U.R.S.I.

The Radioscientist

The magazine of URSI ISSN 1170-5833

Editor: R. L. Dowden Vol 4 N° 1 March, 1993

Day on Diffraction p. 27

Global Change, the Greenhouse Effect and the Ionosphere
by Henry Rishbeth — p. 7

Radio Tomography of the Ionosphere
by V. E. Kunitsyn and E. D. Tereshchenko — p. 12

W. N. Christiansen
by Don Mathewson — p. 9

Book Reviews
by James R. Wait — p. 26

LETTERS
The Future Magazine, Reciprocity, Cosmology — p. 5

The Radioscientist

Richard L. Dowden
Editor-in-Chief
Department of Physics
University of Otago
P.O.Box 56
Dunedin
New Zealand
email: dowden@otago.ac.nz

W. Ross Stone
Associate Editor
Expersoft Corporation
1446 Vista Claridad
La Jolla, CA 92037
U.S.A.
Ph: +1 619 4598305 (24 hrs)
fax: +1 619 4597140

Rudolf A. Treumann
Associate Editor
MPI für Physik und Astrophysik
Institut für Extraterrestrische Physik
D-8046 Garching
Germany
email via SPAN:
mpe::tre

Kristian Schlegel
Max-Planck-Institut für Aeronomie
Postfach 20
D-3411 Katlenburg-Lindau 3
Germany
fax: +49 5556 401240

Per Høeg
Dept. of Geophysics
Danish Meteorological Institute
Lyngbyvej 100
DK-2100 Copenhagen Ø
Denmark
fax: + 45 1 271080
email: hoeg@os1100.uni-c.dk

J. H. Cloete
Department of Electrical and Electronic Engineering
University of Stellenbosch
Stellenbosch 7600
Rep. South Africa
fax: +27 2231 774981

Ari Sihvola
Electromagnetics Laboratory
Helsinki University of Technology
Otakaari 5 A
SF-02150 Espoo
Finland
Ph: +358 0 4512261
fax: +358 0 4512267
email:ari.sihvola@hut.fi

Gentei Sato
Faculty of Science and Technology
Sophia University
7-1, Kioicho
Chiyoda-Ku
Japan
Ph: + 81 3 3238 3330

A. J. Smith
British Antarctic Survey
High Cross Madingley Road
Cambridge CB3 0ET, UK
phone: +44 223 61188
fax: +44 223 62616
Telex: 817725 BASCAM G
email: U_AJS@vaxc.nerc-bas.ac.uk or
SPAN: ECD1::323AJS

James R. Wait
Review Editor
2210 East Waverly
Tucson
AZ 85719 USA
phone: +1 602 325 1005

The Radioscientist is published quarterly by Radio Science Press Avenue Circulaire 3 Brussels, B-1180, Belgium
and issued on **1st March, June, September and December.**

The opinions, statements and facts contained in *the Radioscientist* are solely the opinions of the authors and/or sources identified with each article. Articles with no author identified can be attributed to the Editor.

NOTICE TO CONTRIBUTORS

All material should be sent direct to the Editor, preferably by email or on disk as "flat" or pure ASCII text files. The Editor reserves the right to accept, reject, defer and/or edit any material and all material submitted.

COVER: Peterhof Gardens, St. Petersburg, Russia. From left: Edward Jull (Vancouver), Viktoria Slavyanov (St. Petersburg), Natalie Grigorieva (St. Petersburg), Natalie Yashina (Kharkov), Erich Mann (Stuttgart), Staffa Ström (Stockholm).

A Green URSI?

A role for URSI scientists in monitoring global change is indicated in this issue. The increasingly "wireless" replacement of telephone lines, etc, could be seen as a change for a better, less polluted (at least visually) world. As quoted from the IEEE *Antennas and Propagation Magazine* (February, 1993), and the IEEE *Spectrum* (p. 81, January, 1993), a team from the societies in IEEE identified the *Seven Grand Challenges in Electrotechnology* which are expected to become key factors in driving the development of new technologies. The seven challenges are:

- To be or not to be reachable any time, anywhere (world-wide personal communication networks, wire- and fibre-less communications)
- To have instant access to all information (data bases, high-speed links, flat-panel displays and interfaces)
- To be present or absent any time, anywhere (virtual presence and reality)
- Abundant, clean, safe and affordable energy
- Intelligent highways and transportation systems (increased safety, optimum automatic routing to minimise congestion, personal global navigation)
- The paperless office (flat-panel displays, pen-based and tablet computers)
- The cashless society (electronic purse and wallet)

All of these involve radio or other technology within the span of URSI. By contributing to these *Seven Grand Challenges in Electrotechnology* would URSI appear "green" in the sense of clean and safe? But without looking carefully at likely side effects of such technology URSI might appear green in the other sense (naive). The British Government has recently warned that EM pollution or "electronic smog" from personal computers, mobile telephones, radios and other gadgets is putting lives at risk. The British Minister of Trade and Technology, Mr Edward Leigh, sees the rapid increase in use of this "wireless" technology as behind the problem.

"In the UK, interference caused a computer-controlled crane to drop its load prematurely, killing one worker," he said. "In Japan, interference caused robots to go out of control causing two deaths." Mr Leigh highlighted the dangers at the launching of a nationwide awareness campaign to help British firms beat the threat. In one incident, a portable radio sent out a signal causing a semi-submersible oil platform to move of its own volition. Mobile radios in police cars caused the vehicles' locking systems to operate. "In another case electric trains caused the malfunction of computers 5km away."

It is neither necessary nor appropriate for URSI to oppose the advance of radio technology. But to be green in the good sense, URSI scientists as individuals and in collaboration with the CCIR need to be resolving the EM pollution problem. It is an international problem and not necessarily best resolved by legislation.

The Future Mag.

You will find two pages of LETTERS to the Editor in this issue. I have expressed my personal opinions in these Editorial pages to arouse some response from readers on such LETTERS pages. This seems to have borne fruit, with a whole page on suggestions for the future form (beginning with the March, 1994 issue) of *the Radioscientist* and *Bulletin* magazines, combined or not.

A comment in a personal letter to me, and so not included on that page was: "I expect the uncertainties on the status of *the Radioscientist* will not help the subscriptions and contributions". To this I hasten to answer that contributions are still coming along nicely (there are a few which I cannot fit in this issue and must hold for later). Subscriptions are not a problem since all scientific participants at Kyoto will become subscribers for the following three years, 1994-97.

The "uncertainties"? Well nothing is *certain*, but unless there is a silent majority out there with a contrary view, the vibes I get are for a growing status. Looking back over the issues — I recently made a bound set because for some issues I found only one or two copies — I found appreciable change over the $2^1/2$ years of the existence of *the Radioscientist*. For example, I was initially against having contributed articles refereed but I changed my mind — at first for "research letters" and then for articles as well. Since I was learning the job of editing and publishing, it is not surprising that I didn't get everything right at the start. The important thing is that it *did* start. I like to think it is getting better and I hope that the March, 1994 issue, whatever its name, will be better still.

CRC

In recent weeks I received a technical article of excellent standard from one source, and a call for papers from another source, both professionally typeset and sent to me as Camera Ready Copy (CRC). Both of these items will appear in *the Radioscientist* after we have keyed the texts into our computer, including equations, and redrawn the diagrams by computer.

Why not use the CRC as is? I could point out that such CRC is never in exactly the right style, font, leading, column width, page number, etc, for direct use. But that is beside the point. The printer requires the issue completely in digital form, pictures and all.

So if you want to save us some work, send your contribution in plain ASCII by email. A $\TeX$ file by email *in addition* is useful as a check on equations and symbols. If you send it on

SCANNING THE ISSUE

disk, include a version in MS Word, Word for Windows or Word Perfect. The "high density" disks (1.44 MB on 3.5 inch diskettes) work on both Macintosh and PC. If you want to make it *really* easy for us, use a Macintosh to put the text in MS Word 5, with equations using Equation Editor, Times and Symbol fonts, 10 pt, column width of 82 mm, and graphics in MacDraw (Pro or II).

Editors?

I didn't get any volunteers, so I will invite some individually. This way, I hope to split the job between about five Editors, each of which will be expected to do all of what I have been doing, including the Editorials, but on average doing only about 20% of the work load. This way they get all the advantages of being Editor without a big workload. But it may not be too late to volunteer yourself or someone.

Scanning the issue

Do you find this section useful or do you prefer to do your own scanning or skimming though the issue? My inclination is to make omit the summary aspect and give only the "story behind the story" aspect. There is not much of this this time. I first met "Chris" Christiansen at Pott's Hill (see **W. N. Christiansen** , p. 9) in 1954 during a summer vacation research assistantship with CSIRO while I was a student. This was about the same time, or a little before, Don Mathewson, the author's article, joined the CSIRO staff to work with Chris. It was there at Pott's Hill that I met Henry Rishbeth (the author of **Global Change**, p.7) who was visiting from UK at the time. The centenary of the birth of Sir Edward Appleton (pictured at Pott's Hill on p. 9) was celebrated last year at the UK URSI meeting in Bradford, his birth place. Another coincidence, for what it is worth, is that I was born on the very day — maybe the hour — of the beginning of the world's oldest set of daily ionosoundings (from Slough). Maybe this, rather than my constellation, determined my destiny in Commissions G-H!

The feature article this issue, **Radio Tomography of the Ionosphere**, was previously published in the *IEEE Antennas and Propagation Magazine* (October, 1992) by arrangement with the Editor-in-Chief (and Associate Editor of *the Radioscientist*), Ross Stone. I chose this because, apart from its excellence, it should be of particular interest to URSI people who do not see the *IEEE Antennas and Propagation Magazine.* In his editorial, Ross pointed out the dilemma he faces when editing a paper from authors for whom English is not their native language. I try to stress the international nature of *the Radioscientist* by encouraging such papers. It is my policy to edit heavily to produce standard English grammar, style and spelling as a service to the original authors who usually ask for it. Sadly, this means that the style and flavour of the author's culture is lost. So, apart from some minor corrections, I have used Ross's version including additions he made in the text within square brackets.

ERRATA

We apologise for the following errors which appeared in past issues of the Radioscientist.

Diffraction by Mountains (J. R. Wait), Vol. 3, #1 (March, 1992):

Page 21 $(ka/3)^{1/3}$ should read $(ka/2)^{1/3}$.

Lateral EM Waves (J. R. Wait), Vol. 3, #3 (September, 1992):

Page 67 (1st para, 11th line): "However they do not give..." should read: "However they do give..."

Near Field Measurements... (E. Goldbohm), Vol. 3, #4, (December, 1992)

Page 89 Right column top: Insert between lower and antenna: "lower sidelobes, optimum beamwidth and precision in beam shaping"

Page 91 Left column bottom: insert "... as a first approximation ..."

Page 92 L column, last paragraph, 4th line: "voltages rn .." should read "voltages ρ^n..."

Page 93 L column, end of first paragraph, insert underlined part: "alleviate the mutual coupling problem and reduce cross polarisation and Greenberg grating lobes inherent in some types of slotted waveguides."

Page 95 R column, bottom paragraph, second line, delete: 'simple and"

Page 96 R column second line from bottom, last paragraph, delete K in CHLK.

The future magazine name

In my view, you've done a first-rate job in getting the magazine started. It contains interesting articles. If, as I understand, it's proposed to combine it with the URSI Bulletin, then I'd urge that the title "The Radioscientist" be kept. The main reason is that, if the articles are regarded as "referenceable" (as I think they are), then it's important to maintain the continuity of title. If "The Radioscientist" were to change its title after Vol.4 (say), the continuity would be lost. I realise the "URSI Bulletin" is a long-standing publication; I think the best solution is to call it "The Radioscientist" with sub-title "incorporating URSI Bulletin", or something like that.

Regarding your bleat about telephone noises: I don't think I'd want to have them all the same. I find it rather comforting when I get the familiar "burr burr.....burr burr.....burr burr" to know that the British installed the phones. British Telecom directories have helpful notes (in the section that gives the international dialling codes) to indicate what are the ringing and engaged tones for each country. Can't KiwiTelecom (or whatever it's called) do the same?

Henry Rishbeth

I am very sensitive to continuity in both periodical names and volume/issue numbering, perhaps because I worked in a library for a short time. When the *AP-S Newsletter* became the *IEEE Antennas and Propagation Magazine*, I surveyed a number of librarians. There was almost unanimous agreement: continue the numbering in sequence and try to incorporate as much continuity as possible in the name. Thus, I suggest *the Radioscientist* and the *URSI Bulletin*, presented graphically on the cover in a fashion similar to this:

the Radioscientist

and the URSI Bulletin

I would continue the numbering of the *Bulletin*, since it is the older publication. My reasoning is that it is *the Radioscientist* which is likely to be of primary archival interest to libraries, so this is the name we should stress. However, prior to *the Radioscientist*, it was the *Bulletin* which contained (at least in the "earlier days") all of the information which might otherwise have appeared in the new publication. Even if the decision is made to continue the numbering with the sequence following the current numbering of *the Radioscientist*, I would still vote to have the name as shown above. A box identifying the two predecessor publications and explaining the numbering systems for all three should be carried as part of the "masthead page" in each issue.

W Ross Stone

What an excellent idea to have a new-look URSI magazine! I would be in favour of a new name. What about "Radio Communications"? In this case, the sense is not communications by radio, but communications for radio scientists and engineers.

Michael J. Rycroft

It has been been suggested that *the Radioscientist* and the *URSI Bulletin* be combined into a new URSI publication which would cover the two separate fields which so far have been the domains of these journals. This brings up the question of the most appropriate title of the new publication. It is my opinion that it would not be good to keep either name. Keeping the name as the *Bulletin* would suggest that *the Radioscientist* died without replacement even when the new *Bulletin* would contain some of its sections. Keeping *the Radioscientist* as the name would suggest that the *Bulletin* died would be just as bad because it has served well for many years. One therefore should have a new name for the combined new URSI publication .

There are several possibilities. One suggested by the editor is "the URSI-Magazine". The name *Magazine* suggests that it would contain information of the kind the *Bulletin* has provided, but that it also would contain articles of scientific content and discussions as *the Radioscientist* was intended for. Both former journals would merge into this kind of journal giving space to a variety of sections but at the same time not offending anybody and not leaving the impression that either of the above journals has been deleted because of political reasons. Some might not be happy with the name *Magazine* being too close to the Boulevard jargon. If this would cause a problem then one should think of an apparently more serious title as for instance *The Radio Review — An URSI Journal for the Advancement of Radio Science.* This would cause high expectations which would be nice but not easy to satisfy. I myself would be pleased having the Radioscientist and the Bulletin merged into a more modest URSI Magazine.

It would also be nice if there could be regular Review papers invited for at least one of the issues per year. Something like in *Physics Today* with or without figures but of reasonable length and more specialised to the fields which interest the radio community, not so general as *Physics Today* but well understandable for the entire community.

Rudolf A. Treumann

Tx-Rx Reciprocity

Can non-gyrotropic media be nonreciprocal?

The above question was recently raised, and while until now I felt that the answer was obvious, I now have the feeling that it may not be. I would therefore appreciate it very much if anyone could answer this question.

As far as I know, nonreciprocity in passive media is related to gyrotropy, i.e. to some rotational effect produced by a magnetic bias. This is observed in ferrites, semiconductors, optical fibres, etc. The same effect also appears in magnetised plasmas, however the latter would not be considered to be passive media.

Is there any way to obtain nonreciprocity within passive linear (or linearised) media that are not gyrotropic? Or is gyrotropy a basic absolute requirement? Is there some profound (but if possible understandable) reason why nonreciprocity should be linked to magnetic bias? If you know of any passive material that exhibits nonreciprocity in the absence of a magnetic bias (external or internal), please let me know.

I am looking forward to receiving many responses.

Fred Gardiol, LEMA-EPFL
ELB-Ecublens
CH-1015 Lausanne Switzerland
e-mail: GARDIOL@LEMAHP1.EPFL.CH

[Ed — Fred Gardiol is suggesting you contact him direct. Fine, but please share your views with us in these columns in the June issue. If you want more bait, please bite on the following.

Consider an ***isothermal*** *universe containing, among any other passive things including gyrotropic media, magnetoactive plasma, etc., two antennas each terminated by a resistor. The Second Law of Thermodynamics says that the resistor in one antenna cannot warm up at the expense of the resistor in the other antenna. We dispose of any perpetual motion machine claim the same way — by appealing to the First or Second Laws of Thermodynamics, not by examining the mechanical details of gears and pumps, etc. So any claim of reciprocity (in this sense) breakdown has to square it with the Second Law.]*

Cosmology

I enjoyed Pr Pfleiderer's article on "New Developments in Cosmology" in the September issue (pp 80 – 82). I had long wondered how the inflationary hypothesis could violate Special Relativity; I didn't realize it did not apply to expansion of space itself.

Close inspection of the Hubble parameter H_O — I don't like to call it a constant, as it = f(t) — reveals that it actually has units, or a dimension, of *frequency*, Hz. Working through the conversions — easily done on an hp-28Cm which knows about Mpc and so on — for 50 Km/s/Mpc you get 1.62 E-18 Hz or 1.62 aHz (attoHz). Taking the reciprocal of this to get the period, one obtains 0.617 Es (Exas, 1. E18 s), or 19 560 M (million) years, 19.56 billion (thousand million) years. H_O = 100 gives 9 780 M yr.

These figures correspond to the estimated age of the universe, of 10 to 20 000 million years! I wonder if there is any significance to this.

Roger A C Williams

[The above letter was referred to the author for the following reply.]

You are quite right. The reciprocal present Hubble constant or present Hubble parameter H_O is indeed related to our estimate of the age of the universe. If H were constant in time (that is, $H(t) = H_O$), it would precisely give the time needed for expanding the universe from zero to the present state. This would be true for all distances r. Let the radial velocity be $v = H_O r$ (Hubble law), then the time t needed for a galaxy to move by the distance r with constant velocity v is, of course, $t = r/v = 1/H_O$. The standard model states a decrease of expansion due to gravitational pull, such that the time-averaged velocity is larger than the present value v because v was larger in the past. Correspondingly, the age T of the universe, or the time since expansion started, is smaller than $1/H_O$; that is, $r/v_{aver} < r/v_{present}$ if $v_{aver} > v_{present}$. Inflation does not change the picture because it is restricted to a very short time in which total expansion is small even if the relative expansion is by many powers of ten.

Inflation predicts $\Omega \approx 1$, that is, the (average) density is expected to be very close to the critical one which separates open and closed universes. In this case, $T = 2/3H_O$ (or roughly 13 billion years for $H_O = 50$). In plain words, this means that $H_O = 50$ is compatible with other observations only if all objects in the universe turn out to be not older than about 13 billion years. Without inflation, Ω may appreciably deviate from unity. Then the relation between T and $1/H_O$ is different, but always $T < 1/H_O$. Since we are pretty sure that the oldest observed objects are at least, say, 10 billion years old (probably older), the standard model, with or without inflation, is not compatible with observations if H_O turns out to be around 100.

It should also be stated that the decrease of v with time, true for all standard models outside the period of inflation,

Continued on page 11

GLOBAL CHANGE, THE GREENHOUSE EFFECT, AND THE IONOSPHERE

With its Committee for the IGBP, URSI is one of the many scientific bodies that are interested in the question of global change. For much longer — indeed, throughout most of its history — URSI has taken a keen interest in the ionosphere. This article describes recent work that brings together the two subjects.

Discussion of global change in the atmosphere has focused on the lower regions — the troposphere and stratosphere. The idea that higher regions could have any relevance to "global change" has been treated dismissively in some quarters. However, in 1989 Dickinson and Roble [1] published a theoretical paper describing how increased abundance of carbon dioxide and methane in the middle atmosphere would change the thermal structure at higher levels. They estimated that a doubling of the CO_2 and CH_4 concentrations at 60 km height — as is expected to occur by the middle of the 21st century — would cool the mesosphere by around 10 K, because of the increased infra-red emissivity at this height. In the thermosphere above 100 km, the drop in global mean temperature would be greater, amounting to 50 K at heights above 200 km, with accompanying changes in chemical composition. They suggested that this cooling would not only lead to greater orbital lifetimes of artificial satellites, but might also affect the ionosphere.

Using straightforward physical considerations, Rishbeth [2] showed how the thermal contraction produced by such cooling would affect the ionosphere. The predicted 50 K drop of mean thermospheric temperature would lower the height of the F2 peak (hmF2) by 15-20 km. From the point of view of long-distance radio propagation, this would cause a small increase (about 4%) of the M3000 factor, which is proportional to the maximum useable frequency over a 3000 km path. The E-layer height (hmE) would also drop, but only by about 2 km, which would be hardly noticeable. Despite the drop in the height hmF2, the critical frequency foF2 is hardly affected, because it is insensitive to temperature changes (There are second order effects on foF2, of order 1%, because the cross-sections that control the rates of recombination and diffusion are weakly temperature-dependent).

The Boulder "Thermosphere Ionosphere Global Coupled Model" (TIGCM) [3] has been used for more detailed studies of how "greenhouse cooling" would affect the F2 layer. In general, the global maps produced by the TIGCM show that doubling of mesospheric CO_2 and CH_4 reduces hmF2 by 10-20 km in most places. As before, the changes in NmF2 are small and hardly significant [4]. The TIGCM results thus confirm the simpler analysis [2].

What prospects exist for detecting these long-term changes experimentally? Only two techniques can be seriously considered for this purpose: ionosondes and incoherent scatter radar. Rocket data are much too sparse, and satellites do not give useful measurements of hmF2. Though ionosondes are good at measuring the critical frequencies (i.e. the peak electron concentrations) of ionospheric layers, the measurement of longterm changes in the F2-layer height (hmF2) is not straightforward, for several reasons.

First, for any given sounder, the ionosonde circuitry may introduce a small error in height measurements, which will change if the sounder is changed or even re-adjusted; the local conventions for scaling ionograms may also influence the published data. Second, despite the simplicity of the "radar principle" that is involved, the determination of hmF2 requires the inversion of the integral equation that gives the measured two-way time of flight of the radio pulses:

$$t = \frac{2}{c}\int \mu' \, dh \qquad (1)$$

where c is the speed of light, μ'(h,fo) is the group refractive index of the ionospheric plasma for the sounding frequency (in this case, the critical frequency fo), and the integration extends from the ground to the height of reflection. Before the advent of modern digital sounders, the solution of (1) was not performed routinely, and the published data on hmF2 are too sparse to be useful for synoptic studies. Although digital sounders can be programmed to compute hmF2 routinely, they have only been in service for a few years. For conventional ionosondes, a more practical approach is to use an empirical formula [5,6] that links hmF2 to the M3000 factor:

$$\text{hmF2} = A/(\text{M3000} + \Delta M) - B \quad \ldots (2)$$

where A and B are numerical constants (conventionally A = 1490 km, B = 176 km) and ΔM is a correction for the effect of the underlying E and F1 layers. Despite its seemingly arbitrary form, equation (2) has been verified in a number of studies, e.g. [7], and it can be widely applied because the parameter M3000 is included in routinely published data.

In principle, hmF2 can be derived from the "power profiles" P(h) measured by incoherent scatter radars. A difficulty is that the scattered power depends not only on the electron density profile, N(h), but also on the electron/ion temperature ratio (Te/Ti):

$$P(h) \propto \sigma N(h)/[(1 + Te/Ti)h2] \qquad (3)$$

where σ is the Thomson cross-section. Since Te/Ti may vary with height, the height hmF2 cannot be accurately determined unless Te/Ti is also measured, which cannot always be done with sufficiently good height resolution. Furthermore, the existing radars (except perhaps the Millstone Hill radar) do not have long enough datasets for really long-term studies. One may conclude that, for the foreseeable future, ionosondes provide the best method of monitoring long-term changes in the upper atmosphere. This provides a new justification for continuing ionospheric monitoring [8].

The length of the "ionospheric record" is now quite respectable. Regular soundings at Slough (UK) began on 11 January 1931 [9]

(the 60th anniversary was celebrated at a Royal Astronomical Society meeting that marked 150 years of geomagnetic recordings, which fortuitously took place on 11 January 1991 [10]). The daily sequence of Slough soundings began on 20 September 1932, though it was not until 27 December 1933 that swept-frequency ionograms were routinely recorded. A few other stations opened during the 1930s, and by the late 1940s ionosondes were routinely operating in several parts of the world. Several decades of well-calibrated, quality-controlled ionosonde data are therefore available in World Data Centre archives.

In looking for long-term changes, careful allowance must obviously be made for the fact that hmF2 varies systematically with time of day, season and latitude, and is greatly affected by solar and geomagnetic activity. These variations are greater than the effect being sought, but their pattern is known from decades of observation. Success in detecting a long-term change has already been claimed. Using 33 years of data (1957-1990) from Juliusruh (Germany), with careful allowance for solar and geomagnetic effects, Bremer [11] has found evidence of a progressive decrease of F2 layer height. Averaging over all seasons, the decrease amounts to 8 km in 33 years, or 0.25 km/year. If continued, this would amount to 15 km in 60 years, just about the drop predicted in [4].

Global changes in the ionosphere are not necessarily restricted to the effects of "greenhouse cooling". Upper atmosphere tides are forced (driven) by the heating due to the atmospheric absorption of solar radiation, the major contribution being ultraviolet absorption in stratospheric ozone. If the ozone becomes seriously depleted by chemical pollution, this may change the atmospheric tides in ways that are hard to predict, but may eventually be detectable through their ionospheric effects. The equatorial region, where tidal effects are especially prominent, would be the place to seek such effects. It has been suggested that temperature changes in the lower ionosphere might be directly detected through their effect on radio-wave absorption [12]. Contamination of the upper atmosphere, arising from largescale space programmes, might change upper atmosphere chemistry, perhaps increasing the occurrence of sporadic E layers. A different kind of global ionospheric change — though not man-made — can be anticipated from the progressive changes in the geomagnetic dipole field, which is currently decreasing by around 6% per century; this may affect ionospheric characteristic in some regions, notably the South Atlantic, within a few decades. If the geomagnetic dipole field eventually reverses, the ionospheric effects will be profound [13].

To conclude: Reliable evidence of global warming in the lower atmosphere is notoriously difficult to establish from meteorological data, because of the many complicating factors. The accompanying "greenhouse cooling" in the upper atmosphere may be easier to detect, through long-term measurements of the height of ionospheric layers. The well-established network of ionosondes is thus a potential tool for monitoring the "greenhouse effect" — provided extreme care is taken in allowing for solar and geomagnetic effects on hmF2. This gives URSI an added interest in the IGBP, and a new use for ionosondes. A fitting thought for the centenary of Sir Edward Appleton (1892-1965), the pioneer of ionospheric research?

References

[1] Roble R.G. & Dickinson R.E., *Geophys. Res. Lett.* **16**, 1441-1444 (1989).

[2] Rishbeth H., *Planet. Space Sci.* **38**, 945-948 (1990).

[3] Roble R.G., Ridley E.C., Richmond A.D. & Dickinson R.E., *Geophys. Res. Lett.* **15**, 1325-1328 (1988).

[4] Rishbeth H. & Roble R.G., *Planet. Space Sci.* **40**, 1011-1026 (1992).

[5] Shimazaki T., *J. Radio Res. Labs.* **4**, 309-332 (1957).

[6] Bradley P.A. & Dudeney J.R., *J. Atmos. Terr. Phys.* **35**, 2131-2146 (1973).

[7] Berkey F.T. & Stonehocker G.H., *J. Atmos. Terr. Phys.* **51**, 873-877 (1989).

[8] *Synoptic Data for Solar Terrestrial Physics*, The Royal Society, London, 1992.

[9] Gardiner G. W., Rishbeth H. & Lane J. A., *Radio & Electronic Engr.* **52**, 111-121 (1982).

[10] Rishbeth H., *Q. J. Roy. Astron. Soc.* **32**, 409-421 (1991).

[11] Bremer J., *J. Atmos. Terr. Phys.* **54**, 1505-1511 (1992).

[12] Serafimov K. & Serafimova M., *J. Atmos. Terr. Phys.* **54**, 847-850 (1992).

[13] Rishbeth H., *Ann. Geophys.* **3**, 293-298 (1985).

[18 November 1992]

H. Rishbeth
Department of Physics
University of Southampton
SO9 5NH, U.K.

W. N. CHRISTIANSEN

Professor Wilbur Norman Christiansen, a past President of URSI and a present Honorary Life President, has never been known by these given names. So despite an editorial policy to avoid both nick names and formal titles, I must leave him as "Chris" here, the way we have always known him —Ed.

The photograph of Chris explaining some intricate detail of his famous 32-element grating interferometer at Potts Hill to his two visitors is very typical. I can just hear him saying, "now if we give this quarter-wave matching section a little tweak like this our SWR will be almost 1 ... don't you think?" The only thing out of place is the coat and tie.

The first time I met Chris was at Potts Hill in 1955. I was a fresh graduate from Queensland down in Sydney for an interview for a job to work as an assistant to Chris for his new project, the Chris-Cross, a 64 element crossed-grating interferometer to be built at Fleurs Field Station. Joe Pawsey, the Head of the Radioastronomy Group at CSIRO had driven me out to Potts Hill to meet Chris. We had stopped at Ashfield to buy two enormous bags of bananas and lamingtons for which Joe apparently had a weakness. Laden with these bags, we were walking down the edge of the reservoir along which was erected the 32-element interferometer. Coming towards us was a man dressed in khaki shirt, bombay shorts with a battered sunhat pulled low over his eyes and rolling a cigarette. Much to my surprise Joe introduced me to my prospective new boss, Dr. Christiansen. His first words were, "Don't eat too many of those things", nodding towards the two bags, "they're dynamite when eaten together". A rather belated warning as I'd already ingested considerable amounts in a polite attempt to impress Joe. Chris gestured towards a length of coaxial cable lying on top of a fibro-hut, "that saved Parthasarthy's life. He accidentally fell into the reservoir whilst working late one night and his Indian colleague, Govind Swarup, pulled him out with that. Only managed to see where he was because Govind had the presence of mind to tell Parthasarthy to roll his eyes!" (Govind Swarup FRS is now the dynamic leader of the construction of India's Giant Metre-wave Radio Telescope).

I immediately warmed towards him - his laconic style and wry sense of humour captivated me. We went for a walk along the adjacent bank of the reservoir where there was a second grating array at right angles to the main array. Chris explained how for the past year this N-S array was used together with the E-W array to strip-scan the Sun during most of the daylight hours. Over this time, the Earth's rotation changed the angle of scan across the Sun's disk so 1-D brightness distributions were obtained at many angles. A double Fourier transformation would then give a 2-D picture of the Sun. Little did I realize that what was being explained to me was a revolutionary new technique for obtaining very high resolution radio maps of the cosmos. A technique which is known as earth rotational synthesis and which is used by the major radio telescopes all over the world. The fact that not a lot of astronomers know that Chris is the father of earth rotational synthesis is due to the extreme modesty of this inventive genius.

Then Chris took me across to the opposite bank of the reservoir and showed me the improvised 21 cm line receiver which he and Jim Hindman had put together in a matter of

At Potts Hill, Sydney, during the 1952 General Assembly of URSI. From left: "Chris", Edward Appleton, Balth van der Pol.

weeks to confirm H. C. Ewen's discovery of that radiation from neutral hydrogen in our Galaxy. Not only did they confirm it but the observations provided the best evidence for the existence of galactic spiral arms.

That evening, back at Radiophysics, Joe told me I had the job and I still remember my intense excitement at the prospect of working with Chris. I was never disappointed for Chris taught me many things, not all of them scientific. For example, there seemed to be interminable delays to actually start building the Chris-Cross even though Taffy Bowen, the then Chief of the Division of Radiophysics, has approved the project. Whilst a lesser man would have patiently waited, not so Chris. One morning with a worried frown and some unintelligible mutterings about administrators in general, he bundled his secretary and me in a battered old truck together with a load of metal starposts, fencing wire, strainers and sledge hammers and headed for Fleurs Field Station. All day we belted in the starposts, strained wires etc, etc and the next day and the next until the cross-shaped fence was completed. Then Chris sent Taffy a memo with an estimate of the cost in salaries for erecting the fence and announced that next week the same team would commence pouring the concrete foundations for the antennae. Within one week, a team of workmen had been assembled at Fleurs to start the construction of the Chris-Cross (much to my relief!).

The Chris-Cross team would have done anything for Chris. He was a staunch supporter of human rights, a champion of the underdog, a no-nonsense egalitarian and a superb scientist. He had the deep respect of all of us. This was enhanced by the fact that his charming wife, Elspeth, is a fantastic cook and used to regularly give to Chris a big bowl of bouillabaisse which she had learnt how to prepare when Chris was helping to design a large radio interferometer at St. Michel in Haute Province. This was a welcome relief to our rather basic diet.

I was often amazed at Chris' even temperament. He never seemed to lose his temper (only with politicians and bureaucrats!). Not even when inadvertently one morning, I left the gate open and a stray herd of cows got into the aerial enclosure and started scratching themselves against our carefully matched (almost 2 km) of twin transmission lines! And not even when the groundsmen accidentally cut through a vital coaxial cable with his lawn mower and guiltily tied the cable together with a beautiful reef knot and placed a heap of cut grass over it. Eventually, after hours of searching for the fault, we found it but all Chris said was, "The sneaky old bastard ... don't you think?" I agreed!

In 1960 Chris left Radiophysics to become Professor and Head of the Department of Electrical Engineering of the University of Sydney where he formed a strong radio-astronomy group and upgraded the Chris-Cross into a powerful earth rotational synthesis telescope for extra-galactic studies. Other research groups which he set up in the fields of energy conversion, power distribution and radio aids for air navigation have achieved considerable international reputations.

For most of his professional career, Chris has been an important and familiar figure in the astronomical community all over the world. He has held prestigious appointments in France, the Netherlands, India and China, whilst helping them design their grating arrays and earth rotational synthesis arrays. His book *Radiotelescopes* with Dr. J. A. Högbom is regarded as the standard text by radioastronomers. It is published by Cambridge University Press, 1st edition 1969, 2nd edition 1985 with Russian and Chinese editions. A paperback version was released in 1987 and the 2nd Russian edition in 1988.

Chris has given long service to international scientific organisations; as the President of the radio-astronomy commission of URSI, 1963-66; a Vice-President of URSI, 1972-78, the President of the Union, 1978-81 and President Sortant, 1981-84. In 1984 at Florence he was elected Honorary President of URSI for life. Chris was a Vice-President of the IAU from 1964-70 and a member of the General Committee of ICSU from 1978-81.

Nationally, Chris was Chairman of the National Committee for Radio Science, 1960-72 and President of the Astronomical Society of Australia, 1975-79. He was a member of the Australia-China Council of the Department of Foreign Affairs, 1979-82 and Chairman of the Australia-Japan Committee of the Academy of Science, 1982-85.

In the course of his career, Chris has received numerous honours from national and international scientific bodies. Elected to the Australian Academy of Science in 1959, he was a member of the Council of the Academy for some years and was their Foreign Secretary from 1981-85.

Chris was awarded the prestigious Medaille de l'Adion in 1976 for his contributions to Astronomy and Astrophysics and for his role in the development of international collaboration in this field. He received the Syme Medal for Research from the University of Melbourne who also awarded him the Doctorate of Science for his work in radio astronomy and in 1982 an Honorary Doctorate of Engineering. In 1980 he received an Honorary Doctorate of Science in Engineering from the University of Sydney. In 1970, Chris received the premier award of the Institution of Engineers of Australia, the Peter Nicol Russell Medal. Chris has also been made a Fellow of many physical and engineering societies both in Australia and the U.K.

Perhaps the following paragraph extracted from the speech of Professor Shou Guangzhoa, President of the Chinese Academy of Sciences, at the XXII General Assembly of ICSU held in Beijing in 1988 allows some insight into Chris' non-conformist attitude to life, his concern for society and his caring and unselfish nature :

W. N. CHRISTIANSEN

"Due to historical reasons, for nearly 30 years from 1949, communication between the mainland China and the Western world in science and technology was cut off. This brought untold difficulties to the development of science and technology in China. However, we can never forget the courage displayed by some scientists who during this period of time extended their friendly hands to us. Among them are Joliot Curie of France, Joseph Needham of the U.K., Wilbur Norman Christiansen of Australia, Niels Bohr and Aage Bohr of Denmark, and Shoichi Sakata and Shinichira Tomonaga of Japan and many overseas Chinese."

[Ed — It was some time after these reminiscences were received and planned for this issue that we heard of the untimely death of Chris's son, Peter, who was a plasma physicist well known to the URSI community. We extend our deepest sympathy to Chris and Elspeth Christiansen.]

Don Matheson
Professor of Astronomy
Australian National University
Canberra, ACT
Australia

LETTER & NEWS

Continued from page 6

predicts a deviation of the observed Hubble relation from the linear Hubble law, the reason being that we look back in time and expect distant galaxies which we see closer than they are today, to move faster than they would move today. Then H_0, the slope of the v-r relation, would be a function of distance. The actual observations are, however, not precise enough to allow the detection of that non-linearity. Reasons are the peculiar velocities of individual objects (we measure $v = H_0 r - v_{peculiar}$) and, particularly, large — and possibly systematic — uncertainties in the distance determinations.

By the way, the standard model, with and without inflation, starts with infinite expansion velocity — again only apparently in contradiction to Special Relativity because same does not apply, as you are right to state, to the expansion of space itself.

Jörg Pfleiderer
Institut für Astronomie
Der Universität Innsbruck
Austria

Hertz Medal to Budden

At its meeting of December 6-7, 1992, the IEEE Board of Directors selected **Dr Kenneth G Budden**, as recipient of the 1993 IEEE Heinrich Hertz Medal, with the citation "For major original contributions to the theory of electromagnetic waves in ionised media with applications to terrestrial and space communications." The presentation took place [expected at the time of writing on Feb. 1 — Ed] at the IEEE Honours Ceremonies to be held at the Sheraton Chicago Hotel and Towers in Chicago, Illinois on Saturday evening, February 27, 1993.

Previous Heinrich Hertz Medal Recipients are:

1989 – Nathan Marcuvitz "For fundamental theoretical and experimental contributions to the engineering formulation of electromagnetic field theory"

1990 – John D Kraus "For pioneering work in radio astronomy and the development of the helical antenna and the corner reflector antenna"

1991 – Leopold B Felsen "For highly original and significant developments in the theories of propagation, diffraction and dispersion of electromagnetic waves"

1992 – James R Wait "For fundamental contributions to electromagnetic theory, to the study of propagation of Hertzian waves through the atmosphere, ionosphere and the earth, and to their applications in communications, navigation and geophysical exploration"

Max Planck Prize

Congratulations to **John Whiteoak** (Australia Telescope National Facility) and **Richard Wielebinski** (Max Planck Institute für Radioastronomie), who have been awarded the Max Planck Prize for collaborative research.

Free Subs extension!

The subscriptions to *the Radioscientist* were originally planned to end with the June, 1993, issue. This was later extended to end with the September, 1993, issue and later still, with the December, 1993, issue, the last issue under the present scheme. From 1994 onwards, the General Assembly scientific participants will get a 3-year subscription as part of the registration deal. Non-participants can take out annual or 3-year subscriptions (probably only for whole volumes) at rates to be determined.

Meanwhile, all current subscriptions to *the Radioscientist* (including the *Bulletin*) due to run out in June or September, 1993, are hereby extended to December, 1993, at no extra charge.

Radio Tomography of the Ionosphere

Abstract

This paper provides on overview of tomographic approaches to ionospheric remote sensing in the radio-wave range. The ionosphere has a very complicated structure. Thus, it is reasonable to divide tomographic methods into deterministic and statistical ones. The deterministic tomography problems can be subdivided into ray radio tomography and diffraction radio tomography. The statistical radio tomography approach is used when it is necessary to reconstruct the statistical structure of a great number of inhomogeneities, on the basis of measurements of field statistics (instead of one realization of the reconstruction of an inhomogeneity). The methods of solving radio-tomography problems, and their connection with inverse-scattering problems, are considered. The results of some first experiments are described, which show the possibilities of the radio tomography approaches. In conclusion, we discuss perspectives, directions of the development of radio tomography, and problems which appear.

1. Introduction

This is an expository article on a new approach to radio-probing of the ionosphere: radio tomography (RT) of the ionosphere. It should be stressed that an application of tomographic methods is an inevitable evolutionary step for almost all remote-sensing systems. Tomographic reconstruction of the medium's spatial structure is only possible due to a sufficiently-high level of development of remote-sensing techniques, and of the means for data processing. In many areas, the tomographic approaches have transformed diagnostic methods, and have given new results, in principle. The impressive advances of tomography in medicine and molecular biology are well known. Tomography permitted the discovery of new geophysical phenomena. In particular, the roughness of the boundary between the Earth's core and mantle, as well as the specific global variations of seismic-wave velocity, were found out by seismic tomography. Acoustic tomography of the ocean lead to the revelation of the mesoscale velocities. Remote sensing by means of satellites and modern radio-probing techniques allows us to sound the ionosphere over a wide range of transmitter-receiver positions, and to use tomographic methods.

The ionosphere has a very complicated structure, which combines the quasi-layered background, characterized by big-scale electron-density variations, and local inhomogeneities, with different scales, including turbulent areas. So, the problems of reconstruction of the inhomogeneous structure of the ionosphere can be divided into deterministic and statistical problems. Further, both above-mentioned classes can be subdivided into problems of diffraction radio tomography (DRT), and of ray radio tomography (RRT) wherein the diffraction effects are neglected. Mathematicians very often use designations such as the inverse problem and the inverse scattering problem, for such problems of structure reconstruction based on the scattered field. Here, we use the terms inverse-scattering problem and diffraction radio tomography as synonyms. The deterministic inverse problem is connected with the reconstruction of the structure of localized inhomogeneities (scatterers), or of a group of inhomogeneities. When a large number of inhomogeneities occupies some spatial area, it is not reasonable to reconstruct the structure of the whole region. In this case, one can define as the task the spatial-structure reconstruction of the statistical characteristics of the inhomogeneities, such as the correlation function of the electron density, etc.

The term "tomography" has two meanings. The narrow, original one refers to the investigation of an object's structure by the successive reconstruction and registration of layers [of two-dimensional "cuts" through a three-dimensional object]. The broader meaning implies the recording of different cross-sections or projections of an object (or of a particular transformation of it, for example, the Fourier transformation), and the subsequent reconstruction of the object's structure on this basis. The problems of radio-probing of the ionosphere, by means of satellites, considered here, include the reconstruction of the spatial structure of the ionospheric inhomogeneities, or their statistical characteristics, using sets of different data of the tomographic type (cross-sections, projections, etc.) It is reasonable to name such an approach to the solution of these problems, including its experimental realization, "Radio Tomography of the Ionosphere."

2. Physical formulation of tomographic radio probing

The propagation of radio waves in the ionosphere, and their scattering by plasma irregularities, are described by Maxwell's equations, combined with the material equations [1]. In the general case, even in the absence of a magnetic field, the plasma permittivity is a tensor, due to the spatial dispersion. But for ionospheric irregularities (both for natural and artificially-generated ones), the spatial dispersion may be neglected, as electron thermal velocities are much less than the speed of light. Thus, the approximation of a "cool" plasma is valid. By analogy, the typical velocities of diffusion, mixing, and other transport processes, and the velocities of receiving and transmitting systems, do not exceed 10 km/s ($v/c < 3\text{x}10^{-5}$). Thus, the quasi-stationary approximation may be used, and the "slow" dependence of the medium and the fields on time may be accounted for as dependence on a

* A version of this article appeared in the *IEEE Antennas & Propagation Magazine*, October, 1992. The original is Copyright © 1992 by IEEE Inc. and is used here with permission. In this version the curly font is replaced by a Times font embellished by a concave overbar as in: **R**, *Z*, *R*

parameter. In this approximation, phenomena such as the Doppler frequency shift, and time variations of group delays, are accounted for up to the relativistic effects.

Below, it is convenient to use equations for the complex amplitudes $\mathbf{E}$ of monochromatic components, instead of the equations for the radio-wave field, $\vec{E}(r,t) = \mathbf{E}(\mathbf{r},t)\exp(-i\omega t)$. So, later on, the complex amplitudes, $\mathbf{E}(\mathbf{r},t)$, with "slow" dependence on time, will be called "the field." Taking into account the previous remarks, the following equation results from Maxwell's equations, within the quasi-stationary, "cool"-plasma approximation:

$$\nabla^2\mathbf{E} + \frac{\omega^2}{c^2}\bar{\varepsilon}\mathbf{E} - \text{grad div }\mathbf{E} = 0 \qquad (1)$$

where $\bar{\varepsilon}$ is a complex permittivity tensor, and $\omega/2\pi = f$, where f is the frequency. Investigation of radio-wave propagation, in an inhomogeneous magneto-active plasma with tensor $\bar{\varepsilon}(\mathbf{r},t)$, is a very complicated problem. In the general case of an arbitrary dependence of $\bar{\varepsilon}(\mathbf{r},t)$ on coordinates, there are no methods for calculating the radio signal, or the field parameters, $\mathbf{E}(\mathbf{r},t)$. Due to this fact, the structure reconstruction of a general $\bar{\varepsilon}(\mathbf{r},t)$ is unlikely to be reasonable. But at high probing frequencies, the non-diagonal tensor elements may be neglected, as they are less than $\sim (f_N/f)^2 f_H/f$, where f_N is the plasma frequency, f is the probing frequency, and f_H is the gyrofrequency [1]. For example, the maximum density in natural conditions is $N_0 \sim 10^6$ cm^{-3}. For this value, at $f > 50$ MHz, $\sim (f_N/f)^2 f_H/f < 0.001$. By analogy, at high frequencies, the last term of equation (1) may also be neglected, as its order of magnitude is determined by the ratio of the source wavelength to the typical scale of density changes.

Therefore, in the case of a high probing frequency, the vector equation is reduced to three scalar equations, and it is sufficient to consider equations only for the component:

$$\nabla^2 E + k^2\varepsilon(\mathbf{r},\omega)E = 0 \qquad (2)$$

where

$$\varepsilon(\mathbf{r},\omega) = 1 - \frac{4\pi r_e N(\mathbf{r})}{k^2[1 + i\nu(\mathbf{r})/\omega]}$$

and $k = 2\pi f/c$ is the wave number in vacuum, and r_e is the classical electron radius. The expression for ε has the above form in both the SI and the cgs systems of units: only the value of r_e changes. $\nu(\mathbf{r})$ is the effective electron collision frequency, and the "ion" contribution to the permittivity may be omitted [1]. Further, it will be convenient to introduce a complex function $q(\mathbf{r},\omega) = k^2(1-\varepsilon)$, and to divide it into two parts: $q = q_0(z,\omega)+q(\mathbf{r},\omega)$. One of these corresponds to the regular, stratified ionosphere, with vertical- coordinate dependence $N_0(z)$, $\nu(z)$, and the other corresponds to the three-dimensional irregularities $N_0(\mathbf{r})$, $\nu(\mathbf{r})$, in the stratified medium. The introduction of q is justified by the fact that $q \sim 1-\varepsilon$ is a generalized susceptibility [2], which characterizes the medium response to the applied field. Besides, the scalar Helmholtz equation is transformed to the stationary Schroedinger equation with the complex potential, q:

$$\nabla^2 E + k^2 E - q_0(z,\omega)E - q(\mathbf{r},\omega)E = \delta(\mathbf{r} - \mathbf{r}_0) \qquad (3)$$

The delta function on the right-hand side of the equation describes a point source, which is a good approximation in most satellite radio-probing experiments, as within the main lobe of the power pattern, the source wave may be treated as spherical.

The inverse problem for equation (3) may be formulated in the following way. The structure of the irregularities is to be reconstructed based on field measurements over a limited surface, in a limited frequency range, and in a limited range of source coordinates. If the complex function $q(\mathbf{r},\omega)$ is found, both $N(\mathbf{r})$ and $\nu(\mathbf{r})$ can be reconstructed. We also note that equation (3) is suitable for describing HF scattering when polarization effects may be neglected, *i.e.*, when the polarization correlation is small, the inverse problem for equation (3) may even be stated for the case of HF probing. Also, the changes in the polarization components are less than the components themselves, when the source frequency is only 1.5-2 times higher than the critical frequency.

Let us now mention the main special features of the problem of irregularity reconstruction, for the case of ionospheric measurements. The dimensions of the transmitting and receiving systems are much less than the distances to the irregularities to be reconstructed, which are several hundreds of kilometers: *i.e.*, the aperture angles are small. Since reconstruction with a large number of receivers is an expensive project, aperture synthesis with respect to one coordinate is obligatory. This may be obtained, for example, when the transmitter is placed on board a moving satellite. Due to the small values of aperture angles, it is reasonable to consider the problem of reconstruction of the irregularities with a resolution larger than the wavelength. That is why we shall deal with the problem of the large-scale (with respect to the wavelength) irregularity reconstruction. However, compared to the Fresnel-zone size, the scales are not always large, and thus diffraction effects should be taken into account.

The scheme of the radio tomography experiments is presented in Figure 1. The satellite, with a transmitter on board, moves at the altitude $z = z_s$; the receiving system is located in the plane $z = z_R$ (on the ground). The receiving system can be a transverse array of receivers for diffraction radio tomography

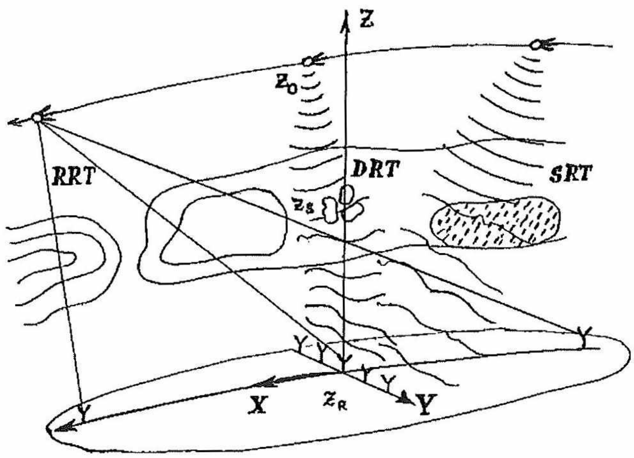


Figure 1. The geometry of radio tomography experiments. Ray radio tomography (RRT) is used for studies of large-scale, global ionospheric structure. A small number of widely-spaced receivers is used, located in the plane of the satellite's trajectory (along the x *axis). Diffraction radio tomography (DRT) is used to study localized inhomogeneities. It uses an array of receivers separated by distances of about 100 km along a line (the* y *axis) transverse to the satellite's path. Statistical radio tomography (SRT) uses the same geometry as diffraction radio tomography, but processes the data to reconstruct the statistical properties of the medium.*

or statistical radio tomography problems (or a collection of transverse arrays). Receivers situated along the direction of satellite movement will be used in ray radio tomography problems, for reconstructing global structures. The scatterer (a group of irregularities) is located at the altitude $z = z_s$. In the case of diffraction radio tomography or statistical radio tomography, the approximate location of a scatterer is assumed to be known. The problem of measuring the scatterer's coordinates will be considered in Section 3. In ray radio tomography problems, for reconstruction of global structures, it is possible to reconstruct the two-dimensional cross section of the ionosphere up to the satellite height, without any information about the coordinates.

3. Inverse scattering problems

There are no strict [exact] results for the solution of the inverse problem (3) with a complex potential. But it should be noted that for propagation of waves of different nature in real media, the potential, q, is a complex function, in principle, and it is possible to deduce certain dispersion relations, which connect its real and imaginary parts [2].

It is necessary to indicate here the fundamental results which have been obtained in [3,4] for the three-dimensional inverse problem, for the Schroedinger equation with a real potential. But for the case of complex potentials, there are no exact solutions, even for the one-dimensional inverse problem, *i.e.*, the generalization of the Gelfand-Leviathan-Marchenko algorithm is unknown, let alone for an arbitrary dependence of the potential on energy (the frequency, ω) [5]. The solutions for the inverse problem of the three-dimensional reconstruction of $q(r,\omega)$ are also unknown for the case of a stratified background.

Due to these reasons, approximate approaches to the three-dimensional inverse scattering problem are, undoubtedly, of interest. The geometrical-optics approximation is valid for the description of radio-wave propagation in the regular ionosphere. The scattering by weak irregularities is described by the well-known Born and Rytov approximations (BA and RA). For strongly-scattering irregularities, more specialized methods will be developed.

There are many papers connected with approximate approaches to the inverse scattering problem [6-10]. The scattering by weak irregularities was described within the Born approximation and the Rytov approximation. The iterative methods were used for strong-scattering irregularities. But there are some special features of ionospheric problems: the size of irregularities is very big (it can exceed the probing wavelength by 10^3 to 10^4 times), and the ionospheric irregularities can be either weak scatterers or strong scatterers. It is very difficult to directly use iterative methods for large, strong-scattering irregularities. However, it is sufficient to use the small-angle approximation, depending on whether one is dealing with the large-size irregularities or their details. In what follows, we consider the methods of inverse-scattering problem solutions only, based on the asymptotic approximation for small-angle, forward scattering.

It should be noted that it is particularly interesting, for tomographic methods, to consider such cases of small-angle scattering when the wavelength of the sounding radiation is much less than the scales of object-specific details. This is a necessary condition to reconstruct the complicated internal structure of the object.

In the beginning, it is useful to consider the inverse scattering problem in the high-frequency limit, *i.e.*, when the source-field frequency is essentially higher than the critical frequency of the regular ionosphere. In this case, the refraction index is close to unity, and the influence of the regular ionosphere may be neglected. Then, instead of equation (1), the following equation should be used:

$$\nabla^2 E + k^2 E - q(\mathbf{r}, \omega) E = \delta(\mathbf{r} - \mathbf{r}_0) \tag{4}$$

This differential equation is equivalent to the Lippmann-Schwinger integral equation,

$$E(\mathbf{r}) = E_0(\mathbf{r}) + \int G(\mathbf{r} - \mathbf{r}') E(\mathbf{r}') q(\mathbf{r}', \omega) d^3 r' \tag{5}$$

where $G(r) = -(4\pi r)^{-1} \exp(ikr)$ is the Green's function for a vacuum, and $E_0(\mathbf{r}') = G(\mathbf{r}-\mathbf{r}'_0)$ is the source field. It is necessary to bear in mind that the potential, q, depends on N and ν as follows (the usual condition for ionospheric radio probing, $\nu << \omega$, is taken into account):

$$q = 4\pi r_e N(\mathbf{r}) / [1 + i\nu(\mathbf{r}) / \omega] \cong 4\pi r_e N(\mathbf{r})[1 - i\nu(\mathbf{r}) / \omega] \quad (6)$$

For the case of small-angle scattering, the transmitter, a scattering object, and the receiver, are situated approximately along a straight line. Assuming that the direction of this straight line is close to the direction of the z-axis, one can obtain an approximate equation, describing the forward small-angle scattering, instead of (5) [11,12]:

$$\mathrm{U}(\mathbf{r}) = 1 + \int F(\mathbf{r},\mathbf{r}') U(\mathbf{r}') q(\mathbf{r}',\omega)\, d^3r' \equiv 1 + \hat{F}Uq \quad (7)$$

Here, $U=E/E_0$.is the normalized field. In the derivation of equation (7), the Fresnel approximation was used for the Green's function, G, depending on the sounding-wave field. After some transformations, we come from equation (5) to formula (7), where the kernel, F, of equation (7) contains the coordinates of the transmitter, z_0, the finite scatterer, z_s, and the receiver, z_R:

$$F(\mathbf{r},\mathbf{r}') = -\frac{1}{4\pi\zeta}\exp\left[i\frac{k}{2\zeta}(\rho' - \mathbf{s})^2\right]$$

$$\mathbf{s} = \rho_R(z_0 - z_s)/(z_0 - z_R) + \rho_0(z_s - z_R)/(z_0 - z_R) \quad (8)$$

$$\zeta = (z_0 - z_s)(z_s - z_R)/(z_0 - z_R)$$

In the general case, the formulae for $\mathbf{s}$ and ζ have to include the integration variable ζ' instead of z_s. But if the object scale is less than the longitudinal Fresnel resolution, the variable z' can be changed to the constant z_s.

There is another form of equation (7), using the complex phase $\Phi = \ln E$, $\Phi - \Phi_0 = \ln U$,

$$\Phi - \Phi_0 = \ln\left[1 + \hat{F}q\exp(\Phi - \Phi_0)\right] \quad (9)$$

which includes the Rytov approximation (the first iteration of the non-linear equation (9)):

$$\Phi - \Phi_0 = \ln\left(1 + \hat{F}q\right) \cong \hat{F}q \text{ or } U = \exp\left(\hat{F}q\right) \quad (10)$$

Taking into account equations (7) and 10), and making use of the Fresnel transformation, we have the algorithm for reconstruction of a two-dimensional cross-section of the potential q [11]:

$$q_z(\rho,\omega) \equiv \int q(\mathbf{r},\omega)dz = (k/2\pi\zeta)^2 \int V(\mathbf{s})\exp\left[-ik(\mathbf{s}-\rho)^2/2\zeta\right]d^2s \quad (11)$$

The integral projection, $q_z(\rho)$, can be obtained after transformation of the field data. For the case of the Born approximation , we have $V = -4\pi\zeta(E - E_0)/E_0$, and for the case of the Rytov approximation, $V = -4\pi\zeta(\Phi - \Phi_0)$ [11]. Changing the direction of the incident sounding wave ("turning" the z-axis), one can obtain a set of two-dimensional projections, which make possible the tomographic reconstruction of the three-dimensional structure.

To reconstruct the two-dimensional structure of ionospheric inhomogeneities using the transformation (11), we need information about the approximate coordinates of the scatterer. Let us briefly discuss a method for the determination of the distance to the scatterer, which is essential for irregularity reconstruction by integral transformations. If only an approximate value of the distance is known, then there are errors which appear in $\mathbf{s}$ and ζ and, hence, the reconstructed function is distorted. Let us consider an example in which a source is placed on board a satellite, and the corresponding distortions which arise in this case. The distance between the satellite and the receivers, $(z_0 - z_R)$, is known quite precisely. However, in determining the distances "source-scatterer," $(z_0 - z_S)$, and "scatterer-receiver," $(z_S - z_R)$, a systematic error, Δ, is present: . It may be shown that reconstruction errors are small for values of Δ which correspond to the longitudinal resolution of the measuring system. This conclusion is also confirmed by numerical simulations [12].

It easy to show that when the error, Δ, is less than the longitudinal resolution, $\Delta << \lambda 2\zeta^2/(\max s)^2$, the reconstructed function is

$$\tilde{q}_z(\rho) \cong q_z\left(\frac{x}{u_x},\frac{y}{u_y}\right)\exp\left[i\frac{k}{2\zeta u_x u_y}\left(y^2 - x^2\right)\right] \quad (12)$$

where

$$u_x = 1 - \Delta/(z_s - z_R),\ u_y = 1 + \Delta/(z_0 - z_s)$$

This equation makes it possible to determine the distance to the scatterer by performing the reconstruction with different values of Δ. At the true location of the scatterer ($\Delta = 0$), the "phase front" curvature of the function, q, under reconstruction, changes to the opposite sense with respect to each coordinate.

These problems are considered in detail in [12] and partly in [13]. There, one can find the generalization of the method for an ionosphere with a layered (stratified) structure, as well as the method for determination of the parameters of inhomogeneities ("mass," space coordinates, size, and other moments of the potential, q) by means of a small number of receivers, and solutions of the inverse problem based on back-scattered data.

It is possible to consider the more general case, namely, the strong-scattering case. For this case, in accordance with equations (7) and (10), we reconstruct the projection, Q_z, of the product of the potential and the normalized field, $Q = qU$, namely,

$$\int qUdz = Q_z(\rho) \tag{13}$$

It should be stressed that, in general, the normalized field, $U(q)$, depends on the potential and on the direction of the incident sounding wave. So, it is impossible to solve the problem of the reconstruction of the product qU by means of the direct transformation of a set of projections such as equation (13). It is possible to suggest iteration procedures of the inverse-scattering- problem solution to equation (13). However, if the scale of ionospheric inhomogeneities is more than 10^3 to 10^4 times the sounding wavelength, it is even complicated to solve the direct-scattering problem. So, for such cases, it is necessary to use asymptotic methods. The special asymptotic methods for the solution of the inverse scattering problem for the case of large, strong scatterers were developed in [12, 14]. For example, the following asymptotic representation of the normalized field was used:

$$U(\rho,z) = \exp\left\{ \begin{array}{l} -\dfrac{i}{2k}\displaystyle\int_{-\infty}^{z} q(\rho+z')dz' \\ +\dfrac{1}{4k^2}\displaystyle\int_{-\infty}^{z}\left[(z-z')-\dfrac{\partial^2}{\partial\rho^2}q(\rho+z')\right]dz' \\ +O(k^{-3}) \end{array} \right\} \tag{14}$$

This formula is correct for an infinitely-smooth potential. Corresponding additional terms in the sum in equation (14) will appear when there are discontinuities in the derivatives of the potential. The formula (14) permits us to construct a simple iteration procedure for the solution of the inverse scattering problem, when it is not necessary to numerically solve either the direct-scattering problem or the inverse-scattering problem. The first guess given for the potential q (based on *a priori* information, or on transformation under the assumption of weak-scattering conditions) defines the approximation of the normalized field functional $U(q_1)$, according to equation (14). Using this approach, it is possible to solve the usual tomo-graphic problem of the reconstruction of q(r), in equation (13), with known "weight" U due to $Q_z(\rho)$, with different directions of incidence of the sounding wave. Later on, the iteration procedure, with the potential approximations obtained, is repeated.

The representation in equation (14) permits us to formulate the conditions of applicability for the weak-scattering approximations. According to this condition, the first term (of order k^{-1}), and all successive terms of expansion (14), have to be small. The restriction on the first term gives us the well-known condition for the Born approximation to be applicable,

$$qr_m / 2k << 1 \tag{15}$$

Here, q is the typical (mean) value of the potential, and r_m is the maximum scale of the inhomogeneity. In the case where the wavelength of the sounding radiation is $\lambda = 2$ meters, and the value of the disturbance of the ionospheric electron density is of the order of , condition (15) leads to the inequality r_m << 2 km. The fluctuations in the electron density which scatter the radio waves have to be measured relative to the quiescent background of the regular layered (stratified) ionosphere. So, if the quiescent value of the density is $N \approx 10^{11}$ el/m^3 and the disturbances are sufficiently strong (say, 10%), the Born approximation is valid up to sizes of dozens of kilometers. But for the case of the main ionospheric density maximum $N \approx 10^{12}$ el/m^3, the scale restriction is significant, and it is necessary to take into consideration the first term of equation (14). The second term of equation (14) is less (kr_m>>1) than the first one, for simple scatterers without internal structure. In cases when there are some internal details inside the scatterer with a scale $a >> \lambda$, and for typical values of the potential q', the second term can be more than the first. Hence, the other necessary condition of the Born approximation is that the second term (with the transverse derivative) be small:

$$q'r_m / (4k^2a) << 1 \tag{16}$$

In many practical cases, it is sufficient to take into account only the first term of equation (14), but the scatterer is not a Born scatterer, according to equation (15), and the inequality (16) is valid. Such conditions allow us to get a simple analytic formula which connects the function, Q, reconstructed from the experimental data, and the projection of the scattering potential, q_z, per equation (14):

$$Q_z(\rho) = 2ik\{\exp[-iq_z(\rho)/2k]-1\} \tag{17}$$

This formula is the basis of tomographic reconstruction for most of the ionospheric applications. Really, inhomogeneities with a scale of about ten or more kilometers, the deviations of which are about 10% with respect to the norm, are strong inhomogeneities (the left hand side of relation (15) is greater than or approximately equal to 6, when $\lambda = 2$ m); but the inequality (16) is valid for internal details with a scale of more than hundreds of meters, and with electron-density disturbances of about 100% compared with the norm.

Also, it is necessary to mention here the holographic approach to the inverse scattering problem for ionospheric diagnostics. This approach was suggested in [15], and was developed in [16-18]. Earlier, we showed [13, 18] that the holographic approach is equivalent to the solutions to the inverse scattering problem obtained in the case of small-angle recording apertures. Three-dimensional reconstructions of segments of the ionosphere were obtained using this approach [20].

The uniqueness of solutions of similar inverse scattering problems was considered many times earlier. For example, we mention only one review [19]. Some exact results are known. For the problems in question, the uniqueness of the transformation Q_z (11) and the following reconstruction (13, 17) of projections can be easily proven for a finite-volume scatterer [11-13].

4. Diffraction radio tomography of ionospheric irregularities

The results described in the previous sections allow us to get two-dimensional projections of localized ionospheric inhomogeneities with the help of a moving satellite transmitter and a transverse array of earth-based receivers. If there are arrays of receivers separated by distances of about one hundred kilometers along the line of the satellite's path, it is possible to obtain some two-dimensional projections. Having a set of two-dimensional projections, one can also reconstruct the structure of the three-dimensional inhomogeneities. Such an experiment (with arrays of receivers) is rather complicated, and it has not been realized, yet. Nowadays, experiments connected with the reconstruction of two-dimensional localized inhomogeneities have been carried out [12, 13]. This is also the tomography problem, because it is possible to reconstruct the two-dimensional inhomogeneity projection, or the two-dimensional cross-section of its spectrum, after the corresponding transformations, by means of a set of one-dimensional field records at each receiver. The numerical experiments, which were carried out earlier, showed the possibility of reconstructing two-dimensional projections of inhomogeneities on the basis of discrete data, with a finite limit on resolution [12]. Moreover, these reconstructions are stable with respect to noise. It is reasonable to evaluate the errors by computing the number δ, which shows the deviation of the function being reconstructed, , from the true function, q:

$$\delta = \frac{\|q - \tilde{q}\|}{\|q\|}$$

The norms of the spaces l^2 and l^∞ can be helpfully used. According to the results of numerical experiments, reconstruction of discrete-set function values with noise in the range of 0 to 10% gave errors of the same order.

The experiments connected with the two-dimensional reconstruction of the structure of the inhomogeneities were carried out at the Polar Geophysic Institute (Murmansk). The transverse array included 32 receivers separated by 1550 m. The Soviet and American satellites, such as the "Transit" satellite [the US Navy Navigational Satellite System satellites], were used in these experiments. These satellites have circular orbits, with an approximate height of about 1000 km, and transmit on two coherent frequencies at about 150 MHz and 400 MHz. The 400 MHz signal is influenced much less by the inhomogeneities than is the 150 MHz signal. Thus, it was used as a reference signal. Small distortions which appear in the reference wave were removed in the receiving system [12]. Receivers, ρ_R, situated along the y axis, record the field as a function of time, t, while the satellite moves along the x axis. This makes it possible to realize the synthesis of a rectangular (on **s**) aperture. In accordance with the formulae (8) for **s**, the change in the satellite position, $\rho_0(t)$, can be recalculated into the equivalent change of the positions of the receivers, ρ_R, for a constant ρ_0. Thus, movement of the satellite is equivalent to "movement" of the receiving array along the x axis, with a corresponding change of scales [this is analogous to an inverse synthetic aperture along the x axis].

Some examples of reconstructions of the structure of two-dimensional localized inhomogeneities, which were made on November 17, 1984, and on May 5, 1987 [12,18], are given in Figure 2 and Figure 3, respectively. If units of 10^{10} el/cm^2 are used [for the vertical axis], the maximum values of N are equal to 3.02 and 0.91, respectively. The resolution along the x-axis (the direction of the satellite movement) is 0.25 km, and along the y-axis, it is 1 km. It should be noted that the inhomogeneity in the former case (Figure 2) is a strong-scattering one. Thus, formula (17) was used for reconstruction.

5. Ray radio tomography of the ionosphere

In this paragraph, we consider the solution of the satellite radio tomography problem for large-scale ionospheric irregularities, when diffraction effects may be neglected. The diffraction of small-scale irregularities may also be smoothed by means of corresponding filtration. The ordinary methods of tomography, using linear integrals, are the theoretical foundation of ray radio tomography for the large-scale, global structure. Measuring the linear integrals for a series of rays crossing some area, it is necessary to reconstruct the

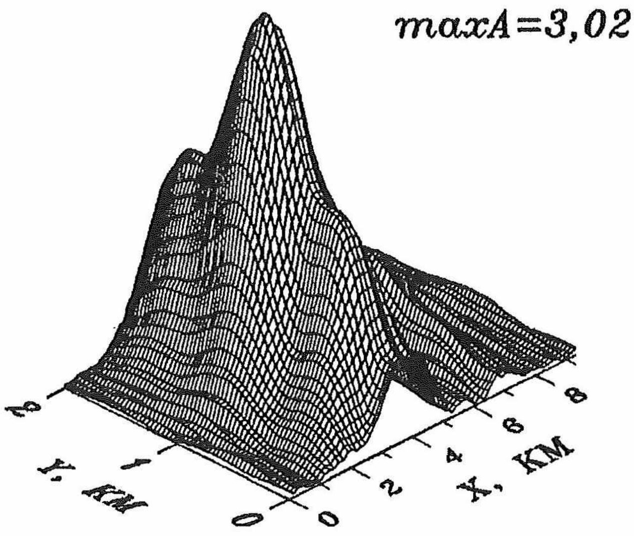


Figure 2. An example of a reconstruction of the electron density of a localized inhomogeneity, made on November 17, 1984 [12]. The x *and* y *axes correspond to the geometry shown in Figure 1 for diffraction radio tomography. The resolution along the* x*-axis (the direction of the satellite movement) is 0.25 km, and it is 1 km along the* y*-axis. This is a strongly-scattering inhomogeneity: Equation (17) was used for reconstruction.*

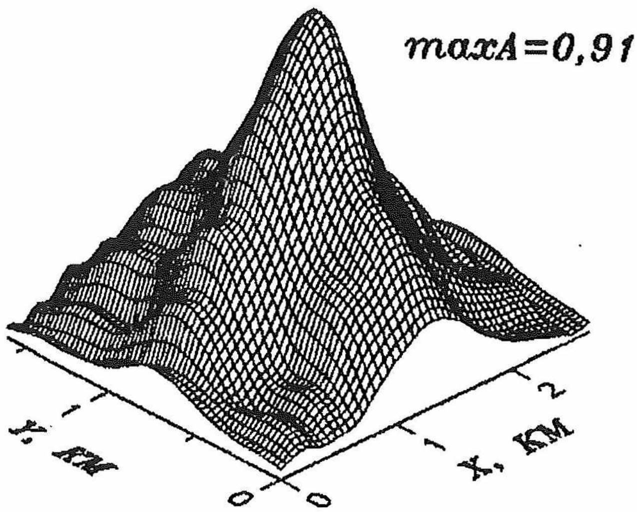


Figure 3. An example of a reconstruction of the electron density of a localized inhomogeneity, made on May 5, 1987 [18]. The x *and* y *axes correspond to the geometry shown in Figure 1 for diffraction radio tomography. The resolution along the* x *axis (the direction of the satellite movement) is 0.25 km, and it is 1 km along the* y*-axis.*

structure of this area. There are different variants of ionospheric ray radio tomography, based on measurements of the group delay, the total electron content, or the phase, etc. The ray radio tomography versions based on measurements of the total electron content or on the absolute radio signal phase were suggested earlier [21, 22]. This scheme is identical to the seismic tomography scheme [23]. However, the direct application of seismic tomography methods to ionospheric problems leads to many serious difficulties. The essential feature of ray radio tomography problems is a small number of receivers. These receivers should be situated in the plane of the satellite's trajectory, and should be separated by sufficiently-large distances. Therefore, we have the problem of small-foreshortening tomography with the fan [data-collection] scheme.

The following equations are the basis for reconstruction of the distribution of the electron density (N) and the effective electron collision frequency (ν):

$$\begin{aligned} \lambda r_e \int N d\sigma &= \phi \\ -\frac{\lambda r_e}{\omega} \int N \nu d\sigma &= \chi \end{aligned} \qquad (18)$$

where λ is the wavelength, $\int d\sigma$ denotes integration along the trajectory, χ is defined as the logarithm of the ratio of the amplitude of the measured field to the field of the probing wave, and ϕ is the corresponding phase difference. Here, as well as in the case of diffraction radio tomography, it is reasonable to use the two-frequency satellite for sounding. The formulae (18) are a consequence of the relations (6) and (11), in the limiting case of . So ray radio tomography is the limiting case of diffraction radio tomography. Ordinary tomography, using linear integrals, is used in the problem of reconstruction of the product $N\nu$ by means of measurements of χ. We have complicated the situation for the reconstruction of N. This is connected with the errors in absolute phase measurements in the irregular-ionosphere case. The absolute phase is determined within up to $2\pi m$ radians, where m is an integer. If the complex multi-frequency, multi-positional systems are not used, it is possible to have a constant error for the phase curve registered by each receiver. The numerical simulation [25, 26] shows that a small error, of the order of one percent, leads to bad results in the radio tomography reconstruction. The reason for this is that the constant displacement for the phase curves of different receivers can have different signs. Thus, the experimental data become uncoordinated, and the tomography reconstruction algorithms give bad results for such uncoordinated and contradictory data. But it is extremely difficult to reach an accuracy of absolute phase determination less that of the order of a few percent. Therefore, the method of phase-difference radio tomography was suggested in [25]. Thus, the problem of reconstruction of the two-dimensional distribution of the electron density is the problem of radio tomography using phase-difference measurements.

The reconstruction of the two-dimensional distribution of the electron density can be realized in a polar-coordinate system (r,α), connected with the center of the earth; (r_0,α_0) are the satellite coordinates. Here, it is better to use coordinates (h,τ), where is the height above the surface of the earth with radius R, and $\tau = \alpha R$ is the distance along the surface of the Earth. Then, the linear integral of the electron density along a ray will look like this:

$$\int_0^{h_0} \frac{F(h,\tau)(R+h)}{\left(R^2 \sin^2 \beta + 2Rh + h^2\right)^{1/2}} dh = I(\beta, \tau_i) \quad (19)$$

where τ_i is the coordinate of the ith receiver, h is the height of the satellite, and β is the angle under which the satellite is seen by the ith receiver. The reconstruction function, F, will be proportional to either $N\nu$ or to N in equation (18). The discretization of satellite positions (β_{ij}) allows us to get a series of discrete values of the linear integrals $\{I_{ij}\}$. The problem of tomographic reconstruction is thus the determination of the samples $\{F_{m,n}\}$ by means of the measured series $\{I_{i,j}\}$.

There are many variants of the discretization of equations (19). If we use the piecewise-constant approximation for the function F, and introduce the length, $L_{i,j}^{m,n}$, of the (i,j)th ray in the (m,n)th rectangle, we obtain the following system of linear equations:

$$L_J^M F_M = I_J \quad (20)$$

where "the renumbering" $(i,j) \to J$, $(m,n) \to M$ is carried out, and summations over repeated indices are assumed. Using the approximations between the samplings F_m of higher order, we get the other matrices of the operator $\hat{L}: F \to 1$. It should be noted that the true "natural" operator $\hat{L}_0: F \to 1$ has a higher order of approximation, *i.e.*, we smoothly replicate the phase curve. If we restrict ourselves to the piecewise-constant ("stair-step") approximation of F, the phase curve will have discontinuities in the derivative with respect to the satellite angle. But there are no such gaps in the experimental data. The solution of the discretized radio tomo-graphy problem is reduced to the search for the inverse operator, $\hat{L}^{-1}$, in equation (20). It is necessary to bear in mind that, if the direct operator $\hat{L}$ is defined "incorrectly," *i.e.*, if it departs significantly from the true one, the solution of radio tomography problems using it will give bad results. The results of numerical simulations carried out by us show that to reconstruct smooth functions which describe the distribution of the ionospheric parameters, it is necessary to use a piecewise-planar approximation. A detailed description of the construction of the operator, $\hat{L}$ by means of higher-order approximations, takes more space than is available here. An example of the construction of $\hat{L}$, using a piecewise-planar approximation based on triangular elements (these elements fit the two-dimensional function's surface with triangular or tetrahedral elements) is given in [12].

Using such approximations, it is possible to calculate the derivative of the operator $\hat{L}$, with respect to the satellite angle, α_0, and to thus obtain the system of linear equations for the phase-difference ray radio tomography:

$$A_J^M F_M = D_J \quad (21)$$

where A_J^M is the derivative, of the matrix L_J^M, with respect to the satellite angle α_0, and $D_J = \Delta I_J / \Delta\alpha_0$ is the phase-difference data. The finite [difference] derivative D is measured experimentally with high accuracy. So, we do not need the additional "determination constant" operation, here.

The solution of the type of systems of linear equations in equations (20, 21) is a sufficiently complicated numerical problem. There are a great number of different methods in the literature for doing this. If we reconstruct an ionospheric area with scales of hundreds or thousands of kilometers, using a discretization of tens of kilometers, then for the matrices of equations (20, 21) we have ranks A ~ 10^3 -10^4, and condition numbers vary, but in the limit are ~ 10^3 -10^5 and more. For such systems, it is preferable to use iteration methods [22, 25, 26]. Numerical modeling carried out by us showed that it is possible to reach a relative accuracy of reconstruction, δ, of about 10%, for measurement errors (of the noise type) of a few percent. To find the most optimal algorithms of reconstruction, which, certainly, depend on the geometry of the discretization scheme, it will be necessary to carry out a great number of numerical experiments.

The solution of the linear equation systems (20, 21) is unique in the sense of pseudo-reciprocal matrix construction. If the object of the reconstruction is finite, the solution to the ray radio tomography problem will be unique. The tomography problem can be reduced to the radio tomography of a finite volume by means of the assembling of data with successive satellite flights. If the ionosphere "on the boundaries" of the area is stable during the duration of the time between the flights of two successive satellites, such a version of ray radio tomography permits us to reduce the problem to the reconstruction of a finite object. At the same time, it is possible to use the pure phase methods in this case, because it is not difficult to reconstruct the absolute phase, beginning from the edge of the area reconstructed. A scheme such as this matches radio tomography to artificial formations which appear under ionospheric heating, chemical releases, missile launches, etc. The situation is significantly worse for the case of an infinite area of reconstruction and a finite number of receivers, because there will always be zones through which an insufficient number of rays (or none) pass. It is clear that reconstruction of the ionospheric structure is impossible in these zones. If the initial approximation of an iteration method strongly distorts the ray integrals in these zones, the reconstruction results can be made significantly worse. Here, we do not consider the limitations of radio tomography, because this question was well discussed in detail in [24].

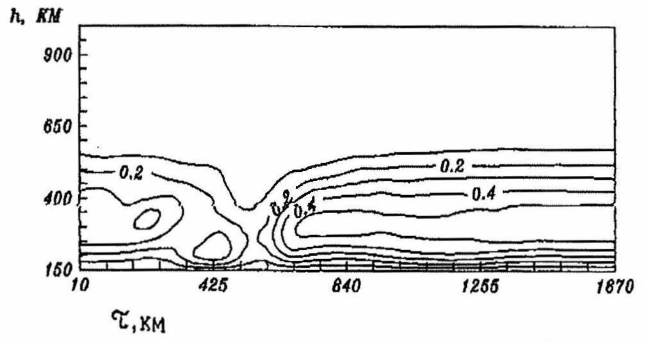


Figure 4. A radio tomographic reconstruction of a two-dimensional cross section of the ionosphere, made using phase-difference radio tomography. This is a plot of isolines of electron density in units of 10^6 el/cm^3, in the coordinates (h,t)*, based on experimental data recorded on April 7, 1990. The coordinates of* t *are Murmansk, 10 km; Kem, 433 km; and Moscow, 1475 km. The ionospheric trough structure can be seen well.*

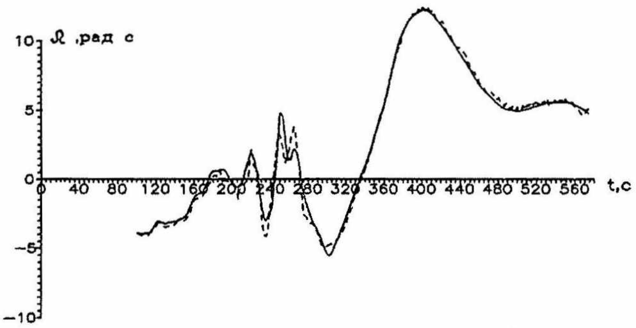


Figure 5. The Doppler frequency for the receiver situated near Murmansk, corresponding to the two-dimensional reconstruction of Figure 4. The solid curve is the measured Doppler frequency; the dashed curve is the Doppler frequency calculated using the reconstructed cross-section shown in Figure 4.

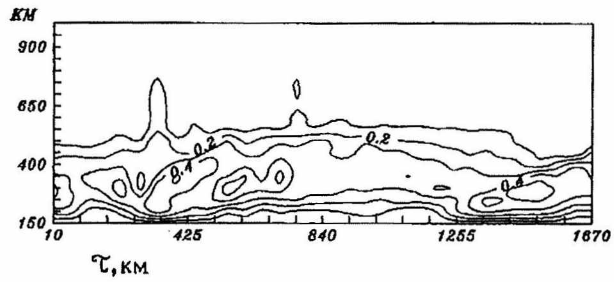


Figure 6. A radio tomographic reconstruction of the two-dimensional cross section of the night-time ionospheric trough, made using phase-difference radio tomography. The data were recorded on March 28, 1990. All other parameters are the same as for Figure 4.

Here, we consider linear radio tomography problems. We use the term "linear" in the sense that the ray travels along a straight line, independent of the electron-density distribution. In the VHF range, such an approximation is valid up to a discretization step of ~20-30 km. For smaller discretization sizes, it is necessary to take into account the curvature of the rays, because they can even pass through the other discretization elements [that is, discretization elements not along a straight ray path] [12].

It is implied that the ionosphere is for practical purposes unchanged during the recording time interval (which is of the order of tens of minutes for areas of thousands of kilometers). This actually occurs in most cases, as the large-scale structure is only changed slightly during such time intervals. The duration of [recording the data for] radio tomography of artificial formations is of the order of minutes, so these formations should be stationary during this time interval.

It is possible to develop other versions of ray radio tomography, such as group-delay ray radio tomography, polarization ray radio tomography, Faraday-rotation ray radio tomography, etc. However, it now seems that these provide less perspective for ionospheric diagnostics.

As the conclusion of this section, let us give some experimental results [25-27] of the radio tomographic reconstruction of the two-dimensional ionospheric cross-section, using phase-difference radio tomography. The experiments were carried out in 1990-91. The satellite passive navigation system was also used in the experiments. Receivers were situated near Murmansk, Kem (Karelia), and Moscow. In most cases, we observed the regular, smooth cross-section of the ionosphere. An example of a reconstruction of the two-dimensional structure of the ionospheric trough is presented in Figure 4. This is a plot of isolines, in the coordinates (h, τ), in units of 10^6 el/cm^3, based on the experimental data recorded on April 7, 1990. The coordinates of τ are Murmansk, 10 km; Kem, 433 km; and Moscow, 1475 km. The ionospheric trough structure can be seen well. The solid curve in Figure 5 shows the experimental Doppler frequency for the receiver situated near Murmansk. The dashed curve is the Doppler frequency calculated using the reconstructed two-dimensional cross-section of the electron density. As usual, the agreement is excellent ($\delta \sim 10^{-3}$) after 20-30 iterations. The ionospheric trough was observed at night, and it often had a complicated structure, with many additional extrema. An example (recorded March 28, 1990) of the reconstruction of the night-time ionospheric trough is presented in Figure 6.

6. Statistical radio tomography of the ionosphere

The very complicated structure of the ionosphere should be taken into account in many practical applications. The extended spatial areas are often occupied by a great number of ionospheric irregularities. Thus, it is reasonable to reconstruct statistical characteristics of the ionosphere, without a detailed description of internal elements. It is reasonable to name such a reconstruction, of the random, statistical properties of the ionosphere using the measured field statistics, the statistical inverse problem, or the statistical radio tomography problem.

There are many different methods for the estimation of random ionospheric parameters. Most of them are based on some suggestions about the fluctuation spectra of random models of the ionospheric models. These modeling approaches make it possible to define mean scales, the orientation and the "intensity" of irregularities, the spectral-power index, and other parameters. All such approaches to the inverse problem of a randomly-inhomogeneous ionospheric reconstruction are limited by the freedom in choosing the model: thus, the inverse problem's solution is not unique. This disadvantage, common to all modeling approaches, is essential when there is a lack of *a priori* or empirical arguments for the model choice. Such a situation is typical for the investigation of ionospheric irregularities. In contrast to all other approaches, we consider the non-modeling inverse problem for the reconstruction of the spectrum of irregularities.

We consider the reconstruction of the ionospheric electron-density fluctuation spectrum by means of satellite radio-probing data. There are analogous problems in other branches of science. Similar probing can be carried out with seismic, acoustic, electromagnetic (including microwave), or other kinds of waves. All of these problems have the same basis, independent of the type of probing.

For random, inhomogeneous media, the measured statistical properties of the scattered field are related to the statistical properties of the media (projections or cross-sections). Integral equations, which relate the measured field to the medium's structure, are probably the most convenient and adequate mathematical technique for tomography. In this paper, we shall show how to derive such equations. The theory of the propagation and scattering of waves in random, inhomogeneous media is quite well developed. For weak fluctuations, many results are obtained by means of the well-known Rytov and Born approximation techniques. Strong fluctuations were analyzed by the Dyson and Bete-Salpeter integral equations, the Feynman-diagram technique, the generalized Huygens-Fresnel principle, and the parabolic-equation method. It was shown [28, 29] that, under certain assumptions, these methods give the same results for the second moments. So, we shall use formulas obtained in the parabolic- equation approach.

Mathematically, the statistical inverse problem is reduced to a determination of the statistical properties of q given by the statistical properties of the measured field, E. For simplicity, it is reasonable to use two frames of reference. The first, "laboratory" frame of reference, $\mathbf{r}=(x,y,z) = (\rho,z)$, we conventionally call the "global" one. Its origin is related to the receiving system as in the previous section: the z axis is directed vertically upward, perpendicular to the stratified medium structure, and the plane $y = 0$ is the transmitter orbit plane. The origin of the second frame of reference, $\check{\mathbf{R}} = \left(\check{X}, \check{Y}, \check{Z}\right) = \left(\mathbf{P}, \check{Z}\right)$, can be reasonably located at one of the transmitter positions, and with the $\check{Z}$ axis directed toward the center of the receiving system. As the transmitter moves, it is convenient to use several such "local" frames with different orientations. Such frames are introduced to make derivations shorter, because the scattering of the probing wave in each local frame may be treated as "almost forward" small-angle scattering.

Let's consider the spherical probing wave E_0, which is scattered by a layer filled with irregularities. The lower boundary of the layer is z_d, the upper boundary is z_u, and z_0 is the transmitter height, in the global frame, r. After performing the Fresnel expansions of exponents in the Lippman-Schwinger equation (5) for small-angle scattering, we obtain the integral equation (7) for U. This equation is written in the local reference frame:

$$\check{S}\left(\check{Z} - \check{Z}_0\right) = \left(\check{Z}' - \check{Z}_0\right)\check{\mathbf{R}} = \left(\check{Z} - \check{Z}'\right)\check{\mathbf{R}}_0$$

$$\check{D}\left(\check{Z} - \check{Z}_0\right) = \left(\check{Z}' - \check{Z}_0\right)\left(\check{Z} - \check{Z}'\right)$$

For making formulas shorter, we assume that the transmitter is located exactly at the local-frame origin, *i.e.*, at the satellite coordinates $\check{\mathbf{R}} = \left(\mathbf{P}_0, \check{Z}_0\right) = (0,0,0)$.

To reduce calculations and to use known results, we transform equation (7) to the parabolic equation in new variables $\xi = 1/\check{Z}$, $\sigma = \mathbf{P}/\check{Z}$, $\xi = 1/\check{Z}'$. Then

$$\left(\check{S} - \mathbf{P}'\right)^2 / \check{D} = (\sigma - \xi' \mathbf{P}')^2 / (\xi' - \xi)$$

and U satisfies the differential equation

$$\left(-2ik\frac{\partial}{\partial \xi} + \Delta_\sigma - \xi^{-2} q\right) U(\xi, \sigma) = 0 \qquad (22)$$

Equation (22) is derived from equation (7) by differentiating, and making use of the following relation for the fundamental solution of the Schroedinger operator. We note that the step function $\theta(\check{Z} - \check{Z}') = \theta(\xi' - \xi)$ should be present in the integrand of equation (7), as may be shown by making accurate transformations of equation (5). Having derived the parabolic equation, we use the methods developed to obtain equations for the first and the second moments of U [28, 29]. Let us also assume that the random field q is to be Gaussian and δ-correlated along $\vec{Z}$:

$$B(\mathbf{P}_1,\mathbf{P}_2) \equiv \left\langle q\left(\Pi_1,\vec{Z}_1\right) q\left(\Pi_2,\vec{Z}_2\right)\right\rangle = \delta\left(\vec{Z}_2-\vec{Z}_1\right)A_q\left(\Pi_1-\Pi_2\right) \quad (23)$$

In a similar way, from equation (22) and using the variables (σ,ξ), it is possible to derive equations for the second moments of the normalized field,

$$\gamma\left(\vec{\mathbf{R}}\right) = E / \left\langle E\left(\vec{\mathbf{R}}\right)\right\rangle$$

giving, respectively, the first coherence function and the second coherence function of the second order:

$$\Gamma_{1,0}\left(\mathbf{P},\vec{Z}\right) = \left\langle \gamma\left(\mathbf{P}_2,\vec{Z}\right)\gamma^*\left(\mathbf{P}_1,\vec{Z}\right)\right\rangle$$

$$\Gamma_{2,0}\left(\mathbf{P},\vec{Z}\right) = \left\langle \gamma\left(\mathbf{P}_2,\vec{Z}\right)\gamma\left(\mathbf{P}_1,\vec{Z}\right)\right\rangle$$

As the calculations are described in the papers mentioned above, we present only the final result in the variables $P_+ = (P_1+P_2)/2$, $P = P_2-P_1$, and for a statistically-homogeneous layer, when the dependence on P_+ is absent:

$$\left[ik\left(\frac{\partial}{\partial\vec{Z}}+\frac{\mathbf{P}}{\vec{Z}}\frac{\partial}{\partial\mathbf{P}}\right)+\frac{\partial}{\partial\mathbf{P}^2}+\frac{i}{4k}A_q(\mathbf{P})\right]\Gamma_{2,0}\left(\mathbf{P},\vec{Z}_u\right)=0$$

$$\Gamma_{2,0}\left(\mathbf{P},\vec{Z}_u\right)=1 \quad (25)$$

Equation (25) was written in the local reference frame, for the case where there is an oblique layer (between $\vec{Z}_d$ and $\vec{Z}_u$). Here, we have used the relation $\vec{Z}\cos\theta \to z_0 - z$, where θ is the angle at the satellite, measured from the vertical direction in the global reference frame r.

The following formula for $\Gamma_{1,1}$ is well known [28, 29]:

$$\Gamma_{1,1}\left(\mathbf{P},\vec{Z}\right) = \exp\left[\frac{1}{4k^2}\int_{\vec{Z}_u}^{\vec{Z}} A_q\left(\rho\frac{\vec{Z}'}{\vec{Z}}\right)d\vec{Z}'\right] \quad (26)$$

The integral equation, corresponding to equation (25), has the form

$$\Gamma_{2,0}\left(\mathbf{P},\vec{Z}\right) = 1+\frac{i}{16\pi k}\int d^3\vec{R}'\frac{A_q(\mathbf{P}')}{\vec{D}}\cdot \Gamma_{2,0}\left(\mathbf{P}',\vec{Z}'\right)\exp\left[\frac{ik}{4\vec{D}}\left(\vec{S}-\mathbf{P}'\right)^2\right] \quad (27)$$

Equation (27) is analogous to equation (7), and follows from equation (25). Similar to the way that equation (22) was derived from equation (7), equation (25), in the variables (σ,ξ), may be obtained after differentiating equation (27). The resulting integral equation is also valid at $\mathbf{P}_0 \neq 0$, $\vec{Z}_0 \neq 0$.

The integral equation (27) is the basis of the statistical radio tomography reconstruction methods. Experimentally-measured wave-coherence functions allow us to determine projections of the complex potential correlation function q. According to equation (23), A_q(P) is the projection of the correlation function,

$$\int B\left(\mathbf{P},\vec{Z}\right)d\vec{Z} = A_q(\mathbf{P})$$

To begin with, let's assume that irregularities occupy a sufficiently extensive layer, oblique to the direction of the probing wave. Using the weak-scatterer approximation, and substituting 1 for $\Gamma_{2,0}\left(\mathbf{P},\vec{Z}\right)$ in the integrand of equation (27), we may invert the Fresnel transformation with respect to P [12]. Inversion is possible if the dependence of $\vec{D}$ on the $\vec{Z}'$ coordinate may be neglected. This is valid because the layer thickness is less than the longitudinal Rayleigh resolution, which is some tens of kilometers for ionospheric experiments.

$$\int A_q(\mathbf{P})\,d\vec{Z} \cong A_q(\mathbf{P})L = \frac{k^3}{i\pi\vec{D}}\int d^2\vec{S}\left[\Gamma_{2,0}\left(\vec{\mathbf{S}}\right)-1\right]\exp\left[-\frac{ik}{4\vec{D}}\left(\vec{\mathbf{S}}-\mathbf{P}\right)^2\right] \quad (28)$$

Here, L is the layer thickness, and $\vec{D}$ contains the fixed layer coordinate $\vec{Z}' = \vec{Z}$. Equation (28) defines the projection of the correlation function A_q(P), provided the function and the coordinates of the source, the receivers, and the scattering layer coordinate $\vec{Z}_s$ are given. The two-dimensional projection A_q(P) may be found using a transverse linear receiving array (along the y axis) and aperture synthesis by a moving satellite along the x axis.

To reconstruct the projection A_q(P), it's necessary to determine the layer coordinate, $\vec{Z}_s$. This may be done by a single receiver. A special procedure for the determination of the scattering layer $\vec{Z}$ coordinate was developed [14, 30].

The regions containing irregularities may have arbitrary borders. In many situations, randomly-inhomogeneous media represent statistically quasi-homogeneous fields with slowly- varying statistical properties, *i.e.*, such fields for which the correlation radius of the differential argument is essentially less than the scale of the variance, σ. In other words, the correlation function is represented as a product $B(\vec{\mathbf{R}}_1, \vec{\mathbf{R}}_2) = \sigma^2(\vec{\mathbf{R}})\, \vec{K}(\Delta \vec{\mathbf{R}}\, \vec{\mathbf{R}})$, where $\vec{\mathbf{R}} = (\vec{\mathbf{R}}_1 + \vec{\mathbf{R}}_2)/2$, $\Delta \vec{\mathbf{R}} = \vec{\mathbf{R}}_1 - \vec{\mathbf{R}}_2$. A randomly inhomogeneous field with a constant correlation coefficient (D), but with varying fluctuation variance $\sigma^2(\vec{\mathbf{R}})$, may be called an "additive" field, because the changes in electron density influence only the intensity of the fluctuations, but the dependence of the correlation coefficient on the argument $\vec{\mathbf{R}}$ is absent. Assuming the field q to be δ correlated, as was done above, it is possible to obtain similar equations by the same technique. The projection of the correlation function $A_q(\mathrm{P})$ in the integrands should be replaced by $\sigma^2(\vec{Z})K(\mathrm{P})$. Here, $K(\mathrm{P}) = \int K\left(\Delta \vec{R}\right) d\left(\Delta \vec{Z}'\right)$ is the projection of the correlation function. Then the formula for $\Gamma_{1,1}$ and the equation for $\Gamma_{2,0}$ have the form

$$\Gamma_{1,1}\left(\mathbf{P}, \vec{Z}\right) = \exp\left[\frac{1}{4k^2}\int_{Z_u}^{\vec{Z}} \sigma^2\left(\vec{Z}'\right) K\left(\rho \frac{\vec{Z}'}{\vec{Z}}\right) d\vec{Z}'\right] \tag{29}$$

$$\begin{aligned}\Gamma_{2,0}\left(\mathbf{P}, \vec{Z}\right) = 1 + \frac{1}{16\pi k}\int d^3\vec{R}' \frac{\sigma^2\left(\vec{Z}'\right) K(\mathbf{P}')}{\vec{D}} \cdot \\ \Gamma_{2,0}\left(\vec{\mathbf{R}}'\right) \exp\left[\frac{ik}{4\vec{D}}\left(\vec{\mathbf{S}} - \mathbf{P}'\right)^2\right]\end{aligned} \tag{30}$$

Formulae for projections of correlation functions, like equation (28), cannot be derived from equations (29, 30), as they contain the unknown function $\sigma^2(\vec{\mathbf{R}})$. So, the problem of reconstruction of the correlation function is divided into two parts: the problem of reconstruction of the variance in the fluctuations, $\sigma^2(\vec{\mathbf{R}})$, and the problem of the reconstruction of $(\Delta \vec{\mathbf{R}})$, given the measured projections, $K(\mathrm{P})$.

Equation (29) allows us to determine integrals along the direction (the $\vec{Z}$ axis) of propagation of the probing wave. If a set of different integrals is given for a region filled with irregularities, we arrive at a tomography problem, *i.e.*, at the problem of reconstruction of a function, given its linear integrals. Usually, in the experiments there exists a natural limit to the number of projections and to the angular range of propagation directions of the probing waves. Hence, the problem should be solved when data are known for a small range of angles. A similar problem was solved in the case of ray radio tomography.

Information about the fluctuation intensity distribution $\sigma^2(\vec{\mathbf{R}})$ is sufficient to reconstruct a set of projections of correlation functions given by measured coherence functions. Methods of solution for the statistical radio tomography problem are similar to those already discussed, with the substitution of the product, $\sigma^2(\vec{\mathbf{R}})K(\mathrm{P})$, of the known function $\sigma^2(\vec{\mathbf{R}})$ and the correlation function projection $K(\mathrm{P})$, instead of A_q.

A set of projections $K(\mathrm{P})$ allows us to perform tomographic reconstruction of the correlation coefficient (D) or its spectrum. As the correlation function is smooth enough, "simple" and also symmetric, it is reasonable to make an expansion over a set of certain polynomials. The Fourier transform of each projection of the correlation coefficient defines the cross section of the Fourier transform of the correlation coefficient (the linear Fourier transform). By means of the given set of projections, the statistical radio tomography reconstruction problem is easily reduced to the solution of a set of linear equations with respect to expansion coefficients in the chosen polynomial expansion series.

An example of the practical reconstruction of the cross section of the spectrum fluctuations, based on data from a satellite experiment in the VHF range (using the navigation satellites), is now given. According to experimental data from January 27, 1988, there is one extended random-homogeneous layer in the ionosphere, the height of which is approximately 280-300 km [30]. The set of experimental data consisted of 17 projections, for which the satellite positions differed by approximately 1.7 degrees. After processing the two-dimensional electron density fluctuations, the spectrum was reconstructed:

$$\hat{B}(\chi) = \int B(x', z') \exp\left(i\chi_x x' + i\chi_z z'\right) dx'\, dz'$$

Here, the z' axis is directed along the symmetry axis of the reconstructed spectrum, which is perpendicular to the direction of the magnetic field (the x axis). A normalized two-dimensional spectrum cross-section,

$$\hat{B}(\chi) \,/\, \hat{B}(\chi_0, \theta = 0)$$

is presented in Figure 7, as a function of polar coordinates ($\chi = \sqrt{\chi_x^2 + \chi_z^2}$, $\theta = \arctan(\chi_x / \chi_z)$) in the range from $\chi_0 = 0.1\ \mathrm{km}^{-1}$ to $\chi = 2.5\ \mathrm{km}^{-1}$. It is seen that the spectrum shape depends strongly on the angle. Furthermore, local extrema are present, which points to the complex nature of the spectrum and to the presence of resolved scales. The similarly-complicated structure of such spectra has been observed quite often.

7. Conclusion

The results described in this review are the first steps in

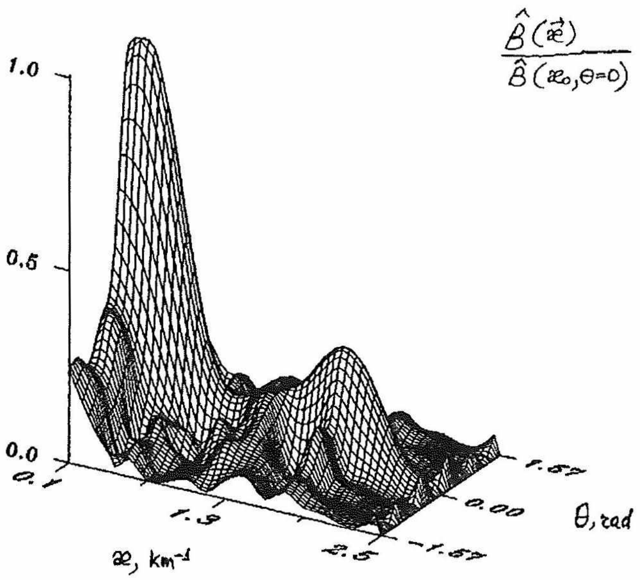


Figure 7. A normalized two-dimensional spectrum cross-section, showing $\hat{B}(\chi) / \hat{B}(\chi_0, \theta = 0)$ as a function of polar coordinates ($\chi = \sqrt{\chi_x^2 + \chi_z^2}$, $\theta = \arctan(\chi_x / \chi_z)$), in the range from $c_0 = 0.1\ km^{-1}$ to $c = 2.5\ km^{-1}$. It is seen that the spectral shape depends strongly on the angle. The data were recorded on January 27, 1988, when there was one extended, randomly-inhomogeneous layer in the ionosphere at a height of approximately 280-300 km [30]. The data used in computing the spectrum consisted of 17 projections for which the satellite positions differed by approximately 1.7 degrees.

ionospheric radio tomography. The experiments carried out showed the great possibilities of radio tomographic methods for sounding, for such applications as determining the two-dimensional structure of isolated inhomogeneities; cross sections of the global ionosphere, including the main ionospheric trough; and the cross section of the correlation-function spectrum of electron-density fluctuations, which was obtained for the first time. Nevertheless, it is clear that we are at beginning of the path, and further development of satellite radio tomography will open vast perspectives for its applications, for diagnostics of the ionosphere and atmosphere.

We would like to briefly indicate some areas, applications, and problems which will arise in the development of the different directions of radio tomography.

• *Diffraction radio tomography.* Applications include diagnostics of natural and artificial localized ionospheric formations (chemical releases, rocket launches, active plasma experiments, ionospheric heating, etc.). It is necessary to develop methods and algorithms for three-dimensional diffraction radio tomography, which can be realized with the help of one-dimensional arrays of receivers.

• *Ray radio tomography.* The monitoring of global ionospheric structures. This includes three-dimensional ray radio tomography, done on the basis of a set of two-dimensional cross-sections and with the use radio-astronomy techniques, and also with radio stars as sources. It is necessary to develop and to optimize the methods of phase-difference ray radio tomography, phase ray radio tomography with subtraction, and algorithms with higher-order approximations. It is important to check and to calibrate the results of ray radio tomography by comparing them with incoherent-scatter radar results.

• *Statistical radio tomography.* Applications include diagnostics of ionospheric turbulence, and investigation of the random ionosphere under different physical conditions. It is necessary to develop methods and algorithms for the two-dimensional and three-dimensional reconstruction of correlation functions and electron-density fluctuation spectra, as well as methods for multi-dimensional spectrum evaluation of confidence intervals.

The methods of satellite radio tomography make possible the creation of global and regional systems for the monitoring and control of space conditions near the earth. Existing radio-location means, and ionosondes for control and ionospheric stations, allow us to carry out only local measurements of medium parameters. The creation of a sufficiently-dense net of observing stations using traditional means is extremely complicated and very expensive. A system for satellite radio tomography is a distributed sounding system, *i.e.*, the moving satellites and the net of receivers permit us to realize the continuous probing of the medium in different directions, and to reconstruct the spatial structure of the ionosphere. A system for satellite radio tomography based on a network of autonomous receivers, together with the traditional means of ionospheric probing, will give us the possibility of realizing global and regional monitoring and control of the space near the earth. To inculcate the radio tomographic methods of sounding, it is necessary to solve many theoretical and practical problems. However, without any doubt, creation of different satellite radio tomographic systems will bring significant progress in practical applications, as well as new, fundamental knowledge.

References

[1] V. L. Ginzburg, *Propagation of Electromagnetic Waves in Plasma*, New York, Gordon and Breach Science Publishers, Inc., 1961.

[2] L. D. Landau, E. M. Lifshitz, *Statistical Physics*, New York, Pergamon Press, 1980.

[3] L. D. Faddeev, "Three-dimensional inverse scattering problem," *J. Sov. Math.*, **5**, pp. 334-360, 1976.

[4] R. G. Newton, "Inverse scattering II. Three dimensions," *J. Math. Phys.*, **21**, pp. 1698-1715, 1980.

[5] K. Chadan, P. C. Sabatier, *Inverse Problems in Quantum Theory*, New York, Springer-Verlag, 1977.

[6] A. J. Devaney, "Geophysical diffraction tomography," *IEEE Trans. Geosci. Remote Sensing*, **22**, 1, pp. 3-13, 1984.

[7] R. K. Mueller, M. Kaveh, G. Wade, "Reconstructive tomography and applications to ultrasonics," *Proc. IEEE*, **67**, 4, pp. 567-587, 1979.

[8] D. Lesselier, D. Vuillet-Laurent, F. Jouvie et al., "Iterative solutions of some direct and inverse problems in electromagnetics and acoustics," *Electromagnetics*, **5**, pp. 147-189, 1985.

[9] K. J. Langeberg, "Applied inverse problems for acoustic, electromagnetic and elastic wave scattering," in P. Sabatier (ed.), Basic Methods of Tomography and Inverse Problems, Bristol, Adam Hilger, pp. 127-467, 1987.

[10] W. Tabbara, B. Duchene, C. Pichot. et al, "Diffraction tomography: contribution to the analysis of some applications in microwaves and ultrasonics," *Inverse Problems*, 4, pp. 305-331, 1988.

[11] V. E. Kunitsyn, "Determination of the structure of ionospheric irregularities," *Geomagnetism and Aeronomy*, **26**, 1, pp. 58-62, 1986.

[12] V. E. Kunitsyn, E. D. Tereshchenko, *Tomography of the Ionosphere*, Moscow, Nauka, 1991 (in Russian).

[13] V. E. Kunitsyn, E. D. Tereshchenko, *The Reconstruction of the Ionosphere Irregularities Structure*, Preprint Polar Geophys. Inst., 90-01-69, pp. 1-60, 1990.

[14] V. E. Kunitsyn, "Inverse scattering problem for strong-scattering irregularities in paraxial approximation," in *Wave Motion and Diffraction*, Moscow, pp. 23-27, 1988.

[15] G. Schmidt, A. Taurianen, "The localisation of ionospheric irregularities by the holographic method," *J. Geophys. Res.*, **80**, 31, pp. 4313-4324, 1975.

[16] W. R. Stone, "A holographic radio camera technique for the three-dimensional reconstruction of ionospheric inhomogeneities," *J. Atm. Terr. Phys.*, **38**, 6, pp. 583-592, 1976.

[17] E. D. Tereshchenko, "On application of radioholography for investigation of the ionospheric irregularities," *Geomagnetism and Aeronomy*, **24**, 6, pp. 1016-1018, 1984.

[18] V. E. Kunitsyn, N. G. Preobrazhensky, E. D. Tereshchenko, "Reconstruction of ionospheric irregularities structure based on the radioprobing data," *Dokl. Akad. Nauk USSR*, **206**, 3, pp. 575-579.

[19] B. Hoenders, "The uniqueness of inverse problem", in *Inverse Source Problems in Optics*, New York, Springer-Verlag, pp. 41-82, 1978.

[20] W. R. Stone, "The Holographic Radio Camera Demonstration Experiment," PhD Dissertation, Department of Applied Physics and Information Sciences, University of California, San Diego, 1978 (available from University Microfilms).

[21] R. J. Austen, S. J. Franke, C. H. Liu, "Ionospheric imaging using computerized tomography," *Radio Science*, **23**, 3, pp. 299-307, 1988.

[22] T. D. Raymond, J. R. Austen, S. J. Franke, C. H. Liu, J. A. Klobuchar, and J. Stalker, "Application of computerized tomography to the investigation of ionospheric structures," *Radio Science*, **25**, 5, pp. 771-789, 1990.

[23] M. Gustavsson, S. Ivansson, P. Moren et al., "Seismic borehole tomography-measurement system and field studies," *Proc. IEEE*, **74**, pp. 339-346, 1986.

[24] K. C. Yeh, T. D. Raymond, "Limitations of ionospheric imaging by tomography," *Radio Science*, **26**, 6, pp. 1361-1380, 1991.

[25] V. E. Kunitsyn, E. D. Tereshchenko, E. S. Andreeva et al., *Radio tomography of Global Ionospheric Structures*, Preprint Polar Geophys. Inst., 90-10-78, pp. 1-30, 1990.

[26] E. S. Andreeva, V. E. Kunitsyn, E. D. Tereshchenko, "Phase difference radio tomography of the ionosphere," *Annales Geophys.*, 1992 (in press).

[27] E. S. Andreeva, A. V. Galinov, V. E. Kunitsyn et al., "Radiotomographic reconstruction of ionization trough in the plasma near the earth," *JETP Lett.*, **52**, 3, pp. 145-148, 1990.

[28] V. I. Tatarski, *Wave Propagation in a Turbulent Medium*, New York, McGraw-Hill, 1961.

[29] A. Ishimaru, *Wave Propagation and Scattering in Random Media*, Orlando (Florida), Academic Press, 1978.

[30] V. E. Kunitsyn, E. D. Tereshchenko, "Determination of the turbulent spectrum in the ionosphere by a tomographic method," *J. Atm. Terr. Phys.*, **54**, 10, pp1275-1282, 1992.

Vyatcheslav E. Kunitsyn
Physics Department
Moscow University
Moscow, 119899
Russia

Evgeni D. Tereshchenko
Polar Geophysical Institute
Murmansk, 183023
Russia

Dielectric Properties of Heterogeneous Materials

Edited by A.Priou, 398 + xvii pages, ISBN 0-444-01646-X. Elsevier Science Publishing Corporation, Inc. 1992, New York, US price $86.

This volume is No 6 in the Series, Progress in Electromagnetic Research, whose Editor-in-chief is Prof. Jin Au Kong of MIT Typically, they consist of chapter length articles written by specialists on selected electromagnetic topics. The present volume deals mainly with models of inhomogeneous dielectrics such as might represent composite materials. The authors (surnames indicated) are listed as follows: Aussudre, Combes, Ezquerra, Greffe, Grosse, Kremer, Lindell, Lakhtakia, Lopez, Ma, Maurens, Nelson, Priou, Sihvola, Tinga, Varadan (V.K. and V.V.), and Wegner. These investigators deal with the following topics: Introduction to mixture laws and microwave/material interactions, static permittivity of emulsions including the comparisons between theory and experiment, modelling of numerous idealized configurations such as distributions of particles in a homogeneous background, radiative transfer theory, random media effects, pulverized and granular materials, AC properties of insulator/conductor composites, and microwave sintering, ferrite composites, and chiral composites.

One of the central themes is to devise a procedure to predict the effective dielectric constant or permittivity of a specified mixture of two or more "phases" where interactions of the dispersed ones are properly accounted for. Actually, as originally shown by Maxwell, an idealized lumpy medium, consisting of small spheres embedded in a uniform background, could be treated by potential theory whether we were dealing with a conductor or a dielectric. Indeed, most of the contributions in the present volume could be rephrased to deal explicitly with conductors. In fact, the most general approach is to designate the various regions as complex conductors which may have any desired, but physically acceptable, frequency dependence. For example, as pointed out in the reviewer's chapter No 1, in Volume 1 (1989), electrochemical interactions between the constituent metallic particles and the electrolytic host could be accounted for by a suitably defined interface boundary condition. In such cases, effective dielectric constants (relative to free space) of 104 to 10^6, at 100 Hz, are possible. This aspect of the subject was not described in the present Vol 6 nor were eddy currents in the dispersed particles treated*.

There is a considerable overlap in the material being covered in the volume being reviewed but such is not undesirable because the subject matter benefits from the different viewpoints. Some kind of a common understanding is achieved when it is shown by several authors (e.g. Tringa) that seemingly diverse mixture laws in the past literature are physically equivalent†. In fact, the general multiple scattering approach can be specialized to recover many of the earlier quasi-static models. But, if we wish to single out the most versatile of the simpler models, the Bruggeman (1933) law is the most remarkable. In spite of its rather empirical underpining, it seems to 'work' even when the volume loading of the "dispersed phase" can be more than 50% of the host volume. But it does fail to properly account for "percolation" and related critical effects.

I would consider this volume an important benchmark in the current and past developments on the electromagnetic characterization on inhomogeneous materials. The material could also be a useful supplement to a graduate course in applied electromagnetic theory because most of the classical texts pay little attention to the constitutive properties of the media. The price of the book is not unreasonable — at least by today's standards.

James R. Wait

* For example, see J R Wait, Complex permeability of spherical metal particles, Proc. Inst. Radio Engrs. Vol 41, 1665, 1953.

† (at least for small volume loading).

RADAR 92

Conference Publication No 365, Institution of Electrical Engineers, London, ISBN 0 85296 553 2, 544 pages, hard bound, 1992.

This impressive document consists of the author-produced papers given at a conference held in Brighton, UK, 1992. There are 130 individual contributions printed in various type styles but, for the most part, they are easy to read. The authors are mostly from Europe but strong representations are included from other parts of the world particularly from Australia. The general categories are: Radar simulation and modelling, Sea and land clutter, Multifunction and monopulse radar, Propagation and target measurement, Surveillance and tracking, Detection and clutter suppression, Antennas, Air traffic control, Signal processing, Remote sensing, Synthetic aperture radar, and Target understanding, imaging and classification. Taken as a whole, the document gives a good overall view of the current developments in the topics mentioned above in so far as the security classifications would allow. It is a pity that no review papers appear and no attempt seems to have been made to unify the notation and provide a glossary of terms and symbols. Many of the abbreviations would be unknown to the general reader. It is also a pity that discussions following each paper were not included in one form or another. Also it is unfortunate that the editor(s) didn't insert the authors' mail address so purchasers of these Proceedings could contact the speakers to seek needed clarifications.

This reviewer was most interested in the propagation aspects which permeated many of the papers. In particular the implementation of the split step parabolic equation method for dealing with laterally varying media has now been realised by one group in the UK (Appleton Rutherford Labs) and also in the US (San Diego Navy Lab). There was an important paper by G D Dockery (US) who showed clearly that the performance of focussed wave pulses may suffer similar diffraction limitations on beam width as for simple Gaussian pulses with similar frequency content.

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 1992 or 1993. Of course, you may keep the book after you have fulfilled your commitment.

Mail reply to: **James R. Wait, 2210 East Waverly, Tucson AZ 85719-3848, USA.**

Various other propagation related papers, on the problems of detecting low level targets, were sprinkled throughout but no break-throughs here were evident.

The price of the Proceedings volume seems rather high ($156.00 in the US). It is available from PPL Dept., IEEE Service Centre, 445 Hoes Lane, PO Box 1331, Piscataway, NJ 08855-1331, and elsewhere from the IEEE, Faraday House, Stevenage, Herts, SG1 2AY United Kingdom).

James R. Wait

NEWS

Day on Diffraction

St Petersburg, Russia, June 3-5, 1992

Days on Diffraction are jointly organised by the St Petersburg Branch of the Mathematical Institute of the Russian Academy of Sciences and the Physics Institute of the University of St Petersburg. This year's meeting, organised by Professors V M Babich, V S Buldyrev and V S Buslaev consisted of two days of papers presented at the VA Steklov Mathematical Institute in central St Petersburg with the final day at the campus of the University of St Petersburg in Petrodvoretz, southwest of the city.

Days on Diffraction began about 20 years ago as annual seminars of the famous Leningrad diffraction school founded by V A Fock and V I Smirnov. These seminars attracted scientists from other parts of the USSR and eventually became all union. Recently foreigners have also participated and this year English was the working language. There were no parallel sessions; each speaker had 30 minutes for presentation and discussion. In order to accommodate the foreign papers several local Russians in attendance did not present their papers. The papers presented were from Russia (16), Ukraine (8), Finland (2), Sweden, Germany and Canada. Overhead projectors were available, but interestingly many of the Russian scientists preferred the blackboard.

Papers were invited on diffraction and propagation of acoustic, elastic and electromagnetic waves. Most of the presentations dealt with general problems in electromagnetic wave scattering, inverse scattering and propagation in isotropic, bi-isotropic, homogeneous and inhomogeneous media (17 papers). There was also a session of 7 papers on waveguides and corner regions and 5 papers on nonlinear waves, including acoustic and ocean waves. The mathematics and physics of wave processes provided the common thread. Applied mathematicians are naturally interested in all areas of science amenable to similar mathematical techniques. For radio scientists papers on waves outside electromagnetics are educational opportunities which are frequently useful.

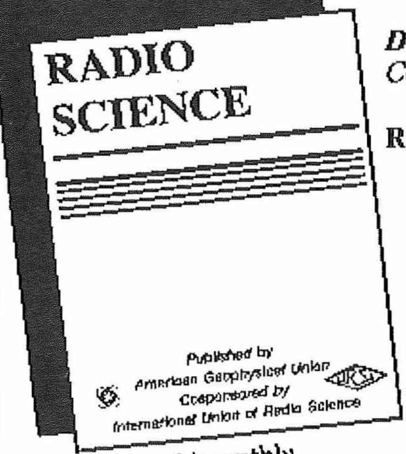
Lunches were included in the modest registration fee, and those at the "Metropole" were sumptuous. The social program also included an evening of excellent ballet and a bus tour of St Petersburg, surely to become again one of the great tourist cities of the world. Several of us also were taken to visit the splendid gardens (see cover) of the magnificent palace of Peterhof. At the end of the third day there was a picnic in the woods near the Petrodvoretz campus, a traditional finale to "Days on Diffraction". June is the time of the "white nights" and this was indeed a beautiful evening. The many flies which attempted to join the party were soon dispersed by a roaring fire and the songs of our Russian hosts.

In making "Day on Diffraction" an international seminar the organisers are providing a valuable link with foreign colleagues, for there is much research in their institutes which we have not been able to follow. For this the organisers have our thanks, our congratulations for the success of this meeting and our hopes for many more.

E. V. Jull

SUBSCRIPTIONS

RADIO SCIENCE



bimonthly

David Chang, University of Colorado, Editor
Co-sponsored by URSI International

Radio Science contains original articles on all aspects of electromagnetic phenomena related to physical problems. The coverage embraces the propagation through and interaction of electromagnetic waves with geophysical media, biological media, plasmas, and man-made structures. Also included, but not limited to, are papers on the application of electromagnetic techniques to remote sensing of the Earth and its environment, telecommunications, signals and systems, the ionosphere, the magnetosphere, and radio astronomy. All frequencies, including optical, are discussed.
*Vol. 28. ISSN: 0048-6604. **Print or microfiche.***

U.R.S.I. Members!
Subscribe at AGU member price.

Enter your subscription today.

1993 Subscription Rates

URSI and AGU Members	***$44.00***
AGU Student Members	***$30.00***
Surface Postage outside the U.S.	***$ 9.00***
Air Freight Postage	***$26.00***
Air Mail Postage	***$66.00***

AGU encourages contributions to **Radio Science** from authors throughout the world. Publication is independent of an author's ability to honor page charges. Contact AGU Publication Office, Washington, DC for submission instructions.

Published by American Geophysical Union AGU

To order: Subscription must be prepaid by check, money order or credit card. AGU accepts American Express, VISA, and MasterCard. Credit card payments can be placed over the phone Monday through Friday, 8:30 a.m. to 6 p.m. Eastern time. Please reference AGU code URSI when ordering.

WRITE: AGU - Orders
2000 Florida Avenue, N.W.
Washington, DC 20009

CALL: 1-800-966-2481 (toll-free in North America.)
202-462-6900 (in Washington, D.C. or outside North America.)

FAX: 202-328-0566

E-Mail: cust__ser@kosmos.agu.org

URSI

Get the four 1993 issues (March, June, September, December) of **both** *the Radioscientist* and the URSI *Bulletin*, including air delivery anywhere in the world, and qualify for the discounted subscription rate for *RADIO SCIENCE* as detailed in the AGU ad on your left, **all for only US$14.**

Pay by mailing us a *personal* cheque in any convertible currency equivalent to US$14, or just send us your *VISA* number or **MasterCard** number with its expiry date, by fax or email, and we will do the rest. The mail address, fax and email are given below.

Volume 4 issues already published (e.g., this one) when we receive your order will be sent with our acknowledgment of your order.

Note from the Editor: The term "URSI Members" used above is a temporary (until the Kyoto G.A.) designation for all radio scientists who receive a *personally addressed copy* via KLM of *the Radioscientist* and the *Bulletin*, whether as a paying subscriber or as an URSI official. The names on this KLM mailing list have been given to AGU to provide an "URSI Membership" list for the purposes of this discounted subscription rate to *RADIO SCIENCE*. National Members of URSI who are on the General Secretariate's list are also included.

The Radioscientist
Department of Physics
University of Otago
P.O.Box 56
Dunedin
New Zealand
email: dowden@otago.ac.nz
fax: +64 3 479 0964