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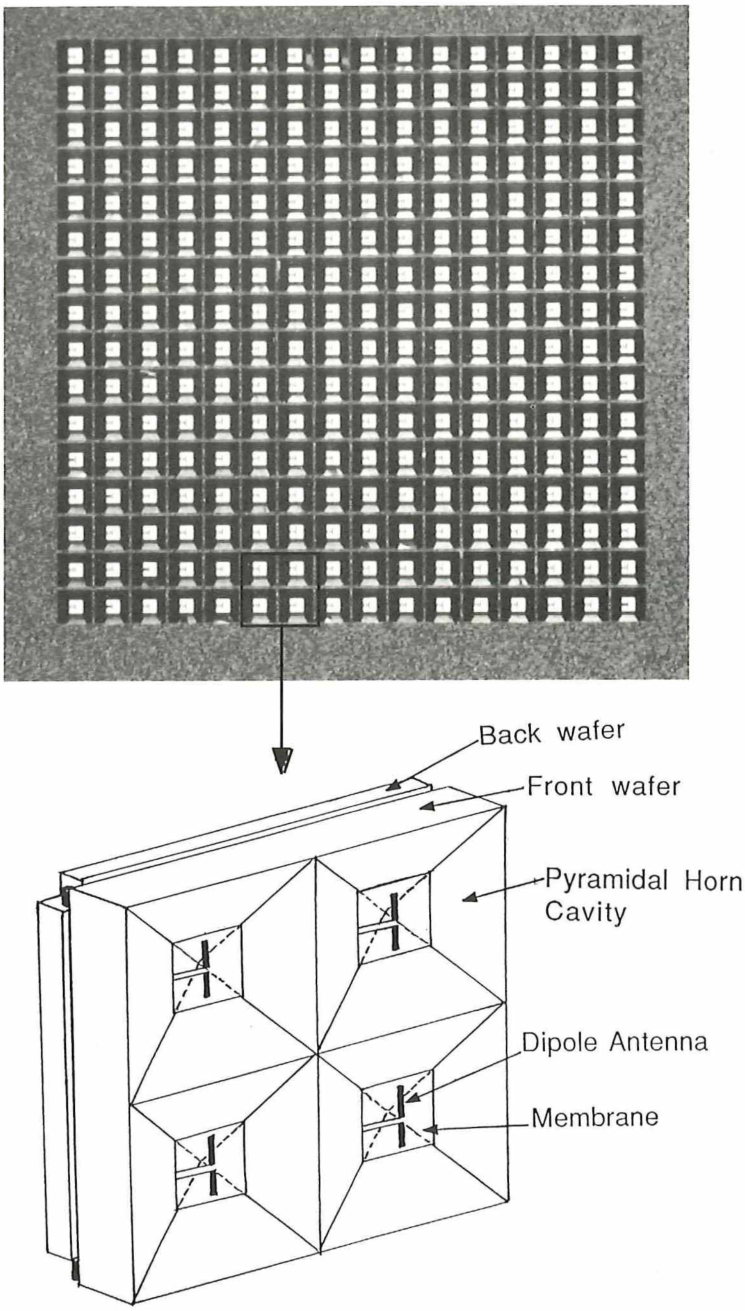

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The
Radioscientist

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COVER: Upper: 256 horns in 8 x 8 mm antenna array for 800 GHz. Lower: Detail for 4 horns (approx. 1 x 1 mm).

URSI Magazine

It is proposed that, from the first issue of 1994 (March), *the Radioscientist* and the *Bulletin of Information* will be combined. The format would be A4 as the present *Radioscientist* but it would have many more pages. All scientific participants (that is, excluding only the Accompanied Persons and students) will automatically become subscribers for the following three years at no extra cost beyond their Kyoto Registration Fee. Thus any who invariably attend URSI General Assemblies will always get this combined magazine. There will be an annual and triennial subscription fee for those unable to attend the Kyoto G.A. as well as one for libraries.

What to call it? James Wait (our Review Editor among many more prestigious titles) points out (see the current issue of the *Bulletin*) that there could be confusion between the journal *RADIO SCIENCE*, the magazine *Radioscientist*, and the triennial *Review of Radio Science*. One could therefore call the combined magazine the *Bulletin*, on the grounds that the latter has been around for a very long time, but the new magazine would be clearly different if it contained all the features and format (A4) of the present *Radioscientist*. Maybe it would be better to devise a new name with the subtitle, "incorporating *the Radioscientist* and the *Bulletin of Information*." The present subtitle of *the Radioscientist* is "The magazine of URSI" (in white on the blue banner). The *IEEE Antennas and Propagation Magazine*, with which we have a close association, is frequently abbreviated to *AP-S Magazine*. Any suggestions? I'm sure the URSI Council at Kyoto, which has to make the decision, will welcome such suggestions. In the meantime, write a letter to *the Radioscientist* so that we can have some discussion on this. If you feel that *the Radioscientist* should be simply discontinued so that the *Bulletin* should continue alone, your letter will be particularly welcome. It will (I hope!) make the discussion more lively.

The Editor of the combined magazine will have a bigger job than mine at present if the whole job (soliciting contributions, seeking referees, copy editing (and virtually translating in some cases), composing, typesetting, illustration placing and proofreading!) is to be done by one person in his/her spare time. Not that it is not a rewarding task—for better or worse it is a work of art or skill which one sets one's self and which can give one satisfaction. Having begun the *URSI NEWS* following the Tel Aviv G.A., and enlarged this into *the Radioscientist* at the Prague G.A., it might be time for some one else to take over. Besides, I cannot cope with the increased job if I have an URSI role as well, though I could bring out the last issue (December, 1993) of *the Radioscientist.*

Candidates for the editorship need to have had experience and have the skills for all tasks mentioned above. A few names have been suggested but I feel it would be better if aspiring candidates should suggest themselves and seek to take over part of my job **now**. This way they could learn on the job and be up to speed in time to take over the full job. In this age of electronic communications (email, FTP, etc.), and since *the Radioscientist* is completely electronic, such a "serious" assistant editor need not be physically close to the Editor-in Chief to be fully effective, though it would help if we use the same tools (Macintosh, Word 5, PageMaker, unless I'm the one to relearn!). So, if you would like to take on this challenge, send me an email, fax or letter (to Germany until the end of October).

1993 URSI G. A.

I must confess to my Czech friends that I voted against having the 1990 URSI General Assembly at Prague. I had participated at a General Assembly (not URSI) at Prague in the "bad old days" and found the visa difficulties and currency problems most irksome. To cap it all, I unthinkingly shaved off my beard and nearly failed to get out of the CSSR since my passport photo still showed a large beard!

How wrong I was to vote that way! The 1990 General Assembly at Prague was the best ever for URSI and the most enjoyable and memorable of any such meeting I have ever attended.

At Prague, as a V.P. and so with no vote, I had misgivings about having the 1993 General Assembly at Kyoto. I felt the higher cost of holding it there would put the Registration fee too high for many URSI people. Once again I was wrong. **The Kyoto Registration fee supplies less than one third of the cost of holding the 1993 General Assembly**. The rest comes from Japanese industry and institutions. The fee is actually lower than that for similar General Assemblies at other places at about this time (1990's), but what you get for it is considerably more than what you would get at General Assemblies of most other Unions. In addition to the three-year subscription mentioned above, there will be some kind of continuing individual membership until the following General Assembly (1996), the details of which will be decided at Kyoto by Council.

As you read this, it is less than a year away, so do something soon about getting travel support from your institution or company. There will be 100 Young Scientists supported at Kyoto (the most ever), so if you are "young" (< 35), photo copy and fill in the form which appears on page 79.

Telephone tones

Why can't there be an international standard for telephone signals (dial tone, ringing tone, engaged tone, unobtainable tone, etc.)? During my six months in Europe, instead of in NZ and 12 hours out of phase with Europe, I have been able to phone people in their, and my, working hours. But how am I supposed to know what "beep beep..." means in Russia, England or South Africa? Now phones are wireless, can URSI fix it?

SCANNING THE ISSUE

The cover article is a fascinating description of millimetre-wave integrated horn antennas. The ability to control the geometry, the flexibility in determining matching impedance, and the option to have the front-end of the receiver integrated directly onto the same substrate as the antenna are exciting. I am greatly indebted to the authors and Ross Stone, Editor-in-Chief of the *IEEE Antennas and Propagation Magazine*, for permission to reprint this article from February issue of his *Magazine*.

In 1935, K. Posthumus published a paper in a Dutch journal on the calculation of radiation patterns generated by a linear antenna array. To the best of the author's (E. Goldbohm's) knowledge, this paper has never been cited in the English language scientific literature and appears to have escaped attention, probably because the original text was not easily accessible or in English. The version presented here is an annotated and abridged translation by Professor Goldbohm.

Our present understanding of cosmology owes much to radio astronomy but cosmology should be of interest to all radio scientists. The "hot big bang" model is well established by the evidence but there are still some problems. Jörg Pfleiderer brings up to date in this article.

Nicolai Danilkin from Moscow presents a strong case for an international, integrated system of satellite and ground-based ionosondes to monitor the ionosphere in particular and the Earth's near-space in general. The continued health of the ionosphere may have importance for the biosphere beyond HF communications regarded by some as superseded anyway. The problem is, who would finance it? What the world needs is an International Science Foundation with some $\$10^{12}$ to distribute annually to scientists anywhere in the world with good ideas for research.

All of the book reviews this issue are by the Review Editor, James Wait. If you would like to help out, please read Jim's note in the box on page 78—not only do you get to keep the book after reviewing it, you can nominate the book to start with! Having had to do them all, he gives five of them as "mini reviews." Two of the latter are about the development of radar, the jubilee of which we have celebrated by the cover stories of the two previous issues of *the Radioscientist* (and note in this issue that Posthumus had a hand in radar development too). One is also of relevance to Joseph Shapira's note in the current issue of the *Bulletin*.

Subscriptions

Get both *the Radioscientist* and the *Bulletin* airmailed to you for only $14 for the next four issues (December, 1992, to September 1993, inclusive), or $17 for the next (and final) five issues before the start of the new combined magazine. If you are one of the lucky URSI officials who get the *Bulletin* mailed free to you from Belgium in a personally addressed envelope (NOT just from your local committee from bulk mailed *Bulletins*) then you can have *the Radioscientist* added for only $5 for the next four issues (December '92 - September '93).

In either case, send your order with name and magazine address, and with cheque (bank or personal, in any hard currency) or credit card (***VISA*** or **MasterCard**) with owner name, card number and expiry date —

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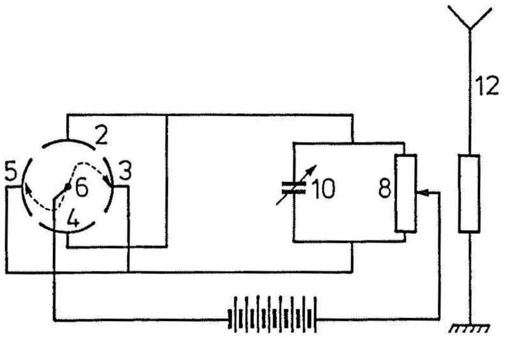
Interesting and striking photographs for *the Radioscientist* front cover are **still wanted**. The subject should be identifiable as radio physics or engineering within the URSI range of Commissions A to K. Until we can afford colour, prints should be glossy black and white or colour, suitable for digital scanning (size, within reason, is no longer important). The "portrait" format used so far on our cover is preferred but a striking photograph or graphic (e.g., analogue data) which needs "landscape" mode (short and wide) is also welcome. Please send submissions together with a descriptive caption to the Dunedin, NZ, address above (**not** to the German address).

POSTHUMUS' ANTENNA THEORY

Posthumus' early array theory of equivalent antennas

Introduction

In remembrance of Dr. Klaas Posthumus—a Dutch engineer and scientist who died in October 1990—it seems appropriate to recall some of his pioneering achievements and in particular his work on equivalent antennas, which is relevant to URSI activities and therefore is the main theme of this paper. In his early years, when employed at the Philips Physical Laboratory in Eindhoven under the direction of Dr. Balthasar van der Pol, Posthumus designed transmitting tubes and amplifiers.

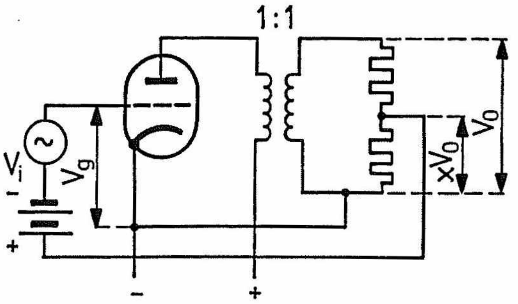


Circuit Diagram of the original patent application of the Posthumus Magnetron, indicating the rotating field.

During the development of a wideband measurement amplifier, he was confronted with stability problems. This inspired him to invent the idea of **negative feedback** in September 1928. In addition to improved stability, the new design featured much wider bandwidth and reduced distortion [1]. The patent on his invention was granted only in 1934, just about the time when Black of Bell Telephone obtained a similar patent.

Another field into which he endeavoured, as a consequence perhaps of his work on transmitting tubes, was that of the **split-anode magnetron**. His acknowledged evolution, in 1933, of the 4 segment magnetron and the rotating field theory of operation, by which he explained its advantage over a similar 2 segment system, was an outstanding contribution [2]. Of the possible modes of oscillation his travelling wave mode proved to be the most efficacious for practical microwave magnetrons! He applied for three patents on the magnetron in September 1933 [3]. The fundamentals of its operation were set out in *Wireless Engineer* [4] and *Nature*.

In early samples he obtained efficiencies of 40% at 50 cm wavelength. Some 50 cm magnetrons were delivered to the German Navy, apparently for radar [8] experiments. With a short circuited Lecher Line as a resonant output circuit, he further reduced the wavelength to 19 cm by incorporating the short inside the glass envelope [5]. The output power was 10 watt. The first practical application was on radio links, e. g., one between Eindhoven and Tilburg, another one between Eindhoven and Nijmegen, first at 90 cm later at 25 cm [6]. And so often inventions emerge almost simultaneously and independently in different countries. In France, Gutton of SFR also chose the split-anode magnetron as the most likely to achieve power at microwave frequencies.



Negative feedback. In this circuit (voltage feedback) a fraction xV_0 of the anode signal voltage, V_0 is fed back to the control grid in opposite phase to the input voltage V_i.

In 1936 he set about developing a 16 cm version and then improved power output. He successfully pioneered multisegment anodes and by 1937 the New M 16 with 8 segments produced 10 watt at 15% efficiency. The idea was patented in 1937 and tested in Le Havre. Radar range obtained was 5 km. In 1939 power was pushed to 300 watt by application of the new oxide cathode.

Megaw of GEC Wembley discussed results with Gutton. In May 1940 Dr. Ponte of SFR visited Wembley with some samples of the M16. With the oxide cathode they produced 0.5 kW at 16 cm wavelength. It is possible that Gutton was informed about Posthumus' developments, since two French Naval Officers witnessed a demonstration at the Philips Lab in 1939 of the magnetron in a **radar system**, which was under development since 1935. A small team with C.F.K.H. Staal as a project manager and headed by Posthumus tested the CW radar near Den Helder [5]. The set was very clutter sensitive and only after the introduction of pulse modulation were results achieved. In May 1940 ranges of better than 3.5 km on small ships were achieved in IJmuiden. The German invasion discontinued further tests on the spot, but further development continued in secret in Eindhoven until 1942. Since the Board of Philips did not know of the radar development a very low priority was given to the project. It was essentially a one-man job.

POSTHUMUS' ANTENNA THEORY

Posthumus published in 1935 in a Dutch Journal [7] a paper dealing with the synthesis, or rather the construction, of radiation patterns radiated from linear arrays. His theory, which did not make use of Fourier transforms as such, provided proof that the same power pattern may be radiated from arrays with n radiators for 2^{n-1} different element excitations.

In this paper, which is an abbreviated and annotated translation of the original, the principle of construction of n element arrays by repeated multiplication of 2 element (dual) arrays is demonstrated for 3 and 4 element arrays. For the sake of brevity the final part of his paper, dealing with 5 radiators, the binomial array, arrays with 2 radiators at n-uple distance and the parallelogram antenna have been omitted.

Posthumus' Early Array Theory : Equivalent Antennas—Directional Antennas with Equal Radiation Patterns but Different Current Distribution.

Question : Are there multiple combinations of array element excitation coefficients possible yielding the same relative radiation pattern?

Let us assume the far field of the array is :

$$E = \left[i_1 + i_2 e^{jx} + i_3 e^{2jx} + \ldots \right] \quad \text{and } i_i = r_i e^{j\alpha_i}$$

$$\text{so} \quad E_p = E \left[r_i e^{j\alpha_1} + r_2 e^{j(x+\alpha_2)} + r_3 e^{j(2x+\alpha_3} \right]$$

$$\text{or} \quad E_p^2 = E^2 \left[\sum_1^N r_i^2 + 2\cos x \sum_1^{N-1} r_i r_{i+1} \cos(\alpha_{i+1} - \alpha_i) \right.$$

$$- 2 \sin x \sum_1^{N-1} r_i r_{i+1} \sin(\alpha_{i+1} - \alpha_i)$$

$$+ 2 \cos 2x \sum_1^{N-2} r_i r_{i+2} \cos(\alpha_{i+2} - \alpha_i)$$

$$- 2 \sin 2x \sum_1^{N-2} r_i r_{i+2} \sin(\alpha_{1+2} - \alpha_i)$$

$$\left. + 2 \cos 3x \sum_1^{N-3} r_i r_{i+3} \cos(\alpha_{i+3} - \alpha_i) \right] \quad \text{etc.}$$

If for other current values the expressions above are required to be identical, that is, for every value of x, all coeff. of cos x, cos 2x etc. should be equal.

Thus : if $R_i = |R_i| e^{j\beta_i}$, the expressions for other illumination currents are :

$$\sum R_i^2 = \sum r_i^2 \tag{1}$$

$$\sum R_i R_{i+1} \cos(\beta_{i+1} - \beta_i) = \sum r_i r_{i+1} \cos(\alpha_{i+1} - \alpha_i) \tag{2}$$

$$\sum R_i R_{i+1} \sin(\beta_{i+1} - \beta_i) = \sum r_i r_{i+1} \sin(\alpha_{i+1} - \alpha_i) \tag{3}$$

Finally :

$$R_1R_n \cos(\beta_n - \beta_1) = r_1r_n \cos(\alpha_n - \alpha_1) \qquad (4)$$

$$R_1R_n \sin(\beta_n - \beta 1) = r_1r_n \sin(\alpha_n - \alpha_1) \qquad (5)$$

Equation (1) expresses the identity without mutual coupling. The other expressions contain extra energy by mutual coupling, or in other notation :

$$\sum R_i^2 = \sum r_i^2$$

$$\sum R_iR_{i+1}\, e^{j(\beta_{i+1} - \beta_i)} = \sum r_ir_{i+1}e^{j(\alpha_{i+1} - \alpha_i)}$$

etc.

$$\sum R_1R_ne^{j(\beta_n - \beta_1)} = \sum r_1r_ne^{j(\alpha_n - \alpha_1)}$$

in which only phase *differences* are taken into consideration.

Posthumus then treats the case of 2 and 3 radiators and states that an array with n elements can be decomposed in (n-1) dual antennas. In the 2 element case a typical example might be

$2 \bullet\!\rule{2cm}{0.4pt}\!\bullet 5e^{j\emptyset}$ is equivalent with $5 \bullet\!\rule{2cm}{0.4pt}\!\bullet 2e^{j\emptyset}$

because thus $R_1^2 + R_2^2 = r_1^2 + r_2^2$ and $R_1R_2 \cos\beta = r_1r_2 \cos\alpha$ and $R_1R_2 \sin\beta = r_1r_2 \sin\alpha$.

It follows therefore : $R_1{}^2 + R_2{}^2 = r_1{}^2 + r_2{}^2$ (pos. real values) and thus : $R_1R_2 = r_1r_2$ and also $\beta = \alpha$, $R_1 = r_2$ and $R_2 = r_1$.

Three elements derived by multiplication of two element arrays

$a\overset{x}{\underset{\mathrm{I}}{\rule{2cm}{0.4pt}}}b \qquad c\overset{x}{\underset{\mathrm{II}}{\rule{2cm}{0.4pt}}}d$

multiply I by II yields : $ca\overset{x}{\rule{2cm}{0.4pt}}(cb + da)\overset{x}{\rule{2cm}{0.4pt}}db$

The relative radiation pattern of the combination is the product of the two relative patterns (ab or cd).

By taking the mirror image of one or both sub-arrays (i.e. moduli exchanged, phase the same) we obtain the same pattern!

For a three-element array this gives four different excitations yielding the same relative radiation pattern viz.

Suppose sub array 1 : $r_1r_2e^{j\phi}$ and sub array 2 : $r_3r_4e^{j\theta}$Here a = r_1 b = $r_2e^{j\phi}$ c = r_3 d = $r_4e^{j\theta}$

Now since the new array is : ca ——— (cb + da) ———db, there are four solutions viz. :

r_1r_3 ———$r_2r_3e^{j\Phi} + r_1r_4e^{j\theta}$ ———$r_2r_4e^{j(\Phi+\theta)}$ (6)

r_2r_3 ———$r_1r_3e^{j\Phi} + r_2r_4e^{j\theta}$ ———$r_1r_4e^{j(\Phi+\theta)}$ (7)

r_1r_4 ———$r_2r_4e^{j\Phi} + r_1r_3e^{j\theta}$ ———$r_2r_3e^{j(\Phi+\theta)}$ (8)

r_2r_4 ———$r_1r_4e^{j\Phi} + r_2r_3e^{j\theta}$ ———$r_1r_3e^{j(\Phi+\theta)}$ (9)

By inspection it is clear that (6) and (9) possess equal moduli in reversed order. This also applies to (7) and (8). Furthermore phase differences between outer elements are always the same, whilst the phase of the centre element in each case is different. Also the real product of the outer elements always equals $r_1r_2r_3r_4$. As an illustration we take two simple antennas without phase difference i.e. : multiply 1-2 by 1-3 then it follows :

1.2	2.1	1.2	2.1
3.6	6.3	3.6	6.3
1.5.6	2.7.3	3.7.2	6.5.1

As a check we see $1^2 + 5^2 + 6^2 = 2^2 + 7^2 + 3^2 = 62$ (eq. 1)

power equality $\sum R_n^2 = \sum r_n^2$

and 1.5 + 5.6 = 2.7 + 7.3 = 35 (eq. 2)

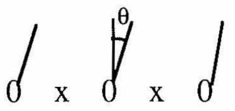
and 1.6 = 2.3 = 6 (eq. 4)

and also 1 + 5 + 6 = 2 + 7 + 3 = 12 (sum of voltages equal).

Note:

The author observed that the roots of the polynomial 1.5.6 are -1/2 and -1/3 and the roots of the polynomial 2.7.3 are -2 and -1/3. We see that -2 is the reciprocal of -1/2, which is in accordance with the observation made below.

This array can be represented by :



If $\Phi = \frac{2\pi x}{\lambda} \sin\theta$, there are two configurations,

$e^{-j\Phi} + 5 + 6e^{j\Phi}$ and $2e^{-j\Phi} + 7 + 3e^{j\Phi}$ for any Φ.

It is easy to prove their identity as regards the power radiation patterns.

Next Posthumus extends the method to the general case of n elements. The reader is referred to the original paper for the mathematics. He derives and proves that for an n element equally spaced array there are 2^{n-1} solutions, some of which may be trivial (e.g. by mirror symmetry). At page 128 of his paper, he states that when a dual antenna is replaced by its mirror image, we should replace its root

$r_i = r_i e^{j\Phi_i}$ by $\frac{1}{r_i} \,.\, e^{j\Phi_i}$ i.e. by its reciprocal complex conjugate.

He then proceeds to argue, that if the roots of the polynomial (page 128), are respectively Z_1 ... Z_{n-1}, we can write for the currents :

$$i_1 = 1$$

$$i_2 = Z_1 + Z_2 + \ldots\ldots Z_{n-1}$$

$$i_3 = Z_1Z_2 + Z_2Z_3 + Z_3Z_4 + \ldots\ldots Z_1Z_4 \text{ etc.}$$

$$i_4 = Z_1Z_2Z_3 + Z_1Z_2Z_4 + \ldots\ldots\ldots\ldots\ldots \text{ etc.}$$

$$i_n = Z_1Z_2Z_3 \ldots\ldots Z_{n-1}.$$

or for four elements :

$$i_1 = 1$$

$$i_2 = r_1 e^{j\Phi_1} + r_2e^{j\Phi_2}\; r_3e^{j\Phi_3}$$

$$i_3 = r_1r_2e^{j(\Phi_1+\Phi_2)} + r_2r_3e^{j(\Phi_2+\Phi_3)} + r_1r_3e^{j(\Phi_1+\Phi_3)}$$

$$i_4 = r_1r_2r_3e^{j(\Phi_1+\Phi_2+\Phi_3)} \qquad (10)$$

When now a dual antenna associated with Z_i is replaced by its mirror image $\frac{1}{Z_i^*}$ then $r_ie^{j\Phi i}$ $\frac{1}{r_i}$ $e^{j\Phi i}$ and in addition each element must be multiplied by a constant factor C, because otherwise the new antenna will not have the same strength.

So for the 4 element array above we obtain :

$$i'_i = C \quad i'_2 = C\left(\frac{1}{r_1}\, e^{j\Phi_1} + r_2e^{j\Phi_2} + r_3e^{j\Phi_3}\right)$$

$$i'_3 = C\left(\frac{r_2}{r_1}\, e^{j(\Phi_1+\Phi_2)} + r_2r_3e^{j(\Phi_2+\Phi_3)} + \frac{r_3}{r_1}\, e^{j(\Phi_1+\Phi_3)}\right)$$

$$i'_4 = C\,\frac{r_2r_3}{r_1}\, e^{j(\Phi_1+\Phi_2+\Phi_3)}$$

Now it follows from $i_4.i_4 = i'_4\, i'_4$ that $C = r_1$ so

$$i'_1 = r_1$$

$$i'_2 = e^{j\Phi_1} + r_1r_2e^{j\Phi_2} + r_1r_3e^{j\Phi_3}$$

$$i'_3 = r_2e^{j(\Phi_1+\Phi_2)} + r_1r_2r_3e^{j(\Phi_2+\Phi_3)} + r_3e^{j(\Phi_1+\Phi_3)}$$

$$i'_4 = r_2r_3e^{j(\Phi_1+\Phi_2+\Phi_3)}$$

We will call the above set (11) and call the sets for when r_2 and r_3 are replaced, (12) and (13). When r_2 and r_3 are replaced simultaneously by $\frac{1}{r_2}$ and $\frac{1}{r_3}$ we obtain $C = r_2.r_3$

and $i''_1 = r_2r_3$

$$i''_1 = r_1r_2r_3e^{j\Phi_1} + r_3e^{j\Phi_2} + r_2e^{j\Phi_3}$$

and $i''_3 = r_1r_3e^{j(\Phi_1+\Phi_2)} + e^{j(\Phi_2+\Phi_3)} + r_1r_2e^{j(\Phi_1+\Phi_3)}$

$$i''_4 = r_1e^{j(\Phi_1+\Phi_2+\Phi_3)}$$

calling this set (14) and similarly for (15) and (16).

Finally when r_1, r_2 and r_3 are replaced :

$$i_1''' = r_1r_2r_3$$

$$i_2''' = r_2r_3e^{j\Phi_1} + r_1r_3e^{j\Phi_2} + r_1r_2e^{j\Phi_3}$$

$$i_3''' = r_3e^{j(\Phi_1+\Phi_2)} + r_1e^{j(\Phi_2+\Phi_3)} + r_2e^{j(\Phi_1+\Phi_3)}$$

$$i_4''' = e^{j(\Phi_1+\Phi_2+\Phi_3)} \qquad (17)$$

(17) is seen to be the mirror image of (10) if all terms are multiplied by $e^{-j(\Phi_1+\Phi_2+\Phi_3)}$

Similarly (11) & (14), (12) & (16), and (13) &(15) are mirror images. Posthumus then goes on with five element arrays, the binomial antenna etc. etc.

From the above it can be said, that Posthumus had already synthesized linear arrays in 1935, making use of the roots of the array polynomial

$$E = \sum_{1}^{N} a_n Z_n$$

though it was more an analysis of a step by step construction of linear arrays than a synthesis.

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BOOK REVIEWS

Lateral Electromagnetic Waves

by Ronold W.P. King, Margaret Owens, and Tai Tsun Wu, Springer Verlag, 1992, xxvii + 746 pages, $80.00, ISBN 0-387-97679-5

This monumental book deals quite generally with the electromagnetic fields associated with sources in the vicinity of an interface between two homogeneous regions. The emphasis is on various analytical approaches which lead to explicit expressions for the electric and magnetic field components in terms of elementary functions. The book is based, for the most part, on the research carried out by the authors at Harvard University over the past several decades. At various places in the text, the authors call attention to related work by others but this does not seem to be the thrust of their treatise. However, they do not give some prominence to the monograph *Dipole Radiation in the Presence of a Conducting Half-Space" by* A. Banos, Jr.. (Pergamon Press, Oxford, 1966) who had provided some relatively simple approximate formulas for the fields of dipole antennas in the presence of a planar earth model of relatively high conductivity. The present monograph, under review, develops the subject in much greater depth but, to some extent, such has been done at the expense of much greater complexity.

An outline of the contents of the book is given as follows: Chapter 1 contains an interesting historical sketch of the subject of lateral waves written from the author's perspective; Chapter 2 is a useful review of the relevant basic electromagnetic theory including some detailed plots of Fresnel reflection coefficients; Chapter 3 presents derivations for the fields of a VED (vertical electric dipole) in the presence of a planar interface working directly with field components rather than exploiting the more conventional Hertz vectors; Chapter 4 deals with some specific applications from Chapter 3; Chapter 5 now deals with the horizontal electric dipole where explicit integral formulas are given for the fields in both regions (above and below the interface); Next Chapter 6 discusses various approximate formulas from the above and shows comparisons with both the exact expressions and measurements; Chapter 7 includes many further applications with particular reference to communicating with submarines and related underwater problems; Chapter 8 deals with the oceanic lithosphere treated as an isotropic conducting half-space and relevant experimental data are discussed; Chapter 9 extends the theory to anisotropic half-space models; Chapter 10 is concerned with the effect of vertical discontinuities in the electrical properties such as a land/sea boundary; Chapter 11 is devoted to layered earth models where again any curvature is neglected; Chapter 12 applies the above to a three-layer sea floor; Chapter 13 gives exact expression for the pulse response of a delta function source over the interface between two dielectric half-spaces; Chapter 14 then extends this to lossy regions but approximations are made; Chapter 15 discusses related problems of open microstrip configurations; Chapter 16 treats bare cylindrical linear antennas near boundaries; Chapter 17 follows up with the analysis of the terminated insulated antenna; and finally Chapter 18 is an extensive analysis of the Beverage Wave Antenna and similar grounded wire configurations. Appendices A through G provide some mathematical material such as the evaluation of Bessel function integrals.

The authors are strong advocates that analytical approaches to this topic yield valuable insight not immediately available in purely computationally oriented procedures. A striking example, where this situation arises, is when the dipole is located on the surface of a pure or low-loss dielectric half-space. The field strength vs. distance curves exhibit fine scale interference patterns which are not apparent in a computational approach unless, of course, one might have had some idea that such would occur. The authors go to great pains to develop this point of view and some may not agree with their emphatic opinions in this regard.

One curious omission in the authors' otherwise comprehensive coverage is the very important case where the distances in the lower conducting half space are allowed to be comparable with skin depth but such distances are small compared with wavelength in the air. Such a condition is very common in geophysical exploration and the relevant theory has been covered in several places (e.g. *GeoElectromagnetic* by J. R. Wait, Academic Press, 1982 and M. N. Nabighian, editor, *EM Methods in Applied Geophysics*, vol. 1, Soc. of Exploration Geophysicists, Tulsa, 1987). Here displacement currents in the air are not ignored but the fields are quasi-static while they are dynamic in the lower conducting half-space i.e. $k_2 r << 1$ and $k_1(r^2 + z^2)^{1/2}$ is unrestricted. It is also assumed here that $|k_2/k_1|^2 << 1$.

The authors state in their preface that "Although complete in itself, this book is restricted to electromagnetic waves in the presence of plane boundaries". They go on to ask "What happens to a lateral wave generated by a vertical monopole on the surface of the spherical earth?". The authors offer a qualitative answer and then they conclude by saying that "upon its solution depends an accurate understanding of long-range radio communication and over-the-horizon radar". This reviewer believes that the matter can be resolved by first looking at the van der Pol-Bremmer solution for the total ground wave field of a radial dipole over an imperfectly conducting sphere. This residue series expression, in the limit of zero curvature (i.e. flat curve), goes over to a string of pole contributions that can be replaced by a contour integral that is equivalent to a lateral wave. The authors' reference, to Hill and Wait (1980), discusses a closely related problem.

In spite of any qualifying comments to the contrary, this reviewer feels that this treatise is an extremely valuable

Continued on page 78

Integrated Horn Antennas for Millimeter-Wave Applications

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Abstract

This paper reviews the development of integrated horn antennas since their introduction in 1987. The integrated horn is fabricated by suspending a dipole antenna, on a thin dielectric membrane, in a pyramidal cavity etched in silicon. Recent progress has resulted in optimized low- and high-gain designs, with single and double polarizations for remote-sensing and communication applications. A full-wave analysis technique has resulted in an integrated antenna with performance comparable to that of waveguide-fed corrugated-horn antennas. The integrated horn design can be easily extended to large arrays, for imaging and phased-array applications, while still leaving plenty of room for the RF and IF processing circuitry. Theoretical and experimental results at microwave frequencies and at 90 GHz, 240 GHz, and 802 GHz are presented.

1. Introduction

Millimeter-wave systems are becoming increasingly important in many scientific and military applications. They provide better resolution than microwave systems, and are less affected by atmospheric conditions than infrared systems. The wide range of applications, in areas such as remote sensing, radio astronomy, plasma diagnostics, radar, and communication systems, have demanded low-noise receivers from about 60 GHz to 600 GHz [1-4]. Millimeter-wave receivers and transmitters have traditionally been waveguide-based systems [5]. These are expensive to manufacture, for frequencies between 90 and 250 GHz, and are simply not available for frequencies higher than 300 GHz. A monolithic receiver, which consists of a planar antenna integrated directly with a matching network and a mixer, is an attractive solution for the millimeter-wave frequency range. Integrated receivers are easier to manufacture, more reliable, and much less expensive than waveguide receivers. The integration also allows the use of linear or two-dimensional arrays, without a dramatic increase in the cost and weight of the system.

The heart of an integrated receiver is the planar antenna and the antenna/mixer matching network. The coupling efficiency between the planar antenna and the incoming radiation is the first loss encountered in the receiver, and contributes directly to the noise figure (or, for radiometry, the noise temperature) of the receiver. Therefore, it is essential to have an efficient antenna, with a symmetrical main beam and low sidelobes. However, planar antennas integrated on dielectric substrate have traditionally suffered from poor patterns and low efficiency (about 25%-35% at 100 GHz), and in the last few years many researchers have attacked the problem in several different ways [6-9]. We have concentrated our efforts on the development and optimization of a high-efficiency integrated horn antenna (Figure 1 and Cover). This antenna was developed by Rebeiz and Rutledge, at the California Institute of Technology [10,11], and, recently, most of the research has been done by Rebeiz' group at the University of Michigan. The antenna consists of a dipole suspended on a 1mm dielectric membrane, in a pyramidal cavity etched in silicon or GaAs. The horn collects the energy, and focuses it to the probe antenna on the membrane. Alternatively, a monopole probe can be integrated on the membrane, to guide the energy from the horn cavity to a coplanar-waveguide transmission-line on the Silicon (or GaAs) wafer. All of the probe dipoles, detectors, and interconnections are integrated on the back side of the front wafer, making this implementation fully monolithic (Figure 2). The membrane is so small compared to a free space wavelength that the dipole antenna effectively radiates in free space. The dielectric losses are eliminated, and the design can be easily scaled for different wavelengths. A major advantage of this approach is in imaging and communication arrays, because the probe dipoles are much smaller than a unit cell: typically, the membrane occupies less than 20% of the wafer surface, for medium-gain horns (12 dB), and less than 4% of the wafer surface for high-gain horns (20 dB). The rest of the space is available for RF, IF,

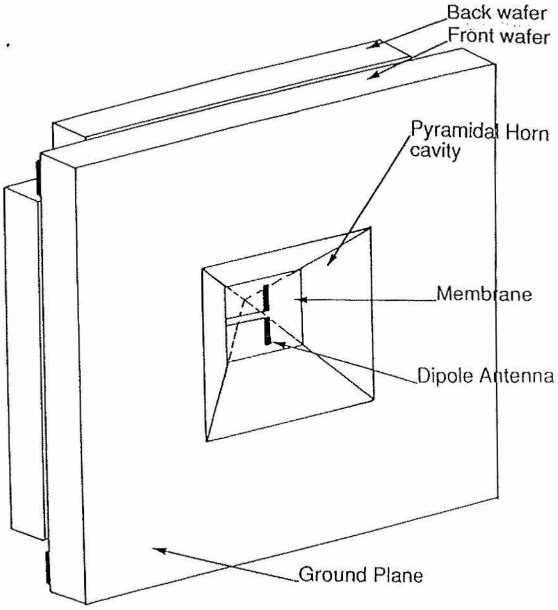


Figure 1. An integrated horn antenna in an infinite ground plane.

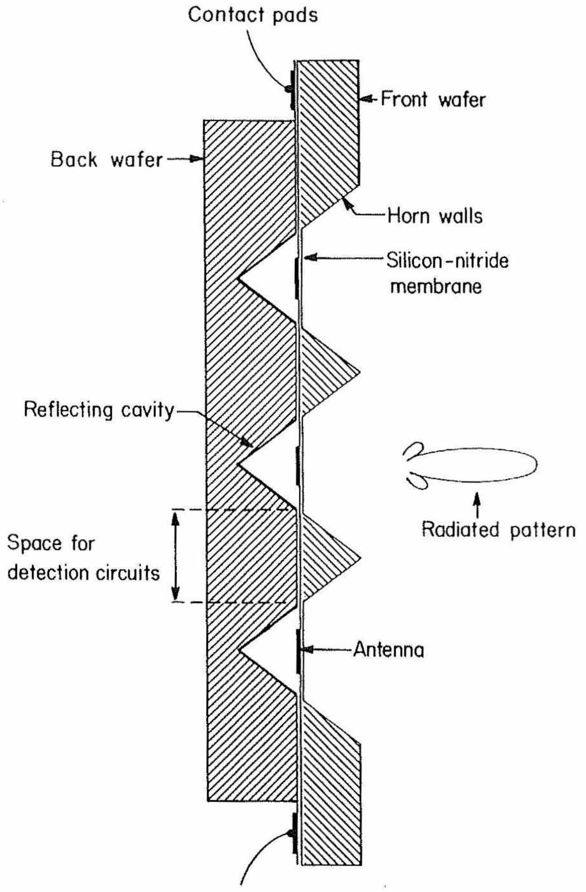


Figure 2. Side view of a horn array. Notice the available space for RF, IF, and DC electronics.

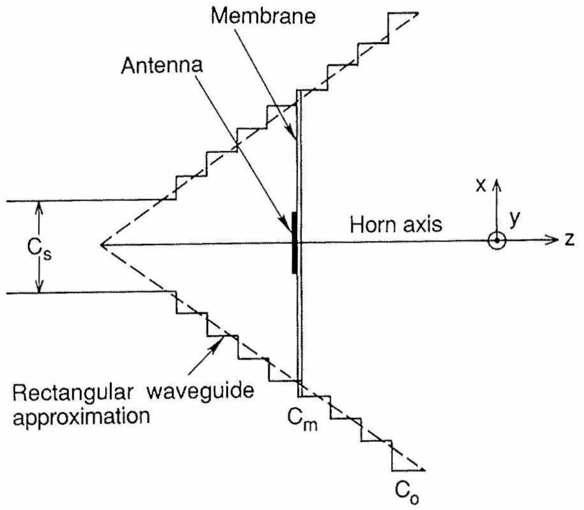


Figure 3. A stepped-waveguide approximation of a pyramidal horn. C_0 is the aperture waveguide, and C_m is the membrane waveguide.

and DC electronics.

2. Analysis and Design of the Horn Structure

We have considered two different horn-antenna designs: 1) a single-horn antenna in a ground plane, for receivers requiring one input channel; and 2) a two-dimensional horn antenna array, for imaging and communication applications. The Green's function of a dipole-fed horn antenna in an infinite ground plane is obtained by treating the horn as a multi-stepped waveguide discontinuity, and the mode-matching technique is applied at each waveguide step (Figure 3). The transition to free space is rigorously modelled, and the fields in space are given by a continuous spectrum of plane waves. The calculated Green's function is used to get an integral equation for the strip-dipole current, enabling the evaluation of the input impedance and the resonant properties of the feeding strip. The field on the aperture is also found, and the far-field patterns are calculated using Fourier transforms. The mathematical detail and experimental verification are described in [12,13]. For the case of a two-dimensional array, the far-field patterns are obtained simply using reciprocity and the Floquet-mode representation in free space. A full description of this method is found in [10].

The design of the horn antenna involves the selection of the horn aperture size and of the dipole position in the cavity. From our models, we find that for a 70° flare angle and for single and two-dimensional designs, horn apertures from 1.0λ square to 1.6λ square, with dipole positions between 0.36λ and 0.55λ from the apex, result in relatively wide band dipole impedances and good radiation patterns. Gains are between 11 dB and 13 dB. Imaging arrays already fabricated include a 77 array, with 1λ-square apertures at 92 GHz, and a 99 array, with 1.45λ-square apertures at 240 GHz [10].

The patterns for a 1.35λ–square horn in a ground plane and in a two-dimensional array are shown in Figure 4. This design yields nearly equal 10-dB beamwidths, of 90°, in the E, H, and 45° planes. The H and 45° planes are smooth and similar in both cases, due to the TE_{10} tapering of the electric field across the aperture. In the case of the E-plane in a two-dimensional array, the horn sees the array, and the spikes and nulls in the patterns are due to energy scattered into successively higher-order Floquet modes. Impedance measurements were done on a microwave scale model for a 1.35λ dipole-fed horn. The input impedance and resonant length are a strong function of the dipole position inside the cavity (Figure 5), and vary from 40Ω to 160Ω and from 0.37λ to 0.6λ, respectively. The horn has about a 10% and a 20% bandwidth, for feed positions of 0.38λ and 0.51λ, respectively. These bandwidths are adequate for most millimeter-wave applications.

3. Fabrication

The horn array is composed of two or more stacked silicon wafers, with a crystal orientation. The opening of the front wafer determines the aperture size, while its thickness determines the position of the antenna inside the horn. The horn cavity is made by anisotropic etching of the silicon wafers. The etching process forms pyramidal holes, bounded by the

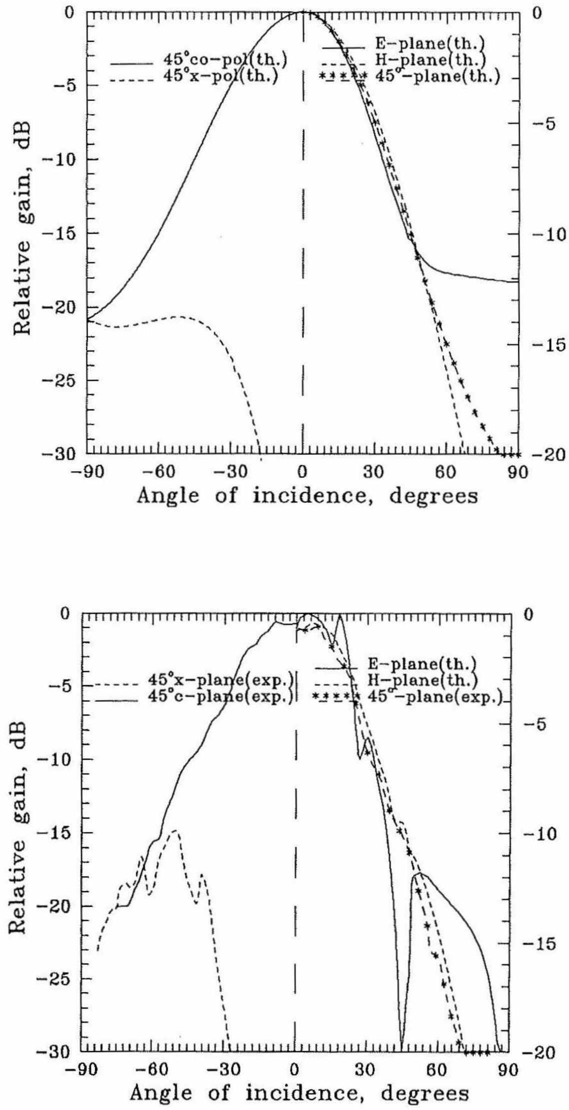


Figure 4. (a) The E-, H-, and 45°-plane patterns of a 1.35λ horn antenna in a ground plane and (b) of a single 1.35λ horn antenna in a two-dimensional array. The 45° patterns in (b) are measured results. Notice the expanded scale on the left, showing the cross-polarization levels. The experimental patterns [13] agree very well with theory at 3 GHz, 92 GHz, and 240 GHz, and are not shown.

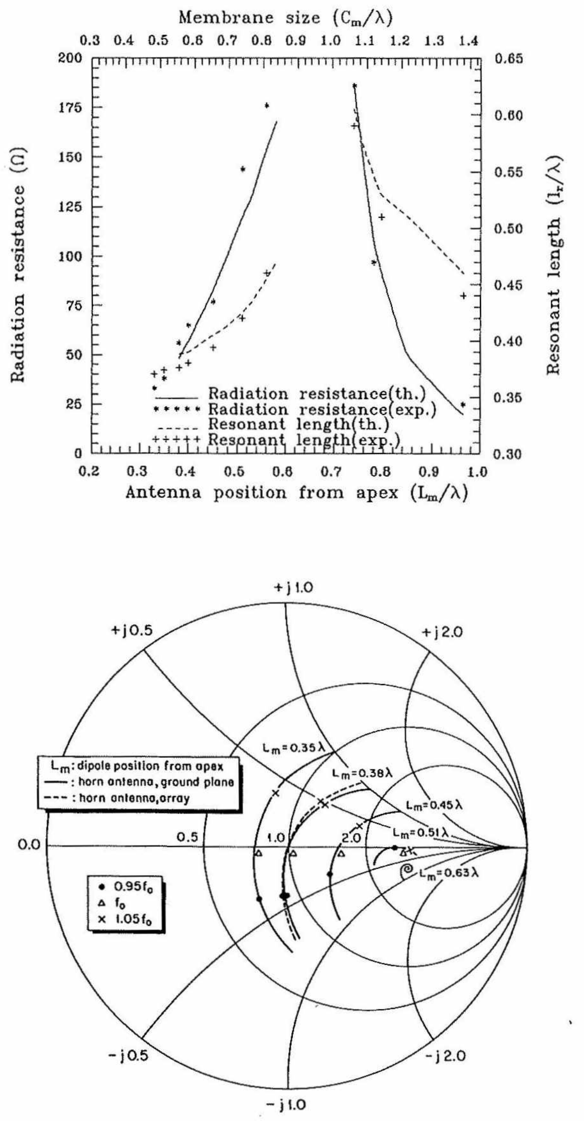


Figure 5. (a) Measured (at 1.2 GHz center frequency) and predicted dipole resonant resistance and resonant length versus dipole position from the apex; (b) the input impedances versus frequency for various feed positions in the horn cavity. The dashed line is the measured impedance of a dipole in a 33 array (at 7.3 GHz center frequency).

crystal planes, and produces a horn flare angle of 70.6° [14]. It is also possible to achieve this angle using anisotropic etching of GaAs wafers [15]. This is important, because one could possibly integrate these antennas with GaAs Schottky-diode detectors. The membrane layer is fabricated by depositing a 3-layer SiO_2/Si_3N_4 dielectric on the front wafer, and etching the underlying silicon until the transparent membrane appears. The dipole antennas and detectors are then deposited on the back side of the front wafer. The horn walls are coated with gold, to reduce losses. The wafer stack is finally aligned and assembled together to form the horn antenna (Figure 6).

The feeding structure for a dipole position of 0.39λ from the apex is shown in Figure 7. The antennas are 2000 Å-thick silver (or gold), and the detectors are 4mm-square bismuth microbolometers evaporated directly onto the membrane, or hybrid Schottky-diodes mounted at the dipole apex. It should also be possible to integrate SIS detectors on the membranes. For a dipole antenna, the 0.54λ membrane allows the integration of a simple coplanar-strip transformer, which results in a very large parallel impedance at the dipole apex. The RF detector presents a much lower impedance there, and absorbs all the received power. The coplanar strip acts as a simple RF filter, and provides a DC and a low-frequency connection to the detector. For GaAs wafers and monopole

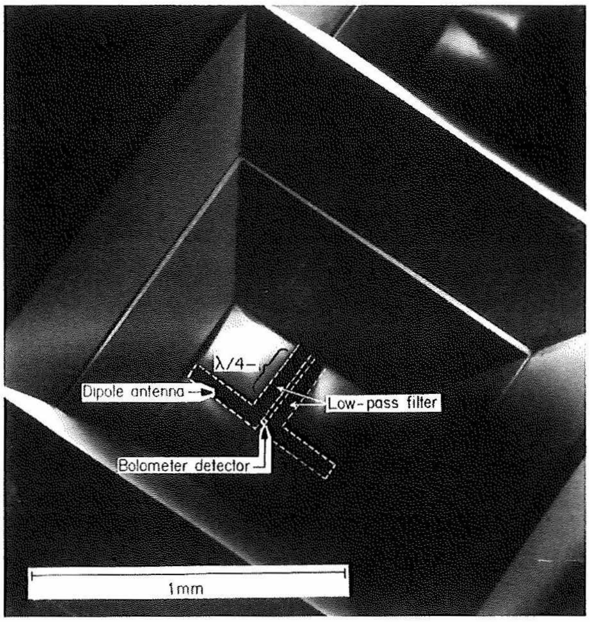


Figure 6. Scanning electron micrograph of a finished horn antenna for 242 GHz. The misalignment between the wafers is about 20mm.

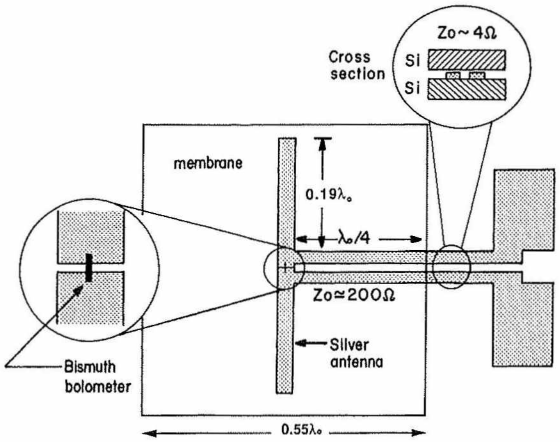


Figure 7. Millimeter-wave dipole design at a feed position of 0.38λ from the apex. The co-planar strips act as an RF filter and provide DC and low-frequency connection to the bolometer or Schottky-diode detector.

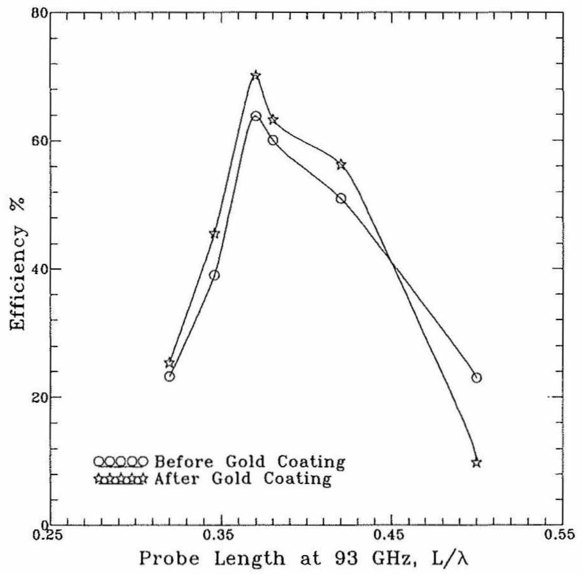
probes, Schottky-diode detectors and RF amplifiers could be integrated near the membrane on the semiconductor wafer.

The dielectric membrane is very robust mechanically, and similar structures are used in pressure and temperature sensors under severe environmental conditions [14]. We have been able to make membranes up to 1x1 cm, thereby resulting in 15 GHz-horn designs. However, these are not practical, because the associated wafers become very thick. Also, the hydrostatic strength of the membrane (i.e., its resistance to normal forces) decreases linearly with its linear size, and small membranes are therefore more robust than large ones. In practical applications, it is possible to easily fabricate integrated horn antennas for frequencies above 50 GHz (3 mm-square membranes and smaller), and we have concentrated our efforts on 94 GHz antennas. We have successfully attached beam-lead diodes to the 94 GHz antennas, and these have passed standard industrial vibration and temperature tests. Also, we regularly dip 2x2 mm membranes in liquid nitrogen and suffer no loss due to breakage.

4. Aperture Efficiency Measurements

(This section and the corresponding figures are condensed from a paper by Yong Guo and Dave Rutledge at the California Institute of Technology [16]). The horn aperture efficiency is defined as the power received by the bolometer divided by the total power incident in a plane wave on the horn aperture. The aperture field of an integrated horn antenna, in a two-dimensional array with an aperture dimension between 1.0λ and 1.5λ, is dominated by a TE_{10} distribution. The aperture efficiency is therefore around 75%-80%, when phase errors are included.

A number of 1.0λ aperture horns, with dipole probes varying in length from 0.32λ to 0.50λ, were fabricated for 75-110 GHz measurements. The bolometers' resistances were in the range of 50Ω to 100Ω, with typical responsivities of 20,000Ω/Ω. Details on absolute power measurements at 75-110 GHz



Loss component	Loss, dB
Intrinsic pattern loss	0.9
Mismatch loss	0.4
Total calculated loss	1.3
Measured loss	1.4

Figure 8. (a) Measured aperture efficiencies at 93 GHz versus antenna length; (b) the summary of the measured and calculated loss breakdown.

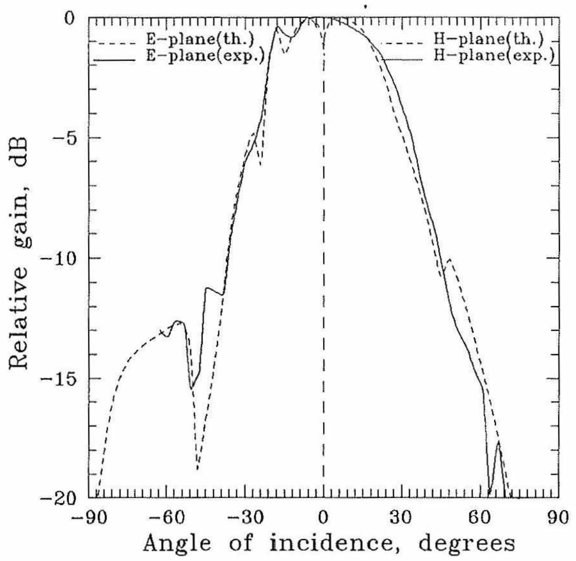


Figure 9. The measured theoretical and experimental E- and H-plane patterns at 802 GHz of the 256-element two-dimensional-horn imaging array shown on the cover.

and on the calibration procedure are given in [16]. Figure 8a shows the measured efficiencies for different antenna lengths at 93 GHz. Measurements were first made for horns without gold plating. After the horn wafers were coated with gold, the efficiencies were measured again. The efficiency reaches its peak value, 72%, for a length of 0.37λ. Figure 8b shows the estimated loss breakdown. The total calculated loss is 1.3 dB, compared with the measured value of 1.4 dB. There is still some mismatch loss (0.4 dB), because the bolometer resistance was 90Ω, and the resonant antenna impedance was 50Ω. These measurements indicate the absence of substrate-mode and dielectric losses in the horn structure, and that the maximum attainable aperture efficiency for a 1.0λ horn in a two-dimensional array is around 80%.

5. 802 GHz Imaging Array

The 256-element imaging array [17] shown on the cover of this issue has been fabricated and tested at 802 GHz (Figure 9). The array period is 500mm, yielding total array dimensions of 8x8 mm. The patterns measured at 802 GHz agree very well with theory (Figure 9b), and the associated directivity, for a 1.4λ horn aperture, calculated from the measured E- and H-plane patterns, is 12.3±0.2dB. The measured patterns are symmetrical, but only half patterns are shown for clarity purposes. The cross-polarization level was not measured, and is expected to be around -15 dB [10]. The patterns show a main-beam efficiency of 88% in a 100° beamwidth, and are suitable for f/0.8 reflector systems. We would like to note that this result presents one of the best patterns measured on a planar antenna at frequencies higher than 500 GHz. An immediate application area is "CCD-like'' arrays for plasma diagnostic imaging experiments at sub-millimeter-wave frequencies.

6. Double-Polarized Antennas

A two-dimensional (5x5) dual-polarized monolithic horn-antenna array [18] has been designed for 92 GHz (Figure 10a). The antenna consists of two perpendicular dipoles, suspended on the same membrane inside the horn cavity. The dipoles couple to an orthogonal set of waveguide modes, and are therefore effectively isolated from each other. The IF or video signals are taken out through a bias structure along the horn walls, which leaves room at the center of the membrane for the orthogonal dipoles. The measured mutual coupling between the antennas, on a microwave scale model, was less than -30 dB. A design with an square aperture of 1.35λ and a feed position of 0.38λ was fabricated. The antennas are linearly polarized, and a polarization isolation better than - 23 dB was measured at 92 GHz (Figure 10b). The measured E-, H-, and 45°-plane patterns agree well with theory, and are virtually identical for both polarizations (the patterns are given in Figure 4). Additional application areas for this structure include millimeter-wave

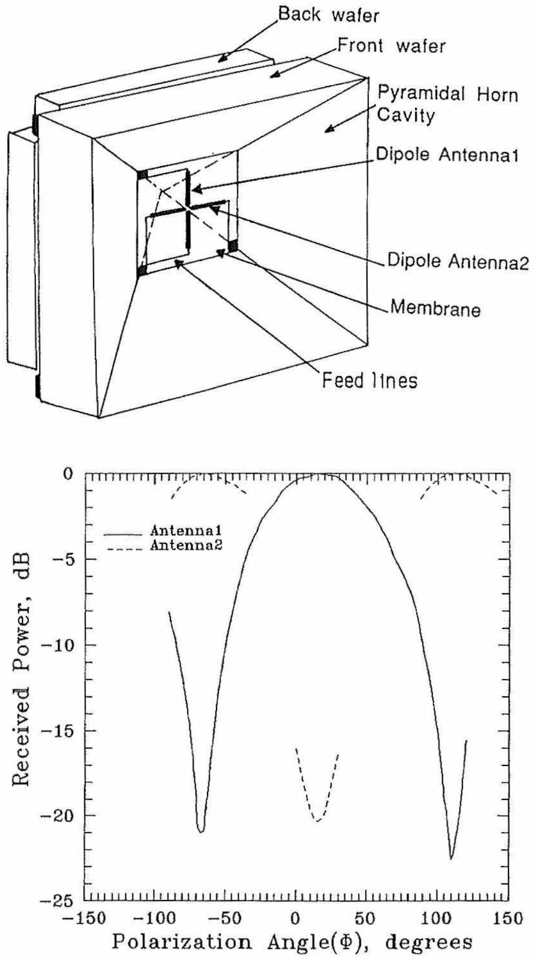


Figure 10. (a) Monolithic dual-polarized horn antenna element (in a two-dimensional array) with a novel bias and feeding structure and (b) the measured polarization response of the orthogonal antennas at 92 GHz. The patterns of the individual channels are identical to Figure 4(b).

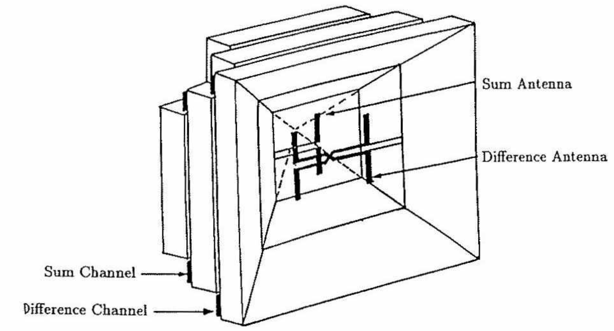


Figure 11. A monolithic azimuthal monopulse antenna. The horn aperture size in 1.4λ, and the feeding dipoles are at 0.38λ and 0.77λ from the apex for the sum and difference channels, respectively.

polarimetric synthetic-aperture radars and high-efficiency balanced mixers.

7. Monopulse Antennas

Figure 11 presents a 94 GHz monopulse antenna system, suitable for placement in the focal-plane of a collimating aperture (reflector or lens) [19]. The monopulse system achieves direction finding in the azimuthal plane using two separate antennas within the same horn cavity. In addition to the standard single dipole antenna (the sum antenna), a dual-dipole antenna (the difference antenna) is connected by a coplanar-strip transmission line which is crossed over at the center. This antenna couples primarily to the TE_{20} mode of the cavity, and produces a pattern which contains a sharp null at normal incidence. The difference detector is integrated at the center of the membrane, where the coplanar striplines meet. The sum and difference antennas are located 0.4λ and 0.8λ from the apex of the horn cavity, with a square aperture of 1.4λ. The corresponding cavity cross sections are 0.6λ and 1.1λ, and are slightly larger than the waveguide cut-off dimensions for the TE_{10} and TE_{20} modes, respectively. The mutual coupling measured using microwave scale models was less than -25 dB. The antennas are designed to yield an input impedance around 50Ω (Figure 12a). A 92 GHz monopulse antenna was constructed at the University of Michigan. The sum channel directivity is 12.5 dB, and the measured difference patterns from 90 to 94 GHz show a sharp null (-30 dB) at normal incidence (Figure 12b). The measured cross-polarization level was lower than -20 dB for the sum and difference channels. A fully-integrated 94 GHz monopulse receiver, with a 23 GHz local oscillator and sub-harmonic mixing, is currently being constructed at the University of Michigan.

8. High-Gain Step-Profiled Diagonal Horn Antennas

The main limitations of the integrated horn antenna stem from its large flare angle of 70.6°, which does not allow us to fabricate apertures greater than 1.6λ before the phase errors become too large. This results in gains around 13 dB, and a 10 dB beamwidth of 90°. We have investigated a new step-profiled horn, which reduces the effective flare angle of the horn to 30°-40°, and allows us to achieve gains around 20 dB (Figure 13) [20]. The circular symmetry is also enhanced by positioning the exciting dipole along the diagonal of the horn. The stepped-horn configuration allows the fabrication of a very large number of horns, using chemical etching in silicon. All of the horns' side walls are etched together on separate wafers, and then aligned and glued together. It is possible to simultaneously fabricate about one hundred 18 dB-gain horns for 94 GHz on a 10-cm wafer.

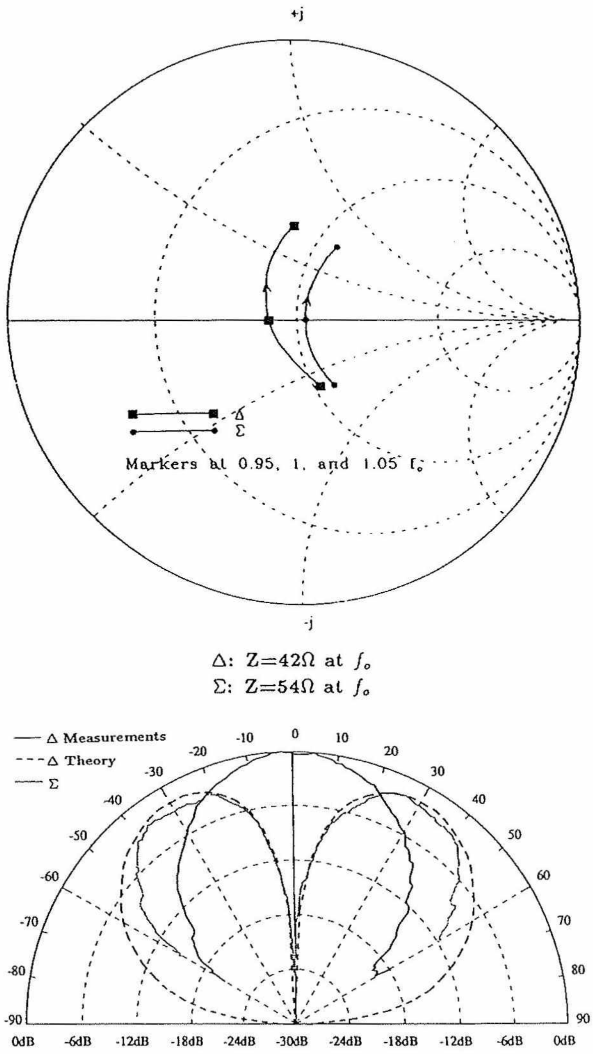


Figure 12. (a) Measured input impedances on a microwave model of the sum and difference channels, and (b) the measured 92 GHz sum and difference patterns.

A specific step-profiled horn has been designed for millimeter-wave applications. The horn geometry has an effective flare-angle of 30°, and an aperture size of 2.9λ. It is synthesized using 16 wafers, each of 0.3λ thickness. The step size for each wafer discontinuity is 0.13λ. The calculated patterns show a 10 dB beamwidth of 40°, with a directivity of 18.5 dB (Figure 14a). The 45° plane is wider than either the E or H planes, but matches them quite well up to the -15 dB

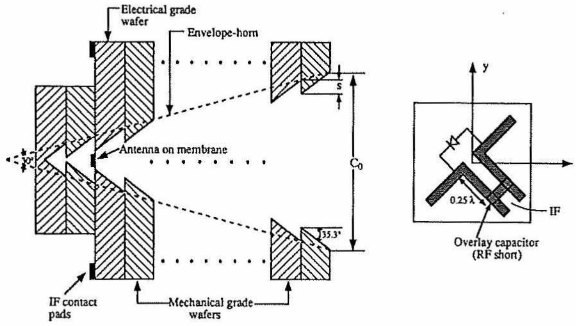


Figure 13. The stepped-horn antenna and the diagonal-feed dipole. This design yields high gain and good circular symmetry.

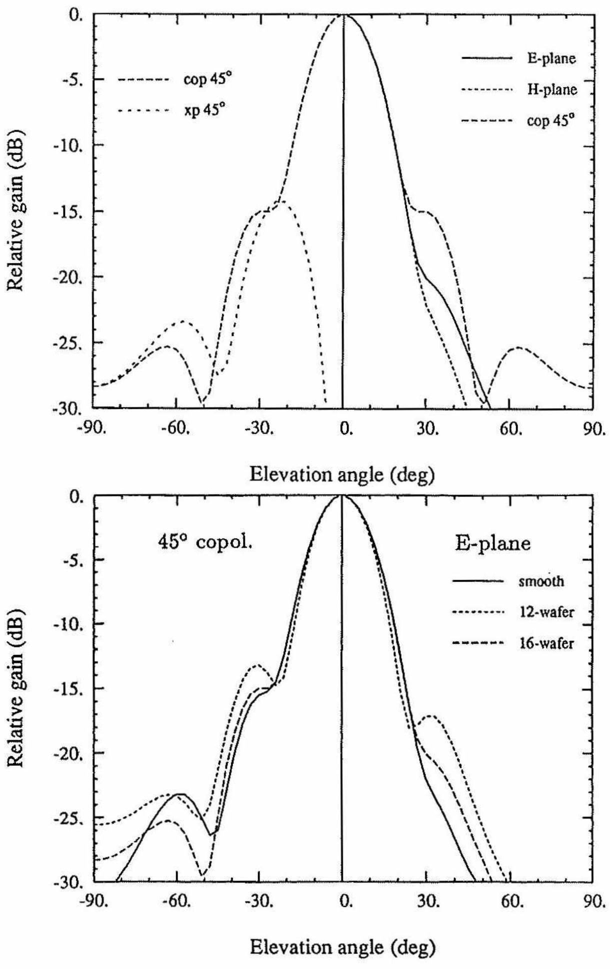


Figure 14. (a) Calculated E-, H- and 45°-plane patterns for a 16-step 2.9λ-square diagonally-fed horn, and (b) comparison between a smooth horn and a 16-step horn. Measurements at 12.1 GHz agree very well with theory and are not shown.

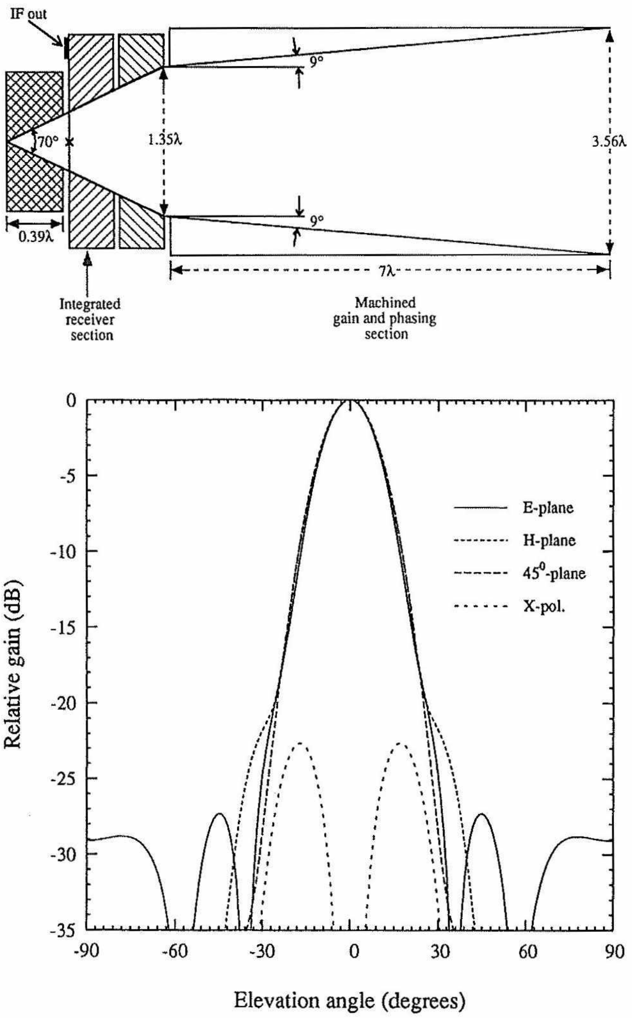


Figure 15. The 20 dB quasi-integrated horn antenna with a square machined portion attached to the integrated portion, and the predicted far-field patterns.

points. The peak cross-polarization level is -15 dB. The step-profiled horn is also compared to a horn with a cavity defined by its smooth outer envelope and with the same aperture size. It is seen that the patterns match well up to -17 dB in the E-plane and -14 dB in the 45° plane (Figure 14b). The calculated coupling efficiency to a Gaussian beam is 83%. This horn array can be used in communication and imaging systems requiring a large number of high-gain antennas.

9. Dual-Mode Quasi-Integrated Horn Antennas

In a drive to further improve the radiation characteristics of horn antennas, a new dual-mode integrated horn antenna, with performance comparable to that of waveguide-fed corrugated horn antennas, has been developed (Figure 15). The quasi-integrated section consists of a flared, machined section, attached to a standard integrated horn antenna [21,22]. The minimum dimension of the machined section is about 1.4λ, which permits the fabrication of the multi-mode horn up to 1.5 THz [terrahertz]. Any processing electronics can be integrated using the silicon portion of the horn. Alternatively, a thin GaAs wafer could be sandwiched between the silicon wafers for integration of high-speed devices.

The abrupt change of the flare-angle at the junction between the integrated and the machined section of the horn acts as a

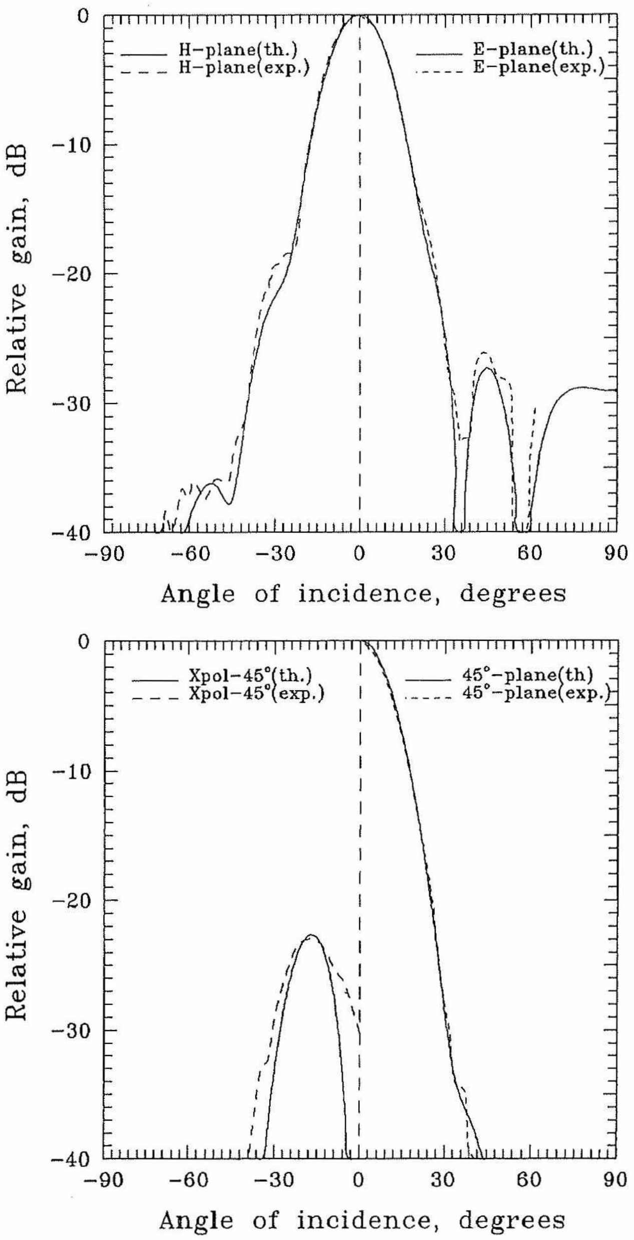


Figure 16. (a) Predicted and measured patterns at 91 GHz for the E and H planes, (b) and for the 45° planes. The pattern is very symmetrical up to -20dB, with a 34° 10 dB beamwidth. To our knowledge, this represents the best measured millimeter-wave pattern from any integrated antenna, so far.

mode converter, which mainly excites the TE_{10}, TE_{12}/TM_{12}, and TE_{30} modes. The modes are subsequently properly phased on the radiating aperture by selecting the length and the flare angle of the machined section. A 20 dB horn was designed using a full-wave analysis technique, already developed for dipole-fed horn antennas [12]. The characteristics measured at 91 GHz agree very well with theory (Figure 16), and showed equal E, H, and 45° patterns, with a cross-polarization of -23 dB, a 10 dB beamwidth of 34°, a 97.3% coupling efficiency to a Gaussian beam, and a main-beam efficiency (to -10 dB) of 86%. It is also found that, for a bandwidth of 5%, the beamwidth does not vary by more than 0.6°, the cross-polarization level remains lower than -21 dB, and the Gaussian-beam coupling efficiency is always above 96.5%. The impedance of the probe dipole has been measured at 6 GHz, and is very similar to the 0.38λ locus in Figure 5b. This antenna provides significant improvement in planar-antenna designs, and is suitable for all millimeter-wave and terahertz applications. A 23 dB design is currently under development, and receivers using this antenna are being constructed at 91 GHz and 250 GHz.

10. Conclusions

The integrated horn antenna has been shown to be a high-efficiency millimeter-wave antenna, with a wide range of applications. The input impedance and radiation patterns of the integrated horn antenna have been solved rigorously, using mode-matching techniques and full-wave analysis. The analysis allows us to design high-efficiency medium- and high-gain antennas with single and double polarization, monopulse antennas, and submillimeter-wave "CCD-like" imaging arrays. Also, integrated horn antennas, with performance comparable to waveguide-fed diagonal-horn antennas and to corrugated antennas, have been developed. Currently, the research effort is concentrated on integrating monopole probes on the membrane, and coupling them to Schottky-diode mixers and 94 GHz HEMT amplifiers. This would result in high-efficiency millimeter-wave receivers and transmitters. Other emerging research areas are integrated horns for phased-array applications, and for multi-beam communication arrays at millimeter-wave frequencies.

(Principal author's note: Many other antennas have been developed on thin membranes for millimeter-wave and terahertz applications. They include the wide-band log-periodic antenna [23], the integrated corner-cube antenna [24,25], and the double-dipole antenna and integrated-reflector antenna [26,27]. The interested reader is asked to check the literature or to contact the authors).

Acknowledgments

Prof. Gabriel Rebeiz would like to thank Prof. Steven Schwarz at the University of California, Berkeley, for graduating Prof. David Rutledge at the just the right time. Gabriel also thanks Dave for his support, encouragement and, most important, his patience with him when he was a graduate student, and Dr. Dayalan Kasilingam for his invaluable help in the early stages of this project. Prof. Rebeiz is also indebted to Prof. Ulaby, at the University of Michigan, for believing in him and giving him unlimited support and encouragement. This work is supported by the NASA Center for Space Terahertz Technology, the University of Michigan, and the Army Research Office.

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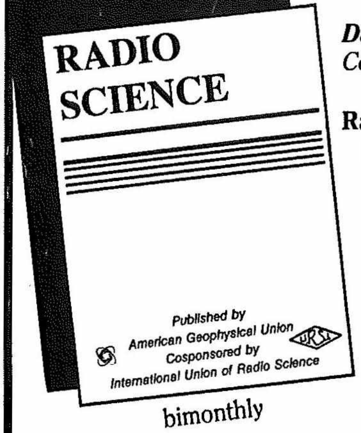

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Continued from page 67

addition to the literature of wave propagation in the presence of boundaries between contrasting media. From the standpoint of computer validation, the authors' analytical results should play an enduring role. Also the physical insight provided and the very large number of graphical results will be admired for the years to come.

Reviewed by:
James R. Wait
2210 East Waverly
Tucson AZ 85719-3848, USA

Generalized Vector and Dyadic Analysis

Chen-To Tai
133 pages, IEEE Press Inc. New York
ISBN 0-87942-288-2, 1992
(IEEE Order No. PCO283-2, price : US$45 approx.)

This slim monograph is based, for the most part, on Professor's Tai's recent studies on vector and dyadic analysis. It is a scholarly treatment of the subject. A definite highlight of the presentation is a new symbolic method which permits many of the principal results of the subject to be developed in a systematic manner. In fact, all vector identities can be derived by the algebraic manipulation of two partial symbolic vectors without actually performing any differentiation.

The author admits that the specific topics on vector analysis are comparable to that found in books by others (e.g. by Wilson, Gans, and Phillips). However, he treats material on curvilinear orthogonal systems in much greater depth. While the generalized approach seems rather formidable at first glance, the informal style, adopted by Professor Tai, makes for easy assimilation. He also clears up some confusion on notation and terminology that can be found in the current text-book literature.

Note from the Review Editor :
If you are interested and willing to review books for the Radioscientist, send me a complete description of the item and the name (and address if possible) of the publisher. Publication dates should be 1991 or 1992. Of course, you may keep the book after you have fulfilled your commitment.

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This reviewer was interested in Professor Tai's provocative and insightful comments on the misleading pedagogical labelling of such things as $\nabla \bullet \mathbf{f}$ and $\nabla \times \mathbf{f}$ as "scalar and vector products", respectively. Indeed, as I pointed out in one of my own books (*EM Wave Theory*, 1984) "... the r contribution of $\nabla \bullet \mathbf{f}$, in cylindrical coordinates, is not $\partial f_r / \partial r$. Similar inconsistencies would arise if one applied the dot product rule in the spherical system. Possibly this is a good reason to use the classical notation div **f** and curl **f** ".

James R. Wait, Tucson
2210 East Waverly
Tucson AZ 85719-3848, USA

Mini Book Reviews

The following books from the publisher Peter Peregrinus Ltd., Michael Faraday House, Six Hills Way, Stevenage, Herts. SG1 2AY, United Kingdom (in North America, available from PPL Dept./IEEE Service Center, PO Box 1331, Piscataway, NJ, 08855-1331 USA) have been received:

HERTZ AND THE MAXWELLIANS, by J. G. O'Hara & W. Pricha, 1987, 151 pages. This book contains many of the letters and correspondence between Heinrich Hertz and other pioneers of electrical science in the 19th. century. It includes many important photographs and listing of original sources. It is a must for science historians. (ISBN 0 86341 101 0, US price, $65)

TECHNICAL HISTORY OF THE BEGINNINGS OF RADAR, by S. S. Swords, 1986, 325 pages. This book is a very readable and enjoyable account which documents the early history of radar or "RDF" as it was called. The narrative backed by copious references, ranges from the early concepts of Nikola Tesla in 1900 and experiments of Christian Hulsmeyer in 1904 to the key developments in the years preceding World War II in Britain, Germany, and the United States. The material on the invention of the microwave cavity magnetron is a major highlight of this book. (ISBN 0 86341 043 x, US price, $95)

RADAR DEVELOPMENT TO 1945, edited by R. W. Burns, 1988, 528 pages. This is an edited collection of articles written by workers and participants in the early development of radar. The massive book, with many original photographs nicely complements the above item by Swords. The immediate post war developments are also described. Science historians will need to have this magnificently produced offering on their shelf. (ISBN 0 86341 139 8, US price, $114)

Continued on page 82

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New Developments in Cosmology

For decades now, the so-called standard model of cosmology has been considered as essentially describing all observational facts. This "hot big bang" model is based on General Relativity (with vanishing cosmological constant) and on the so-called "cosmological principle" of homogeneity and isotropy of the universe as first discussed in detail by the Russian mathematician Alexander Friedmann in 1922. The hot early universe was introduced by George Gamov in 1948. The model states that the universe began in a singularity with infinite density, infinite temperature and infinite expansion velocity. Density and temperature decrease in the course of the adiabatic expansion which itself is decelerated by the mutual gravitational attraction of all masses (or, more strictly, of all energy) in the universe. Space and time begin with the universe, that is, there is no "before" and no "outside". Stephen Hawking was able to prove that under rather general premises such a singularity is unavoidable. The proof essentially expresses the fact that an ever-attracting force such as gravitation will always decelerate the expansion (or accelerate a contraction) : The universe must begin or end in a singular state.

The cosmological principle is a pre-requisite for any "simple" model, that is one which can be described in plain language. This is because the principle assures the existence of a universal "cosmic time" which can be used everywhere. Without that, one could not generally and uniquely speak of past and future.

The main observational evidence for the hot big bang can be summarized as follows :

1. The red shifts in the spectra of distant galaxies, indicating that they are receding from us, or, more strictly, that space expands during the travel time of the light ray. The world was, in former times, smaller and denser. The famous Hubble law states that recession velocity and distance are proportional which implies that some 10 to 20 billion (10^9) years ago, all observable matter was located essentially at one and the same point.

2. The 3 K microwave background radiation, predicted by Gamow and detected by Penzias and Wilson who received the Nobel prize for it. It proves that the universe was, at some earlier time, hot, gaseous, opaque and homogeneous.

3. The primeval chemical composition of the universe, consisting of hydrogen, roughly 25% helium and essentially no heavier elements. This composition is seen today in the very oldest stars we know of. The evidence proves that the universe went through a state of nuclear fusion which, however, differed in two ways from what is today occurring in the centres of stars : The expansion caused cooling, and free neutrons were involved. Since these are unstable with a lifetime of about ten minutes, the total duration of this state cannot have lasted much longer, and took place in a very early stage of the universe.

4. The homogeneity and isotropy of the matter distribution on very large scales above 100 Mpc (megaparsec; 1 pc is about 3 light years). This observational result is, however, the most uncertain one and still under research. It indicates that condensation into galaxies and clusters of galaxies occurred only well after matter and radiation were decoupled by the universe becoming transparent.

5. The estimated age of all objects in the sky is smaller than, or about equal to (that is, at least not much larger than) the estimated age of the universe. This, of course, is a necessary requirement for any reasonable model.

Thus, observational cosmology seemed to consist of the "search for 2 numbers" (title of a famous paper by Allan Sandage twenty years ago). The present expansion rate (Hubble constant H_0), and the time change of it (present deceleration parameter q_0).

The present Hubble constant H_0 is, due to uncertainties in the distance determination, still uncertain by a factor of about 2, with a value between 50 and 100 km/sec/Mpc, i.e., two objects receding from each other with a velocity of 10 000 km/s will have a distance of between 300 and 600 million light years. However, only the smaller values of H_0 do comply with requirement 5 above. While the standard model requests a positive, decelerating q_0, its direct observational determination is very uncertain, allowing even negative values (acceleration of the expansion). q_0 is, however, related, in the standard model, to the mean energy density in the universe which seems easier to measure. If it turns out to be larger than a critical density of about 10^{-29} g/cm^3 mass equivalent (roughly one hydrogen atom per cubic meter), the universe is closed (spherical metric, finite volume, and finite total mass). It will eventually come to a stand still and then contract again, to end in a singularity similar to the start ("big crunch"). Else, it is open (hyperbolic metric, infinite volume, and infinite total mass), and will expand infinitely. The limiting ("parabolic") case has Euclidean (i.e. flat) space metric. It is, however, unstable in the sense that the slightest change in mass (addition or elimination of just one electron-positron pair, even for a very short time only) will propel the universe into the first or the second case.

There are essentially two difficulties with the standard model. The first is given by the observational result that homogeneity seems to exist even for two regions of the universe that had never enough time to communicate with each other because signals running between them with the largest possible velocity, the speed of light, would take a longer time than the age of the universe. The homogeneity cannot have developed by a physical process of interaction but has rather to be introduced as an initial condition of the big bang. The second difficulty is also a time question : the time interval between the homogeneous stage of the universe and the fully developed inhomogeneity of galaxies and clusters of galaxies is shorter than any reasonable theory of fragmentation is asking for. Several possible remedies exist and have been discussed.

Inflationary cosmology is based on "grand unifying theories" (GUTs) which state that "strong interactions" (nuclear forces) merge with "weak interactions" (e.g., beta decay) and electromagnetic interactions at very high energies and, thus at very high temperatures. A phase transition occurs in the early universe when these interactions decouple due to temperature decrease. During the transition, the universe runs through a state of sudden tremendous expansion of exponential (therefore "inflationary") form, to be followed, after the end of the phase transition, by the much slower standard-model expansion. Matter which had already settled to thermodynamic equilibrium and, in particular, to homogeneity is blown up so much that the possibility of communication by light signals may be lost until much later, even until the present time.

Such phenomenon is easily seen to imply expansion with a velocity greater than the speed of light. Nevertheless, this is *not* in contradiction with Special Relativity. It would be if matter were receding from other matter within a resting space. Contrarily, cosmic expansion means that matter rests in space but the space itself is expanding.

Density fluctuations may be implanted as seeds such that they are not seen in the 3K radiation but nevertheless develop, later on, to the present small-scale inhomogeneities. Inflationary standard models do not allow for extra time possibly needed for the condensations to actually take place. The theory predicts a present energy density very close to the critical one, i.e. it predicts a universe that is nearly flat.

The present observable matter density is at least a factor of ten below the critical value. The missing mass may exist in the unobservable form of non-baryonic (= neither protons nor neutrons) "cold dark matter" : Neutrinos if they happen to have non-vanishing rest mass, or "exotic" particles not even proven yet to exist.

Another obvious possibility to overcome the mentioned difficulties of the standard model would be to slow down the expansion for a while. It has recently been shown by Wolfgang Priester and collaborators that this is indeed possible.

When Einstein's original field equations of General Relativity were applied to the universe, it turned out that there was no stationary solution, simply because gravitation is ever-attracting. He then introduced the so-called cosmological constant into his equations, but later on abandoned it again when it was shown that a stationary solution was possible but that it was unstable. Also, the detection of the expansion of the universe made a stationary solution no longer desirable. On the other hand, if the field equations are derived from a very basic variational principle, then the cosmological constant is a legal and necessary part of the theory even if a zero value is not excluded. That is, the constant appears to be a new constant of nature ("inherent curvature of space-time"). Models with non-vanishing constant have first been discussed by Friedmann in the twenties and by the Belgian Father George Lemaître in the thirties.

The cosmological constant can be understood as corresponding to a repelling force working rather on very large distances (billions of light-years) only. Another correspondence, perhaps easier to grasp but certainly also not exact in a theoretical sense, is that to a constant-density agent behaving, in some respect, like negative matter. It accelerates the expansion. In a small universe, the total amount of the agent is small, its contribution to the dynamics is also small. Thus, the universe expands essentially as if there were no such thing as repulsion. The larger the universe becomes, the larger and the more effective becomes the agent (constant density!), finally taking completely over and implying an ever-expanding universe with accelerated expansion. Priester was able to show that a good choice of the constant (the value of which we can deduce only from cosmological observations) can make a closed universe not to contract again but rather to nearly stop expansion for a long time, some 10 to 15 billion years, just at the right time when fractionalisation needs it. The model is open to falsification in as far as it predicts that dark matter should not exist (or only in small amounts), that the Hubble constant should be on the upper side of the present uncertainty range, and that q_0 should be negative.

The cosmological constant can also be used for decoupling the creation of space-time which may have existed forever, and of matter which is created by a phase transition when the volume of the universe has a small but finite minimum ("big bounce") and no momentary expansion. Thus any big-bang singularity can indeed be circumvented (Hawking's proof is not applicable), and original homogeneity is enforced during an early low-expansion stage.

Very recently, additional evidence has come up in support of these new ideas. The clusters of galaxies are not more or less homogeneously distributed, as was originally thought, nor are they clustering at a higher level, as was also thought possible, but they are rather arranged in sheets surrounding nearly empty regions (the so-called voids), like a sponge. The size of the voids in our cosmic vicinity is about 30 Mpc, well compatible with the assumption of homogeneous distribution of matter on larger scales as described above.

In larger distances, voids cannot be directly detected but their existence can be inferred from other observations. Light passing through a galaxy or through intergalactic hydrogen filaments will suffer strong line absorption from the hydrogen gas. Light going through many galaxies will show many absorption lines, each indicating the specific recession velocity of a galaxy, or of a galaxy group with similar velocities of recession. Voids show up by gaps of little or no absorption between such strong absorption lines. The size of the voids can be found from the size of the gaps if the Hubble law of cosmic expansion is applied.

When looking in far distances, one looks also back in time and sees the objects as they were some time ago. In cosmic distances, one sees the objects as they were at times when the universe was much smaller than today. The voids, if they then existed, were also much smaller. Priester showed that the sizes of these voids as derived from the gap sizes correspond, if expanded to the present state, well to the measured size of neighbouring voids, if his cosmological model is applied. There is no good correspondence for other models still under discussion, particularly for the standard model.

However, the voids not only help us to find cosmological models, but they also put the unanswered question before us: How did they originate?

We know from observations that voids are empty (or at least very diluted) in respect to galaxies and in respect to other easily detectable matter. We do not know whether they are void of anything. Direct evidence against matter in more exotic forms is lacking. Some think that a central supermassive black hole could contain all the mass originally present in the volume of the void. Again, it is the time element that is troubling : There is not enough time for forming such black holes if the universe was, in early stages, as homogeneous as the 3K radiation infers, but there would be enough time for galaxies to fall into the voids. The best guess seems to be that voids are indeed diluted voids.

It has been known for some time that regions of sufficiently increased density do not take part in the cosmic expansion. Thus our solar system, the stars, our Milky Way, the local group of galaxies, even clusters of galaxies have decoupled from the expansion. More strictly is it the space that has decoupled : the metric describing these regions is stationary not expanding. Only the size of the stationary region increases with the cosmic expansion. This is simply a result of the fact that gravitation is always attracting. Matter can contract by the influence of gravitation but cannot expand. The time in these stationary regions runs slower than the cosmic time but so little that the difference is not yet noticeable.

Thus, voids should never emerge from gravitational attraction. Diluted voids with a metric differing from the surrounding standard model have been shown to be possible but they should be created right at the big bang or even earlier - whatever that is supposed to mean. We are presently working on a theory where again the cosmological constant is used to create voids from originally small density fluctuations by letting them expand faster than regions with higher density. We do not yet know whether or not this is possible. Time will show, but we can be sure that if that question is answered, new and unexpected ones will emerge which will make cosmology an everlasting fascinating subject of research.

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BOOK REVIEWS

PERSONAL & MOBILE RADIO SYSTEMS, edited by R. C. V. Macario, 1991, 328 pages. The book deals comprehensively with current private mobile services, the forthcoming pan-European radio telephone system and future (European) cordless telecommunication concepts. Topics such as equipment approval and radio site operation are also covered, apparently, for the first time. The chapters are written by individuals who are active and the competent editor has done a nice job in providing continuity. (ISBN ISBN 0 86341 219 x, US price, $87) (also available in paperback).

INTERNATIONAL CONFERENCE ON COMPUTATION IN ELECTROMAGNETICS, 381 pages, B. A. Austin et al., 1991. This is a proceedings of a conference held in London, 25-27 Nov. 1991. The author-produced collection covers the following topics: Finite element methods, comparison of numerical methods, boundary and integral methods, parallel processing, transmission line methods, finite difference methods, method of moments, ray methods, integral equation methods, and related analytical techniques. Presumably many of these papers will appear in the open refereed journal literature at a later date. In the meantime one can get a perceptive glimpse of the emerging discipline. (ISBN 0 85296 529 x, US price, $104).

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Towards an international global real-time satellite-based ionosonde system.

Only five years after the start of the "space era", the first ionosonde satellite was launched—Alouette-1. A series of ionosondes was launched during the 70s and 80s: Alouette-2; ISIS-1, ISIS-2; Explorer-XX, ISS-b, ISS-c (Japan), Intercosmos-19, and Cosmos-1809 (Russian). These gave us a vast ocean of ionosphere knowledge, allowing us to work up a new theory of ionosphere-magnetosphere interaction. The new American ionosonde sounds from the DMSP 5D2 spacecraft and automatically determine Nh-profiles in the topside ionosphere. The Russian "Cosmos-1809" served the ionospheric network in the former USSR.

On the agenda is the construction of the International Global Real-Time Satellite-based Ionosonde System for all countries and users.

Why does humanity need the construction of a special earth-space system? Why it is insufficient to have only a ground-based system, like we have now? Providing answers to these questions is the purpose of this paper.

An ionosphere as a medium occupies a key position in the system controlling parameters and processes taking place in the near-Earth space and the atmosphere. It serves as a sensitive detector for processes both in the magnetosphere, where the vertical current system leads to ionospheric heating, as well as in the neutral atmosphere and even in the lithosphere. That is, oscillating processes are intensified when passing through the atmosphere due to the barometric low, and are transferred to the upper conductive ionospheric layers where they are easily registered.

The reason that radio sounding now and always in the future will occupy a key position in the system of ionospheric control and prediction is quite simple and rests on the following fundamental basis:

Resonant radio wave reflection from the main ionospheric component (electrons) carries the information. And **resonance** is the physicist's best method of measurement. The current worldwide ionospheric network by ground-based ionosondes is based, as mentioned above, on the same principle but does not completely meet the ever increasing requirements of humanity.

The limitations of the ground-based ionosonde network

1. The network is helpless when total radio waves absorption in the ionospheric D-region occurs.

2. The network is inhomogeneous. In some places the absence of stations is irreplaceable (for example, near the planet's poles and over the oceans).

3. Measurement of the topside ionosphere is impossible from the ground, but the role of the topside ionosphere will increase as trans-ionospheric radio communication lines are developed while variations in ionospheric disturbances limit the possibilities of their practical application.

4. The ground network does not allow continuous measurement of electron concentration dependence along any direction to take account of horizontal gradients.

5. The ground network is unable to trace the movement of local ionospheric disturbances and plasma waves.

6. Last, but not least, the main argument for today is as follows: It is necessary to measure the dynamical regime of the ionosphere life, especially the rhythmical changes of the electron cover of the Earth. Because now we understand—especially from studies of the database from the experiment with Intercosmos-19—that the main influence of space weather on the Earth's atmosphere is the rhythmical changes of plasma cover of our planet. If earlier we measured the static characteristics of the topside and bottomside ionosphere in different experiments, nowadays we must measure and see the picture of the **dynamic** life of the plasma of the Earth's atmosphere cover. Especially here the peculiarities of the dynamic processes determine many of the rhythmical properties of the bottomside ionosphere and of the biosphere as a whole.

That is why it is necessity to pass on from local and spatial measurements of the ionospheric plasma—electron concentration, Nh-profiles, etc.—to the dynamic characteristics of the whole plasma cover of the atmosphere: periods, times of start, amplitudes of plasma waves, heterogeneities, oscillations and details of the global ionosphere as a whole.

The ionospheric services must see the full picture of conditions and variations of the global ionosphere. Figuratively speaking the ionospheric service must see "the ionosphere breathing" under space weather.

The advantages of adding satellite ionosondes to the current network of ground-based ionospheric stations.

Let us consider the capabilities of such a ground-based space system for ionospheric monitoring based on the radio sounding technique as principally the most suitable one. In so doing we shall assume that network data feed continuously and in real-time into the ionospheric mathematical model which then produces answers for solutions of applied problems. Data of optimum value are obtained when use is made of all four possible methods of radio sounding: ground-based vertical and inclined, topside and trans-ionospheric.

A SATELLITE IONOSONDE CLUSTER

A simple analysis shows that a system of four satellites with on-board ionosondes added to the ground-based network of ionospheric stations removes the first five of the six above mentioned limitations of the ground-based network. As regards the sixth point, the correct orbital location of two satellites (one in the plane of midday-midnight, and one in the dawn-dusk plane) will give the ability to check the dynamical processes.

The author thinks it obvious that humanity will eventually take control of the state of near-Earth space, initially that in the ionosphere. And the duty of scientists concerned with geophysics, from my point of view, is to bring this about as soon as possible. For it cannot come too early, but its delay is only too possible. The history of the "ozone hole" and of the "ionospheric holes"—which are more understandable to us, and started with American lunar rocket launches making huge holes in the ionosphere, never before detected by the ionospheric network—is only one illustration that the current system is unable to resist man's attacks on his Environment. Therefore it seems quite timely (maybe even too late, since nobody knows the future) to consider now how to complement the available ionospheric ground-station network with space ionosondes.

To use satellite radio sounding to monitor the near-polar ionosphere is particularly advisable. Firstly, monitoring from below is very often impossible in this case due to total radio wave absorption, while from above the control offers no difficulties. Secondly, in the Arctic and Antarctic regions much trouble is needed to locate ground-based stations. Thirdly, all satellites pass over the Arctic and Antarctic in every orbit, so four satellites can provide practically continuous monitoring of the most inaccessible and most complex parts of the ionosphere which determine its entire dynamics.

On the whole, a 21st century ionospheric network may be thought of as operating on a radio sounding basis and consisting of ground-based and on-board satellite ionosondes arranged so that all four kinds of radio sounding are being realised—bottomside, inclined, topside and trans-ionospheric. Ground-based stations could operate in accordance with a standard program as follows. When one of the satellites with an on-board ionosonde appears within telemetry range, ionograms of topside sounding are received over the telemetry channel, independent of the ground-based one.

Ionograms of inter satellite radio sounding are under study at present. A decision on the possibility of their utilisation in the network operation will be taken subsequently.

Simultaneously, a ground-based ionosonde is synchronised by satellite on-board ionosonde pulses and inverse trans-ionograms (Earth -satellite) are registered on-board the spacecraft. These, together with topside sounding ionograms over the telemetry channel at a fixed frequency (e.g., 137 MHz), are transmitted to the ground-based ionospheric station. Direct trans-ionograms (satellite - Earth) are registered on the ground-based ionospheric station either by a receiving unit of the ionosonde or by a separate receiver. Processing of topside ionograms is well-known and that of trans-ionograms using both direct and inverse methods has been tested experimentally and offers no difficulties from the point of view of methodology. It is natural that recording and partial processing of ionograms on-board the spacecraft and their subsequent transmission to the Information Processing Centre situated in different regions of our planet and in different states will be envisaged. At present it is possible on an experimental basis in some regions of the planet to incorporate the system of topside and trans-ionospheric sounding into the operational practice of ionospheric services.

It may also be of interest for countries which at present have no ionospheric stations of their own. In this case a simple passive unit, for which the cost is much lower than the cost of an ionospheric sounding station, and which is ecologically pure as it has no transmitter and does not go on the air, can partially substitute for the ionospheric station. The author thinks it both feasible and advisable to make use of current conversion of space technology taking place in Russia with the view of establishing an international satellite system for ionospheric monitoring.

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