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Fifty Years of Radio Scattering

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Radio scattering from atmospheric irregularities has served for about half a century as a mechanism for both remote sensing of certain properties of the atmosphere and for reliable radio communication beyond the horizon to distances of 2000 kilometers.

In its earliest form, radio scattering was used to observe layers and their changes in the lower atmosphere. In mid-career, i.e., 25 years ago, it was introduced as a sensor of the properties of the upper ionized atmosphere, and most recently it is widely used to observe winds especially in the troposphere and stratosphere.

As a communication mechanism, radio scattering by tropospheric irregularities, discovered quite by accident, was explained and exploited to provide links over distances of a few hundred kilometers. With time the terminals became more powerful and sensitive, the links became longer and the height of the scattering irregularities increased climaxing with ionospheric forward scatter. Continuing the upward search for scatters led quite naturally to incoherent scatter. Powerful radars spawned MST's (mesosphere, stratosphere, troposphere) wind measuring capabilities.

It is an honor to join in paying homage to an early giant of atmospheric science.

It is an honor and a privilege to join in the Golden Jubilee Celebration honoring Professor S. K. Mitra, and I am grateful to Professor A. P. Mitra for inviting me to participate.

To put the celebration in perspective, we note that radio waves have been propagating for billions of years through the universe — since the beginning of time, give or take a few nanoseconds! Radio waves propagating purposefully are less than 100 years old by a few years, if Hertz in 1888 was first, i.e., another Hertz on another planet in another solar system didn't precede him.

Radio wave propagation and the communication revolution it spawned, however, are products of the twentieth century. Guglielmo Marconi, inspired by Hertz, set the pace with his bold experiment perhaps in part based on Tesla's conjecture of a high reflecting layer in the atmosphere. In December 1901 Marconi transmitted a series of code S's from Poldhu in Wales to St. Johns in Newfoundland, 3000 km around the curve of the earth using radio waves that were supposed to travel in straight lines and initiated wireless telegraphy across the ocean. Heaviside and Kennelly[1] "indisputably" explained the channel within a year, establishing the present pattern in which theoreticians in no time at all explain observations that experimentalists sweat over for years.

Heinrich Hertz generated, propagated, and received radio waves, and recognizing the problem inherent in his broad-band spark-source thought that the communication of information would not be feasible.

Microwaves whose beginnings we normally associate with the remarkable mobilization of scientific and engineering talent during World War II were in fact produced, radiated and received before the end of the 1800's — 4 GHz in 1894 by Sir Oliver Lodge in a demonstration at a meeting of the American Association for the Advancement of Science, and 60 GHz in 1897 by J. Chunder Bose[2] in Calcutta. The ideas were not followed since practical interests were in long waves. In the course of this celebration I should like to learn more about the other radio pioneers in India and in particular about S. K. Mitra.

The radio scientists of India joined the International Union of Radio Science (URSI) in 1950. The formal resolution was passed at the URSI General Assembly in Zurich. The reports of the radio scientists of India to the URSI provide a source of information on the early work on the ionosphere.

The Report of the National Committee of India to the Zurich General Assembly includes a note on the activities for 1948-49 of the Radio Research Committee of the Council of Scientific and Industrial Research of India:

(1) General — The Radio Research Committee of the Council of Scientific and Industrial Research was constituted in 1943 and has been functioning ever since. The work of the Radio Research Committee covers all aspects of research in wireless communication and radar;

(2) Utilisation of Completed Schemes — Several schemes of research conducted under the Radio Research Committee have been completed and definite results achieved. Particular mention in this connection may be made of the researches on salvaging of electrolytical condensers and reconditioning of lead acid batteries. A patent application on "Improvements in or relating to the manufacture of volume controls" arising out of the scheme on manufacture of cheap radio sets by Dr. G. R. Toshniwal has already been filed;

(3) Schemes in Operation — The Schemes at present in operation under the Radio Research Committee are: (i) Manufacture of radio valves in India by Prof. S. K. Mitra, Calcutta; (ii) Ionospheric investigation by Prof. S. K. Mitra, Calcutta; (iii) Theoretical investigations of the upper atmosphere by Prof. M. N. Saha, Calcutta; (iv) A new technique of investigating the ionosphere by Mr. B. M. Banerjee, Calcutta; (v) Polarisation of down coming waves by Dr. S. R. Khastigir, Banaras Hindu University, Banaras.

In 1952 at Sydney the Report of the National Committee to Commission III on the Ionosphere included:

(1) Institutions — In India, researches on the ionosphere were first started in 1930 in the University of Calcutta under Professor S. K. Mitra. The ionosphere station participated in the Polar Year observations of 1932-1933 when regular records of E and F layer virtual heights were kept. The Council of Scientific and Industrial Research sanctions grants for researches to be conducted at the Universities and other research organizations. During the last two years, ionospheric investigations were conducted under its auspices at (a) University of Calcutta under Profesor S. K. Mitra and under Professor M. N. Saha; (b) Banaras University under Dr. S. S. Banerjee and under Dr. S. R. Khastgir; (c) Physical Research Laboratory under Dr. K. R. Ramanathan.

(2) Ionospheric Observatories Working Regularly in India (see Table at the end).

(3) Research Reports — mention rates of electron production in both regions E and F2; the seasonal variation in temperature; coefficient of recombination; the earth's magnetic field at region F2 heights; 27-day recurrence tendency; solar tidal drifts; formation and structure of the D-layer; structure and the properties of sporadic E-region; Es at the geomagnetic equator; the Z trace; the sodium twilight glow; dissociation of N_2 molecules; and Solar Eclipse.

Professor S. K. Mitra along with K. S. Krishnan and A. P. Mitra attended the Assemblies in 1952 (Sydney) and 1954 (The Hague).

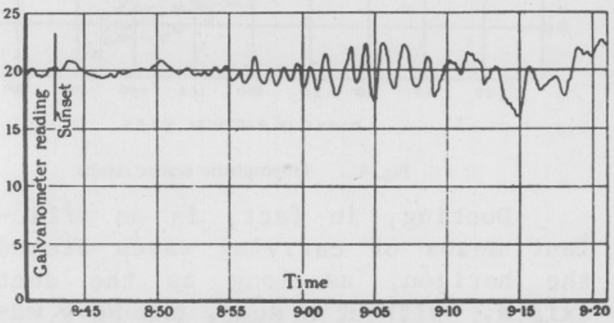

Fig. 1. The results of Appleton and Barnett.

The first direct measurements of the ionosphere were made in 1925 by Appleton and Barnett[3] in London by varying the phase of a CW signal and noting the interference, Fig. 1, between the direct and reflected waves at a nearby receiver; in the same year, Breit and Tuve[4] transmitting and receiving pulses recognized ground and sky waves, Fig. 2, laying the foundation for ionosonde networks and predictions of the maximum usable frequencies for various communication paths and times.

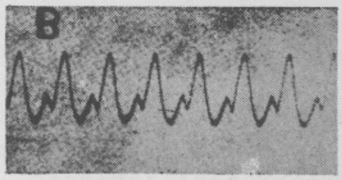

Fig. 2. The results of Breit and Tuve.

S. K. Mitra and Syam[5] in 1935 announced that they had detected regular reflection of radiowaves at vertical incidence from an equivalent height of about 55 km. About a year later on March 8, 1936, Mitra and Bhar[6] made a further announcement that they had recorded echoes of radio waves from still lower heights (Figure 3). Soon after Colwell and Friend[7] from West Virginia, U.S.A., reported the recording of echoes from regions between 55 and 5 km and a little later Watson Watt, Bainbridge-Bell, Wilkins and Bowen[8] announced that they also had occasionally recorded echoes from similar heights.

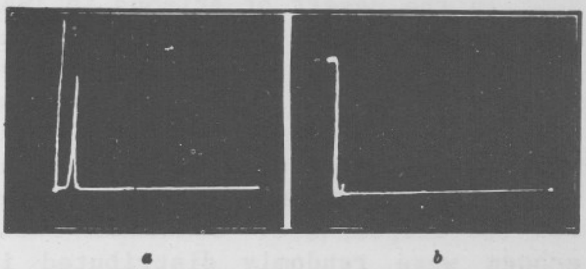

FIG. 3. Echoes from: (a), C_1 region (55 km.); (b), C_2 region (20 km.).

These observations from three independent sources situated in three widely different parts of the world showed that the atmosphere below 90 km is also stratified particularly during daytime into ionized layers like the upper ionosphere. The layers were found to be grouped roughly in three different heights; one at about 55 km another round 30 km and the third in the upper troposphere between 5 and 15 km. It is now generally agreed that the 55 km layer, which might be said to have been rediscovered by Mitra and Syam, should retain the original designation — the D layer — as suggested by Appleton and that the 30 km. and the lower layers should be called C regions — C_2 and C_1 for instance.

Reflections of radio waves from these low heights raise points of great theoretical interest. Firstly, what is the mechanism of the reflections? The usual Eccles Larmor theory of bending of radio waves by an ionized atmosphere is, on account of the high collisional frequency between the electrons and ions and the gas particles, certainly inoperative. Secondly, in any mode of reflection in which a large density of ions or electrons is necessary the question arises — what is the origin of the ionization at such low heights of comparatively high atmospheric density? These three paragraphs quoted from Mitra, Bhar and Ghosh[9] provide the earliest report of radio scattering from a turbulent atmosphere, and I shall use this as my point of departure.

In the desert of Arizona in 1945 Arthur Crawford of the Bell Telephone Laboratories had a very sensitive microwave radar which he pointed vertically in the atmosphere. The radar was sufficiently sensitive that it could detect weak echoes throughout the troposphere. Sometimes these echoes were randomly distributed in height and time, and at other times they would be concentrated in the vicinity of particular heights. That is, they occurred more or less in layers.

At an early stage, I[10] wrote a paper saying that those echoes were produced by differences in refractive index between bubbles of air and their surroundings. Those differences would produce a small reflection or more precisely a small scattering. The differences arise in two ways: (1) convection from a heated ground and (2) shear at a boundary of two air masses.

Katzin[11] reported some experiments in the Atlantic conducted by the U. S. Navy. In 1945, they discovered that radio waves traveled far beyond the radio horizon (Figure 4), and good communications could be established between ships that were well beyond the line of sight. The extended communication range could not be accounted for by radio ducting, a common overwater phenomenon.

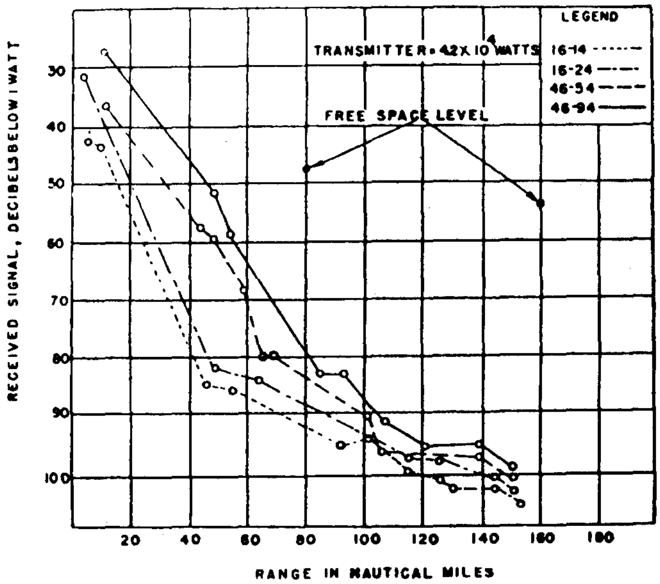

Fig. 4. Tropospheric scatter results.

Ducting, in fact, is an efficient means of carrying waves around the horizon, as long as the duct exists. Without a duct, the Navy was observing much weaker but still useful signals. Those observations stimulated Booker and me[12] to look for an explanation. The explanation we proposed was based on radio scattering in the troposhere by irregularities tied to the turbulence normally embedded in the atmosphere. Like Crawford's observation, here was another example of radio scattering in the troposhere, and it nicely explained the distant observations over the water. This became known in the literature as troposheric scatter. The Caribbean Islands today, for example, are linked by tropospheric scatter as are the NATO countries in Western Europe.

Troposcatter takes a powerful transmitter and large antenna on each end because the scattered signals are weak. But, it does provide reliable communcation channels. Particularly where line-of-sight microwave links are not practical (longer overwater paths) or where fewer terminals are wanted. Having had some success with radio scattering in the troposphere, Booker and I both were looking for other ways to extend the idea. I concentrated on the stratosphere and produced a paper[13] on stratospheric forward-scatter for communications purposes and showed that distance of the order of 600 miles were achievable (the distances are larger because the scatters are in fact higher). Henry Booker, on the other hand, thought of forward scatter from a rather higher height in the vicinity of 90 or 100 kilometers, and this was a very successful endeavor.[14] He predicted forward scatter from ionospheric turbulence. Scattering in this layer has characteristics that are quite different because the refractive index is dominated by a component that depends on the electron density difference rather than the temperature and moisture. Although I wasn't directly connected with Booker's success, it represented a progression in the altitude of the scattering. I was intrigued by the prospect of scattering in the atmosphere at heights that would be in the upper part of the ionosphere. It was in the spring of '58 when it all came to a climax. One evening I calculated what turned out to be the radius of the electron or the scattering cross-section of an electron. It's an extremely little bit scattered by a single electron but if the ionosphere has large numbers of electrons present that product begins to make the scattering cross-section of some volume of the ionosphere not so minute, and so it was worth looking at the possibility of doing a communications scheme involving the F region.

The scattering is based on the fact that the electrons are there, and the electrons scatter an incident radio wave. Since each electron would scatter independently, the scattering from many electrons is incoherent so that the total scattering might amount to something. That something, was it large enough that it could be detected, that it could be used as a communication means? When you do the calculation, and ask how much power do you have to put into a transmitter, and how big an antenna do you have to build, then you are quickly discouraged. You discover that in terms of a communication link, it clearly isn't economical.

To illustrate it, jump ahead for a moment. You know how big the Arecibo antenna is (1000 ft. diameter) and how it has a powerful transmitter associated with it. If you wanted to communicate between two points on the ground, they now could be a few thousand kilometers apart, and you would have a rather dependable communication scheme - except that it would take an Arecibo antenna on each end, and that's clearly not very practical.

Now let's go back to the point. Communication is not feasible using state-of-the-art hardware, but could you study the medium? That is, could you measure the number of electrons that were present at each height in the ionosphere and, therefore, get some detail that was previously not available through the ionosphere? It's not hard to write an expression for the backscatter from the electrons if you know the scattering cross-section. If you know something about the available hardware: the receivers, and the transmitters, then the only unknown is the antenna. In round numbers at least, you need an antenna which is 1000 feet[15] in diameter, and a thousand feet in diameter is a rather large antenna, by anyone's standards.

Having gotten this far with the idea, I began to have discussions with Henry Booker, who was happy to discuss the details of the calculations, and he pointed out that when he was a graduate student back at Cambridge he had made the same calculation. That is, he had calculated the scattering cross section of a single electron, and in fact it had been done a long time ago, of course, by people like Thomson.

The thing that was different in 1958 was that it was possible to use this cross-section with available hardware and with a thousand foot dish, if it could be built. The excitement in this experience at Cornell must echo that at Calcutta when S. K. Mitra and his collegues were developing the equipment for their pioneering observations.

One of the students at Cornell, not long before that, had been a student of Henry Booker's named Ken Bowles. We talked to Ken about incoherent scatter, and he was a very fine engineer. He immediately grasped what was going on and knew that the Bureau of Standards happened to have a rather large field or antennas in Illinois and a powerful transmitter.

In October I gave a paper on incoherent scatter. I started the paper by saying to the audience something like the following, "My purpose is to tell you about incoherent back scatter from the ionosphere, and the possibility of building a tool to make use of it in studying the ionosphere. And then I want to tell you about a telephone call that I just had." And so I went through the paper that had been prepared and then added the conversation that I'd just had on the phone with Ken Bowles, who had received the first incocherent back scatter echoes from the ionosphere. A dramatic touch that was added to that meeting.

After that day in October when he made his first observations, he, of course, repeated the observations many times, and two important things came out of the observations[16] — incoherent scatter was real, electrons did back scatter. In my view, the electrons were going to behave completely independently, and, therefore, the broadening of the transmitted frequency by the scattering could be associated simply with the thermal motions of the electrons and would have a band width which might be on the order of a megahertz or so.

What Ken observed, however, was that the bandwidths were more like a kilohertz rather than a megahertz. This, he correctly deduced, was associated with the fact that in addition to the electrons being present, there were ions present, of course, and that the Coulomb attraction between the electrons and the ions was sufficient that the spectrum that came back was controlled by the motion of the ions, rather than by the motion of the electrons. That was important for many reasons. Obviously, if the ions have an influence on what's happening, then one can learn something about the ions, or the ion motion and ion temperature, as well as the electron temperature, as long as that isn't completely suppressed by the ion control.

The theory of incoherent scattering had to be put on sound grounds. Salpeter[17] proceeded to do that and at more or less the same time people like Farley and Daugherty[18] produced a theory of back scattering in some detail, and there were others who did the theory from a variety of approaches. All of the approaches, fortunately, resulted in common results. The results were that the back scatter spectra would contain not only things like the electron density but also ion temperature, electron temperature and perhaps something about the ion composition.

Incoherent scatter observations are revealing the secrets of the ionosphere at Arecibo in Puerto Rico, Jicamarca in Peru, Millstone Hill in the U.S., Sondrestrom in Greenland, Tromso in Norway, St. Santin in France, Shigeraki in Japan and soon in India as a capability of a proposed MST radar (mesosphere, stratosphere, troposphere).

Atmospheric irregularities are providing wind velocity profiles for research (MST) and in networks (ST) for meteorological purposes.

HF, which many thought would become obsolete with the increased usage of short waves and satellites, is still of great interest in communication, in beyond-the-horizon radar, and in ionospheric studies (plasma heating).

Healthy activity is bearing fruit in all parts of the spectrum. The marrige of computers and communication into information systems puts pressure on spectrum use challenging the engineers for better, faster and cheaper information exchanges. Remote sensing in its wide array of applications opens avenues for information gathering about resources on and in the earth, on conditions of atmospheres and oceans and diagnosing and treating human ailments.

The propagation of radio waves in media of all types provides fascinating problems for radio engineers and scientists, theoreticians and experimenters. I know of no way to look 100 years ahead but it is clear that the next decade or two will be exciting. The technical meetings should be alive with stories of new discoveries by theorists with the vision of a Maxwell and experimenters' with the courage of a Marconi and the foresight of a Mitra.

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Station	Nature of Apparatus	Ionospheric Parameters Recorded (U.R.S.I. Nomenclature)	Sponsoring Agency
Delhi 28°35' N 77°5' E	Manual (Panoramic recorder will be utilized)	foF2, hpF2, M(3000)F2 and MUF's	All India Radio
Calcutta 22°33' N 88°22' E	Semi-automatic (Automatic recorder will soon be under operation)	foE, fEs, foF2, h'Es hpF2, h'F2, M(3000)F2 and MUF's	Radio Research Committee (C.S.I.R.)
Bombay 19° N 73° E	Manual	foF2, hpF2, M(3000)F2 (only for 0600-1800 hrs)	All India Radio
Madras 13° N 80° 15' E	Manual	foF2, hpF2, M(3000)F2 (only for 0600-1800 hrs)	All India Radio
Tiruchirapalli 10°50' N 78°50' E	Manual	foF2, hpF2, M(3000)F2 (only for 0600-1800 hrs)	All India Radio