Submillimeter-Wave Receivers—A Status Report

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(Invited Paper)

***Abstract*—A recent survey of U.S. and Western European research groups, working on heterodyne submillimeter receivers in the 300–1000-GHz frequency range, is presented. This survey provides a description of the technology that each research group is developing, and information on the state-of-the-art of submillimeter receivers and local oscillator sources. A brief description of submillimeter receiver components is also given.**

I. INTRODUCTION

A SURVEY of U.S. and Western European research groups, working on heterodyne submillimeter receivers in the 300–1000-GHz frequency range, has been made. This survey provides information on the latest developments in the field, the technology area of each research group surveyed, and an updating of recent review papers in this field [1]–[3]. At this time, the applications which drive submillimeter technology are radio astronomy, atmospheric measurements, plasma diagnostics, and laboratory spectroscopy. Other possible applications, such as communications and radar, are limited by the large atmospheric attenuation in this frequency range.

The key components used in submillimeter receivers are briefly described below. In the 300–1000-GHz frequency range, superheterodyne receivers are used exclusively since RF amplifiers are not available. A room-temperature mixer or a cooled mixer is used as the first stage of the receiver, and this is typically followed by a low-noise GaAs FET amplifier. The main types of mixer structures in use are corner reflectors, waveguide, and biconical antenna mounts. The corner-reflector mixer, as shown in Fig. 1, has been widely used because it has good performance and is easier to construct than other mixers at these high frequencies [4], [5]; however, the coupling efficiency is less than 50 percent, which introduces undesired loss. Fundamental and harmonic waveguide mixer mounts have been made up to 600 GHz [6] and have shown equivalent performance to the corner reflectors with better coupling efficiency. The biconical antenna mixer mounts [7] have been used in plasma diagnostic applications, but their fabrication problems and poorer performance have limited further development. These submillimeter mixers have used low-capacitance GaAs Schottky barrier diodes contacted by a small wire whisker. Another type of waveguide submillimeter mixer uses an InSb bolometer cooled to liquid helium temperatures [3]. These InSb bolometer mixers operate below 600 GHz with low-noise temperatures, but have IF bandwidths of only ~1 MHz.

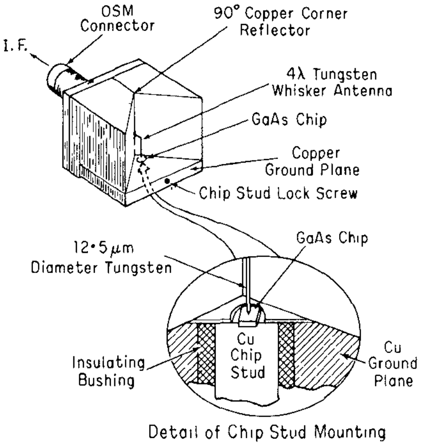

Fig. 1. Submillimeter corner-reflector mixer sketch [4].

One of the main limitations in the use of submillimeter receivers is the availability of reliable, broad-band LO sources. Typically, room-temperature Schottky diode mixers require 1 mW of LO power, and cooled mixers 0.1 mW, which is difficult to generate at submillimeter wavelengths. The most powerful source of submillimeter LO power is the carcinotron, and carcinotrons have been built to operate up to 500 GHz with output powers of 10–100 mW [8]. Carcinotrons also have been used with frequency multipliers to provide LO signals up to 600 GHz, and can be phase-locked to provide good stable sources for submillimeter radiometers. However, their cost, limited lifetime, and the expense of the high-voltage high-current power supply required are disadvantages.

Above, 600 GHz submillimeter lasers, pumped by a 10-μm CO_2 laser, have been used as LO sources [4]. These LO systems can be phase-locked and provided powers of 10–100 mW; however, they are complicated and bulky, and capable of operation at only selected frequencies corre-

Manuscript received July 11, 1983. The work described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

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sponding to molecular transitions. For the cooled InSb bolometer mixers, lower LO powers are required (~ 10 μW) and it is possible to use klystrons below 200 GHz, with frequency multipliers, to produce the required LO signals. Higher efficiency frequency multipliers are currently under development, and when used with lower frequency solid-state oscillators, they are likely to become future sources of submillimeter LO power.

The final key component in a submillimeter receiver is the LO/RF diplexer. Because of the low LO powers available, and the requirement to minimize losses in the signal path, quasi-optical diplexers have been developed. Dual-beam interferometers (Michelson), multiple-beam interferometers (Fabry–Perot), and beam splitters have been used in various receivers to combine the LO and RF signals. An excellent discussion of quasi-optical components has recently been written by Goldsmith [9].

In the following sections, details of the submillimeter research in the United States and Western Europe will be presented, along with a summary of the state-of-the-art for receivers and local oscillators.

II. U.S. Developments

A summary of the submillimeter development work in the U.S. is shown in Table I. Some of the most successful submillimeter radio astronomy observations were made in 1980 by personnel from the Goddard Space Flight Center, Lincoln Laboratory, and the University of Massachusetts [4]. A block diagram of their 690-GHz receiver is shown in Fig. 2. This receiver was used at 14,000-ft altitude on Mauna Kea in Hawaii to observe the emission from interstellar carbon monoxide. This receiver used a formic acid submillimeter laser, coupled through a quasi-optical LO diplexer, to provide 40 mW of power at 690 GHz to drive a corner-reflector mixer. This receiver had a single sideband (SSB) noise temperature of 6000 K.

At a slightly lower frequency, 345 GHz, a cryogenic radiometer was developed by Erickson [10] and used at the McDonald Millimeter-Wave Observatory for a variety of radio astronomy observations. A waveguide mixer, using a klystron with a frequency multipler for the local oscillator, was used to achieve a SSB receiver noise of 1200 K.

Lincoln Laboratory had a laboratory spectroscopy program to study rocket plumes and has developed a receiver at 752 GHz with a corner-reflector mixer and submillimeter laser LO. This receiver had a wide-band IF with a SSB temperature of 45 000 K, which was adequate for their measurements [11]. Lincoln Laboratory and the University of Massachusetts also have developed a 600-GHz receiver using a waveguide mixer, shown in Fig. 3, with a submillimeter laser LO, and achieved a SSB noise temperature of ~ 6000 K [6]. Using this mixer as a harmonic mixer at 556 GHz, pumped by a 278-GHz carcinotron, they obtained a SSB receiver noise temperature of 46 000 K [6].

Work on planar arrays for millimeter-wave imaging also was done by Lincoln Laboratory and the University of Massachusetts, and results at 140 GHz are encouraging. Their work has produced receivers with double sideband (DSB) noise temperatures of 12 000 K [12]. They have plans to extend this research to 700 GHz. Another approach to monolithic millimeter-wave circuits at Lincoln Laboratory has been demonstrated by Clifton [2], who metalized a slot coupler and a Schottky diode on a thin wafer of GaAs and mounted this in a waveguide horn. He achieved a SSB noise temperature of 1100 K at 110 GHz,

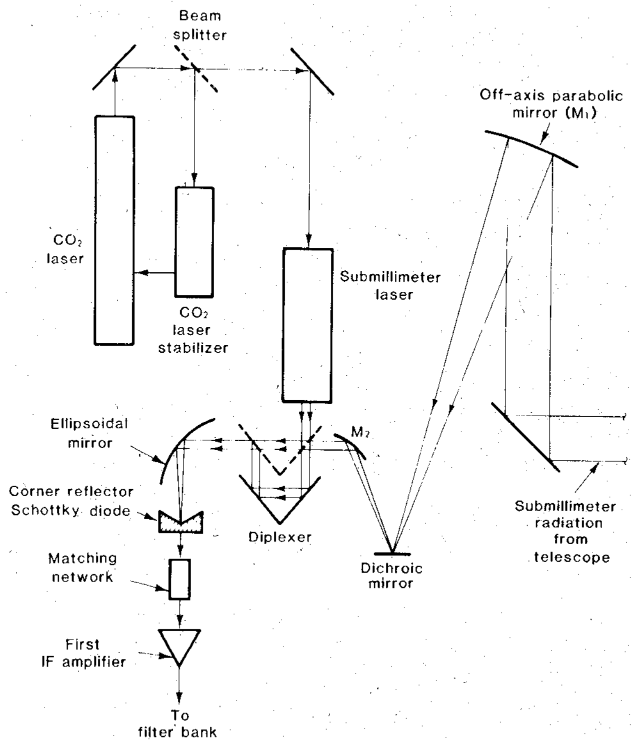

Fig. 2. 691-GHz radiometer used for radio astronomical observations, using a corner-reflector mixer and submillimeter laser LO [4].

TABLE I
U.S. Submillimeter Development Work

ORGANIZATIONS	APPLICATIONS	CURRENT DEVELOPMENTS
GODDARD SPACE FLIGHT CENTER, LINCOLN LABORATORY, U MASS.	RADIO ASTRONOMY AT MAUNA KEA	691 GHz RADIOMETER [4] CORNER REFLECTOR MIXER SUB-MM LASER LO T_S = 6,000K
U MASS	RADIO ASTRONOMY AT U. TEXAS's McDONALD OBS	250-350 GHz RADIOMETER [10] WAVEGUIDE MIXER FREQ MULT WITH KLYSTRON T_S = 1,200K
LINCOLN LABORATORY U MASS. MILLITECH CORP	SPECTROSCOPY FOR PLUME DETECTION	752 GHz RADIOMETER [11] CORNER REFLECTOR MIXER SUB-MM LASER LO X-BAND IF T_S = 45,000K
		557 GHz RADIOMETER [6] WAVEGUIDE 2nd HARMONIC MIXER CARCINOTRON LO T_S = 46,000K
		600 GHz RECEIVER [6] WAVEGUIDE MIXER SUB-MM LASER LO T_S = 6,000K
LINCOLN LABORATORY AND U MASS.	RECEIVER DEVELOPMENT	PLANAR ARRAYS FOR IMAGING [12] 140 GHz RESULTS, 700 GHz PLANS, 900 GHz SIS DEVELOPMENT
LINCOLN LABORATORY	RECEIVER DEVELOPMENT	MONOLITHIC INTEGRATED CIRCUIT RECEIVERS [2] T_S = 1,100K AT 110 GHz T_S = 13,000K AT 350 GHz
CALIF INST OF TECHNOLOGY	RADIO ASTRONOMY FOR C-141, MAUNA KEA 10-m AND OWENS VALLEY INTERFEROMETER	InSb MIXER RADIOMETERS TO 600 GHz [3] T_S = 350K AT 500 GHz SIS MIXER RADIOMETERS AT 230 GHz T_S = 230K
	RECEIVER DEVELOPMENT	SUBMILLIMETER IMAGING [15] PLANAR ANTENNA ARRAYS
JET PROPULSION LABORATORY, CALIF INST OF TECHNOLOGY	PLANETARY RADIO ASTRONOMY, ATMOSPHERIC PHYSICS FOR C-141 LABORATORY SPECTROSCOPY	550-625 GHz RADIOMETER [16] InSb MIXER, COOLED SCHOTTKY MIXER CARCINOTRON WITH FREQ MULT LO
UCLA "CENTER FOR MILLIMETER-WAVE AND HIGH FREQUENCY ELECTRONICS"	PLASMA DIAGNOSTICS RECEIVER DEVELOPMENT	300-671 GHz RADIOMETER [17] CARCINOTRON LO SUB-MM LASER LO CORNER REFLECTOR MIXERS BICONICAL MIXERS

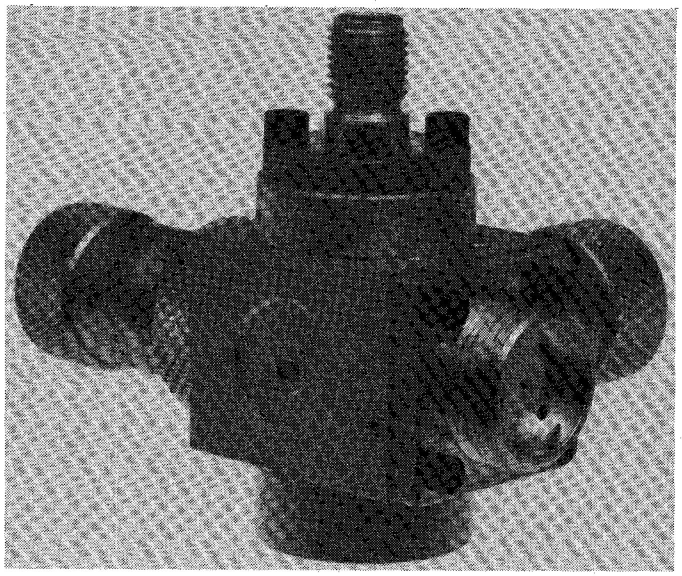

Fig. 3. 600-GHz waveguide mixer/frequency multiplier with integral feed horn [6].

and has scaled this design to 350 GHz and achieved a DSB mixer noise temperature of 6500 K.

On the West Coast, submillimeter work is done at the California Institute of Technology (Caltech), the Jet Propulsion Laboratory, and the University of California at Los Angeles (UCLA). At Caltech, InSb bolometer mixer receivers have been used on the C-141 Kuiper Airborne Observatory to make astronomical observations of up to 575 GHz with cooled DSB receiver noise temperatures of ~ 350 K [3], [13]. Caltech also has a program in developing superconducting insulator superconducting (SIS) mixer receivers and has achieved SSB receiver temperatures of 230 K at 230 GHz [14]. Above 300 GHz, SIS mixers will degrade due to Josephson-effect-induced noise; however, it may be possible to use magnetic suppression or superconducting insulator normal (SIN) metal structures mixers up to 700 GHz [3]. Another submillimeter research program at Caltech is the development of integrated-circuit imaging arrays [15]. Arrays for 1.2 mm and 119 μm have been fabricated and evaluated using bolometer detectors. Future plans are to incorporate GaAs diodes in the arrays to improve their sensitivity.

Submillimeter receiver work at the Jet Propulsion Laboratory is motivated by radio astronomy and atmospheric measurements applications. In cooperation with Caltech, a 575-GHz radiometer using an InSb bolometer mixer, with a carcinotron oscillator at 287 GHz and a $\times 2$ frequency multiplier, was developed. A photograph of part of this receiver is shown in Fig. 4 [16]. To obtain a lower noise, wider band receiver, a cryogenic Schottky diode waveguide mixer receiver, also using a carcinotron LO system with a $\times 2$ frequency multiplier, is being developed for 600-GHz measurements. In addition to this work, a dual 183- and 380-GHz cryogenic receiver using Schottky diode waveguide mixers is under construction.

At UCLA, submillimeter receiver development has been driven by the requirements for plasma diagnostics. Radiometers from 300–671 GHz have been developed using both corner-reflector and biconical mixers, and using both carcinotrons and submillimeter lasers for LO's [17]. Performance has been adequate for the plasma diagnostic work. UCLA is also establishing a "Center for Millimeter-Wave and High Frequency Electronics" and has plans for continued research in this field of low-noise submillimeter receivers [18].

III. European Developments

A summary of the European research groups surveyed is shown in Table II. One of the main sponsors of submillimeter work in western Europe is the European Space Agency (ESA) with applications of radio astronomy and atmospheric physics in mind. The ESA, along with University College Cork, Farran Assoc. and Thompson CSF, are developing a 300–500-GHz radiometer using corner reflector mixers and carcinotrons for local oscillators [19]. The overall system noise temperature is expected to be $\leqslant 5000$ K from 300–500 GHz. Thompson CSF is developing the carcinotrons and have achieved 30–50 mW of power in the 300–500-GHz range. An 800–1000-GHz tube is currently under development [8].

For a number of years, ESA has developed and used submillimeter receivers up to 400 GHz to make radio astronomy observations from the C-141 Kuiper Airborne Observatory. In one of their latest experiments in this program, ESA, along with the University of Utrecht and the University College Cork, developed an InSb bolometer mixer receiver from 460–500 GHz using a carcinotron with a $\times 2$ frequency multiplier for astronomical observations of interstellar CO. This receiver has achieved a DSB receiver noise temperature of 1000 K [20].

In England, at the Rutherford–Appleton Laboratory, work is concentrating on developing cryogenic receivers in the 230–270-GHz frequency range for use on the new UK–Dutch 15-m millimeter-wave radio telescope being built on Mauna Kea, Hawaii [21]. They have plans for designing cryogenic receivers near 350 and 470 GHz in the future.

Also in England, the Radio Astronomy Research Group at Queen Mary College has developed a number of InSb bolometer mixer receivers, using klystrons with frequency multipliers, for local oscillators. They have achieved 320-K DSB noise temperatures in the 300–420 GHz-frequency range and 750 K at 470 GHz. They have plans to operate at a physical temperature of 0.3 K with a He^3 system, which may reduce the noise temperature by a factor of 2 [22].

At the Institute for Millimeter-Wave Radio Astronomy (IRAM) in Grenoble, France, the main development effort is concentrating on developing receivers up to 230 GHz for the 30-m IRAM telescope is Spain; however, they plan to develop receivers at 345 GHz in the future [23].

In Bonn, at the Max Planck Institute for Radio Astronomy, a 693-GHz radiometer using a corner-reflector mixer with a submillimeter laser LO, with 5 mW of power, has been used at the 0.76-m Jung Fraujoch telescope in Switzerland to make observations of the planets and of

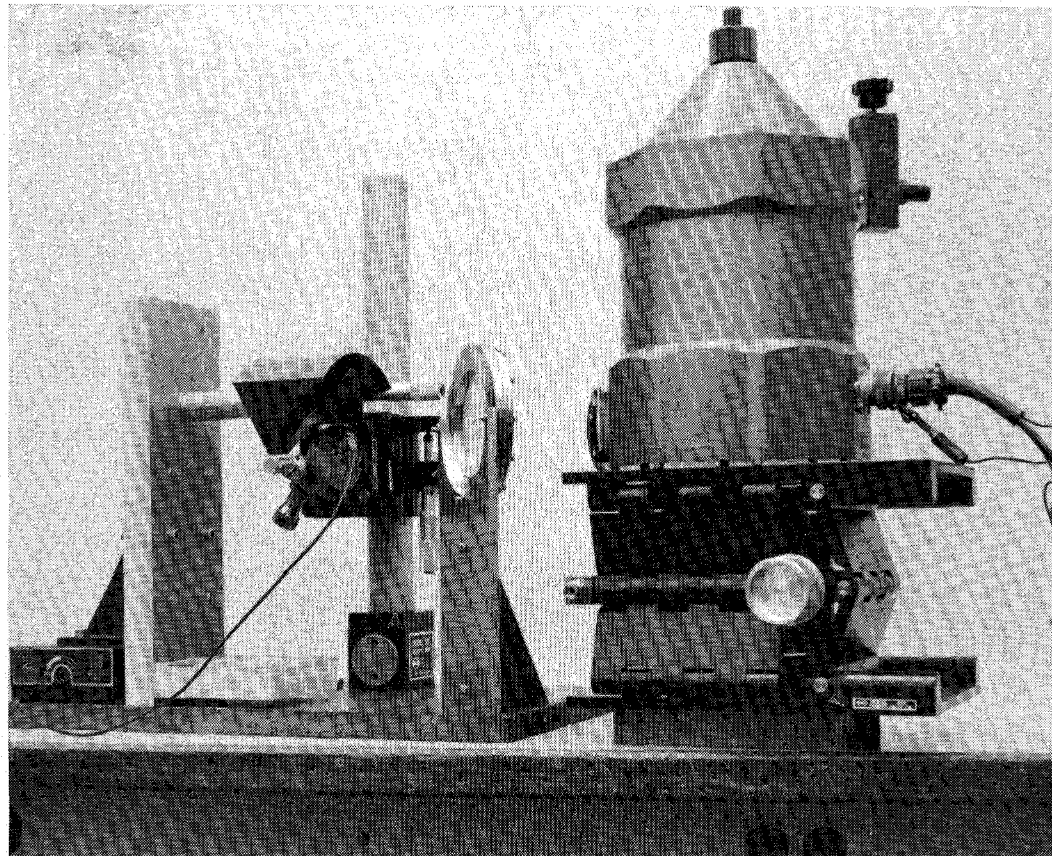

Fig. 4. 600-GHz receiver showing corner-reflector frequency multiplier, focusing mirror, beam splitter LO/RF diplexer, and liquid He Dewar with the InSb bolometer mixer [16]. The carcinotron LO source is not shown.

TABLE II
EUROPEAN SUBMILLIMETER DEVELOPMENT WORK

ORGANIZATIONS	APPLICATIONS	CURRENT DEVELOPMENTS
EUROPEAN SPACE AGENCY, THE NETHERLANDS; UNIV COLLEGE, CORK, IRELAND; FARRAN ASSOC, IRELAND; THOMPSON CSF, FRANCE	RADIO ASTRONOMY, ATMOSPHERIC PHYSICS FOR C-141 AND SPACE OBSERVATIONS	300-500 GHz RADIOMETER[19] WIDEBAND CARCINOTRON LO's[8] 330-400 GHz, 30-50 mW 405-500 GHz, 30-50 mW 800-1000 GHz - IN DEVELOPMENT CORNER REFLECTOR MIXERS
UNIV UTRECHT, THE NETHERLANDS; EUROPEAN SPACE AGENCY, THE NETHERLANDS; UNIV COLLEGE, CORK, IRELAND	RADIO ASTRONOMY	460-500 GHz RADIOMETER[20] CARCINOTRON WITH X2 FREQ MULTIPLIER InSb MIXER, $T_s \approx 1000K$
RUTHERFORD APPLETON LABORATORY, ENGLAND	RADIO ASTRONOMY FOR 15-m UK/DUTCH MILLIMETER-WAVE TELESCOPE ON MAUNA KEA	DESIGNING 300-500 GHz MIXER RECEIVERS[21] LN_2 CRYOGENIC RECEIVERS AT 230 AND 270 GHz SCHOTTKY DIODE WAVEGUIDE MIXERS KLYSTRONS WITH FREQ MULTIPLIERS $T_s \approx 1700K$
QUEEN MARY COLLEGE, ENGLAND	RADIO ASTRONOMY	InSb MIXER RECEIVERS[22] 330-360 GHz $T_s = 325K$ 400-420 GHz $T_s = 320K$ 460-470 GHz $T_s = 750K$
INST FOR MILLIMETER-WAVE RADIO ASTRONOMY (IRAM), FRANCE	RADIO ASTRONOMY FOR 30-m IRAM TELESCOPE IN SPAIN	PLANS FOR 350 GHz RECEIVERS[23]
MAX PLANCK INST FOR RADIO ASTRONOMY	RADIO ASTRONOMY AT JUNG FRAUJOCH 0.76 m TELESCOPE	693 GHz RADIOMETER[5] CORNER REFLECTOR MIXER SUB-MM LASER LO $T_s = 9400 K$

atmospheric CO [5]. A DSB receiver noise temperature of 3700 K was measured and an acoustical optical spectrograph with 1024 channels over 210 MHz was used to measure the spectra.

IV. SUMMARY OF RESULTS

A summary of the receiver noise temperatures achieved versus frequency and receiver type is shown in Fig. 5, along with references for this data. Data on receivers from 100–300 GHz are also shown to give a picture of the trend versus frequency. For room-temperature receivers, the SSB receiver noise temperature goes from ~800 K at 100 GHz to ~8000 K at 700 GHz—a nearly linear increase with frequency. For cooled Schottky diode mixer receivers, only one result has been reported above 300 GHz; however, a number of groups have plans to build cooled Schottky mixer receivers in this frequency range. Cryogenic receivers, using InSb bolometer mixers, have been developed up to 575 GHz with noise temperatures < 500 K. However, because of their small IF bandwidth and poor performance above 600 GHz, development is now concentrating on cooled Schottky diode mixer receivers.

As noted earlier, one of the major limitations to the development of submillimeter receivers is the lack of convenient wideband LO sources. In Fig. 6, a plot of LO power which has been achieved as a function of frequency and type of LO is shown. Again, information from 100–300 GHz has been included to give an indication of the trend versus frequency. Above 300 GHz, the direct sources are carcinotrons or submillimeter lasers which produce powers of 10–100 mW. With cooled receivers, less LO power is required, e.g. 0.1 mW, and lower frequency Gunn oscillators, klystrons, or carcinotrons can be used with frequency multipliers to produce the required LO powers, as shown in Fig. 6. The development of new solid-state devices or

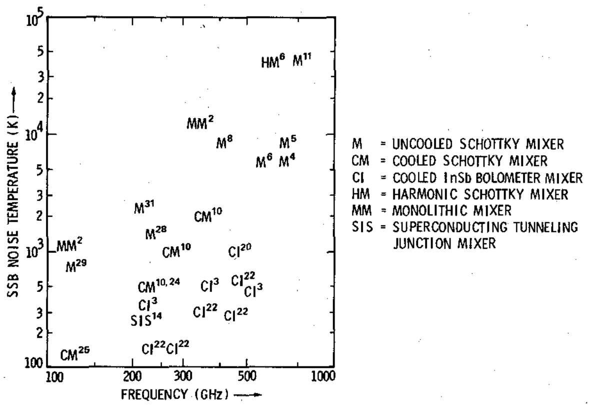

Fig. 5. Current receiver noise temperatures versus frequency. The different receiver types are noted and the superscripts refer to the references.

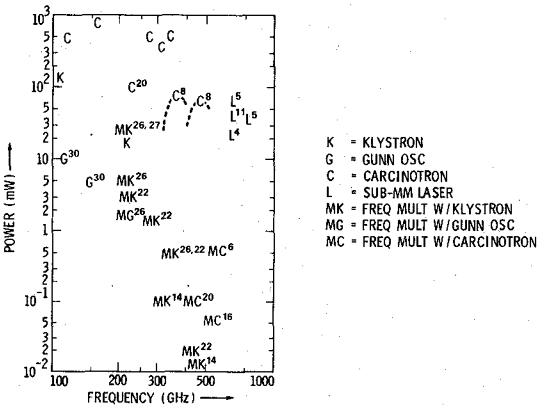

Fig. 6. Current LO powers which are available from the different types of sources as noted. The superscripts refer to the references.

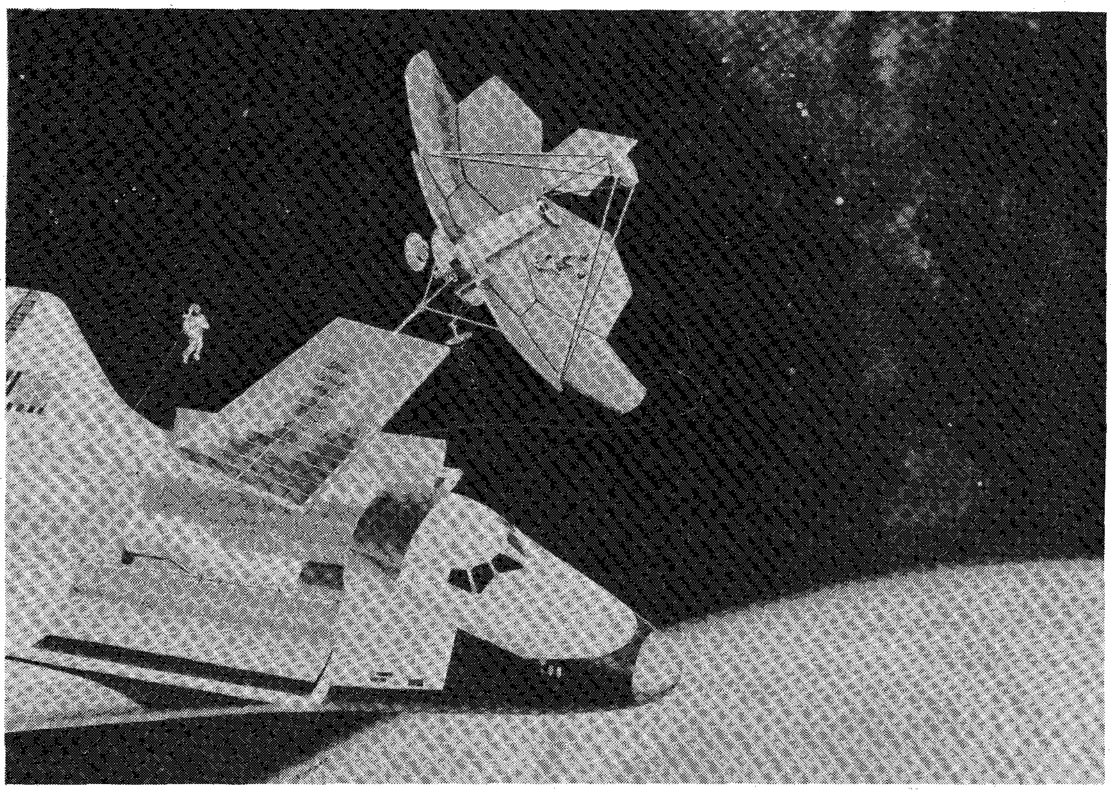

Fig. 7. An artist's sketch of the submillimeter/IR Large Deployable Reflector Observatory proposed by NASA for the mid-1990's.

efficient frequency multipliers with solid-state sources is required for future submillimeter receivers.

V. Future Trends

Progress in submillimeter receivers is now concentrated in two main areas—cooled Schottky diode mixers and solid-state local oscillators using frequency multipliers. However, the motivation for the future developments of submillimeter receivers is related to the availability of observational facilities. Today, the main operational facilities are the C-141 Kuiper Airborne Observatory and the optical/IR telescopes in Mauna Kea, Hawaii. Facilities which are currently under development are the IRAM 30-m telescope in Spain, the Max Planck 10-m telescope in Arizona and the UK–Dutch 15-m telescope on Mauna Kea. In the near future, Caltech is planning to locate a submillimeter 10-m antenna on Mauna Kea. On a longer time scale, NASA is proposing a submillimeter/far-IR, 10–15-m Large Deployable Reflector (LDR) satellite for the 1990's as shown in an artist's concept in Fig. 7. Given the availability of these submillimeter facilities, it is likely that the development of better submillimeter receivers will continue.

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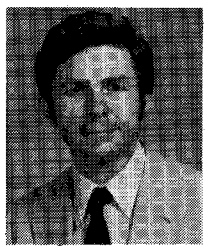

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From 1964 to 1967 he served in the U.S. Air Force, working on military communication satellites. In 1970 he joined the Aerospace Corporation, Los Angeles, CA, and was involved in the design and construction of the millimeter-wave receivers and radio astronomy observations. In 1976/1977 he was an Assistant Professor in the Electrical Engineering Department at the University of Texas at Austin. He returned to Aerospace in 1977, where he was involved with research in millimeter-wave radiometers and low-noise receivers. In 1980 he joined the staff of NASA's Jet Propulsion Laboratory, Pasadena, CA, and is the Supervisor of the Microwave Advanced Systems Group. At JPL, he has been working on low-noise millimeter-wave and submillimeter-wave components, radiometers and systems for a number of spacecraft instruments.

Dr. Wilson is a member of the American Astronomical Society, Commission J of the International Union of Radio Sciences (URSI), the International Astronomical Union, Tau Beta Pi, and is an associate member of Sigma Xi.