost no application to actual radar systems. There are at least two reasons for this lack of interest. First, other low-noise receiver front-ends are better suited for most radar applications even though they may not be as sensitive as cryogenic devices. Second, in many radar applications the advantages of a low-noise front-end do not outweigh the disadvantages, so that the system engineer might prefer to not use a low-noise device at all. These two points are discussed further.

The maser was the first extremely low-noise amplifier considered for radar application. However, in radar it has been superseded by the uncooled parametric amplifier whenever a low-noise radar receiver front-end is desired. Although its noise temperature is not as low as that of a maser, the parametric amplifier is commercially available in a convenient small-size package that requires no critical adjustments, and it is of an affordable price. The parametric amplifier is attractive at the higher microwave frequencies. At the lower microwave frequencies the transistor is often used instead as the receiver front end. The transistor may not be as sensitive as the parametric amplifier, but it is sufficiently sensitive for most radar applications and it is a simpler device than the parametric amplifier. Figure 2 plots the noise

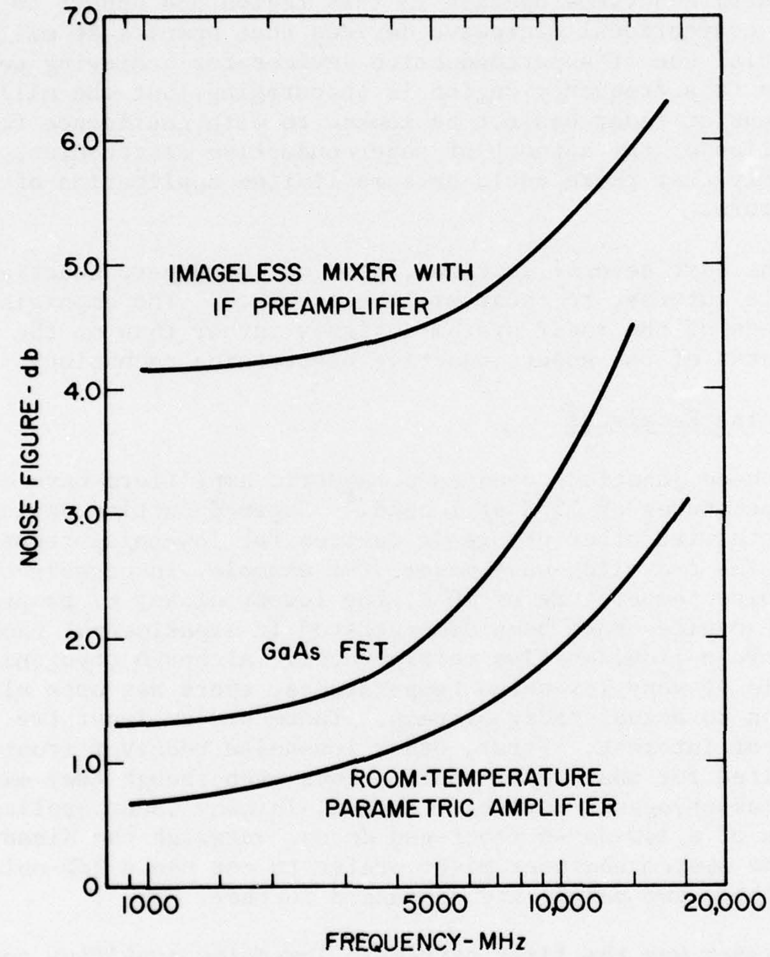

Fig. 2 — Noise figure of typical microwave devices

figure of typical microwave devices as a function of frequency to illustrate the competition that superconductive electronics face. There are, of course, other characteristics than the noise temperature, cost, and complexity to be considered in the selection of a receiver front-end. The bandwidth, gain, and saturation characteristics are also important. Superconductive electronics do not seem especially competitive in these aspects also.

The second point mentioned above that limits the utility of any low noise device has to do with system considerations. Even if an extremely low-noise receiver were available in a practical and affordable form, there are several reasons why it might not be wanted in some military radars. These have to do with (1) the level of the natural external noise and its effect on system sensitivity, (2) the unavoidable internal loss in the RF portion of the radar that limits receiver sensitivity, (3) the increased susceptibility to interference and jamming with low-noise receivers, and (4) the reduction in dynamic range and the susceptibility to saturation in some low-noise devices. Each of these will be discussed below:

(1) External Noise. There is no advantage in having a receiver noise temperature significantly lower than the sky temperature. Therefore, an extremely low noise receiver would be of interest only in the middle portion of the microwave region, from about 1 to 4 GHz.[5] Certainly at UHF and below, as well as in the millimeter band and above, there is little incentive for extremely low noise receiver front-ends.

(2) Internal Loss. The loss between the antenna and the receiver contributes to the receiver noise temperature. The system temperature of a receiver of effective temperature T_e preceded by a transmission line of loss L at a thermal temperature T_o, and with an antenna (sky) temperature T_a, is

$$T_s = T_a + T_o(L-1) + LT_e \qquad (1)$$

The loss L is due not only to the loss in propagating through any transmission line, but also to the losses in the duplexer and in the rotary joint (if a mechanically scanned antenna). Each of these might have a loss of from 0.5 to 1.0 dB. When $T_o = 270^0$K, a 1.0 dB loss contributes an added noise component of 75^0K. Thus if $T_a = 0$ in Eq. (1), and T_e, the front-end noise temperature were 10^0K, the system noise temperature would be 88^0K. A loss of 2 dB increases the noise temperature to 185^0K. The effect on noise temperature of loss between antenna and receiver is well known in radio astronomy and great pains are taken to minimize it so as to take full advantage of the capabilities of a low noise front-end. The radar systems engineer usually does not have the freedom available to the radio astronomer. In most radar systems, a rotary joint and a duplexer are necessary, each with unavoidable loss. Their losses must be tolerated until substitutes are found which make less contribution to the noise temperature than the current state-of-the-art devices.

(3) Increased Interference. The lower the receiver noise temperature, the greater will be the susceptibility of the radar to interference from other radars and electromagnetic radiations. In a military radar, the added vulnerability to hostile jamming that results with a low-noise receiver is to be avoided. The cost of the higher power transmitter needed to offset the absence of a low-noise receiver is often a good investment for a military radar that must operate in a hostile environment.

(4) Compromise of other Capabilities. A receiver with a low-noise front end can introduce limitations in other receiver characteristics that might not be present with more conventional (mixer front-end) receivers.[6] For example, the dynamic range of a low-noise receiver such as a parametric amplifier is about 25 dB less than that of a diode mixer since the gain of the low-noise stage must be sufficient for its output noise to exceed, or mask, that of the mixer stage. The increased gain of the input stage will decrease by a like amount the largest signal that can be handled by the receiver. The superior dynamic range of the diode mixer is an important reason why they have been widely employed in radar. Although the diode mixer has the largest dynamic range of any other current microwave device, its dynamic range will be reduced in proportion to the gain of any low-noise amplifier that precedes it. When the dynamic range of a receiver is exceeded, the receiver is said to saturate, an undesirable condition. It is important that the receiver recover quickly. The low-noise maser, for example, not only saturates at a relatively low signal level, but it requires a relatively long time for recovery. Still another consideration in the use of low-noise receivers is the limitation it imposes on sidelobe cancelers and other devices that require auxiliary receivers. If the radar uses a low-noise front-end, then the sidelobe cancelers should also be of low noise. Furthermore, it is important that the radar and the sidelobe canceler receivers be as identical as possible, especially with regard to their frequency response functions.

Thus, there are several reasons why it is not likely that superconductive devices will have major application in radar as low-noise receivers. There not only exist other low-noise devices that offer practical advantages over superconductive electronics, but the applicability of low-noise receivers is not always desired in many operational military radar applications.

4. Stable Noise-Free Sources

The Josephson junction shows promise of providing a stable RF source of exceptional purity. CW and MTI radars usually require good short-time stability and pure signals for the best performance. In radar, short-term stability is referenced to the round-trip echo time or the total signal integration time. Long-time drift is generally not as important.

The short-term frequency stability of a superconducting microwave source has been said to approach 1 part in 10^{15}, an exceptionally high value. At 10^{10} Hz (3 cm wavelength, or X band) a stability of one part in 10^{15} implies that the frequency does not change more than 10^{-5} Hz. To measure this stability requires an observation time of 10^{5} sec or almost 28 hours. There are few, if any, radar applications that can tolerate this long an observation time. Thus, it is unusual to find an application in radar where a stability of 1 part in 10^{15} is necessary. Generally, 1 part in 10^{10} might be considered good for most applications requiring stable sources.

A typical 3000 MHz (S band) MTI radar with an improvement factor of 50 dB (a good value) using an uncoded 2-μs pulse that requires MTI out to a range of 100 nmi should have a transmitter frequency change within the pulse width of about 1 part in 10^{7}, a coho (coherent reference oscillator) short-term frequency stability (at IF) of 1 part in 10^{8}, and short-term stalo (stable local oscillator) stability (at RF) of 1 part in 10^{10}.[7] Thus the most stringent requirement is on the stalo. This represents a difficult (but not insurmountable) problem with current technology.

Similar considerations apply in a pulse doppler radar. In addition, the pulse doppler radar usually requires that the spurious modulations be small (good signal purity), else they can appear as "targets" to the target-detection circuitry. Thus the AM and FM modulations of the transmitted signals and of the local oscillators in the receiver must be small for good pulse doppler performance, which is the detection of desired weak-echoes from moving targets in the presence of undesired large-echoes from stationary clutter. Spurious AM or FM modulations might occupy the same portion of the received spectrum as desired targets. For example, the allowable frequency deviation of the carrier-frequency modulation might be less than a fraction of a Hz in a good pulse doppler radar.[8] To have any impact on doppler radar a SCE source must have a frequency deviation of less than 0.1 Hz.

The AM and FM noise generated by the RF sources in a CW radar must also be low if they are not to generate spurious target responses in the receiver. According to Saunders,[9] the FM noise modulation of a good high-power klystron amplifier driven by a klystron oscillator having either an active or a passive FM stabilizer is about 133 dB below the carrier in a 1-Hz bandwidth 10 KHz removed from the carrier. The noise power decreases approximately as $1/f^2$ at larger offsets. The corresponding AM noise is 150 to 160 dB below the carrier. This is the competition that superconductive electronics faces.

There are, of course, several techniques other than superconducting electronics for achieving very stable frequencies such as with crystal oscillators, atomic and molecular standards, and masers that have frequency stabilities of 1 part in 10^{14} for periods of 1 second.[10]

It should also be kept in mind that one of the more important pulse doppler radar applications is in an airborne platform. Cryogenic devices must offer some special attributes over other devices if their added complexity is to be tolerated in an airborne environment.

5. Digital Signal Processing

Digital processing in radar has had a profound and extensive effect on the capabilities of modern radar. It has probably been the most important new development in microwave radar in the past 20 years. Digital processing has made possible the practical implementation of theoretical concepts developed many years ago but which could not be implemented economically with past technology. Although digital processing has made significant impact on radar, there is more to be done.

Digital processing of signals has been used in radar for:

- Automatic detection
- Signal integration
- Automatic tracking
- Constant-false-alarm-rate receivers (CFAR)
- MTI (moving target indication) and pulse doppler
- Pulse compression
- Synthetic aperture radar
- Target classification
- Antenna beam forming
- Adaptive processing

The above generally require three basic devices: (1) an analog-to-digital (A/D) converter, (2) storage, or memory, and (3) arithmetic operations to carry out the logical processing. The limitations with current systems have usually been with the A/D converter. The A/D converter must have a sufficiently high sampling rate and sufficiently small bit size to preserve the information content of the signal to be processed.

MTI (doppler) Processing. In an MTI radar the signal processor must filter out the doppler frequency shift of the moving target from the dc component due to the clutter. The clutter signal might be 60 dB, or more, greater than the target signal. The filtering process in an MTI radar is made difficult by the fact that the signals are sampled at a rate (equal to the pulse repetition frequency) that is usually less than the doppler frequency. Hence, fold-over, or aliasing, occurs. There are two basic methods for achieving MTI filtering. The more usual is to employ one or more delay-line cancelers, or time-domain filters. The other method is to use a bank of frequency-domain filters. In either event, the processing is now almost universally done digitally. Thus the requirements on a digital processor may be given in terms of the sampling rate, the number of bits required for quantization, and the total number of samples to be held in storage, and the time required for storage.

The sampling rate of a digital processing system must be twice the radar bandwidth. Since the product of the bandwidth and the pulse width is approximately unity in a well designed radar, a one-microsecond pulse width requires approximately one megahertz bandwidth, and therefore a two-megahertz sampling rate for the A/D converter. The degree of quantization, or the number of bits, depends on the amount of cancellation required to remove the clutter. (The MTI designer refers to this as the improvement factor for clutter.) For each 6 dB of cancellation required, there needs to be one bit of quantization. A "garden variety" MTI radar of past vintage might have had 30 dB of cancellation, which would require a 5 bit A/D converter. Since clutter can be 60 or more dB greater than system noise, the A/D converter for the best MTI radars might require 10 to 12 bits of quantization.

Figure 3 illustrates the state-of-the-art in A/D converters as published several years ago. It is probably still representative of current technology. For most MTI radar applications the current A/D technology is satisfactory. If an MTI were required with an improvement factor of 60 dB or more with higher range resolution (wider bandwidth) than is currently the practice, then the A/D converter would probably represent a problem. It is probably not likely that greater bit-capacity will be required of an MTI A/D converter since at the level of 60 dB improvement factor, other effects enter in the radar to limit its ability to remove clutter. Wider bandwidth A/D converters, however, might be desired for other tasks.

The design of airborne MTI radar is more difficult than ground-based MTI not only because of the restrictions imposed by the airborne platform, but because the clutter is more extensive and is in relative motion with respect to the aircraft. The chief problem with current A/D converters for this application, according to some designers, seems to be their relatively large size. It is not likely that superconductive devices can aid in the solution of this problem.

Synthetic Aperture Radar. The synthetic aperture radar (SAR) obtains resolution in angle (cross range) by flying a small antenna and storing the resulting data so as to obtain the effect of a large aperture. That is, instead of generating a large array antenna by the simultaneous use of a large number of individual radiating elements, the effective antenna can be generated sequentially by time sharing a single radiating element as it travels across the aperture. A crucial part of a SAR is the storage medium on which the data is stored and the mechanism by which it is processed. A SAR with 3 m resolution in both range and azimuth requires a signal with bandwidth of 50 MHz that must be stored for as long as several seconds. The processing of SAR data is more complex than ordinary radar data since the number of samples to be summed (integrated) varies with range, a phase and amplitude weight must be applied to each returned signal that can also vary with range, and pulse compression must be applied in the range dimension. In the past such processing could not be done conveniently in real time. The signal information in the

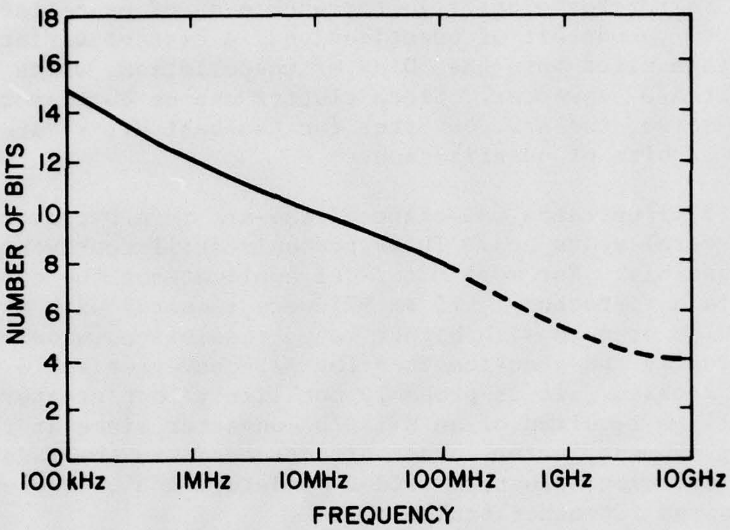

Fig. 3 — Approximate relation between maximum number of bits and frequency performance of A/D converters. Dashed portion of the curve represents performance of experimental devices.

aircraft was recorded on film, brought back to ground and processed optically. As digital processing technology has improved, it has become more practical to use it in SAR. It is now the preferred approach.

The A/D converter must be able to operate with bandwidths of 50 MHz to perhaps 500 MHz. A four to six-bit quantization is desirable, but it may be possible in some applications to operate with only one-bit quantization. This is not too far removed from current A/D converter technology as was shown in Fig. 3. If a real time storage medium were used it would require of the order of 10^8 to 10^9 bits of storage. If the signal were stored for later processing on the ground it might be desirable to have perhaps 10^{11} to 10^{12} bits of storage capacity.

Pulse Compression. Pulse compression is employed when a long pulse must be used to obtain sufficient energy for detection but where it is desired to have the good range resolution of a short pulse. The long pulse is modulated, by frequency or phase, so as to "tag" or mark it throughout its duration. On reception, the "tagged" substructure of the pulse is then selectively delayed or advanced so as to compress the pulse. This is a rather simplified way of describing pulse compression. More fundamentally, the filter used in a radar receiver should be designed to maximize the output signal-to-noise ratio (an intuitively nice thing to do). This is called a matched filter. The output of such a filter is the auto-correlation function of the input signal. The width of this auto-correlation function is approximately equal to the reciprocal of the signal bandwidth. Therefore, to increase signal bandwidth, and thus effectively narrow the output pulse of the receiver, the pulse can be internally modulated. Linear frequency modulation (called chirp) is widely used. Phase-coded modulation (called coded pulse) is also used for some purposes.

There are two somewhat different applications of pulse compression. In one, a pulse of conventional width, perhaps 1 μs in duration and 1 MHz bandwidth, is frequency modulated to give, for example, a 500 MHz bandwidth and a compressed pulse width of 2 ns, or 0.3 meter (one foot). The currently preferred pulse-compression device for this application is the surface acoustic wave (SAW) dispersive delay line. It is small and relatively cheap. The other type of application is to start with a long pulse, perhaps several hundred microseconds, and compress the pulse to say 1 or 2 μs. A charge-coupled device (CCD) looks attractive in such applications. Although the SAW and the CCD have been cited as examples of pulse compression filters, there are about a dozen different devices that can be used.

It has been suggested that with superconductive electronic devices, a pulse compression ratio (product of pulse width and bandwidth) of 10^9 can be achieved. This compares with maximum pulse compression ratios of about 10^4 to 10^5 with current practice. It is not obvious where a 10^9 pulse compression ratio would be useful. Most radar applications seem to be satisfied with pulse compression ratios of from 10^2 to 10^3.

Current devices can provide the necessary technical characteristics. The designer is interested today in what might be called engineering improvements such as small size, less cost, less loss, and more reliability.

Antenna Beam Forming. The Fourier transform appears in many places in radar, such as in MTI, matched-filter processing and pulse compression. Therefore, any device that can calculate the Fourier Transform is of interest. This is especially true of the Fast Fourier Transform (FFT). One particularly interesting application of the FFT is as a means to form multiple simultaneous beams from a single antenna. A receiver at each antenna array element generates a voltage that is sampled and converted to a digital number. From this point on, the formation of parallel antenna beams, pulse compression, signal integration and doppler processing are all done by "number crunching" in a single FFT processor. This almost complete utilization of digital processing is possible only if the RF bandwidths can be handled with current technology.

If A/D converters of bandwidth comparable to microwave frequencies (a few GHz) were available it would be possible to do RF beamforming or any other form of antenna processing by digital means rather than analog. It is not clear that this is a desirable (i.e., competitive) thing to do. To be attractive, each of these wideband A/D converters would have to be small and inexpensive since many (several hundred, perhaps) would have to be used.

RF vs Video Processing. With current digital technology, the RF (or IF) signals are converted to video (baseband) so as to remove the carrier and leave the modulation that contains the information content. It is the modulation that is acted on by the processor. The possibility of wideband A/D converters and digital processing with several gigahertz bandwidths offers the possibility of doing the processing at RF rather than the video. Video processing requires two channels (I and Q) with two mixers whereas RF processing can be performed with but a single channel. The single RF channel, however, is usually more complicated. Generally, it would seem that there is little justification for digital processing at the RF carrier frequency for applications in which the information rate is a small percentage of the total capability of the processing system. Therefore, it would be more convenient to remove the carrier and process the modulation with much narrower bandwidth. The processing of signals at baseband rather than at RF, lessens the requirements for wideband A/D converters.

In the preceding, it was stated that the antenna beamforming could be carried out at RF with high speed A/D converters and wideband processors. The same considerations regarding RF and baseband processing apply here as well. It would probably be better to convert the antenna signals to baseband rather than process at RF.

Target Classification by Range Resolution. Radar can provide more information about a target than just its location. One technique for determining the nature of a target is to examine the structure of the echo when illuminated by a high-range-resolution radar. Bandwidths might be 500 or 1000 MHz with resolutions of 0.5 to 1.0 foot. A pulse compression radar, as described previously, would probably be used in such an appli[illegible]tion. The high range resolution data has to be sampled and quantiz[illegible]litude. Correlations have to be performed with stored refe[illegible] determine to which class of target the echo belongs. [illegible]cation, the A/D converter is the critical device. A 1 GHz band[illegible]3 bits of quantization is what might be needed for some applica[illegible]ons.

6. <u>Other Applications</u>

In this section several miscellaneous potential applications that have been suggested for possible employment of superconductive devices will be briefly commented upon.

<u>Over-the-horizon radar</u>. The heart of a successful HF OTH radar is the signal processing. It is characterized by low bandwidths (10's of kHz), long storage times (10's of seconds) and large dynamic range (60 to 90 dB). The RF sources must also be of good stability. However, there is nothing in these characteristics that seems to suggest superconductive devices.

An HF OTH radar uses a large antenna. Receiving antenna arrays might be from 200 to 2000 meters in extent. Superconductive antennas offer the possibility of reducing the size of the individual elements. The advantages of small individual elements in this application are not strong, since the use of superconductive elements does not reduce the overall size of the array antenna and does not seem to offer any advantage over the simpler antenna elements that have been used.

<u>Radiometry</u>. The Josephson junction low-noise receiver has received attention, especially at the higher frequencies (millimeter wavelengths) as a sensitive microwave radiometer. The chief interest is for radio astronomy. Microwave radiometers have been considered as remote sensors and have even been flown in satellites for this purpose by NASA. When used as remote sensors the sensitivity of a microwave radiometer is generally less than that of an equivalent device used for radio astronomy, even with the same observation time. The radio astronomer looks at the cold sky with temperatures that might be a few tens of degrees Kelvin. The remote sensor, however, often looks at the relatively hot earth at 300^0K. Therefore there is little need for a receiver with a better noise temperature.

<u>Harmonic Mixing</u>. There has been interest in the use of efficient SCE harmonic mixing to obtain RF sources at millimeter wavelengths. Because of the low power and inefficient operation, they have been limited primarily to laboratory use. Power sources at millimeter

wavelengths have been improving considerably in recent years and should make harmonic mixing less attractive.

Prime Power Generation and Transmission. There are many radar applications where smaller, lighter and more efficient electrical generators are desired. Any benefit in this area would be welcomed, as it would for other than radar applications.

Low-loss Microwave Transmission Lines. The waveguide-run between the transmitter and the antenna can introduce significant loss, especially in shipboard application. The loss is due to the attenuation through a long length of line, plus any added loss due to the bends and joints that are needed to fit the transmission line on board ship. Supercooled lines can relieve the problem of normal attenuation but can aggrevate the losses due to the physical restrictions imposed by the ship environment.

7. Practical Considerations in the Use of Superconductive Devices in Radar

Although this report has been concerned about potential areas of application of superconductive devices, it might be worth mentioning some of the practical aspects of their use in radar application. Closed-cycle refrigeration (CCR) for IR sensors has been built with high reliability and many years of failure-free life for space applications, but the problems of attaining failure-free electronics for superconductive electronics in a ground environment, on ship or in an aircraft are entirely different and are usually harder to solve than in space. (This includes the non-technical as well as technical problems.)

The employment of cryogenic devices in the Fleet will introduce new problems not found with other electronic devices. Special training in its use and maintenance will be required. A low-noise parametric amplifier or a charge-coupled device is not much different than the electronics for which most Navy electronic technicians (ETs) were trained. A superconductive device requires the ETs (or someone else) to have some of the skills of a physics lab technician to operate and maintain cryogenic devices. There will have to be special consideration given to the successful use of cryogenics in a military environment. The problems of keeping a 4.2^0K superconductive system operating in the laboratory without heat leaks, loss of refrigeration, and magnet quenchings has proven frustrating in the past. A colleague of the writer who successfully developed superconductive traveling-wave masers for radar application has said that his sanity reappeared only when he was allowed to leave the 4.2^0K regime and return to the regime of room-temperature devices. He vows never to work again at 4.2^0K.

A cryogenic device, such as a low-noise receiver must operate at the antenna to avoid the degradation in noise temperature caused by loss in the transmission lines. Thus in some tracking radar designs it has to operate in an environment subject to rapid acceleration. This was true for the traveling wave maser development for the MIPR system which employed a closed-cycle liquid-helium refrigerator and superconducting magnet.[3] In addition to withstanding motions due to being mounted at the antenna, the devices had to be isolated from their cryogenic environment. The device was tested under field conditions at WSMR. It was found that the average field technician could not and did not want to work with superconductive equipment or with liquid helium. In spite of the desirable properties of this device it slowly faded into disuse.

Among the other potential problems that need to be addressed in converting superconductive devices from the laboratory to wide application in the field are:

1. Adequate mechanical ruggedness to operate in the desired environment.

2. Redundancy in the event of a compressor failure.

3. Ease of maintenance in the field.

4. Overload protection, which may significantly reduce overall performance.

5. Cryogenic holding-time in the event of a power failure.

6. Cool-down time and capacity of the CCR.

7. Production of superconductive materials in the quantities and the quality needed for large-scale application.

8. The RF matching of cryogenic devices with their normally low impedance to the world of "50 ohm" impedance.

8. Discussion

The practical problems associated with the use of superconductive electronics as described in the above are important, but they should not be fundamentally limiting. They can be overcome and superconductive devices will be made to work in a practical environment. However, the burden of operating electronic devices under cryogenic conditions is a serious handicap when competing with other devices that accomplish the same purpose. The radar applications of superconductivity that have been discussed here all have a noncryogenic competitor which can usually satisfy the radar designer's requirements. The reluctance of the radar engineer to accept superconductive electronics seems due to the lack of an obvious application where it, and only it, is uniquely qualified for the job. Even in those radar applications where they might possibly be used in spite of competition, it is not likely that they would be employed in large enough numbers to offer encouragement to those hopeful of seeing them play a major role in radar technology.

It would appear that at present there are no obvious applications of superconductive electronics that would excite the radar engineer's serious attention since they do not seem competitive with current practice or with the new developments in other device technologies. Superconductive technology, however, offers unique characteristics that could change this conclusion at some future time. Therefore the radar engineer should continue to be alert to new developments in this field, and to encourage the pursuit of new knowledge of superconductivity along with the demonstration of its applications. Since the successful transfer of superconductive device technology to a systems application like radar depends in large part on the superconductive scientist recognizing the potential of his device and making it known to the systems engineer, those working in the field of superconductivity have the problem of alerting, or nudging, the unattentive engineer to what he might be missing.

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