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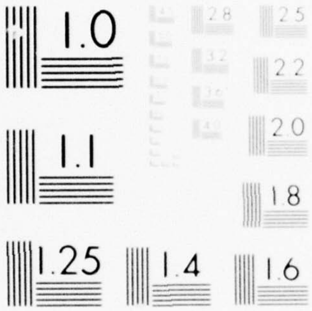

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New Horizons in Receiver Technology

Electronics Research Laboratory
The Ivan A. Getting Laboratories
The Aerospace Corporation
El Segundo, Calif. 90245

20 October 1977

Interim Report

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Los Angeles Air Force Station
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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.

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

Efficient military communication by means of electronic (including optical) signal transmission depends on the available bandwidth, transmitter power and transmission losses, detector sensitivity and dynamic range, and the ability to discriminate against interference or jamming. Theoretical as well as practical performance limits are set by the receiver sensitivity, an element of the system for which the system engineer desires a performance near the theoretical limit. This report describes the theoretical and environmental constraints, as well as significant new device developments that will make possible →

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communications over approximately three decades of presently unused spectrum, from EHF through the IR. Recently, new sources have been developed in this spectral region, and simple, efficient mixers will permit wideband, multichannel communication systems that can take advantage of the shorter wavelengths and unique transmission properties of the atmosphere. At the short-wavelength end of the spectrum, new room-temperature Schottky diode and hot carrier mixers are inherently sensitive and offer a bandwidth in excess of 10 GHz. At these short wavelengths, high directivity can be achieved with a small aperture, a particularly attractive feature for satellite-satellite communications. High atmospheric absorption permits short-range terrestrial and air-to-air communications, relatively interference free, with frequent reuse of the spectrum. The large available bandwidths provide extra link security by means of such techniques as spread spectrum or frequency hopping. At millimeter and longer wavelengths where clear atmospheric windows are available, newly discovered receiver techniques that employ cryogenic Schottky diode mixers and parametric amplifiers will provide receiver noise figures well under 1 dB. This can improve the performance of communication links such as satellite-to-ground, air-to-ground, and air-to-air.

It is important for system planners to be aware of these emerging device technologies that offer significant opportunities to improve the performance of communication links through increased receiver sensitivity, expanded spectrum availability, and selectivity for privacy and anti-jam performance. Hardware developed for the EHF to IR spectral region will require not only new active devices but an optimal integration of both microwave and optical signal transmission techniques, analogous to integrated optics.

CONTENTS

FIGURES

1. Introduction

Efficient military communication by means of electronic (including optical) signal transmission depends on the available bandwidth, transmitter power and transmission losses, detector sensitivity and dynamic range, and the ability to discriminate against interference or jamming. Theoretical as well as practical performance limits are set by the receiver sensitivity, an element of the system for which the system engineer covets a performance near the theoretical limit.

This paper describes the theoretical and environmental constraints as well as significant new device developments which will make possible communications over approximately three decades of presently unused spectrum, from EHF through the IR. New sources have been developed in this spectral region and simple, efficient mixers will permit wideband, multichannel communication systems which can take advantage of the shorter wavelengths and unique transmission properties of the atmosphere. At the short wavelength end of the spectrum new room temperature Schottky diode and hot carrier mixers are both inherently sensitive and offer a bandwidth in excess of 10 GHz. At these short wavelengths, high directivity can be achieved with a small aperture, a particularly attractive feature for satellite-satellite communications. High atmospheric absorption permits short range terrestrial and air-to-air communications relatively interference free with frequent reuse of the spectrum. The large available bandwidths provide extra link security via such techniques as spread spectrum or frequency hopping. At millimeter and longer wavelengths where clear atmospheric windows are available, newly discovered receiver techniques employing superconducting Schottky diode mixers and parametric amplifiers will provide receiver noise figures well under 1 dB. This can improve the performance of communication links such as satellite-to-ground, air-to-ground and air-to-air.

Receiver technology is developing rapidly. Receivers at frequencies extending through the microwave region are designed under a variety of constraints and the state of the art is such that the receiver noise figure can usually be stated with precision. The intent of this paper is not to discuss exhaustively the steady advances being made in state of the art receiver designs, but rather, to illustrate order of magnitude advances in bandwidth, noise figure, and frequency response made possible by new quantum electronic devices and techniques.

Some limitations imposed on receiver design are fundamental in nature and some are practical. For example, a fundamental lower limit on the noise figure of a receiver can be derived from statistical mechanics. The full realization of that noise limit is often prevented by non-ideal components. In the extension of receiver technology beyond the microwave and millimeter wave regions, fundamental device limitations are often obscured by our inability to solve commonplace problems. New receiver techniques will be discussed for the 3 GHz to 30,000 GHz frequency range (30 cm to 10μm wavelengths).

2. Receiver Concepts

2.1 Basic Receiver Configuration

The class of receivers under discussion in this paper are properly called heterodyne or coherent receivers. Incoherent or video receiver configurations can only be competitive with the wideband coherent receiver for communications applications in the visible or optical portion of the spectrum. Coherent receivers, characterized by a local oscillator-low noise mixer front end as shown in Figure 1, are by far the most sensitive per unit bandwidth and most convenient for accurate reproduction of transmitted information in this spectral region. The signal bandwidth is translated from the carrier frequency f_c to some convenient intermediate frequency (IF) with the addition of noise power

$$P_N = kT_R B \qquad (1)$$

where T_R is the receiver noise temperature and B is the bandwidth. The single-sideband receiver noise temperature can be expressed as

$$T_R = T_M + L_c T_{IF} \qquad (2)$$

where T_M is the mixer noise temperature, L_c is the total conversion loss from f_c to IF, and T_{IF} is the noise temperature of the IF amplifier following the mixer. The practical parameters T_M, L_c and T_{IF} characterize the receiver.

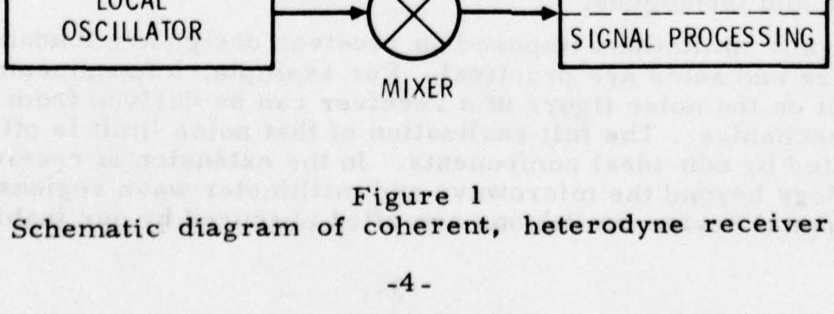

Figure 1
Schematic diagram of coherent, heterodyne receiver

If an ideal receiver were constructed the fundamental detector noise limit would be achieved

$$P_N = hfB\left\{\left[\exp\left(\frac{hf}{kT}\right) - 1\right]^{-1} + 1\right\} \tag{3}$$

where hf is the Planck constant frequency product, B is the receiver bandwidth, and kT is the Boltzman constant temperature product. This expression is perfectly general [1] and describes the noise limit in any detector reflecting the fluctuation in the equilibrium radiation power. Only a factor of two reduction of P_N can be obtained by preservation of the phase of the signal, e. g., in the homodyne mode. A plot of P_N versus frequency is shown in Figure 2 and the familiar limits at low and high frequencies can be identified.

Today receivers are being designed which approach this fundamental limit. With the emerging availability of local oscillators, it is useful to inspect the frequency dependence of communications system performance.

2.2 System Trade-offs

Our concern in this paper is with communication systems which operate in the atmosphere or in space at sufficiently long ranges that the appropriate antenna pattern is given by the far field or Fraunhofer expression. A receiver with an effective antenna diameter D_r will receive at range R a power P_r given by

$$P_r = P_t\left[\frac{D_r^2 D_t^2}{R^2\lambda^2}\right] \tag{4}$$

assuming no loss in the intervening medium and P_t and D_t the transmitter power and effective diameter, respectively. It would seem advantageous to decrease λ to the shortest possible wavelength in order to decrease the so-called space loss. Practical values of D_r and D_t alter the λ dependence; diffraction limited large antennas are easier to construct at microwave frequencies than at laser frequencies. Also, the available transmitter power is wavelength dependent.

Utilizing Equations (3) and (4), familiar asymtotic values of the signal-to-noise ratio (S/N) can be found in the low frequency or thermal limit,

$$S/N \simeq \frac{P_t}{kTB}\left[\frac{D_r^2 D_t^2}{R^2\lambda^2}\right], \quad kT >> hf \tag{5}$$

and in the high frequency or quantum noise limit

$$S/N \simeq \frac{P_t}{hfB}\left[\frac{D_r^{\,2} D_t^{\,2}}{R^2 \lambda^2}\right], \; kT << hf. \qquad (6)$$

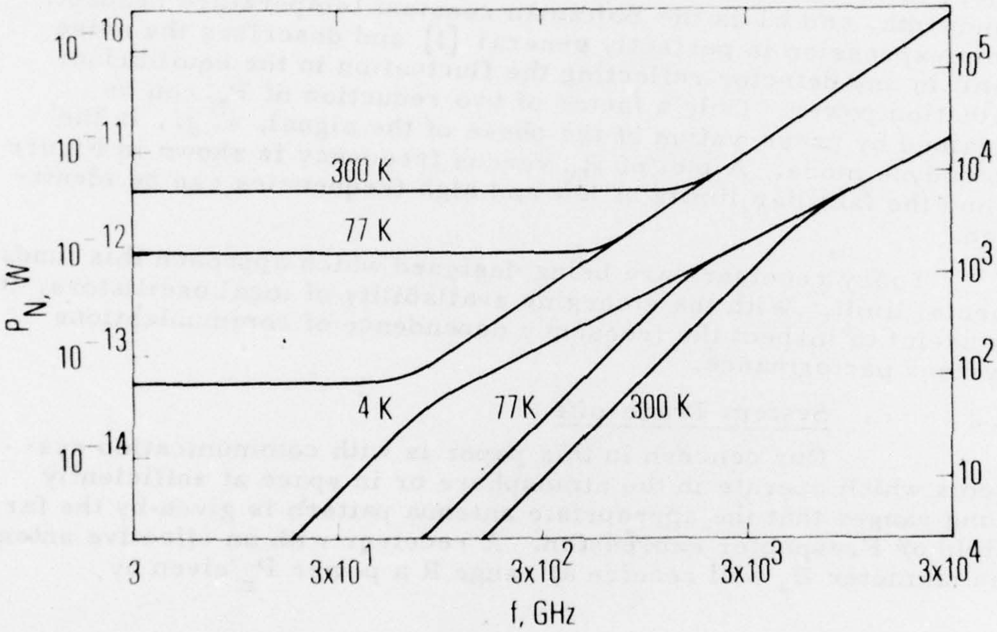

Figure 2

Noise power P_N in an ideal receiver calculated for a 1 GHz bandwidth and calculated signal-to-noise ratio, S/N, for a synchronous satellite-to-ground link with constant 0.5 m diameter antennas under ideal conditions.

Figure 2 shows the dependence of P_N and S/N as a function of frequency assuming constant values of P_t, D_r, and D_t. Although the quantum noise increases with frequency in the high frequency limit, the reduction in space loss yields a linear increase of S/N with f.

In a space-to-space communication link, the ideal receiver expressions clearly indicate that the highest possible f is desireable to maximize the S/N and available bit rate. For terrestrial or space-to-earth communications the influence of atmospheric absorption must be introduced. Both attenuation of the transmitted signal and the introduction (emission) of noise by the absorbing medium are important. (Less important at these wavelengths are the effects of scintillation which we will ignore.) Figure 3 shows a calculated spectrum of the zenith attenuation from 10 to 300 GHz for a standard model of the atmosphere. Good agreement has been found between measured and computed attenuation which contains the effects of O_2, O_3, and H_2O. Examples of other atmospheric absorption curves at higher frequencies can be found in the literature. Several windows are found at higher frequencies. For example, windows occur at 690 GHz and 870 GHz where absorption will not affect the performance of a hypothetical communications system (to a mountain top) as much as noise radiated by the atmosphere. For a dense medium at 300 K this noise dominates the noise figure of a receiver system provided $kT \ll hf$, or for frequencies $\leqslant 6000$ GHz.

At millimeter wavelengths, e.g., in the atmospheric window at 100 GHz, the ultimate performance of a system can be calculated using the expression

$$T_S \approx T_R + T_a L_a \tag{7}$$

where L_a and T_a are the attenuation temperature of the atmosphere. Actually T_a and L_a vary with altitude and an integral expression correctly establishes this contribution. Ignoring these complexities, one can deduce by taking the approximate values $T_a \sim 300$ K and $L_a = 0.1$ that

$$T_N \approx T_R + 30 \text{ K}$$

and we find that a receiver noise temperature less than 30 K is desirable for an earth-to-space communication system.

Figure 2 shows that the minimum detectable signal power P_N increases linearly with frequency, and therefore the corresponding lowest useful noise temperature increases correspondingly. Thus for ideal devices the need for cryogenic cooling exists only at the longer wavelengths ($\gtrsim 500$ µm).

System concepts have been dealt with here in a cursory manner, but in enough detail to put new receiver ideas in perspective.

3 Local Oscillators

The desirable attributes of a local oscillator source are well known. Spectral purity and freedom from residual frequency modulation are needed to minimize LO noise contributions. Sufficient power is needed to maximize the mixer conversion ratio and some frequency tunability is desired. At frequencies up to and slightly above 100 GHz, klystrons work well and are readily available. Impatt diodes now emit enough power to be useful in this same frequency region.

Above, say, 300 GHz the picture is not bright. For Schottky

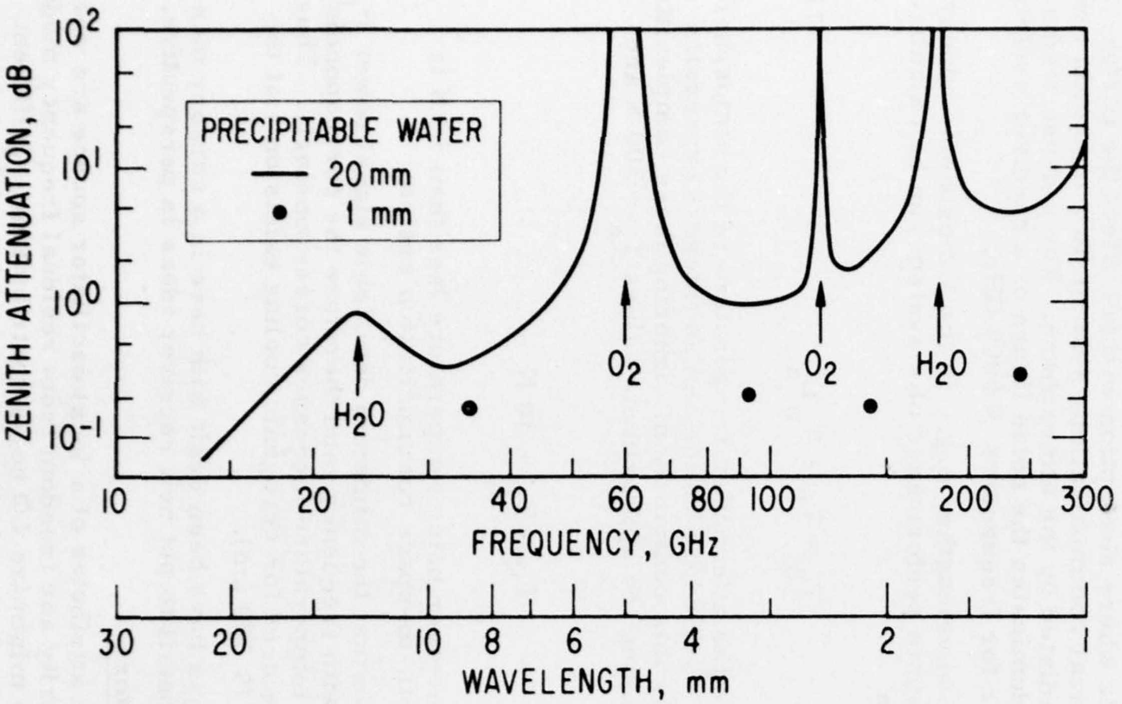

Figure 3

Calculated total zenith attenuation for a standard model of the atmosphere. Variation in the "window" attenuation is shown for 1 and 20 mm total precipitable water vapor.

diodes, a power level on the order 10 to 100 mW is needed. We plot the output power from a variety of sources in Figure 4. Above 300 GHz, only carcinotron and lasers emit adequate power. The carcinotron is commercially available and can be tuned over a limited frequency region. The indicated class of FIR laser sources [2] emit at a single frequency since the emission is peculiar to a particular laser molecule. However, hundreds of laser molecules have been discovered in the FIR or submillimeter wave spectral region of which only a few have been plotted in Fig. 4. Although other types of atomic and molecular lasers are occasionally discovered to emit FIR radiation, the generic class of FIR waveguide lasers [2] is the most important local oscillator source. The spectral purity is very good indeed and one compact model is now commercially available. At still higher frequencies near 30,000 GHz diode lasers are specifically noted because they are tunable and can be utilized with diode mixers.

For the near future, electron tube and solid state local oscillator sources are the best choices below 300 GHz with FIR waveguide lasers as the best choice above 300 GHz.

4.0 Heterodyne Receiver

The key to successful development of a heterodyne receiver is the mixer which is required to efficiently downconvert the input signal spectrum (RF) to some IF where low noise amplification and efficient signal processing can be carried out. Of principal concern are the mixer conversion efficiency, noise, bandwidth (both RF and IF), and dynamic range. Intimately connected with these characteristics are the mixer impedances and required local oscillator (LO) power. We will see that new device developments will make it possible to achieve wideband response over the entire spectrum of interest. At certain frequencies the projected performance of the mixers is sufficiently good that the system performance is limited by the IF amplifiers. Therefore low noise amplifiers also become a topic of interest.

4.1 Wideband Mixers

Candidates for wideband low noise mixers in the EHF to IR region are Schottky barrier diodes, photoconductive diodes, hot electron diodes, Josephson junctions, superconducting-Schottky diodes, and metal-insulator-metal tunnel diodes. Although other devices can detect at these frequencies they are generally narrowband and are not of interest for communication applications.

4.1.1. Schottky Barrier Diode Mixers

The Schottky barrier diode is the dominant mixer at microwave frequencies where it provides the best bandwidths and noise figure. In the last several years the Schottky diode has been under development for millimeter and submillimeter wavelengths [3].

A Schottky-barrier diode consists of a metal contact to a

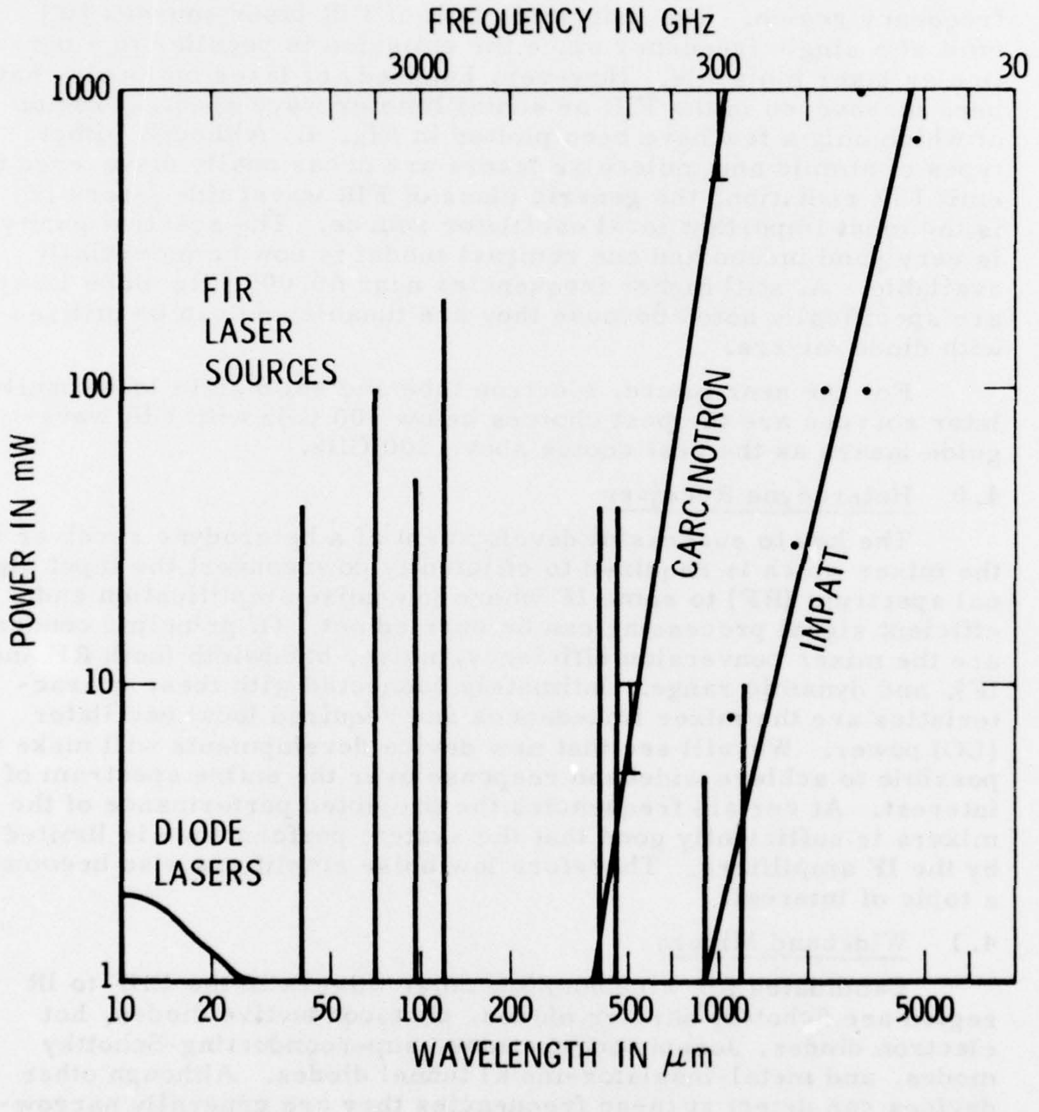

Figure 4

State-of-the-art sources in the 30-1000 GHz region.

semi-conductor. The diode current voltage (I-V) characteristic is given to a good approximation by [3]

$$I = I_o \left[\exp\left(\frac{qV}{nkT}\right) - 1 \right] \tag{8}$$

where I_o is determined by the area and material parameters of the diode, and n is the ideality factor which is approximately unity for low- to moderately-doped semiconductors. This nonlinear function is responsible for its success as a detector and mixer. When operated as a mixer a large LO voltage is impressed on the diode to produce a conductance which is periodic at the LO frequency f_ℓ. In the presence of a signal at frequency f_s, the intermediate frequency $f_{IF} = |f_\ell - f_s|$ is generated. For low LO power the efficiency of this conversion process is a strong function of (qV_l/kT) where V_l is the amplitude of the LO voltage. With large LO power the conversion efficiency of the device saturates at a value determined by the impedance terminations on its input and output ports.

The sensitivity of a mixer (receiver) is expressed in terms of its mixer noise temperature T_M given by

$$T_M = L_c T_d \tag{9}$$

where L_c is the total conversion loss of the mixer, defined as the ratio of available power from the RF source to the power absorbed in the IF load, and T_d is the noise temperatures of the mixer diode. In fabricating a mixer, utmost attention must be paid to minimizing L_c because of Eqs. (2) and (9).

The conversion loss L_c of a mixer in a tunable mount is conveniently expressed as the product of three terms

$$L_c = L_0 L_1 L_2. \tag{10}$$

The intrinsic conversion loss L_0 arises from the conversion process within the nonlinear resistance of the diode and includes the impedance mismatch losses at the RF and IF ports. Analysis of L_0 as a function of $(qV_l/n\,kT)$ for a properly-terminated sinusoidally-pumped broadband mixer yields the result shown in Fig. 5. The RF and IF losses, L_1 and L_2, respectively, are associated with the parasitic elements of the diode. These losses are given by

$$L_1 = 1 + \frac{R_s}{R} + \omega^2 C^2 R R_s \tag{11}$$

$$L_2 = 1 + \frac{R_s}{R_2} \tag{12}$$

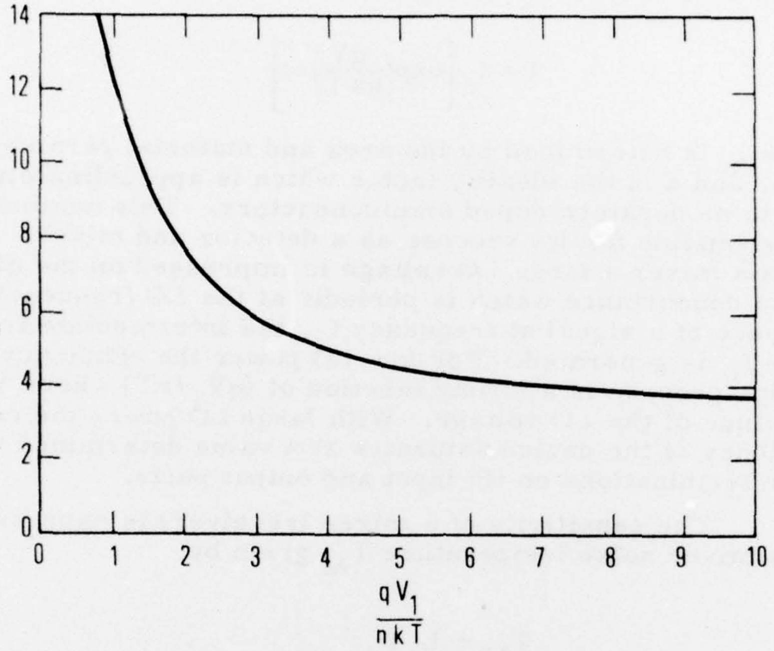

Figure 5
Intrinsic conversion loss in dB as a function of local oscillator voltage, V_1.

where R_s and C are defined in Fig. 6, and ω is the signal angular frequency. R is the equivalent impedance of the local oscillator pumped nonlinear resistance, and R_2 is the IF load impedance. The ω^2 dependence of the third term in (11) is responsible for the degradation in the performance of Schottky-barrier mixers at high frequencies. However, both L_1 and L_2 are geometry and material dependent and by manipulation of these terms one can reduce L_c at high frequencies.

A straightforward method for minimizing the third term in (11) is to reduce the contact area and hence C. Diameters greater than 1 μm are commonly obtained by photolithographic techniques. Submicron dimensions with diameters as small as 0.1 μm have been obtained by McColl, et al.[4], using electron lithography.

The loss terms in (11) and (12) proportional to R_s are inversely proportional to the mobility of the semiconductor. N-type GaAs has a high mobility, functions at room temperature, and is commercially available. For these reasons nearly all millimeter and submillimeter wave Schottky-barrier mixers utilize this material.

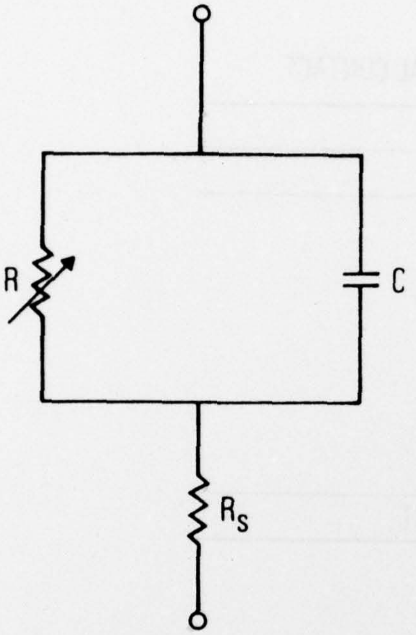

Figure 6

Equivalent circuit of a Schottky diode. R is the nonlinear resistance, C is the shunting capacitance, and R_s is the series spreading resistance which results from the crowding of the current in the semiconductor near the small metal contact.

The epitaxial diode structure shown in Fig. 7 is the standard design for high frequency Schottky-barrier mixers. The epitaxial layer is as small as 1000 Å and the substrate is very heavily doped in order to reduce the diode spreading resistance. Moderate doping is chosen for the epitaxial layer in order to minimize the diode noise temperature T_D.

Electrical contact to a Schottky barrier diode is currently made by a whisker as shown in Fig. 7. The whisker functions as an antenna to couple RF radiation to the junction, IF power out, and supply the required DC bias.

A contact array diode is under development [4] as a favorable alternative to the epitaxial diode for efficient high frequency mixing. Utilizing a structure consisting of a large number of small Schottky-barrier diodes connected in parallel, L_1 is reduced. The number is chosen sufficiently large to maintain a low value of L_0. Diodes with more than 100 contacts, each 0.35 μm in diameter, have been fabricated to date. Figure 8 is a sketch of the cross section of the diode.

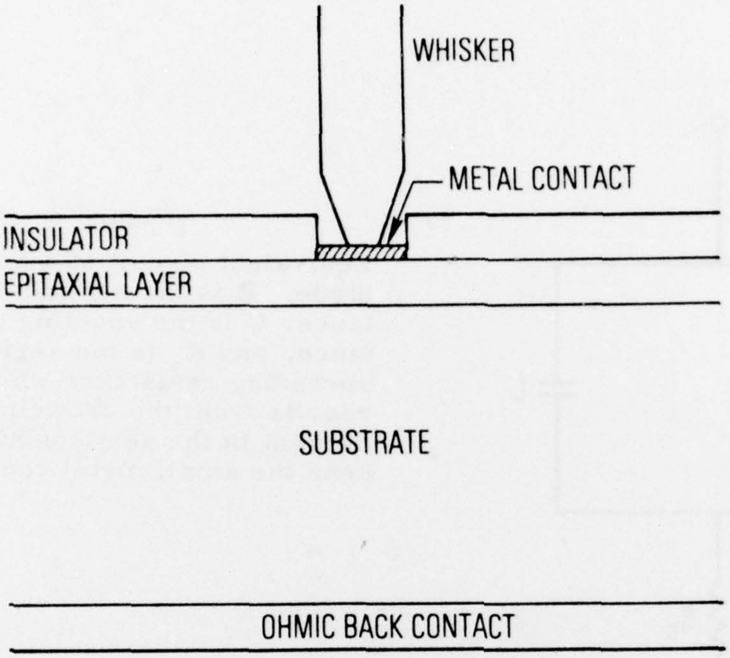

Figure 7
Standard design for high frequency Schottky barrier diode mixers.

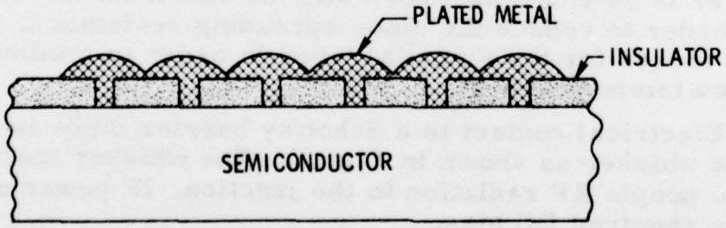

Figure 8
Cross-sectional drawing of the multi contact array diode.

The function of the mixer mount is to both couple the radiation to the diode and provide a method to reactively tune out the capacitance C. The use of single mode waveguide mixer mounts is the standard method at microwave and millimeter wavelengths, and these are available commercially for frequencies up to 325 GHz.

In Table I we summarize a few of the important heterodyne results for Schottky-barrier diodes at room temperature. Results are commonly reported in the literature in terms of the minimum detectable power kT_M. As the operating frequency increases the minimum detectable power increases rapidly reflecting primarily the difficulty in matching to these very small diodes at short wavelengths.

TABLE I

f(GHz)	$kT_M (WHz^{-1})$	Source
231	1.7×10^{-19}	Schneider & Wrixon [5]
600	10^{-17}	Gustincic [6]
890	5×10^{-15}	Fetterman [7]

4.1.2 Superconducting-Schottky Mixer

A variation of the Schottky diode employs a superconducting metal contact to a heavily doped semiconductor and is called the super-Schottky diode. This diode operates at cryogenic temperatures and obeys the same equations as the conventional Schottky for voltages up to the superconducting energy gap valtage, typically 10^{-3} V. However the diode has an ideality factor $n = 1$ and a diode noise temperature $T_D = T$. In extensive experiments at 10 GHz and 1 Kelvin, Pb/p-GaAs mixers produced $T_M = 6$ K with 2×10^{-8} W of LO power[8]. (See Figure 9) The higher frequency performance is

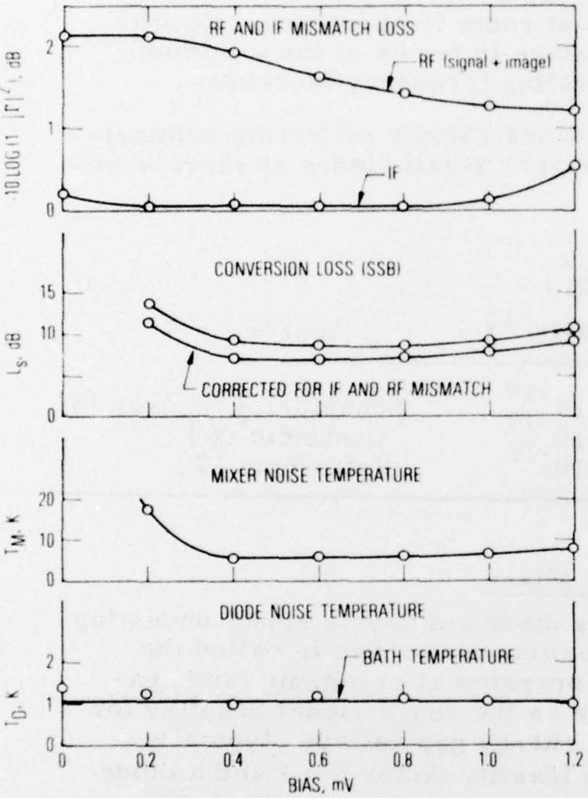

Figure 9

Measured performance of a Pb/p-GaAs super-Schottky diode mixer at 9 GHz and 1 kelvin.

limited by the parasitic loss L_1, principally from the series spreading resistance. This is being overcome by the use of higher mobility semiconductors (n-InSb) and the contact array structure.

At 100 GHz and above we expect the super-Schottky diode mixer to be quantum noise limited. In this case the receiver performance will be dominated by the IF amplifier. This is a good place to point out that from a fundamental standpoint good receivers at millimeter wavelengths and below should be cooled to achieve optimum T_R; above $\sim$ 600 GHz the requirement for cooling diminishes rapidly. Practical device limitations have required cryogenic cooling of IR detectors while at microwave frequencies room temperature mixers are commonly used despite noise temperatures $\gtrsim 10^3$ K. To date all receivers with $T_N \lesssim 300$ K at f $\gtrsim$ 15 GHz are cryogenically cooled. This situation is not likely to change except cryogeneration will become easier as refrigeration capability is developed.

The super-Schottky mixer is limited to signal powers of the order of the LO, $\sim 10^{-8}$ W. However, since the noise limit is $\approx$ 10 K there is a dynamic range of 10^5 for a 1 GHz bandwidth.

4.1.3 Josephson Junction Mixers

A Josephson junction is a completely superconducting tunnel diode which has unique electrical properties beyond those of a normal tunnel junction. It can be operated as a low noise mixer over a very wide frequency spectrum with very small LO power. The details of its operation will not be discussed here but the following characteristics have been demonstrated.

Josephson junctions can be fabricated by several methods including point contacts, microbridges, and oxide barrier evaporated films. The latter method promises to be the most reproducible and reliable, but most high frequency detection experiments have been performed with point contacts and microbridges. The electrical behavior is dominated by the relation

$$I_S = I_o \sin \left(\frac{4\pi e}{h} \int V dt\right) \tag{13}$$

where I_S is the supercurrent, I_o is a characteristic current determined by material properties, temperature, and geometry, and V is the instantaneous voltage across the junction. Because of this relation the response to RF and DC is extremely non-linear.

The Josephson junction has been used as a downconverter at 891 GHz with a self-generated harmonic of a 10 GHz local oscillator [9], although mixer noise temperature parameters have only been measured at 36 [10] and 300 GHz [11]. The theoretical prediction is

$$T_M \approx 10^{-8} fT \tag{14}$$

where f is the input (signal) frequency. However saturation occurs at about 10^{-11} W, making this device a poor choice for communication systems.

4.1.4 Hot Electron Diode Mixer

The hot electron diode is a new candidate for efficient mixing in the IR and FIR spectrum. Erler and Aukerman [12] at The Aerospace Corporation have recently demonstrated an InAs hot electron detector and mixer at wavelengths as short as 10.6 μm. This device utilizes an ohmic contact to n-InAs fed by a whisker antenna. Because n-InAs has an n^+ surface there is no Schottky barrier and the IR currents injected by the antenna are strongly absorbed by the electrons in the "spreading resistance" region of the contact. These heated electrons generate a thermoelectric voltage proportional to the incident power I_{RF}^2R. An analysis of the expected performance shows that the sensitivity can approach that of an efficient Schottky diode to within a factor of two. The bandwidth is determined by the electron-lattice relaxation time, expected to be 10^{-11} - 10^{-12} sec. at room temperature, suggesting bandwidths near 100 GHz. Experiments mixing two CO_2 lasers showed an IF response at 55 GHz.

N-InAs appears well suited as a hot electron mixer since there is no competing Schottky barrier at the surface of this material. The response is expected to be flat from 10 μm to microwaves and fabrication by electro-lithographic methods should produce reliable, rugged, radiation insensitive mixers with wide bandwidth and good sensitivity.

4.1.5 Other Mixers

Fast detector types which have not been explicitly discussed above include some photoconductors which only offer advantages near the 10 μm spectral region and metal oxide metal (MOM) mixers. The state of the art of photoconductors cannot obviously be extended into the ~ 300 GHz region and be competitive with the above approaches. The MOM is less sensitive than the Schottky diode and suffers from a fragile and unstable geometry limiting its usefulness.

4.2 Amplifiers

Amplifiers are important technology elements in a heterodyne receiver when they are used as a low noise RF preamplifier (preceding the mixer) or as a low noise IF amplifier following an efficient low noise mixer. The only candidates are masers and Josephson junctions, both cryogenically cooled amplifiers.

Masers have bandwidths limited by crystal resonance linewidths and are not projected to be useful above 90 GHz. However at 10 GHz and below they can serve as IF amplifiers if the bandwidth is adequate.

Josephson junctions can operate as parametric amplifiers up to 1000 GHz. Predicted noise temperatures are in the low tens of degrees but the dynamic range in almost all reported experiments is near 10 dB. Again it appears that RFpreamplifiers will not be of practical importance to communication system receivers.

4.3 Coupling to Mixers

One of the major problems to be solved is that of proper input impedance matching to the class of mixers discussed above. Traditional methods used at microwave frequencies become inefficient at EHF and FIR frequencies. Nevertheless essentially all experiments to date have utilized fine wire antennas (whiskers) similar to the microwave mixer. The group at The Aerospace Corporation is developing a 600 GHz single mode waveguide mixer mount integrated with a horn antenna to couple incident radiation to the waveguide structure. At the Jet Propulsion Laboratory Gustincic [6] is developing a 600 GHz quasi-optical mixer mount consisting of a biconical horn antenna with the diode situated at the gap of the antenna. Incident radiation is focused on the antenna which converts the power to an RF voltage across the diode. Tuning is provided by a curved wraparound back-short structure.

Better solutions to this problem are provided by quasi-optic, integrated optic, and stripline techniques. This approach is a further extension of microwave integrated circuit technology to dimensions requiring sub-micron tolerances. These tolerances are within the capability of modern holographic and electro-lithographic technologies. At Lincoln Laboratory the group is utilizing these techniques to develop a planar transmission line structure for 600 GHz operation. One can reasonably expect this matching problem to be solved in the next two years.

5. Receiver Performance

The receiver noise temperature for important wideband receivers is shown in Fig. 10. The best results are achieved by the super-Schottky. A combination of a super-Schottky and a low noise J-J IF amplifier is expected to yield an excellent performance at millimeter wavelengths. At frequencies above 300 GHz Schottky diodes have produced the best results, typically $P_N \sim 10^{-17}$ W/Hz or $T_N \sim 10^6$K at 600 GHz. Mixing has been observed in Schottky diodes at up to 3×10^4 GHz.

6. Applications

The technology described here is most applicable to the systems of tomorrow since the techniques are new and for the most part untried in prototype systems. In the frequency region below 100 GHz the super-Schottky mixer will find immediate application in existing systems to upgrade and improve the system performance. For example, radiometry for millimeter wave radio-astronomy, the detection of atmospheric molecular species, and imaging are important applications for which the super-Schottky mixer is ideally suited. Nearly an order of magnitude reduction in observation time can be achieved with an overall system noise temperature near 50 K at 100 GHz. Similarly the accuracy and sensitivity of measurement of

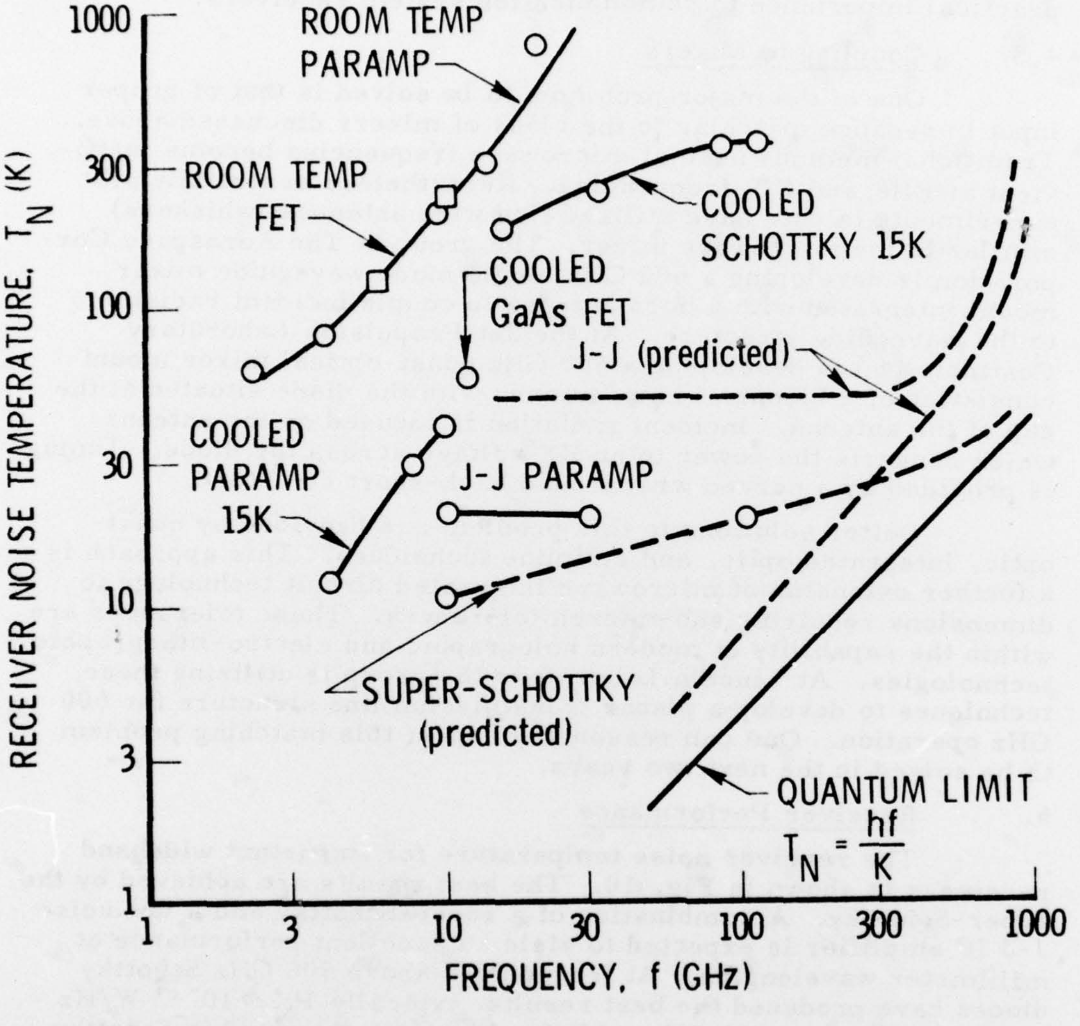

Figure 10

Comparison of low noise microwave/millimeter wave receivers.

molecular species can be improved. Of considerable importance is the measurement of ozone. Figure 11 shows a recent radiometer measurement of the 101.737 GHz, $4_{0,4}-4_{1,3}$ rotational emission line of ozone [13] taken with the Aerospace Corp. 4.6 m antenna and a conventional Schottky mixer with a ~ 1000 K single-sideband system noise temperature. This measurement is performed with 64 contiguous 250 kHz channels and demonstrates the multichannel capability of millimeter wave receivers. The line profile is well

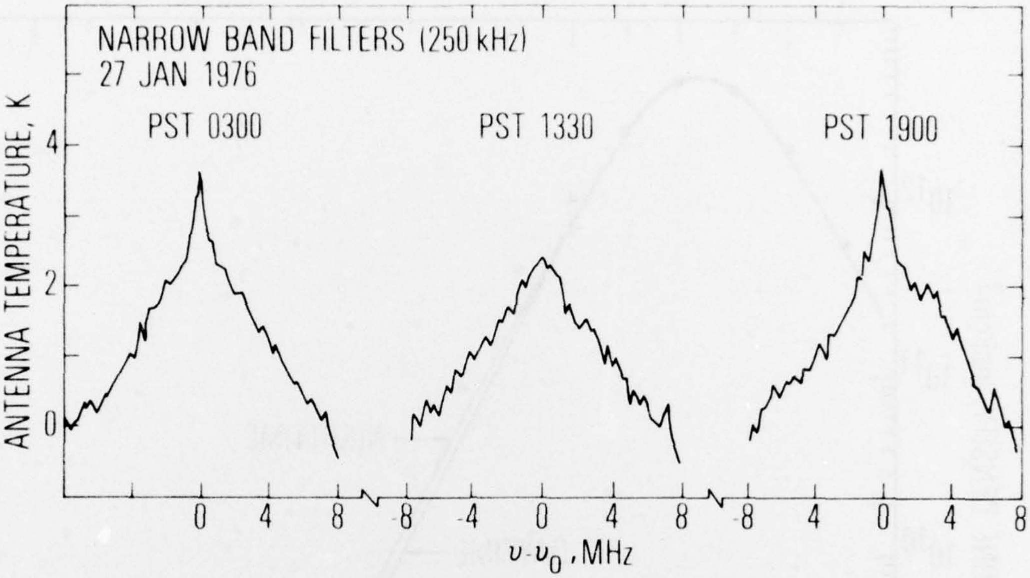

Figure 11
Emission spectra of atmospheric ozone at 101.737 GHz showing day-night variation of the spectral shape [13]

resolved with the narrowband 250 kHz channels and permits the extraction of the daytime and nighttime ozone distribution shown in Fig. 12. Higher receiver sensitivity will improve these and other similar data.

Military radiometry applications often provoke a compromise between resolution and the fog, rain, smoke, and haze penetration capability as a function of the operating frequency. Obviously, the higher frequencies near 300 GHz offer increased resolution and smaller antenna size at the expense of atmospheric interference. Imaging at 90 GHz with a coherent radiometer has been demonstrathrough clouds [14]. Cultural targets such as runways, aircraft, and ship wakes are easily identified. Natural environmental features such as rivers and lakes are distinguished by a lower emissivity.

Potential military communication applications favor higher frequencies and lower noise receivers for reasons which have been cited. Security of the link is often an important factor and both the increased angular resolution of antennas as the frequency increases and the intentional use of molecular absorption lines offer this possibility. Also, the enormous bandwidth (several GHz) of the Schottky and super-Schottky classes of diode mixers permits spread spectrum operation.

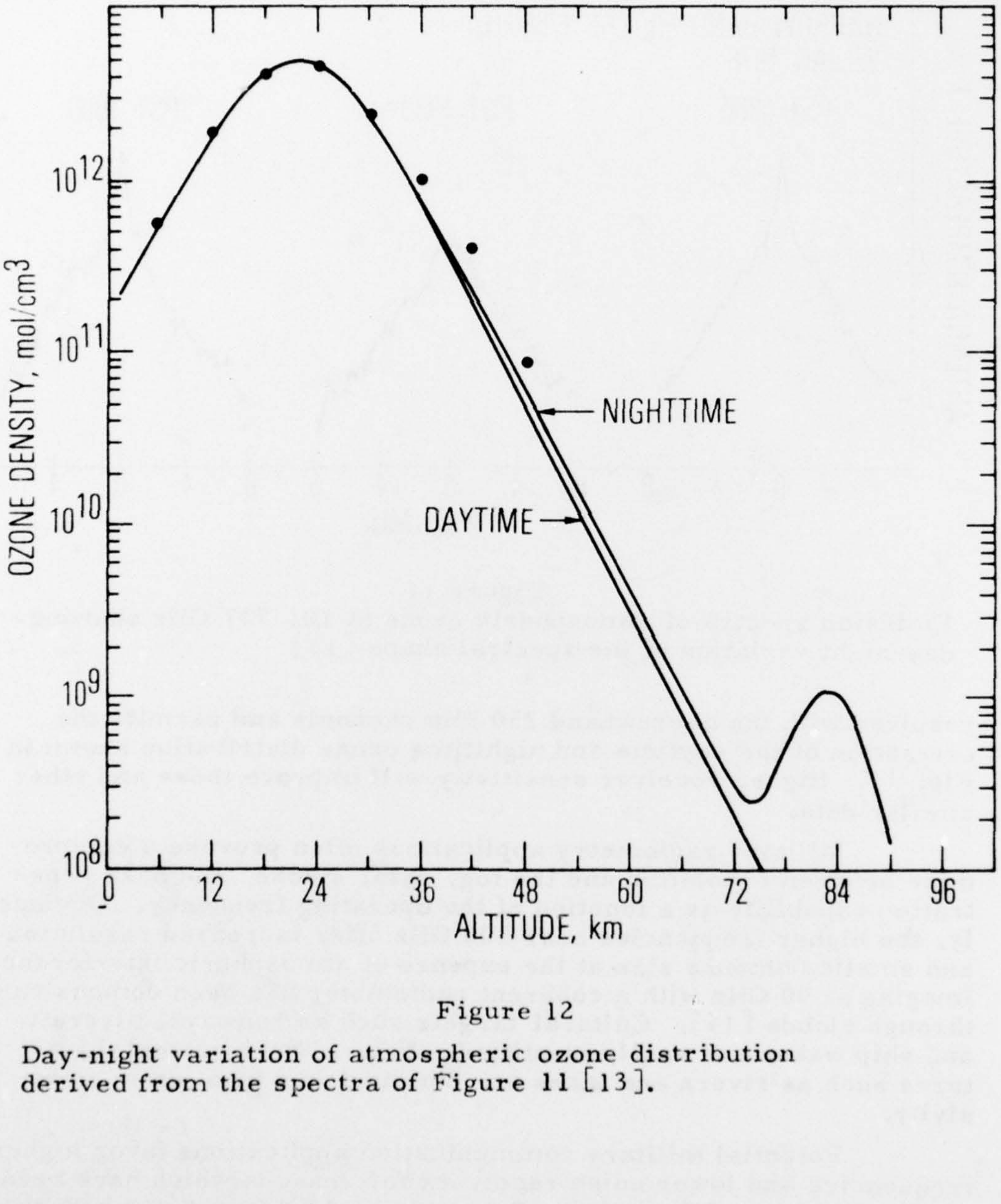

Figure 12

Day-night variation of atmospheric ozone distribution derived from the spectra of Figure 11 [13].

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