Millimeter and Submillimeter Techniques

John E. Carlstrom and Jonas Zmuidzinas

Division of Physics, Mathematics, and Astronomy
California Institute of Technology
Pasadena, CA 91125

to appear in
"Reviews of Radio Science 1993 – 1995"
ed. W. R. Stone
Oxford, The Oxford University Press, 1996.

Editing and formatting differences may exist between this manuscript and the final version.

Millimeter and Submillimeter Techniques

John E. Carlstrom and Jonas Zmuidzinas

Division of Physics, Mathematics, and Astronomy
California Institute of Technology
Pasadena, CA 91125

1 Abstract

A review of recent developments in the techniques and instrumentation used for sensitive millimeter– and submillimeter–wave astronomical observations is given. The capabilities of existing and planned ground based observatories are summarized. Methods for compensating for the fluctuations in the atmospheric emission and refraction are briefly discussed. Heterodyne receivers, sources of local oscillator power, spectrometers and correlators, are reviewed, with extensive discussion of recent advances in SIS mixers. Improved incoherent detection systems using cooled bolometer arrays are also discussed.

2 Introduction

This review concentrates on recent developments in the techniques and instrumentation used for ground–based astronomical observations at millimeter and submillimeter wavelengths. The wavelength band of interest (5 mm to 300 μm) is determined both by the nature of the instrumentation and the opacity of Earth's atmosphere. The atmospheric opacity under good weather conditions above a high altitude site is plotted in Figure 1. The shortest wavelength for which the atmosphere permits observations in the radio spectrum is 300 μm (1 THz). At wavelengths longer than $\sim$5 mm (60 GHz), receivers using low-noise preamplifiers are universally used, while at shorter wavelengths receivers using low-noise mixers or incoherent detectors offer the best performance. Therefore, the present discussion is limited to techniques used in the $\lambda \sim 5.0 - 0.3$ mm band. The atmospheric oxygen lines around 5 mm also provide a natural long wavelength limit; with the exception of the water vapor line at 1.4 cm, the atmospheric opacity dramatically improves at longer wavelengths, until the cut off wavelength of the ionosphere is reached at around 10 meters.

The submillimeter band is a transitional region for sensitive radiometric techniques. Whereas heterodyne receivers are used exclusively at centimeter and longer wavelengths, and incoherent detectors are used at infrared wavelengths, both techniques are used in the submillimeter. Heterodyne receivers offer essentially unlimited spectral resolution, but only over a small band ($\sim$ 1 GHz). The resolution is set by the spectrometer used at the receiver output and in practice by the required sensitivity and finite observing time. These receivers are used for high resolution spectroscopy of molecular and atomic transitions (of order $\Delta\nu/\nu = 10^{-6} = 0.3$ kms^{-1}). The spectral resolution of incoherent detection, using cooled bolometers, is set by the optics and filters preceding the detector. For maximum sensitivity to continuum emission, usually thermal emission from interstellar dust, the filters are designed to fit the available atmospheric windows and have bandwidths of $\sim$ 100 GHz. The 1.3 mm, 800 μm, 600 μm, 450 μm, and 350 μm bands are apparent in Figure 1. The relative sensitivity of these techniques is discussed in several papers [e.g. Phillips 1988].

There is a large gap in resolution between the standard filters used in continuum bolometer systems and the ~ 1 GHz total bandwidth of heterodyne receivers. Medium resolution spectroscopy ($\Delta\nu \sim 1$ GHz) can be achieved with a bolometer preceded by a Fourier Transform Spectrometer (FTS). Such an FTS has been built and used on the 10.4 m submillimeter–wave telescope of the Caltech Submillimeter Observatory (CSO) [Serabyn et al. 1995], and on the 15 m submillimeter–wave James Clerk Maxwell Telescope (JCMT) [Naylor et al. 1991, 1994]. Both systems have been used to investigate the spectral dependence of the atmospheric opacity above Mauna Kea. The CSO system also has been used to obtain broadband spectra of the planets and of the Orion molecular cloud core [see also Serabyn and Weisstein 1995].

There is an enormous amount of research being done in the area of millimeter and submillimeter techniques. The space allotted here is only adequate to cover a small fraction of this research. Luckily there are good reviews of many of the relevant technologies. These are cited in the sections below. For more background information the reader is referred to the excellent reviews in the *Proceedings of the IEEE* “Special Issue on THz Technology” [**80**, November 1992]. Forums for the presentation and discussion of the state–of–the–art are provided by the annual *International Symposia on Space Terahertz Technology* and the biennial *Applied Superconductivity Conference*. Many of the papers to these conferences are cited in the sections belows; the reader is referred to the proceedings for more details. Selected papers from the THz symposia are published in *IEEE Trans. Microwave Theory Tech.* “Special Issues on Space THz Technology” [see **40**, May 1992; **41**, April 1993; **42**, April 1994; **43**, April 1995], and proceedings of the superconductivity conference are published in special issues of *Applied Superconductivity* [see **3**, March 1993; **5**, June 1995].

This review is organized as follows: Section 3 provides an overview of observatories, telescopes and capabilities. Atmospheric issues, in particular efforts to actively compensate the phase of an interferometer for fluctuations of the path length through the atmosphere, are discussed in section 4. Section 5 reviews heterodyne receivers. Substantial emphasis is given to SIS receivers as they have allowed significant improvements to the sensitivity of heterodyne receivers over the last few years. Section 5 also reviews low-noise amplifiers, other mixer technologies, sources of local oscillator power, and briefly reviews spectrometers and correlators. Finally a review of incoherent detection is given in section 6.

3 Observatories, Telescopes, and Capabilities

3.1 0verview

The quest for higher angular resolution and increased sensitivity has led to larger telescopes and interferometric arrays. The 45 m telescope of the Nobeyama Radio Observatory (NRO) and the 30 m telescope of the Institut de Radioastronomie Millimétrique (IRAM) are currently the largest operating filled aperture telescopes dedicated for millimeter–wave astronomy [Ukita and Tsuboi 1994, Baars et al. 1994]. The University of Massachusetts and Mexico are jointly planning to build the Large Millimeter Telescope (LMT), which will have a diameter of 50 m [Schloerb 1995]. The IRAM telescope routinely operates at wavelengths as short as a 1 mm giving an angular resolution of $\sim 10''$. Telescopes with more accurate surfaces and located at higher altitudes have been built for submillimeter–wave observations: the 15 m JCMT and 10.4 m CSO telescopes located near the 4200 m summit of Mauna Kea, the 3 m University of Cologne telescope (KOSMA) located at 3250 m in the Swiss Alps, and the 15 m Swedish–European Southern Observatory (ESO) telescope (SEST) located at 2300 m on La Silla, Chile, have been productive telescopes for several years. The 10 m Heinrich Hertz Telescope of the Submillimeter Telescope Observatory (HHT/SMTO) located at 3200 m on Mt Graham, Arizona, and the 1.8 m Antarctic Submillimeter Telescope and Remote Observatory (AST/RO) located at the South Pole, began routine operation in 1994. The larger submillimeter-wave telescopes have an angular resolution around $\sim 10''$ at 350 μm.

Interferometry is needed to obtain angular resolution better than $\sim 10''$. There are four operational millimeter–wave interferometers: the Berkeley-Illinois-Maryland-Association mm–array (BIMA) [Welch 1994, Welch et al. 1995], the Nobeyama mm-array (NMA) [Morita 1994], the Owens Valley Radio Observatory mm-array (OVRO) [Scoville et al. 1994], and the IRAM mm-array [Guilloteau et al. 1992, Guilloteau 1994]. All of these arrays have undergone substantial upgrades over the last few years: BIMA has expanded from three 6.1 m telescopes to six and is currently expanding to ten, the NMA has expanded from five 10 m telecopes to six, OVRO has expanded from three 10.4 m telescopes to six, and the IRAM array has expanded from three to four 15 m telescopes and a fifth is under construction. All four arrays are able to make images with up to $\sim 2''$ angular resolution at wavelengths in the 3 mm atmospheric window (80 – 115 GHz). This is well matched to typical 'seeing' conditions (see section 4). Telescope stations to provide baselines up to 1 km North–South have been added to the BIMA array and used to obtain subarcsecond resolution [Welch et al. 1995]. Complementary stations to provide 1 km East–West baselines are being constructed. At Nobeyama, tests have been made to link the Nobeyama 45 m telescope with the NMA. There are plans to upgrade all of the millimeter arrays for operation at wavelengths in the 1.3 mm atmospheric window. The NMA already has capabilities in the 2 mm window, and OVRO has been operating within the 1.3 mm window for several years.

The CSO and JCMT telescopes are used periodically as a submillimeter–wave interferometer [Carlstrom et al. 1994]. The increased sensitivity to thermal dust emission at submillimeter wavelengths and the high resolution of the interferometer ($\sim 0.5''$ at 850 μm) have made it possible to resolve accretion disks around nearby, young solar–like stars [Lay et al. 1994b].

Millimeter and submillimeter interferometry has proven to be a powerful tool for investigating a large range of astrophysical phenomena [for a review see Sargent and Welch 1993]. Consequently, a number of increasingly powerful arrays are being built or planned: The Smithsonian Astrophysical Observatory is building a six element submillimeter–wave array (SMA) of 6 m telescopes to operate from 2 mm to 350 μm and to be located near the summit of Mauna Kea [Moran 1994]. The SMA is expected to be operational in 1997. The U. S. National Radio Astronomy Observatory (NRAO) is planning the Millimeter Array (MMA) [Brown 1994], a 40 element array of 8 m telescopes to operate from 1 cm to 800 μm. Japanese astronomers are planning the Large Millimeter and Submillimeter Array (LMSA) with as many as 50 10-m telescopes and operating from 1 cm to 350 μm. Both the MMA and the LMSA are planned to be located on very high sites: $\sim$ 4000 to 5000 m sites are being considered on Mauna Kea and on high plateaus in Chile. ESO has discussed plans to build a large millimeter-wave array in the southern hemisphere [Booth 1994]. The design goals of these arrays specify angular resolutions as high as $0.1''$.

A large jump in angular resolution is provided by mm–VLBI [for a recent review of VLBI see Rogers 1993, and of mm-VLBI see Bååth 1994]; resolutions of order 50 μarcsec have been obtained. The large gap in resolution and therefore extreme decrease in brightness sensitivity makes mm-VLBI impractical for observations of thermal emission from molecular clouds, circumstellar disks, planets, etc. Instead, mm–VLBI mainly is used to investigate nonthermal emission from compact sources which more standard centimeter–wave VLBI observations have not been able to resolve, such as the Galactic center source SGR A^* [Rogers et al. 1994].

Telescopes have also been designed and built for making large surveys at low angular resolution, but with high surface brightness sensitivity. For example, the Tokyo-NRO 60 cm telescope is being used to survey CO J=2-1 emission from the Galaxy with the same resolution as used for the CO J=1-0 emission with the Columbia–CfA 1.2 m telescope [Sakamoto et al. 1994]. Plume and Jaffe [1995] used a reimaging device for the CSO to convert the full 10.4 m telescope into a small (< 1 m) off-axis telescope for surveying large regions of the sky. An unbiased survey of Galactic [CI] emission is being carried out with the AST/RO 1.8 m submillimeter telescope. Unfortunately, there is not enough space in this review to give an overview of the many productive millimeter–wave telescopes in use today.

3.2 Telescope Surface Measurements

To adjust the surface of a millimeter or submillimeter wave telescope accurately, a measurement of the surface must be made with the primary in place and, if possible, at several zenith angles. In the traditional holographic method [Scott and Ryle 1977], the amplitude and phase of the far–field pattern is measured by correlating the signal received by the telescope with that received by a second reference telescope. Once the field pattern is properly sampled, it is a simple matter to transform the data and obtain the phase and amplitude of the aperture field pattern. This approach is particularly easy to implement at the millimeter arrays and good results are obtained using strong quasars, and planets when the baseline to the reference telescope is not long enough to resolve the planet disk. For single dish telescopes, a small secondary telescope can be used. In this case a strong artificial source is often used to compensate for the low gain of the secondary telescope.

Two alternative approaches have been used with good results. At the CSO, Serabyn et al. [1991] use a shearing interferometer to interfere two images from a single telescope. One of the images can be offset pointed before the images are recombined and detected. Inserting a $\lambda/4$ length of path for the 'reference' image gives the quadrature component. Rather than use a single $\lambda/4$ path length segment, Serabyn et al. use a FTS with a cooled bolometer detector. The sensitivity of this technique is high enough to achieve sufficient accuracy to adjust the individual panels of the primary, when observing a planet. This is due to the broad bandwidth of the detector and keeping one image pointed directly at the astronomical source.

The method commonly used at the JCMT is based on the phase-retrieval technique first demonstrated by Ellder et al. [1984]. In this technique only the amplitude of the far–field pattern is measured, but for at least two focus settings. The two measured beam patterns and the known focus offset provide sufficient constraints to solve for the aperture fields using an interative or a least squares method. The beam patterns are measured using a bright astronomical source or an artificial source. A recent description of technique as applied to the KOSMA 1.8 m telescope is given by Fuhr et al. [1993]. It is also used to measure the surface of the IRAM 30 m telescope [Baars et al. 1994]. High accuracy measurements of the primary with this technique require the use of an artificial source.

4 Atmospheric Opacity and Path Length Fluctuations

The atmospheric opacity is severe at millimeter– and submillimeter–wavelengths and ground based observations can only be carried out in windows defined by atmospheric lines, as shown in Fig. 1. The 3 mm band is defined by the oxygen lines around 5 mm (50–70 GHz) and at 2.54 mm (118 GHz). The series of high opacity lines at shorter wavelengths are due to water vapor. Opacity far from the center of the atmospheric lines is due to pressure broadening, and at wavelengths from ~ 300 to 20 μm no astronomical observations can be made from the ground. The scale height of water is roughly 2 km and therefore high dry sites are necessary for submillimeter–wave observations.

The atmospheric opacity and refraction are not constant spatially or temporally. The fluctuations are caused primarily by water vapor which is not well mixed in the atmosphere since the temperature is close to the condensation point of water. The delay fluctuations distort the incoming wavefronts and produce phase errors in interferometers, and in extreme cases can cause significant pointing errors for large diameter telescopes [see Masson 1994, Thompson et al. 1986].

For a Kolmogorov spectrum of turbulence (Tatarskii 1961, 1971) the RMS phase fluctuations introduced by the atmosphere scale as (baseline)$^{5/6}$ for baselines smaller than the vertical extent of the turbulence and as (baseline)$^{1/6}$ for those that are much larger [Treuhaft and Lanyi 1987]. The most extensive measurement of the structure function at radio wavelengths was by Armstrong and Sramek [1982]. Since the power law index is less than unity the radio "seeing" is worse at shorter wavelengths; it is typically about $1''$ to $2''$ at millimeter wavelengths even though subarcsecond observations are fairly routine at centimeter and longer wavelengths.

Atmospheric induced phase fluctuations can be overcome by self calibration techniques if a source of emission contained within the field of view of the interferometer is strong enough to measure its phase during the atmospheric coherence time. However, this is usually not the case for observations of molecular and thermal dust emission.

There is currently a substantial effort to correct for fluctuations in the atmospheric delays by using the emission from the water vapor in each telescope beam to estimate a phase correction; this is essentially adaptive optics for synthesized apertures. There are several schemes: both BIMA and IRAM intend to measure small changes in the system temperature of the telescope receivers [Welch 1994, Welch et al. 1995, Bremer 1995]; VLBI experiments have used separate radiometers at 22 GHz to measure the water vapor line emission [Moran and Rosen 1981, Elgered 1993] and this technique is also being attempted at OVRO; and the CSO–JCMT Submillimeter Interferometer is experimenting with radiometry of the 183 GHz water vapor line. In addition, Holdaway and Owen [1995] have been investigating fast position switching (of order 1s) between the target source and a nearby phase calibrator as a method of tracking the atmospheric phase.

Active compensation for atmospheric delay fluctuations must be accomplished before routine subarcsecond resolution observations can be obtained at millimeter and submillimeter wavelengths. It is still too early to determine which method will work best, and perhaps a combination of techniques will be necessary. A working system should be demonstrated before building large high resolution arrays, as some techniques place severe constraints on the specifications of the array elements, such as slewing and acquisition rates, and well characterized and minimal spillover.

5 Heterodyne Receivers

Major progress in millimeter and submillimeter heterodyne receiver technology has been achieved over the past several years, particularly in the development of lower noise and higher frequency mixers which use superconducting tunnel junctions (SIS junctions). Due to their very low noise, SIS mixers have replaced GaAs Schottky-diode mixers at nearly all major radio observatories which operate in the millimeter or submillimeter bands. Further significant improvements to the single sideband system temperatures, which include atmospheric noise, may be obtained by sideband separation receivers [Akeson, Carlstrom, and Woody 1993] or by terminating the image sideband in a cold load. Array receivers will increase the sensitivity for mapping extended sources. A number of papers describing progress on array receivers appear in the ASP volume "Multi–feed Systems for Radio Telescopes," [Emerson and Payne 1995]. This volume also contains papers which discuss optical issues related to array receivers. A general review of quasioptical techniques used at millimeter and submillimeter wavelengths is presented by Goldsmith [1992].

5.1 Low-noise HEMT Amplifiers

At frequencies below 50 GHz, sensitive heterodyne receivers use cooled ($\sim$ 15 K) low-noise amplifiers built with discrete InP High–Electron–Mobility–Transistors (HEMT). These amplifiers offer outstanding performance, high reliability, and require fairly simple refrigeration systems. A recent review of the state–of–the–art of HEMTs and predicted performance at frequencies up to 120 GHz is given by Pospieszalski [1993]. Receiver noise temperatures of 10 K have been achieved at 40 GHz [Pospieszalski et al. 1994, Duh et al. 1994]. These amplifiers are also capable of large instantaneous bandwidths; Pospieszalski et al. [1995] report a 40 – 50 GHz 5-stage hybrid amplifier with an average amplifier noise temperature of ~ 15 K and a receiver using a 60 – 75 GHz amplifier with a ~ 48 K average receiver temperature (which includes contributions from the dewar window and feed horn).

High frequency Millimeter–Integrated–Circuits (MMIC) also have given good results, although not as impressive as amplifiers built with discrete devices. Room temperature tests of a 110 – 115 GHz MMIC gave receiver noise temperatures of ~ 600 K and, after correction for losses, an amplifier noise temperature of ~ 400 K [Wang et al. 1993]. Similar results were found for a broadband 75 – 110 GHz MMIC amplifier [Duh et al. 1994]. A 140 GHz device has been tested, but no noise temperature was reported [Wang et al. 1995a]. Outstanding results would be obtained upon cooling if they behave like hybrid amplifiers, where cooling to ~ 18 K has resulted in a factor of ~ 8 reduction in the noise temperature. However, initial tests have shown only modest improvements; Erickson et al. [1994] report a receiver noise temperature with no correction for input losses, of 110 K at 103 GHz for a MMIC amplifier at an ambient temperature of ~ 20 K.

The above results and the predicted performance of high frequency HEMT amplifiers indicate that they may be competitive with SIS receivers at frequencies up to ~ 115 GHz. SIS receivers are expected to achieve double sideband noise temperatures of two to three times $h\nu/k_{\rm B}$ (10 – 15 K at 100 GHz), while HEMT receivers are likely to be a few times worse. However, there are several additional factors to consider: 1) For spectroscopy the single sideband SIS receiver temperature is appropriate and this is likely to be a factor of 2 higher than the DSB values, while for HEMTs the downconversion process produces essentially no S/N degradation since it is performed after amplification and filtering. 2) The large instantaneous bandwidth of an amplifier can be used for continuum studies. 3) HEMT amplifiers require only simple cryogenics 4) MMICs are readily adapted for array receivers.

5.2 Schottky Mixers

Below 700 GHz, SIS receivers are typically 5 – 10 times more sensitive than their Schottky-diode counterparts. Therefore, SIS receivers are preferred for most radio astronomy applications at millimeter and submillimeter wavelengths. However, there are several exceptions. One major advantage of Schottky mixers is that they can operate over a very wide temperature range, including room temperature, and can therefore be used in applications in which cryogenic cooling is undesirable or prohibitively expensive. For instance, radiatively cooled Schottky mixers will be used in several submillimeter space projects [e.g. Waters 1992; Erickson 1992a].

Schottky mixers are also used at terahertz frequencies, where other technologies are simply unavailable at present. Pioneering astronomical observations in the 700-3000 GHz band have been made by several groups over the past decade using receiver systems consisting of optically pumped far-infrared lasers and corner-reflector Schottky mixers. Chin [1992] reviewed this receiver technology and described some of the astrophysical results, which were obtained using ground-based telescopes as well as the NASA Kuiper Airborne Observatory. Crowe et al. [1992] presented an excellent discussion of the physics and engineering of high-frequency Schottky diodes and mixers. There has been steady progress in this field, and optimization of the diode structure for high-frequency operation continues to yield improvements in performance [e.g. Röser et al. 1994]. Further reductions in mixer noise may be possible using Schottky diodes with epitaxially grown heterostructures, which are now under development [Hong et al. 1994].

Another area of intense activity is the development of planar diodes and mixer circuits [Crowe et al. 1992; Grüb et al. 1993]. Most Schottky mixers use whisker-contacted diodes, which are generally fragile and difficult to assemble. Planar, lithographically fabricated diodes have recently been developed to overcome these difficulties, with little sacrifice in performance. Examples include a 250 GHz monolithic, twin-slot antenna quasioptical mixer [Gearhart and Rebeiz 1994] with $T_{\mathrm{rec}} =$ 2250 K (DSB), and a 585 GHz waveguide mixer [Hesler et al. 1995] with $T_{\mathrm{rec}} = 3470$ K (DSB). Both mixers were tested at room temperature.

5.3 SIS Mixers

Dramatic advances in millimeter and submillimeter astronomy have resulted from the development of sensitive SIS mixers, which now offer unsurpassed performance from 70 GHz to 1 THz. The noise temperatures of a number of recently developed SIS receivers are plotted as a function of frequency in Figure 2. In principle, the sensitivity of SIS mixers is limited only by the zero-point quantum fluctuations of the electromagnetic field. In terms of the single-sideband (SSB) noise temperature, this limit is $h\nu/k_{\mathrm{B}} \approx 0.05$ K/GHz. In practice, the SSB noise temperatures of the best SIS receivers now fall below 0.5 K/GHz over the 100-700 GHz band. Note that 0.3 K/GHz is the level of performance of HEMT amplifiers in the 45 GHz band. SIS mixers have improved to the point that optical elements such as the cryostat vacuum window and the LO injection beamsplitter often contribute a significant fraction of the receiver noise.

The progress in SIS mixers is largely the result of the development of robust, small area, high quality Nb/Al-Oxide/Nb junctions integrated with low loss Nb thin-film tuning circuitry. These junctions have been used in both waveguide and quasi-optical circuits. Other materials such as niobium nitride (NbN) continue to be developed for yet higher frequencies. Blundell and Tong [1992] and Wengler [1992] have recently reviewed SIS mixer technology. An in-depth discussion of the physics of SIS mixers can be found in the excellent review article by Tucker and Feldman [1985].

5.3.1 Waveguide Mixers

Most SIS mixers use waveguide mounts. Waveguide feedhorns have clean beam patterns and high efficiencies, which result in good telescope coupling and low spillover. In addition, adjustable backshort tuners can be used to optimize the mixer performance. Early SIS mixers relied purely on these backshort tuners to match the highly capacitive SIS junction impedance. One of the major themes over the past few years has been the widespread adoption of integrated tuning circuits, which use thin-film inductors to resonate the junction capacitance. This technique was first applied in the mid-1980's to millimeter-wavelength mixers, and has now been extended to submillimeter mixers. Examples of recent work are given in the papers by Blundell et al. [1995a, b], de Lange et al. [1994a], Karpov et al. [1995a], Kerr et al. [1992], Kooi et al. [1994b], Noguchi, Shi, and Inatani [1995], Withington et al. [1994]. Several of these receivers are fixed-tuned, and do not require any mechanical adjustments. This is possible because integrated tuning circuits have a reasonably broad bandwidth, which is limited primarily by the RC product of the SIS junction. The best receiver sensitivity at $\lambda = 0.8$ mm is only a factor of 4 above the quantum limit [Karpov et al. 1995a].

By 1992, low-noise SIS waveguide mixers had been developed to about 500 GHz [see Blundell and Tong 1992]. Since then, work has focused on developing mixers for the 650 GHz [Febvre et al. 1994; Kooi et al. 1994a] and 850 GHz [de Lange et al. 1994b; Honingh et al. 1995; Kooi et al. 1995a] atmospheric windows. A 650 GHz fixed-tuned waveguide mixer with excellent performance has also been demonstrated [Tong et al. 1995a]. The binding energy of Cooper pairs in niobium corresponds to a photon frequency of 700 GHz. Above this frequency, niobium integrated tuning circuits become quite lossy and this reduces the mixer sensitivity. A 1 THz mixer substituting aluminum in place of niobium for the tuning circuit has been tested by van de Stadt et al. [1995a, b], with results already comparable to Schottky mixers.

Waveguide mixers become increasingly difficult and expensive to construct at higher frequencies because the critical dimensions scale with the wavelength. The waveguide block is more difficult to machine, the SIS devices are harder to fabricate because the substrates become extremely thin ($<$ 50 μm), and even mounting and aligning the SIS substrate in the waveguide block poses a challenge. These difficulties are practical, not fundamental. For instance, a 2.5 THz corrugated horn has been fabricated by using vacuum sputter deposition (instead of electroforming) on a conventionally machined mandrel [Ellison et al. 1994].

Another possibility is to use silicon micromachining techniques, which use lithography and anisotropic etching to create three-dimensional micron-scale structures. Millimeter-wave micromachined waveguides have been demonstrated [McGrath et al. 1993], along with silicon nitride membrane air-bridges which in the future could be used to integrate SIS junctions [Wright et al. 1995]. SIS junctions have been fabricated on membranes [Garcia, Jacobson, and Hu 1993]. In this process, the SIS junctions are fabricated on relatively thick silicon substrates covered with a $\sim$ 1 μm thick layer of CVD-grown Si_3N_4, and the silicon is subsequently etched from the back side. SIS junctions on membranes have recently been used in a conventionally-machined 800 GHz waveguide block [Kooi et al. 1995a, b]. Although this avoids the necessity of fabricating junctions on ultrathin substrates, it is still difficult to mount and align the junction in the waveguide block. A complete 100 GHz micromachined SIS mixer has been developed by de Lange et al. [1995a, b]. This mixer uses a planar dipole antenna integrated with an SIS junction on a silicon nitride membrane, and a pyramidal horn formed from a stack of micromachined silicon wafers. The noise temperature and bandwidth of this mixer are not yet competitive but should improve significantly when integrated tuning circuits are incorporated. Another interesting example of the use of micromachining techniques is the planar tuning element developed by Lubecke, McGrath, and Rutledge [1994].

5.3.2 Quasioptical Mixers

Quasioptical mixers rely on the fact that *two-dimensional* microstructures are easily fabricated using conventional lithography. In this approach, a planar antenna, a microstrip impedance transformer, and an SIS junction are integrated on a dielectric substrate. A substrate lens can then be used to increase the directivity of the planar antenna. Quasioptical mixers are much simpler to fabricate than either conventional or micromachined waveguide mixers.

The main challenge in constructing low-noise quasioptical mixers is to obtain efficient radiation coupling. For applications in radio astronomy, the planar antenna must be carefully chosen to have low sidelobes, a symmetric main beam, and low phase aberrations. The coupling efficiency to a fundamental Gaussian mode is a good test of these characteristics and indicates the quality of the planar antenna and optics. There is no fundamental reason that planar antennas cannot have a high efficiency; in fact, detailed calculations [Filipovic et al. 1993] predict efficiencies around 90% for twin-slot antennas on antireflection-coated silicon lenses. Another challenge is to obtain a proper impedance match between the antenna and the SIS junction. Quasioptical mixers do not have adjustable tuners, which means that the on-chip circuit must be designed correctly. Fourier-transform spectrometer measurements are very useful for verifying design calculations and assumptions [Hu et al. 1988; Büttgenbach et al. 1992; Dierichs et al. 1993; Belitsky et al. 1995a; Gaidis et al. 1995a, b].

Early work [Wengler et al. 1985; Büttgenbach et al. 1988] used broadband antennas and untuned Pb-alloy junctions. Subsequent efforts have focused on higher frequencies, improved planar antennas and coupling optics, antireflection coatings, integrated tuning circuits for lower noise, and Nb/Al-Oxide/Nb junction technology for much greater reliability and reproducibility [Belitsky et al. 1992, 1995b; Büttgenbach et al. 1992; Gaidis et al. 1995a, b; Hu et al. 1989; Rothermel et al. 1994; Schuster, Harris, and Gundlach 1993; Skalare et al. 1993; Zmuidzinas and LeDuc 1992; Zmuidzinas et al. 1994, 1995a]. Above 500 GHz, quasioptical mixers now have noise temperatures equivalent to the best waveguide mixers, and have demonstrated high telescope coupling efficiencies [Zmuidzinas et al. 1995b; Chamberlin 1995]. A 1 THz quasioptical mixer with niobium junctions and an aluminum normal-metal tuning circuit has recently achieved $T_{\rm rec} = 850$ K (DSB) [Bin et al. 1995], which is substantially better than the best Schottky mixers.

5.3.3 SIS Tuning Circuits

An SIS junction can be approximated as a parallel RC circuit. Tuning circuits can usually be separated into two classes, depending on whether the tuning inductance is placed in series or in parallel with the junction. The tuning inductance is usually a short section of superconducting microstrip line. For parallel tuning, the inductance is terminated with an RF short-circuit element such as a radial stub. In the series inductance case, the resulting impedance is lower than the junction resistance by a factor of $(\omega RC)^2$, and a multisection stepped quarter-wave transformer is needed to raise the impedance back to a level that matches the quasioptical antenna or waveguide probe. An alternative approach is to use *two* SIS junctions separated by a microstrip tuning inductance, fed asymmetrically from one side, or fed antisymmetrically from both sides. This method is attractive since the RF short-circuit element or the multisection transformer are not required. Excellent results have been obtained using this technique with submillimeter quasioptical mixers [Belitsky et al. 1995a, b, and references therein; Zmuidzinas et al. 1994; Gaidis et al. 1995a, b] and with a 100 GHz waveguide mixer [Noguchi et al. 1995].

Both single-junction and two-junction tuning circuits have bandwidths of $\Delta\nu \sim (2\pi RC)^{-1} \sim$ 100 GHz [Kerr et al. 1995; Zmuidzinas et al. 1994]. Broader bandwidths are possible using distributed circuits. Tong et al. [1995b] recently demonstrated a very low noise ($\sim$ 80 K DSB) 460 GHz waveguide mixer which uses a narrow, long (0.2×40 μm) SIS junction as a lossy microstrip line. The radiation is coupled in from one end, and is gradually absorbed as it propagates due to the photon-assisted tunneling currents. This device is intrinsically broadband and is not limited by the junction RC product. This implies that very high quality, low current density junctions can be used; however, the current density should not be made so low that the loss is dominated by the surface resistance of the electrodes. Another important advantage is that the IF impedance of this device should be fairly insensitive to the LO frequency. It should be possible to achieve a similar result using an ordinary microstrip line that is periodically loaded with discrete micron-size junctions. The asymmetrically-fed two-junction circuit can be considered to be the first step in this direction. An analysis of this circuit was carried out by Zmuidzinas et al. [1994], who demonstrated that the mixer performance is not adversely affected by the unequal LO power sharing by the two junctions. Presumably, this conclusion can be generalized to the periodically-loaded microstrip case as well as to the lossy SIS-junction transmission line case.

5.3.4 Alternative Materials

Almost all recent high-performance SIS mixers use Nb/Al-Oxide/Nb junctions. However, niobium becomes lossy above 700 GHz (the gap frequency), and the upper frequency limit for efficient mixing in niobium-based junctions is 1.4 THz. Other materials with larger critical temperatures and energy gaps may be more suitable for frequencies above 700 GHz. So far, niobium nitride (NbN) appears to be the most promising material because high-quality submicron tunnel junctions can be fabricated [e.g. LeDuc et al. 1991]. A key ingredient in the success of niobium SIS mixers is the fact that the RF surface resistance of niobium is very low below the gap frequency. This results in very low losses in the on-chip tuning circuit. Unfortunately, the submillimeter-wave surface resistance of ordinary polycrystalline NbN films may be rather large, making it necessary to use higher quality (perhaps epitaxial) NbN films [Kohjiro, Kiryu, and Shoji 1993]. Progress in this direction is described by Barber, Tricker, and Blamire [1995] and by Wang et al. [1994]. Mixed-electrode NbN/Nb junctions have been tested in 350-650 GHz SIS mixers [van de Stadt et al. 1995b], but the noise temperatures so far are not competitive and appear to rise rapidly with frequency. Mixers using all-NbN junctions have been demonstrated at 205 GHz [McGrath et al. 1991] and at 160 GHz [Karpov et al. 1995b]. While these initial results are promising, the frequency dependence of the tuning circuit loss is not well known, making it essential to obtain mixer measurements at higher frequencies. It is encouraging that photon-assisted tunneling steps have been observed at 762 GHz in NbN/AlN/NbN junctions [Uzawa et al. 1995], but the implications of this measurement for SIS mixers are not clear because a tuning circuit was not used and the coupling efficiency was low.

5.4 Hot Electron Bolometer Mixers

Niobium-based SIS mixers will not operate above 1.4 THz. Although this barrier might be surmountable using NbN or other higher-gap materials, the large capacitance of SIS junctions makes them inherently unsuitable for THz frequencies. It is therefore necessary to consider alternative devices such as hot-electron bolometer mixers [McGrath 1995].

As discussed in section 6, bolometers are thermal radiation detectors that are typically used for sensing broad–band continuum radiation. They can also be used as heterodyne mixers if local oscillator radiation is applied. However, typically bolometers have slow thermal time constants (milliseconds), and the resulting intermediate-frequency (IF) bandwidth is much too low to be useful.

Hot electron bolometer mixers rely on nonequilibrium heating of the electrons in a superconductor or semiconductor. Lithographic techniques are used to reduce the active volume to $<< 1\ \mu m^3$, which results in an extremely low electronic heat capacity and thermal conductivity. The device can be coupled to an antenna, and absorbs radiation by ohmic heating. This dissipation mechanism is effective for frequencies below the electron elastic scattering rate, which in most cases implies that the device should operate well into the THz region. The heated electrons can cool by emitting phonons or by diffusing out of the active volume. Provided that the resistance of the device is a function of electron temperature, the result is a sensitive bolometer which can have a very fast response time under proper conditions.

A straightforward example is a very thin superconducting film, patterned into strips with $\sim \mu$m dimensions. The film is biased near its transition temperature, so that the resistance is a strong function of temperature. This device was discussed and analyzed by Gershenzon et al. [1990, 1992] and Ekström et al. [1995a]. The electrons cool by emitting phonons which escape into the substrate. The IF bandwidth therefore depends on the strength of the electron-phonon interaction in the superconductor, the thickness and quality of the film, and the substrate material. For instance, Ekström et al. [1995a] have obtained an IF bandwidth of 80 MHz for a 20 GHz mixer using a 90 Å niobium film on a silicon substrate. Recent work has demonstrated that $\sim$ 1 GHz IF bandwidths are possible using NbN films [Ekström et al. 1995b; Kawamura et al. 1995; Okunev et al. 1995]. At 100 GHz, Okunev et al. [1995] measured a noise temperature of 450 K (DSB) and an IF bandwidth of 1.5 GHz. This is very encouraging since the noise temperature should not degrade rapidly at higher frequencies. However, these mixers are not well understood at present, and the experimental results are often poorly described by theory. Much work remains to be done to fully characterize and optimize the mixers and to demonstrate higher frequency operation.

Prober [1993] suggested that a superconducting hot-electron bolometer with submicron dimensions would have a wide IF bandwidth because the timescale for electrons to diffuse into the surrounding normal-metal electrodes would become very short. This concept was recently demonstrated in a 533 GHz waveguide mixer [Skalare et al. 1995] using a $0.14\ \mu m \times 0.28\ \mu m \times 100$ Å niobium bolometer element. The receiver noise temperature of 650 K (DSB) and IF bandwidth of 1.8 GHz are extremely promising for future THz mixers.

Yang et al. [1993] investigated hot-electron mixing effects in the two-dimensional electron gas created in AlGaAs heterostructures. At 94 GHz, a 1.7 GHz IF bandwidth and a 18 dB conversion loss was measured. They project that a 10 dB conversion loss and $T_{\rm rec} \sim 500$ K (DSB) should be achievable with an optimized device. Note however that the noise temperature prediction does not include the effect of electron temperature fluctuations. Judging from the data of Yang et al. [1995], this effect will increase $T_{\rm rec}$ by a factor of 2-3.

5.5 Local Oscillators

At frequencies below $\sim$ 750 GHz, solid–state local oscillator systems have rapidly replaced systems using gas lasers and vacuum tube oscillators such as klystrons, carcinotrons, and backward–wave oscillators. Although the older systems are capable of producing substantial output power, their large size, high voltage requirements, low reliability and short lifetimes make them awkward for use at ground based observatories and clearly undesirable for space based observatories. In contrast, solid–state systems are compact, reliable and long lived. Current research has been directed at pushing solid state devices to higher frequencies and output powers. The commonly quoted goal of 100 μW at 1 THz with a completely solid-state system has almost been achieved: Zimmermann et al. [1995] reported 60 μW at 1 THz with a InP Gunn oscillator followed by a cascade of two whisker–contacted Schottky varactor triplers; and Erickson and Tuovinen [1995] report 110 μW at 800 GHz using a InP Gunn oscillator, a balanced doubler, and a tripler.

Currently Gunn oscillators are the preferred devices for the generation of local oscillator power at frequencies up to $\sim$ 150 GHz and Gunn oscillator/Schottky varactor multiplier combinations for frequencies up to 1 THz. The widespread use of Gunn oscillators is due to their ease of phaselocking, high tunability, high output power, and superior noise properties.

Considerable research has been directed toward other sources such as HEMT oscillators, TUNNETT oscillators, Josephson oscillators, resonant-tunneling diodes, and photomixing. Although these techniques offer the promise of fundamental power generation at submm wavelengths, they have yet to provide sufficient power, reliability, and ease of phaselocking to compete with Gunn oscillator/varactor multiplier combinations, although recent work on TUNNETT diodes has yielded promising results [Eisele and Haddad 1995a, b]. IMPATT oscillators are capable of producing substantial power at millimeter wavelengths, but their excessive noise, due to the avalanche process, makes them undesireable as local oscillators for low-noise receivers. They are not discussed further in this review. Recent work on the various devices is briefly reviewed below.

Fine frequency control and stabilization of the local oscillator is accomplished by using a standard phase-lock loop. The phaselock IF is obtained by combining a sample of the oscillator signal and a high–level lower frequency reference in a harmonic mixer. An alternative approach has been suggested in which a weak reference tone is diplexed with the sky signal at the input to the receiver and then the receiver's low-noise mixer is used to generate the phaselock IF [Padin 1989]. This scheme could allow the use of fundamental LO sources at high frequencies which have low output powers and would be difficult to phaselock using the standard technique outlined above.

5.5.1 Gunn Oscillators

Typically, Gunn oscillators use InP devices in wideband, mechanically tunable cavities of the type described by Carlstrom et al. [1985]. These oscillators operate in a second harmonic mode. Mechanical adjustment of a coaxial cavity which is resonant at the fundamental frequency sets the operating frequency. The fundamental cavity is embedded in rectangular waveguide which is beyond cut off for the fundamental, but allows propagation of the second harmonic. A radial line transformer (a disk within the coaxial cavity) and a sliding short in the rectangular waveguide enable high efficiencies over broad bandwidths to be achieved.

Recently, output powers of 65 mW at 140 GHz have been reported using reliable, commercially available, encapsulated InP devices [Crowley et al. 1994]. These devices operate in a stable depletion layer mode rather than an unstable propagating accumulation layer or dipole [Zybura et al. 1995]. Comparison of models with experimental data for a mechanically tuned, second harmonic oscillator covering 120 − 145 GHz show excellent correlation.

Gunn oscillators are capable of producing useful output power at higher frequencies: Rydberg [1990] has reported 5 mW of power at 188 GHz from a second harmonic device. More recently, Eisele and Haddad [1995b] have reported fundamental power of 100 mW at 132 GHz and more than 15 mW at 150 GHz using InP devices on diamond heat sinks. They have also reported second harmonic powers of more than 0.3 mW at frequencies between 280 and 290 GHz [Eisele and Haddad 1994], and 100 mW at 105 GHz from GaAs TUNNETT diodes mounted on diamond heat sinks [Eisele & Haddad 1995a, b]. The efficiencies and phase noise measurements they report are comparable to those obtained with state-of-the-art InP Gunn oscillators.

5.5.2 Resonant Tunneling Diodes

The fast negative differential resistance associated with double-barrier resonant tunnelling can be used as the basis of high frequency oscillators (see the reviews by Brown [1994] and Salmer et al. [1993]). Oscillations as high 712 GHz have been reported for InAs/AlSb material [Brown et al. 1991]. To achieve acceptable linewidths, oscillator designs include a high Q resonator, such as that provided by a confocal open cavity resonator [Brown et al. 1992]. Such a device was used to drive a SIS receiver operating at 195 GHz and its performance was compared with a frequency doubled Gunn oscillator [Blundell et al. 1993]. The 20 μW output power of the RTD oscillator was insufficient to drive the mixer optimally without increasing the LO coupling to 10%. Replacing the RTD oscillator with the Gunn oscillator/doubler combination while maintaining the same 10% coupling gave similar receiver noise performance, indicating that the excess noise of this RTD oscillator is fairly low.

5.5.3 Josephson Oscillators

Josephson effect oscillators have received attention as a viable source of coherent radiation over the millimeter and submillimeter range [Monaco 1990, Lukens 1990]. The maximum amount of power extracted from a single junction is small ($\sim$nW), but this can be increased by using N junctions in series. Recently, Han et al. [1994] have demonstrated ~ 50 μW of power coupled to a 68 Ω load at 394 GHz from a 500 junction series array. The large number of junctions operating in phase also decreases the linewidth; they report linewidths less than 1 MHz [see also Bi et al. 1993]. Typically, the experimental setups used in the study of Josephson oscillators include two devices; one to serve as the local oscillator for an integrated SIS mixer and the other as the signal under investigation. This clearly demonstrates the practicality of fabricating Josephson arrays for the generation of submillimeter local oscillator power. Additional noteworthy results have been reported for one dimensional arrays [Wan et al. 1989], for two dimensional arrays [Benz & Burroughs 1991; Martens et al. 1993; Wengler et al. 1995], and with long single junction flux flow oscillators [Zhang et al. 1993; Koshelets et al. 1994]. Using Josephson arrays or flux-flow oscillators to provide local oscillator power for SIS receivers could offer several attractive features, such as broad frequency coverage and integrated fabrication with the SIS devices [see Koshelets et al. 1995]. However, frequency stability and control must be demonstrated for them to become useful sources of LO power for radio astronomy receivers.

5.5.4 HEMT Oscillators and Power Amplifiers

The frequency limit of transistor oscillators has been pushed far into the millimeter band [see review by Salmer et al. 1993]. Using gate lengths of order 50 nm and source drain separation of $\sim 0.25\ \mu$m, Rosenbaum et al. [1995] have realized a 213 GHz HEMT oscillator. However, the output power is only about 1 μW. They report a similar device operating at 155 GHz with $\sim 25\ \mu$W output power. Transistor oscillators operating at 100 GHz and 131 GHz have been reported, but again the output powers are low, 2 mW and 0.2 mW, respectively [Kwon et al. 1993, Kwon et al. 1994].

Millimeter-wave transistor oscillators are therefore not currently competitive as a source of fundamental local oscillator power. However, transistor power amplifiers combined with lower frequency oscillators and multipliers are able to produce substantial power at millimeter wavelengths. Erickson et al. [1992b] used a commercial Ka–band YIG oscillator with a 30 dB gain power amplifier followed by a varactor tripler to drive their 15 element Schottky array receiver. This completely electronically tuned LO system covered 85 to 115 GHz with an output power of 2 - 6 mW. A similar system is being considered by NRAO for the MMA project. Erickson et al. noted that the 8 dB noise figure of the power amplifier and hard drive level of the varactor tripler could add substantial noise and that filtering is necessary to ensure the best receiver performance. Similar LO systems using MMIC technology have been developed; Ho et al. [1994] report 10.6 dBm at 92 GHz, and Wang et al. [1995b] report 2 mW at 95 GHz with a 5 GHz tuning range.

High frequency HEMT power amplifiers can be used to boost the levels of W–band signals for driving further multiplication stages. For example, starting with a 47 GHz transistor oscillator, Ho et al. [1993] have produced 90 mW at 94 GHz. HEMT amplifiers have been shown to have considerable power handling capabilities; up to 100 mW with 9 dB gain at 94 GHz [Aust et al. 1995, Smith et al. 1995], and up to 370 mW with 13.8 dB gain at 60 GHz [Sharma et al. 1994]. Smith et al. discuss the possibilities of much higher frequency operation.

5.5.5 Photomixers

Photomixers are a promising source of coherent power generation at THz frequencies. Low temperature growth (LTG) GaAs is used as a photomixer by focusing laser beams on an array of submicron interdigitated electrodes on the top surface. The electrodes are biased at a large potential and are coupled directly to a spiral or slot antenna [Brown et al. 1994, Brown et al. 1995]. The short carrier lifetime, high electrical breakdown field, and high carrier mobility make the LTG GaAs suitable for operation well into the THz range. Results have been reported for frequencies as high as 3.8 THz [Brown et al. 1995]. Only low output powers have been achieved to date ($\sim 50\ \mu$W at 100 GHz and falling 12 dB/octave beyond 500 GHz. Although it should be feasible to frequency stabilize the drive lasers and the beat frequency, this has yet to be demonstrated.

5.5.6 Frequency Multipliers

Frequency multipliers are generally used for the generation of LO power at frequencies above $\sim$140 GHz. An excellent review is provided by Räisänen [1992], so only recent results are discussed here.

Whiskered varactor multipliers are used almost exclusively. As stated at the beginning of this section the goal of 100 μW at 1 THz by a solid–state local oscillator system has nearly been obtained [Zimmermann et al. 1995, Erickson et al. 1995, Rydberg et al. 1993], although Rydberg et al. used a carcinotron to provide a high pump power (10 mW at 250 GHz).

For power generation up to $\sim$ 400 GHz, single stage triplers and quadruplers are usually used.

However, power generation at higher frequencies is difficult with a single multiplier stage, since the intermediate harmonics must be terminated properly to achieve high efficiency. Furthermore there is trade off between the power handling capabilities of the multiplier diode and its capacitance and therefore its high frequency performance; the high pump powers ($\sim$ 100 mW at 100 GHz) necessary to obtain sufficient power at frequencies greater than $\sim$500 GHz can only be handled with fairly large anode diodes. The best results have been obtained with cascaded multipliers, usually with a doubler or tripler, followed by tripler. Multipliers using two diodes have been designed to further increase the power handling capabilities of the first stage [Erickson 1990, 1995].

The main limitation to the reliability of efficient varactor frequency multipliers is the whiskered contact. Great care must be taken to isolate the contact from mechanical stresses. It is also difficult to control the physical and electrical characteristics of a whisker contact, making it hard to obtain reproducible results. Planar diodes offer an attractive solution to these problems. They also make it possible to construct multipliers using diode arrays thereby increasing the power handling capabilities [Chiao et al. 1995; Rizzi et al. 1993; Tuovinen and Erickson 1995]. However, the large parasitic capacitances of these devices has limited their use to frequencies below $\sim$300 GHz [Bishop et al. 1987, Archer et al. 1990, Bishop et al. 1991, Newman et al. 1991]. A discussion of both planar and whisker diodes is given in Crowe et al. [1992]. Erickson [1995] discusses the design criteria for multipliers using high frequency planar devices and proposes a self–biased anti-parallel device.

The efficiency of a Schottky varactor multiplier can be improved by cooling the device, mainly because the mobility of the free carriers increases. Louhi et al. [1993] report theoretical calculations that indicate cooling varactor diodes to less than $\sim$ 150 K could increase the multiplier output power at 1 THz by as much as 10 dB.

Several other types of diodes have been proposed and evaluated [Tolmunen and Frerking 1991, Rydberg et al. 1990, Räisänen 1992, Nilsen et al. 1993, also see review in Salmer et al. 1993], including the single barrier varactor (SBV) diode [Kollberg and Rydberg 1989]. The symmetry of the structure leads to a symmetric C-V characteristic, resulting in only odd harmonic generation. Therefore triplers can be made without any idler circuits, and a quintupler needs only one. A single barrier varactor quintupler has been reported by Räisänen et al. [1995]. The best results for this and other SBV multipliers fall far short of those obtained with conventional Schottky–varactor multipliers.

5.6 Spectrometers, Correlators and Tracking Delays

High speed digital correlators are used exclusively at the millimeter arrays for high spectral resolution observations. Typically, a few subbands with bandwidths ranging from about 1 MHz to 128 MHz are synthesized with up to several hundred channels. An autocorrelation spectrometer is in use at the JCMT telescope, and many other single dish facilities are planning to implement them in the future. Currently, most single dish observatories use acousto-optical spectrometers (AOS) as they provide high resolution over $\sim$ 1 GHz bandwidths at reasonable cost. The reproducibility and flexibility of digital systems make them attractive, especially for systems with multiple receivers. Recent reports on existing and planned correlator systems, including a thorough review by Hayward [1993] can be found in the proceedings of the NRAO workshop "New Generation Digital Correlators", held in Tucson, AZ, 25–26 February 1993.

An effort has also been made to increase the sensitivity of continuum observations by increasing the instantaneous IF bandwidth of SIS receivers and the associated backend. Bandwidths of 1 GHz are now routine, and Padin et al. [1995] have demonstrated 4 GHz with an integrated SIS mixer/HEMT IF amplifier. For maximum sensitivity to continuum emission, the millimeter arrays use either broadband (1 GHz) analog single channel correlators in parallel with high resolution digital correlators [Padin 1994], or a portion of the digital spectrometer is configured to synthesize a large fraction of the available IF bandwidth [e.g. Guilloteau et al. 1992, Welch 1995].

Increasing the IF bandwidths for interferometers introduces severe constraints on the IF tracking delays. Delay systems using digital circuits offer high precision and stability, but are difficult to implement for 1 GHz and higher bandwidths. Commercial fiber optic technology allows analog bandwidths in excess of 10 GHz to be transmitted. However, the limited dynamic range of available high speed optical transmitter/receivers and the roughly 1 dB loss per optical switch make it impractical to use fiber optics for the large number of delays steps needed for GHz bandwidth tracking delays. Instead hybrid systems which use fiber optics only for the larger delay segments have been built [OVRO: Soares and Padin 1994, CSO–JCMT: Lay et al. 1994a, see also Moslehi 1994]. The OVRO system has a 4 GHz bandwidth and delay steps spanning 1/128 ns to 512 ns in a binary sequence.

6 Incoherent Detection - Bolometers

Although heterodyne receivers are well suited for high-resolution spectroscopy, their sensitivity to broadband continuum radiation is compromised by their limited IF bandwidth. In contrast, direct detectors such as bolometers have very wide bandwidths and offer better continuum sensitivities for single-dish telescopes. The bandwidth (50-100 GHz typically) is normally set by an optical filter, which for ground-based work is chosen to match an atmospheric window. Bolometers are also used for low to medium resolution spectroscopy [e.g. Naylor et al. 1991; Naylor, Clark, and Davis 1994; Maffei et al. 1994; Weisstein and Serabyn 1995]. Richards [1994] has recently written a comprehensive review article on bolometers, which serves as an excellent introduction as well as a resource for more detailed information than is given here.

Bolometers are thermal radiation detectors. The radiation heats an absorbing element, and a resistance thermometer is used to sense the resulting temperature change. The ultimate sensitivity of a bolometer is determined by the thermal fluctuations of the absorbing element, according to the formula $\mathrm{NEP}^2 = 4k_{\mathrm{B}}T^2G$. Here NEP is the noise-equivalent power in $\mathrm{W}/\sqrt{\mathrm{Hz}}$, T is the operating temperature, and G is the thermal conductivity between the absorbing element and the thermal bath. The sensitivity of a bolometer can be increased by reducing either the temperature T or the thermal conductivity G. However, if the absorber has a heat capacity C, it will have a thermal time constant of $\tau = C/G$. If G is reduced to improve the sensitivity, C must usually also be reduced to ensure that τ is kept much shorter than the characteristic modulation time of the signal radiation.

For a given telescope and wavelength band, it is desirable to reduce the bolometer noise to a level that is below the fluctuations in the thermal background radiation incident on the detector. With state-of-the-art bolometers, this situation can now be achieved for most ground-based applications. Experiments that would still benefit substantially from improvements in sensitivity are millimeter-wave CMB observations from balloons [e.g. Clapp et al. 1994] and far-infrared observations from satellites, especially those with cooled optics [e.g. Lange et al. 1994]. Ground-based continuum observations are most often limited by "sky noise", which is the result of emissivity fluctuations caused by atmospheric turbulence and variations in water vapor content. Experimenters working with focal-plane arrays have known for some time that sky-noise fluctuations tend to be highly correlated across the array. Recently, instantaneous differencing between adjacent pixels in the focal plane has been shown to be very effective for suppressing sky noise [Wilbanks et al. 1994]. This scheme relies on a novel electronic differencing technique in which the bolometers are operated in an AC bridge [Devlin et al. 1993; Glezer, Lange, and Wilbanks 1992; and references therein]. Kuno et al. [1993] have also used the AC bridge technique for a 150 GHz 7-element array that is used on the Nobeyama 45 m telescope.

6.1 Technology Status

Composite bolometers which use neutron-transmutation-doped (NTD) germanium thermistors have achieved NEP $\sim 1 \times 10^{-16}$ W/$\sqrt{\mathrm{Hz}}$ and $\tau \sim 11$ ms at 300 mK [Alsop et al. 1992]. At 100 mK [Tanaka et al. 1994], this improves to NEP $\sim 2 \times 10^{-17}$ W/$\sqrt{\mathrm{Hz}}$ with $\tau \sim 30$ ms . An even lower NEP of 7×10^{-18} W/$\sqrt{\mathrm{Hz}}$ with $\tau = 6$ ms was obtained with a silicon monolithic bolometer at 70 mK [Richards 1994]. More recently, Bock et al. [1995] have developed a novel bolometer which uses a NTD Ge thermistor with a micromachined 1 μm thick silicon nitride membrane as the absorber. The membrane is patterned into a fine mesh or "spider web", and long Si_3N_4 legs serve as the thermal isolation. The demonstrated performance at 300 mK is outstanding, NEP $= 4 \times 10^{-17}$ W/$\sqrt{\mathrm{Hz}}$ with $\tau \sim 40$ ms, and further improvements in both sensitivity and speed appear likely.

It is possible to drastically reduce the heat capacity and thermal conductivity of a bolometer by shrinking the absorber down to microscopic volumes, $< 1\ \mu\mathrm{m}^3$. In this case, an antenna must be used to couple the radiation into the absorber [Richards 1994]. An interesting example is the SIN hot-electron microbolometer. The radiation is absorbed by the electrons in a small volume of normal metal through ohmic heating, and an SIN tunnel junction serves as a thermometer of the electron temperature [Nahum, Richards, and Mears 1993; Nahum and Martinis 1993; Tang and Richards 1995]. Antenna-coupled microbolometers promise high sensitivities and fast time constants, and should allow straightforward construction of imaging arrays.

6.2 Bolometer Arrays

Given that present bolometers are sensitive enough to be background or sky-noise limited for many applications, the emphasis for these cases shifts from developing more sensitive bolometers to building large imaging arrays. At the University of Chicago, bolometer arrays for far-infrared and submillimeter imaging [Harper et al. 1995] and polarimetry [Platt et al. 1991; Schleuning et al. 1996] have been under continuous development since the early 1980's. Instruments have been built for both airborne and ground-based observatories. The arrays use composite bolometers with Winston cones, and achieve NEP $\sim 5 \times 10^{-16}$ W/$\sqrt{\mathrm{Hz}}$ and $\tau \sim 3$ ms at 300 mK [Platt et al. 1991]. At present, the airborne far-infrared photometer has 60 pixels, while the polarimeters have two 32-pixel arrays.

Kreysa et al. [1993] have constructed a 7-channel $\lambda = 1.2$ mm bolometer array for the IRAM 30m telescope. The array elements use conical feedhorns and composite bolometers with NTD germanium thermistors. A larger 19-channel 1.2 mm array has recently been constructed, and 37-element arrays for the IRAM telescope at 1.2 mm and for the HHT/SMTO 10 m submillimeter telescope at 350 μm are planned.

SCUBA [Cunningham et al. 1994] is a bolometer array camera developed for the 15 m JCMT submillimeter telescope. It has two hexagonal close-packed detector arrays: a long wavelength array with 37 pixels for the 850/750/600 μm bands, and a short-wavelength array with 91 pixels for the 450/350 μm bands. SCUBA uses composite bolometers with NTD germanium thermistors and single-mode conical feedhorns. The bolometers are cooled to 100 mK using a dilution refrigerator. At this temperature, the low-background NEP is $\sim 8 \times 10^{-17}$ W/$\sqrt{\mathrm{Hz}}$ and $\tau \sim 5$ ms. SCUBA is expected to be background-limited in all of its wavelength bands.

Wang et al. [1994] are developing a 24-element ^{3}He-cooled array for the Caltech Submillimeter Observatory. The array is optimized for the 450/350 μm bands, but will also have a filter for the 850 μm band. The bolometers are silicon monolithic linear arrays [Moseley, Mather, and McCammon 1984]. The coupling is purely optical; no feedhorns or cones are used. Low-background NEP's around 10^{-16} W/$\sqrt{\mathrm{Hz}}$ are expected at 300 mK, with $\tau < 10$ ms.

7 Acknowledgements

The authors received valuable input from O. P. Lay and M. Pospieszalski, and are thankful to the many authors who supplied copies of their recent work. J. C. acknowledges support from a NSF Young Investigator award and the David and Lucile Packard Foundation.

8 References

R. Akeson, J. E. Carlstrom, and D. P. Woody [1993], "Development of a Sideband Separation Receiver at 100 GHz," *Proc. Fourth Intl. Symp. Space Terahertz Tech.*, March 30-April 1, 1993, UCLA, Los Angeles, CA, pp. 12-17.

D. C. Alsop, C. Inman, A. E. Lange, and T. Wilbanks [1992], "Design and Construction of High Sensitivity Infrared Bolometers for Operation at 300 mK," *Appl. Opt.*, **31**, pp. 6610-6615.

J. W. Archer, R. A. Batchelor, and C. J. Smith [1990], "Low–Parasitic Planar Schottky Diodes for Millimeter–Wave Integrated Circuits," *IEEE Trans. Microwave Theory Tech.*, **38**, pp. 15–22.

J. W. Armstrong and R. A. Sramek [1982], "Observations of Tropospheric Phase Scintillations at 5 GHz on Vertical Paths," *Radio Science*, **17**, 6, pp. 1579–1586.

M. Aust, H. Wang, M. Biedenbender, R. Lai, D. C. Streit, P. H. Liu, G. S. Dow, and B. R. Allen [1995], "A 94–GHz Monolithic Balanced Power Amplifier Using 0.1 μm Gate GaAs-based HEMT MMIC Production Process Technology," *IEEE Microwave and Guided Wave Lett.*, **5**, pp. 12–14.

L. B. Bååth [1994], "MMVLBI," in "Astronomy with Millimeter and Submillimeter Wave Interferometry," IAU Colloquium 140, eds. M. Ishigura and Wm. J. Welch, *ASP Conf. Series*, **59**, pp. 44–49.

J. W. M. Baars, A. Greve, H. Hein, D. Morris, J. Penalver and C. Thum [1994], "Design Parameters and Measured Performance of the IRAM 30-m Millimeter Radio Telescope," *Proc. IEEE*, **82**, 5, pp. 687–696.

Z. H. Barber, D. M. Tricker, and M. G. Blamire [1995], "The Fabrication and Characterization of NbCN/AlN Heterostructures," *IEEE Trans. Appl. Supercond.*, **5**, pp. 2314-2317.

V. Yu. Belitsky, M. A. Tarasov, S. A. Kovtonjuk, L. V. Filippenko, and O. V. Kaplunenko [1992], "Low Noise Completely Quasioptical SIS Receiver for Radioastronomt at 115 GHz," *Int. J. IR and MM Waves*, **13**, pp. 389-396.

V. Yu. Belitsky, S. W. Jacobsson, L. V. Filippenko, C. Holmstedt, V. P. Koshelets, and E. L. Kollberg [1995a], "Fourier Transform Spectrometer Studies (300-1000 GHz) of Nb-Based Quasi-Optical SIS Detectors," *IEEE Trans. Appl. Supercond.*, **5**, pp. 3445-3451.

V. Yu. Belitsky, L. V. Filippenko, S. W. Jacobsson, and E. L. Kollberg [1995b], "Broad Band Twin Junction Tuning Circuit for Submillimeter SIS Mixers," *Microwave and Opt. Tech. Lett.*, **9**, in press.

S. P. Benz and C. J. Burroughs [1991], "Coherent Emission From 2-dimensional Josephson Junction Arrays," *Appl. Phys. Lett.*, **58**, 19, pp. 2162–2164.

A. L. Betz and R. T. Boreiko [1995], "A Practical Schottky Mixer for 5 THz," to appear in *Proc. Sixth Intl. Symp. Space Terahertz Tech.*, March 21-23, 1995, Caltech, Pasadena, CA.

M. Bin, M.C. Gaidis, J. Zmuidzinas, T. G. Phillips, and H.G. LeDuc [1995], "THz SIS Mixers with Normal Metal Al Tuning Circuits," presented at the *5th Intl. Superconductive Electronics Conference (ISEC '95)*, September 18-21, 1995, Nagoya, Japan.

B. Bi, S. Han, and J. E. Lukens [1993], "Radiation Linewidth of Phase–Locked Distributed Array in the Submillimeter Wave Range," *Appl. Phys Lett.* **62**, 22, pp. 2745 – 2747.

W. L. Bishop, K. McKinney, R. J. Mattauch, T. W. Crowe, and G. Green [1987], "A Novel Whiskerless Schottky Diode for Millimeter and Submillimeter Wave Applications," in *1987 IEEE MTT-S Int. Microwave Symp. Dig.*, **2**, pp. 607–610.

W. L. Bishop, T. W. Crowe, R. J. Mattauch, and P. H. Ostdiek [1991], "Planar Schottky Barrier Mixer Diodes for Space Applications at Submillimeter Wavelengths," *Microwave and Optical Technology Letters*, **4**, pp. 44–49.

R. Blundell and C.-Y. E. Tong [1992], "Submillimeter Receivers for Radio Astronomy," *Proc. IEEE*, **80**, pp. 1702-1720.

R. Blundell, D. C. Papa, E. R. Brown, and C. D. Parker [1993], "Resonant–Tunneling Diode Oscillator as an Alternative LO for SIS Receiver Applications," *Electronic Letters*, **29**, 3. pp. 288 – 290.

R. Blundell, C.-Y. E. Tong, D. C. Papa, R. L. Leombruno, X. L. Zhang, S. Paine, J. A. Stern, H. G. LeDuc, and B. Bumble [1995a], "A Wide–Band Fixed-Tuned SIS Receiver for 200–GHz Operation," *IEEE Trans. Microwave Theory Tech.*, **43**, pp. 933-937.

R. Blundell, C.-Y. E. Tong, J. W. Barrett, J. Kawamura, R. L. Leombruno, S. Paine, D. C. Papa, X. L. Zhang, J. A. Stern, H. G. LeDuc, and B. Bumble [1995b], "A Fixed-Tuned SIS Receiver for the 450 GHz Frequency Band," to appear in *Proc. Sixth Intl. Symp. Space Terahertz Tech.*, March 21-23, 1995, Caltech, Pasadena, CA.

J. J. Bock, D. Chen, P. D. Mauskopf, and A. E. Lange [1995], "A Novel Bolometer for Infrared and Millimeter-Wave Astrophysics," in *Infrared and Submillimeter Space Missions in the Coming Decade*, ed. H. Thronson, M. Sauvage, P. Gallais, and L. Vigroux, *Space Science Review*, **74**.

R. S. Booth [1994], "A Southern Hemisphere Millimeter Array," in "Astronomy with Millimeter and Submillimeter Wave Interferometry," IAU Colloquium 140, eds. M. Ishigura and Wm. J. Welch, *ASP Conf. Series*, **59**, pp. 413–418.

M. Bremer, S. Guilloteau, and R. Lucas [1995], "Phase Correction with the Dual Frequency Receivers," IRAM Newsletter, May 1995.

E. R. Brown, J. R. Söderström, C. D. Parker, L. J. Mahoney, K. M. Molvar, and T. C. Mcgill [1991], "Oscillations up to 712 GHz in InAs/AlSb Resonant–Tunneling Diodes," *Appl. Phys. Lett.* **58**, 20, pp. 2291–2293.

E. R. Brown, C. D. Parker, K. M. Molvar, and K. D. Stephan [1992], "A Quasioptically Stabilized Resonant-Tunneling–Diode Oscillator for the Millimeter– and Submillimeter–Wave Regions," *IEEE Trans. Microwave Theory Tech.*, **40**, 5. pp. 846–850.

E. R. Brown [1994], "High-Speed Resonant–Tunneling Diodes," in "Heterostructures and Quantum Devices," eds. N. G. Einspruch and W. R. Frensley, Chapter 10, Academic Press, San Deigo, pp. 305–350.

E. R. Brown, K. A. McIntosh, K. B. Nichols, M. H. Manfra, and C. L. Dennis [1994], "Optical–Heterodyne Generation in Low–Temperature–Grown GaAs up to 1.2 THz," in *Nonlinear Optics for High–Speed Electronic and Optical Frequency Conversion*, *SPIE*, **2145**, pp. 202–208.

E. R. Brown, K. A. McIntosh, K. B. Nichols, and C. L. Dennis [1995] "Photomixing up to 3.8 THz in Low–Temperature–Grown GaAs," *Appl. Phys. Lett.*, **66**, 3, pp. 285–287.

R. L. Brown [1994], "The Millimeter Array," IAU Colloquium 140, eds. M. Ishigura and Wm. J. Welch, *ASP Conf. Series*, **59**, pp. 398–404.

T. H. Büttgenbach, R. E. Miller, M. J. Wengler, D. M. Watson, and T. G. Phillips [1988], "A Broad-Band Low–Noise SIS Receiver for Submillimeter Astronomy". *IEEE Trans. Microwave Theory Tech.*, **36**, pp. 1720-1726.

T. H. Büttgenbach, H. G. LeDuc, P. D. Maker, and T. G. Phillips [1992], "A Fixed Tuned Broadband Matching Structure for Submillimeter SIS Receivers," *IEEE Trans. Appl. Supercond.*, **2**, pp. 165-175.

J. E. Carlstrom, R. L. Plambeck, and D. D. Thornton [1985], "A Continuously Tunable 65 – 115 GHz Gunn Oscillator," *IEEE Trans. Microwave Theory Tech.*, **33**, 7, pp. 610–619.

J. E. Carlstrom, R. E. Hills, O. P. Lay, T. G. Phillips, A. E. Schinckel, B. Force, and C. G. Hall [1994] ,"The CSO–JCMT Submillimeter Interferometer," in "Astronomy with Millimeter and Submillimeter Wave Interferometry," IAU Colloquium 140, eds. M. Ishigura and Wm. J. Welch, *ASP Conf. Series*, **59**, pp. 35–40.

R. A. Chamberlin [1995], "The 490.7 GHz South Pole Sky Opacity: Early Season 1995 Results," submitted to *Antarctic Journal of the U.S.*

J.–C. Chiao, A. Markelz, Y. Li, J. Hacker, T. Crowe, J. Allen, and D. Rutledge [1995], "Terahertz Grid Frequency Doublers," to appear in *Proc. Sixth Intl. Symp. Space Terahertz Tech.*, March 21-23, 1995, Caltech, Pasadena, CA.

G. Chin [1992], "Optically Pumped Submillimeter Laser Heterodyne Receivers: Astrophysical Observations and Recent Technical Developments," *Proc. IEEE*, **80**, pp. 1788-1799.

A. C. Clapp, M. J. Devlin, J. O. Gundersen, C. A. Hagmann, V. V. Hristov, A. E. Lange, M. Lim, P. M. Lubin, P. D. Mauskopf, P. R. Meinhold, P. L. Richards, G. G. Smoot, S. T. Tanaka, P. T. Timbie, and C. A. Wuensche [1994], "Measurements of Anisotropy in the Cosmic Microwave Background Radiation at Degree Angular Scales Near the Stars Sigma Herculis and Iota Draconis," *Ap. J. (Letters)*, **433**, pp. L57-L60.

T. W. Crowe, R. J. Mattauch, H. P. Röser, W. L. Bishop, W. C. B. Peatman, and X. L. Liu [1992], "GaAs Schottky Diodes for THz Mixing Applications," *Proc. IEEE*, **80**, pp. 1827–1841.

J. D. Crowley, C. Hang, R. E. Dalrymply, D. R. Tringali, F. B. Fank, L. Wandinger, and H. B. Wallace [1994], "140 GHz Indium Phosphide Gunn Diode," *Electronics, Lett.*, **30**, 6, pp. 499–500.

C. R. Cunningham, W. K. Gear, W. D. Duncan, P. R. Hastings, and W. S. Holland [1994], "SCUBA: The Submillimeter Common-User Bolometer Array for the James Clerk Maxwell Telescope" in *Instrumentation for Astronomy VIII*, SPIE, **2198**, pp. 638-649.

G. de Lange, C. E. Honingh, M. M. T. M. Dierichs, H. H. A. Schaeffer, R. A. Panhuyzen, T. M. Klapwijk, H. van de Stadt, and M. W. M. de Graauw [1994a], "Quantum Limited Responsivity of a $Nb/Al_2O_3/Nb$ SIS Waveguide Mixer at 460 GHz," *Physica B*, **194**, pp. 93-94.

G. de Lange, C. E. Honingh, J. J. Kuipers, H. H. A. Schaeffer, R. A. Panhuyzen, T. M. Klapwijk, H. Van de Stadt, M. M. W. M. de Graauw [1994b], "Heterodyne Mixing With Nb Tunnel Junctions Above the Gap Frequency" *Appl. Phys. Lett.* **64**, pp. 3039-3041.

G. de Lange, B. R. Jacobson, and Q. Hu [1995a], "Micromachined Millimeter-Wave SIS Mixers," *IEEE Trans. Appl. Supercond.*, **5**, pp. 1087-1090.

G. de Lange, B. R. Jacobson, A. Rahman, and Q. Hu [1995b], "Micromachined Millimeter-Wave SIS Mixers," to appear in *Proc. Sixth Intl. Symp. Space Terahertz Tech.*, March 21-23, 1995, Caltech, Pasadena, CA.

M. Devlin, A. E. Lange, T. Wilbanks, and S. Sato [1993], "A DC-Coupled, High Sensitivity Bolometric Detector System for the Infrared Telescope in Space," *IEEE Trans. Nucl. Sci.*, **40**, pp. 162-165.

M. M. T. M. Dierichs, C. E. Honingh, R. A. Panhuzen, B. J. Feenstra, A. Skalare, J. J. Wijnbergen, H. van de Stadt, and Th. de Graauw [1993], "Evaluation of Integrated Tuning Elements with SIS Devices," *IEEE Trans. Microwave Theory Tech.*, **41**, pp. 605-608.

K. H. G. Duh, S. M. J. Liu, S. C. Wang, M. Y. Kao, P. Ho, P. M. Smith, P. C. Chao, and M. W. Pospieszalski [1994], "InP HEMTS – Next Generation Millimeter–Wave Devices," *Proc. 1994 Asia-Microwave-Conference*, Tokyo, Japan, Dec 6 – 9, 1994, pp. 1053–1056.

H. Eisele and G. I. Haddad [1994], "D–Band InP Gunn Devices with Second–Harmonic Power Extraction up to 290 GHz," *Electronics Lett.*, **30**, 23, 1950–1951.

H. Eisele and G. I. Haddad [1995a], "GaAs TUNNETT Diodes on Diamond Heat Sinks for 100 GHz and Above," *IEEE Trans. Microwave Theory Tech.*, **43**, 1, pp 210–213.

H. Eisle and G. I. Haddad [1995b], "InP Gunn Devices and GaAs TUNNETT Diodes as Low–Noise High–Performance Local Oscillators in Fundamental Mode," to appear in *Proc. Sixth Intl. Symp. Space Terahertz Tech.*, March 21-23, 1995, Caltech, Pasadena, CA.

H. Ekström, B. Karasik, E. Kollberg, and K. S. Yngvesson [1995a], "Conversion Gain and Noise of Niobium Superconducting Hot-Electron Mixers," *IEEE Trans. Microwave Theory Tech.*, **43**, pp. 938-947.

H. Ekström, B. Karasik, E. Kollberg, G. Gol'tsman, and E. Gershenzon [1995b], "350 GHz NbN Hot-Electron Bolometer Mixer" to appear in *Proc. Sixth Intl. Symp. Space Terahertz Tech.*, March 21-23, 1995, Caltech, Pasadena, CA.

J. Ellder, L. Lundahl, and D. Morris [1984], "Test of Phase-Retrieval Holography on the Onsala 20m Radiotelescope," *Electronics Lett.*, **20**, pp. 709-710.

B. Ellison, M. L. Oldfield, D. N. Matheson, B. J. Maddison, C. M. Mann, and A. F. Smith [1994], "Corrugated Horns at Terahertz Frequencies – Preliminary Results," *Proc. Fifth Intl. Symp. Space Terahertz Tech.*, May 10-12, 1994, U. of Mich., Ann Arbor, MI, pp. 851-860.

G. Elgered [1993], in *Atmospheric Remote Sensing by Microwave Radiometry*, ed. Janssen, M. A., Wiley and Sons. pp. 215-258

D. T. Emerson and J. M. Payne (eds.) [1995], "Multi–feed Systems for Radio Telescopes," *ASP Conf. Series*, **75**, (San Francisco:ASP).

N. R. Erickson [1990], "High Efficiency Submillimeter Frequency Multipliers," in *1990 IEEE MTT-S Int. Microwave Symp. Dig.*, **3** , pp. 1301–1304.

N. R. Erickson [1992a], "Low-Noise Submillimeter Receivers Using Single-Diode Harmonic Mixers," *Proc. IEEE*, **80**, pp. 1721-1728.

N. R. Erickson, P. F. Goldsmith, G. Novak, R. M. Grosslein, P. J. Viscuso, R. B. Erickson, and C. R. Predmore [1992b], "A 15 Element Focal Plane Array for 100 GHz," *IEEE Trans. Microwave Theory Tech.*, **40**, 1, pp. 1–11.

N. R. Erickson, S. Weinreb and B. C. Kane [1994], "Cryogenic Performance of Monolithic Amplifiers for 85 – 115 GHz," *Proc. Fifth Intl. Symp. Space Terahertz Tech.*, May 10-12, 1994, U. of Mich., Ann Arbor, MI, pp. 309-315.

N. Erickson and J. Tuovinen [1995], "A Waveguide Tripler for 800–900 GHz," to appear in *Proc. Sixth Intl. Symp. Space Terahertz Tech.*, March 21-23, 1995, Caltech, Pasadena, CA.

N. R. Erickson [1995], "A Self–Biased Anti–Parallel Planar Varactor Diode," to appear in *Proc. Sixth Intl. Symp. Space Terahertz Tech.*, March 21-23, 1995, Caltech, Pasadena, CA.

P. Febvre, W. R. McGrath, P. Batelaan, B. Bumble, H. G. LeDuc, S. George, and P. Feautrier [1994], "A Low-Noise SIS Receiver Measured From 480 GHz to 650 GHz Using Nb Junctions With

Integrated RF Tuning Circuits," *Int. J. IR and MM Waves*, **15**, pp. 943-965.

P. Febvre, M. Salez, W. R. McGrath, B. Bumble, and H. G. LeDuc [1995], "Performance Limitations of Niobium-Based Submillimeter-Wave Quasiparticle Mixers Operating Near the Gap Frequency," *Appl. Phys. Lett.*, **67**, pp. 424-426.

D. F. Filipovic, S. S. Gearhart, and G. M. Rebeiz [1993], "Double-Slot Antennas on Extended Hemispherical and Elliptical Silicon Dielectric Lenses," *IEEE Trans. Microwave Theory Tech.* **41**, pp. 1738–1749.

W. Fuhr, J. Staguhn, A. Schulz, R. E. Hills, A. N. Lasenby, J. Lasenby, M. Miller, R. Schieder, J. Stuzki, et al. [1994], "Surface Adjustment of the KOSMA 3m Telescope Using Phase Retrieval Holography," *Astron. Astrophys.*, **274**, pp. 975–982.

M.C. Gaidis, M. Bin, D. Miller, J. Zmuidzinas, H.G. LeDuc, and J.A. Stern [1995a], "Design and Characterization of Two-Junction Tuning Circuits for SIS Mixers" to appear in *Proc. Sixth Intl. Symp. Space Terahertz Tech.*, March 21-23, 1995, Caltech, Pasadena, CA.

M.C. Gaidis, M. Bin, D. Miller, J. Zmuidzinas, H.G. LeDuc, and J.A. Stern [1995b], "Characterization of Quasi-Optical Twin-Slot Double-Junction Submillimeter SIS Mixers," to be presented at the *5th Intl. Superconductive Electronics Conference (ISEC '95)*, September 18-21, 1995, Nagoya, Japan.

E. Garcia, B. R. Jacobson, and Q. Hu [1993], "Fabrication of High-Quality Superconductor-Insulator-Superconductor Junctions on Thin SiN Membranes," *Appl. Phys. Lett.*, **63**, pp. 1002-1004.

S. S. Gearhart and G. M. Rebeiz [1994], "A Monolithic 250 GHz Schottky-Diode Receiver," *IEEE Trans. Microwave Theory Tech.*, **42**, pp. 2504-2511.

E. M. Gershenzon, G. N. Gol'tsman, I. G. Gogidze, Y. P. Gusev, A. I. Elant'ev, B. S. Karasik, and A. D. Semenov [1990], "Millimeter and Submillimeter Range Mixer based on Electronic Heating of Superconducting Films in the Resistive State," *Superconductivity*, **3**, pp. 1582-1597.

E. M. Gershenzon, G. N. Gol'tsman, B. S. Karasik, G. Ya. Lugova, N. A. Serebryakova, and E. V. Chinkova [1992], "IR Radiation Detectors Based on Electronic Heating of Films Made From Conventional Superconductors in the Resistive State," *Superconductivity*, **5**, pp. 1126-1137.

E. N. Glezer, A. E. Lange, and T. M. Wilbanks [1992], "Bolometric Detectors – Optimization for Differential Radiometers," *Appl. Opt.*, **31**, pp. 7214-7128.

P. F. Goldsmith [1992], "Quasi–Optical Techniques," *Proc. IEEE*, **80**, pp. 1729-1747.

A. Grüb, A. Simon, V. Krozer, and H. L. Hartnagel [1993], "Future Developments for Terahertz Schottky-Barrier Mixer Diodes," *Archiv für Electrotechnik*, **77**, pp. 57-59.

S. Guilloteau, J. Delannoy, D. Downes, A. Greve, M. Gué lin, R .Lucas, D. Morris, S. J. E. Radford, J. Wink, J. Cernicharo, T. Forveille, S. Garcia–Burillo, R. Neri, J. Blondel, A. Perrigouard, D. Plathner, and M. Torres [1992], "The IRAM Interferometer on Plateau de Bure," *Astron. Astrophys.*, **262**, pp. 624–633.

S. Guilloteau [1994], "The IRAM Interferometer on Plateau de Bure," in "Astronomy with Millimeter and Submillimeter Wave Interferometry," IAU Colloquium 140, eds. M. Ishigura and Wm. J. Welch, *ASP Conf. Series*, **59** pp. 27–34.

S. Han, B. Bi, W. Zhnag, and J. E. Lukens [1994], "Demonstration of Josphson Effect Submillimeter Wave Sources with Increased Power," *Appl. Phys. Lett.*,**64**, 11, pp. 1424 – 1426.

D. A. Harper, D. M. Cole, R. F. Loewenstein, T. McMahon, R. J. Pernic, and C. Wirth [1995], "The Yerkes Observatory 60-Channel Far Infrared Camera for the Kuiper Airborne Observatory," in *Proc. Airborne Astronomy Symp. on the Galactic Ecosystem: ¿From Gas to Stars to Dust*, ed.

M. R. Haas, J. A. Davidson, and E. F. Erickson (San Francisco:ASP), pp. 535.

R. Hayward [1993], "A Survey of Digital Correlation Spectrometers," in the proceedings of *Workshop on New Generation Digital Correlators,* February 25, 1993, NRAO, Tucson, Arizona, pp. 203–227.

J. Hernichel, R. Schieder, J. Stutzki, B. Vowinkel, G. Winnewisser, and P. Zimmermann [1992], "A 492 GHz Cooled Schottky Receiver for Radio Astronomy," *Proc. Third Intl. Symp. Space Terahertz Tech.*, March 24-26, 1992, U. Mich., Ann Arbor, MI, pp. 724-730.

J. L. Hesler, T. W. Crowe, R. M. Weikle, R. F. Bradley, S.-K. Pan, and G. Chattopadhyay [1995], "The Design, Construction, and Evaluation of a 585 GHz Planar Schottky Mixer," to appear in *Proc. Sixth Intl. Symp. Space Terahertz Tech.*, March 21-23, 1995, Caltech, Pasadena, CA.

P. T. P. Ho [1994], "The Smithsonian Submillimeter Array," IAU Colloquium 140, eds. M. Ishigura and Wm. J. Welch, *ASP Conf. Series*, **59**, pp. 384-391.

T. C. Ho, S. W. Chen, K. Pande, and P. Rice [1993], "A W-Band Integrated Power Module Using MMIC MESFET Power–Amplifiers and Varactor Doublers," *IEEE Trans. Microwave Theory Tech.*, **41**, 12, pp. 2288–2294.

T. C. Ho, S. Chen, S. Tadayon, K. Pande, P. Rice, and M. Ghahremani [1994], "A High-Performance W–Band Integrated Source Module using GaAs Monolithic Circuits," *IEEE Microwave and Guided Wave Lett.*, **4**, 7, pp. 241–243.

M. A. Holdaway and F. N. Owen [1995], "A Test of Fast Switching Phase Calibration with the VLA at 22 GHz," NRAO Millimeter Array Memo 126.

K. S. Hong, P. F. Marsh, G. I. Ng, D. Pavlidis, and C. H. Hong [1994], "Optimization of MOVPE Grown $In_xAl_{1-x}As/In_{0.53}Ga_{0.47}As$ Planar Heteroepitaxial Schottky Diodes for Terahertz Applications," *IEEE Trans. Electron Devices*, **41**, pp. 1489-1497.

C. E. Honingh, K. Jacobs, S. Haas, D. Hottgenroth, and J. Stutzki [1995], "Niobium SIS Mixers at 490 GHz, 690 GHz, and 810 GHz," *IEEE Trans. Appl. Supercond.* **5**, pp. 2216-2219.

Q. Hu, C. A. Mears, P. L. Richards, and F. L. Lloyd [1988], "Measurement of Integrated Tuning Elements for SIS Mixers with a Fourier Transform Spectrometer," *Int. J. IR and MM Waves*, **9**, pp. 303-320.

Q. Hu, C. A. Mears, P. L. Richards, and F. L. Lloyd [1989], "MM-Wave Quasioptical SIS Mixers," *IEEE Trans. Magn.*, **25**, pp. 1380-1383.

K. Jacobs, U. Müller, U. Schwenk, D. Diehl, C. E. Honingh, and S. Haas [1994], "SIS Receivers with Large Instantaneous Bandwidths for Radio Astronomy," *Proc. Fifth Intl. Symp. Space Terahertz Tech.*, May 10-12, 1994, U. of Mich., Ann Arbor, MI, pp. 60-72.

A. Karpov, J. Blondel, M. Voss, and K. H. Gundlach [1995a], "Four Photons Sensitivity Heterodyne Detection of Submillimeter Radiation with Superconducting Tunnel Junctions," *IEEE Trans. Appl. Supercond.* **5**, pp. 3304-3307.

A. Karpov, B. Plathner, K. H. Gundlach, M. Aoyagi, and S. Takada [1995b], "Noise Properties of a Mixer with SIS NbN Quasiparticle Tunnel Junctions," to appear in *Proc. Sixth Intl. Symp. Space Terahertz Tech.*, March 21-23, 1995, Caltech, Pasadena, CA.

J. Kawamura, R. Blundell, C.-Y. E. Tong, G. Gol'tsman, E. Gershenzon, and B. Voronov [1995] "NbN Hot-Electron Mixer Measurements at 200 GHz" to appear in *Proc. Sixth Intl. Symp. Space Terahertz Tech.*, March 21-23, 1995, Caltech, Pasadena, CA.

A. R. Kerr, S.-K. Pan, A. W. Lichtenberger, and D. M. Lea [1992], "Progress on Tunerless SIS Mixers for the 200-300 GHz Band," *IEEE Microwave and Guided Wave Lett.*, **2**, pp. 454-456.

A. R. Kerr, S.-K. Pan, A. W. Lichtenberger, F. L. Lloyd, and N. Horner [1993], "A New SIS Mixer for the 2-mm Band," *Proc. Fourth Intl. Symp. Space Terahertz Tech.*, March 30-April 1, 1993, UCLA, Los Angeles, CA, pp. 1-10.

A. R. Kerr [1995], "Some Fundamental and Practical Limitations on Broad-Band Matching to Capacitive Devices, and the Implications for SIS Mixer Design," *IEEE Trans. Microwave Theory Tech.*, **43**, pp. 2-13.

S. Kohjiro, S. Kiryu, and A. Shoji [1993], "Surface Resistance of Epitaxial and Polycrystalline NbCN Films in the Submillimeter Wave Region," *IEEE Trans. Appl. Supercond.*, **3**, pp. 1765-1767.

E. Kollberg and A. Rydberg [1989], "Quantum–Barrier–Varactor Diodes for High–Efficiency Millimeter–Wave Multipliers," *Electron. Lett.*, **25**, pp. 1696–1697.

J. W. Kooi, C. K. Walker, H. G. LeDuc, P. L. Schaffer, T. R. Hunter, D. J. Benford, and T. G. Phillips [1994a], "A Low-Noise 665 GHz SIS Quasiparticle Waveguide Receiver," *Int. J. IR and MM Waves*, **15**, pp. 477-492.

J. W. Kooi, M. S. Chan, B. Bumble, H. G. LeDuc, P. L. Schaffer, and T. G. Phillips [1994b], "180-425 GHz Low-Noise SIS Waveguide Receivers Employing Tuned Nb/Al-Ox/Nb Tunnel Junctions," *Int. J. IR and MM Waves*, **15**, pp. 783-805.

J. W. Kooi, M. S. Chan, M. Bin, B. Bumble, and H. G. LeDuc [1995a], "The Development of an 850 GHz Waveguide Receiver Using Tuned SIS Junctions on 1 μm Si_3N_4 Membranes," *Int. J. IR and MM Waves*, **16**, pp. 349-362.

J. W. Kooi [1995b], private communication.

E. Kreysa, E. E. Haller, H.-P. Gemünd, C. G. T. Haslam, R. Lemke, and A. W. Sievers [1993], "First Results From a Small Bolometer Array on the IRAM 30-m Telescope at 250 GHz," *Proc. Fourth Intl. Symp. Space Terahertz Tech.*, March 30-April 1, 1993, UCLA, Los Angeles, CA, pp. 692-697.

N. Kuno, H. Matsuo, Y. Mizumoto, A. E. Lange, J. W. Beeman, and E. E. Haller [1993], "Seven Matched Bolometers for Millimeter Wave Observations," *Intl. J. IR and MM Waves*, **14**, pp. 749-762.

Y. W. Kwon, D. Pavlidis, T. L. Brock, and D. C. Streit [1993], "A D–Band Monolithic Fundamental Oscillator Using InP-Based HEMTS," *IEEE Trans. Microwave Theory Tech.*, **41**, 12, pp 2336–2344.

Y. W. Kwon, D. Pavlidis, P. Marsh, T. Brock, and D. C. Streit [1994], "A 100–GHz Monolithic Cascode InAlAs InGaAs HEMT Oscillator," *IEEE Microwave and Guided Wave Lett.*, **4**, 5, pp. 135–137.

V. P. Koshelets, A. V. Shchukin, S. V. Shitov, L. V. Filippenko, G. M. Fischer, and J. Mygind [1994], "Integrated Flux-flow Oscillators For Submillimeter-wave Receivers," *Physica B*, **3**, pp. 81-82.

V. P. Koshelets, S. V. Shitov, A. M. Baryshev, I. L. Lapitskaya, L. V. Filippenko, J. van de Stadt, J. Mees. H. Schaeffer, and T. de Graauw [1995], "Integrated Sub–MM Wave Receivers," *IEEE Trans. App. Supercond.*, **5**, 2. pp. 3057–3060.

A. E. Lange, M. M. Freund, S. Sato, T. Hirao, T. Matsumoto, and T. Watabe [1994], "The Far-Infrared Photometer on the Infrared Telescope in Space," *Ap. J.*, **428**, pp. 384-392.

O. P. Lay, R. E. Hills, R. E., and J. E. Carlstrom [1994a], "IF Fiber Optics and and Digital Correlating Spectrometer on the JCMT–CSO Interferometer," in "Astronomy with Millimeter and Submillimeter Wave Interferometry," IAU Colloquium 140, eds. M. Ishigura and Wm. J. Welch, *ASP Conf. Series*, **59**, pp. 117–118.

O. P. Lay, J. E. Carlstrom, R. E. Hills, and T. G. Phillips [1994b], "Protostellar Accretion Disks Resolved with the JCMT–CSO Interferometer," *Astrophys. J. Lett.* **434**, 2, pp. L75–L78.

H. G. LeDuc, A. Judas, S. R. Cypher, B. Bumble, B. D. Hunt, and J. A. Stern [1991], "Submicron-

Area NbN/MgO/NbN Tunnel Junctions for SIS Mixer Applications," *IEEE Trans. Magn.*, **27**, pp. 3192-3195.

V. M. Lubecke, W. R. McGrath, and D. B. Rutledge [1994], "A Micromechanical Tuning Element for a 620 GHz Integrated Circuit," in *Dig. 19th Intl. Conf. on IR and MM Waves*, October 17-20, 1994, Sendai, Japan.

J. Lukens [1990], "Josephson Arrays as High Frequency Sources," in "Superconducting Devices," eds. S. T. Ruggiero and D. A. Rudman, Academic Press, San Diego, pp. 135–167.

J. T. Louhi, A. V. Räisäsen and N. R. Erickson [1993], "Cooled Schottky Varactor Frequency Multipliers at Submillimeter Wavelengths," *IEEE Trans. Microwave Theory Tech.*, **41**, 4, pp. 565–571.

B. Maffei, F. Pajot, T. G. Phillips, D. Benford, E. Caux, R. Gispert, N. Halverson, T. Hunter, G. Jegoudez, M. Josse, J. M. Lamarre, J. P. Lepeltier, H. Moseley, A. Origné, S. Petuchowsky, M. Rabottin, J. C. Renault, C. Rioux, G. Serabyn, and N. Wang [1994], "A Medium Resolution Ground Based Submillimeter Spectrometer," *Infrared Phys. Tech.*, **35**, pp. 321-329.

J. S. Martens, A. Pance, K. Char, L. Lee, S. Whiteley, and V. M. Hietala [1993] "Superconducting Josephson Arrays as Tunable Microwave Sources Operating at 77-K," *Appl. Phys. Lett.*, **63**, 12, pp. 1681-1683.

C. R. Masson [1994], "Atmospheric Effects and Calibrations," in "Astronomy with Millimeter and Submillimeter Wave Interferometry," IAU Colloquium 140, eds. M. Ishigura and Wm. J. Welch, *ASP Conf. Series*, **59** pp. 87–95.

W. R. McGrath, J. A. Stern, H. H. S. Javadi, S. R. Cypher, B. D. Hunt, and H. G. LeDuc [1991], "Performance of NbN Superconductive Tunnel Junctions as SIS Mixers at 205 GHz," *IEEE Trans. Magn.*, **27**, pp. 2650-2653.

W. R. McGrath, C. Walker, M. Yap, and Y.-C. Tai [1993], "Silicon Micromachined Waveguides for Millimeter-Wave and Submillimeter-Wave Frequencies," *IEEE Microwave and Guided Wave Lett.*, **3**, pp. 61-63.

W. R. McGrath [1995], "Hot-Electron Bolometer Mixers for Submillimeter Wavelengths: an Overview," to appear in *Proc. Sixth Intl. Symp. Space Terahertz Tech.*, March 21-23, 1995, Caltech, Pasadena, CA.

R. Monaco [1990], "Josephson Millimeter Wave Oscillators," *Int. J. Infrared and Millimeter and Waves*, **11**, 4, pp. 533–564.

J. M. Moran and B. R. Rosen, B. R. [1981], "Estimation of the Propagation Delay through the Troposphere from Microwave Radiometer Data", *Radio Science*, **16**, 2, pp. 235–244

J. Moran [1994], "The SAO Submillimeter Wavelength Array," *IAU Symposia*, **158**, pp. 27–35.

K.–I. Morita [1994], "The Nobeyama Millimeter Array," in "Astronomy with Millimeter and Submillimeter Wave Interferometry," IAU Colloquium 140, eds. M. Ishigura and Wm. J. Welch, *ASP Conf. Series*, **59** pp. 18–26.

S. H. Moseley, J. C. Mather, and D. C. McCammon [1984], "Thermal Detectors as X-Ray Spectrometers," *J. Appl. Phys.*, **56**, pp. 1257-1262.

B. Moslehi [1994], "Fiber–Optic Delay Line Signal Processing Architectures," in "Photonic Aspects of Modern Radar," eds. H. Zmuda and E. N. Toughlian, Artech House, Boston, chapter 17, pp. 459–522.

M. Nahum, P. L. Richards, and C. A. Mears [1993], "Design Analysis of a Novel Hot-Electron Microbolometer," *IEEE Trans. Appl. Supercond.*, **3**, pp. 2124-2127.

M. Nahum and J. M. Martinis [1993], "Ultrasensitive Hot-Electron Microbolometer," *Appl. Phys. Lett.*, **63**, pp. 3075-3077.

D. A. Naylor, T. A. Clark, A. A. Schultz, and G. R. Davis-GR [1991], "Atmospheric Transmission at Submillimeter Wavelengths from Mauna Kea," *MNRAS* , **251**, 2, pp. 199–202.

D. A. Naylor, T. A. Clark, and G. R. Davis [1994], "A Polarizing Fourier-Transform Spectrometer for Astronomical Spectroscopy at Submillimeter and Mid-Infrared Wavelengths," in *Instrumentation for Astronomy VIII*, SPIE, **2198**, pp. 703-714.

T. Newman, W. L. Bishop, K. T. Ng, and S. Weinreb [1991], "A Novel Planar Diode Mixer for Submillimeter-wave Applications," *IEEE Trans. Microwave Theory Tech.*, **39**, 12, pp. 1964–1971.

S. M. Nilsen, H. Grönqvist, H. Hjelmgren, A. Rydberg, and E. L. Kollberg [1993], "Single Barrier Varactors For Submillimeter-wave Power-generation," *IEEE Trans. Microwave Theory Tech.T*, **41**, 4, pp. 572–580.

T. Noguchi, S. C. Shi, and J. Inatani [1995], "Parallel Connected Twin SIS Junctions for Millimeter and Submillimeter-Wave Mixers - Analysis and Experimental Verification," *IEICE Trans. Elect.*, **E78C**, pp. 481-489.

O. Okunev, A. Dzardranov, G. Gol'tsman, and E. Gershenzon [1995], "Performance of a Hot-Electron Superconducting Mixer for Frequencies Less than the Gap Energy: NbN Mixer for 100 GHz Operation," to appear in *Proc. Sixth Intl. Symp. Space Terahertz Tech.*, March 21-23, 1995, Caltech, Pasadena, CA.

S. Padin [1989], "Scheme for Phase–Locking a Local Oscillator in Submillimeter–Wave Receiver," *Electronics Lett.*, **25**, 13. pp. 874–875.

S. Padin [1994], "A Wide–Band Analog Continuum Correlator for Radio Astronomy," *IEEE Trans, Inst and Meas.*, **43**, 6, pp. 782–785.

S. Padin, D. P. Woody, J. A. Stern, H. C. LeDuc, R. Blundell, C. Y. E. Tong, and M. W. Pospieszalski [1995], "An Integrated SIS Mixer and HEMT IF Amplifier," to appear in *Proc. Sixth Intl. Symp. Space Terahertz Tech.*, March 21-23, 1995, Caltech, Pasadena, CA.

J. M. Payne, J. W. Lamb, J. G. Cochran, and N. Bailey [1994], "A New Generation of SIS Receivers for Millimeter-Wave Radio Astronomy," *Proc. IEEE*, **82**, pp. 811-823.

T. G. Phillips [1988], 'Techniques of Submillimeter Astronomy," in "Millimetre and Submillimetre Astronomy," eds. R. D. Wolstencroft and W. B. Burton, Kluwer Academic Publishers, pp. 1-26.

S. R. Platt, R. H. Hildebrand, R. J. Pernic, J. A. Davidson, and G. Novak [1991], "100-μm Array Polarimetry from the Kuiper Airborne Observatory: Instrumentation, Techniques, and First Results," *Pub. Astron. Soc. Pac.*, **103**, pp. 1193-1210.

R. Plume and D. T. Jaffe [1995], "The World's Smallest 10-meter Submillimeter Telescope," *Pub. Astron. Soc. Pac.*, **107**, 711, pp. 488–495.

M. W. Pospieszalski [1993], "Ultra–Low–Noise Receivers for the 1 to 120 GHz Frequency Range," *Proc. of 23rd European Microwave Conf.*, Madrid, Spain, September 1993, pp. 73–79.

M. W. Pospieszalski, L.D. Nguyen, M. Lui, T. Lui, M.A. Thompson, and M. J. Delaney [1994], "Very Low Noise and Low Power Operation of Cryogenic AlInAs/GaInAs/InP HFET's," *Proc. 1994 IEEE MTT-S Int. Microwave Symp.*, San Dieo, CA. pp. 1345–1346.

M. W. Pospieszalski, W. J. Lakatosh, L. D. Nguyen, M. Lui, T. Liu, M. Le, M. A. Thompson, and M. J. Delaney [1995], "Q– and E–Band Cryogenically–Coolable Amplifiers Using AlInAs/GaInAs/InP HEMT's," *IEEE MTT-S Int. Microwave Symp.*, May 1995, pp 1121–1124.

D. E. Prober [1993], "Superconducting Terahertz Mixer Using a Transition-Edge Microbolometer," *Appl. Phys. Lett.*, **62**, pp. 2119-2121.

A. V. Räisänen [1992] "Frequency Multipliers for Millimeter and Submillimeter Wavelengths," *Proc. IEEE*, **80**, 11, pp. 1842–1852.

P. L. Richards [1994], "Bolometers for Infrared and Millimeter Waves," *J. Appl. Phys.*, **76**, pp. 1-24.

B. J. Rizzi, T. W. Crowe, and N. R. Erickson [1993], "A High Power Millimeter–Wave Frequency Doubler Using a Planar Diode Array," *IEEE Microwave and Guided Wave Lett.*, **3**, 6, pp. 188–190.

A. E. E. Rogers [1993] "Advances in VLBI Techniques," in *Review of Radio Science 1990–1992*, ed. W. Ross Stone, Oxford Science Pub., pp. 657-676.

A. E. E. Rogers, S. Doeleman, M. C. H. Wright, G. C. Bower, D. C. Backer, S. Padin, J. A. Phillips, D. T. Emerson, L. Greenhill, J. M. Moran, and K. I. Kellerman [1994], "Small–Scale Structure and Position of Sagittarius A* at the Galactic Center," *Astrophys. J. Lett.*, **434**, 2, L59–L62.

S. E. Rosenbaum, B. K. Kormanyos, L. M. Jelloian, M. Matloubian, A. S. Brown, L. E. Larson, L. D. Nguyen, M. A. Thompson, L. P. D. Katehi, and G. M. Rebeiz [1995], "155–GHz and 213-GHz AlInAs/GaInAs/InP HEMT MMIC Oscillators," *IEEE Trans. Microwave Theory Tech.*, **43**, 4, pp. 927–932.

H. P. Röser, H. W. Hubers, T. W. Crowe, and W. C. B. Peatman [1994], "Nanostructure GaAs Schottky Diodes for Far-Infrared Heterodyne Receivers," *Infrared Physics and Technology*, **35**, pp. 451-462.

H. Rothermel, K. H. Gundlach, and M. Voss [1994], "A 350 to 700 GHz Open Structure SIS Receiver for Submillimeter Astronomy" *Journal de Physique IV*, **4**, pp. C6-267 - C6-272.

A. Rydberg [1990],"High Efficiency and Output Power from Second– and Third– Harmonic Millimeter Wave InP–TED Oscillator at Frequencies above 170 GHz," *IEEE Electron Device Lett.*, **11**, 10, pp. 439–441.

A. Rydberg, H. Grönqvist, and E. Kollberg [1990], "Millimeter– and Submillimeter–Wave Multipliers Using Quantum–Barrier–Varactor (QBV) Diodes," *IEEE Electron Device Lett.*, **11**, pp. 373–375.

A. Rydberg, B. N. Lyons and S. U. Lidholm, [1992] "On the Development of a High Efficiency 750 GHz Frequency Tripler for THz Heterodyne Systems," *IEEE Trans. Microwave Theory Tech.*, **40**, 5, pp. 827–830.

S. Sakamoto, M. Hayashi, T. Hasegaw, T. Handa, and T. Oka [1994], "A Large–Area CO (J=2-1) Mapping of the Giant Molecular Clouds in Orion," *Astrophys. J.*, **425**, 2, pp. 641–652.

G. Salmer, P. A. Rolland, and D. Lippens [1993], "New Trends in High–Speed and Microwave III–V Devices," in *Review of Radio Science 1990–1992*, ed. W. Ross Stone, Oxford Science Pub., pp. 209–230.

A. I. Sargent and Wm. J. Welch [1993], "Millimeter and Submillimeter Interferometry of Astronomical Sources," *Ann. Revs. Astro. Astrophys.*, **31**, pp. 297–343.

D. A. Schleuning, C. Darren Dowell, and S. R. Platt [1996] "Array Polarimetry of the Orion Nebula from the Caltech Submillimeter Observatory," to appear in *Polarimetry of the Interstellar Medium*, ed. W. G. Roberge and D. C. B. Whittet (San Francisco: ASP).

F. P. Schloerb [1995], "The Large Millimeter Telescope", in *IAU Symp. 170*, "CO: 25 Years of Millimeterwave Spectroscopy," Kluwer, to be published.

K. F. Schuster, A. I. Harris, and K. H. Gundlach [1993], "A 691 GHz SIS Receiver for Radio Astronomy" *Int. J. IR and MM Waves* **14**, pp. 1867-1887.

N. Scoville, J. E. Carlstrom, S. Padin, A. Sargent, S. L. Scott, and D. P. Woody [1994],"The Owens

Valley Millimeter Array," in "Astronomy with Millimeter and Submillimeter Wave Interferometry," IAU Colloquium 140, eds. M. Ishigura and Wm. J. Welch, *ASP Conf. Series*, **59** pp. 10–17.

P. F. Scott and M. Ryle [1977], "A Rapid Method for Measuring the Figure of a Radio Telescope Reflector," *MNRAS*, **178**, pp. 539–545.

E. Serabyn, T. G. Phillips, and C. R. Masson [1991], "Surface Figure Measurements of Radio Telescopes with a Shearing Interferometer," *Applied Optics*, **30**, 10, pp. 1227–1241.

E. Serabyn and E. Weisstein [1995], " Fourier Transform Spectroscopy of the Orion Molecular Cloud Core," *Astrophys. J.*, submitted.

E. Serabyn [1995], "Astronomical, Atmospheric, and Wavefront Studies with a Submillimeter Wavelength Interferometer," in *Amazing Light: a Volume Dedicated to Charles H. Townes on his 80th Birthday*, ed. R.Y. Chiao, AIP, Springer–Verlag.

A. K. Sharma, G.P. Onak, R. Lai, and K. L. Tan [1994], "A V–Band High–Efficiency Pseudomorphic HEMT Monolithic Power–Amplifier," *IEEE Trans. Microwave Theory Tech.*, **42**, 12, pp. 2603–2609.

A. Skalare, M. M. T. M. Dierichs, J. Mees, H. van de Stadt, R. A. Panhuyzen, Th. de Graauw, and T. M. Klapwijk [1993], "SIS Mixers Using Endfire and Broadside Double Dipole Antennas at 435 and 480 GHz," *Proc. Fourth Intl. Symp. Space Terahertz Tech.*, March 30-April 1, 1993, UCLA, Los Angeles, CA, pp. 639-651.

A. Skalare, W. R. McGrath, B. Bumble, H. G. LeDuc, P. J. Burke, A. A. Verheijen, and D. E. Prober [1995], "A Heterodyne Receiver at 533 GHz Using a Diffusion-Cooled Superconducting Hot Electron Bolometer Mixer" *IEEE Trans. Appl. Supercond.* **5**, pp. 2236-2239.

P. M. Smith, S. M. J. Liu, M. Y. Kao, P. Ho, S. C. Wang, K. H. G. Duh, S. T. Fu, and P. C. Chao, [1995], "W–Band High-Efficiency InP–Based Power HEMT with 600 GHz $f_{\max}$," *IEEE Microwave and Guided Wave Lett.*, **5**, 7. pp. 230–232.

S. Soares and S. Padin [1994], "A Wide–Band Tracking Delay for Radio Astronomy," *IEEE Trans. Microwave Theory Tech.*, **42**, 6. pp. 951–955.

A. A. Stark [1995], "Installation of the Antartic Sub–mm Telescope and Remote Observatory (AST/RO)," to appear in *Proc. Sixth Intl. Symp. Space Terahertz Tech.*, March 21-23, 1995, Caltech, Pasadena, CA.

S. T. Tanaka, A. Clapp, M. Devlin, M. Fischer, C. Hagmann, A. E. Lange, and P. L. Richards [1993], "A 100 mK Bolometric Receiver for Low Background Astronomy," *SPIE Proc. Infrared Detectors and Instrumentation*, **1946**, pp. 110.

A. Tang and P. L. Richards [1995], "Quantum Effects in the Hot Electron Microbolometer," *IEEE Trans. Appl. Supercond.*, **5**, pp. 2599-2603.

V. I. Tatarskii [1961], *Wave Propagation in a Turbulent Medium*, Dover: New York.

V. I. Tatarskii [1971], *The Effects of the Turbulent Atmosphere on Wave Propagation*, Israel Program for Scientific Translations: Jerusalem.

A. R. Thompson, J. M. Moran, and G. Swenson [1986], *Interferometry and Synthesis in Radio Astronomy*, Wiley-Interscience.

T. J. Tolmunen and M. A. Frerking [1991], "Theoretical Performance of Novel Multipliers at Millimeter and Submillimeter Wavelengths," *Int. J. Infrared and Millimeter Waves*, **12**, 10, pp. 1111–1133.

C.-Y. E. Tong, R. Blundell, D. C. Papa, J. W. Barnett, S. Paine, X. Zhang, J. A. Stern, and H. G. LeDuc [1995a], "A Fixed Tuned Low Noise SIS Receiver for the 600 GHz Frequency Band," to appear in *Proc. Sixth Intl. Symp. Space Terahertz Tech.*, March 21-23, 1995, Caltech, Pasadena, CA.

C.-Y. E. Tong, R. Blundell, B. Bumble, J. A. Stern, and H. G. LeDuc [1995b], "Quantum-Limited Heterodyne Detection in Superconducting Nonlinear Transmission Lines at Submillimeter Wavelengths," *Appl. Phys. Lett.*, **66**, in press.

R. N. Treuhaft and G. E. Lanyi [1987], "The Effect of the Dynamic Wet Troposphere on Radio Interferometric Measurements", *Radio Science*, **22**, 2, pp. 251–265.

J. R. Tucker and M. J. Feldman [1985], "Quantum Detection at Millimeter Wavelengths," *Rev. Mod. Phys*, **57**, pp. 1055-1113.

J. Tuovinen amd N. R. Erickson [1995], "Analysis of a 170–GHz Frequency Doubler with an Array of Planar Diodes," *IEEE Trans. Microwave Theory Tech.*, **43**, pp. 962-968.

N. Ukita and M. Tsuboi [1994],"A 45-m Telescope with a Surface Accuracy of 65 μm," *Proc. IEEE*, **82**, 5, pp. 725–733.

Y. Uzawa, Z. Wang, A. Kawakami, and B. Komiyama [1995], "Submillimeter-Wave Responses in NbN/AlN/NbN Tunnel Junctions," *Appl. Phys. Lett.*, **66**, pp. 1992-1994.

H. van de Stadt, A. Baryshev, P. Dieleman, Th. de Graauw, T. M. Klapwijk, S. Kovtonyuk, G. de Lange, I. Lapitskaya, J. Mees, R. Panhuyzen, G. Pokopenko, and H. Schaeffer [1995a], "A 1 THz Nb SIS Heterodyne Mixer With Normal Metal Tuning Structures," to appear in *Proc. Sixth Intl. Symp. Space Terahertz Tech.*, March 21-23, 1995, Caltech, Pasadena, CA.

H. van de Stadt et al. [1995b], "Nb and NbN SIS Junctions in Mixers up to 1.06 THz," presented at *Third Intl. Workshop on Terahertz Electronics*, August 31 - September 1, 1995, Zermatt, Switzerland.

K. Wan, A. K. Jain, and J. E. Lukens [1989], "Submillimeter Wave Generation Using Josephson Junction Arrays," *Appl. Phys. Lett.*, **54**, pp. 1805-1807.

H. Wang [1993], T. N. Ton, K. L. Tan, D. Garske, G. S. Dow, J. Berenz, M. W. Pospieszalski and S. –K. Pan, "110 – 120 GHz Monolithic Low–Noise Amplifiers," *IEEE J. of Solid–State Circuits*, **28**, pp. 988-993.

H. Wang, R. Lai, D. C. W. Lo, D. C. Streit, P. H. Liu, R. M. Dia, M. W. Pospieszalski, and J. Berenz [1995a], "A 140-GHz Monolithic Low–Noise Amplifier," *IEEE Microwave and Guided Wave Lett.*, **5**, 5, pp. 150–152.

H. Wang, K. W. Chang, D. Smith, G. S. Dow, K. L. Tan, A. K. Oki, and B. R. Allen [1995b], "A W–Band Source Module using MMICS," *IEEE Trans. Microwave Theory Tech.*, **43**, 5, pp. 1010–1016.

N. Wang, T. R. Hunter, D. J. Benford, E. Serabyn, T. G. Phillips, and S. H. Moseley [1994], "A Monolithic Si Bolometer Array for the Caltech Submillimeter Observatory," in *Instrumentation for Astronomy VIII*, SPIE, **2198**, pp. 749-756.

Z. Wang, A. Kawakami, Y. Uzawa, and B. Komiyama [1994], "High Critical-Current Density NbN/AlN/NbN Tunnel Junctions Fabricated on Ambient-Temperature MgO Substrates," *Appl. Phys. Lett.*, **64**, pp. 2034-2036.

J. W. Waters [1992], "Submillimeter-Wavelength Heterodyne Spectroscopy and Remote Sensing of the Upper Atmosphere," *Proc. IEEE*, **80**, pp. 1679-1701.

E. W. Weisstein and E. Serabyn [1994], "Detection of the 267 GHz J=1-0 Rotational Transition of PH_3 in Saturn with a New Fourier Transform Spectrometer," *Icarus*, **109**, pp. 367-381.

Wm. J. Welch [1994], "The Berkeley-Illinois-Maryland Array", in "Astronomy with Millimeter and Submillimeter Wave Interferometry," IAU Colloquium 140, eds. M. Ishigura and Wm. J. Welch, *ASP Conf. Series*, **59** pp. 1–9.

Wm. J. Welch, D. D. Thornton, R. L. Plambeck, M. C. H. Wright, J. Lugten, L. Urry, M. Fleming, W. Hoffman, J. Hudson, W. T. Lum, J. R. Forster, N. Thatte, X. Zhang, S. Zivanovic, L. Snyder, R. Crutcher, K. Y. Lo, B. Wakker, M. Stupar, R. Sault, Y. Miao, S. Rao, K. Wan, L. Dicker, L.Blitz, S. N. Vogel, L. Mundy, W. Erickson, P. J. Tueben, J. Morgan, T. Helfer, L. Looney, E. de Geus, A. Grossman, J. E. Howe, M. Pound, and M. Regan [1995], "The Berkeley–Illinois–Maryland–Association Millimeter Array," *Pub. Astron. Soc. Pac.*, **108**, pp. 93–103.

M. Wengler, D. P. Woody, R. E. Miller, and T. G. Phillips [1985], "A Low Noise Receiver for Millimeter and Submillimeter Wavelengths," *Int. J. IR and MM Waves* **6**, pp. 697-706.

M. J. Wengler [1992], "Submillimeter-Wave Detection with Superconducting Tunnel Diodes," *Proc. IEEE*, **80**, pp. 1810-1826.

M. J. Wengler, B. Guan, and E. Track [1995], "190 GHz Radiation from a Quasi-Optical Josephson-Junction Array," *IEEE Trans. Microwave Theory Tech.*, **43**, pp 984-988.

T. M. Wilbanks, P. A. R. Ade, M. L. Fischer, W. L. Holzapfel, and A. E. Lange [1994], "Measurement of the Sunyaev-Zel'dovich Effect Toward Abell 2163 at a Wavelength of 2.2 Millimeters," *Ap. J.*, **427**, pp. L75-L78.

S. Withington, K. G. Isaak. S. A. Kovtonyuk, and R. A. Panhuyzen [1994], "A Horn-Reflector SIS Mixer for 450–500 GHz," *Proc. Cologne Workshop on SIS Mixers*, September 1994, Cologne, Germany.

J. A. Wright, S. Tatic-Lucic, Y.-C. Tai, W. R. McGrath, B. Bumble, and H. LeDuc [1995], "Integrated Silicon Micromachined Wavguide Circuits for Submillimeter Wave Applications," to appear in *Proc. Sixth Intl. Symp. Space Terahertz Tech.*, March 21-23, 1995, Caltech, Pasadena, CA.

J.-X. Yang, F. Agahi, D. Dai, C. F. Musante, W. Grammer, K. M. Lau, and K. S. Yngvesson [1993], "Wide-Bandwidth Electron Bolometric Mixers: a 2DEG Prototype and Potential for Low-Noise THz Receivers," *IEEE Trans. Microwave Theory Tech.*, **41**, pp. 581-589.

J.-X. Yang, J. Li, C. F. Musante, and K. S. Yngvesson [1995] "Microwave Mixing and Noise in the 2-Dimensional Electron Gas Medium at Low Temperatures," *Appl. Phys. Lett.*, **66**, pp. 1983-1985.

Y. M. Zhang, D. Winkler, and T. Claeson [1993], "Linewidth Measurements of Josephson Flux-Flow Oscillators in the Band 280-330 GHz," *Appl Phys. Lett.*, **62**, 24, pp.3195–3197.

R. Zimmermann, T. Rose, T. W. Crowe and T. W. Grein [1995], "An all Solid–State 1 THz Radimoeter for Space Applications," to appear in *Proc. Sixth Intl. Symp. Space Terahertz Tech.*, March 21-23, 1995, Caltech, Pasadena, CA.

J. Zmuidzinas and H. G. LeDuc [1992], "Quasi-Optical Slot Antenna SIS Mixers," *IEEE Trans. Microwave Theory Tech.*, **40**, pp. 1797-1804.

J. Zmuidzinas, H. G. LeDuc, J. A. Stern, and S. R. Cypher [1994], "Two-Junction Tuning Circuits for Submillimeter SIS Mixers" *IEEE Trans. Microwave Theory Tech.*, **42**, pp. 698-706.

J. Zmuidzinas, N. G. Ugras, D. Miller, M. Gaidis, H. G. LeDuc, and J. A. Stern [1995a], "Low-Noise Slot Antenna SIS Mixers" *IEEE Trans. Appl. Supercond.* **5**, pp. 3053-3056.

J. Zmuidzinas, M. Bin, A. Clapp, M. Gaidis, D. Miller, and J. Ward [1995b], "Quasioptical SIS Mixers in Submillimeter Astronomy," in *Extended Abstracts of the 5th Intl. Superconductive Electronics Conference (ISEC '95)*, September 18-21, 1995, Nagoya, Japan.

M.F. Zybura, S.H. Jones, J.E. Carlstrom, J.D. Crowley [1995], "D Band Transferred Electron Oscillators," to appear in *Proc. Sixth Intl. Symp. Space Terahertz Tech.*, March 21-23, 1995, Caltech, Pasadena, CA.

M.F. Zybura, S.H. Jones, B. Lim, J.E. Carlstrom, and J.D. Crowley [1995] "125-140 GHz Transferred

Electron Oscillators," Submitted to *Solid State Electronics*.

Figure Captions

Figure 1. Model of the zenith atmospheric transmission on Mauna Kea at an altitude of 4200 m for the case of 1 mm of precipitable H_2O [from Serabyn 1995].

Figure 2. The ratio of double-sideband (DSB) receiver noise temperature to frequency $T_{\rm rec}/\nu$ is plotted. The dashed line represents a *single-sideband* noise temperature of $5h\nu/k_{\rm B}$, i.e. 5 times the quantum limit. All data are uncorrected for optical losses. Receivers are SIS waveguide unless otherwise indicated; QO represents quasioptical SIS. The data are from: Be - [Belisky et al. 1995b] (QO); Bi - [Bin et al. 1995] (quasioptical Al-wiring SIS); Bl - [Blundell et al. 1995a, b]; Bz - [Betz and Boreiko 1995] (corner-reflector Schottky); Bu - [Büttgenbach et al. 1992] (QO); dL - [de Lange et al. 1994a, b]; Fe - [Febvre et al. 1994, 1995]; Ga - [Gaidis et al. 1995a, b] (QO); He - [Hernichel et al. 1992] (waveguide Schottky); Ho - [Honingh et al. 1995]; Ja - [Jacobs et al. 1994]; Ka - [Karpov et al. 1995a]; Ke - [Kerr et al. 1993]; Ko - [Kooi et al. 1994a, b, 1995a, b]; No - [Noguchi et al. 1995]; Ro - [Rothermel et al. 1994] (QO); Sk - [Skalare et al. 1993] (QO); Sk-bol - [Skalare et al. 1993] (waveguide hot-electron bolometer); To - [Tong et al. 1995a, b]; vS - [van de Stadt et al. 1995a, b] (waveguide Al-wiring SIS).