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Radar probing of ionospheric plasmas precisely confirms linear kinetic plasma theory (Hannes Alfvén Medal Lecture)

Donald Farley
School of Electrical and Computer Engineering, Cornell University, Ithaca, NY, USA

In 1958 W. E. Gordon first suggested that huge radars could probe the ionosphere via scattering from independent electrons, even though the radar cross section of a single electron is only 10^{-28} m^2. This suggestion quickly led to the construction of two enormous radars in the early 1960s, one near Lima, Peru, and one near Arecibo, Puerto Rico. It soon became apparent that the theory of this scatter was more complicated than originally envisaged by Gordon. Although the new theory was more complicated, it was much richer: by measuring the detailed shape of the Doppler frequency spectrum (or alternatively the signal autocorrelation function, the ACF), a radar researcher could determine many, if not most, of the parameters of interest of the plasma. There is now a substantial network of major radar facilities scattered from the magnetic equator (Peru) to the high arctic latitudes (Svalbard and Resolute Bay), all doing important ionospheric research. The history of what is now called Incoherent Scatter (even though it is not truly incoherent) is fascinating, and I will touch on a few highlights. The sophisticated radar and data processing techniques that have been developed are also impressive.

In this talk, however, I want to focus mainly on the details of the theory and on how the radar observations have confirmed the predictions of classical linear plasma kinetic theory to an amazingly high degree of precision, far higher than has any other technique that I am aware of. The theory can be, and has been, developed from two very different points of view. One starts with "dressed particles," or Coulomb "clouds" around ions and electrons moving with a Maxwellian velocity distribution; the second starts by considering all the charged particles to be made up of a spectrum of density plane waves and then invokes a generalized version of the Nyquist Noise Theorem to calculate the thermal amplitudes of the waves. Both approaches give exactly the same results, results that allow us to predict exactly the scattered power and Doppler spectrum for any given set of plasma parameters (e.g., electron and ion temperatures, ionic composition, mean drifts and currents, the geomagnetic field, and particle collisions). So far, these predictions have not failed, although in recent years we have had to resort to numerical simulations to do a proper calculation of electron Coulomb collisions when the radar beam is pointed very nearly perpendicular to the magnetic field. This is because no analytic way has yet been found to properly apply the Fokker-Planck Coulomb collision model to the scattering process. Of course the theory predicts the spectrum, given all the plasma parameters, when what we really want to do in ionospheric research is the inverse, namely find the parameters, given the radar data. This inverse process can be quite difficult to do optimally if there are too many unknown parameters. Statistical inverse theory can require enormous computing power, but progress is being made.