The Radioscientist

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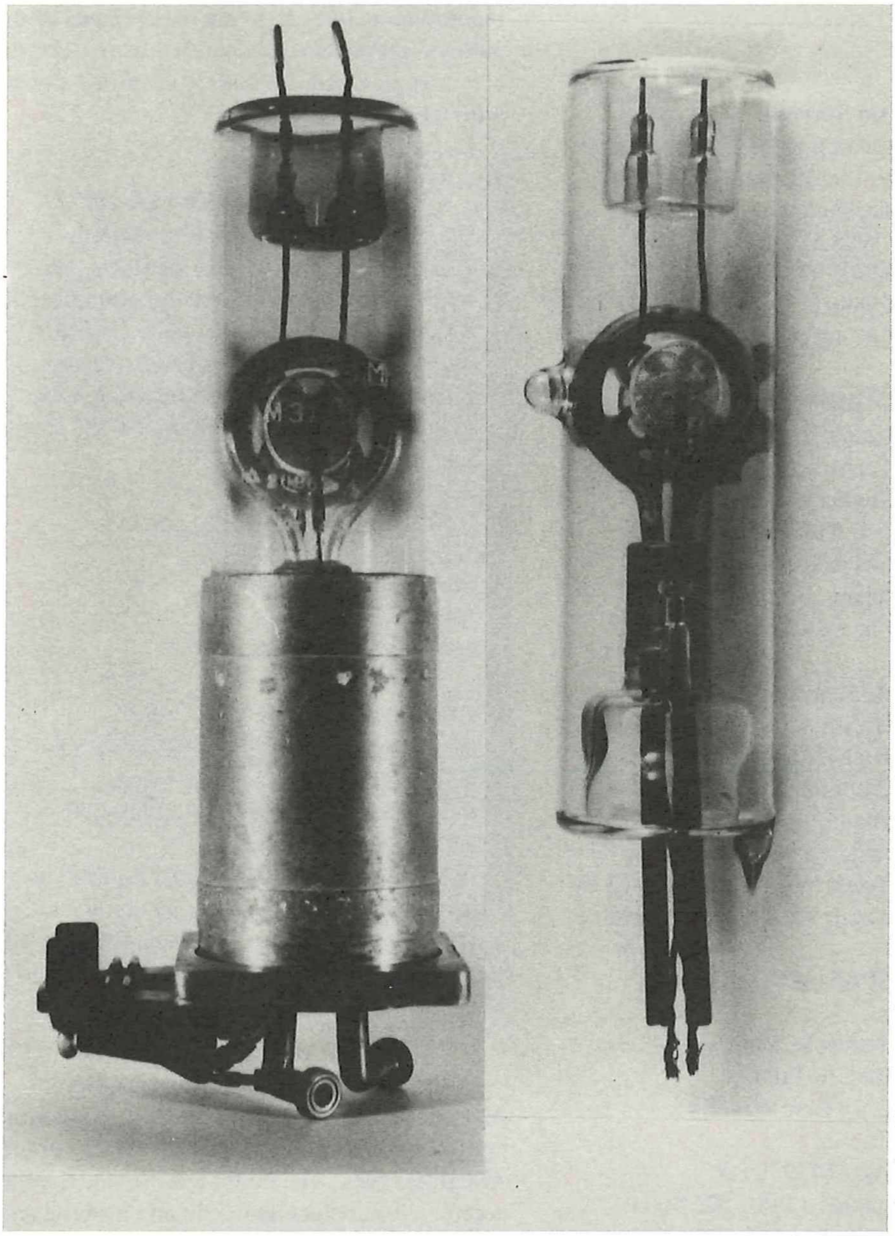

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The Radioscientist

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COVER: 10 cm, water cooled magnetrons, 500 W continuous output power, developed by Japan Radio Co. in 1939.

THE EDITOR'S PAGE

Yet more benefits

Although you may read this in June, I am writing it in April before the URSI Board Meeting at the end of April. While this magazine is not the place to report official business anyhow, I cannot announce even the likely price of future subscriptions because the cost of the March issue under the new system is being worked out only now. However it is reasonable to assume that the subscription announced in this issue (US$14 for the next four issues of both *the Radioscientist* and the *Bulletin*) is unlikely to be as low as this ever again. *The Bulletin alone* is officially US$20 for four issues!

Another "learned" journal in the field of URSI, this time from Europe, is likely to be sponsored by URSI in a similar way to *RADIO SCIENCE.* There is to be a special subscription price for *the Radioscientist* subscribers but the details must await the next issue.

From now on, classified advertisements may be placed free by *Radioscientist* subscribers, provided they are "personal" in some sense, that is, of benefit to the radioscientists placing the advertisements. Basically this includes individuals who would have to meet the cost if there was a cost but it excludes from the free list advertisements from firms selling their products or from universities and institutes seeking professional staff in the normal way.

All electronic

This is the first *completely* electronic issue in the sense that I have all the text and all the pictures in machine readable form on my computer. This means that I place and scale (if necessary) all the illustrations. Some contributors provide their text on diskette, some even in Word for Macintosh complete with equations. To these my deep gratitude. If future contributors send their line drawings in EPS (Encapsulated PostScript) and their photographs as TIFF, I'll be quite ecstatic! TIFF compressed by PageMaker 4 will more easily fit on a diskette (1.44 Mbyte for preference). However, contributions in *any* form remain very welcome.

Who benefits?

I spent the last two months as the advocate for *Space* research in NZ. This field includes astronomy and ground based research in solar terrestrial physics. From URSI's point of view, this includes Commissions E, F, G, H and J. Virtually *all* the money for science in this country, and that includes affiliation fees to International Scientific Unions, comes from the Public Good Science Fund. So whenever funding is sought for anything in science, the question asked is: "Who benefits?". If an end user, such as the electronics industry, the radioscientists as a group or membership, or any other body, can be identified, then *that* is who pays. Only if the public as such is the main beneficiary, does the Public Good Science Fund pay.

This policy of "user pays" or "the market economy" came to us from the UK via Australia, but it seems to be the way the whole world is going. As I said in the December issue, URSI needs to take this policy into account, like it or not. I won't repeat that here, but it is interesting to note from the March issue of the *Bulletin* that the need for URSI to become more marketable was realised over 25 years ago. I think we all hope this doesn't mean losing anything in URSI we hold important, but it does mean we all need good arguments to "sell" URSI to our funders in our various countries. In particular, *we need yours.* So share your ideas with us in ***News and Views.***

Scanning the issue

The feature article is again Radar in World War II, this time from the Japanese viewpoint. As a general policy I have all articles reviewed though in a less formal way than research papers in journals so the obvious reviewer was R S Unwin, the author of the NZ version in the March issue. The two authors were on opposite sides in World War II, as were Geiger and his ex-student Marsden in World War I, so with Unwin's permission I give you his comments:

"It is surprising to learn that in Japan developments towards a cavity magnetron in the 'Mandarin' type were taking place as early as 1937, and a true cavity magnetron had been developed a year or more before the British version produced in Birmingham in 1940.

"Another surprise is that frequency modulation of a CW signal was used in the early microwave Japanese radars, the potentialities of both pulse modulation and VHF for aircraft warning not being appreciated before 1941 when they learnt of pulse radar used by the British.

"Their ability to get a super-regenerative microwave receiver to work is amazing—it staggers me that it was not until 1944 that they adopted a superheterodyne system. And the mentality of a government that would permit qualified engineers to be recruited into the army as privates is also amazing. Lucky for the Allies, but disastrous for them.

"I was familiar with their VHF radars, types 11, 12 and 13 through listening to them on radar search missions conducted in US 'ferret' aircraft. We played a sort of hide and seek with the Japanese radar operators, who switched off when they thought we homing in on them, subsequently switching on briefly for a quick check. Even so we managed to find and destroy a few in the Southern Philippines, Borneo and Sulawesi."

I expect there are more surprises for you, such as the development of megawatt magnetrons for shooting down aircraft!

The article about Lindman was sent to me by Ari Sihvola, one of the authors and one of our editors. Karl Lindman did his research in radiophysics in the 1920s as if he was still in the previous century (“*the last Hertzian*”) yet he was 40 years ahead of the pack. When this arrived, I realised I could fit it in if I removed my whistler article (see below) but it was too late to get the three illustrations scanned since the printers were closed over Easter (nearly a week here). So I redrew them in MacDraw Pro and saved them as EPSF for inclusion in this “electronic” issue. What you lose is the historical charm of Lindman’s own drawings. For Figure 3 the fit is to a $\cos^2$ function of the rotation angle for each of his data sets. I did this using MacDraw in a similar way to that discussed in the whistler article (which after all that I had to put a shortened form back in). And got the same answers!

Short pieces are lacking in this issue (no *News and Views*). These are needed to fill the odd corners to make up 28 pages exactly. If I only get long articles, the last one is likely to be too long or too short. So I would like both long *and* short contibutions from you.

The next is about “GICs”, Geomagnetically Induced Currents, in Finland. These caused loss of the power grid in Quebec on March 13, 1989—six million people were without commercial electric power for nine hours. They occur here in NZ too, because our geomagnetic latitude is nearly 10° greater than our geographic latitude (46°S in Dunedin). Power grid loss has been very close at times but has not actually caused harm.

There are two book reviews. *Ultra Wide Band Radar*, as pointed out by our reviewer and review editor (James Wait), is not too strange for Maxwell's equations and has been used in solid earth geophysics for decades. I might add, that if measured in octaves rather than in hertz, *Ultra Wide Band Radar* is not new to the whistler fraternity either, who have used natural sferics (lightning impulses) for this purpose for over 40 years.

The final article came about because I have been preparing for my sabbatical in Germany. In particular, I needed to take a whistler spectrum analyser and a means to analyse whistlers for magnetospheric path location. What we use here is impossibly large to take. My solution may appeal to some of the Commission H people who work with whistlers. I originally wrote a introduction for those uninitiated in this field, but I had to remove it and one of the illustrations to fit the article in. As a result it may be cryptic to the uninitiated. In some respects, it is a review of two commercial Macintosh applications, *MacRecorder* and *MacDraw II* which I used together for whistler analysis.

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

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Japanese Radar Development in World War II

Research on magnetrons

The Japan Radio Company began research on magnetrons and Barkhausen-Kurg oscillators in early 1932. Five years prior, in 1927, Dr. Kinjiro Okabe of Tohoku University invented the Split Anode Magnetron, and thereafter, some universities were performing research on microwave tubes. However, no one in those days ever thought of an application for microwaves. It was the same in Japan — there was much criticism from inside and outside of the Japan Radio Company, a private enterprise, for investing in research in such an unknown area. However, seeing the trend of using higher and higher frequencies — from long wave, to medium wave, to short wave — I was confident that the time would come for great practical use for VHF and microwaves.

The following year, in late 1933, there was a movement to start research and development of magnetrons by the Japanese Naval Technical Research Institute. Japan Radio Company immediately put in a request for coordinated research and was accepted by the Institute. The reason behind the determination of the Naval Technical Research Institute to start the research on magnetrons, is that, Dr. Yoji Ito (Navy Ordnance Commander and later Navy Captain) who was responsible for this research, had continued his research on the Kenelly-Heaviside Layer and had learned by experience that by using shorter wavelengths, reflection of waves from aircraft and ships can be received. Dr. Ito had submitted his findings to the Science Research Committee of the Japanese Ministry of Education in March 1932 but no conclusion was reached. Therefore, Dr. Ito decided to develop the oscillator by himself.

The coordinated research group between the Japanese Navy and Japan Radio Company was primarily devoted to research on the oscillator mechanism of the magnetron. The coordinated efforts produced fruit in 1937 with the invention of the 8 split Mandarin type anode by the Naval Research Institute, and *it was the first stabilised microwave oscillator to be developed.* As the theory of the oscillator mechanism became clear, a wide range of anodes were developed by many research coordinators. These ranged from the 20-cm one mentioned above to one of only 7 mm wavelength.

In 1939 the Japan Radio Company produced a cavity magnetron, the M3, with a Mandarin type anode, having a wavelength of approximately 10 cm, a continuous output power of 500 W, and a water-cooled system developed and manufactured from copper sheet having a thickness of 1.2 cm. Figure 1 shows the anode of this magnetron. The one on the right side of Figure 1 is an anode for 5.35 cm wavelength. The complete M3 magnetron is shown on the cover of this issue on the right. The one on the left is the M312, a later development of the M3.

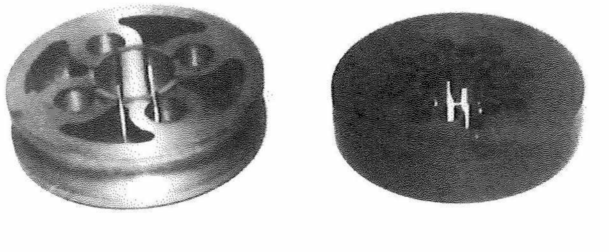

Fig. 1. On left is an M3 anode for 10 cm wavelength. That on the right is an anode for 5.35 cm wavelength.

After the War, I had an opportunity to visit the Science Museum of London in April 1953 and I was very much surprised to see the cavity magnetron invented in 1940 by the Birmingham University. On examining this magnetron, the dimensions of glass covering the vacuum, the water-cooling system around the anode, and the anode mechanism, I was struck by the similarity with ours. At first, I could not distinguish it from the water-cooled magnetron we developed! This is a good example of an old Japanese proverb saying that "there is no difference in intelligence between the East and the West".

Radar for the Japanese Navy.

In 1937, the Japanese Navy considered that strengthening the battle capability in night-attack was of prime importance, and in order to avoid collisions between our own destroyers when gathering into battle formation, a request by the Navy was made to develop a system to measure the distance between warships in the dark of night. In order to meet this requirement of the Navy, we began research in September 1939 using a wavelength of 3 cm, a transmitter with sharp directivity, and FM modulation to measure the distance. In our test on land, we were only able to detect the reflected echo from a factory chimney located a few kilometres away due to the very low output power of the transmitter. During this time, we were also engaged in research on IFF equipment (Identification, Friend or Foe) using microwaves of 16 cm wavelength. In the fall of 1940, we were successful in receiving a clear reflected echo from a warship anchored in Tokyo Bay.

With the above two experiences, we were confident that warships could be detected even at night by using microwaves. Therefore, we began research on the local oscillator for a microwave receiver and on various other circuitries.

INFORMATION ON PULSE MODULATED RADAR OF THE ENGLISH MILITARY RECEIVED IN 1941.

In May 1941, a Japanese Military observation group visited Germany, and according to some members of this group, it was reported that a VHF pulse modulated radar was being used by the English military on European fronts. Receiving this report, the Japanese Navy was very much surprised and started research and development on two kinds of radar using pulse modulation. One was an Early Warning and Targeting Radar using VHF and the other one was a microwave radar for detection and targeting of warships, as it was considered theoretically difficult to detect warships by VHF radar.

The VHF Radar of 3-m is an Early Warning Radar which was completed five months after the start of the research and installed at Katsuura in November 1941. Katsuura is located on the Pacific coast about 100 km from Tokyo. This radar was used to detect aircraft approaching Japan until the end of World War II.

DEVELOPMENT OF MICROWAVE RADARS FOR VARIOUS WARSHIPS AND FOR LAND BASE USE

Japan Radio company developed a 10-cm surface detection radar for warships using the 10-cm water-cooled magnetron M312 (see the left side of the cover photograph), a modified M3 (also in the cover photograph on the right) developed in 1939, and designed a super regenerative receiver using magnetron M60 for the local oscillator (see Figure 2). The manufacturing of the prototype of this radar system was completed in October 1941.

In April 1942, the Japanese Navy made a plan to attack Midway and Kiska in the Aleutians. The plan was carried out two months later in June. During this short period of time, 1.5-metre wavelength early warning radar No.21 and 10 cm wavelength surface detection radar No.22 were installed onboard warships "Ise" and "Hyuga". The result was that No.21 radar (l = 1.5-m) could detect a single carrier attack plane at an altitude of 3000 m and distance of 55 km, and could detect warships at a distance of 20 km.

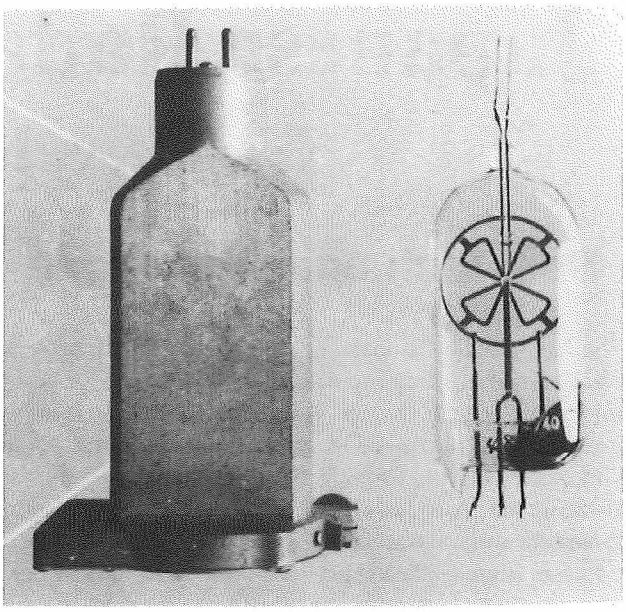

Fig. 2. 10 cm local oscillator magnetron M60.

The No.22 (l = 10 cm) radar had a capability of detecting surface targets at a distance of 35 km and it proved the importance of 10-cm radar, but it could not detect aircraft as the antenna was designed for horizontal rotation only. The Navy staff considered that Air Defence was more important and for this purpose only the meter wavelength was necessary. Further, we had no information that microwave radars were used by England, USA and Germany. There were further very strong opinions that we should concentrate our effort in developing a meter wavelength radar since we were short of engineers and materials. However, there were some Naval Captains who insisted on the development of microwave radar, and we, the radar engineers felt sure that the essence of radar is the use of microwaves. Therefore, we did not stop our research despite much criticism. During this time of confusion within Japan, 100 sets of No.22 radars were produced and it was decided to install these radars onboard frigates and other small warships.

In October 1942 in the battle of Guadalcanal, shells started hitting Japanese warships in the black of night. This surprised the Naval staff and they were compelled to reconsider the use of microwave radar. So in the Spring of 1943, it was decided that microwave radars were to be installed onboard all kinds of warships. Another reason for the delay in adopting microwave radar by the Military, was that, we, the engineers had adopted the use of the super regeneration type receiver which required qualified personnel to tune the receiver for high sensitivity. This was very complicated for unqualified personnel to tune properly. From 1943 we changed from this and began to use the self-heterodyne system, and from September 1944, we changed again to use the superheterodyne system. Together with the use of the Rehbock system, for which technical information was supplied by the German Government, we were able to have the

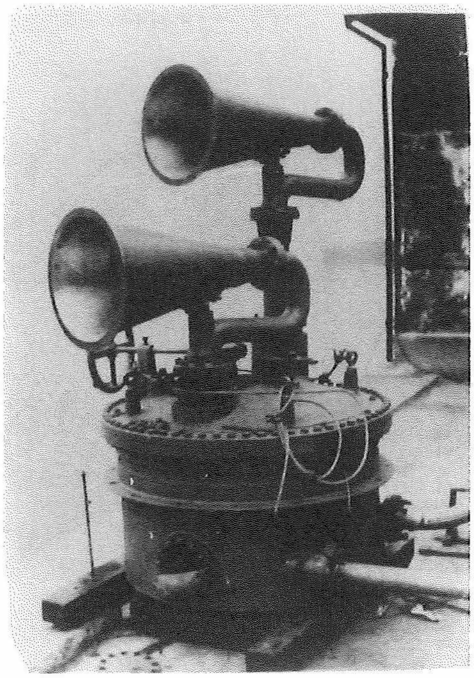

Fig. 3. Waterproof, pressure-proof antenna for 10 cm radar for submarines

receiver in tune at all times, and it could even be used by unqualified personnel.

Under these difficulties and painful efforts, the 10-cm microwave radar No.22 was completed and installed on warships and submarines as surface detection radar. A total of 300 sets were produced and used in various battles. Figure 3 shows the antenna of a 10-cm wavelength radar installed on a submarine. This is the original design using a 2-horn antenna which was later modified to a single horn antenna (see Figure 4) by using an elliptical transformation waveguide.

It was surprising to learn that the US Navy also had a radar of approximately 10-cm wavelength. It was noted that with 10-cm radar onboard our submarines, an enemy warship could be detected merely by keeping only the receiver of the radar in operation at all times.

VHF radar for early warning was completed by the Japanese Navy in November 1941 prior to the outbreak of the Pacific War. A total of 30 sets of this No.11 radar, having wavelengths of 2 m and 1.5 m, were produced and put to use in Japan and battle fronts in various South-East Asian countries.

Radars with wavelength 1.5 m for No.12, 2 m for No.13 and 6 m for No.14, were installed on the mast of warships and on trailers for land mobile usage. Including all the various radars, a total of over 2000 sets were produced. Radar No.12, with a wavelength of 1.5 m, had a detection capability of 150-200 km for aircraft in formation and 70 km for single aircraft. The 2-m radar, No.13, had a detection capability of 150 km for aircraft in formation and 100 km for single aircraft. It was also installed on submarines. The 6-m radar, No.14, had a detection capability of 450 km for aircraft in formation and 250 km for a single plane. No.13 radar had a capability of receiving the IFF signals of the US Military from a distance of 300 km. Figure 4 shows the antennas of the 10-cm No.22 radar (horn), the 2-m No.13 radar (on mast at top of photo) and the countermeasure equipment, E-27, installed onboard a submarine.

The use of airborne radar by the Japanese Navy started in mid 1942, and was installed principally on large aircraft. The radar had a wavelength of 2 m and was called the H-6. About 2000 radars of this type were produced. Another 2-m radar, the FK-3, was produced (about 100 sets) and installed on small aircraft. Furthermore, about 100 sets of 60 cm and 2 m wavelength Targeting Radars for aircraft were completed in August 1944 but were not put into use.

We, the engineers, regret that all of the Japanese radars used in the last war were confined to the A-scope form of display (echo amplitude versus range). When the war broke out, Mr. Kenjiro Takayanagi, a television expert, became a civilian employee of the Japanese Navy and showed interest in PPI theory (Plan Position Indicator — the now familiar polar map of

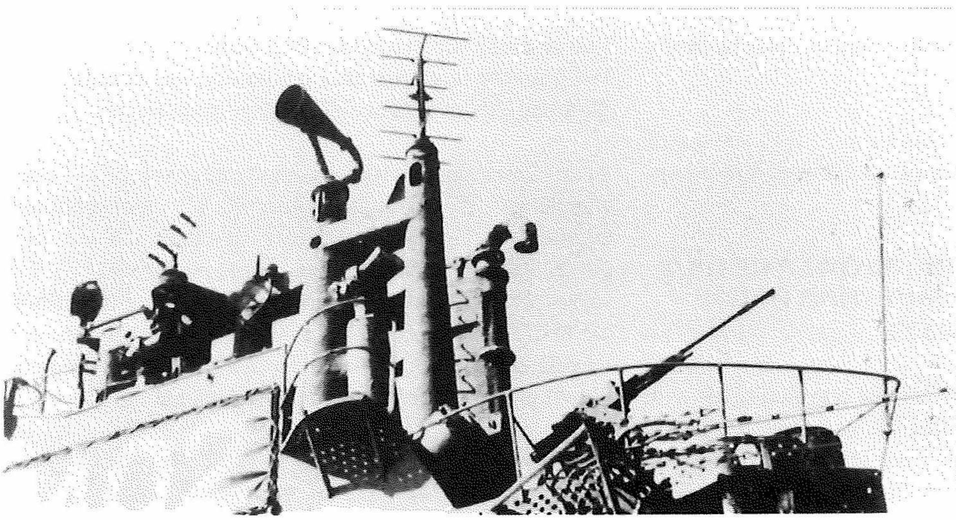

Fig. 4. Antennas on submarine for 2 m (top) and 10 cm (horn to left) radars, and countermeasure equipment.

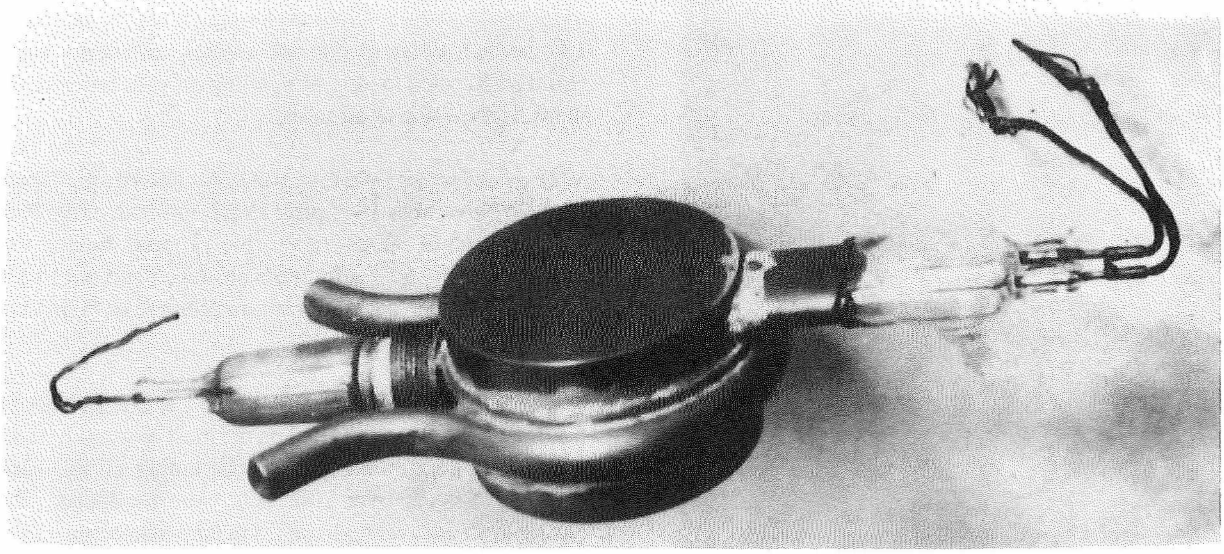

Fig. 5. All-metal magnetron

range versus azimuth in which echo amplitude appears as intensity). Another gentleman, Mr. Shoji Baba, a Navy Commander and later Captain, also had interest in a similar idea. However, we were too short of engineers to get involved in the development of such an idea. The military had no basic policy in drafting personnel, even the engineers who were working on development of weapons were drafted into the Army as private enlisted soldiers. When the war broke out, I had 800 engineers working for me in research and development of magnetrons and radars, and during the war, my staff was cut to one-half. These events weakened the military strength. Despite this, ten sets of a prototype PPI radar for night warfare were eventually completed in July 1945. The cavity magnetron which we developed in 1939 was used as the transmitting magnetron for this 10-cm radar. We also completed a prototype of an all-metal magnetron (see Figure 5) with a permanent magnet in 1941, but we could not proceed any further owing to shortage of materials for the permanent magnets and shortage of manufacturing facilities.

In addition to the above, 100 sets of airborne IFF, 100 sets of Radar Altimeter and 2500 sets of countermeasure equipment were produced.

RESEARCH ON SUPER HIGH POWER OUTPUT MAGNETRONS FOR SHOOTING DOWN AIRCRAFT

The Japanese Navy had the idea of blasting an aircraft with a very powerful microwave beam to make the aircraft lose its flying controls. The reason this came about is as follows. It seems the Japanese Navy had forecast from the beginning of World War II that the Japanese would be defeated unless a super unique weapon was developed to change the tide of the war. In 1939, information was received that the United States had successfully completed a model experiment demonstrating the practical use of nuclear energy. At around this time, a law was issued to prohibit the outflow of uranium ore from the United States. This information had imposed a tremendous instability within the Japanese Army/Navy authorities. Therefore, committees were organized within the Army and Navy which included several professors from the universities to study the possibility of developing a nuclear bomb. The conclusion of the committees after their study was that ***It will be difficult even for the United States to develop a weapon utilising nuclear energy by the end of the War.*** Therefore, the Japanese Navy began research and development of super high power magnetrons.

The Navy had confidence in the magnetron research at the Japan Radio Company, and was confident that, given sufficient manpower and material, it could develop magnetrons having an output of several hundred kW to several MW. This research was started in 1942, and in the following year, 1943, a very large research laboratory was constructed in Shimada City, a distance of 200 km from Tokyo.

At this Laboratory, two prototypes were developed — one of wavelength 15 cm, input power 90 kW and continuous output power 20 kW, and one of wavelength 20 cm, input power 500 kW, and continuous output power 100 kW. Two views of the latter one are shown in Figure 6. Furthermore, we had planned to develop a higher output magnetron of wavelength 10 cm, input power 2.2 MW, and continuous output power 500 kW, when the war ended.

The Japanese Navy had the idea of blasting an aircraft with a very powerful microwave beam to make the aircraft lose its flying controls.

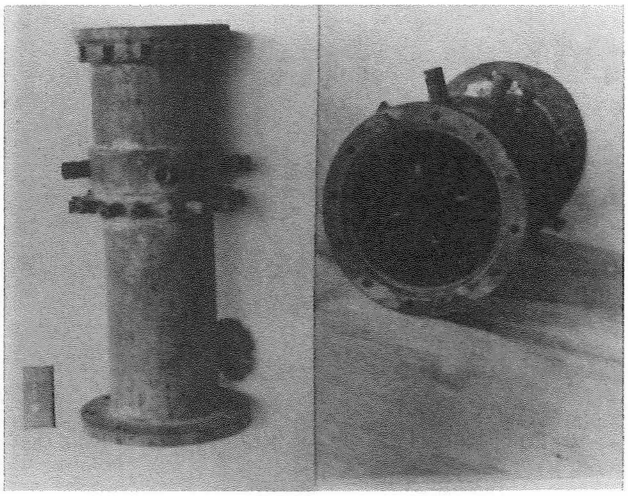

Fig. 6. High power magnetron, wavelength 20 cm, continuous output power of 100 kW.

Radar for the Japanese Army

DETECTING REFLECTED WAVES FROM AIRCRAFT USING VHF

The Doppler method was begun in 1937, and later in 1940 it was developed as a weapon. In 1937 at the Army Science Research Institute, Major Kinji Satake succeeded in catching the VHF reflected waves from aircraft by the Doppler method. This bistatic CW Radar was developed as a weapon in 1940 and used from the beginning of the Pacific War as an early warning equipment.

VARIOUS VHF RADARS

From 1941, research of pulse modulated radar was started and later developed as an early warning radar. It had a peak power output of 50 kW using 4.4 m and 3.9 m wavelengths and it could detect an aircraft at a distance of 300 km. A total of 5 radars were built and actually used. Further, a modified version using 3.7 m wavelength was developed and used.

Taki No.1, using 1.5 m wavelength and having a peak power of 10 kW, was used onboard aircraft as an early warning and targeting radar. It was able to detect a warship from a distance of 100 km and a surfaced submarine from a distance of 20 km. It was installed on patrol aircraft and torpedo aircraft, and further, it was used in combination with a radar altimeter. Tachi No.1, used as a land mobile targeting radar, could detect an aircraft from a distance of 20 km. Thirty of these mobile radar were produced and a total of 200 of the two modified versions were produced.

COPYING OF GERMANY'S TARGETING RADAR, "WÜRZBURG"

Japan received the design documents together with engineers, Mr. Forders and others, from the German Government for the 50-cm targeting radar "Würzburg". The copying of this radar started in the fall of 1943 and 2 sets were completed by at the end of war but were not used.

OTHERS

Besides above, the Army was engaged in the research of magnetrons and various other radars.

Conclusion

My report principally covers the general outline of radars of the Japanese Army and Navy up to the end of the War. Japan had very few scientists and engineers, and a serious shortage of materials as compared to the US and European countries before and during the war period. In general, I believe the Japanese scientists and engineers were not properly treated and fully utilised in the various researches of the Army and Navy. I also believe that radar was a big factor in the Pacific War, and there was no comparison between Japan and the US and England concerning the research program and production capability.

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ABOUT THE AUTHOR

Shigeru Nakajima graduated from the Faculty of Electrical Engineering, Waseda University, in 1930. The following year he joined the Japan Radio Company, to which he became Director in 1947, Managing Director in 1960 and Executive Managing Director in 1967. During 1937–1938 he studied inh Germany and took out a doctorate in engineering in 1949. In 1971 he became President of Aloka, and remained Advisor to Aloka from 1977 to 1987. In recognition of his scientific and technical achievements, he was decorated with the Purple Ribbon Medal in 1963 and with the Third Class Order of the Sacred Treasure in 1977.

Karl F Lindman — the last Hertzian and a harbinger of electromagnetic chirality

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Who was Karl F Lindman?

Karl F Lindman was born in the small coastal town Ekenäs close to the south western corner of Finland on June 7, 1874 as the only son to Karl Gustav Lindman and his wife Lovisa, born Lignell. Karl Gustav Lindman had made it from humble origins to an independent farmer and was honoured later in his life by an appointment to a minor clerical function. As he had made good, he was able to put his son Karl Ferdinand to school. The rest is the usual story of a young man of great talent and prodigious energy: graduation from secondary school at the age of 18 and a university degree in physics at the age of 21 in 1895. Lindman took a long time to decide to major in physics. The alternative was history. Throughout Lindman's life, history remained a dear hobby to this physicist and extreme specialist of electromagnetic waves. Lindman got his PhD at the Helsinki University in 1901 with a thesis work done in Leipzig.

For 20 years Lindman served as an innovative secondary school teacher in various towns in Finland. He was finally appointed Lecturer at Svenska Normallyceum, a national institute of a school in Helsinki. As early as in 1909 Lindman introduced laboratory courses into the curriculum of Svenska Normallyceum. His various biographies also make one understand that Lindman was able to keep his classes under exemplary discipline. Lindman wrote a large number of textbooks on physics, astronomy and chemistry, both in the Swedish and in the Finnish language. These books were in use till the Second World War and beyond. Lindman was also an active populariser of science. He published a large number of articles in various newspapers and magazines aimed at the public at large. In 1907 he spent half a year in England and Scotland to study the methods of teaching in English schools.

After his appointment to the Chair in Physics at Åbo Akademi, Lindman became deeply involved in University politics. He served for 24 years as the Dean of the Faculty of Mathematics and Natural Sciences. He was Vice Rector of the University from 1921 to 1929. Lindman was honoured by two national prizes for his research, the Hallberg Prize in 1933 and the Homen Prize also in 1933. It may be of interest to notice that Lindman also took part in the discussion on Einstein's theory of relativity. Without ever publishing an original research article on the question, Lindman expressed severely critical opinions on the theory in his textbooks. It appears that the great experimentalist of electromagnetic waves that he was, never came to believe that the transformation properties of the fundamental equations of his subject had changed physics for good.

Lindman never grew tired of his work. He continued teaching and doing research after his retirement in 1942. He carried a full teaching load till 1945 and published his last paper as late as in 1947. One may be struck by the absence of co authors in the published work of Lindman. In his research he was a lone wolf. He trained only one PhD student, Hilding Slätis, who became his successor in the Chair of Physics for one year before moving on to Sweden.

Karl F Lindman died on February 14, 1952. He left behind one son, Sven Lindman.

Karl F Lindman as a Hertzian physicist

As already mentioned above, Lindman was brought into electromagnetics at the University of Leipzig in 1899-1901. The University of Leipzig had a tradition in electrodynamics founded by Wilhelm Weber, a student of C F Gauss and Professor of Physics in Leipzig 1943-1849. Right before Lindman's stay, Paul Drude came to the Chair of theoretical

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Studies on geomagnetically induced currents in the Finnish high–voltage power transmission system

Abstract. The geoelectric field induced by a temporal variation of the geomagnetic field produces Ohmic currents, called geomagnetically induced currents (GICs), in power transmission systems and other man–made conductors. In general, GICs may cause inconveniences to the particular system. In power systems, this is due to saturation of transformers. The GIC phenomenon has been studied by measurements and theoretical calculations in the Finnish 400 kV power grid since 1977. This paper deals with the research from the geophysical viewpoint, and particular attention is paid to a GIC project accomplished in Finland in 1991 to 1992.

Fig. 1. Finnish 400 kV power transmission system in 1992.

GIC PROBLEM

Faraday's law of induction implies that a time variation (disturbance or storm) of the geomagnetic field is accompanied by a geoelectric field. The latter in turn drives Ohmic currents in all conductors, particularly in the earth. When flowing in man–made technical systems, such as electric power transmission grids, telecommunication cables or pipelines, the currents are known as geomagnetically induced currents (GICs). From the viewpoint of the technical system in question, geomagnetic induction is a possible source of harmful effects [1]. In power systems, GICs, which are dc currents compared to the 50 or 60 Hz frequency, can saturate transformers resulting in economically significant disturbances in the operation of the power system or even in permanent damage of transformers [2]. In pipelines problems associated with corrosion arise [3]. Anyway so far, practically no inconveniences of geomagnetic origin have been observed in the Finnish power grid, natural gas pipeline or any other technical system, but due to the location at geomagnetically active auroral latitudes, investigations about the phenomenon are necessary.

Collaboration between the Imatran Voima Oy power company (IVO) and the Finnish Meteorological Institute (FMI) on GICs in the Finnish 400 kV power system has been continuing since 1977 including current recordings (mainly at the Huutokoski station, Fig. 1) and theoretical calculations [4, 5]. Studies of geomagnetic induction in the Finnish natural gas pipeline have been performed with the Neste Oy oil company [6].

APPLICATION OF GICS TO GEOPHYSICAL RESEARCH

The primary source of a geomagnetic variation and the associated geoelectric field is a time–varying electric current system in the ionosphere and the magnetosphere. Secondarily, the geoelectromagnetic field is affected by currents and charges induced in the earth. Consequently, geomagnetic variations and the electric field involve geophysical information of ionospheric–magnetospheric processes and of the earth's electromagnetic structure. The corresponding information is transferred to GICs, too. Thus, the significance of studies on GICs is not limited to engineering viewpoints, but GICs also provide a tool for basic geophysical research. In this respect power transmission networks etc. can in fact be regarded as vast passive antennas, and GICs represent spatially–integrated geoelectric fields (geovoltages) over large areas (hundreds of kilometres). In other words, GICs are not sensitive e.g. to small–scale inhomogeneities of the earth which greatly distort the (local) geoelectric field [7]. However, derivation of geophysical parameters from GIC data is a complicated inverse problem, and a unique mathematical inversion is certainly impossible. In practice measured GIC values should be fitted to results obtained by forward modelling.

CALCULATION OF GICS

Theoretical calculation of GICs in a power system is convenient to be performed in two steps:

The first "geophysical" step consists of the estimation of the horizontal geoelectric field, so it requires modelling of ionospheric–magnetospheric sources and the earth's electromagnetic structure.

The second "engineering" step is the calculation of GICs produced by the electric field included in the first step. Since geomagnetic phenomena are slow a dc treatment is permissible. Based on straightforward, but complicated, circuit theory, matrix equations expressing GICs can be derived [8]. They are utilized in our computer program which allows the geoelectric field to have given values at specified grid points covering the particular network. The program thus permits the use of any geophysical model in the first step.

A very simple model yielding an estimate of the geoelectric field is composed of a homogeneous earth with a vertical plane wave. The following time–domain relationship between a horizontal geomagnetic variation and the accompanying horizontal geoelectric field can easily be derived then [4, 5]:

$$E(t) = -\frac{1}{\sqrt{\pi\mu_0\sigma}} \int_{-\infty}^{t} \frac{g(u)}{\sqrt{t-u}}\,du \qquad (1)$$

Here E and g are a horizontal electric field component and the time derivative of the perpendicular horizontal magnetic field component, respectively. The conductivity of the earth is denoted by σ, and μ_0 is the (vacuum) permeability.

Expressing formula (1) in the frequency domain and considering σ a frequency–dependent apparent conductivity, the basic magnetotelluric equation widely used in electromagnetic studies of the earth's structure is obtained [9]. The applicability of the equation has, however, been much discussed during many years, e.g. [10, 11]. In spite of the extension concerning the validity of the basic magnetotelluric formula and presented in [12], its use still remains questionable at auroral latitudes because of source effect distortion due to the vicinity of ionospheric currents. This is clearly demonstrated in [13] based on a realistic model of the auroral electrojet current system [14].

As stated above, GICs in a given network are affected by the spatially–integrated electric field. It may therefore be believed that the use of the plane wave formula (1) is not as fatal in a GIC computation as in a magnetotelluric study at a single site in the auroral region.

Formula (1) was applied to a statistical investigation of the occurrence of GICs in the Finnish 400 kV power system [4]. From the engineering viewpoint, it is important to know the statistical probability that GIC flowing through a transformer has a given magnitude and also the average duration of this current magnitude. In a theoretical estimation, similar GIC statistics are directly obtained for each transmission line, too. It should be pointed out that GIC through a transformer or in a transmission line refers to the sum of GICs flowing in the phase conductors, i.e. GIC is equal to three times the phase GIC.

In [4] the conductivity σ became an "event–dependent time–domain apparent conductivity", which evidently compensates ionospheric source distortion and shortcomings of the assumption of a homogeneous earth.

A model that contains a line current simulating an electrojet and which is thus more appropriate at auroral latitudes than formula (1) has also been used in connection with a calculation of GICs in the Finnish 400 kV power system [15]. A future aim would be to use the general electrojet system model [14] in the first step of the estimation of GICs.

GICS IN THE FINNISH 400 KV POWER SYSTEM

The Finnish 400 kV power grid shown in Fig. 1 has essentially changed during the 15 years of GIC studies performed. Thus measured or calculated GIC results for a particular time need not be valid for another time, and to obtain statistically reliable information the analysis has to cover at least a sunspot cycle significant in connection with geomagnetic disturbances.

The largest GIC measured at the main recording station Huutokoski is 165 A (a ten–second mean value), and the highest GIC ever recorded in Finland is 200 A (a one–minute mean value) at Rauma (Fig. 1). Both values refer to the current flowing in the earthing lead of the 400 kV transformer neutral. Generally speaking, GICs exceeding 100 A seem to be rare in Finland but the magnitudes greatly vary from site to site.

The Finnish 400 kV system is galvanically connected to the Swedish grid, which makes it possible that GICs flow from one country to another. This fact also enlarges the network that has to be considered in the second step of GIC calculations. However, it has been shown in [16] that accurate results in Finland can be obtained by neglecting the Swedish part of the high–voltage grid; in other words, GICs do not essentially flow between Sweden and Finland, i.e. distances in the order of several hundreds of kilometres. The galvanic connection is interrupted at the Russian border station Vyborg, so that no approximation is made in a GIC calculation by stopping the grid there.

As indicated above, different model calculations of GICs flowing in the Finnish 400 kV power system have been carried out. Table 1 concerns one of them showing the insensitivity of GICs to spatial details of the geoelectric field. Only the stations and the line which are measuring sites in the GIC project (see below) are considered. A spatial variation is simulated by adding a uniformly distributed random northward field ΔE to the constant northward field $E_0 = 1$ V/km at each point of a 20 km x 20 km grid covering the Finnish 400 kV power network. GICs induced are shown in columns 1 and 2 of Table 1 by assuming two different values for the maximum variation $|\Delta E|_{max}$. For comparison, GICs associated with a spatially constant northward field of 1 V/km are given in the 3rd column. It is seen that spatial geoelectric variations do not have much influence on GICs. This conclusion is also supported by an eastward field calculation not included here.

Table 1. Geomagnetically induced currents at four 400 kV stations (earthing current) and in one 400 kV transmission line when the horizontal geoelectric field equals $E_0+\Delta E$ with $E_0 = 1$ V/km northwards, and ΔE is a northward electric field with a uniform random distribution in the range 1) –0.25 V/km...0.25 V/km, 2) –1.0 V/km...1.0 V/km, 3) $\Delta E = 0$, i.e. the electric field is constant (= 1 V/km). The electric field is given in a 20 km x 20 km grid, and it is interpolated using a 4–point formula.

	1	2	3
Huutokoski	–3.6	–8.4	–4.2
Pirttikoski	71.9	71.8	70.7
Rauma	–13.3	–8.1	–14.1
Yllikkälä	–11.1	–4.7	–10.1
Loviisa–Nurmijärvi	–17.9	–12.3	–13.9

GIC PROJECT

To verify and possibly improve the statistics derived previously on GIC occurrence in the Finnish 400 kV power transmission system [4], IVO and FMI started a one–year GIC project in June 1991. The time chosen is slightly after

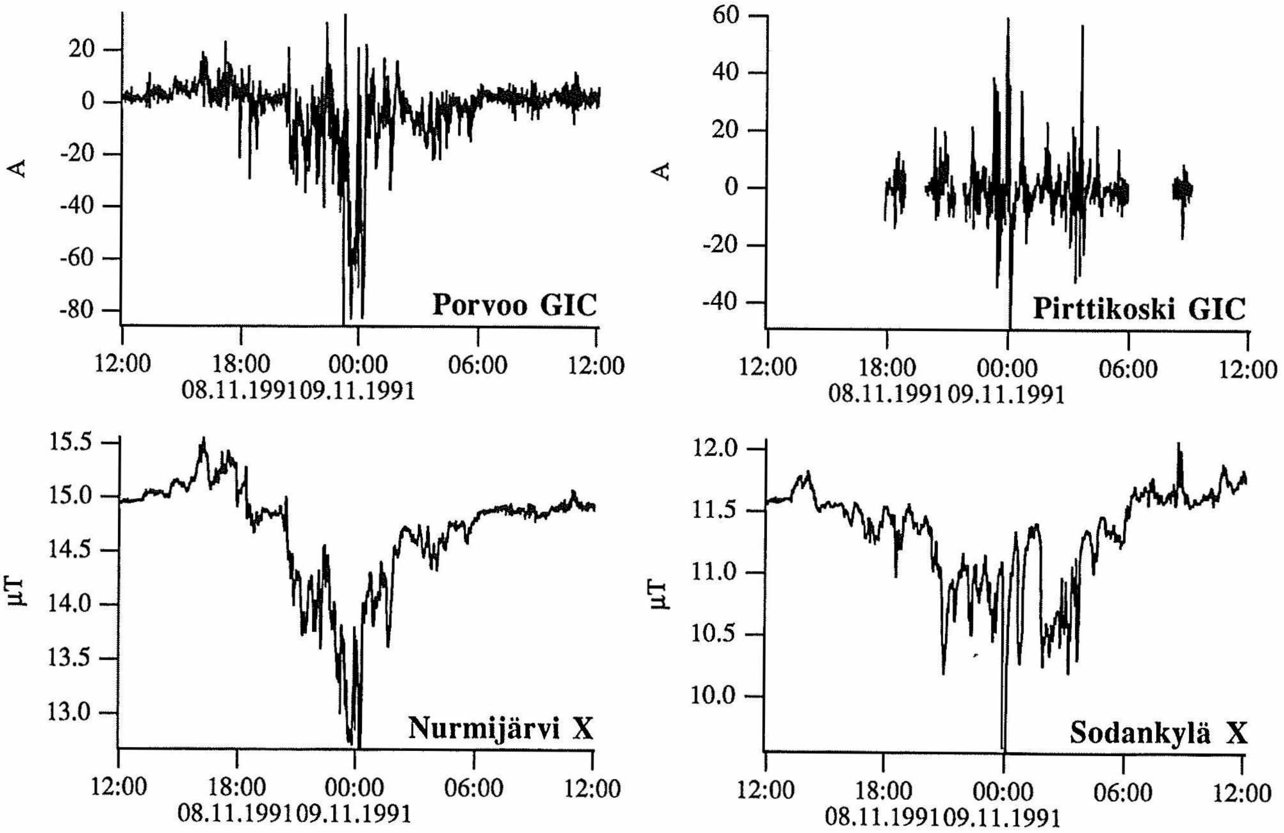

Fig. 2. GIC in the earthing lead of the 400 kV transformer at Pirttikoski on November 8–9, 1991. GIC observed in the Loviisa–Nurmijärvi 400 kV line at Porvoo and the variation of the geomagnetic north component (X) at the Nurmijärvi and Sodankylä Observatories are also shown.

a sunspot maximum so that large geomagnetic disturbances and GICs are expected. In contrast to previous Finnish GIC investigations, consideration of the 220 kV grid, which is galvanically–connected to the 400 kV network through autotransformers, is also explicitly taken into account now.

In the project, GICs are recorded in the earthing leads of 400 kV transformer neutrals at the Huutokoski, Pirttikoski, Rauma and Yllikkälä 400 kV stations (Fig. 1). GIC flowing in the Loviisa–Nurmijärvi 400 kV line is also monitored by observing geomagnetic variations at Porvoo. The difference of these variations from variations recorded at a reference station far enough from the line is due to GIC. Now the Nurmijärvi Geophysical Observatory (Fig. 1) is regarded as the reference. GIC data are collected in digital form as 10 s mean values on computer diskettes, and the data are compared and correlated to geomagnetic recordings at the two permanent Finnish observatories at Nurmijärvi and Sodankylä (Fig. 1). Magnetic data from Sweden and from temporary stations are also available. Fig. 2 shows an example of the recordings in the project. As seen, high GIC values are connected with large variations of the geomagnetic field, but an exact quantitative correlation is not so straightforward to find. It should also be noted that even the simple model discussed above gives an integral dependence between the electric field (i.e. GICs) and the magnetic variation (formula (1)).

CONCLUSIONS

Faraday's law of induction explains the basic principle of the flow of electric currents (geomagnetically induced currents or GICs) in man–made conductors in connection with time variations of the geomagnetic field. Such an induction may cause inconveniences to the conductor system in question: e.g. in power transmission grids transformers can be saturated leading to disturbances or even to permanent damage. Thus GIC research is of practical importance especially at auroral latitudes where geomagnetic disturbances are the greatest.

Practically no GIC harm has been found in the Finnish power system, which is due to the structure of the transformers etc. used. However, investigations of GICs in the Finnish high voltage power transmission grid have been made by measurements and theoretical calculations for many years. A special GIC project, in which GICs are monitored at five sites simultaneously, was carried out in 1991 to 1992. The practical purpose of the project is to derive reliable statistics of the occurrences and durations of GICs in the Finnish power network. In addition, valuable data applicable to geophysical studies of ionospheric–magnetospheric processes and of the earth's structure are obtained.

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LINDMAN—THE LAST HERTZIAN

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physics in 1894. Characterised as "mastering equally theory and experiment" he obviously had a strong influence on Lindman. In order to set things into perspective, it may be worth mentioning that people like Boltzmann, Debye and Heisenberg also have held chairs at the University of Leipzig[1].

EXPERIMENTAL EQUIPMENT

Lindman returned to Finland in November 1901 with a completed PhD thesis to be presented at the University of Helsinki. The title of the work was "On Stationary Electric Waves, an Experimental Study" (in German). He described an experiment on standing electromagnetic waves from a Hertzian dipole with extendable arms and a spark gap ('oscillator' O in Figure 1). The dipole was fed with audio-frequency high voltage generated by a Tesla coil (T) whose primary had a circuit containing a Leyden jar (K), a tunable spark gap (F) and a Ruhmkorff inductor (I). The inductor again was fed from a battery with a circuit breaker (not shown in Figure 1) producing 40 Hz current pulses. The spectrum of the radiated signal contained a peak of main frequency between 0.6 – 7 GHz determined by the arm lengths of the dipole and a decaying band of higher and lower frequencies.

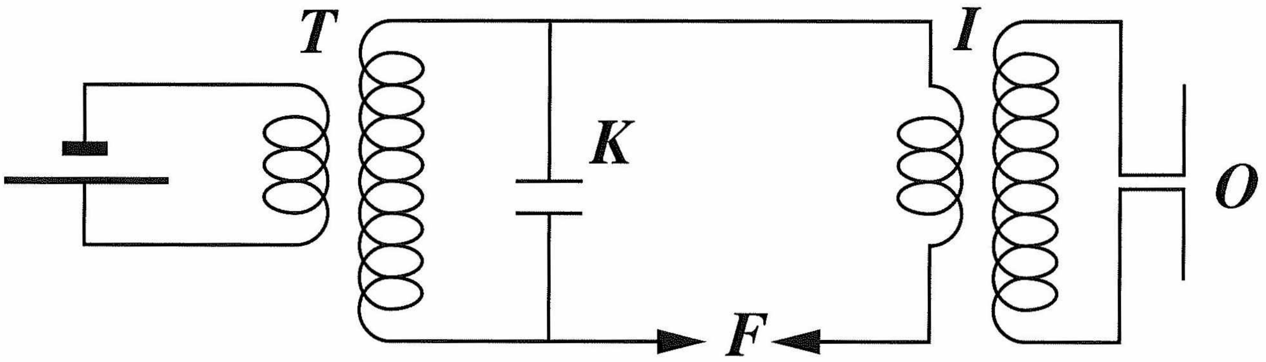

Fig. 1: Transmitting spark-gap antenna ('Oscillator') with adjustable dipole arms together with its feeding circuit. This wide-band Hertzian generator remained practically unchanged in his experiments for half a century, producing microwave, millimetre wave and even infra-red frequencies [Ed: Redrawn].

The receiving antenna ('resonator') was tuned to some frequency, and its current heated a load resistor connected to a thermocouple whose weak current pulse created a deflection in a galvanometer. Since there was no detector for the signal level at the transmitter, Lindman made use of another antenna at a fixed position ('standard indicator') coupled to a second galvanometer. He developed a technique of reading the two galvanometer deflections with one glance to get the relative signal as quotient of the two readings. The galvanometers were by far the most sensitive elements of the system. They were carefully shielded against external mechanical and magnetic effects. When Lindman became professor at Åbo Akademi in 1918, he actually could not begin with his measurements because the building was not steady enough. He had to wait until another building was found for his laboratory. Magnetic disturbances from electric streetcars forced him to do his measurements at nighttime.

This same method, developed and perfected at the turn of the century, was to be applied in Lindman's experiments for half a century with only minor changes in the apparatus. A major disaster occurred in 1940. During the Winter War in Finland, the equipment was transferred to a shelter. In this process one of the two galvanometers was damaged. The rest of Lindman's experiments were done with a single galvanometer and two consecutive readings, one for the measured quantity and another for the reference signal. Lindman was always very careful in his work and satisfied only when repeated measurements showed no marked change in their readings.

HERTZIAN STUDIES OF ELECTROMAGNETISM

Lindman's PhD thesis was about a phenomenon he had encountered observing standing waves in front of a conducting plate. Unlike the other peaks and valleys, the first maximum seemed significantly shifted towards the plate from its theoretical distance $\lambda/4$. Lindman explained the effect as being due to the second harmonic frequency induced in the tuned receiving dipole because of the wide band of the transmitted signal.

After the thesis, Lindman continued his studies on electromagnetic wave problems. His last paper appeared in 1947. We will return to his work on chiral media in the next section. Apart from this major area, his work dealt with resonance of wire antennas, macroscopic models of different media, millimetre wave and infra-red wave propagation in various media, diffraction grids, scattering problems, wave propagation in Sommerfeld single-wire transmission lines and metal-tube waveguides. All these experiments were carried out with the same equipment!

His aims were physical in a purely Hertzian manner: to demonstrate an effect and increase knowledge on it, not to find practical applications. Measuring wavelengths on the Sommerfeld single-wire line, however, he could determine from his thin-wire samples the permeabilities of many different materials with high accuracy. His work on scattering (he called it reflection) from small particles led to a method which allowed the detection of bigger stones in a concrete wall. The steps from this to a practical radar could not have been completed with his limited skills in engineering.

A great deal of Lindman's work was done on finding resonances of different wire antennas ('resonators'). This was necessary for his experiments: in order to know what frequency in the wide spark gap spectrum was being measured, the exact tuning of the receiving antenna was of prime interest. He developed numerical correction factors for dipoles depending on all conceivable parameters: length, thickness, material and end geometry of wires. One of his reports on wire antennas in Åbo Akademi (which always first published his results) consists of 201 printed pages. In addition to dipole and loop antennas, he studied the helical antenna in 1933. Being only interested in the basic resonance, he failed to discover the axial radiation mode found by John Kraus as late as after the Second World War.

In 1909-1910 Lindman investigated wave propagation through a grid of wire scatterers. He found that the distance between scatterers had a great effect on the propagation. Von Laue and Bragg had investigated reflection of X rays from crystals in 1912 and interpreted the results in terms of scattering from a grid. Lindman studied the electromagnetic wave reflection from a grid of wire loops in 1921 and verified Bragg's law on a macroscopic scale. Later he went on and studied various frequency-selective surfaces with which he could separate different frequencies out of his broad-banded transmitted signal for further use. With a grid of small lead spheres, for example, he could obtain a peak of frequencies in the millimetre-wave region. He was also able to demonstrate that the spectrum from the spark-gap transmitter contained infra-red waves. In one of his last papers in 1945, Lindman exploited IR waves thus produced in an investigation of the absorption of IR waves in different materials.

Lindman was a full blooded experimentalist. His papers contain few equations. The Maxwell equations can be found in them only once, in a footnote. Nevertheless, he regularly checked his experimental results against theoretical predictions obtained by others. He never reproduced derivations of the few formulas cited in his papers nor did he make comments on them. Glancing at his papers through the 1920s and the 1930s, almost all of his references seem to go back to the turn of the century, either to the 1890s or the 1900s. We can easily feel sympathy for Lindman, the only 20th century physicist studying electromagnetism while the mainstream of physics was following quantum and relativity paths. He does not seem to have had contacts with the electrical engineering community either, not so well developed in Finland at the time. Perhaps the most dramatic contrast to the outside world is detected when looking at Lindman's paper on wave propagation in a circular metal tube and between two metal plates in 1942. At a time when there was a tremendous amount of world-wide effort devoted to problems of microwave propagation along metal waveguides for radar development, Lindman's problem was a shift in the principal frequency of a broad band signal propagating through a tube. If the principal frequency from the generator was below a certain critical frequency he found an out coming peak at a higher frequency, while higher main peak frequencies did not change. A relation of the critical wavelength to the diameter of the tube was experimentally obtained. This reflects the pure physicist interested in one problem among a multitude of others in total ignorance of the fact that the problem happened to be among the hottest engineering topics of the day.

LINDMAN—THE LAST HERTZIAN

Pioneer in chiral studies

Why are today's electromagneticists so enthusiastic about Karl F Lindman's results from almost a century ago? The explanation is that Lindman was focusing, as early as in the first and second decades of the century, on a field that was to evolve into the extremely hot topic that it is today. This topic is the electromagnetism of chiral media.

CHIRAL MEDIA

Chiral materials are a subclass of bi anisotropic media, more general than the normal isotropic media describable through the material parameters permittivity, permeability, and conductivity. Chiral media, or handed media, display an intrinsic asymmetry with respect to the distinction between left and right. On the level of constitutive relations, this is visible in the magneto electric coupling:

$$\mathbf{D} = \varepsilon\mathbf{E} - j\kappa\sqrt{\mu_o\varepsilon_o}\,\mathbf{H} \tag{1}$$

$$\mathbf{B} = \mu\mathbf{H} + j\kappa\sqrt{\mu_o\varepsilon_o}\,\mathbf{E} \tag{2}$$

Here **E** is the electric and **H** the magnetic field strength, **D** is the electric and **B** the magnetic flux density. The material parameters expressing the connection between these quantities are the permittivity ε and permeability μ characterising the electric and magnetic copolarisability of the material. The third, κ, stands for the magneto electric coupling and contains the (dimensionless) degree of chirality. ε_o and μ_o are the permittivity and permeability of the vacuum. There are also other notations for the material parameters of chiral media, see e.g.[2]. Because of the scalar nature of the material parameters a medium with constitutive relations of the form (1), (2) is isotropic in the sense that its electromagnetic response does not depend on the field vector direction: it is bi-isotropic. Note also that the equations (1), (2) do not describe the most general bi-isotropic medium: for non reciprocal chiral media, a fourth material parameter is needed.

The effect of chirality on electromagnetic wave propagation is a rotation of the plane of a linearly polarised wave. In classical optics, this has been a well-known phenomenon since the early nineteenth century from the studies by Biot, Arago, and Fresnel. It has been given the name *optical activity*. Pasteur showed somewhat later that the optical activity results from the handed structure of the material: a material that differs from its mirror image is capable of rotating the polarisation plane of linearly polarised light. Honouring his work, a chiral medium obeying the relations (1), (2) carries the name "Pasteur medium".

The potential applications in microwave, millimetre wave and infrared frequencies gave the impetus to the "second wave" of chirality research which we are witnessing today. Among such applications are couplers, microstrip and lens antennas, wave guiding structures, and anti reflection coatings. The number of publications on electromagnetic waves in chiral media have increased tremendously, for references see e.g.[3]. A book has been published on chiroelectromagnetics[4], and an introductory article into the field can also be found[5]. SPIE Optical Engineering Press has published a selection of treatises on optical activity and chiral electromagnetics[6].

LINDMAN'S ROLE

These recent publications do not fail to recognise the work of Karl F Lindman. His two pioneering papers on microwave chirality are cited and sometimes even reproduced. Lindman's papers appeared in German language in the venerable journal *Annalen der Physik* in 1920 and 1922 with the titles

Über eine durch ein isotropes System von spiralförmigen Resonatoren erzeugte Rotationspolarization der elektromagnetischen Wellen (Vol.63(4), p.621-644, 1920).

and

Über die durch ein aktives Raumgitter erzeugte Rotationspolarisation der elektromagnetischen Wellen (Vol.69(4), p.270-284, 1922).

As a curiosity, let it be mentioned that today's scientists obviously, referring to these publications, treat the experiments described there as having been performed in the 20s. Lindman, however, writes in his 1920 paper

die Versuche wurden im physikalischen Institut der Universität Helsingfors im Sommer 1914 aufgeführt,

and hence, his pioneering work is in fact six years older than normally recognised. The objection that Lindman did not publish his results until 1920 (with the implicit presumption that the date of publication is the date of discovery) does not hold water. Lindman indeed did publish his work in 1914 before the outbreak of the First World War[7].

Let us take a closer look into the contents of these two publications.

LINDMAN'S PUBLICATION IN 1920

Already the nineteenth century saw the proof that optical activity is a geometrical property and arises from the dissymmetric molecular structure of substances displaying such activity. Drude had presented a model for the wavelength dependence of the amount of the rotation of the polarisation plane ϕ in an optically active material:

$$\phi = \sum_i \frac{k_i}{\lambda^2 - \lambda_i^2} \tag{3}$$

Here λ is the wavelength of light, and the summation i takes into account all the "characteristic vibrations of the electron groups" in the parlance of late-nineteenth century physics: λ_i the corresponding resonant wavelength and k_i the strength of this resonance.

All this was known to Lindman, and this was also his starting point. He was interested in testing the validity of Drude's model at lower frequencies, with radio waves, or, as he himself calls it "Hertzian waves". He notes that this means a situation similar to "ultraviolet electrons", i.e. in Drude's formula the case that the wavelength is much longer than the characteristic wavelengths of the resonant modes:

$$\lambda >> \lambda_i \tag{4}$$

Hence, Drude's model gives

$$\phi \approx \frac{k'}{\lambda^2} \tag{5}$$

where k' is now the strength of the lowest order mode. Because of the strong inverse wavelength dependence of ϕ, there is no measurable optical rotation to be expected at Hertzian waves. This formula (5) was known as Biot's first law.

Hence, what to do? Lindman's answer to this problem was scaling. If molecular dissymmetry produced optical activity, radio-wave (or electromagnetic) activity should result from dissymmetry that manifests itself on spatial scales on the order of centimetres. The artificial creation of this kind of material was the next step.

Lindman synthesised a chiral medium by coiling small helices from copper wire, immersing these in cotton balls, and then positioning these in a cardboard box with random orientations. The length of the wire before coiling was 9 cm and the thickness 1.2 mm. The diameter of the spirals was 10 mm and there were 2.5 turns in each spiral. The cardboard box had the linear dimension of 26 cm and the total number of spirals in was 700. Lindman made both left-handed and right-handed helices.

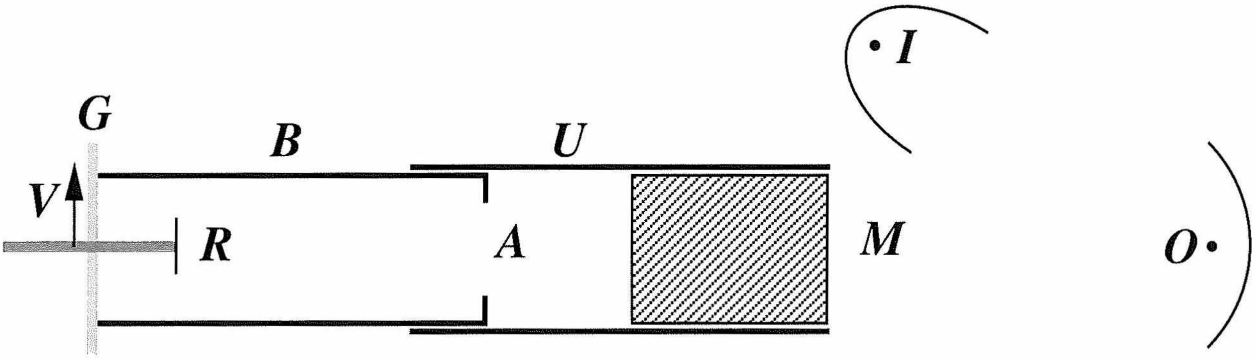

Fig. 2. Lindman's measuring equipment. The transmitting oscillator O stands beside a reflector. I is the "standard indicator" discussed in the text. B and U are hollow metal tubes. The sensor dipole R can be turned with the stick T, and the rotation angle is read in the display formed by V and G. M is the box containing the chiral sample[Ed: Redrawn.

Lindman put his chiral box into his measurement system shown in Figure 2. He directed linearly polarised radio waves through the metal guide where the sample was located, and measured the linearly polarised component of the intensity of the received signal as a function of the rotation angle of the receiving linear antenna. For a linearly polarised wave this function should be the square of the cosine. The polarisation rotation could be read from the maximum of this curve.

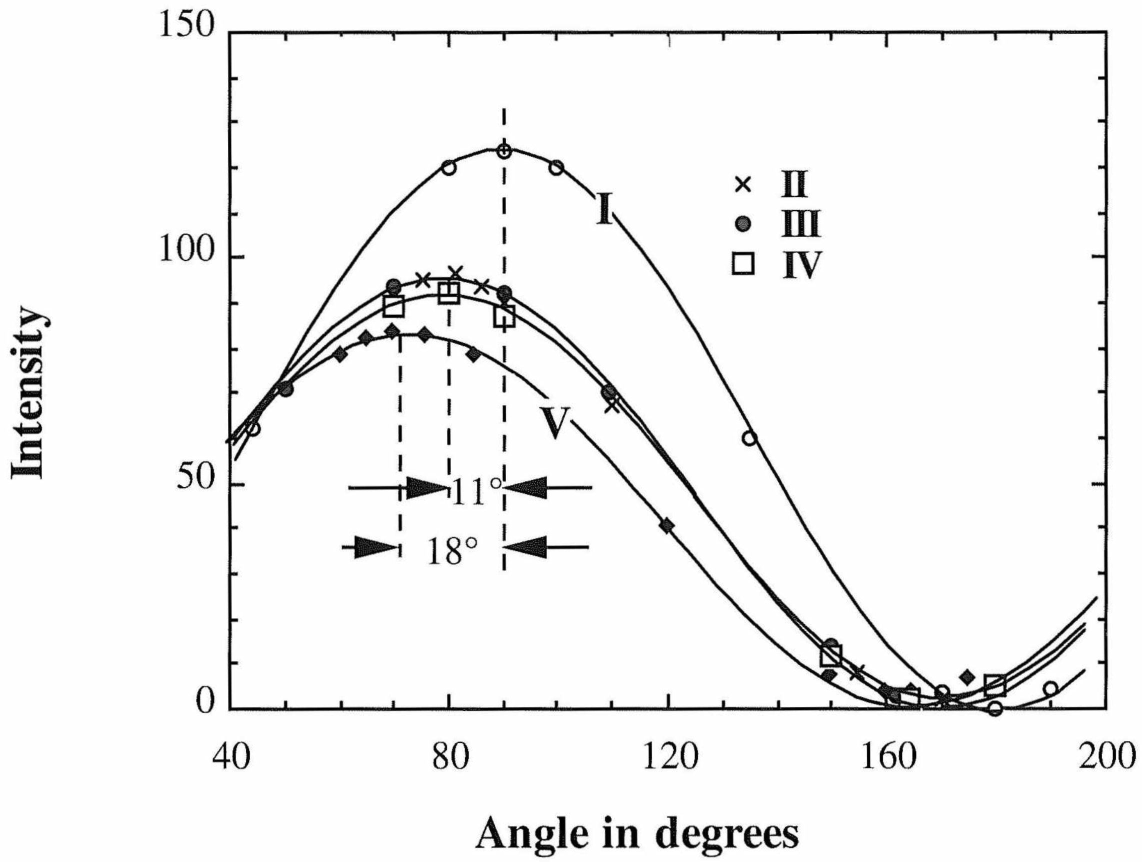

Fig. 3. Measured intensity curves as functions of the rotation angle of the receiving antenna. Curve I is measured without a sample. It shows maximum polarisation matching for 90° angle. Data sets II, III and IV are for a chiral sample with 300 spirals on the propagation path of the wave. The three sets (only two curves are shown) are for three different orientations of the same sample. Curve V represents a sample with 500 spirals, displaying the linear relation between the number of chiral elements and the amount of the rotation of the polarisation plane[Ed: Redrawn].

His results are shown in Figure 3 at the frequency 1.2 GHz. It can be clearly seen that the polarisation plane has been rotated due to the cardboard box on the wave path: there is a clear shift in the peak of the curves. The figure also shows that Lindman's chiral sample is isotropic: three different orientations (Curves II, III, IV) lead to the same shift. Finally, he shows that the angle of rotation is directly proportional to the number of helices in the box: 300 helices produce a rotation of 11° and 500 helices correspond to 18°. This is in accord with the modern result that the polarisation rotation can be given as the integral of the chirality parameter along the wave path[8]

$$\phi = k_o \int \kappa \, ds \qquad (6)$$

where κ is the chirality parameter and k_o is the wave number.

The basic aim of the study was, however, to investigate the dispersion, i.e. the wavelength dependence. The polarisation rotation was measured at wavelengths from 12 cm to 35 cm (frequencies 1 to 3 GHz). Lindman then took Drude's model (3) with only one mode (one term in the summation) and compared the measured curve with the model. With eight frequencies and only two free parameters (λ_o and k) the agreement is good except at wavelengths close to the "resonant" wavelength λ_o of the model.

Lindman was also able to show that equal amounts of left-handed or right-handed spirals bring about the same rotations in opposite directions.

LINDMAN'S PUBLICATION IN 1922

It can be a refreshing experience to take a look at scientific publications of the good old times such as those of Lindman. The personal tenor in the reporting and the wordy descriptions about the background and motives for various assumptions in attacking problems sometimes can convey deep insight into the way physical laws were conceived at those

continued on page 52

Ultra-Wideband Radar: Proceedings of the First Los Alamos Symposium

Edited by Bruce Noel, CRC Press Inc.
2000 Corporate Blvd. NW Boca Raton, Florida 33431
USA
ISBN 0-8493-0198-X, 1991
Approx price US$120. 565 pages, no subject index!

This "edited" and "refereed" collection of 37 papers was selected from 75 presented at a symposium in Los Alamos held in March 1990. There was also a classified (i.e. secret) session which is not covered in the document under review. The editor speculated that members of the "establishment" have suppressed research on UWBR to protect their interests in developing large and expensive conventional radars. Also he mentions the idea of countering Stealth technology by employing UWBR and finally he brings into prominence the contention that Maxwell's equations need modification when impulses are transmitted into lossy media. This is pretty heady stuff to set the scene for the actual papers that follow. Collectively they are a mixed bag.

The basic concept of UWBR is really quite simple. Rather than radiating a pulse modulated carrier signal of limited bandwidth, the scheme is to pump out the baseband signal directly which, in the extreme limit, would be a Dirac delta function. As you can imagine, the technological problems of designing the antenna are horrendous. Many of the papers tackle this aspect of the subject. But the most interesting contributions deal with the characteristics of the target response where it is pointed out that "anti-reflective" coatings may become completely ineffective and could, in effect, enhance the scatter. Some of the more military minded authors discuss the consequences and opportunities for operational radars of the future. Also some of the related papers on target identification are important if you still want to tell the difference between a Mig27 and an F4.

I feel that the early highlighting of the spurious "need" to modify Maxwell's equations in lossy media is somewhat of a red herring. Also I am surprised that none of the authors have cited any of many published papers on transient electromagnetic methods in applied (solid earth) geophysics which have appeared in the journal *GEOPHYSICS** for the past several decades.

The advertized price seems excessive since the papers are all from the authors' photo-ready manuscripts. But anybody with a need for up-to-date information on this topic will have to have access to this publication.

* Notably the Special issue "Time domain Electromagnetic Methods of exploration", Vo.49, No.7, July 1984, edited by M N Nabighian.

James R. Wait

Electromagnetic Waveguides—Theory and Applications

S.F.Mahmoud
Published by Peter Peregrinus Ltd.
London, United Kingdom
Price: $60 (approx).

This is a unique book. Under the general heading of electromagnetic waveguides, Dr Mahmoud gives a concise presentation of the theory of wave propagation in a variety of waveguiding structures, with the emphasis placed on their applications in telecommunications, microwave/millimeter-wave circuits, and integrated and fiber optics components.

The book is carefully organized in such a manner that can serve as a text for a graduate course on electromagnetic guided waves. Indeed, the development of the underlying theory is in an order of increasing complexity, starting with closed waveguide, moving on to open waveguides and one on guided waves in subsurface tunnels. In addition to their importance from an application point of view, Dr Mahmoud takes advantage of the complexity of the waveguiding structures presented in the last two chapters to illustrate how the various results developed in the earlier chapters can be used to tackle more difficult problems. A collection of problems at the end of each chapter gives the reader the opportunity to exercise some of the presented concepts and mathematical procedures as well as to probe further in the relevant literature, a task which is greatly simplified by the careful selection of references included at the end of the chapters.

Several topics, not likely to be found in other graduate texts on electromagnetic wave theory, have been included in this text. Among them, we mention the detailed study of the effect of impedance walls on the propagation characteristics of waveguides for a variety of cross sections, and the mode orthogonality and mode coupling in open waveguides along with their application to the analysis of the reflection and transmission characteristics of discontinuities in dielectric slab waveguides.

The uniqueness of this text stems from the perfect blend of detailed and rigorous mathematical presentation of the underlying guided wave theory with carefully justified approximations that lead to simple design equations for a variety of waveguides. It is this blend that makes the book extremely useful not only to researchers in the field but also to microwave and optics engineers involved in the design and application of waveguide components and structures.

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USA

WORKSHOP ANNOUNCEMENT

International Workshop on Electromagnetic Phenomena Related to Earthquake Prediction

1. Date: 6-8 September, 1993

Just after the URSI General Assembly in Kyoto (23 Aug - 3 Sep 1993)

2. Location:

The University of Electro-Communications
1-5-1 Chofugaoka. Chofu Tokyo, 182 Japan

3. Objectives:

There have been many reported candidate phenomena for the precursors to earthquakes. In recent years electromagnetic (EM) phenomena are becoming a more important component in earthquake prediction research. The aim of this workshop is to assemble observational evidence on the precursory electric and magnetic phenomena in different frequency ranges (DC, ULF, ELF/VLF, LF and HF) and to present new experimental measurements by means of new techniques. Another aim is to promote interaction between EM workers and those who are working in different areas including (1) seismic patterns, seismic wave propagation, and crustal deformation, (2) geochemical changes, and (3) ionospheric and magnetospheric effects for future extensive collaboration. The EM phenomena associated with volcano eruptions are also welcome. The topics to be covered are:

- Precursory electric and magnetic (and electromagnetic) phenomena associated with earthquakes in a wide frequency range covering from DC, ULF, ELF/VLF to HF: their findings and possible use in earthquake prediction.

- New technologies in detecting electromagnetic phenomena, including multi-station network, direction finding etc.

- Seismogenic effects in ionospheric and magnetospheric plasma and radio wave propagation.

- Laboratory experiments on electric and magnetic phenomena associated with rock fracturing.

- Active experiments such as artificial explosions and associated phenomena.

- Physical mechanisms of EM radiations.

- Recent results on the precursory geophysical phenomena including: (i) crustal parameters (seismicity, stress, strain, etc), (ii) geochemical parameters (airglow, radon, water level, radio-activity etc).

4. Honorary organizers

Prof T Yoshino
Director, Sugadaira Space Radio Observatory
The University of Electro-Communications
Chofu Tokyo 182, Japan

Prof M B Gokhberg
Institute of Physics of the Earth
B. Gruzinskaya 10
Moscow, Russia

Prof S Uyeda
School of Marine Science & Technology
Tokai University
Orito Shimuzu 424, Japan
and
Department of Geophysics
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Dr Y Fujinawa
National Research Institute of Earth Science
& Disaster Prevention
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Ibaraki, Japan
Fax No: (+81)298-51-5658

Membership of the Organizing Committee will be announced shortly.

5. Proceedings:

It is planned that proceedings containing all the papers presented in the Workshop will be published in due course.

6. Financial Support:

Financial support for travel and staying expenses for foreign participants will be sought, but the travel funds are limited. Your request on the support should be described in the advance registration form (see next page).

ADVANCE REGISTRATION FORM

International Workshop on Electromagnetic Phenomena Related to Earthquake Prediction

Chofu, Tokyo, Japan 6-8 September 1993

Name in Full ___________________________________

Institute/Organization ______________________________

Mailing address _________________________________

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Telephone ________ Telex ________ Fax ________

Please tick in box:

☐ I hope to attend the Workshop and will submit a paper.

Please indicate the tentative title(s) and author(s) of paper(s).

Accompanying person(s) ____________________________

☐ I am interested in the results of the Workshop but unable to attend.

Do you intend to attend the URSI Kyoto General Assembly (23 Aug - 3 Sep 1993)

☐ Yes or ☐ No

Any requests or comments (especially, please give us information on the financial situation of your visit to Japan):

____

____

____

Please return this form as soon as possible (not later than the end of July 1992) to:

Prof M Hayakawa
The University of Electro-Communications
1-5-1 Chofugaoka, Chofu Tokyo 182, Japan

LINDMAN—THE LAST HERTZIAN

continued from page 48

times. Lindman's paper of 1922 is a nice example of this.

Lindman begins his introduction by summarising his 1920 paper and shortly discussing absorption, a topic that was not touched upon too much in the earlier paper. Then he writes

Durch eine briefliche Mitteilung hat Dr Felix Stumpf in Berlin mich darauf aufmerksam gemacht dab die Ergebnisse meiner Versuche sogar bedeutend besser als ich durch Vergleich mit der Drudeschen Formel zuerst fand, dem entsprechen, was man in dem vorliegenden Falle theoretisch erwarten kann.

In other words, a Berliner, Felix Stumpf, had carefully read Lindman's article and noted the discrepancy between Drude's model for the wavelength dependence of the rotation and Lindman's measurements. The disagreement appeared only close to the resonant frequency as observed above. Drude's model predicts infinite rotation at $\lambda = \lambda_0$, whereas Lindman's measurements showed no rotation at all! In his private letter to Lindman, Stumpf suggested that a slightly improved model due to Natanson would lead to extremely good agreement at all frequencies. Natanson had simply included a damping term in the model and derived a somewhat more complicated formula for the polarisation rotation. In a more modern fashion, Natanson's formula can be seen to arise from including an imaginary term in the Drude model via a damping parameter λ_d:

$$\phi = \frac{k}{\lambda^2 - \lambda_0^2 + j\lambda\lambda_d} \qquad (7)$$

from which, by taking the real part,

$$\phi \sim \frac{\lambda^2 - \lambda_0^2}{(\lambda^2 - \lambda_0^2)^2 + \lambda^2\lambda_d^2} \qquad (8)$$

and, indeed, this expression vanishes at the resonant frequency $\lambda = \lambda_0$, which agrees with Lindman's measurements.

The 1922 publication reports testing the Natanson hypothesis. Extensive and careful measurements for this were carried out and repeated. The concluding sentence is affirmative:

Diese Versuche haben also die Natansonsche Formel innerhalb der Genauigkeitsgrenzen der Messungen bestätigt

LATER PUBLICATIONS ABOUT CHIRALITY

Lindman continued studies on the rotation of the plane of a linearly polarised radio wave as it propagates through dissymmetric media. In the mid-1920s he published two articles in the Åbo Akademi report series in Swedish. In these publications Lindman reported his experiments of a different type of synthetic chiral material. He was aware of the objection that the model of randomly oriented helices is perhaps not the most realistic conceivable for a molecular solid. Molecules in solids are arranged in crystalline structures. The large-scale model therefore also should mimic a lattice. Carbon compounds, in particular, were known to display optical activity. In order to model a carbon atom, Lindman simulated its stereochemical structure by a distorted tetrahedron. Discussion about the connection between lattice structure and optical activity was intense during those times—Oseen, Stark, and Born were known to raise questions on the subject.

In the first paper Lindman reports on his new chiral objects out of four identical copper spheres, each with radius of 3.5 cm. He arranged these in the four corners of a distorted tetrahedron. The distances between the spheres were the slightly different length edges of the tetrahedron, 10.5, 10.5, 15, 15, 12.5, and 16 cm. The spheres were connected with each other by wooden rods. With one such "molecule" he was able to rotate the polarisation plane of a 17.6 cm-wavelength wave by 2.5°.

In the latter publication Lindman studied the effect of a composite, where several asymmetric tetrahedra were placed in a cylindrical wooden case to constitute an isotropic chiral object. He was able to produce good agreement between his measurements and Biot's first law[5]. The last chapter of the paper is interesting because he there comes to a negative conclusion about the polarisation rotation by an asymmetric object. He built a model molecule where again four spheres were located at the corners of a regular tetrahedron (edge dimension 11 cm). This time the spheres were of different metals and sizes. One was out of copper with a radius of 3.5 cm. The remaining three were out of brass with radii 2.8, 2.5, and 2.2 cm. This clearly chiral object lead to no measurable rotation of the plane of polarisation of a 17.6 cm-wavelength wave!

AHEAD OF HIS TIME

Lindman was the clear winner in the race to synthetic microwave chiral materials. Forty three years elapsed from Lindman's initial research on chirality till a similar (admittedly more extensive) measurement[9] was carried out in California. From that event, another thirty years were to pass before the technology of manufacturing of chiral composite materials reached a sufficient level of sophistication to prepare samples with predesigned chiroelectromagnetic parameters in the microwave and millimetre wave ranges.

A Conference in Honour of Karl F Lindman

Each year, a National Convention on Radio Science takes place in Finland at some university under the auspices of the URSI National Committee of Finland and the IEEE Finland Section. For the year 1991, Åbo Akademi, the university where Karl F Lindman was Professor of Physics for 27 years, was picked as the venue of the meeting. Åbo Akademi is the university of the 6% Swedish-speaking minority in Finland and it has its campus in the oldest city of Finland whose Swedish name is Åbo and Finnish name Turku. This Convention was largely in honour of Professor Karl F Lindman. In a ceremonial Opening Session, a lecture Hall was dedicated to Lindman by the Rector of Åbo Akademi, Professor Bengt Stenlund. The Conference Chairman and present occupant of Lindman's Chair, Professor Juhani Kurkijärvi, gave a review of the life and achievements of Karl F Lindman.

A special session on chiral and bi-isotropic media was subsequently held in the Karl F Lindman auditorium co-chaired by Professors Ismo Lindell of the Helsinki University of Technology and Gerhard Kristensson of the Lund Institute of Technology, Sweden. Speakers and the audience, which included the present Chairman of the international URSI organisation Professor Edward V Jull, could feel the presence of Professor Lindman in the auditorium. Actually he was closely observing all the proceedings through his portrait on the wall with a benevolent smile on his face. "I knew chirality would grow up to something big".

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Wanted!

Interesting and striking photographs for *the Radioscientist* front cover. The subject should be identifiable as radio physics or engineering within the URSI range of Commissions A to K. Until we can afford colour, prints should be glossy black and white and sized to fit on the cover without enlargement/reduction by us. The "portrait" format used so far on our cover is preferred but a striking photograph or graphic (e.g., analogue data) which needs "landscape" mode (short and wide) is also welcome.

Please send submissions together with a descriptive caption to :

The Editor
The Radioscientist
c/- Physics Department
University of Otago
P.O.Box 56
Dunedin
New Zealand

WHISTLER ANALYSIS BY MAC

The following method was devised for whistler recording and analysis on my Macintosh Power Book 170 using commercial application software. This will work on any Mac from a SE30 upwards if portability is not important.

Introduction

Whistlers are highly dispersed lightning impulses. Part of the lightning impulse within the VLF band can penetrate the ionosphere to travel up into the magnetosphere. Only the right-hand circular polarisation component can propagate in this medium. This is in the same sense of rotation as the gyrating electrons, making up the magnetospheric medium. Thus the wave is strongly coupled to the electrons. In fact, the electron current produced by the wave's electric field is so much greater than the displacement current that the latter can be safely neglected. This has two consequences: (1) the wave's phase velocity is much less than that in free space, c, and is strongly dependent on wave frequency; and (2) the wave is constrained to travel in the general direction of the geomagnetic field.

The net result (there is no space to go into details) is a "whistling atmospheric" or whistler which lasts a few hundred milliseconds and typically ranges in frequency from several kilohertz down to a few (one or two or so). A curious feature is that the whistler "shape" in the frequency-time plane is invariant to the limit of measurement if one scales the frequency and time linearly to fit. Scaling and translating is easily done on a computer drawing program.

This shape is shown in Figure 1. The frequency of earliest arrival of the whistler is called the nose frequency from its shape in the frequency-time plane. Measurement of this nose frequency, f_n, enables determination of the field line path of the whistler. Measurement of the hemisphere-to-hemisphere delay time at f_n enables estimate of the electron density near the top of the path. A single lightning strike can sometimes produce multi-path nose whistlers, each giving a point on the N–v–L profile of the magnetosphere (N is the electron density, L is approximately the radial distance to the top of the field line path in terms of the Earth's radius). Thus whistlers "sound" the magnetosphere and remain the prime source of information about the plasma density profile. In particular, it was through whistlers that the plasma pause or "knee", the sharp boundary between the plasmasphere and the outer magnetosphere, was discovered[4].

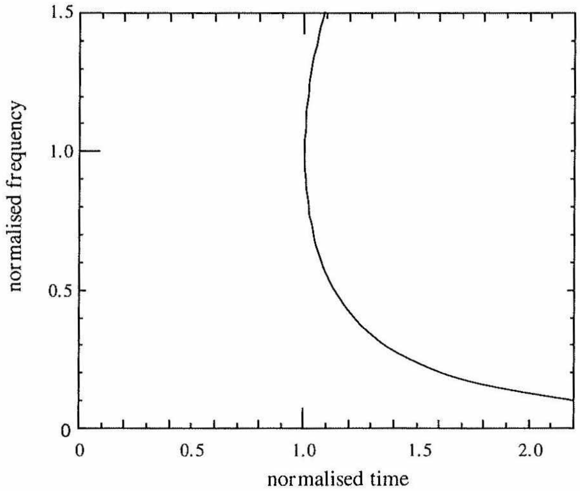

Fig. 1. Normalised whistler, f/f_n –v– t/t_n, plotted from formula given in text.

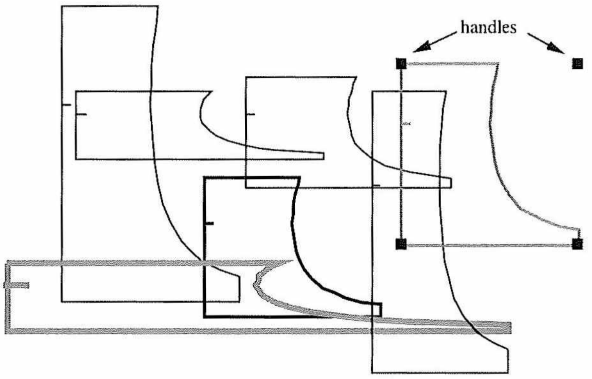

Fig. 2. "Objects" drawn from the curved part of Figure 1. The left hand vertical border corresponds to t = 0. The bottom and top borders correspond to $f = 0$ and $f = 1.5 f_n$, respectively. The tick indicates $f = f_n$. "Dragging" any line moves the object as a whole. Dragging any "handle" moves only that corner and so changes the frequency and/or time scale. Different line thicknesses and greying are shown also.

Finding the nose

Unfortunately, relatively few whistlers extend in frequency above the nose frequency to make the nose frequency measurable. Often the highest frequency observed is less than half the nose frequency. We resolve this by using the normalised whistler is shown in Figure 1. This was calculated from:

$$\frac{t}{t_n} = \frac{2}{\left(3 - \frac{f}{f_n}\right)\sqrt{\frac{f}{f_n}}}$$

and plotted in the conventional form (time axis horizontal). This formula can simply be regarded as an emperical one which works (for more details see the reference at the end). The vertical axis, $t = 0$, corresponds to the "initiating sferic", the instant of the lightning flash. The important feature is that this shape should fit *any* whistler, merely by changing the time and frequency scales.

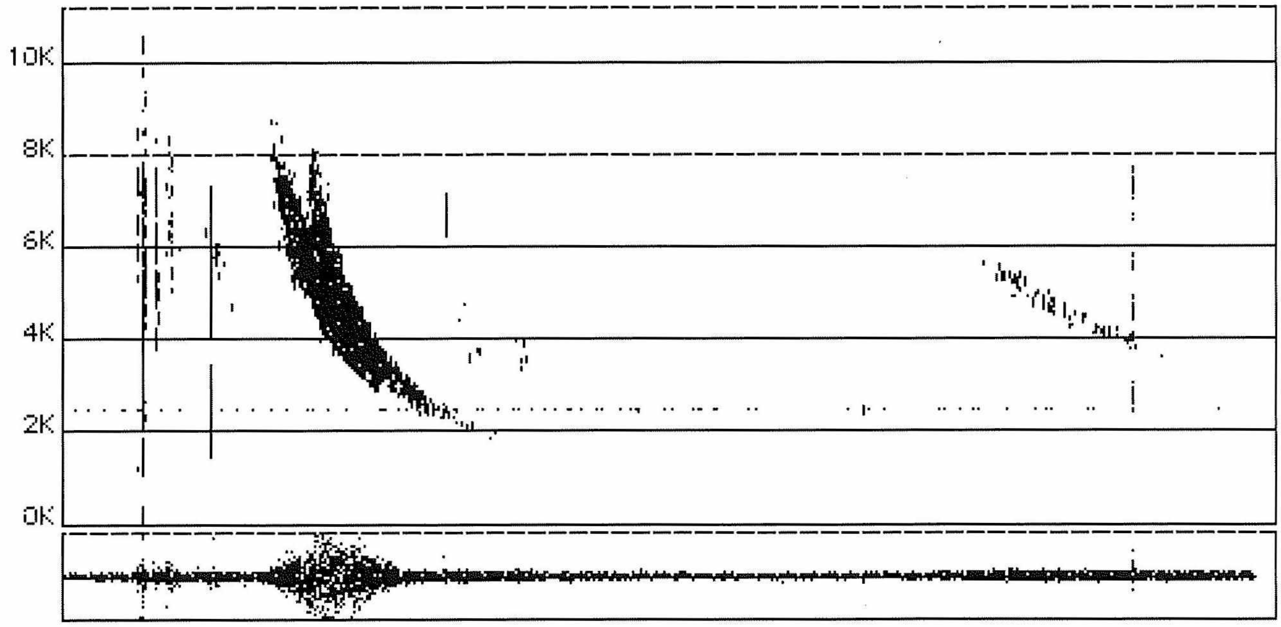

Fig. 3. MacRecorder sonogram made on a Macintosh SE30 and pasted into MacDraw II. The bottom strip is the whistler waveform. The initiating sferic is off the scale to the left. The trace on the right is a 3–hop echo.

Nose whistler "object"

Figure 2 shows a set of "objects" drawn in MacDraw II. The curved part in each one has the shape of the plotted one in Figure 1 and was traced from it. The horizontal lines correspond to $f = 0, f_n$ (short line) and $1.5f_n$, while the vertical lines correspond to $t = 0$ and $2t_n$. All these lines are "grouped" to form a single object within an invisible rectangle defined by the four "handles" (small black squares) made visible when the object is "selected" (Macintosh buffs will be familiar with these terms in quotes). Only one of the set shows these handles in Figure 2. The top right handle can be "dragged" by the mouse to change the time and frequency scales without moving the time and frequency axes. A wide range of frequency–time aspect ratios are shown in Figure 2. Also shown are some in different line widths or in grey (alternate pixels black and white) which shows equally well on a black or white background. On a colour screen, the lines can be in any colour. Although not shown, it is convenient to have objects extending only to f_n or even only to $0.5f_n$. This is because many whistlers do not extend even to $0.5f_n$ and it is easier to use the top right handle where it can be reached on one's screen while watching the match with whistler as described below. It is easy to make a whistler object having the same frequency scale but exactly twice or three times the time scale of another. The two objects can then be aligned and "grouped" to make a single object. Dragging the top right handle then scales both together. This is useful when one is receiving a long sequence (maybe some hours long) of odd or even hop whistlers as illustrated below.

Figure 3 shows a "sonogram" of a whistler made using MacRecorder and pasted into MacDraw II. MacRecorder is a Macintosh application which comes with an 8-bit A/D converter a little larger than a Macintosh mouse. The MacRecorder is a "sound processor" – a counterpart to a word processor. Audio output from a tape recorder (or built-in microphone) is digitised at 22 kHz and recorded on the Macintosh hard disk (using 1 Mbyte per 45 seconds recorded). A large range of "effects" can be applied but here we are interested in the sonogram "effect" or function. Like a word processor, sound records can be selected, cut, copied and pasted.

This sonogram was made on a Mac SE30 using a single-bit black and white screen. On this the whistlers come out black against a white background, which is perhaps best for publication here (on colour screens the whistler intensity appears in false colour coded steps of 6dB to cover a 24 dB range. Grey scale covering this range is also an option). Note the two whistlers merging into one. This is not a chance happening since a pair of whistlers like this occurred several times (maybe 100) over a period of about four hours, the duration of the tape running continuously. Clearly these were due to the same pair of ducts. Note that this whistler is followed by a fainter one of three times the dispersion. This is due to the lightning wave packet travelling three hops, from a lightning strike in the northern hemisphere, to the south, and then back to the north and finally back again to the south. It can be shown that this requires amplification in the magnetosphere of some 10dB to 20dB per hop. During this period of about four hours, all (or most, since they were not all checked) one–hop whistlers were followed by 3-hop echoes like this.

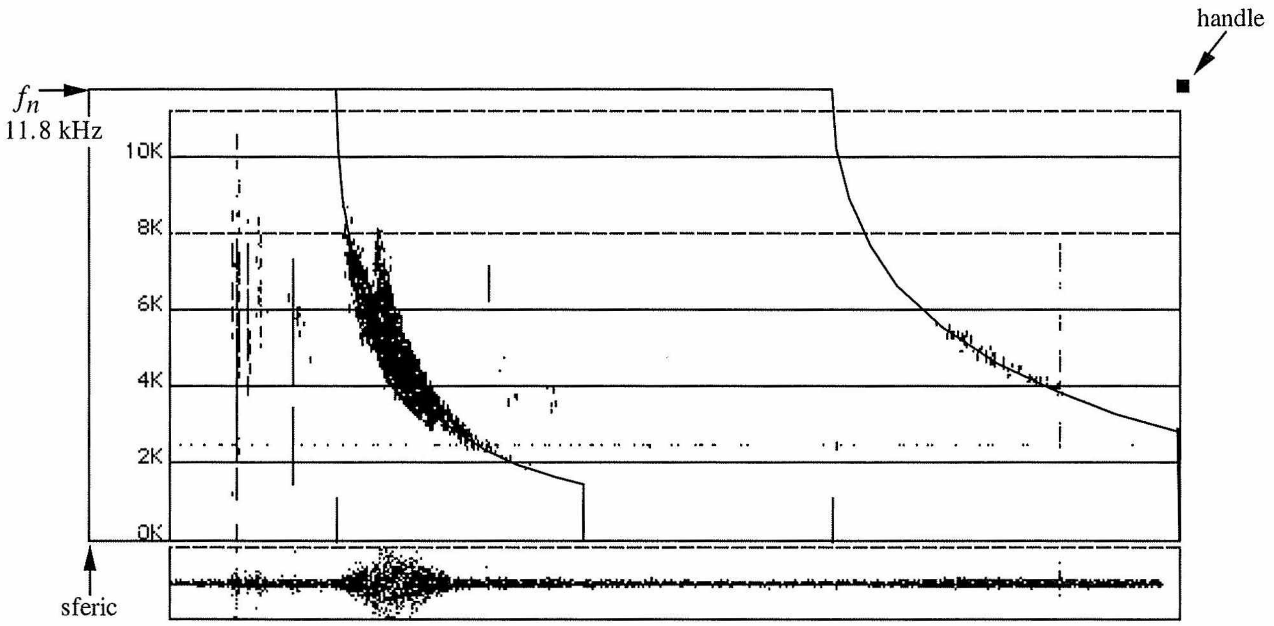

Fig. 4. A double object with a dispersion ratio of 3:1 is superimposed on the sonogram and scaled to fit both the 1–hop and the 3–hop whistlers. The nose frequency is obtained by extrapolating the frequency scale. The sferic is located (vertical arrow which is off scale on the left) from the 2–hop time between the two whistlers..

Figure 4 shows the same sonogram in Figure 3 but included is the standard nose whistler "object" with the $f = 0$ axis set to the sonogram $f = 0$. As discussed above this case calls for a 1:3 double object, particularly since initiating sferics are difficult to see and identify since they must travel to the receiver in the earth-ionosphere waveguide from the opposite hemisphere. In this case, the whistler was captured by MacRecorder too late to see the initiating sferic anyhow. However, at any frequency, the time between the 1–hop and 3–hop whistlers is clearly that for 2 hops at that frequency, so the position of the initiating sferic, or time zero ($t = 0$ axis), can be easily deduced and is indicated here by the arrow (bottom left). Consequently the double object was dragged to this $t = 0$ axis and with the top right handle of the object moved so that the 1–hop standard whistler lies along the left hand or shorter time whistler produced by the inner (nearest the Earth) of the two ducts and the 3–hop standard whistler lies along the 3–hop whistler. This checks deduced position of the $t = 0$ axis and provides f_n and t_n, or would, if there were adequate scales provided by MacRecorder. The frequency scales are not a problem since they are linear and MacDraw II and similar drawing applications provide adequate screen measurement (which does not appear on printout so it is not seen in Figure 4). Using this and the nose frequency read off the top line (f_n), the nose frequency of the inner whistler (left one of the pair) is 11.8 kHz.

Using the same method for the whistler on the right, the nose frequency is found to be 8.7 kHz.

The nose frequencies identify the two ducts as being on the L-shells $L = 3.03$ and $L = 3.36$ respectively. Since the L-value is inversely proportional to the cube root of the nose frequency, it can be determined quite accurately. For many users, the L-shell location may be all that is wanted. To find absolute electron densities (instead of just the density ratio between the two ducts) we would need time marks (e.g. 30 ms pips of 10 kHz every second) to calibrate the sonogram since "sonogram" does not have a time scale. These are best inserted during tape recording but can be added to MacRecorder and mixed into the VLF record later.

As this is not a software review I can only say that *MacRecorder* is a worthwhile investment at about US$250. All but one function, the sonogram, work on any Macintosh but for the process described the sonogram is essential. This requires a Macintosh with "Colour QuickDraw" on its ROM. However, a Mac with this need not have a colour screen or even a grey-scale screen, as we have shown here. It works fine on a *Power Book 170* which allows whistler analysis even while one is flying as a passenger on a commercial flight! *MacDraw II* is quite adequate for making the standard whistler objects and displaying both these and the MacRecorder sonograms. Probably any other Macintosh drawing application would do as well, though I have not tested them all to check this.

REFERENCE

Dowden, R.L., and G.McK.Allcock, [1971]. Determination of nose frequency of non-nose whistlers, *J. Atmos. Terr. Phys*, **33**, 1125-1129.

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