

Focal Plane Imaging Systems for Millimeter Wavelengths

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Abstract—We discuss critical aspects of imaging system design and describe several different imaging systems employing focal plane array receivers operating in the 3mm–2mm wavelength range. Recent progress in millimeter-wavelength optics, antennas, receivers and other components permits greatly enhanced system performance in a wide range of applications. We discuss a radiometric camera for all-weather autonomous aircraft landing capability and a high sensitivity cryogenically cooled array for use in radio astronomical spectroscopy. A near-focus system for identification of plastic materials concealed underneath clothing employs a two element lens, and has been demonstrated in active (transmitting) and passive (radiometric) modes. A dual mode imaging system for plasma diagnostics utilizes both active and passive modes at its $\simeq 140$ GHz operating frequency to study small-scale structure. The radiometric imaging systems employ between 15 and 256 Schottky barrier diode mixers while the imaging receivers for the active systems include 64 element video detector arrays.

I. INTRODUCTION

IMAGING can be considered to be the process of measuring the radiation arriving from different directions. Our experience with imaging derives most directly from our experience with the eye, an optical system employing an array of independent detector elements in the focal surface of an imaging lens. A focal plane imaging array is only one architecture for imaging systems. Obtaining an image of a scene can be carried out in many different ways, several of which are shown schematically in Fig. 1. It is possible to build up an image of a scene by scanning a single pixel receiver, either by moving a detector in the focal plane of an antenna or mechanically or electrically scanning the beam direction of the system. This technique, while slow and cumbersome, has been the only one available at many wavelengths until very recently. Another type of imaging system is the phased array, in which the signals from a number of independent radiating elements can be processed in order to synthesize beams which effectively are sensitive to radiation arriving from different directions. A close relative is the interferometric array widely used in radio astronomy, in which the signals from different antennas are correlated and an image obtained by carrying out an off-line Fourier transformation of the data.

The millimeter wave region has several important advantages in terms of system design, but these very much depend on the precise application. In a general sense, millimeter wavelength propagation is superior to that found in the infrared and visible spectral ranges in poor weather conditions, and is thus preferable for systems that must operate independent of environmental conditions. Millimeter wavelengths clearly offer better angular resolution for a given antenna diameter than do microwaves, and thus have a great potential advantage, particularly for commercial systems which must fit into restricted envelopes. The particular properties of the interaction of millimeter wavelength energy with materials can offer advantages for certain applications, such as remote sensing of trace gases, and this has been used to very great effect recently in studies of the Earth's atmosphere [1].

The millimeter wavelength region of the electromagnetic spectrum is situated between microwave frequencies, in which range coherent signal processing techniques are well developed, and the infrared region, in which incoherent technology has predominated. It is indicative of the position of the technological frontier to compare the lack of imaging arrays at millimeter wavelengths with infrared cameras which already employ focal plane arrays with thousands of elements [2], and highly sophisticated microwave phased array systems [3].

Phased arrays have, however, been limited in their success at millimeter wavelengths due to difficulties designing efficient radiating elements as well as relatively large feed system loss. Interferometers have been restricted to research applications as a consequence of their cost and complexity. Mechanically-scanned systems have been employed for different imaging applications in the millimeter range, but suffer the very major handicaps of expensive, relatively unreliable mechanical systems together with low data rate from the single receivers utilized. Focal plane arrays have to date been little developed due to problems with developing an effective type of feed for coupling between free space and single mode detectors, as well as the significant issues of cost and complexity inherent in systems employing large numbers of pixels.

Extensive work during the last decade or so on overcoming these problems has resulted in much improved feed elements for focal plane imaging systems, and the potential for very low cost individual radiometers to use in large scale focal plane arrays. As a result of these developments, we have adopted focal plane array technology as our design approach for imaging systems in the 2 mm to 3 mm wavelength range. In this paper we indicate some of the design considerations

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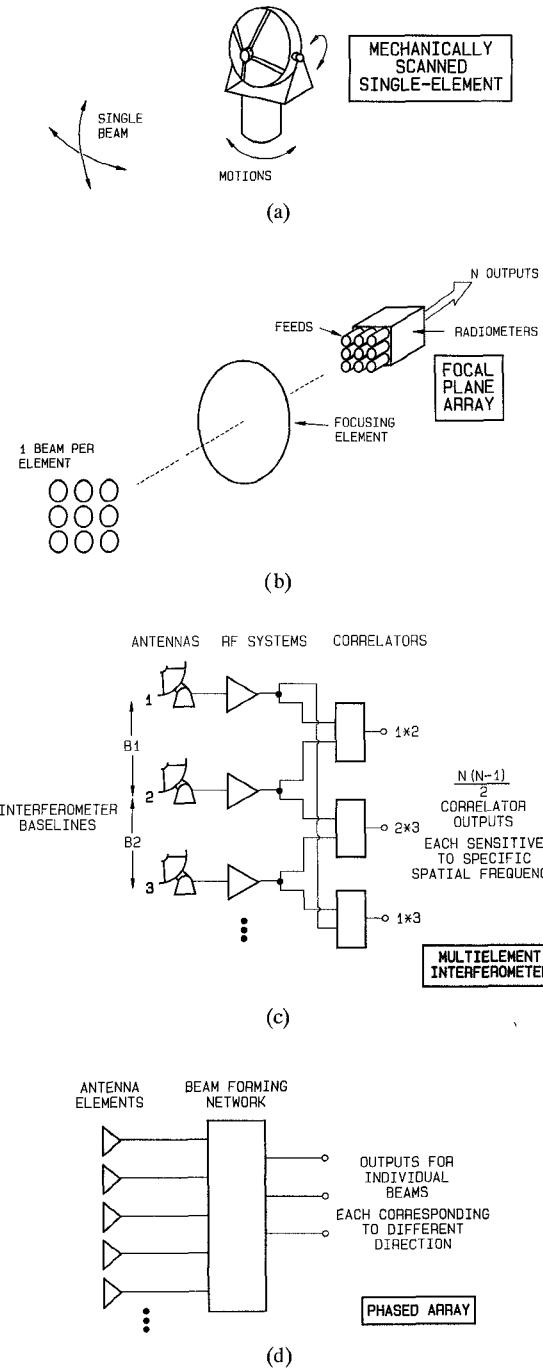


Fig. 1. Schematic of different types of imaging systems (a) mechanically-scanned single element; (b) focal plane array; (c) multielement interferometer; (d) phased array.

which are of critical importance in the development of systems for commercial and research applications. We describe four different systems and present some images that have been obtained to indicate the degree to which this technology has matured.

II. GENERAL CONSIDERATIONS FOR IMAGING SYSTEM SENSITIVITY

The relatively low intensity of thermal emission makes sensitivity an important concern for passive radiometric systems,

while its importance for active systems is very much dependent on the configuration. The basic radiometric equation for the rms uncertainty of the scene temperature that can be measured with a coherent detector system (heterodyne or amplifier) is

$$\Delta T_{\text{rms}} = \beta \epsilon T_s / [\delta f \cdot \tau]^{0.5}, \quad (1)$$

where β is a factor, generally between 1 and 2, which depends on the type of radiometer and how the measurement is performed; ϵ is the coupling efficiency between the radiometer and the scene being measured, which includes both antenna-source coupling effects and losses in the input optical system; T_s is the system noise temperature; δf is the predetection bandwidth; and τ is the integration time. All types of systems benefit from efficient coupling and low noise temperature. Systems which are measuring thermal sources can use a relatively large bandwidth to minimize ΔT . Active systems for which the signal is dominated by the return of a transmitted signal are better characterized by their minimum detectable power, given by

$$\Delta P_{\text{rms}} = k T_{\text{rms}} \delta f = \beta \epsilon k T_{\text{rms}} [\delta f / \tau]^{0.5}, \quad (2)$$

where k is Boltzmann's constant. We see that the minimum detectable power increases as the bandwidth is increased, so that in this case, we want the bandwidth to be large enough only to allow the return signal to be processed. If the signal is sufficiently strong, it can be directly detected without any RF processing. In such video detector systems the sensitivity is set by noise fluctuations in the detector element and the predetection bandwidth is generally not a critical parameter.

The sensitivity limits set by the radiometer equation given above, or by video detector sensitivity, are lower limits. A variety of effects can degrade performance, including both instabilities in the radiometer and characteristics of the scene being imaged. Gain instabilities are well known to radiometer designers and can be countered by employing a rapid calibration cycle or switching between the scene and a comparison load (Dicke switching). Single-pixel imaging systems have relied on mechanical scanning of the beam across the scene [4], with calibration performed by looking at thermal loads [5] or by weak coupling of a noise source [6]. For an imaging system with many pixels, a quasi-optical input switch is essential for load switching as well as for calibration. The Autonomous Aircraft Landing System discussed below employed a mechanical quasi-optical switch, but development of an electronic replacement using PIN diodes has already yielded extremely promising results [7].

In some situations, small-scale variations of the scene temperature which are not of interest set an effective lower limit to the useful sensitivity for studying variations in the scene. As an example, the scenes studied in [6] were characterized by a "clutter" of 2–3 K. With RF/IF bandwidths of several GHz which are now feasible, the noise temperature required to have a radiometric ΔT comparable to or less than this value is quite reasonable, being 10^4 K for $\delta t = 3$ GHz and $\tau = 1/30$ second.

III. EFFICIENCY, PACKING, AND COST OF ARRAY FEED ELEMENTS

These considerations are central to the successful implementation of any focal plane imaging system and have been discussed in some generality [8], [9], [10]. The feed elements have been the subject of very intense development during recent years. Traditional rectangular horn elements have been compared [11] and developed in monolithic form [12]. A variety of different types of travelling wave slot antennas have been proposed and studied including constant width slots [13] and linearly tapered slots [14]. Other types of feed elements include double dipole [15], Yagi [16] and dielectric rod antennas [17], among others. The general criteria that these designs seek to satisfy include:

- 1) efficient illumination of antenna
- 2) low loss
- 3) effective coupling to active devices
- 4) good packing efficiency.

In addition, qualities such as high polarization purity and reasonable angular divergence end up being of importance in many applications, while low cost is a factor that must be borne in mind particularly for commercial applications.

Achieving good illumination efficiency demands low sidelobes and backlobes, which have been persistent problems for antennas on substrates. This is one of the motivations behind the use of lens-coupled printed circuit antennas, which exploit the tendency to radiate into the dielectric and combine this with collimation of the beam by the dielectric lens [18]. Low loss is an issue with feed elements employing dielectric materials. For commercial systems operating at ambient temperature, the effect is also more severe than for radio astronomical systems in which the feed elements are cooled to low temperature, which greatly reduces their added noise as well as reducing their dielectric loss. Most types of planar designs, including travelling wave slot and dipole antennas, offer good coupling to active devices, either mixers or amplifiers; coupling is, however, a more severe problem for dielectric rod and some other types of antennas.

The question of packing efficiency is an interesting one, as well as being very important for development of effective focal plane arrays. Radio astronomical systems observe essentially non-changing scenes and mosaicking an image by repointing the antenna to fill in points in the focal plane not sampled by the array is, in principle allowed. However, it is generally inefficient to have the array elements too widely separated, since some radio sources will not be very extended compared to the footprint of the array on the sky, and array elements are thus not being used effectively. For commercial applications, where near real-time updating of the radiometric image is required, minimum element spacing is of vital importance to achieve a reasonably well-sampled image without any motion of the antenna.

The ability to sample the image in the focal plane of an antenna is intimately related to proper illumination of the antenna itself by the feed element. We assume that an individual feed is used for each pixel. If it is an aperture-type feed (e.g. horn) then it has a characteristic lateral size to produce the

illumination pattern appropriate to the antenna focal ratio. A close-packed array of such horns cannot fully sample the focal plane because the electric field distribution within the horns is generally quite tapered in order to achieve a radiation pattern with low sidelobes. For scalar feedhorns, for example, close packing of the horns produces only approximately every-other beamwidth sampling of the focal plane [10]. Reducing the size of the feed horns results in a broader beam and much reduced antenna efficiency. For travelling wave antennas which derive their gain in part from their length, the situation is more complex, but placing the elements too close together results in interaction via fields and/or currents extending away from the feed elements themselves. In an experimental study, it was found that a 1λ spacing of feeds appropriate for a $f/D = 1$ system was about the minimum that gave acceptable results [17]. Since the distance in the focal plane corresponding to one beamwidth is $\Delta x = f\lambda/D$, this corresponds to about 1 beamwidth spacing.

From a more general viewpoint, full sampling of the focal plane for incoherent illumination of the scene and measurement of the intensity in the focal plane requires an element spacing $\Delta x = 1/2 \cdot (f\lambda/D)$ [19]; in $f/D = 1$ system we thus require an element spacing not much greater than $\lambda/2$. This is far closer to the limiting spacing found theoretically for a variety of feed elements [20]. These authors found that the aperture efficiency for an antenna with slot element feeds, for example, is ≈ 0.5 for $\Delta x \approx 1.15\lambda$ in a $f/D = 1$ system. For a corrugated feedhorn, by contrast, the aperture efficiency has dropped to 0.17 for a spacing just slightly less than this. In the focal plane arrays described below, the constant width slot antennas used with $f/D = 1.1$ optics are generally spaced by 1.35λ , which is about as close as possible without excessive interaction between elements. These systems, while achieving good illumination efficiencies, are clearly far from the desired spacing for full sampling, and from the theoretical limit for reasonable overall system efficiency [21].

IV. IMAGING ABILITY OF FOCUSING SYSTEMS

Analysis of the variation of performance of lens and reflector antennas is a major branch of electromagnetics and has interesting parallels and differences from imaging in optical systems at visible wavelengths. Although work on scanning systems started even earlier, the now classic papers on imaging properties of reflectors [22] and lenses [23] have burgeoned into a literature so vast that is not possible even to summarize the results, but rather only to give a sampling of references [24].

The issue has, in fact, become rather more acute with recent progress in focal plane array technology—the problem has shifted from one only of academic interest, to a critical aspect of developing practical array systems. The critical parameters include maintaining antenna gain, beam size, and beam quality over the range of angles scanned; achieving these goals is made difficult by a combination of factors including the following:

1) Focal plane arrays with $\approx 10^4$ pixels are being seriously considered, with the result that scan angles ≈ 100 beam widths off boresight must be considered.

2) System aperture diameters are relatively small, typically only a few hundred wavelengths for commercial systems, and often less. Blockage loss for symmetric reflector systems of such limited size is generally excessive.

3) The limited volume available restricts f/D for lens systems to values ≤ 1.25 , which seriously restricts imaging capability. For this same reason, off-axis optical systems are generally not acceptable.

Meeting the requirements in the face of these restrictions is often a very difficult challenge. While it is true that there have been no microwave or millimeter focal plane array systems with the number of pixels approaching 10^4 actually implemented, several of the systems discussed below have been designed to be extended to this level, and the imaging properties of the optical systems analyzed accordingly. Imaging lens design studies have primarily been based on analytical treatments, which try to eliminate certain classes of phase error in the aperture plane which are called aberrations. However, the resulting systems are not fully optimized for practical use, given that arrays are modular and the locations of individual feed elements cannot exactly follow a specified focal curve.

Thus it is often necessary to resort to simulations rather than analysis. Full-scale diffraction calculations would be excessively time consuming, so that a hybrid approach that uses Gaussian beam propagation between feeds and optical elements, ray tracing through the lens systems, and finally a single diffraction calculation of propagation to the far-field or to a specified plane where the properties of the beam can be examined is very attractive [25], [26]. With the ever-increasing capability of affordable computers, it should soon be possible to connect this type of imaging analysis program with an optimizing function to obtain best imaging performance over some fixed scan range with appropriate constraints on feed locations. This capability, already available for geometrical optics systems with analysis based purely on ray tracing, should significantly enhance the design capability for diffraction-limited imaging systems.

V. OTHER CONSIDERATIONS

Other considerations in the design of imaging focal plane arrays, which are less fundamental than those discussed above but are nevertheless important, are power dissipation and cost. Even with the current early state of the development of focal plane arrays, it is not too early for these issues to be addressed, especially when extrapolating to larger systems. The basic architecture and geometry of the focal plane array are intimately tied to these questions. For example, while purely planar (e.g. broadside radiating) arrays may be desirable from the point of view of entirely monolithic fabrication, they suffer from problems of inadequate space for complete IF circuits, and potentially from difficulties in thermal dissipation. We have found that the endfire slot antenna geometry is effective in this regard, even though obtaining a two dimensional array requires combining "cards" each with a one dimensional array

(as discussed below). The full three-dimensional geometry is, in fact, extremely important in making a system which not only can contain the required components, but which can be assembled and serviced effectively.

Power dissipation is already a non-negligible issue for existing arrays. The ambient temperature heterodyne systems discussed below for radiometric imaging consume approximately 200 mW per pixel for the IF amplifiers, or approximately 51 W of power for the 256 element array. Even with the relatively large volume available, dealing with this thermal dissipation is a serious issue. Millimeter wavelength transistor amplifiers are currently undergoing rapid development and are receiving consideration for imaging arrays [27], [28]. These components, while very attractive in terms of low noise performance, are presently problematic in regard to power consumption. A 91–95 GHz amplifier employing 8 stages to achieve the 50 dB gain necessary for direct detection dissipates 560 mW, or almost three times more than the heterodyne system [29]. Clearly, further progress will be required to make RF amplifier systems usable in large-scale integrated arrays and further reduction of power consumption of mixer-based systems is definitely desirable.

Cost is always an issue in systems for commercial applications, but in particular for focal plane arrays with large quantities of millimeter-wavelength circuitry, a small change in the cost per pixel can translate into an impressively large variation in the total cost of a system. Again, technology is changing rapidly, but we have found the use of circuit cards fabricated on "soft" dielectric materials with bonding of discrete and hybrid components to be reliable and cost effective. Radio astronomical and other research-oriented systems with relatively fewer high performing pixels will probably continue to employ waveguide and rigid substrate technology to achieve lowest loss and system noise.

VI. DESCRIPTION OF SOME SPECIFIC SYSTEMS AND RESULTS

In the following we describe a number of millimeter-wavelength imaging systems developed for a variety of applications. Along with basic parameters of the systems, we present some imaging results that have been obtained.

A. 140 GHz Plasma Imaging Camera

Diagnostics of conditions in the ionized gas component of a Tokamak fusion reactor is vital for improving the containment of the plasma and understanding energy loss processes. The camera described in this section was designed to determine from a single "event" or ignition whether small scale fluctuating plasma modes in the interior of the plasma are responsible for plasma transport. Test bed plasma fusion reactors to date have been pulsed systems, with measurements being carried out at a few discrete locations. Although this approach has adequate time resolution, it lacks the spatial resolution necessary to identify the modes which fluctuate over periods of tens to hundreds of microseconds and have scale lengths of centimeters. The configuration and properties of the plasma can vary from one run to the next. Thus, "single shot" imaging capability is essential to understand what is happening.

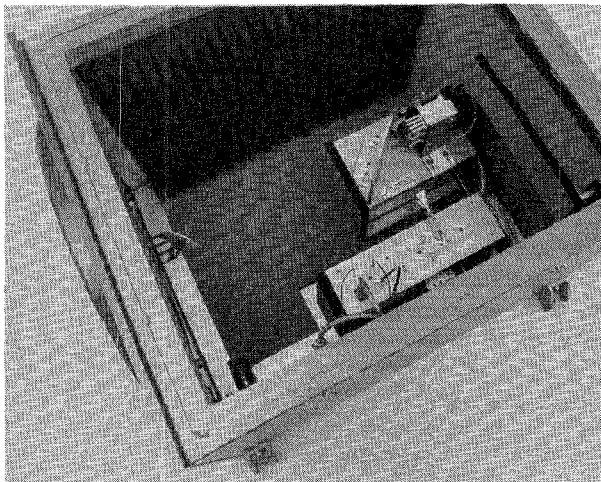


Fig. 2. Photograph of 140 GHz dual mode plasma imaging camera. The transmitter feedhorn is at the lower left, and above it is the 90° reflector to couple its beam to the scene. The focal plane array, local oscillator injection feed, and diplexer, are on the right.

Millimeter wavelength radiation can play several valuable roles in plasma diagnostics. The intensity of emitted radiation allows determination of the plasma temperature, while the reflected signal can yield information about the density structure in the ionized gas [30]. A dual mode plasma imaging camera has been developed for the Princeton Plasma Physics Laboratory to take advantage of both of these capabilities, with an emphasis on studying small-scale fluctuating plasma modes. The imaging system, shown in Fig. 2, includes a 4 by 16 element focal plane array operating at 140 GHz. This frequency is dictated by the properties of the plasma in the Tokamak Fusion Test Reactor.

The feed elements are constant-width slot antennas, and the down converters are second harmonic mixers pumped by a phase locked 70 GHz Gunn oscillator. In its radiometric mode, a 2 GHz bandwidth IF is amplified and detected. For reflectometry, a 30 mW transmitter at approximately 140 GHz illuminates an area of the plasma about 30 cm in diameter. Each beam from the focal plane array is focused by the 1 m diameter lens to an area about 1.5 cm diameter at the plasma, which is approximately 2 m away from the camera. The return signal is processed to obtain in-phase and quadrature signals from which the phase of the reflected signal can be obtained.

B. Detection of Concealed Weapons and Explosives

In recent years the ability to detect plastic weapons and explosives concealed beneath the clothing of airline passengers has received increasing interest by law enforcement and security agencies. To be effective, such detection devices must 1) have a low false alarm rate, 2) be non-invasive, and 3) have high throughput. Both active (reflecting) and passive (radiometric) millimeter wavelength imaging systems have been investigated for these purposes. Frequencies between 30 and 300 GHz provide a number of advantages including 1) low absorption by most dry dielectric materials, 2) moderately high spatial resolution, and 3) good imaging capability via compact optics.

Measurements of a number of materials at 95 GHz (see Table I) have shown that substances such as polycarbonate, polypropylene, rexolite and black delrin have reflectivities in the range -8 to -12 db. The reflectivity of various portions of the human body range from -11 db (calf) to -15 db (jowl). Furthermore, a wide variety of tested clothing items show reflectivities in the range of -15 to -25 db with transmission losses of less than 0.5 db. It appears, then, that dielectric materials of interest have reflectivities 2 to 4 times that of human skin, while clothing provides little in the way of absorption or extended reflectivity.

With imaging spot size being proportional to the product of the imaging lens f/D ratio and the wavelength of operation, it is clear that improved resolution can be obtained by operating at higher frequencies. However, at submillimeter and shorter wavelengths, materials are too lossy and the technology for cost-effective imaging systems is not available. At longer (microwave) wavelengths, the technology is well developed, but the spatial resolution is inadequate. If the system optics are designed such that f/D is approximately 1, then a wavelength of 3 mm gives a spot size adequate for the recognition of potentially harmful hidden plastic objects. To achieve high throughput of subjects, an array of detectors sampled at video rates (30 Hz) is an attractive approach. The necessary optics must be capable of a large field of view (e.g. $+/- 30$ degrees) with diffraction-limited performance.

Reflective imaging makes use of a relatively intense millimeter wave source to illuminate the subject. Higher reflectivity portions of the subject result in a higher output from the system. An extended array of slot antennas can then produce a video image or a smaller array can be mechanically scanned about the subject (albeit at the cost of reduced throughput). The major problem with this approach is the presence of "glints" in the millimeter wave image due to reflections of the illumination sources from boundaries in the subject's clothing. This effect is well known from active millimeter-wavelength imaging of tactical targets [31].

Investigation is proceeding on two approaches to solving this problem: 1) using a number of lower level sources to illuminate the subject from a wide range of angles, and 2) investigating the behavior of a subject rotating in the field of view of the imaging device. It appears that the "glints" are highly dependent on the source-subject-detector geometry and change rapidly as this geometry varies, whereas reflections from real objects have longer duration.

To study the performance of concealed object detection systems, a mannequin was covered with a millimeter wave absorptive material that approximates the absorption characteristics of human skin. The mannequin was then clothed and objects concealed on the torso. A 64 element focal plane array imaging array was used, employing endfire slot antennas each of which was coupled to a detector diode. The illuminating source produces levels of radiation well below current safety thresholds. It consists of a number of Gunn oscillators which are frequency-modulated over a few hundred MHz range, and also amplitude-modulated. An appropriate synchronous detector circuit at the output of the slot antennas converts the reflected return into a dc voltage. The imaging optics

TABLE I
CLOTHING, MATERIALS, AND HUMAN SKIN MEASUREMENTS

Sample	Thickness (mm)	Reflectivity (dB)	Transmission Loss (dB)
Clothing Item Measured at 95 GHz			
Flannel Shirt	0.5	-18	-0.3
Polyester Blazer	1.2	-15	-1.0
Wool Suit	1.4	-13	-0.8
Cotton Sweater	2.1	-30	-0.7
Terry Cloth	1.0	-22	-0.3
Cotton Muslin	0.5	-13	-0.7
Synthetic Blouse	0.1	-24	-0.04
Nylon Shell	0.1	-23	-0.1
Corduroy	0.6	-16	-0.4
Cotton Shirt (Dry)	0.2	-18	-0.3
Cotton Shirt (Wet)	0.2	-14	-1.0
Dielectric Material Measured at 95 GHz			
Polycarbonate	5.5	-8.5	-1.8
Polypropylene	1.5	-8.8	-0.8
Rexolite	7.7	-10.7	-1.6
Ceramic (ATD 6)	2.6	-4.5	-3.0
Black Delrin (Front Knurled)	13.0	-12.0	-3.5
Human Skin Reflectivity 90–100 GHz ¹			
Area		Reflectivity	
Calf	(Mean, Range dB ²)	(Mean, Percent)	
Forearm	-11.3 ± 1.5	7.4	
Palm	-8.4 ± 2.2	14.5	
Back of Hand	-13.4 ± 5.2	4.6	
Jowl	-11.5 ± 3.3	7.1	
Chest	-15.0	3.2	
Average	-8.8	13.2	
	-11.4 ± 4.4 dB	7.2 Percent	

¹Average of parameters measured over this frequency range

²The Mean and Range refer to variation among the 2 to 4 individuals measured except in cases for which no Range is given, where only one individual was measured

consist of a pair of plano-convex lenses with curved surfaces facing together, as shown in Fig. 3. The optics are designed to maximize the field of view over which a uniform focused spot size could be obtained. The detector-lens distance is 30 cm, and the distance between the lens and the focused spot with a waist radius of 0.55 cm is 60 cm. The initial optics design was carried out using standard Gaussian beam design neglecting truncation, and treating the focusing elements as a thin lens [32]. Refinement of the design, emphasizing maintaining the beam waist radius at the subject, was carried out by using hybrid code discussed above [25].

The 64 element imaging system was integrated with an $X - Y$ positioner to allow for extended image scanning over the main torso of the mannequin. In combination with computer-controlled video equipment and rotational platform, video animations were made to show how the output of an extended (48 pixel by 48 pixel) imaging device might appear. Typical video animations consisted of 360 individual static images of a 48 cm by 48 cm portion of the mannequin, each image taken with the mannequin in a slightly different orientation with respect to the camera. These static computer images were overlaid upon the output of a video camera to produce a short video sequence. Fig. 4 shows a still image from a typical animation. The results of the study indicated that real-time imaging of a moving subject to locate hidden plastic objects is quite effective and greatly reduces the confusion associated with the glints seen in static images.

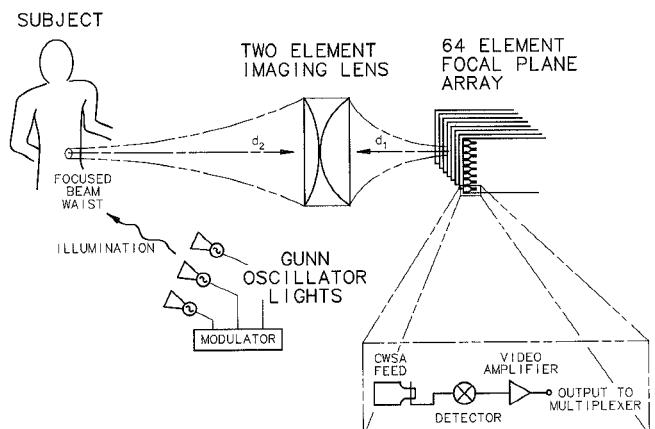


Fig. 3. Schematic diagram of active mode (reflective) contraband detection system.

Radiometric imaging in this context makes use of the thermal emission of the subject and reflected thermal signals from the background. The definition of emissivity, being the complement of reflectivity, implies that a highly reflective target has low emissivity. Thus a radiometric imager sees less of a highly reflective object and more of the background emission. The radiometric detectors receive contributions from the background, the subject and its coverings, and any hidden objects. Reflective objects, having a lower emissivity, would appear cold relative to the body's higher temperature. An

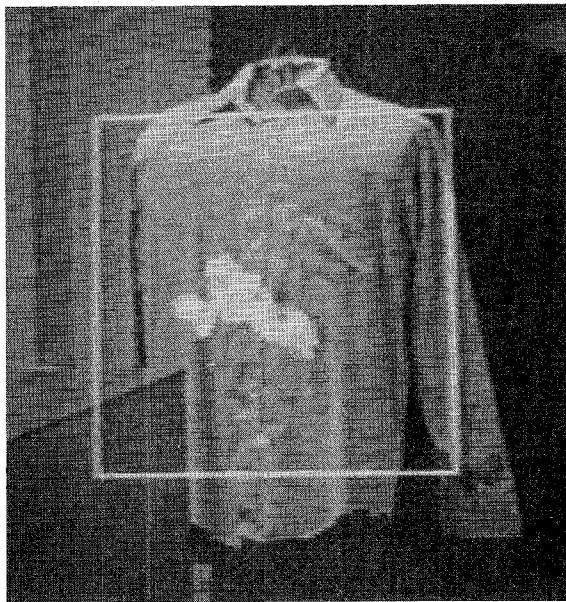


Fig. 4. Image of mannequin with concealed weapon under shirt obtained with active (reflective) imaging system. The 94 GHz image is superimposed on a visual image obtained with a television camera.

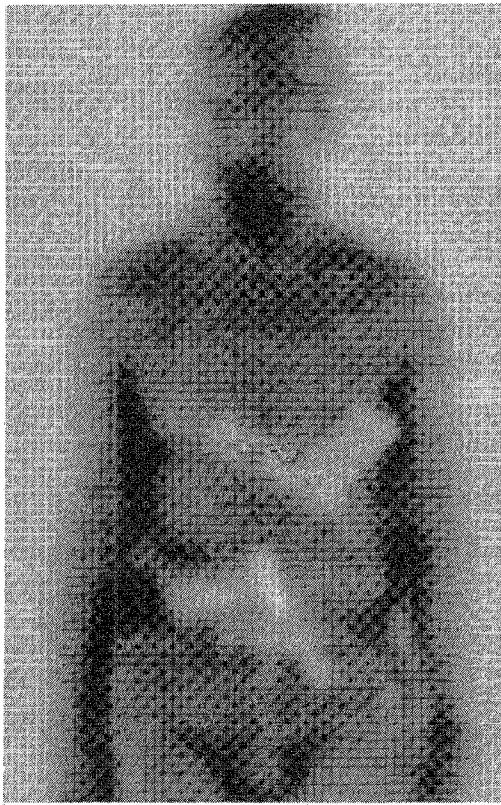


Fig. 5. Radiometric image of male subject carrying concealed weapons under clothing. The upper weapon is a metal gun, while the lower one is a primarily plastic device. Darker areas correspond to regions of increased emission.

example of a radiometric image of a subject carrying two concealed weapons is shown in Fig. 5.

The drawbacks to the radiometric approach are 1) requirement for the high sensitivity necessary to detect natural thermal

emission at millimeter wavelengths, 2) the relatively more complex detector hardware, and 3) the concurrent relatively high cost. However, freedom from glints and the absence of any even low-level "source" illuminating the subject are significant advantages.

In summary, millimeter wave sensing provides an effective method of detecting dielectric objects concealed beneath clothing on human bodies. Imaging using multiple element detector or mixer arrays in the focal plane of the imaging optics can give real-time pictures of objects with a resolution of several millimeters. Both active and passive approaches are successful, with the active approach offering lower cost but at the expense of greater signal processing demands.

VII. AUTONOMOUS AIRCRAFT LANDING SYSTEM

Current auto-pilot landing systems have not received widespread popularity because of their high cost, complexity, and limited flexibility. Millimeter focal plane array, or staring array technology can be applied to develop an autonomous aircraft landing system which provides the pilot with forward-looking millimeter wave vision for landing and takeoff under adverse weather conditions. The system is self-contained and does not need any ground-based supporting facilities. Compared with the active radar scanned images, passive radiometric images are very similar to the visual or IR images due to lack of radar clutter, back scattering or geometrical distortion.

A passive 94 GHz staring image array system, which has been developed to demonstrate the feasibility of this technical approach, is shown in Fig. 6. The array has 64 elements in 8×8 arrangement. The system block diagram is shown in Fig. 7. The 8×8 array offers a field-of-view of 2.9 degrees by 2.9 degrees with a 61 cm diameter Gaussian optics zoned lens which has an angular resolution of less than 0.35 degrees. The far-field spacing of the beams is $\cong 1.05$ FWHM beam width. The Load Comparison and Image Scanning (LCIS) subassembly provides radiometric calibration and over-sampling capability to further enhance the system resolution. The wire grid polarizer assures proper polarization to the LCIS subsystem. The perforated highpass filter is integrated with an EMI shielding enclosure to suppress radiation.

The basic building block for the focal plane arrays is the FPA card, which includes eight radiometer pixel channels. Each pixel channel has an endfire slot antenna, mixer, IF amplifiers, and video processing circuitry. The RF signal (from the scene) and the local oscillator are quasioptically injected to the array by the diplexer. The radiometer pixel noise temperature is 4000 K (DSB) corresponding to a noise figure of 11.6 dB, including the losses of diplexer and highpass filter. Eight such FPA cards are stacked together to make an 8×8 array as shown in Fig. 8.

The 8×8 array can be used as a "subarray" or as the starting point to construct larger arrays. The 8×8 subarray has a physical size of $3.5 \times 3.55 \times 13.0$ cm and power dissipation of 22 watts, of which 13 watts is from the IF amplifiers, and the remainder is contributed by the video amplifiers and multiplexer circuits. The focal plane array with this level of power dissipation can be cooled by forced air.

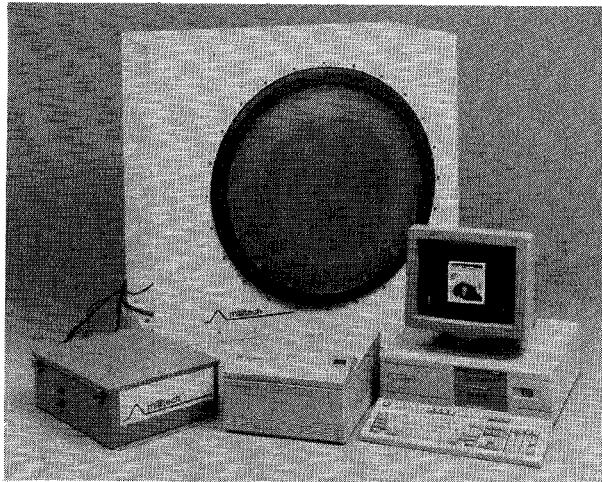


Fig. 6. Millivision™ 64 pixel 94 GHz radiometric imaging system with 60 cm diameter zoned lens. The complete system includes the front-end and optics enclosure, the power supply, and control and display computer.

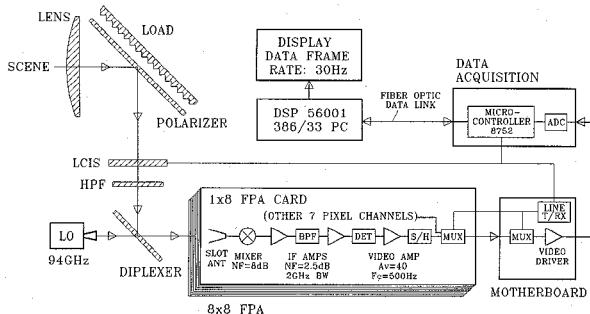


Fig. 7. System block diagram of 8 × 8 pixel 94 GHz focal plane imaging system.

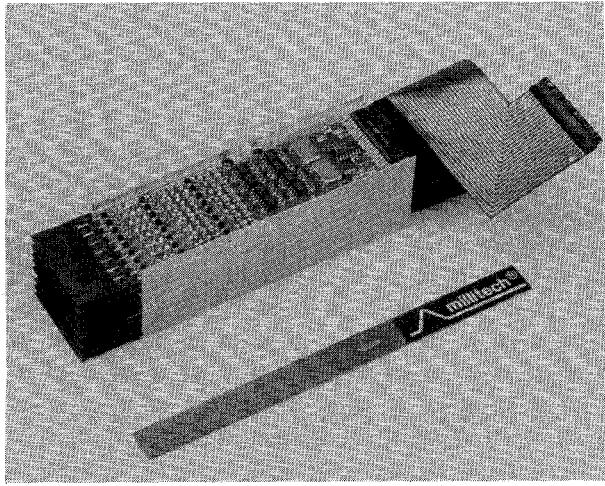


Fig. 8. Photograph of eight cards each with 1 × 8 element array forming a 64 pixel focal plane array. On the top card, the endfire slot antennas are on the reverse side of the dielectric substrate at the left, the IF amplifiers are visible in the middle, and the video amplifiers and processing circuitry are on the right.

This modular approach to focal plane array design allows straightforward extension to larger arrays. A 16 × 16 array as shown in Fig. 9 is based on this approach. Subharmonically-pumped mixers were incorporated in this refined 16 × 16 array.

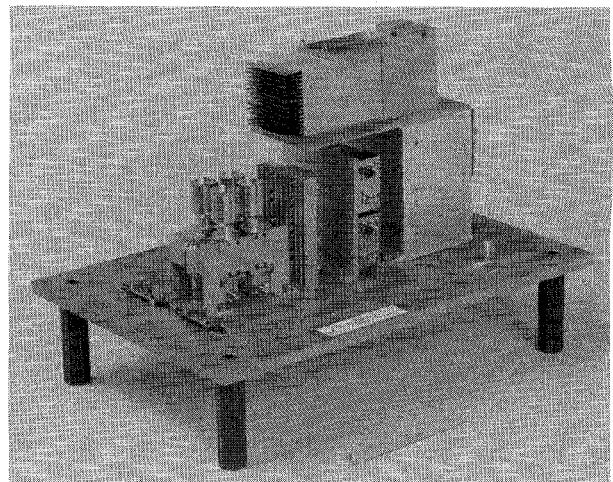


Fig. 9. Photograph of 16 × 16 pixel focal plane array operating at 94 GHz. The four 8 × 8 pixel subarrays can be seen, as can the four local oscillator feed horns, with one L.O. being used to pump the mixers in each subarray. The L.O./signal diplexer has been removed.

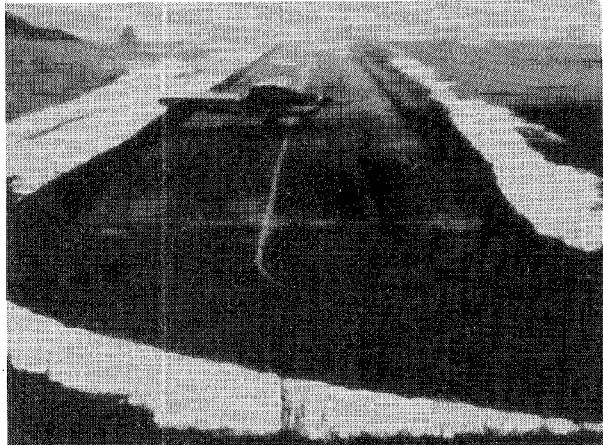
The noise performance of the 16 × 16 array is 5800 K (DSB) or 13.1 dB including the losses of diplexer and highpass filter. In even larger arrays, where the properties of the optical system require that the detectors not line in a plane, the 8 × 8 modules can easily be configured to conform to the required curved surface.

A comparison between visual, 94 GHz passive scanned images of a scene at the Turner's Falls Airport, Massachusetts, is shown in Fig. 10. Fig. 11 shows a 48 × 48 pixel image which was obtained by stepping the 8 × 8 array in azimuth and elevation. The data update rate from the subarray yielded a new 64 pixel image 30 times per second. The value of image processing, and also the good correspondence with visual imaging, are clearly shown here. Atmospheric attenuation over the few km distance of importance in this application does not result in a significant degradation except during extremely heavy rainfall. With their relatively high data rate, simplicity, and comprehensibility of output, combined with sensitivity and field of view, it is evident that millimeter-wavelength focal plane array imaging systems have major potential for autonomous all-weather landing system applications.

VIII. RADIO ASTRONOMICAL SPECTRAL LINE IMAGING SYSTEM

The most important feature of an imaging system is that it reduces the time required for study of spatially-extended objects, and can allow projects to be undertaken that would be quite unfeasible with a single pixel system. The increase in data rate provided by a multi-element receiver is especially important when the system noise temperature of individual receivers is comparable to the emission from the Earth's atmosphere, because when this point has been reached, further improvements in receiver noise temperature do not yield significant improvements in overall system sensitivity.

This is largely the situation at millimeter wavelengths, due to the appreciable atmospheric opacity (particularly at some astronomically important frequencies such as that of the carbon



(a)



(b)

Fig. 10. Images of runway at Turner's Falls Airport with airplane (a) left hand panel is a visual image; (b) right hand panel is 94 GHz radiometric image. Note that horizon is clearly visible, and that airplane appears "double" due to high reflectivity of runway.

monoxide $J = 1 - 0$ transition at 115.3 GHz), combined with the remarkably low receiver noise temperatures that have been obtained with cooled Schottky [33] and superconducting [34] mixer systems. In some situations, such as studying moderately small sources, the packing density of detector elements in the focal plane is an important consideration and tradeoffs similar to those discussed above must be made in choosing the type of feed element. As discussed in [10], most operational radio astronomical imaging arrays employ scalar feedhorns, but current efforts are to a significant degree focusing on other types of feed elements.

A 15 element focal plane array for astronomical spectroscopy in the 85 to 115 GHz region has already been described in some detail [35], but some of its key features are relevant to the themes developed in this paper. In order to maximize sensitivity, not only the mixers and IF amplifiers are cooled to 20 K, but considerable use is made of cryogenic quasioptical techniques. Thus, the feeds,

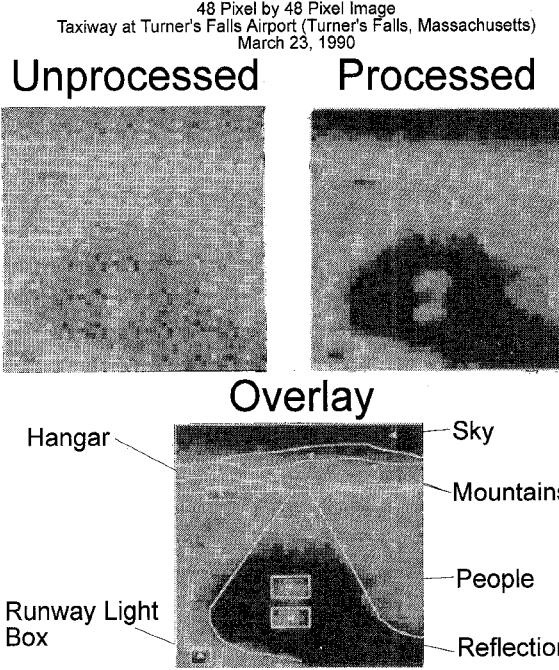


Fig. 11. 94 GHz imaging of scene at airport (a) unprocessed image made from 8×8 mosaic of 64 pixel images with 1 pixel overlap at edges; (b) image processed by median smoothing and histogram equalization; (c) processed image with overlay indicating major visible features.

imaging optics, single sideband filter (a novel design which functions for all 15 beams [36]), and image termination are also cooled. The system uses scalar feedhorns, but with the corrugations removed to form four flat areas which permits a 25% reduction in spacing (including the thickness of the walls and corrugations). The final feedhorn diameter corresponds to a spacing of 2 half-power beamwidths at 105 GHz. To further improve the sampling in the image plane the polarization direction of the beams of the 2×3 subarray are rotated by 90° relative to that of the 3×3 subarray, and then interleaved by means of a wire grid polarization diplexer. The resulting footprint of the array has beams with single beamwidth spacing in one direction by every other beamwidth spacing in the orthogonal direction. The footprint of the array beams on the sky is shown in Fig. 12.

Effective utilization of an astronomical focal plane array requires (as do other array systems) extensive software for dealing with the data in the form of images. In the case of spectral line data, the actual data product is a "data cube" with an image having two spatial and one frequency dimension. Tracing the structure of molecular clouds in the interstellar medium of the Galaxy with such an array is enormously facilitated by using the kinematic information which reflects the relative motion of different parts of these objects. With the 15 element QUARRY array on the Five College Radio Astronomy Observatory 14 m millimeter telescope located in the Quabbin watershed (whence the acronym), the resulting angular resolution is 45" at a frequency of 115 GHz. We show in Fig. 13 an image of the Monoceros R2 cloud (distance 2600 light years) obtained by Dr. Taoling Xie, which contains approximately 167,000 spectra. This data is restricted to a narrow velocity range of 0.65 km/s, in which the sharp

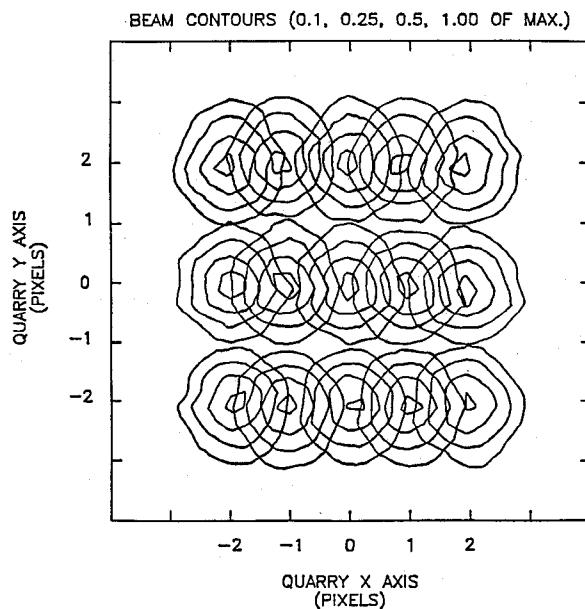


Fig. 12. Contour map of 15 beams from QUARRY focal plane array on FCRAO 14 m telescope measured using Jupiter at a frequency of 110 GHz. The beams overlap at the 0.5 (-3 dB) level in the X direction where polarization interleaving has been employed.

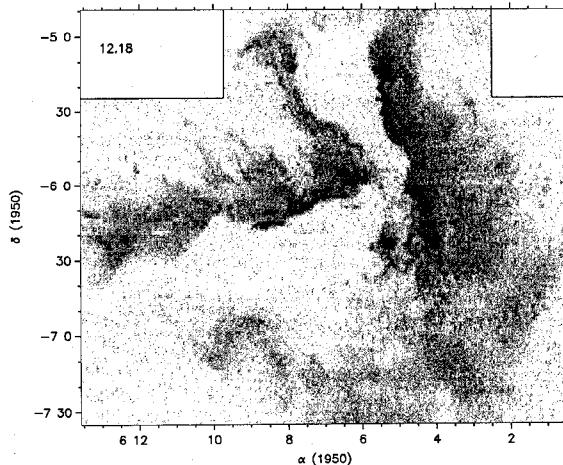


Fig. 13. Map of giant molecular cloud Monoceros R2 made with the QUARRY array system on FCRAO 14 m antenna. The emission is from ^{12}CO in a velocity range 0.65 km/s wide centered on a velocity of the source of 12.18 km/s. The vertical coordinate is declination (degrees and minutes of arc) and the horizontal coordinate is Right Ascension (hours and minutes of time). The entire map covers an area of approximately 2.5 degrees by 3 degrees, while the angular resolution of the telescope is approximately 50''.

boundaries of material in the cloud are particularly prominent. These are likely due to shock waves which plausibly are compressing the gas, and thus initiating the formation of new stars. This type of large scale imaging with high angular resolution is essential for unraveling these complex processes and can only be obtained with focal plane imaging systems.

IX. CONCLUSIONS

The unique characteristics of millimeter waves make this portion of the electromagnetic spectrum extremely valuable, but its full potential can be realized only when images of different scenes can be obtained rapidly and, generally, for

a reasonable cost. As a result of ongoing developments in optics, feed elements, and detectors, millimeter-wavelength focal plane array imaging systems have matured to the point where systems employing tens to hundreds of elements have been developed and used in a wide variety of commercial and research applications. We have described both passive (radiometric) and active (reflected power) systems used for plasma diagnostics, where the frequency allows probing of ionized material in fusion reactors. Millimeter wave radiation propagates through clothing with relatively low loss, and images permit detection of concealed objects including plastic weapons and explosives, offering a valuable tool for airport security. Penetration of weather in conditions of poor visibility allows radiometric imaging of airports and identification of vehicles and other dangerous objects on runways in the context of an autonomous all-weather landing system. Unrivaled sensitivity to emission from molecules at very low temperatures make millimeter-wavelength images enormously valuable for understanding the structure of giant molecular clouds and star formation in the Milky Way Galaxy.

The systems that have been utilized to date undoubtedly represent the first generation of millimeter-wavelength cameras. With further improvements in feed design, it is likely that more complete and efficient sampling of the focal plane will become possible and improvements in sensitivity will result in millimeter-wave images of higher quality having increased fields of view and data rates. This capability will certainly lead to the effective employment of millimeter wave imaging systems in an expanded range of applications.

ACKNOWLEDGMENT

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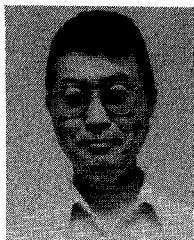
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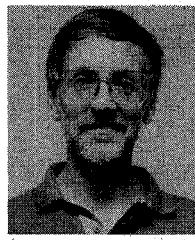
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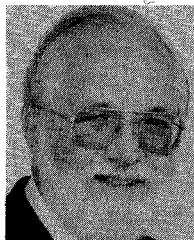
mixers, multipliers, detectors, switches and filters. He previously worked as Senior GaAs MMIC circuit designer at Texas Instruments in 1988 and was responsible for the development of high speed digital frequency dividers. As Staff Engineer at Hughes Aircraft Company, he headed a NASA 60 GHz integrated receiver project in 1982. He was Senior Engineer at Jet Propulsion Laboratory, California Institute of Technology in 1979 and responsible for the development of analog signal chain for the CCD image system in the Hubble Space Telescope.



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the Five College Radio Astronomy Observatory, which constructed telescopes and carried out observations at meter wavelengths and in the millimeter frequency range. Under his leadership, the Five College Radio Astronomy Observatory developed into a \$2 million, 60 person organization. He also developed extensive facilities for millimeter and submillimeter instrumentation development.

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