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Incoherent Scatter: Principles and Applications

Classical electrodynamics teaches that a free charged particle is accelerated in an electromagnetic wave field and excited to radiation, the emission (in the non?relativistic case) being of the same frequency but in other spatial directions with respect to the incident wave. This process can also be interpreted as scattering of the incident wave (Thomson scattering), with a backscattered cross-section allocated to the charged particle as scatter body. The "Thomson scattering cross-section" for electrons is of the order of magnitude of 10^{-24} cm^2.

In 1958, Gordon proposed that scatter experiments, using radar, be attempted on the electrons present in the ionosphere (2), the technical feasibility being demonstrated by Bowles in the same year (1).

In this article, the basic physical principles of incoherent scatter are clarified, using the example of the European EISCAT installation. In contrast to ionospheric echo sounding, the VHF and UHF incoherent scatter radar units make measurements possible in all height ranges of the ionosphere and supply numerous parameters for descriptions of the temporal and spatial changes in the ionosphere.

1.

THE EISCAT INSTALLATIONS IN NORTHERN SCANDINAVIA

There are seven incoherent scatter installations in the world altogether. Two particularly powerful radar systems are operated north of the Arctic Circle by the European Incoherent Scatter Association (EISCAT). The organisation represents a joint scientific effort by several countries: Finland, Norway, Sweden, Great Britain, France and Germany.

The EISCAT system consists of a transmitter/ receiver installation in Tromso, in Norway,

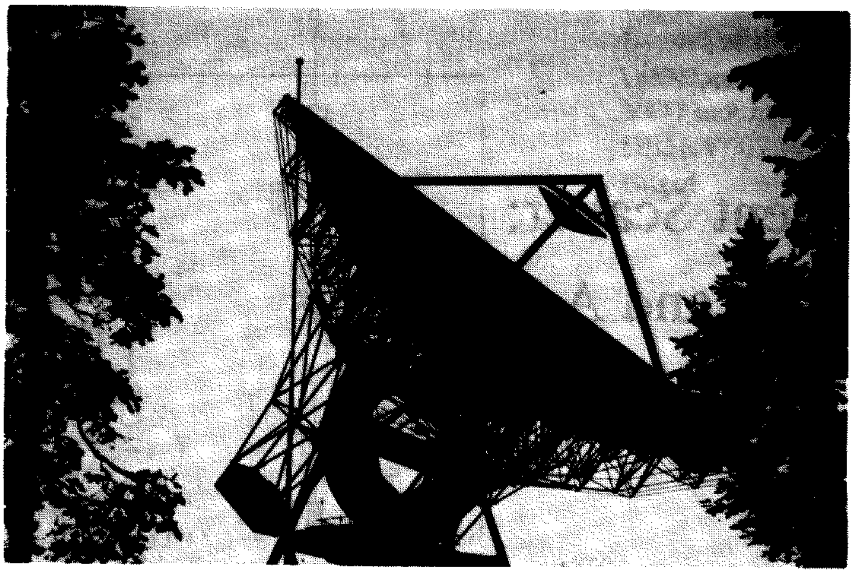


Fig.1: The 32M Parabolic Mirror with Cassegrain Exciter at the EISCAT receiver Station in Sondankylä, Finland. Systems of similar construction are located in Tromsö, Norway and in Kiruna, Sweden. An aerial gain of 48 dB is achieved at the operating frequencies around 931 MHz. The width of the main lobe is 0.6°. (Photograph DF5AI).

and two receiver stations, one in Kiruna (Sweden) and one in Sodankylae (Finland). The transmitter's peak power is 1.7 megawatts at 931 MHz. Each of the three sites has a 32M. dish aerial (Fig.1). The installation in Kiruna is not unknown to radio amateurs, for the dish aerial there has already been used for EME purposes (6).

The 224 MHz VHF installation is also in Tromso. At the moment, the transmitter is being used with a peak power of 1.5 megawatts, and the final transmission power will be 4 megawatts. A dish cylinder aerial measuring 120M x 40M is available as transmitter and receiver aerial. The table below shows the most important system parameters for both installations.

The interest in the observation stations in the far North stems from the peculiarities of the polar ionosphere. The lines of the earth's magnetic field traverse the ionosphere at much steeper angles in Northern latitudes than, for example, in equatorial latitudes. Thus these field lines penetrate more deeply into the magnetosphere, which leads to numerous phenomena which are rarely or never met with in equatorial latitudes.

It may be worth mentioning that the heating installation of the Max Planck Institute for Aeronomy is also being operated in Tromso. Twelve powerful short-wave transmitters (each with a continuous power of 120 kW) bring about the active modification of the ionospheric plasma.

Some of the effects triggered by this can also be observed by the EISCAT installation. A further incoherent scatter installation is at present being planned for Spitzbergen (Polar Cap Radar).

EISCAT Parameter	UHF Radar	VHF Radar
Locations: (TR)	69° 35' N, 19° 13' E	69° 35' N, 19° 13' R
(KI)	67° 51' N, 20° 26' E	
(SO)	67° 22' N, 26° 38' E	
Average Frequency:	931.5 MHz	224.0 MHz
Bandwidth:	8 MHz	3 MHz
Pulse Power	1.7 MW	1.5 MW
Average Power:	280 kW	140 kW
Pulse Duration:	1 us - 10 ms	1us - 1ms
Minimum Pulse Interval:	1ms	1ms
Aerials:	Parabolic Mirror 32 M Diameter	Parabolic Cylinder 40 M x 120 M
Exciter:	Cassegrain	128 Elements
Gain:	48.1 dB	43.1 dB
Polarisation: (TR)	Circular	Circular, Linear
(KI, SO)	Any	
System Temperature: (TR)	90 - 110 K	250 - 350 K
(KI, SO)	30 - 35 K	

TR = Tromsö, KI = Kiruna, SO = Sodankylä

Table: Operating Parameters of EISCAT Radar from (4, 5)

2.
DESCRIPTION OF SCATTER-ECHOS

In the scatter volume of the radar aerials, the contributions from the partial waves scattered into the individual electrons are superimposed on one another without any outstanding phase relationship existing. The incoherent superimposition gave the scatter method its name.

The scatter echo recorded by the receiver is extremely weak, for even the large numbers of electrons "lit up" in the aerial lobe lead, in all, only to a small total cross-section. We imagine that the ionosphere should in general be considered as transparent at frequencies of a few hundred MHz. The difference from one hundred per cent transparency is something worth assessing, using this measurement method.

The scatter volume lit up by an ionosphere radar (circular aerial aperture at 1 degree x 1 degree, 50us. transmission pulse) in the F region (height 300 km., electron density 10^{12} m^{-3}) leads to a total scatter cross-section of approximately 0.2 cm^2.

These areas, several hundred kilometres apart, can trigger no measurement signal from a single radar pulse, so that data integration is essential. For the positively charged ions, the scatter cross-section is smaller by the factor $(m_i/m_e)^2$ (m being the individual particle mass), and so the ionic echo components are completely disregarded.

It is possible to imagine a fictitious electron distribution in which the partial waves would always superimpose to zero. In the same way, it is possible to imagine a structured distribution which favours constructive interference.

On the basis of these concepts, it can be pointed out that not only is the microscopic scatter process of importance but the macroscopic organisation of the scattering medium also plays an important part.

In reality, the electron distribution is irregular and fluctuating. This condition can be simulated mathematically by a superimposition of many short-wave and long-wave processes.

A radar installation is not in a position to do more than sense irregularities, the wavelength of which corresponds to half the radar wavelength. For example, a 2M amateur station is dependent on irregularities with a length of approximately 1M. during an Aurora backscatter, whilst correspondingly smaller structures are responsible for 70cm Aurora contacts.

This relationship applies irrespective of the primary scatter process (the Aurora backscatter events used by radio amateurs are, of course, not connected with the scatter method described here).

The irregularities in electron density are, to a decisive extent, controlled by the positive ions, which have a larger mass (and thus are better carriers). In this way, a signature for the ions in the electron density distribution is obtained. Although the incoherent backscatter is carried exclusively by the electrons, we obtain valuable data on the ions in the ionosphere for this reason.

In a similar way, and to a lesser degree, we also obtain information on the neutral particles (at the heights observed, indeed, only about one-thousandth of the atmospheric particles are ionised, the neutral gas component being the numerically dominant fraction even in the ionosphere).

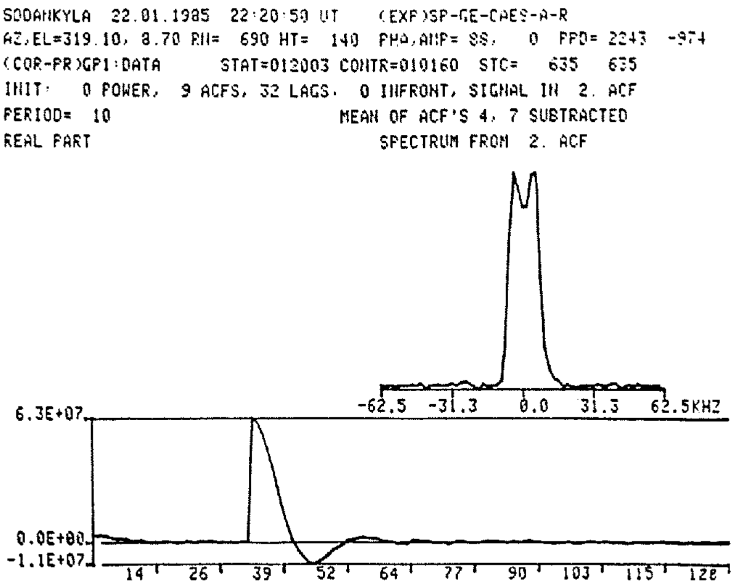
3.
BACKSCATTER SPECTRA

Fig.2 shows a print-out from the data monitor, which shows the instantaneous measurement results from a real experiment. The measurements were carried out using the EISCAT UHF system (3). The diagram shows the scatter echoes obtained in Finland from the Norwegian transmitter. The small partial image shows the typical double hump form of the scatter spectra.

In a real scatter experiment, we are interested in the total backscattered yield (on the basis of which is determined the electron density in the scatter volume), but predominantly in the frequency distribution of the scatter spectra (each of the electrons in motion triggers a Doppler shift, and in total these bring about a continuous total spectrum). The electron and ion temperatures (in the polar ionosphere up to several thousand K) can be derived, among other things, from the form of the scatter spectrum, but conductivity values, the number of collisions and the types of ions involved can also be determined.

The drift speed of the ionospheric plasma (up to several thousands of metres/second in the polar ionosphere) can be determined from the Doppler shift of the total spectrum. The tri?static UHF system here supplies three Doppler measurements different from one another, from which the three coordinates of the speed vector can be calculated.

With knowledge of the local field vector of the earth's magnetism, the strength and direction of the electrostatic field in the ionosphere (typical value in the polar ionosphere: 100 mV/m.) can be determined from the speed components vertical to the magnetic field ($\underline{E} \times \underline{B}$ -drift).



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SODANKYLA  22.01.1985  22:20:59 UT    (EXP)SP-GE-CAES-A-R
AZ,EL=319.10, 8.70 RN=  690 HT=  140  PHA,AMP= 88,   0  PPD= 2243  -974
(COR-PR)GP1:DATA      STAT=012003 CONTR=010160  STC=   635   635
INIT:   0 POWER,  9 ACFS, 32 LAGS,  0 INFRONT, SIGNAL IN  2. ACF
PERIOD=  10                       MEAN OF ACF'S 4, 7 SUBTRACTED
REAL PART                            SPECTRUM FROM  2. ACF
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Fig.2:
EISCAT recording dated 22/01/85, Sodankylä (3). The backscatter echo originates at a height of 140 kmand is 690 km away. The lower section shows the real component of the auto correlation function, averaged over 10 secs, following a first release of noise between the lags 34 - 64. The spectrum arose from a Fourier Transformation of the complex function.

4.
APPLICATIONS

Incoherent scatter radar installations make possible research into short term and long term, small scale and large scale changes in the ionosphere.

The individual measurements attain temporal resolutions in the range between tenths of a minute and minutes, but with the assistance of the data collected in previous years annual oscillations or variations, which are connected with the sunspot cycle, can also be brought out.

The spatial resolution can be a few hundred metres in the vertical or, under the influence of the earth's rotation and the position of the sun which alters with it, can indicate the large-scale horizontal structure of the ionosphere.

The incoherent scatter radar installations installed in the polar latitudes can also provide hints on the magnetospheric processes which take place many thousand kilometres above the ionosphere.

The lines of the earth's magnetic field represent equivalent potential lines, which thicken as they approach the earth from the direction of the magnetosphere. Electrical potential differences triggered in the magnetosphere are in this way reflected in the polar ionosphere under amplification.

Since the magnetospheric processes are connected with the flow of particles from the sun, ionospheric processes can also be studied in relation to the solar wind or to the sector structure of the interplanetary magnetic field. In research of this latter kind, the incoherent scatter data are combined, for example, with the results of the observations from satellite-aided experiments.

5.
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