Donald T. Farley, Appleton Prize 1996: His contributions to Equatorial Aeronomy[1]

Ronald F. Woodman
Jicamarca Radio Observatory

On the 20th URSI General Assembly, Lille, 1996, Dr. Donald T. Farley was awarded the Appleton Prize. The Appleton Prize is awarded, every three years, to distinguished Scientists in the field of Ionospheric Physics by the Council of the Royal Society on the recommendations of the Board of Officers of URSI. This Symposium is an occasion to celebrate... because Don Farley is one of us. The citation of the award reads: "For contributions to the development of the incoherent scatter radar technique and to radar studies of ionospheric plasma instabilities". We could not agree more with the Council's decision. The occasion is especially relevant considering that most of his contributions have been associated with Equatorial Aeronomy.

We will celebrate and at the same time pay homage to Don by recalling the important contributions he has made to our field. This is not an easy task, considering that we would have to review close to 40 years of very productive work. In fact his first contribution to our field was his doctoral thesis, in 1960, where he made the first quantitative study of coupling between the equatorial *E* and *F* regions of the ionosphere along the almost equipotential magnetic field lines. This work is still often referred to in our community. It shows how this coupling weakens with decreasing scale size, and has special relevance in the stabilization of *F* region equatorial irregularities.

While at Cornell, Bill Gordon had published his famous paper on Incoherent Scatter. Soon after Don's graduation, he and John Dougherty publish several theoretical papers on the subject. Ken Bowls had experimentally proven that the magnitude and spectral shape of the incoherently scattered returns did not conform to the simple intuitive predictions of Gordon. Don's theory predicted, using plasma kinetic theory, the statistical characteristics of the echoes in a very precise and rigorous way.

The importance of the ion dynamics in defining the shape of the spectra had been shown experimentally by Ken Bowls. This led, in 1960, to the construction of the Jicamarca Incoherent Scatter Observatory, near Lima, Peru, where the (magnetically induced) ion gyro-resonances could be observed, and motivated Don to include the effects of the magnetic field in his theory. Don, later on, in 1967 publishes the first detection of this resonance: the proton gyroresonance in exact accordance with the theory. He had been the theorist at the Jicamarca Observatory since 1961, but his contributions, as we will see later, were not limited to plasma theory. In fact, he became his Director in 1964. In 1967 he joins Cornell, where we find him nowadays, but still with a very close connection to Jicamarca and, thus, to Equatorial Aeronomy. Don Farley has been for many years, and still is, the PI of the National Science Foundation Cooperative Agreement that supports most of the work at Jicamarca

The power of Incoherent Scatter radars stems from its ability to measure ionic composition and plasma (electron and ion) temperatures as a remote mass spectrometer. This requires that all physical process that could affect the shape of the spectrum of the radar echo returns be taken into account. Ion collision with the neutrals is an important effect in the lower ionosphere. Farley and Dougherty theory is adjusted to include such an effect. Later, it is realized that the free electrons and ions in the lower *F* region are not necessarily at the same temperature, despite the fact that they occupy the same volume. Farley incorporates in the theory the proper practical formulae that allow the quantitative measurements of both temperatures, and from their difference the amount of solar radiation energy being dump into them, and eventually transferred to the neutral gas in the background.

As I already mentioned, Farley's contribution to the incoherent scatter field is not limited to theoretical considerations. We can claim that most of the incoherent scatter radar techniques in use by the Jicamarca radar where developed by him, some times in collaboration with his students. Many have been implemented or are also used in other Incoherent Scatter radars. There are three *classical* papers in Radio Science 4, 1969, which are basic reading for any user of Jicamarca: his papers on incoherent scatter power, Faraday rotation and correlation techniques. These include the mathematical foundations necessary to invert the measurements into the state parameters of the plasma that the technique allows. The Faraday technique allows the absolute measurement of electron densities, independent of the radar parameters that describe the radar characteristics other than the direction of the antenna beam. The correlation techniques allow the determination of temperatures and composition. They now include the use of multiple pulses at

non-redundant spacing, first suggested by him and which drastically improve the correlation estimation efficiency. He was also first to suggest the use of Barker codes to improve the altitude resolution of the measurements without much loss in sensitivity.

His combined expert knowledge of theory and practical techniques has allow him, in collaboration with his students, to make important contributions in regards to the behavior of densities, composition and temperatures at the magnetic equator and other latitudes. This is, of course the reason why the incoherent scatter observatories where created and the reason we have, here at this symposium, an interest in them. We should also mention one important non-equatorial contribution of his: the measurement of counter-streaming velocities of the H^+ and O^+ ions along the magnetic field above Arecibo.

But radars are not limited to study incoherently scatter returns. The ionosphere is full of irregularities and instabilities capable to produce electron density fluctuations and hence very efficient scatters. In most cases the scattering crossections are so large that one does not require the large power and antenna sizes required by the former. The equatorial ionosphere is a very interesting example in this regard. Farley's name is associated with the two most known types of ionospheric irregularities: *E* region equatorial irregularities, related to the electrojet, and *F* region ones related with the equatorial Spread *F*. He, in collaboration with his students and colleagues, has made important contributions to both, from a theoretical and experimental point of view.

There are two types of irregularities present at the equatorial E-region. They are associated with two types of instabilities: two-stream and gradient-drift. Don was the first in presenting a proper kinetic theory that explains the physical mechanism responsible for the first. He did so in a paper in 1963 that became a *Current Content* 'Citation Classic' in 1981 and won a Dept. of Commerce award. The two-stream instability is now known as the Farley-Buneman instability (Buneman described the same instability using a fluid approach). The instability is a true universal type plasma instability that depends only on the local conditions described in a differential volume of the plasma. It occurs whenever the electron drift velocity with respect to that of the ions matches the ion acoustic velocity in a way that resembles the growth of an ocean wave whenever the wind matches the phase velocity of an ocean surface gravity wave. The gradient drift velocity is also driven by the relative drift of the electrons, but requires the existence of a transverse background plasma density gradient, since involves the convection of higher (lower) density plasma into regions of lower (higher) density.

F region equatorial irregularities where first reported by Booker in 1938 using the Huancayo ionosonde. Because of the "spread" nature of the echo traces it produces in an ionogram the phenomenon is known as equatorial Spread *F*. Since the early days of Jicamarca the same irregularities manifested themselves as very strong echoes in the radar, a nuisance that interfered with the Incoherent Scatter signals. Farley and colleagues wrote the first paper that made use of this "clutter" to infer properties of this signals and showed that all of the existing theories at the time (almost 40 years after their discovery) had problems: they did not conformed with the observed properties.

Again, as in the Incoherent-Scatter case, Don has made important contributions in the development of sophisticated radar techniques to observe the equatorial ionospheric irregularities. He was involved, with Mario Ierkic and Bela Fejer, in the development of the "frequency labeled" interferometer technique. It was first used to identify and track the vertical and transverse motion of "hot spots" in the instabilities of the *E* region. This was the first of the now more powerful imaging techniques, which are being used for the imaging of both E- and F-region structure of the irregularities.

Using very precise and careful interferometric experiments, in collaboration with Erhan Kudeki and Dave Hysell, he has measured the extremely high aspect sensitivities of *E* and *F* region irregularities. In the case of the *F* region, the aspect sensitivity was found to be of the order of 0.01 degrees! (A difficult experiment to perform) thereby ruling out some theories.

I have concentrated on his contributions of interest to the Equatorial Aeronomy community, but Don has been active in other latitudes as well. They can be easily identified by the title on the following partial list of a selected set of his more than 120 publications. I am sure the Equatorial Aeronomy community would appreciate to have this list handy. The list should also partially complement the many omissions made --because of the limitations in time and space-- of other important contributions of his. It should also give proper credit to his collaborators. For a more complete list, I refer the reader to the Cornell web pages (http://www.ee.cornell.edu/faculty/Farley/Farley.html or http://www.jro.igp.gob.pe/farley.html)

Last but not least, Don is not only a good scientist but also a good athlete. Those in the Aeronomy community that jog or run can get good advice from Don on how to run, regardless of age, the Boston or

the New York Marathon. In fact, one further contribution of his to the Jicamarca Observatory is the development of the antenna periphery into a nice N* 1200-meter running course. The emphasis here is on the value of N.

Selected list of publications:

Farley, D.T., Jr., A theory of electrostatic fields in a horizontally stratified ionosphere subject to a vertical magnetic field, *J. Geophys. Res.*, 64, 1225--1233, 1959.

Farley, D.T., Jr., A theory of electrostatic fields in the ionosphere at nonpolar geomagnetic latitudes, *J. Geophys. Res.*, 65, 869--877, 1960.

Dougherty, J.P., and D.T. Farley, A theory of incoherent scattering of radio waves by a plasma, *Proc. Roy. Soc. London*, A, 259, 79--99, 1960.

Farley, D.T., J.P. Dougherty, and D.W. Barron, A theory of incoherent scattering of radio waves by a plasma, II. Scattering in a magnetic field, *Proc. Roy. Soc. London*, A, 263, 238--258, 1961.

Dougherty, J.P., and D.T. Farley, Jr., A theory of incoherent scattering of radio waves by a plasma, 3. Scattering in a partly ionized gas, *J. Geophys. Res.*, 68, 5473--5486, 1963.

Farley, D.T., Jr., A plasma instability resulting in field-aligned irregularities in the ionosphere, *J. Geophys. Res.*, 68, 6083--6097, 1963.

Farley, D.T., Jr., The effect of Coulomb collisions on incoherent scattering of radio waves by a plasma, *J. Geophys. Res.*, 69, 197--200, 1964.

Farley, D.T., Jr. A theory of incoherent scattering of radio waves by plasma 4. The effect of unequal ion and electron temperatures, *J. Geophys. Res.*, 71, 4091--4098, 1966.

Farley, D.T., Ionospheric temperature and composition measurements at the magnetic equator, Annales de Geophysique, 22, 448--453, 1966.

Farley, D.T., Proton gyro-resonance observed in incoherent scattering from the ionosphere, Phys. Fluids, 10, 1584--1586, 1967.

Farley, D.T., Incoherent scatter correlation function measurements, *Radio Sci.*, 4, 935--953, 1969.

Farley, D.T., Incoherent scattering at radio frequencies, *J. Atmos. Terr. Phys.*, 32, 693--704, 1970.

Farley, D.T., B.B. Balsley, R.F. Woodman, and J.P. McClure, Equatorial spread F: implications of VHF radar observations, *J. Geophys. Res.*, 75, 7199--7216, 1970.

Farley, D.T., Radio wave scattering from the ionosphere, Chapter 14 in Methods of Experimental Physics; Volume 9B (R. Lovberg and H. Greim, eds.), Academic Press, 1971.

Balsley, B.B., and D.T. Farley, Radar studies of the equatorial electrojet at three frequencies, *J. Geophys. Res.*, 76, 8341--8351, 1971.

Farley, D.T., Multiple pulse incoherent scatter correlation function measurements, *Radio Sci.*, 7, 661--666, 1972.

Ioannidis, G., and D.T. Farley, Incoherent scatter observations at Arecibo using compressed pulses, *Radio Sci.*, 7, 763--766, 1972.

Farley, D.T., and B.B. Balsley, Instabilities in the equatorial electrojet, *J. Geophys. Res.*, 78, 227--239, 1973.

Hagen, J.B., and D.T. Farley, Digital correlation techniques in radio science, *Radio Sci.*, 9, 775--784, 1973.

Fejer, B.G., D.T. Farley, B.B. Balsley, and R.F. Woodman, Vertical structure of the VHF backscattering region in the equatorial electrojet and the gradient-drift instability, *J. Geophys. Res.*, 80, 1313--1324, 1975.

Farley, D.T., and B.G. Fejer, The effect of the gradient drift term on type 1-electrojet irregularities, *J. Geophys. Res.*, 80, 3087--3090, 1975.

Vickrey, J.F., W.E. Swartz, and D.T. Farley, Incoherent scatter measurements of ion counter-streaming, *Geophys. Res. Lett.*, 3, 217--220, 1976.

Farley, D.T., B.G. Fejer, and B.B. Balsley, Radar observations of two-dimensional turbulence in the equatorial electrojet, 3. Nighttime observations of type 1 waves, *J. Geophys. Res.*, 83, 5625--5632, 1978.

Farley, D.T., H.M. Ierkic, and B.G. Fejer, Radar interferometry: A new technique for studying plasma turbulence in the ionosphere, *J. Geophys. Res.*, 86, 1467--1472, 1981.

Farley, D.T., H.M. Ierkic, and B.G. Fejer, The absolute scattering cross section at 50 MHz of equatorial electrojet irregularities, *J. Geophys. Res.*, 86, 1569--1575, 1981.

Farley, D.T., C. LaHoz, and B.G. Fejer, Studies of the self-focusing instability at Arecibo, *J. Geophys. Res.*, 88, 2093--2102, 1983.

Farley, D.T., Theory of equatorial electrojet plasma waves: New developments and current status, *J. Atmos. Terr. Phys.*, 47, 729--744, 1985.

Providakes, J., D.T. Farley, W.E. Swartz, and D. Riggin, Plasma irregularities associated with a morning auroral arc: Radar interferometer observations and theory, *J. Geophys. Res.*, 90, 7513--7523, 1985.

Fejer, B.G., J. Providakes, D.T. Farley, and W.E. Swartz, Auroral E region plasma waves and elevated electron temperatures, *J. Geophys. Res.*, 91, 13,583--13,592, 1986.

Farley, D.T., E. Bonelli, B.G. Fejer, and M.F. Larsen, The prereversal enhancement of the zonal electric field in the equatorial ionosphere, *J. Geophys. Res.*, 91, 13,723--13,728, 1986.

Kudeki, E., and D.T. Farley, Aspect sensitivity of equatorial electrojet irregularities and theoretical implications, *J. Geophys. Res.*, 94, 426--434, 1989.Farley, Donald, and Jason Providakes, The variation with Te and Ti of the velocity of unstable ionospheric two-stream waves, *J. Geophys. Res.*, 94, 15,415--15,420, 1989.

Sahr, J.D., D.T. Farley, W.E. Swartz, and J.F. Providakes, The altitude of type 3 auroral irregularities: Radar interferometer observations and implications, *J. Geophys. Res.*, 96, 17,805--17,811, 1991.

Farley, D.T., W.E. Swartz, D.L. Hysell, and C. Ronchi, High-resolution radar observations of daytime kilometer-scale wave structure in the equatorial electrojet, *J. Geophys. Res.*, 99, 299--307, 1994.

Farley, D.T., and D.L. Hysell, Radar measurements of very small aspect angles in the equatorial ionosphere, *J. Geophys. Res.*, 101, 5177--5184, 1996.

Farley, D.T., Theories of auroral electrojet instabilities, Proceedings of a Workshop held at the Max-Planck-Institut fur Aeronomie in Katlenburg-Lindau, Germany, 24--26 October 1995 (K. Schlegel, ed.), 111--114, Cuvillier Verlag, Gottingen, 1996.

Farley, D.T., Incoherent scatter radar probing, Chap. 14 (pp 415--439) in Modern Radio Science (H. Kohl, R. Ruster, and K. Schlegel, eds.), European Geophys. Society, Katlenburg-Lindau, FRG, 1996.

Haldoupis, C., D. T. Farley, and K. Schlegel, Type-1 echoes from the mid-latitude E-region ionosphere, *Ann. Geophys.*, 15, 908-917, 1997.

Aponte, N., W. E. Swartz, and D. T. Farley, Electron energy balance in the F-region above Jicamarca, *Geophys. Res. Lett* ., 104, 10,041--10,049, 1999.

---

[1] Presented at the International Equatorial Aeronomy Symposium, Atalya, Turkey, 17-23 May, 2000