AD-A101 296 AEROSPACE CORP EL SEGUNDO CA ELECTRONICS RESEARCH LAB F/G 20/3
SPACE APPLICATIONS OF SUPER CONDUCTIVITY.(U)
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Space Applications of Superconductivity

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Electronics Research Laboratory
Laboratory Operations
The Aerospace Corporation
El Segundo, Calif. 90245

16 July 1979

Interim Report

APPROVED FOR PUBLIC RELEASE;
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Prepared for
SPACE AND MISSILE SYSTEMS ORGANIZATION
AIR FORCE SYSTEMS COMMAND
Los Angeles Air Force Station
P.O. Box 92960, Worldway Postal Center
Los Angeles, Calif. 90009

This interim report was submitted by The Aerospace Corporation, El Segundo, CA 90245, under Contract No. F04701-78-C-0079 with the Space and Missile Systems Organization, Contracts Management Office, P.O. Box 92960, Worldway Postal Center, Los Angeles, CA 90009. It was reviewed and approved for The Aerospace Corporation by A. H. Silver, Director, Electronics Research Laboratory. Gerhard E. Aichinger was the project officer for Mission-Oriented Investigation and Experimentation (MOIE) Programs.

This report has been reviewed by the Information Office (OI) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication. Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

Gerhard E. Aichinger
Project Officer

FOR THE COMMANDER

Frank J Bane

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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER SAMSO-TR-79-67	2. GOVT ACCESSION NO. AD-A101296	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) SPACE APPLICATIONS OF SUPERCONDUCTIVITY		5. TYPE OF REPORT & PERIOD COVERED Interim
		6. PERFORMING ORG. REPORT NUMBER TR-0079(4930-01)-2
7. AUTHOR(s) A. H. Silver		8. CONTRACT OR GRANT NUMBER(s) F04701-78-C-0079 ✓
9. PERFORMING ORGANIZATION NAME AND ADDRESS The Aerospace Corporation El Segundo, Calif. 90245		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS Space and Missile Systems Organization Air Force Systems Command Los Angeles, Calif. 90009		12. REPORT DATE 16 July 1979
		13. NUMBER OF PAGES 31
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release: distribution unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Clocks
Communication Receivers
Digital Processors
Frequency Synthesizers
Josephson Junctions
Magnetic Storage
Memory
Microstriplines
Microwave Oscillators
Radiometers
Sensors
Superconductivity
Superconducting-Schottky Diodes

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Superconducting technology is not presently used in space systems. This is not surprising since superconducting technology has essentially no current use outside of the research sector. However, this situation may be about to change as specific applications are found in which superconductivity provides significant advantages over more conventional technologies. This report identifies such applications as they apply to space systems. One of the most challenging problems to the acceptance of superconductivity, and to its implementation for space as well as terrestrial systems, is reliable, -

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convenient, and economical methods of cryocooling. Unfortunately, very little effort has been expended for this purpose.

Functional areas in which superconductivity may significantly outperform conventional technology include communication receivers, radiometric sensors, stable clocks, microwave oscillators, frequency synthesizers, high speed digital processors, high capacity memory, and energy storage. The contribution of superconductivity to these functions is discussed and the special requirements for cooling are indicated.

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A

Introduction

The application of superconductivity to space systems, either military or civil, does not exist today. In fact the present use of superconductivity outside of the research laboratory is insignificant. Therefore this paper clearly looks to the future, to potential applications of superconductivity. We will identify such applications; the probability of implementation will depend on competition with more conventional technology. In specific applications superconductivity will significantly outperform conventional technology. A key problem for all systems applications of superconductivity, but especially for space, is cryocooling. This is a critical need which requires special attention and emphasis.

We envision the future use of superconducting devices either on board spacecraft or in closely related ground terminals or ground support facilities. We make no restriction on orbital parameters or spacecraft mission, except that the activity is earth-oriented, i.e., we will not address deep space applications although many of the concepts put forth here are equally valid for such missions. The principal constraints are that the superconducting elements, including the cryogenic support vessels and machinery, must satisfy the volume, power consumption, heat dissipation, weight, and other environmental restrictions imposed by the spacecraft. Recognizing that the space shuttle will become the principal launch vehicle in the 1980's, these constraints are not as stringent as they are for today's vehicles. This topic has been the subject of several recent studies; of particular note are the reports listed under references [1] and [2]. A review of relevant cryocooler technology can be found in reference [3].

Space applications for which superconductivity may play an important technological role include communications, navigation, earth monitoring, and scientific experimentation. Communications involves both the space-to-earth and space-to-space links and imposes requirements for bandwidth, security, and privacy. By navigation we mean global navigation from satellite reference signals for both civilian and military users. Earth monitoring is a large application area including meteorological satellites for weather and climate prediction, traffic management which involves detection and management of both space and air traffic, and various types of earth surveying. Scientific satellites, in the domain of NASA, include new and challenging experiments in astrophysics, atmospherics, and relativity. The impact of superconductivity will be in the development of significantly improved communication receivers, radiometers, clocks, oscillators, and frequency synthesizers, digital processors, large capacity memory, and energy storage.

Although superconductivity has now been reported at temperatures as high as 25 K, materials which can be presently fabricated into useful devices require operating temperatures well below 20 K. For many applications we will need to achieve liquid helium (LHe) temperatures. This situation will probably persist for the next decade.

The advantages of superconductivity derive from its unique macroscopic quantum-mechanical properties which result in an electron energy gap, diminished electrical resistance, including zero resistance at DC, "perfect" diamagnetism, and other quantum-mechanical properties. These properties are further accentuated by low thermal noise and excellent mechanical stability inherent in most low temperature physical systems.

Energy Storage

The most well known property is that of zero electrical resistance at zero frequency (DC), from which high field persistent current magnets, lossless power transmission lines, efficient rotating electrical machinery, transformers, and electromagnetic shields can be developed. An attractive potential application of this property in space is for energy storage in superconducting magnets. Modest size coils made of superconducting wire, such as Nb_3Sn or NbTi, are capable of storing energy in the form of a lossless, persistent current. The stored energy can be calculated from either $LI^2/2$, where L is the inductance of the magnet and I is the persistent current, or $\frac{B^2\tau}{2\mu_0}$, where B is the magnetic flux density, τ is the volume which the magnetic flux occupies, and μ_0 is the vacuum permeability. B and I are limited by the properties of the superconducting wire and the design of the magnet. Many large superconducting magnets have been built and operated; fields in excess of 10 Tesla and current densities of 10^5 Amp/cm^2, and stored energies approaching 10^6 Joules have been achieved.[2] However, no magnet system has been built specifically for the purpose of energy storage. One expects superconducting magnets to have smaller specific weight and volume than capacitors and to be competitive with batteries at about 10 MJ. The specific weight and volume should decrease for larger magnetic energy systems, increasing their competitive advantage. Efficient methods of charge/discharge at low voltages, no degradation after repeated cycling, easily measured state of charge, and a flat discharge curve could make this method attractive for larger spacecraft which will come along with the shuttle. A principal difficulty is reliable refrigeration capacity, which will probably be of the order of several watts at 4 K.

Digital Processing

A major function of space systems is the transmission of large amounts of information on a global scale. Most information is transmitted in digital form and there is continuing need for both satellite-borne and ground-based digital electronic systems. These systems are required to process and encode information in complex communication networks in order to most efficiently utilize available spectrum and hence minimize the requirements imposed on the communication systems. Generally speaking, high speed, efficient, digital processors and fast, large capacity memories, consistent with weight, volume, and power constraints of the spacecraft, are required. Superconducting digital electronics may provide a major step in increasing the speed and simultaneously reducing the size and power consumption of such digital processors. The principal elements which contribute to these improvements are the superconducting Josephson junction and superconducting microstrip transmission lines.

The necessary elements of digital electronic technology are logic, memory, interfaces, and analog-to-digital (A/D) converters which function at high speed. Superconducting Josephson devices can perform these functions, but so can present semiconductors. The payoff in the use of superconducting logic elements is a unique combination of high speed and low power dissipation which allows high packing density and superior overall performance.

Josephson junctions are nonlinear superconducting diodes which can be fabricated in a number of different ways. Until recently most Josephson device technology has consisted of cat whisker technology, in which two pieces of superconductor are lightly contacted in the manner of a whisker against a flat plate. Two other approaches which are compatible with modern microelectronic batch fabrication have been under investigation: a microbridge which consists of a micron-size link connecting two thin film superconducting electrodes, and a sandwich tunnel junction in which a thin (tens of Angstroms) insulator separates two superconducting thin films. The tunnel junction device most closely approximates the theoretical device and is the most successful of the microelectronic devices.

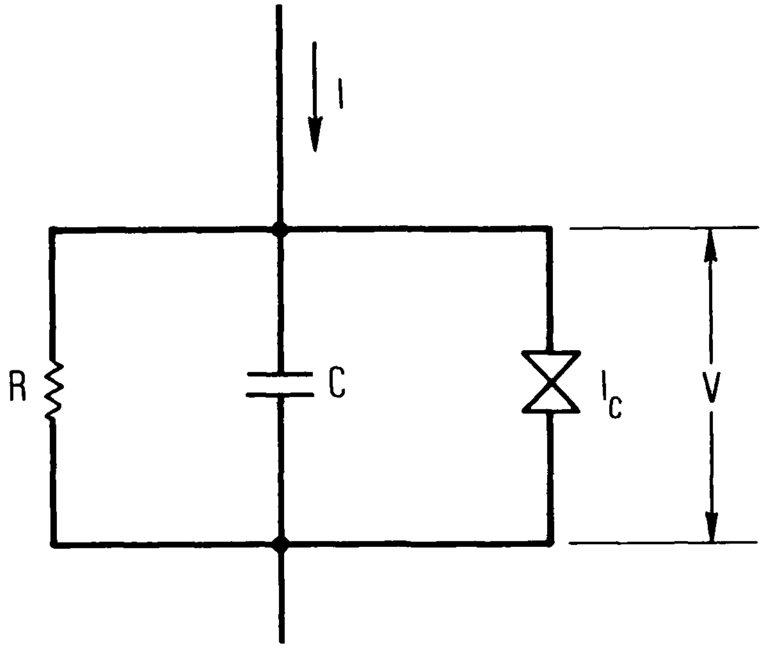

Fig. 1. Equivalent Circuit of a Josephson Junction. R and C are the parasitic normal resistance and capacitance, and I_c represents the maximum supercurrent of the active, nonlinear element.

The equivalent circuit of a Josephson junction is given in Fig. 1, where R and C are parasitic shunt resistance and capacitance, respectively. The active part of the element is distinguished by a maximum, reactive supercurrent I_c and has an electrical characteristic

$$I = I_c \sin \theta \tag{1}$$

$$V = \frac{\Phi_o d\theta}{2\pi dt} \tag{2}$$

where I_c is the maximum supercurrent and $\Phi_o = 2.07 \times 10^{-15}$ Webers is a fundamental constant (h/2e). As a result of these relationships, Josephson junctions are very fast, nonlinear elements which are useful as switches and parametric amplifiers operating at very low power dissipation levels. For stability, the coupling energy of a junction

$$E_J = \frac{\Phi_o I_c}{2\pi} \tag{3}$$

must be large compared to kT, which is $\approx 5 \times 10^{-23}$ joules at T = 4 kelvin. This sets a lower bound on $I_c > 0.17\ \mu A$. The useful operating voltage of Josephson junctions is limited to the superconducting energy gap voltage, $V_g \sim 10^{-3}$ V. Power dissipation is thus limited to

$$P \leq I_c V_g \approx 10^{-9}\ \mathrm{W}. \tag{4}$$

This is the <u>maximum</u> power dissipated for a <u>continuous</u> current I_c at the energy gap voltage. Furthermore, the ideal shunt resistance is given by the ratio of the energy gap voltage to I_c, limiting R to less than $10^4\ \Omega$. The nonlinear element is a pure inductance of modulus

$$L_J = \frac{\Phi_o}{2\pi I_c}\ . \tag{5}$$

The stored energy, Eq. (3), can be equivalently considered as $L_J I_c^{\ 2}$, or as $CV_c^{\ 2}$, where V_c is the characteristic (cutoff) voltage of the junction, essentially the energy gap voltage.

This voltage relates directly to a cutoff frequency or limiting response time. From Eq. (2) this frequency is $V_c/\Phi_0 \approx 10^{-3}$ V/2 x 10^{-15} Wb $\approx 10^{12}$ Hz, and the corresponding switching time is less than one picosecond.

In order to achieve this performance the junction RC time constant must be short enough to respond at 10^{-12} seconds. This places a lower limit on the current density in the junction. Figure 2 shows the normalized RC response times of Josephson tunnel junctions fabricated as metal-metal oxide-metal sandwich devices.[2] The device parameter is the thickness of the oxide layer in Angstrom units.

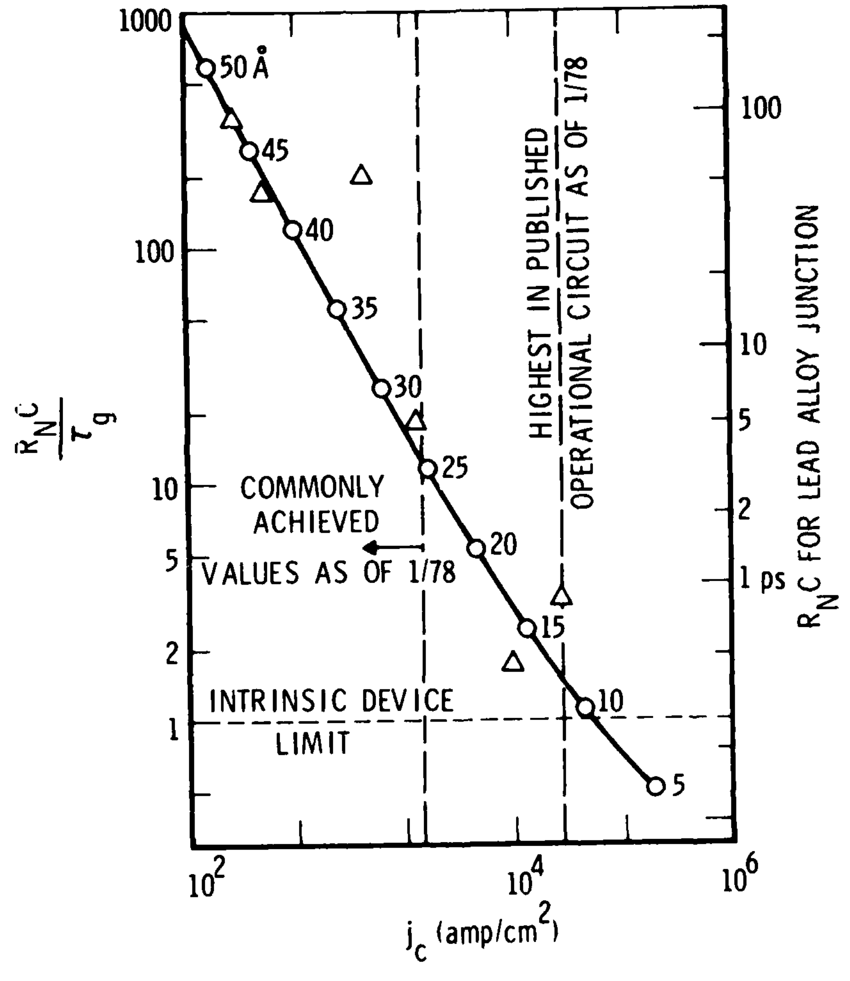

Fig. 2. Response Time of Josephson Tunnel Junctions, in Units of the Gap Angular Frequency, as a Function of the Supercurrent Density, j_c. The numbers next to the open circles are the calculated junction thickness in Angstrom units (after reference 2).

The result is that Josephson junctions can operate as logic elements with picosecond speeds. The energy dissipated per switch depends on the mode of operation, but always $\leq \Phi_o I_c$. Figure 3 shows the power-delay curves for various digital electronic technologies. The region representing Josephson technology is for devices and configurations already demonstrated. The theoretical limit is approximately 10^{-19} joules, 1 ps, 10^{-7} W.

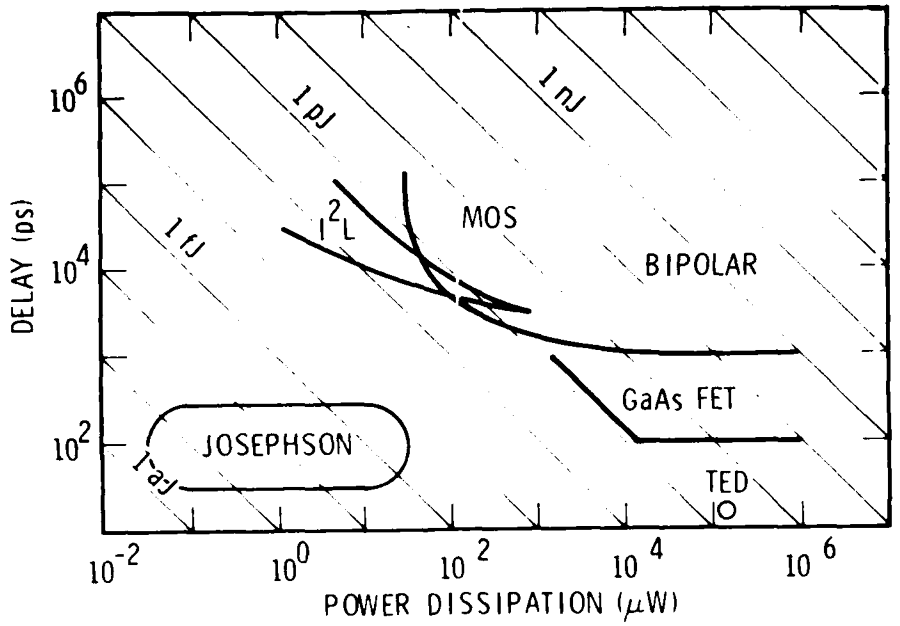

Fig. 3. Power-Delay Relations for Various Digital Technologies (after Reference 2)

In order to optimally utilize these fast switching speeds and low power devices, we will be required to pack devices closely to minimize transmission delays. Josephson tunnel junctions are fabricated in a manner which makes such close packing possible and thus allows a high density of devices on a single substrate. Therefore this technology can overcome the major technical barrier to the use of high speed switching devices. In contrast, fast semiconductor devices not only require higher power dissipation per element, but also are limited in their ability to dissipate this heat. Liquid helium provides an efficient refrigerant to remove the power dissipated in the gates.

Superconducting transmission lines in the form of thin film striplines at very low impedances ($< 10\,\Omega$) are available to provide gate interconnects with minimal loss and dispersion. Fig. 4 compares the calculated properties of 6 Ω microstrip with a linewidth of 2 μm for both normal (N) and superconducting (SC) metallic films. Below the superconducting energy gap frequency the loss for normal metals is at least 10 dB/mm greater than for superconductors. The phase velocity is nearly constant for superconductors compared to more than an order of magnitude variation for normal metals. The latter relationship is important in order to prevent significant pulse spreading for picosecond pulses.

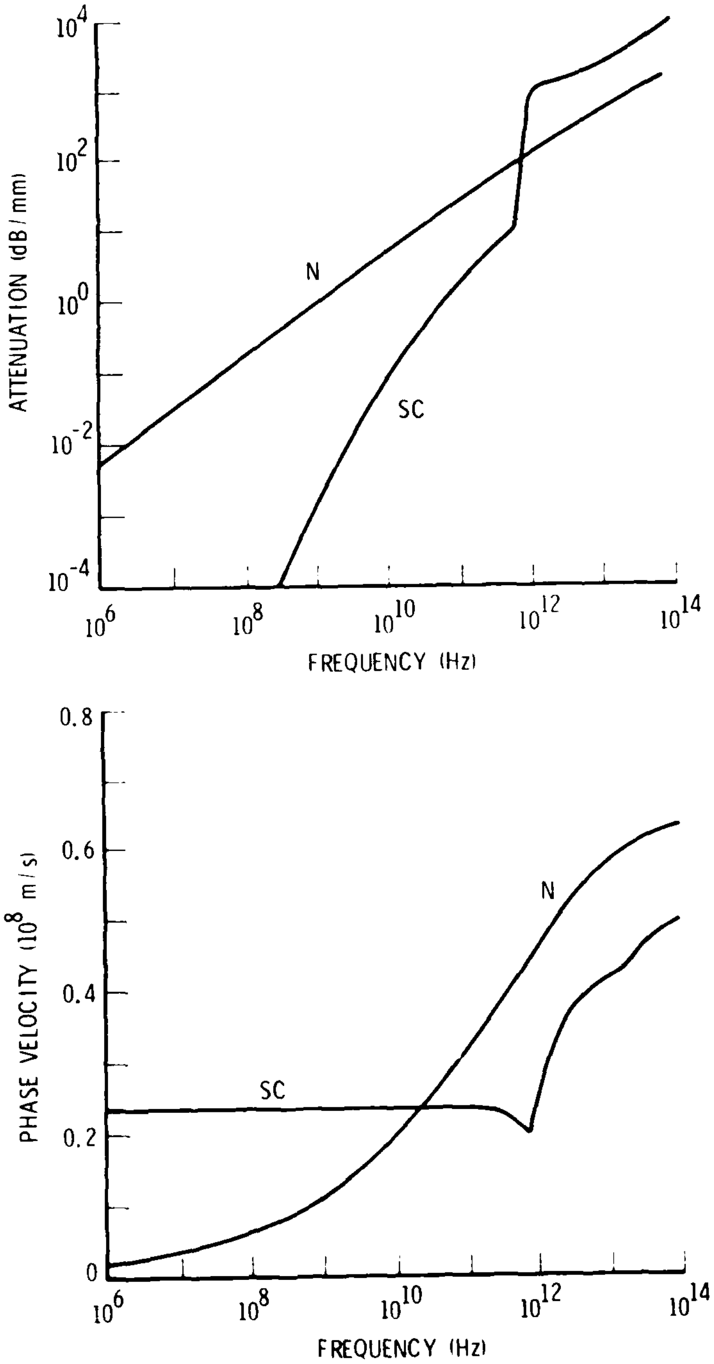

Fig. 4. Attenuation and Phase Velocity for Thin Film Microstriplines with $Z_o = 6\Omega$ and a Line Width of 2 μm. N represents normal metal and SC Superconducting metal (after Reference 2).

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Analog-to-Digital Converters

In order to make efficient use of digital processors and digital communications it is frequently essential to have high speed analog-to-digital (A/D) converters. The state-of-the-art[1] is represented in Fig. 5; no A/D converters are currently available at GHz sampling rates. Furthermore, all conventional devices under development require high energy excitation signals and therefore need preamplification. Josephson junction technology offers a significant opportunity to achieve fast A/D conversion with very low driving power. A very attractive scheme currently under development at Aerospace Corporation[4] has a target of 10 bits quantization at 10 GHz sampling rate with 10^{-8} watts signal power. This concept utilizes Josephson junctions configured in superconducting quantum interference devices[5] (SQUIDs).

A SQUID is a simple, lumped-constant, electronic circuit incorporating one or more Josephson junctions. In its simplest form it consists of one junction loaded by a superconducting inductance. When the circuit inductance L is comparable to the Josephson inductance (Eq. 5), quantum effects become pronounced and dominate the performance of the circuit. This condition can be expressed by a parameter β, such that

$$\beta = \frac{2\pi L I_c}{\Phi_o} \sim 1, \qquad (6)$$

Another common form of the SQUID is a two junction circuit, called a dc SQUID or interferometer. For high frequencies similar circuits containing series resistances R_L will behave as SQUIDs for $\omega > R_L/L$. The equivalent circuits for simple SQUIDs are shown in Figure 6, where the (R, I_c, C) at the left of each circuit represents the Josephson junction as shown in Fig. 1.

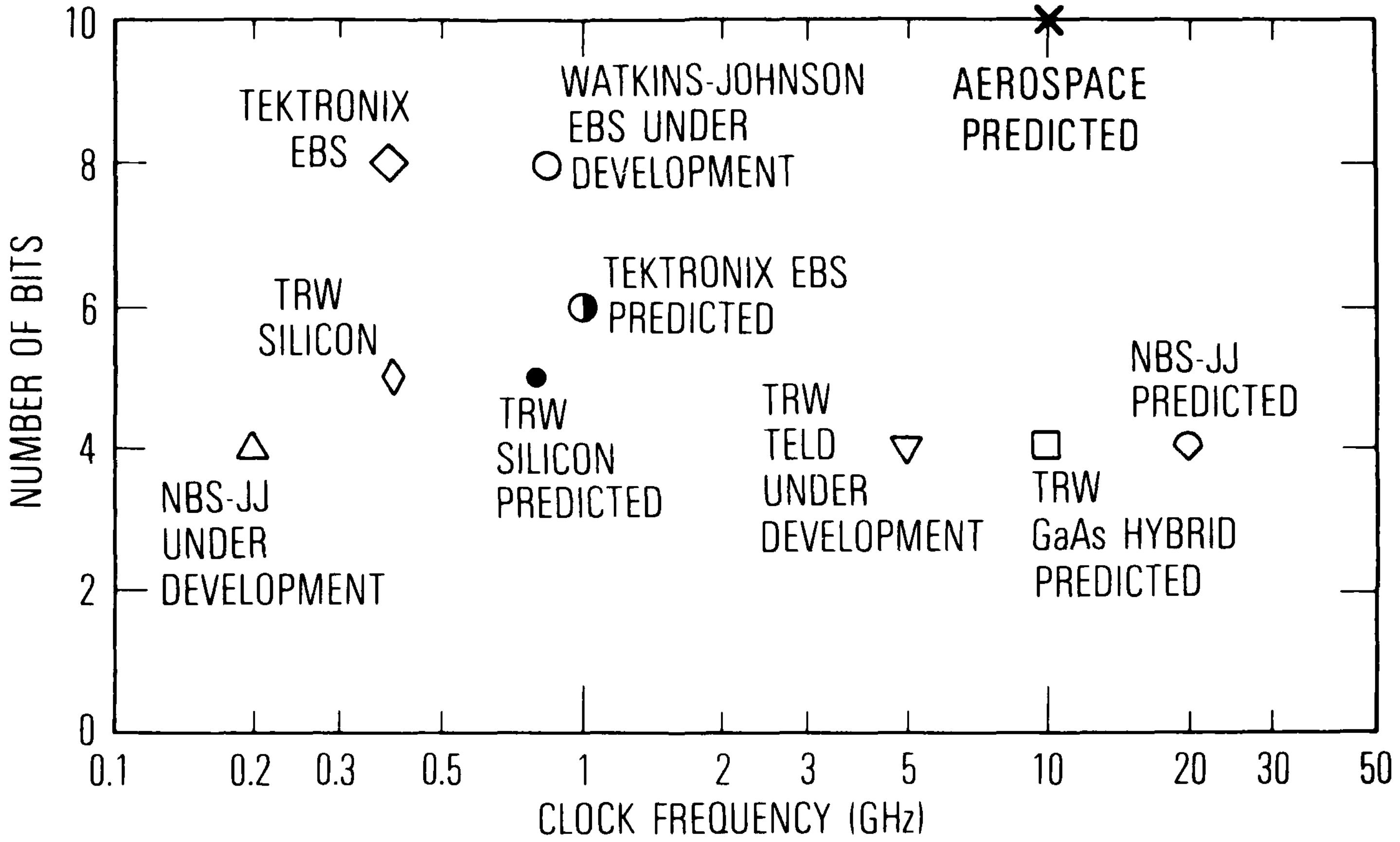
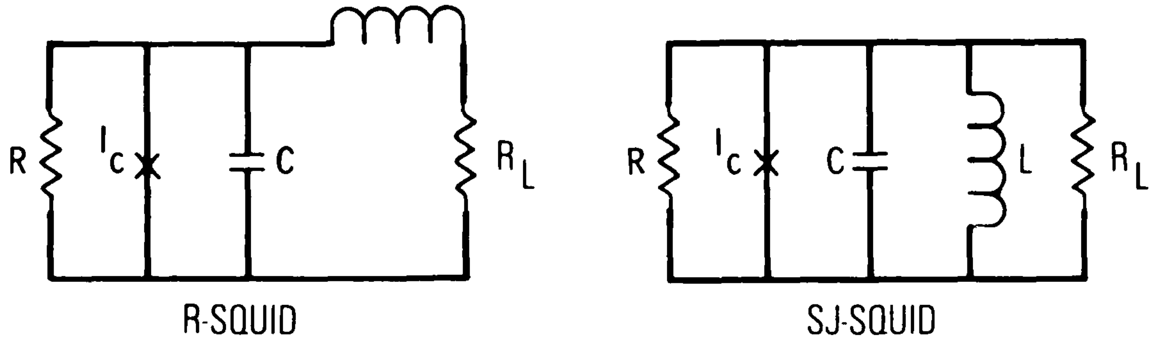


Fig. 5. Comparison of A/D Converter Technologies (after Reference 1)



R-SQUID

SJ-SQUID

Fig. 6. Equivalent Circuits of a Resistive (Left) and Superconducting (Right) Single Junction SQUID

In the case that $\beta \sim 1$, we note that $L \sim L_J$ and $\overset{c}{\theta} \sim R_L/L$. The quantum behavior is easily understood in terms of the passage of quantized magnetic flux (Φ_o) through the junction(s) and into circuit inductance. In the case $\beta \gtrsim 1$, the SQUID is bistable in its magnetization behavior, transients between states correspond to $\delta\theta \sim 2\pi$, and the detailed quantum behavior depends upon the applied magnetic flux, ϕ_x. A SQUID with two identical Josephson junctions with $\beta = \pi$ has the magnetic behavior shown in Fig. 7, where I represents the externally applied current. As the current increases from zero with the SQUID in state A, the magnetic flux ϕ increases reversibly from A → B and then makes an irreversible transition to B'. If I is suitably removed during this transition, the SQUID will then reside in state A'.

Such transitions can be used to generate precisely spaced (in signal flux) pulses with picosecond response times, and furthermore such devices can perform scaling operations to count the pulses and complete an A/D sampling. The schematic diagram for such a device is shown in Fig. 8. This device approaches a fundamental limit in performance since it depends on the natural quantization of SQUIDs in units of Φ_o, a limiting speed of 10^{-12} seconds imposed by the superconducting energy gap, and energy per quantization level associated with the magnetic stored energy, $\Phi_o^2/2L$. For stability against thermal noise, $\Phi_o^2/2L > kT = 2.8 \times 10^{-23}$ joules at 4 kelvin.

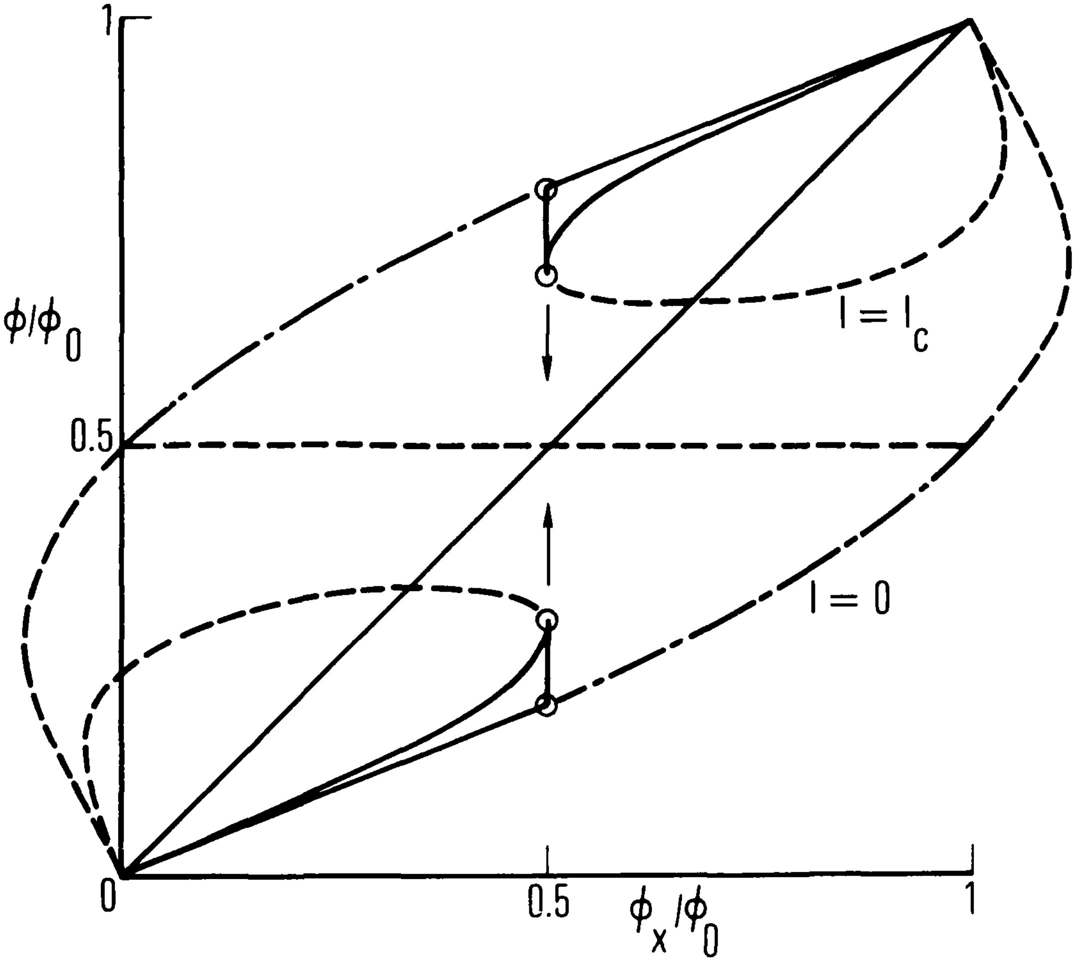


Fig. 7. Magnetic Response Curve for a Symmetric Double Junction SQUID with $\beta = \pi$ for External Current Equal to Zero and Equal to the Maximum Supercurrent, I_c (after Reference 4)

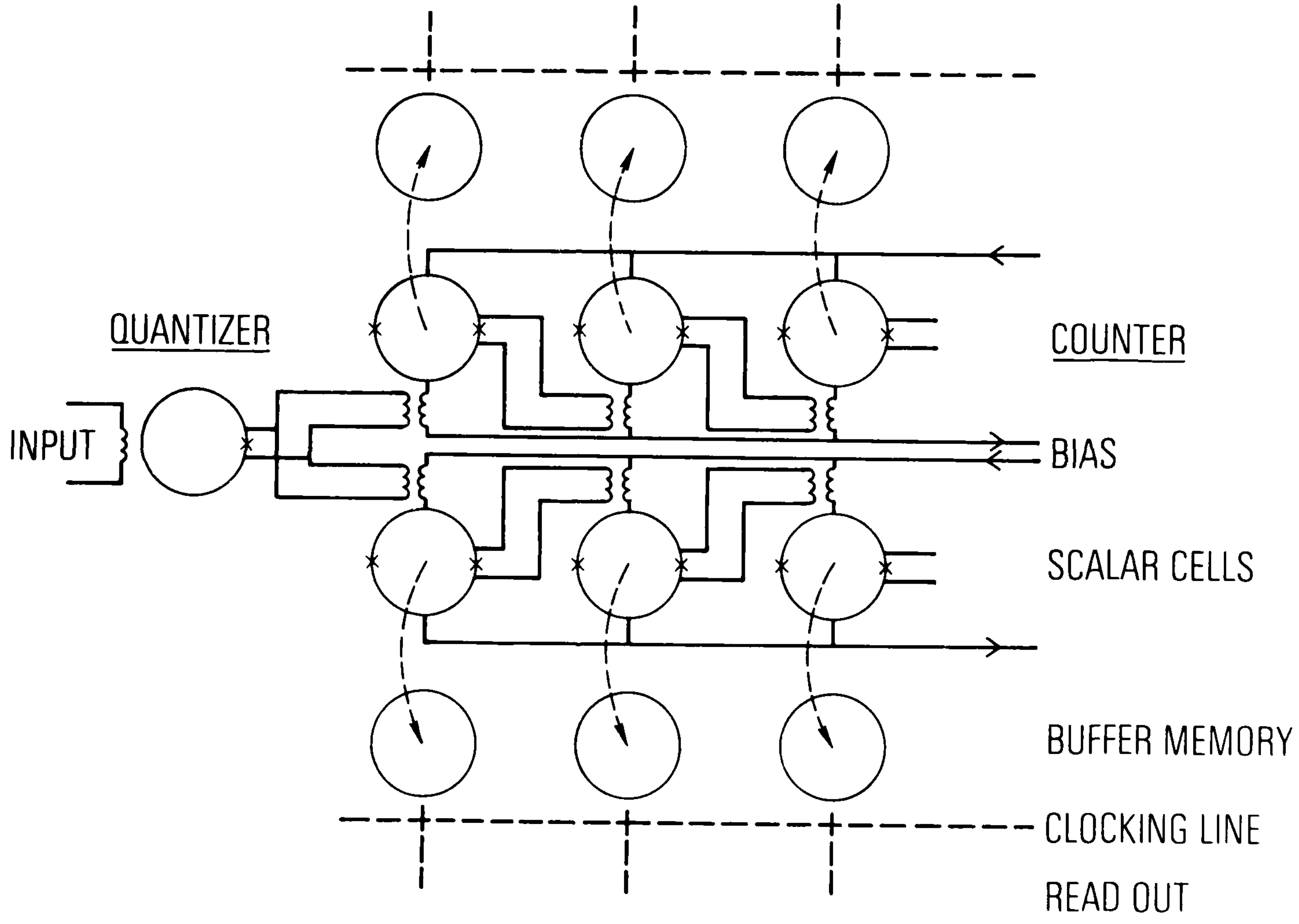


Fig. 8. Conceptual Design of a SQUID A/D Converter (after Reference 4)

Receivers and Radiometers

An important area in which superconductivity can contribute to space systems is in low noise receivers, particularly at microwave and millimeter wavelengths. Fig. 9 shows the one-way attenuation from earth to space at a zenith angles of 0° (solid line), 60°, and 80° over this frequency band.[1] Earth to space transmission for either communication or earth monitoring must fall in the regions of low attenuation (or clear atmospheric "windows"), while space-to-space communication links are most attractive at frequencies where the atmosphere is opaque. The most desirable type of receiver is a heterodyne configuration (Fig. 10) utilizing an efficient, low noise, wideband mixer followed by a low noise intermediate frequency (IF) amplifier. Such receivers are characterized by an excess receiver noise temperature, T_R, given by

$$T_R = T_i(L_i - 1) + L_i[T_d(L_c - 2) + L_c T_{IF}] \tag{7}$$

where T_i is the temperature of the input loss L_i, T_d is the mixer diode noise temperature, T_{IF} is IF amplifier noise temperature, and L_c is the mixer conversion loss. It is advantageous to reduce T_R below the background temperature. For space-to-space links this temperature is approximately 3 K; for earth-space downlink the background in the clear windows can be as low as 30-50 K; for uplinks the background approaches 290 K. Conventional, uncooled receivers above 30 GHz have $T_R \geq 1000$ K; below 30 GHz, $T_R \sim$ 600 K. Thus significant improvement is attractive for the space-to-space and downlinks. Furthermore, improving the receiver sensitivity reduces the required transmitter power, reducing the weight, power, and failure rates on the spacecraft.

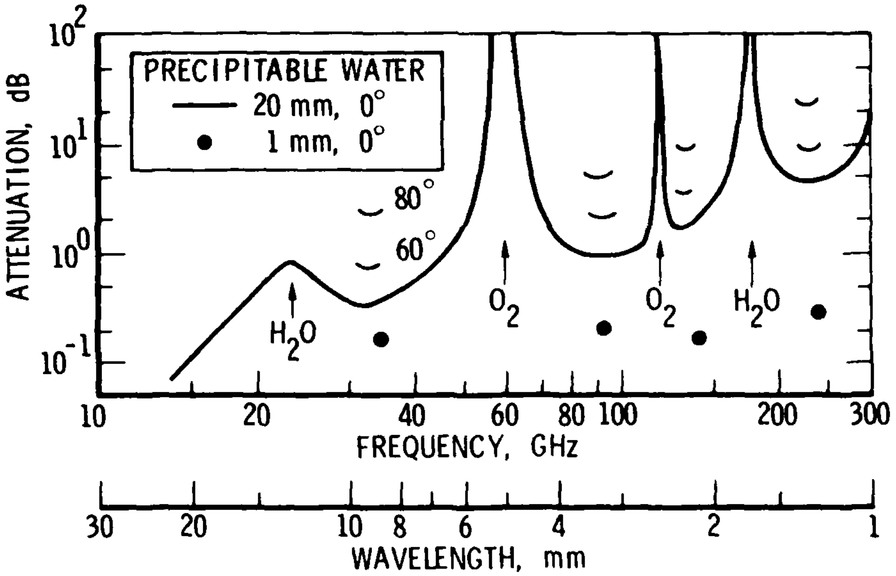


Fig. 9. Atmospheric Attenuation versus Frequency for a One-Way Path Through the Atmosphere. The solid curve is for a zenith angle of 0°; minima for θ = 60°, 80° are also shown.

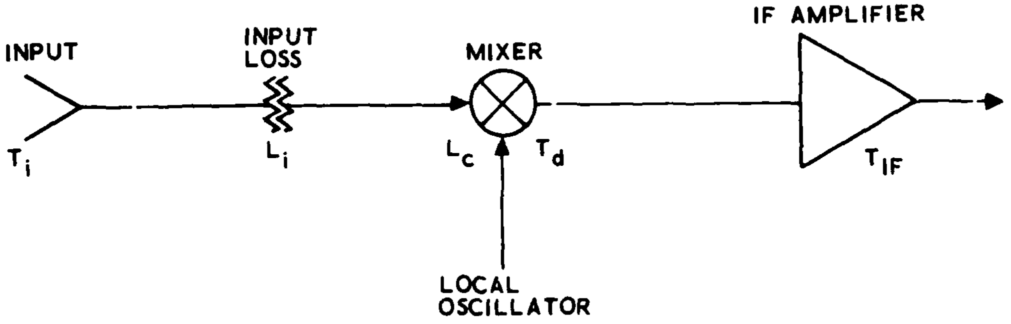


Fig. 10. Heterodyne Receiver Configuration Identifying Terms Contributing to the Receiver Noise Temperature

Superconductivity can result in a significantly smaller T_R by diminishing several terms, the most important being T_i, T_d, and T_{IF}. Low noise mixers using Josephson junctions and superconducting-Schottky diodes are currently under development. The super-Schottky diode using Pb on GaAs has demonstrated $T_d \approx 1$ K with $L_c \approx 6$ at 10 GHz. Furthermore Josephson amplifiers with noise temperatures of several kelvin are expected to be available in the near future. Receiver noise temperatures near 25 K are predicted at 100 GHz within the next several years. This represents an improvement in signal-to-noise ratio of forty.

Another application for low noise receivers at millimeter wavelengths is in radiometric imaging. Passive radiometry at 90 GHz can yield effective imagery with useful resolution as shown by the comparison of simultaneous airborne photography and 90 GHz radiometric imagery of a large ship and its wake (Fig. 11). A quantitative measure of the antenna temperature profile at various positions is given in Fig. 12. Improvement in receiver noise temperature would permit either greater sensitivity or faster scan rates, with greater spatial resolution.

RADIOMETRIC IMAGE

PHOTOGRAPH

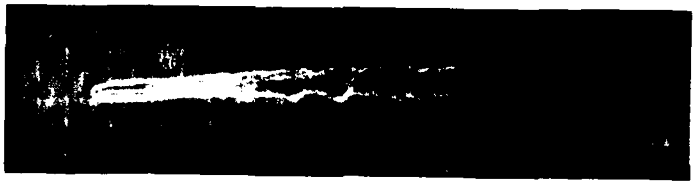


Fig. 11. Airborne 90 GHz Radiometric Image of Ship and Wake Compared with a Photograph Taken at the Same Time (after Reference 6)

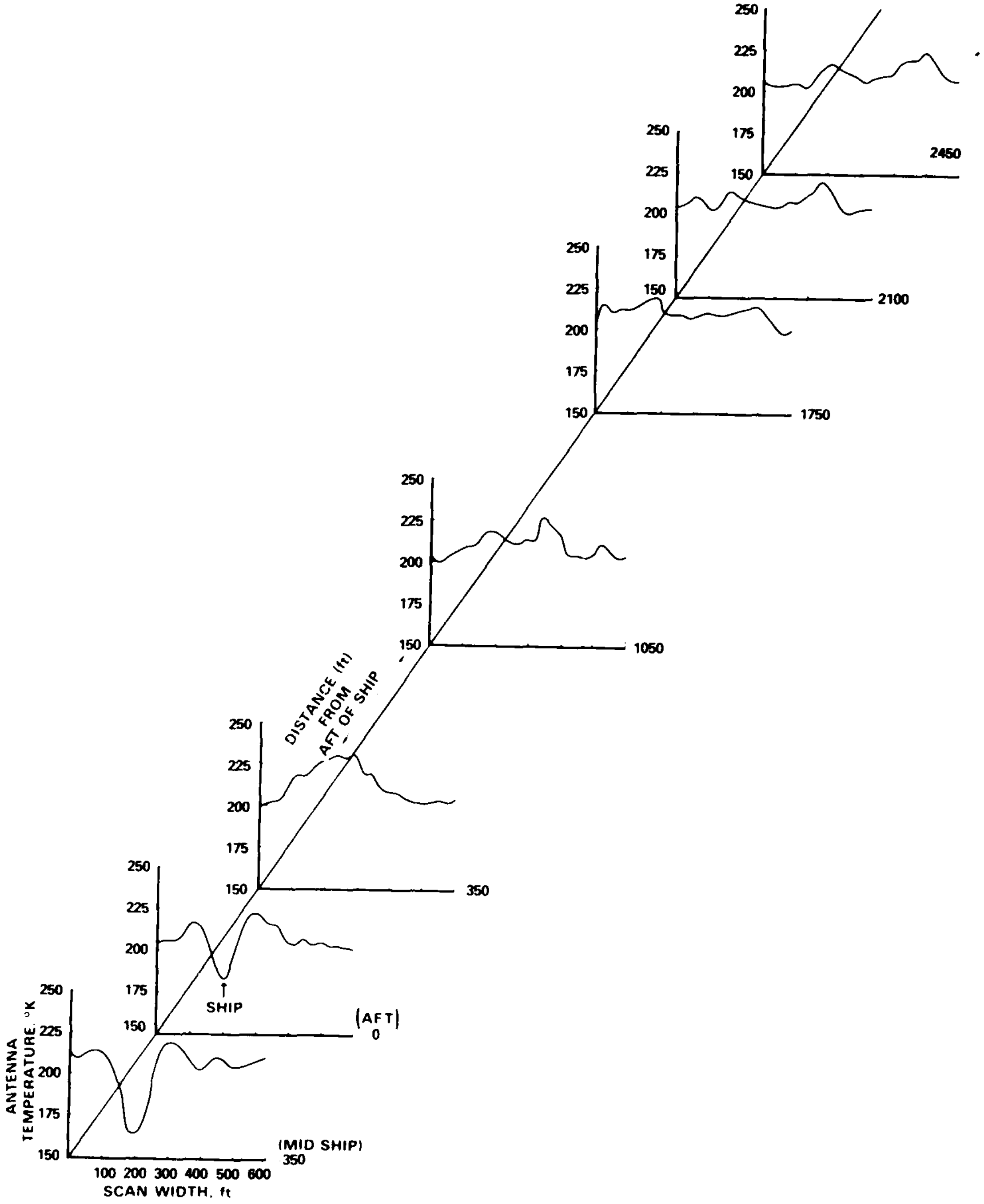


Fig. 12. Temperature Profiles of 90 GHz Radiometric Image Shown in Fig. 11 (after Reference 6)

Oscillators

The final area which we will discuss is the use of superconducting materials to make better clocks and oscillators. The stability and accuracy of electronic oscillators is determined by the stability and losses of the frequency selective circuits. Fig. 13 shows the frequency-dependent surface resistance for various materials. Superconducting metals have orders of magnitude smaller loss than do normal metals even at cryogenic temperatures. Thus, very high Q circuits can be fabricated which will lead to very stable sources [1]. This is of future interest for reference oscillators in satellite navigation systems which currently are using atomic clocks.

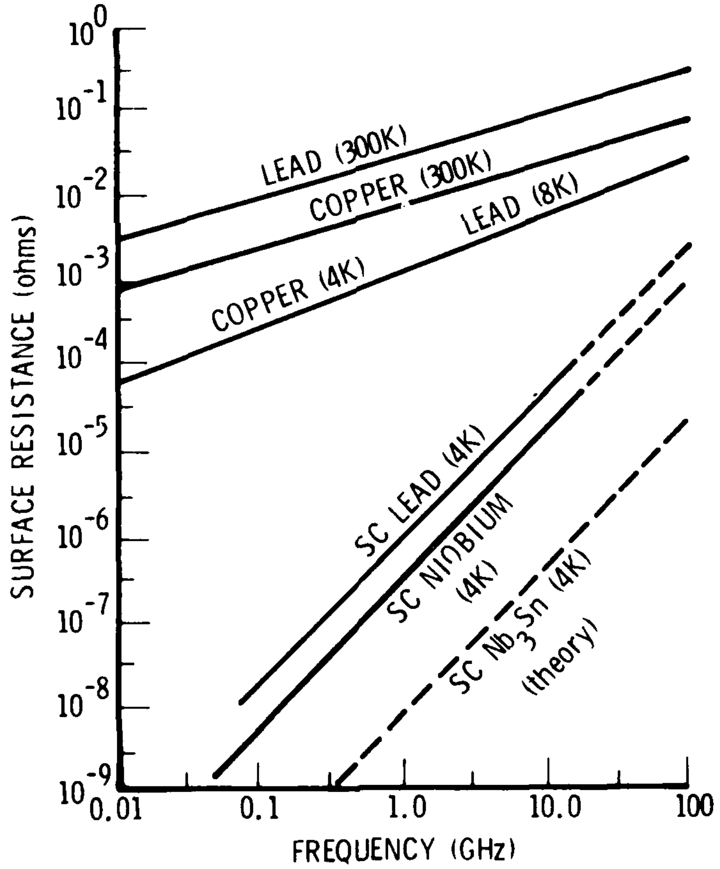


Fig. 13. Frequency-Dependent Surface Resistance of Metallic Conductors (after Reference 1)

A further advantage of the superconducting oscillator is the elimination of radio frequency crystal quartz oscillators. Thus, even in the present atomic standards the active source is a quartz oscillator in the vicinity of 10 MHz. Superconducting cavities can be conveniently made at several GHz, providing a direct reference oscillator. A principal difficulty with sources produced by frequency multiplication is the enhanced phase noise close to the carrier which is similarly multiplied. The superconducting cavity can be combined with Josephson junctions to produce very low noise, stable frequency synthesizers.

Although superconducting cavities have no inherent accuracy in the sense of a standard, they should be very dimensionally stable because of the low operating temperatures. A principal source of drift reported to date is from temperature, pressure, and gravitational effects. In a space environment, the latter two effects should be much less important than on earth.

Summary

The use of superconductivity, particularly in electronic circuits can make an important and useful contribution to space systems. Two principal drawbacks are the lack of reliable, efficient, closed cycle cryocoolers and the minimal effort devoted to electronic systems, as opposed to individual components and circuits.

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LABORATORY OPERATIONS

The Laboratory Operations of The Aerospace Corporation is conducting experimental and theoretical investigations necessary for the evaluation and application of scientific advances to new military concepts and systems. Versatility and flexibility have been developed to a high degree by the laboratory personnel in dealing with the many problems encountered in the nation's rapidly developing space and missile systems. Expertise in the latest scientific developments is vital to the accomplishment of tasks related to these problems. The laboratories that contribute to this research are:

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Chemistry and Physics Laboratory: Atmospheric reactions and atmospheric optics, chemical reactions in polluted atmospheres, chemical reactions of excited species in rocket plumes, chemical thermodynamics, plasma and laser-induced reactions, laser chemistry, propulsion chemistry, space vacuum and radiation effects on materials, lubrication and surface phenomena, photosensitive materials and sensors, high precision laser ranging, and the application of physics and chemistry to problems of law enforcement and biomedicine.

Electronics Research Laboratory: Electromagnetic theory, devices, and propagation phenomena, including plasma electromagnetics; quantum electronics, lasers, and electro-optics; communication sciences, applied electronics, semiconducting, superconducting, and crystal device physics, optical and acoustical imaging; atmospheric pollution; millimeter wave and far-infrared technology.

Materials Sciences Laboratory: Development of new materials; metal matrix composites and new forms of carbon; test and evaluation of graphite and ceramics in reentry; spacecraft materials and electronic components in nuclear weapons environment; application of fracture mechanics to stress corrosion and fatigue-induced fractures in structural metals.

Space Sciences Laboratory: Atmospheric and ionospheric physics, radiation from the atmosphere, density and composition of the atmosphere, aurorae and airglow; magnetospheric physics, cosmic rays, generation and propagation of plasma waves in the magnetosphere; solar physics, studies of solar magnetic fields; space astronomy, x-ray astronomy; the effects of nuclear explosions, magnetic storms, and solar activity on the earth's atmosphere, ionosphere, and magnetosphere; the effects of optical, electromagnetic, and particulate radiations in space on space systems.

THE AEROSPACE CORPORATION
El Segundo, California

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