Recent European Developments in Active Microwave Imaging for Industrial, Scientific, and Medical Applications

JEAN-CHARLES BOLOMEY

Abstract —**At the beginning of the 1980's, research programs devoted to short-range active microwave imaging were initiated in Europe. Since that time, a permanent research effort has been organized and oriented toward the development of microwave imaging equipment for industrial and medical applications. This effort has been conducted within the framework of national or European cooperative programs. This paper presents some representative results which have been obtained during the last decade and discusses the general trends concerning their continuation and extension in the next few years. Without underestimating theoretical aspects and their importance for the further evolution of microwave imaging techniques, special emphasis has been given to equipment which provides the real measure of the impact of the recently developed microwave imaging technologies in a growing field of applications.**

I. Introduction

MICROWAVE imaging terminology applies to a broad and rather ill-defined field of activities. Classification of these activities can be achieved according to more or less arbitrary criteria. Until recently, the denomination of microwave imaging was almost exclusively restricted to remote sensing or radar situations, corresponding to long-range and, respectively, passive or active imaging modalities. At the opposite of these two important areas, which are not within the scope of this paper, microwaves were also used for ISM (industrial, scientific, medical) applications, but without any possible reference to some kind of imaging practice. Indeed, in such applications, testing of materials is achieved by measuring transmission coefficients between two antennas. The measurement suffers from a spatial integration over more or less defined regions.

During the last ten years, microwave techniques have been increasingly used for ISM applications via microwave imaging. Two main tendencies can be distinguished. The first is directly derived from classical radar techniques. In many respects, the second approach is relevant to optical imagery. By the way, numerous attempts have been made to extend imaging concepts from optics to microwaves. However, expectations from holographic techniques, except in very limited cases [1], [2], have been disappointing for the reasons explained below. As a matter of fact, it is worth noting that, for a long time, microwaves have not been really considered a convenient imaging means for at least two reasons. The first one is that microwaves were not expected to provide adequate image quality. The second, and more pragmatic, one consists in the lack of convenient recording facilities, such as films for X rays or visible light. Currently, the prospects have changed significantly with respect to these two factors.

First of all, concerning image quality, only spatial resolution was taken into account, forgetting contrast considerations, which must play a role of at least equal importance. It is true that the propagation of microwaves in inhomogeneous media is relevant to complex phenomena governed by the diffraction rules, resulting in 1) some difficulties in providing well-collimated or focused beams, 2) limited spatial resolution, and 3) possible image artifacts. In addition, 4) microwave interactions are very low or negligible with structures or defects which are small compared to the wavelength. However, microwave interactions with media are primarily sensitive to their dielectric properties (dielectric constant, conductivity) in such a way that microwave images can be expected to provide an indirect access to any physical or chemical factor which these dielectric properties are dependent upon, such as composition, water content, temperature, and phase change. From this contrast aspect, microwaves constitute a very sensitive means to follow the variations of such factors before, during, or after an industrial process or a medical treatment. As for spatial resolution improvement, two approaches can be investigated.

The first aims at reproducing optical or quasi-optical situations by increasing the frequency. This method is limited by the fact that, according to a general trend, the transparency of materials decreases when the frequency is increased. For a given material, it is usually considered that the optimum frequency corresponds to the minimum

Manuscript received April 4, 1989; revised July 14, 1989.

The author is with the Groupe d'Electromagnétisme/Laboratoire des Signaux et Systèmes, Ecole Supérieure d'Electricité, Plateau de Moulon, 91192 Gif-sur-Yvette Cedex, France.

IEEE Log Number 8931362.

0018-9480/89/1200-2109$01.00 ©1989 IEEE

of the loss tangent angle, providing both convenient spatial resolution and penetration. For many materials, this optimum frequency is located in the gigahertz range; consequently the corresponding spatial resolution is of the order of a few centimeters in free space, which is notably insufficient in many cases. This explains why such an approach to spatial resolution improvement is limited to vision applications which require only the definition of environment external boundaries. Such applications are strongly stimulated by the development of millimeter- and submillimeter-wave technology.

The second approach is to attempt to reduce diffraction effects to an acceptable level, and to take them into account as efficiently as possible. Such an approach, although imperfect at the present time, leads to specific electromagnetic wave front processing (free-space transformation, diffraction tomography, inverse scattering, etc.), which is now, for some cases, beyond the capability of personal microcomputers. Although less intuitive and more cumbersome than a quasi-optical approach, this approach appears very promising when quasi-optical concepts fail.

Coming back to the second explanation for the lesser development of microwave imagery with respect to other imaging techniques, it is evident that the difficulty of recording wave fronts, other than mechanically scanning by means of a single probe, has been very discouraging to possible users. Such a dissuasive effect explains why microwave holographic techniques have not really succeeded. Indeed, a probing of microwave wave fronts, over sufficiently large areas, requires too much time and excludes any real-time operation. The evident solution of using probe arrays has the drawbacks of cost and/or complexity. While awaiting the next generation of reliable and inexpensive microwave integrated circuits, the most reasonable approach, using the present state of the art of microwave technology, is to connect a set of probes to the same receiver or at a reduced number of receivers, resulting in microwave multiplexers with an unusually high number of channels, e.g., from a few hundred to a few thousand. Simpler solutions, involving only amplitude measurements, do not pose such problems but prove to be inadequate in view of possible image improvement using wave front processing techniques, which generally require both amplitude and phase probing. However, certain simple techniques (modulated scattering technique, modulated multiplexing technique) have provided convenient technical solutions at supportable cost for ISM applications.

On the other hand, the coherence of microwave sources offers the additional flexibility of storing microwave wave fronts for subsequent processing. It is well known that, according to the synthetic aperture concept, a high spatial resolution can be achieved with a very small and poorly directive antenna. However, this antenna has to be moved over a significant area. Moving the antenna may be a serious constraint, primarily with respect to probing time and subsequent data processing needs. The use of probe arrays seems the only way to obtain real-time or quasi-real-time imaging facilities but, as will be shown later, the synthetic aperture concept can be useful for ISM application.

TABLE I
EUROPEAN R&D PROGRAMS ON MICROWAVE IMAGING FOR ISM APPLICATIONS

	R&D PROGRAM	LABORATORY	SENSOR FEATURES	IMAGING TECHNIQUE
BIOMEDICAL APPLICATIONS	2 45 GHz MICROWAVE PLANAR CAMERA	University of Paris / CNRS (France) Support ANVAR MRT	32 X 32 = 1024 sensors plane retina Modulated Scattering Technique (MST)	mono /multi-views tomographic processing (spectral approach)
	2 45 GHz MICROWAVE CIRCULAR SCANNER	Polytechnic University of Barcelona (Spain) Support CAICYT FISS	64 T/R elements circular array Modulated Multiplexing Technique (MMT)	qualitative (internal structure) quasi-real time
BURIED OBJECTS	1-2 / 2-4 / 9-11/ FMCW RADAR FOR DETECTING & IDENTIFTYING BURIED OBJECTS	Queen Mary Coll London (England)	1 mobile off-set reflector antenna	synthetic pulse, tomogr / SAR processing, identification schemes, qualitative (discontinuity)
	X-BAND LINEAR MICROWAVE CAMERA FOR CONTROLLING REINFORCED CONCRETE	University of Paris / CNRS (France) Support · LCPC	1 linear array of 64 probes Modulated Scattering Technique (MST)	multifrequency tomogr processing (spectral approach), quantitative , quasi-real time
VISION / ROBOTICS	70 GHz RADAR FOR TRAFFIC MONITORING	University of Erlangen - Nurnberg (West Germany) Support . DFG	1 fixed planar Luneburg lens + array of 6 rotating probes	pulse Doppler mm-range
	94 GHz SENSOR FOR AUTONOMOUS INDUSTRIAL VEHICLE	Technical University of Munchen (West Germany) Support DFG	1 fixed corrected horn + 1 rotating plane mirror	tomographic (ext contours) real time polar/rect display
INDUSTRIAL CONTROL	X-BAND LINEAR SENSOR FOR CONTROLLING CONVEYED PRODUCTS	University of Paris / CNRS (France) Support ANVAR MRT	linear array of 128 sensors Modulated Scattering Technique (MST)	reflexion / transmission/ resonant, qualitative/quantitative, high measurement rates
	MICROWAVE SENSOR FOR COMPLEX PERMITTIVITY MEASUREMENTS	University of Sheffield (England)	experimental prototype mechanical scan of T/R antennas	transmission, phase tomography, quantitative

II. ACTIVE MICROWAVE IMAGING IN EUROPE

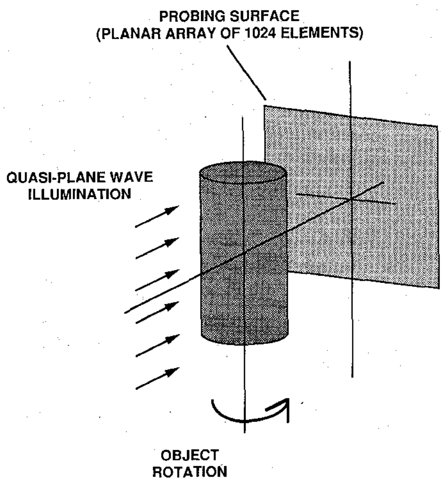
In the early 1980's the European scientific community recognized active microwave imaging as a new area of investigation. The European Microwave Conference awarded its Microwave Prize (Nürnberg, 1983) to this topic [3], and a significant research effort has been organized in Europe to promote microwave imaging techniques from both theoretical and practical points of view. This effort has been conducted within the framework of national or European cooperative programs at three different levels:

- basic research in reconstruction algorithms;
- development of imaging equipments;
- feasibility studies and evaluation of prototypes in view of diversified applications.

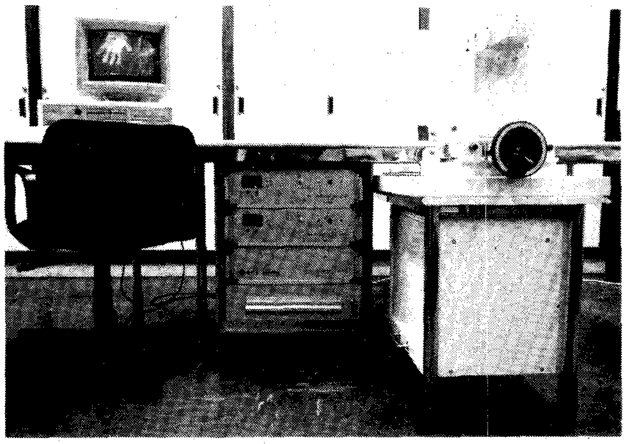
Both medical and industrial applications have been considered. Table I summarizes, by applications, some recent European R&D programs involving microwave imaging. These programs are detailed in the following subsections.

A. Biomedical Applications

The first research activity, undoubtedly, was influenced by the works of Larsen and Jacobi (Walter Reed Army Institute) [4]. Important financial support has been provided, in France, by the Agence Nationale de la Valorisation de la Recherche (ANVAR) and the Ministère de la Recherche et de la Technologie (MRT) for the noninvasive

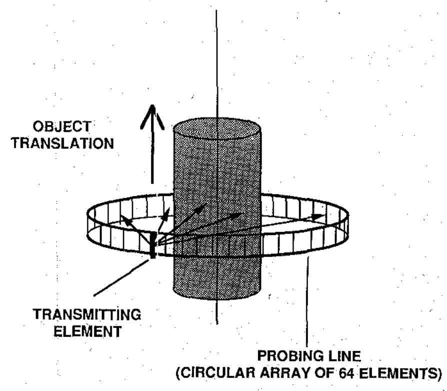


(a)

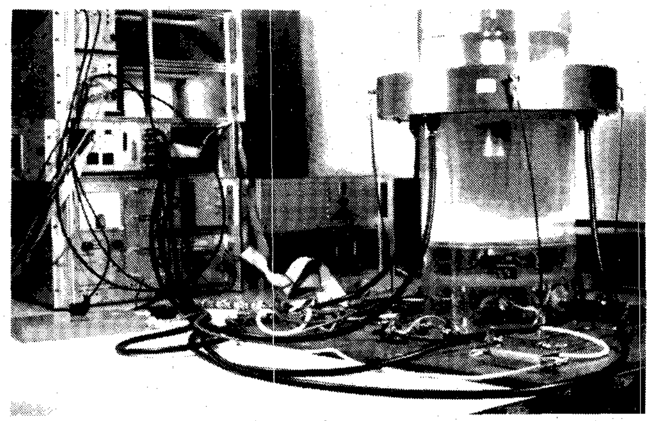


(b)

Fig. 1. Planar microwave camera for biomedical applications at 2.45 GHz. (a) The scattered field is measured on a 22×22 cm^2 area by using a planar array of $32 \times 32 = 1024$ modulated probes. (b) General view of the equipment including a microcomputer for controlling the acquisition process and performing image reconstruction. The water tank between the emitter and the microwave camera has been removed.



(a)



(b)

Fig. 2. Circular array for biomedical applications at 2.45 GHz. (a) The circular array consists of 64 horn antennas, which are used, successively, for transmitting and receiving. When one antenna is transmitting, the scattered field is measured by the others, and so on. (b) Experimental prototype corresponding to the principle described in Fig. 2(a).

thermal control of deep hyperthermia. After some preliminary studies [5]–[7], microwave planar cameras, operating at 2.45 GHz, were fabricated and evaluated for this particular purpose within the French evaluation program TEP [8]–[10] (Fig. 1). The principal aspect of this camera is its sensor of $32 \times 32 = 1024$ sensitive points, which makes it possible to record wave fronts of amplitude and phase over a surface of approximately 22 cm by 22 cm at measurement rates varying between 100 and 1000 points per second. Such performance is achieved by using a modulated scattering technique. Single-view focusing and, when possible, multiview tomographic reconstruction can be achieved, on a personal microcomputer, within a few dozen seconds. In comparison to other imaging techniques (X rays, NMR, ultrasonic) and as partially confirmed by preliminary evaluations, microwaves offer good thermal sensitivity, convenient compatibility with heating equipment, and moderate cost. In addition, they allow permanent monitoring, and their low irradiation levels make them innocuous. With respect to microwave radiometry, which is the only technique currently used clinically for noninvasive thermal control during hyperthermia sessions, active imaging provides much larger investigation depths and/or sensitivity. As an example, temperature gradients of the order of 1°C are visible over depths extending to approximately 20 or 30 cm.

Whereas the above camera is designed to operate in planar geometry, a circular configuration has been studied at the Universitat Politecnica de Catalunya, Barcelona, Spain (Fig. 2). This work has been supported by the Spanish Committee for Scientific and Technical Research (CAICYT) and by the Spanish National Institute for Health (FISS). It has been conducted within French/Spanish and British/Spanish cooperation agreements. A laboratory prototype as well as the corresponding reconstruction algorithms has been developed mainly for detecting thermal gradients in the brain [11]–[14]. The equipment consists of a circular array of 64 antennas operating at 2.45 GHz (Fig. 2). The diameter of the array is approximately 20 cm. When one of the antennas is emitting, the transmitted signal is received by the other ones, and so on. Several laboratory experiments on phantoms and volunteers have confirmed the potentialities of microwave imaging and the limitations imposed by the available recon-

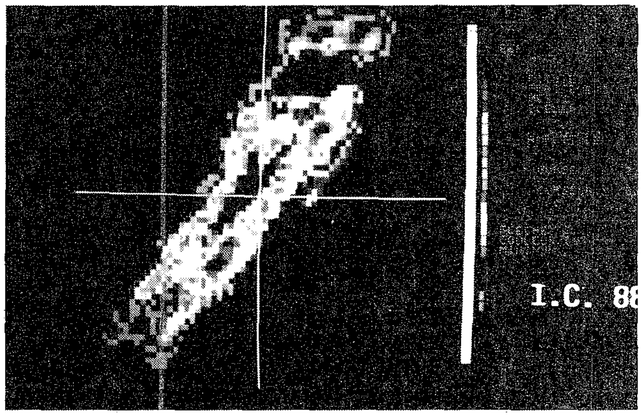


Fig. 3. Microwave image of a human forearm obtained with the microwave camera depicted on Fig. 1 from single view processing using a spectral reconstruction technique. Such an image is obtained within a few dozen seconds on a personal microcomputer (courtesy of Dr. G. Gaboriaud, Institut Curie, France).

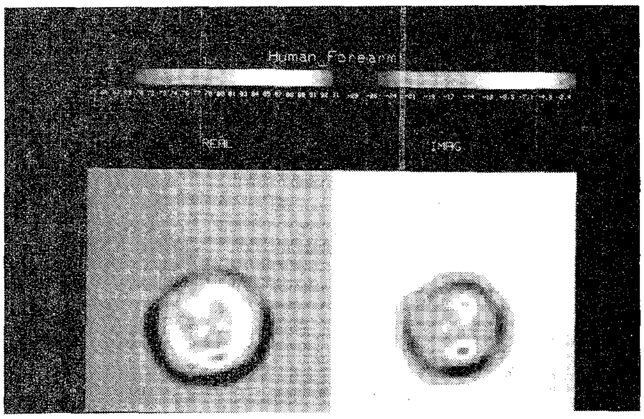


Fig. 4. Multiview tomographic reconstruction of a human forearm obtained with the circular array depicted in Fig. 2 (courtesy of Prof. L. Jofre, UPC, Spain).

struction algorithms. Both planar and circular geometries have their own fields of application, in which they exhibit comparable and/or complementary performances. Thermal sensitivity is about 1°C and spatial resolution in water is around 7 mm, which corresponds to the diffraction limit of half a wavelength in water at 2.45 GHz. In addition to the previous imaging systems, another configuration of equipment has been studied, consisting of an arrangement of two mutually orthogonal linear arrays [15].

Such a pragmatic and prototype-fabrication-oriented approach to biomedical applications has been supported by systematic studies on dielectric tissue characterization under normal and pathological conditions and by theoretical investigations of the possible improvement of reconstruction algorithms. For instance, the variations of complex permittivity with temperature have been studied in order to assess the role of thermoregulatory processes and, hence, evaluate the possibility of calibrating microwave images in terms of temperature. Concerning the reconstruction algorithms, a large effort has been devoted to expand the field of validity of different approximations inherent in the use of the most commonly used spectral approach [16]–[21]. Today, the results obtained by this technique still remain of limited interest in view of morphological imaging, for which more convenient imaging techniques exist. Figs. 3 and 4 show two examples of microwave images obtained *in vivo* from a human forearm. Although the quantitative aspects of such images remain to be established, the bone structures are clearly visible. It is worth adding that such images are obtained within a few seconds without mechanical movement of the patient or of the equipment. However, differential imaging appears to be still more promising during the follow-up of certain parameter changes (temperature, blood flow) during a treatment or due to the natural evolution of a pathology. In the future, this will probably be one of the best areas of application of microwave imaging, for either therapy or diagnosis.

Research is still continuing in deep or endocavitary hyperthermia control, which remains a very motivating challenge. The objective is to integrate microwave control equipment into existing or projected hyperthermia systems consisting of multi-RF applicators or arrays of microwave radiative waveguides. In this way, microwave imaging exhibits unique features when compared to other solutions such as electric impedance tomography or nuclear magnetic resonance (NMR) imaging. Investigations of other possible applications are planned at European clinical centers using the existing 2.45 GHz microwave cameras, e.g., early detection of fibrosis after accidental or therapeutic irradiation (Institut Curie, Paris, France) and follow-up of rejection after renal transplants (Royal Hallamshire Hospital, Sheffield, U.K.). In addition, further work on the algorithms is now being seriously considered, particularly in order to benefit from prior information and to introduce polarization effects. Different optimization techniques seem to be able to remove the limitations imposed by the spectral approach.

B. Buried Objects

The two following examples are representative of different approaches using microwaves in specific fields of applications. The first is devoted to the control of concrete [22]–[24]. The problem consists of detecting and localizing metallic bars and, finally, of estimating their diameter. Such a study has been conducted in France by the Centre National de la Recherche Scientifique (CNRS) with the support of Laboratoire Central des Ponts et Chaussées (LCPC, French Ministry of Transportation). It resulted in a portable linear sensor of 64 sensitive points, covering about one frequency octave around X-band (Fig. 5). Compared with other existing techniques (pachometer, gammagraphy), this sensor provides a unique capability to display concrete tomographic cross sections about 40 cm wide and 10 cm deep (Fig. 6). The success of microwave imaging in this application results from the relative simplicity of the structures under test (circular or square bars) and from the strong contrast between metal bars and the surrounding concrete.

A more complicated case is illustrated by the detection and identification of buried objects [25] using a FMCW

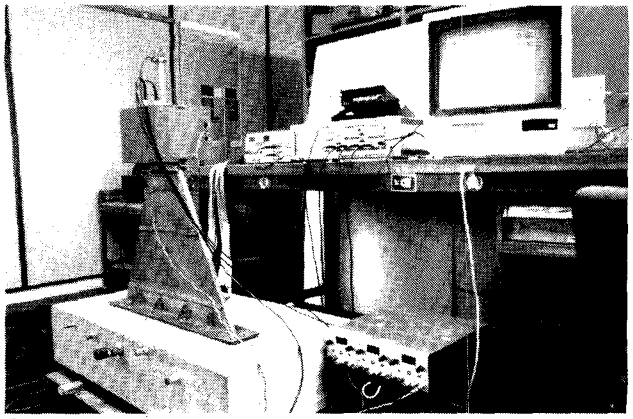


Fig. 5. *X*-band prototype for nondestructive inspection of reinforced concrete (courtesy of Dr. Ch. Pichot, CNRS, France).

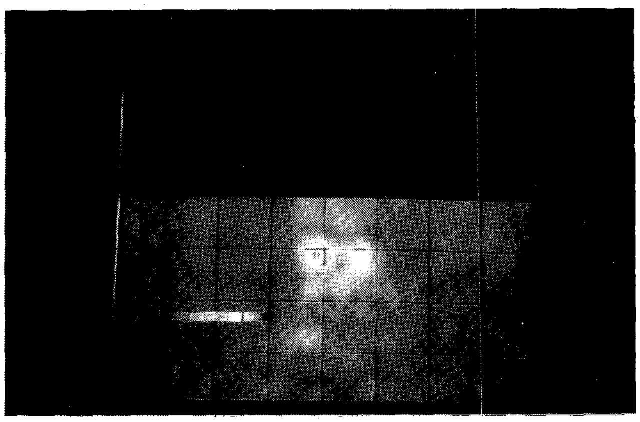


Fig. 6. Typical multifrequency tomographic reconstruction of a concrete calibrated sample with two bars using the equipment depicted in Fig. 3 (range scale: 4 cm/div) (courtesy of Dr. Ch. Pichot, CNRS, France).

radar for short-distance detection. At the Queen Mary College, London (U.K.), three compact versions of FMCW radars covering the 1–2, 2–4, and 9–11 GHz frequency bands have been designed. The radars are controlled by a microcomputer. A number of schemes for signal processing of the radar return have been investigated (FFT, matched filter, targets enhancement), both theoretically and experimentally. Images of buried targets (plastic pipes, metal plates) have been produced by means of synthetic aperture processing of data obtained from several mechanical scans of the radar. Images exhibit some bright spots, from which the main features of the object can be identified. Further work is devoted to achieving cross-polarization measurements. It is strongly recommended that the reader refer to a special issue devoted to subsurface radar [26].

C. Vision and Robotics

A significant effort has been devoted to millimeter-wave radars. Among ISM applications, short-range detection has been studied by six institutes of the Technische Universität München (West Germany) within the framework of a joint research program [27]–[30]. This long-term project started three years ago and will continue for six to nine

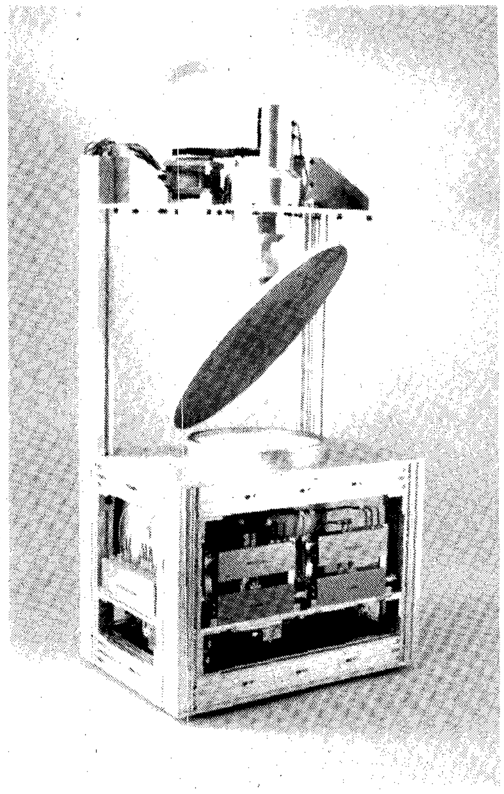


Fig. 7. Advanced prototype of a 94 GHz radar for autonomous vehicle devoted to robotics applications (courtesy of Prof. J. Detlefsen, TUM, West Germany).

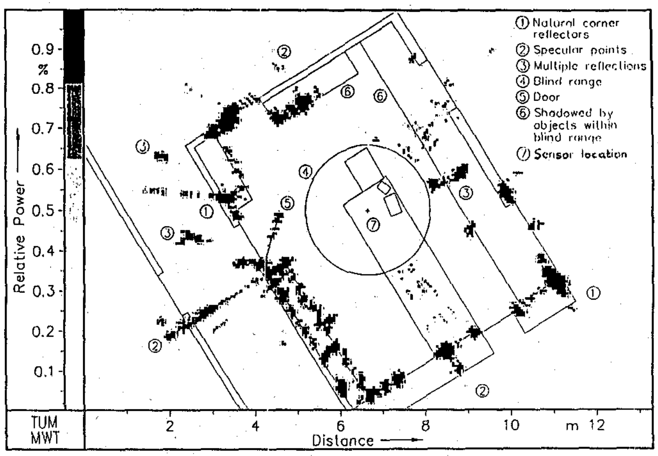


Fig. 8. Microwave image of a laboratory environment obtained at 94 GHz with the prototype depicted in Fig. 5. This view illustrates some typical features of millimeter-wave images: bright spots, diffuse scattering multiple reflections (courtesy of Prof. J. Detlefsen, TUM, West Germany).

years. It is totally federally funded. The objective is to develop a sensor for autonomous vehicles operating in partially predetermined environments, such as production plants. Real-time vision is expected to provide obstacle detection, precise navigation, and route planning for transportation and manufacturing tasks in industrial production. For this application, microwaves provide complementary means compared with more conventional video or acoustical sensors, whose performances are limited by real-time capabilities and range, respectively. Millimeter

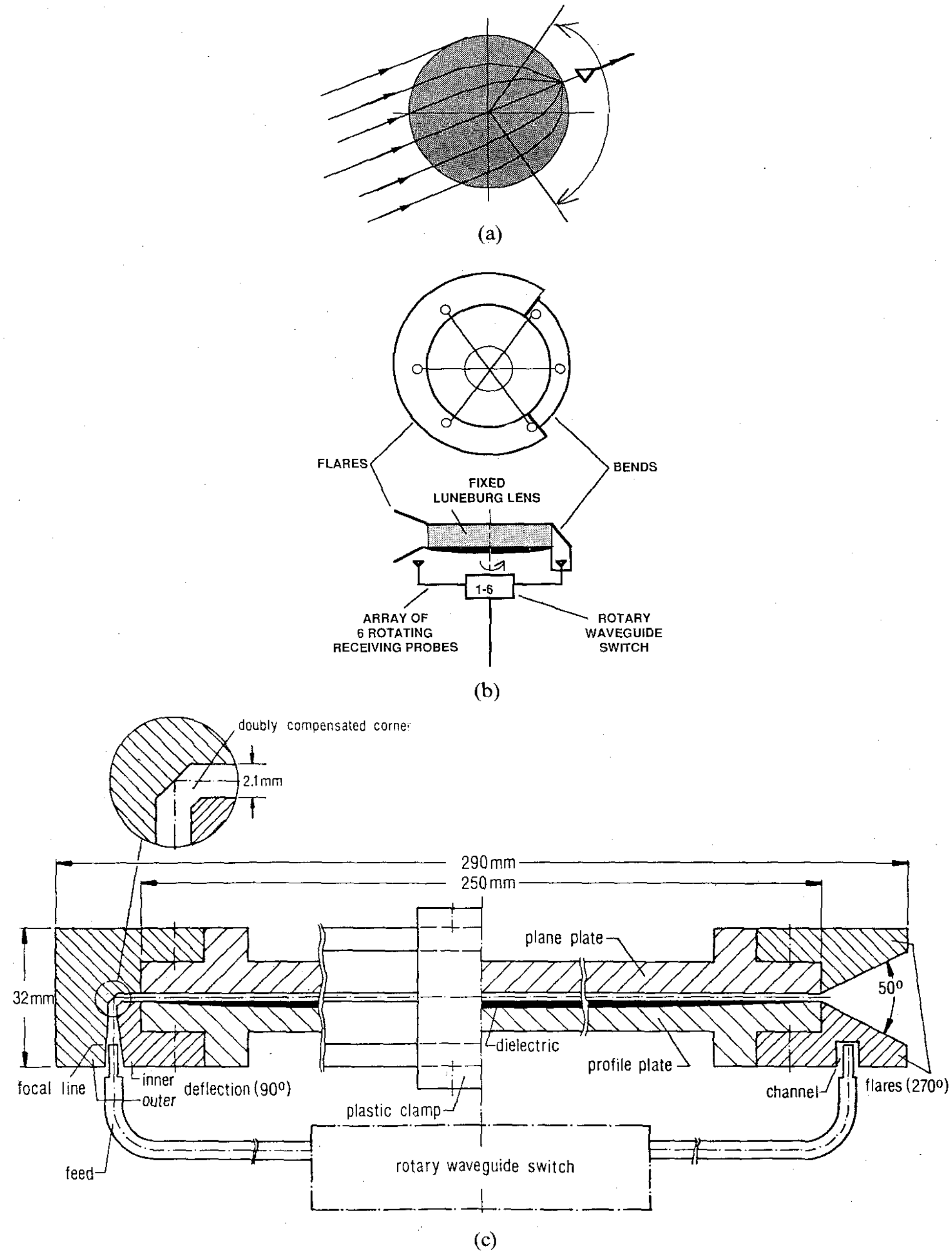


Fig. 9. Receiving Luneburg lens antenna for 70 GHz imaging radar. (a) Principle of a Luneburg lens with mechanical scan of the focal plane by means of a single probe. (b) Scheme of the practical realization for fast scanning. The focal plane of the parallel-plate Luneburg lens is explored by means of an array of six rotating probes. (c) Detailed drawing of the parallel-plate Luneburg lens (courtesy of Prof. H. Brand, Univ. Erlangen-Nürnberg).

waves offer self-illuminating capabilities and direct range and speed determination, as well as complete safety for the environment. A pulse Doppler radar prototype which operates at 94 GHz has been developed (Fig. 7). A deflection mirror, illuminated by a lens-corrected horn antenna, allows one to observe targets under near-field conditions up to 18 m. Azimuth and elevation coverages are, respectively, 360° and $\pm 20°$. With a pulse width of 1.7 ns, the range resolution is 25 cm. The data rate is approximately 10000 resolution cells per second. The prototype is mounted on a demonstration vehicle which is also equipped with a laser camera for scanning the close range up to a few m and a laser position detector up to a few cm. Fig. 8 shows typical results obtained when the radar is operating in a laboratory. The imaging capabilities of millimeter waves through diffuse scattering are clearly illustrated as well as some artifacts due to multiple reflections.

Other aspects of vision have been considered in the millimeter range [31]–[34]. As an example, a significant effort has been devoted to traffic monitoring for car drivers or helicopter pilots. Millimeter-wave radars are expected to provide them with real-time information on possible obstructions so that they can react properly at the right time. In such applications, in addition to usual radar data, it is necessary to determine other parameters, such as geometry and size. As shown in the case of the autonomous vehicle, millimeter-wave images are poorer than optical images due to the absence of diffuse scattering from the objects under investigation. A 70 GHz radar prototype, integrated in a minibus, has been developed and evaluated at the Universität Erlangen-Nürnberg. Radar performance requirements include high resolution, real-time and multiple target capability. Financial support was provided by the Deutsche Forschungs Gemeinschaft (East Germany). The emitting antenna consists of a cylindrical parabolic antenna and produces a frequency-modulated fan beam of broad azimuth angle ($\pm 30°$) but with only 1.5° in elevation. The azimuthal target analysis (64 cells) is measured quasi-optically by means of a plane Luneburg lens which has its focal plane mechanically scanned by an array of six rotating receiving probes. The focusing effect of the lens is achieved by means of a convenient shaping and dielectric filling of a parallel-plate section (Fig. 9). As a result, a picture repetition rate of 25/s is obtained. Within each azimuthal cell, range information is obtained from a 50 channel filter bank system. The range resolution is 2 m. With the existing prototype, imaging faults resulting from multiple reflections or from small displacements caused by ground vibrations or wind have been analyzed. The storage of up to 15 scans provides image improvements for both fixed and moving targets.

D. Nondestructive Testing and Quality Control of Materials

The following two examples illustrate two different approaches in terms of quantitative or qualitative imaging. This difference is very representative of the different possible uses of microwave images. In the first case, the problem consists in retrieving the complex permittivity of the object under test, similar to the way X-ray scanners retrieve the density. In the second case, the objective is "only," at least at the beginning, to "see" the object by means of microwaves. This means that, as in our optical vision of the environment, the objects are visible from their so-called equivalent current distribution. These currents provide a less objective perception of these objects, because equivalent currents are known to depend on both their intrinsic dielectric properties and on the total local field distribution, which in turn depends on the properties of the objects and on the way in which they are illuminated. While quantitative imaging provides more information on the object, it requires more data processing and the use of nonlinear reconstruction algorithms, resulting in a severe restriction of their field of applicability, as already shown in the section devoted to biomedical applications. On the other hand, qualitative imaging is much easier to achieve since only linear inversion is required. But the image is dependent on the illumination conditions. As in optics, the same object can be viewed very differently according to its illumination.

The object of the first example is a fine and quantitative diagnostic of dielectric samples. This objective involves derivation of the absolute complex permittivity using only phase tomograms. As expected from spectral approaches, such a derivation can be achieved only for low diffracting structures, for which Born's approximation is valid [35]. An accurate experimental setup has been realized at the University of Sheffield (U.K.), and the associated reconstruction algorithms compensate for the particular testing procedure, which consists of moving the object under test between two antennas. Experiments on cylindrical shells have demonstrated the efficiency and the limit of image subtraction techniques [35]–[38].

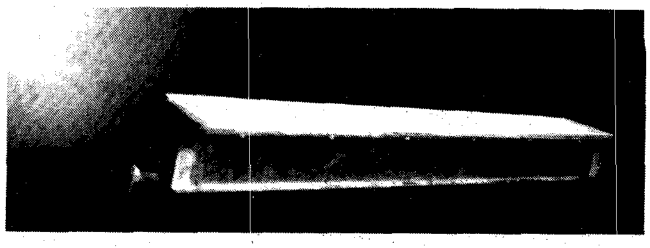


Fig. 10. *X*-band linear microwave sensor for nondestructive testing of conveyed products. Both reflection and transmission analyses are possible, in amplitude and phase, at the 128 modulated probes (courtesy of Satimo, France).

Fig. 10 shows a simpler example, which consists of a multipurpose, 1 m linear microwave sensor primarily designed for the control of conveyed products [39]. The translation of the product or material under test, combined with a rapid transversal multipoint analysis, allows one to obtain the microwave image of products moving at speeds as fast as a few meters per second. The modulated scattering technique technology provides, at moderate cost, measurement rates of the order of 20000 to 100000 points/s. Such a speed accommodates the fastest conveying speeds and considerably enlarges the capabilities of conventional single-point microwave sensors. Such a linear sensor allows one to measure the local reflection and/or transmission coefficients of different materials which are assumed to be representative of some property of this material (humidity, local defect, roughness). In this way, it opens the way to real-time transverse control over distances extending up to several meters. Evaluations are in progress in various domain of applications, among them control of paper humidity during drying processes, detection of defects in wooden boards in view of sawing optimization (Fig. 11), and quality control of laminated/composite layers. In such applications, the required spatial resolution is of the order of 1 cm. This can be rather easily obtained by means of oversampling or wave front processing, such as free-space retropropagation or synthetic aperture treatment. Beside these applications, the linear sensor can also be used for the control of more complicated, passive or active, objects in plane (rectangular, polar) or cylindrical geometries, as is usual in antenna testing [40]–[42].

With respect to other nondestructive testing modalities (X rays, ultrasonics), microwaves offer certain advantages for testing microwave materials, that is, materials to be used at microwave frequencies, such as absorbing or transparent materials devoted to radar or radome applications. Indeed, microwave inspection gives access to the final and global quality of the product in terms of absorption or

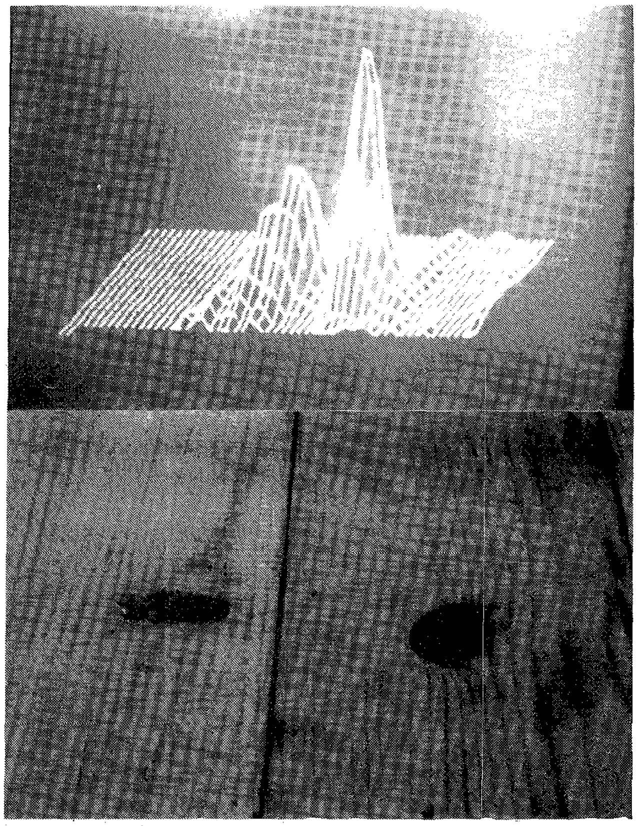


Fig. 11. Wooden board with two nodes and its three-dimensional microwave image obtained by transmission with the linear sensor depicted on Fig. 9 (courtesy of Satimo, France).

transparency, while other techniques provide information on some partial structural characteristic.

III. Conclusion

In conclusion, microwave imaging may be said to be at a turning point in its development. Microwave imaging is now growing by itself with the help of specific tools after a period (before the 1980's, approximately) which was mainly characterized by an attempt to adapt optical holographic techniques. On the one hand, radar techniques are stimulated by the technological progress that has been achieved in the millimeter and submillimeter ranges. On the other hand, it has been possible to consider tomographic techniques thanks to convenient means of recording microwave wave fronts and to numerical reconstruction algorithms which, even if imperfect, have made it possible to demonstrate as never before the possible usefulness of microwave imaging in an increasingly broad field of applications. This paper has been intentionally limited to, roughly speaking, ISM applications, excluding certain others relevant to military radar imagery or antenna testing. There is no doubt that some overlap exists between all these applications. As for the future of microwave imaging, it appears that it will be influenced strongly by the improvement of microwave technologies and by some refinement of algorithms in view of quantitative reconstruction of the dielectric properties. Concerning the second aspect, the rapid progress expected in the performance of microcomputers constitutes a decisive factor in the improvement of the quality of microwave images. The success of microwave imaging equipment will depend, case by case, both on the physical feasibility, which is mainly governed by contrast considerations, and on the commercial feasibility, which depends on the possibility of developing equipment accommodating all the operational constraints at acceptable cost. Thanks to the results obtained with the existing equipment, it can already be seen that microwaves offer some interesting and original features, features than can be used alone or in conjunction with other control techniques which are already well established.

Acknowledgment

The author would like to express his warmest thanks to his European colleagues for their help in preparing this review paper. In particular, Prof. A. P. Anderson, Prof. H. Brand, Prof. J. Detlefsen, Prof. H. Ermert, Prof. L. Jofre, Prof. E. Möller, Prof. A. D. Olver, Dr. G. Gaboriaud, Dr. B. Brusmark, Dr. Ch. Pichot, and Dr. S. Ström are sincerely thanked for providing the author with adequate material.

References

[1] G. Tricoles and N. B. Farhat, "Microwave holography: Applications and techniques," *Proc. IEEE*, vol. 65, pp. 108–121, Jan. 1977.

[2] A. P. Anderson, "Microwave holography," *IEE Rev.*, vol. 124, no. 11R, pp. 946–962, Nov. 1977.

[3] G. Peronnet *et al.*, "A microwave diffraction tomography system for biomedical applications," in *Proc. 13th European Microwave Conf.* (Nürnberg), Sept. 1983, pp. 529–533.

[4] L. E. Larsen and J. H. Jacobi, "Microwave scattering imagery of isolated canine kidney," *Med. Phys.*, vol. 6, no. 5, pp. 394–403, 1979.

[5] J.-Ch. Bolomey, L. Joffre, and G. Peronnet, "On the possible use of microwave active imaging for remote thermal sensing," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-31, pp. 777–781, 1983.

[6] Ch. Pichot, L. Jofre, G. Peronnet, and J. Ch. Bolomey, "Active microwave imaging of inhomogeneous bodies," *IEEE Trans. Antennas Propagat.*, vol. AP-33, pp. 416–425, 1985.

[7] J. L. Guerquin-Kern, M. Gautherie, G. Peronnet, L. Joffre, and J. Ch. Bolomey, "Active microwave tomographic imaging of isolated, perfused animal organs," *Bioelectromagnetics*, vol. 6, pp. 145–156, 1985.

[8] G. Gaboriaud *et al.*, "Microwave tomography in non-invasive control of hyperthermia," in *Proc. 9th IEEE EMB-S Int. Symp.* (Boston), Nov. 1987, pp. 1618–1619.

[9] J. Ch. Bolomey, M. S. Hawley, H. de Talhouet, C. Lavergne, and G. Gaboriaud, "A comparative study of active and passive imaging for non invasive thermal sensing during hyperthermia," in *Proc. 9th IEEE EMB-S Int. Symp.* (Boston), Nov. 1987, pp. 1933–1934.

[10] J. Ch. Bolomey and M. S. Hawley, "Non-invasive control of hyperthermia," in *Clinical Thermology*, M. Gautherie, Ed. New York: Springer (to be published).

[11] L. Jofre, M. S. Hawley, A. Broquetas, E. de los Reyes, and M. Ferrando, "Medical imaging with a microwave tomographic scanner," submitted to *IEEE Trans. Biomed. Imaging*.

[12] J. M. Rius, M. Ferrando, L. Jofre, and A. Broquetas, "Microwave tomography: An algorithm for cylindrical geometries," *Electron. Lett.*, vol. 23, no. 11, 564–565, 1987.

[13] A. Broquetas *et al.*, "Temperature and permittivity measurements using a cylindrical microwave imaging system," in *Proc. 17th European Microwave Conf.* (Rome), Sept. 1987, pp. 892–895.

[14] J. M. Gironès, L. Jofre, M. Ferrando, E. de los Reyes, and J. Ch. Bolomey, "Microwave imaging with crossed linear arrays," *Proc. Inst. Elec. Eng.*, vol. 134, pt. F, no. 3, pp. 249–252, June 1987.

[15] G. Peronnet, L. Jofre, and J. Ch. Bolomey, "Linear array arrangement for microwave tomography," *Radio Sci.*, vol. 19, no. 5, pp. 1342–1346, Sept.–Oct. 1984.

[16] M. Baribaud, F. Dubois, R. Floyrac, M. Kom, and S. Wang, "Tomographic image reconstruction of biological objects from coherent microwave diffraction data," *Proc Inst. Elec. Eng.*, pt. H, vol. 129, pp. 356–359, 1982.

[17] H. Ermert, F. Fülle, and D. Hiller, "Microwave computerized tomography," in *Proc. 11th European Microwave Conf.* (Amsterdam), 1981, pp. 421–426.

[18] H. Ermert and M. Dohlus, "Microwave diffraction tomography of cylindrical objects using 3-dimensional wave-fields," *Nachrichtentech. Z.*, Bd. 8, H5, pp. 111–117, 1986.

[19] H. Ermert, "Medical imaging using microwaves and ultrasound," in *Proc. 16th European Microwave Conf.* (Dublin), Sept. 1986, pp. 42–52.

[20] K. Klingenbeck and J. Regn, "The influence of multiple scattering on microwave imaging," in *Proc. 15th European Microwave Conf.* (Paris), Sept. 1985, pp. 643–648.

[21] W. Tabbara *et al.*, "Diffraction tomography: Contribution to the analysis of some applications in microwaves and ultrasonics," *Inverse Problems*, vol. 4, no. 2, pp. 305–331, May 1988.

[22] J.-Ch. Bolomey and Ch. Pichot, "Applications of microwave imaging techniques to non-destructive testing," *Journées Int. de Nice sur les Antennes*, pp. 485–489, Nov. 1988.

[23] L. Chommeloux, Ch. Pichot, and J. Ch. Bolomey, "Electromagnetic modeling for microwave imaging of cylidrical buried inhomogeneities," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-34, pp. 1064–1076, Oct. 1986.

[24] Ch. Pichot and P. Trouillet, "Active microwave imaging for nondestructive testing in reinforced concrete," presented at Structural Faults and Repair—89 Symp. London, 27–29 June 1989.

[25] A. D. Olver and L. G. Cuthbert, "FMCW radar for hidden object detection," *Proc. Inst. Elec. Eng.*, vol. 135, pt. F, pp. 354–361, Aug. 1988.

[26] Subsurface radar (special issue), *Proc. Inst. Elec. Eng.*, pt. F, Aug. 1988.

[27] J. Detlefsen, "Application of multistatic radar principles to short range imaging," *Proc. Inst. Elec. Eng.*, vol. 133, pt. F, pp. 658–662, Dec. 1986.

[28] J. Detlefsen, M. Lange, and M. Brockmair, "Precise reconstruction of the surface of cylindrical objects by evaluation of microwave tomographic data," *Proc. 1986 URSI Int. Symp.* (Budapest), Aug. 1986.

[29] M. Lange, J. Detlefsen, and M. Brockmair, "94 GHz imaging radar for autonomous vehicles," in *Proc. 18th European Microwave Conf.* (Stockholm), Sept. 1988, pp. 826–830.

[30] J. Detlefsen, "Evaluation of near range 94 GHz radar images for autonomous vehicles," in *Proc. Int. Conf. Radar* (Paris), April 1988, p. C2a.7.

[31] H. Brand, "Abbildung mit elektromagnetischen Mikrowellen, insbesondere von schnell bewegten Objekten, (Real time microwave imaging systems in traffic applications)," *Frequenz*, vol. 40, pp. 181–187, 1986.

[32] S. Osterrieder, "Imaging of moving targets with millimeter waves," in *Proc. Military Microwaves Conf.* (Brighton), 24–26 June 1986, p. 22.

[33] J. Kjellgren and G. Stenström, "On colour-coding of radar pictures," *Opto*, vol. 28, pp. 33–38, Sept.–Oct. 1985.

[34] H. Brand, E. Kreutzer, and M. Vogel, "Realtime 70 GHz-imaging system for close range applications," in *Proc. 13th European Microwave Conf.* (Nürnberg), Sept. 1983, pp. 534–539.

[35] A. P. Anderson and R. Aitmehdi, "Phase tomography in microwave diagnostic," *Electron. Lett.*, vol. 19, pp. 873–874, 1983.

[36] R. Aitmehdi, A. P. Anderson, and M. Ferrando, "The determination of dielectric loss tangent by microwave phase tomography," *Inverse Problems*, vol. 4, pp. 333–345, May 1988.

[37] A. P. Anderson, and M. F. Adams, "Holographic and tomographic imaging with microwaves and ultrasound," in *Inverse Methods in Electromagnetic Imaging*, W. M. Bœrner *et al.*, Eds. Norwell, MA: Reidel, 1985, pp. 1137–1146.

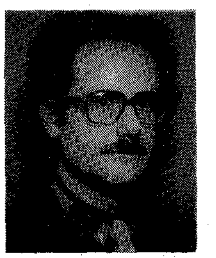
[38] M. F. Adams and A. P. Anderson, "Synthetic aperture tomographic imaging for microwave diagnostics," *Proc. Inst. Elec. Eng.*, vol. 129, pp. 83–88, 1982.

[39] "Linear microwave sensor for industrial applications," Application notes, SATIMO, Gif-sur-Yvette, France

[40] J. Ch. Bolomey, "Fast measurements of antenna near-field," *Journées Int. de Nice sur les Antennes JINA's 86*, pp. 413–421, Nov. 1986.

[41] J. Ch. Bolomey *et al.*, "Rapid near-field antenna testing via arrays of modulated scattering probes," *IEEE Trans. Antennas Propagat.*, vol. 36, pp. 804–814, June 1988.

[42] J. Ch. Bolomey, "La méthode de diffusion modulée: une approche au relevé des cartes de champs micro-ondes en temps réel," *Onde Elec.*, vol. 62, pp. 73–78, May 1982.



Jean-Charles Bolomey was born in Paris, France, in 1942. He received the electrical engineering degree from the Ecole Supérieure d'Electricité, Gif-sur-Yvette, France, in 1963 and the Ph.D. degree from the University of Paris-XI (Orsay), in 1971.

He became Assistant Professor in 1974 and Professor in 1976 at the University of Paris-XI (Orsay). His research activity, conducted in the Groupe d'Electromagnétisme (CNRS-ESE) since that time, has been devoted to general scattering and diffraction, with attention given to both numerical and experimental aspects. Since 1981, his main field of interest has been in near-field imaging, with special emphasis on biomedical applications, antenna measurements, and nondestructive testing.

Dr. Bolomey received the Blondel medal of the Société des Electriciens et des Electroniciens in 1976, the General Ferié Prize de l'Académie des Sciences in 1984 and, with his group, the Microwave Prize of the European Conference in Nürnberg in 1983. From 1977 to 1982, he was President of Section 25 (ondes et signaux) of the Société des Eléctriciens et des Eléctroniciens. From 1978 to 1984, he served as the French delegate to Commission B of the International Union of Radio Science.