# A Workshop to Honor Donald T. Farley (belatedly) on the Occasion of his 80th Birthday and to Consider the Future of Radio and Space Physics

Snee Hall
Cornell University
March 30 – April 1, 2015

After receiving his B.Eng. Phys. and Ph.D. degrees from Cornell University, Donald Farley spent a year at Cambridge University as a NATO Postdoctoral Fellow, a year as Docent at Chalmers University in Sweden, and then six years in Peru at the Jicamarca Radio Observatory, three of them as director, before returning to the United States and joining the Cornell faculty as a full professor in 1967. He returned to Sweden in 1985 for a year as the Tage Erlander Visiting Professor at the Uppsala Ionospheric Observatory and was, in 1995, the Von Humboldt Senior Scientist at the Max-Planck Institute für Aeronomie in Katlenberg-Lindau. He is a Fellow of the Institute of Electrical and Electronics Engineers and a member of the American Geophysical Union, the International Scientific Radio Union (URSI), and the American Association for the Advancement of Science. Farley received U.S. Department of Commerce Distinguished Authorship awards in 1963 and 1964 as well as the U.S. Department of Commerce Gold Medal in 1967. He is the recipient of the 1996 URSI Sir Edward Appleton Prize, the 1997 Royal Astronomical Society Gold Medal for Geophysics, and the 2010 Hannes Alfvén Medal from the European Geophysical Union in addition to awards for teaching and advising at Cornell. Farley was the J. Preston Levis Professor of Engineering in Electrical and Computer Engineering at Cornell before becoming Professor Emeritus in 2006.

## Monday, March 30

8:00 – 8:30 Registration and welcome

**Session I chair: Anthea Coster**

8:30 – 8:55 R. F. Woodman*, An early history of the Jicamarca Radio Observatory: Don Farley's contributions

8:55 – 9:20 D. Campbell*, Making it happen: William E. Gordon and the building of the Arecibo Telescope

9:20 – 9:45 M. C. Kelley*, A History of Cornell research from a rocket scientist viewpoint

9:45 – 10:10 C. La Hoz A partial (pun intended) portrayal of Don Farley by a fan and pupil

10:10 – 10:30 break

10:30 – 10:55 M. F. Larsen*, Wind measurements at altitudes from the troposphere to the thermosphere

10:55 – 11:20 R. F. Pfaff*, An overview of *in situ* measurements of plasma waves driven by the Farley-Buneman instability

11:20 – 11:45 E. Kudeki*, Ongoing saga of 150 km echoes

11:45 – 12:10 E. Bonelli, Dangers of GPS navigation in Brazil, during fair space weather

12:10 – 1:40 lunch

**Session II chair: Marco Milla**

1:40 – 2:05 A. J. Coster*, E. Yizengaw, and F. D. Lind, A Future vision: Incoherent scatter radar in Ethiopia

2:05 – 2:30 C. E. Valladares, LISN - The distributed observatory for the Jicamarca IS radar

2:30 – 2:55 J. P. St. Maurice*, Farley-Buneman waves at large aspect angles

2:55 – 3:20 C. I. Haldoupis*, Farley-Buneman plasma waves in midlatitude sporadic *E* layers

3:20 – 3:40 break

---

* invited presentation

3:40 – 4:05 M. M. Oppenheim, The ongoing saga of the Farley-Buneman instability: from the sun to the lower ionosphere

4:05 – 4:30 Y Dimant and M. M. Oppenheim, Farley-Buneman instability and anomalous ionospheric conductance

4:30 – 4:55 J. C. Foster, D. Tetenbaum, D. R. Moorcroft, J.-P, St. Maurice, and P. J. Erickson, Revisiting early Millstone Hill observations of sub-auroral Farley-Buneman backscatter – magnetospheric connections

4:55 – 5:20 P. J. Erickson, F. D. Lind, J. C. Foster, D. R. Moorcroft, and B. J. Jackel, Sub-auroral Farley-Buneman irregularity scatter observations: the recent MIT Haystack active and passive radar record

7:00 – 9:00 **Banquet, Statler Hotel** J. D. Sahr speaking

## Tuesday, March 31

8:00 – Registration

**Session III chair: Asti Bhatt**

8:30 – 8:55 A. P. v. Eyken*, Whither incoherent scatter radar?

8:55 – 9:20 W. A. Bristow*, The role of ISRs in global-scale studies

9:20 – 9:45 C. J. Heinselman*, EISCAT 3D: A multistatic phased array ISR for auroral studies

9:45 – 10:10 J. L. Chau* and G. Stober, MMARIA: A multi-static and multi-frequency novel approach for specular meteor radars to improve wind measurements in the MLT region

10:10 – 10:30 break

10:30 – 10:55 F. D. Lind*, Next generation geospace radio arrays

10:55 – 11:20 J. W. Meriwether, Optics and radar measurements: Complimentary attributes to solving aeronomic problems

11:20 – 11:45 A. M. Hamza, Subgrid modeling for ionospheric turbulence

11:45 – 12:10 E. Bonelli, A new mechanism to explain the origin of ionospheric bubbles

12:10 – 1:40 lunch

**Session IV chair: Meers Oppenheim**

1:40 – 2:05 M. A. Milla* and E. Kudeki, Incoherent scatter theory and the effect of Coulomb collisions

2:05 – 2:30 J. Vierinen*, New results from upgraded plasma line receivers at Arecibo, Haystack, and Sondrestrom

2:30 – 2:55 M. J. Nicolls*, AMISR: Review of results, and planning for the future

2:55 – 3:20 C. I. Haldoupis, Electron density enhancements in the *D* region ionosphere caused by powerful CG lightning EM pulses

3:20 – 3:40 break

3:40 – 4:05 F. S. Rodrigues, AMISR-14 at Jicamarca: New observations of equatorial spread F

4:05 – 4:30 A. N. Bhatt and A. Strømme, Sub-kilometer scale irregularities detection using ISR plasma lines?

4:30 – 4:55 E Nossa, High time- and height-resolution neutral wind profiles in the daytime E layer based on Arecibo World Day data

4:55 – 5:20 B. Isham*, Stories from the past year, and what they say about the future

**Wednesday, April 1** — moderated discussion

8:00 – Registration

**Session V chair: Mike Nicolls**

8:30 – 8:50 J. L. Chau

8:50 – 9:10 J. D. Sahr, What will radio science graduate students be doing in 20 years?

9:10 – 9:30 D. L. Hysell, Radio and space physics in the 21st century

9:30 – 9:50 C. La Hoz

9:50 – 10:10 M. F. Larsen, Mesosphere and thermosphere dynamics: Is there a broader perspective that we can and should exploit?

10:10 – 10:30 break

10:30 – 12:00 discussion and wrap-up

---

D. L. Hysell, J. D. Sahr, and C. La Hoz workshop organizers

A. Bhatt and A. Strømme
SRI International, Menlo Park, CA

### Sub-kilometer scale auroral irregularities detection with ISR Plasma lines?

Wide-bandwidth plasma line experiments with the Sondrestrom radar in Greenland during auroral precipitation events resulted in unusually broad bandwidth plasma line signatures at frequencies typically considered higher for E-region. These unusual signatures were as broad as 2-3 MHz, compared to the "normal" plasma lines with a bandwidth of a few kHz. These were obtained using uncoded 480us long pulse. The signals were often transient lasting only for one integration period of 10 seconds, but often would last for periods ranging up to 60 seconds, and observed in both up B and off-B radar beam directions. During the same auroral precipitation events, "normal" plasma lines were also observed. Accompanying the "broad" plasma lines was a sharp increase in electron density, and elevated levels of multi-wavelength optical emissions. After eliminating instrumental effects and reviewing evidence of correlation between multi-wavelength auroral emissions and scintillations, we are exploring the hypothesis that the broad plasma lines are a result of sub-kilometer scale irregularities in the radar beam. If proven, this would give a powerful new way of looking at auroral irregularities, since ISR can be used as a diagnostic tool in addition to detection of these irregularities.

E. Bonelli
Dpto. de Geofsica, CCET, UFRN, Natal, Brazil

### A new mechanism to explain the origin of ionospheric bubbles

For several decades, the equatorial ionospheric plasma phenomena, known as "bubbles" and, after radar data, "plumes," are believed to be seeded by an initial wavelike perturbation that pumps neutral air up, into the plasma. Here, it is suggested a new process for the seeding of instabilities, where a strong eastward electric field moves the plasma abruptly up, with a quick reversal afterwards. In this way, the plasma drags neutral air with it and then reverses almost instantly, while the neutral air motion does not. The most suitable example for this would be irregularities driven by the enhancement of the zonal eastward electric field near sunset, with its subsequent reversal. On the other hand, any electric field in such conditions could cause bubbles to appear on the night side, even away from sunset.

E. Bonelli
Dpto. de Geofsica, CCET, UFRN, Natal, Brazil

### Dangers of GPS navigation in Brazil, during fair space weather

GPS signals are known to present problems in equatorial regions, due to the presence of ionospheric bubbles, which may cause signal loss or even loss of satellite tracking. The problem spans over a larger area in Brazil, due to the magnetic anomaly, where the magnetic equator dives thousands of kilometers south, to reemerge northwards into Peru, and back to the 'normal' behavior, close to the geographic equator. For this reason, more air traffic and airports are in a low magnetic latitude region, to where bubbles can propagate, when they go up at the magnetic equator, filling tubes of magnetic field lines. GPS navigation in presence of bubbles may involve large positioning errors, which can have worse effects when large velocities are involved, as in the case of aircrafts. Even more dangerous could be the effect of bubbles on new technologies such as a technology for controlling the simultaneous landing of several planes, using GPS navigation. In this presentation I show that GPS amplitude scintillations are similar in a range of 3000 km from north to south of Brazil, affecting the more active air traffic regions of the country. Adding up to the problem, there is the fact that the occurrence of bubbles, in Brazil, is more frequent during fair space weather, meaning less magnetic storms.

W. A. Bristow
Geophysical Institute, University of Alaska Fairbanks, Fairbanks, AK
**The role of Incoherent-Scatter Radar in global-scale studies**

Incoherent-scatter radar has an over 50-year record of research in geospace science. On the occasion of the 80th birthday of one of the founding fathers of the field, it is appropriate to consider future research potential of this most powerful of remote sensing instruments. This talk presents application of ISR to global-scale research and how it fits in with other instruments. The talk will begin with an overview of the near-term future of geospace research in general and then focuses on how ground-based remote sensing fits into that future. Three specific topics will be addressed and examples of recent observations will be presented. The focus will be on what is unknown in the topics and how ISRs can help answer outstanding questions. The areas of focus will be neutral winds, magnetospheric dynamics, and convection variability. Example observations will be taken from SuperDARN and the PFISR Ion-Neutral Observations in the Thermosphere (PINOT) campaign.

D. B. Campbell
Department of Astronomy, Cornell University, Ithaca, NY
**Making it Happen: William E. Gordon and the building of the Arecibo Telescope**

The successful completion of the 305m Arecibo telescope and radar system in late 1963 was due to the single minded determination of William E. (Bill) Gordon. At a Cornell seminar in early 1958 he laid out the specifications for a radar system to study the Earth's ionosphere via incoherent scatter from the free electrons and proceeded to initiate engineering studies, locate potential sites in Puerto Rico, embrace the suggestion of a spherical reflector to allow limited steerability primarily for planetary studies, secure funding and direct the construction. He was very fortunate in having the support of a talented group of faculty at Cornell with critically needed skills and his timing was perfect, this was the immediate post-Sputnik period when the United States was open to big ideas in science and engineering.

J. L. Chau and G. Stober
Leibniz Institute of Atmospheric Physics, Kühlungsborn, Germany
**A multi-static and multi-frequency novel approach for specular meteor radars to improve wind measurements in the MLT region**

Specular meteor radars (SMRs) have become a widely used tool to observe horizontal winds at the mesosphere and lower thermosphere (MLT). Typically 30- to 120-minute mean winds are obtained assuming horizontal homogeneity of the observed area (i.e., few hundreds of kilometers radius). The quality of the measured wind velocity vector depends on the number of detected meteors per altitude and time bin. In order to improve the wind measurements of typical SMRs, here we propose a multi-static and multi-frequency approach that consists mainly on adding GPS synchronized receiving stations with interferometric capabilities to existing SMRs. Compared to typical SMRs operating in a monostatic mode, our new approach, called MMARIA, (Multi-static and Multi-frequency Agile Radar for Investigations of the Atmosphere), allows us to: (a) increase the number of meteors using the same transmitter (by more than 70%), (b) increase the altitudinal coverage by 5-10 km depending on the geometry used, and (c) derive the horizontal wind field in the observed volume by relaxing the assumption of homogeneity. The latter result is facilitated by having common-volume observations from at least two different viewing angles. We show the feasibility of these three goals from measurements at two different frequencies using a MMARIA configuration between Juliusruh and Külungsborn in northern Germany (separated ∼130 km).

A. J. Coster[1], E. Yizengaw[2], and F. D. Lind[1]
(1) MIT Haystack Observatory, Westford, MA
(2) Boston College, Boston, MA

**A future vision: Incoherent and coherent scatter radar in Ethiopia**

The equatorial ionosphere is one of the most complex ionospheric regions, host to numerous instabilities, interactions, and still unresolved dynamics. Most of what is known about the equatorial ionosphere has been derived from analysis of ground-based instrumentation in one longitudinal region - South America  especially from the region surrounding the Jicamarca, Peru incoherent scatter radar (ISR). In Africa, to date, there is a relative lack of ground-based instrumentation. This is despite the fact that the African continent has the largest landmass under the equator. In addition, satellite observations have consistently shown significant longitudinal differences in equatorial ionospheric structures and electrodynamics. For example, satellite observations have shown that the formation of ionospheric density "bubbles," the regions of large electron density depletions that form after sunset, occur more frequently and form during all seasons over Africa unlike those observed in other longitudinal sectors [Hei et al., 2005; Su, 2005; Burke et al., 2006; Yizengaw et al., 2013, 2014]. Another distinction is that the African "bubbles" rise to higher altitudes (up to 1000+ km) [Burke et al.,2004].

The region near Bahir Dar, Ethiopia provides an attractive future location for a new incoherent scatter radar (ISR). Bahir Dar is essentially on the equator [11.6 deg geodetic latitude, 37.38 deg geodetic longitude; 3.51 deg geomagnetic latitude, 37.26 deg geomagnetic longitude]. Jicamarca and Bahir Dar are at similar geomagnetic latitudes and have similar offsets between geomagnetic and geographic latitudes. However, the background magnetic declination and magnitude differ considerably between these two locations. An ISR in Bahir Dar would significantly improve understanding of the role of the magnetic field in equatorial dynamics and the production of equatorial instabilities. Other potential radar systems under consideration for the Bahir Dar region include MST radars and coherent scatter class radars at varying frequencies. Recently, a 50 MHz VHF coherent scatter radar has been deployed in Bahir Dar. The combination of these assets when co-located provides enhanced insight into equatorial geophysics. In particular, coherent scatter radars can be used to compare and study the varying spatial scales of irregularities excited in the plasma, while MST radars can provide insight into the important coupling between the lower and upper atmosphere. To illustrate the potential of combined coherent and incoherent scatter diagnostics at equatorial latitudes, we will provide examples using the new 14-panel AMISR UHF radar deployment at Jicamarca in conjunction with the existing 50 MHz incoherent scatter radar system. We will conclude by summarizing the benefits of future radar measurements in the African sector at Bahir Dar.

Y. S. Dimant and M. M. Oppenheim
Boston University, Boston, MA

**Farley-Buneman instability and anomalous ionospheric conductance**

The Farley-Buneman (FB) instability generates electron density irregularities in the equatorial and high-latitude E-region electrojets that have been observed by radars for more than sixty years. This small-scale instability, however, has also important macroscopic manifestations. Among those is the effect of strong anomalous electron heating (AEH) observed by radars for more than thirty years. This effect is caused by the FB turbulent electric field, especially by its small component parallel to the geomagnetic field. AEH can increase the E-region electron temperature by more than an order of magnitude. Another less known anomalous effect is the nonlinear current (NC) formed directly by the FB turbulence. The NC has been theoretically predicted and observed in computer simulations. During space weather events that give rise to a strong convection electric field, both AEH and NC can increase the high-latitude ionospheric conductance, reducing the cross-polar cap potential and modifying the entire behavior of the near-Earth plasma. Estimates show that during extreme geomagnetic perturbations, the two anomalous effects combined can more than double the crucial Pedersen conductance responsible for the closure of magnetospheric currents. A quantitative understanding of the anomalous conductance and global energy transfer is important for accurate predictive modeling of Space weather. In particular, the inclusion of the two anomalous effects caused by the FB instability may explain why existing global MHD codes based on laminar conductivities systematically overestimate the cross-polar cap potentials by a factor of two or close.

P. J. Erickson[1], F. D. Lind[1], J. C. Foster[1], D. R. Moorcroft[2], and B. J. Jackel[3]
(1) MIT Haystack Observatory, Westford, MA
(2) University of Western Ontario, London, ON, Canada
(3) University of Calgary, Calgary, AL, Canada

**Sub-auroral Farley-Buneman irregularity scatter observations: the recent MIT Haystack active and passive radar record**

This paper presents an overview of the last two decades of MIT Haystack Observatory results on Farley-Buneman irregularity scatter characteristics at spatial wavelengths in the few meter to sub-meter range. Beyond the pioneering experiments described in this conferences Foster et al paper, hardware and software developments beginning in the mid 1990s added new capabilities to existing radar techniques for probing ionospheric plasma instabilities through radar backscatter experiments. In particular, the large aperture, high power Millstone Hill UHF ionospheric radar acquired greatly improved range ($\sim$km) and temporal ($\sim$second) resolution improvements for coherent backscatter observations. Millstone Hill's narrow ($\sim$ 1 deg) beamwidth and sub-auroral location allows highly aspect-sensitive observations of coherent backscatter with large dynamic range in preferred azimuthal directions, during conditions when the E region electric field exceeds the $\sim$10-15 mV/m onset threshold for the Farley-Buneman instability.

By exploiting the steep magnetic aspect angle dependence of Farley-Buneman scatter at 34 cm wavelength, unique experiments were conducted allowing E region coherent scatter power and velocity determination and a simultaneous determination of driving F region electric fields, through magnetically connected incoherent scatter measurements. A series of these experiments demonstrated a strong connection between irregularity power, velocity, and driving F region electric field, and showed dynamic spatial and temporal scale variations during strong magnetic storm events with large Region 2 ring current associated electric field drivers. Bistatic subauroral experiments during Kp $\sim$ 5 events were also conducted using a combination of Millstone Hill radar illumination and reception at the Algonquin radio telescope in western Ontario, and provided further information on spectral characteristics of UHF irregularity scatter.

During this period, MIT Haystack also applied passive radar techniques for Farley-Buneman scatter events through the Intercepted Signals for Ionospheric Science (ISIS) project, a distributed, coherent software radio array designed for the study of geospace phenomena by observing the scatter of ambient RF signals. Using FM transmitters of opportunity, a network of ISIS receivers deployed in the northeast US observed $\sim$meter scale E region coherent scatter in a manner nearly ambiguity-free for both Doppler and range.

We will review the highlights of this research period, place them in the context of recent physical insights into geospace configurations within the plasmasphere boundary layer, and emphasize results that require further study.

A. P. v. Eyken
SRI International, Menlo Park, CA

**Whither incoherent scatter radar?**

In the fifty-plus years since Incoherent Scatter Radar measurements became first possible, and then practical, and even occasionally routine, the physical technique and its theoretical underpinning have maintained a unique place in geophysical research as the very best, ground-based, single point, remote sensing tool available to serious geophysics researchers.

Today, with the emphasis swinging more and more towards geospace system science and large scale geospace modelling, Incoherent Scatter Radar not only still occupies that unique position but provides essential calibration and ground-truth for all sorts of global monitoring approaches.

At the same time, today's economic funding climate increasingly questions the role and value of the Incoherent Scatter Radar facilities.

Predicting the future is a sure way to be wrong, but, in this presentation, I will present some ideas concerning the future development of Incoherent Scatter Radar, the rational for maintaining, and even extending, the Upper Atmosphere Facility portfolio, and the role the radars can and should play, not only for traditional fundamental research but also as important inputs to the global-change debate and efforts to understand and mitigate such effects.

J. C. Foster[1], D. Tetenbaum[1], D. R. Moorcroft[2], J.-P. St. Maurice[3], P. J. Erickson[1]
(1) MIT Haystack Observatory, Westford, MA
(2) University of Western Ontario, London, ON, Canada
(3) University of Saskatchewan, Saskatoon, SK, Canada

**Revisiting early Millstone Hill observations of sub-auroral Farley-Buneman backscatter – magnetospheric connections**

Beginning in the 1960s, the large UHF and L-band radars at Millstone Hill have reported characteristics of coherent backscatter from E-region irregularities. The large power and aperture of these systems, combined with their narrow (∼1 deg) beamwidth, permit observations spanning $>$ 100 dB of dynamic range. Located at sub-auroral latitude (∼55 Invlat), coherent backscatter is observed from higher latitudes at ∼800 km – 1200 km range where (a) the monostatic radar beam intercepts the E region at near-perpendicular aspect angle and (b) only at times when the electric field exceeds the ∼10–15 mV/m onset threshold for the Farley-Buneman instability. Not surprisingly, Millstone Hill coherent backscatter experiments and associated publications are in synchrony with the 11 year solar activity cycle.

It is only in recent years that the considerable significance of the sub-auroral polarization stream (SAPS) on mid-latitude dynamics has been recognized. In retrospect, it is clear that almost all of the Millstone Hill coherent backscatter observations were made in regions dominated by the SAPS electric field, and on magnetic field lines connecting the ionosphere, magnetospheric ring current, and outer regions of the plasmasphere boundary layer.

Early Millstone Hill coherent backscatter experiments were limited by hardware designed primarily for incoherent scatter observations, and were characterized by spatial resolutions of ∼100 km and 10+ s temporal resolution. The radar's very high sensitivity, however, permitted coherent scatter observations out to ∼10 deg from magnetic perpendicularity. Large-amplitude (∼30+ dB), periodic (5-min) oscillations were often observed during the events recorded.

Since 2012, the Van Allen Probes spacecraft have characterized electric field variability across the outer plasmasphere and ring current near the apex of the field lines mapping to the regions characteristic of subauroral radar experiments. Van Allen Probes electromagnetic observations clearly show a predominance of ULF oscillations with 300 s - 500 s period and 2 mV/m – 5 mV/m amplitude. This talk will review some of the early

Farley-Buneman ionospheric instability observations in light of our current understanding of geospace and in particular of the processes which interconnect the ionosphere and magnetosphere.

C. Haldoupis
Department of Physics, University of Crete, Heraklion, Greece

**Farley-Buneman plasma waves in midlatitude sporadic E layers**

The Farley-Buneman (F-B) instability, which has been studied and applied extensively over the last 50 years, constitutes the cornerstone of E region ionospheric plasma physics. It is accepted as the basic generation mechanism for the so-called "type 1" echoes of E region coherent radar backscatter. These are identified with meter-scale electrostatic plasma waves, which are excited spontaneously in directions close to perpendicular to the earth's magnetic field. According to this theory, the F-B waves grow only if the relative electron-ion (electric current) drift velocity exceeds a threshold that equals the plasma ion acoustic speed, or alternatively, if the ambient electric field, which drives the current, exceeds a threshold of ∼15 mV/m.

Since the early sixties and seventies, coherent radar observations showed the F-B instability to be a regular phenomenon in both, the equatorial and auroral E region plasmas. This is because ionospheric fields at these two latitude zones, which drive strong electrojets near 105 km, attain values which often exceed the instability threshold. In view of the sizable thresholds needed for the F-B instability, the first observation of type 1 echoes at midlatitudes, which was reported much later in the mid-nineties, came as a surprise, because ionospheric (dynamo) electric fields at these latitudes are on the average an order of magnitude less than the instability threshold. The midlatitude type 1 echoes were detected with the Sporadic E Scatter Experiment (SESCAT), a 50 MHz continuous-wave bistatic Doppler system operating in Crete, Greece. SESCAT, which was set up to investigate coherent backscatter from instabilities in sporadic E layers, operated for a period of ∼12 years. During its operation SESCAT made extensive observations of F-B plasma waves in midlatitude sporadic E layers, by means of using a variety of experimental configurations, e.g., measuring high resolution Doppler spectra at 50 MHz, horizontal interferometry measurements at 50 MHz, and concurrent backscatter studies at 50 and 150 MHz (3- and 1-meter plasma waves).

This presentation will review the SESCAT midlatitude observations of Farley- Buneman plasma irregularities and discuss a mechanism which was proposed to account for the large electric fields needed for the excitation of the instability inside sporadic E layer plasmas. These electric fields are similar in nature to the equatorial electrojet polarization fields, which at midlatitude can arise when nighttime sporadic E layer patches have the right geometry. In addition, an effort will be also made to review midlatitude studies of F-B irregularities made by other coherent backscatter radar experiments. As a concluding comment: Although our present knowledge and understanding of Farley-Buneman plasma waves in midlatitude Sporadic E has reached a reasonable level, there are still unresolved questions and problems that need to be answered. The legacy of Farley's instability remains a never-ending educational challenge for scientific inspiration and creativity.

C. Haldoupis
Department of Physics, University of Crete, Heraklion, Greece

### Electron density enhancements in the D region ionosphere caused by powerful CG lightning EM pulses

Tropospheric lightning may couple electrical energy through quasi-electrostatic (QE) and/or electromagnetic pulses (EMP) into the upper atmosphere and lower ionosphere. This electrical coupling is best manifested by the transient luminous events (TLEs), which are momentary luminous phenomena of various types, mainly sprites and elves. On the other hand, lightning discharges may also cause heating and ionization of the overlying D-region ionosphere, therefore leading to conductivity perturbations. These can affect the propagation of very low frequency (VLF) transmissions, which travel long distances in the Earth-ionosphere waveguide, causing abrupt perturbations in the received signal, known as early VLF events. Early events recover in about 100 s and are identified with sprite occurrences caused by QE fields produced by positive cloud-to-ground (+CG) lightning discharges. Here we consider a subclass of VLF early events which do not recover for many minutes, known as long-recovery early events (LOREs). They are identified as a distinct category whose signature may occur either on its own or alongside the short-lived typical early VLF event. Since LORE onsets coincide with powerful lightning strokes of either polarity ($\pm$), we infer that they are due to long-lasting ionization changes in the uppermost D region ionosphere caused by EMPs emitted by strong $\pm$CG lightning peak currents of typically $>$250 kA, which are also known to generate elves. The LORE perturbations are detected when the discharge is located within $\sim$300 km from the great circle path (GCP) of a VLF transmitter-receiver link. The probability of occurrence increases with stroke intensity and approaches unity for discharges with peak currents greater than $\sim$300 kA. The evidence suggests LORE as a distinct signature representing the VLF fingerprint of elves, a fact which, although was predicted by theory, escaped identification in the long-going VLF research of lightning effects in the lower ionosphere. LORE will be discussed here in as much detail as the time permits. This includes the presentation of key observational evidence followed by some ideas for interpretation.

A. Hamza
Department of Physics, University of New Brunswick, Fredericton, NB, Canada

### Subgrid modeling for ionospheric turbulence

The equations governing the nonlinear evolution of density fluctuations in a low-pressure weakly ionized plasma driven unstable by the ExB or gradient-drift instabilities, as they occur in the turbulent E and F regions of the Earth's ionosphere, constitute an archetype for as far as nonlinear PDEs are concerned. A subgrid model suitable for the numerical simulation of these equations which is closely related to renormalized diffusion caused by small-scale fluctuation spectrum will be presented. “Dynamical Renormalization Group” (RNG) methods are employed to obtain the renormalized diffusion. This procedure computes the long-wavelength, long-time behavior of density correlations generated by the evolution equation for the plasma stirred by a Gaussian random force characterized by a correlation function proportional to k$^m$, where k is the wavenumber of the forcing function. The effect of small scales on the large-scale dynamics in the limit k→0 and infinite Reynolds number can be expressed in the form of renormalized coefficients; in our case, renormalized diffusion. If one assumes the power spectra to be given by the Kolmogorov argument of cascading of energy through $k$ space then one can derive a subgrid model based on the results of RNG.

C. J. Heinselman
EISCAT Scientific Association, Kiruna, Sweden

### EISCAT-3D: A multi-static phased array ISR for auroral studies

EISCAT has been an active member of the global incoherent scatter community since the late 1970s and has operated ISRs since 1981. My own first visit to EISCAT brought me to a radar school in Tromsøin August 1986 where Don Farley gave one of the key lectures on incoherent scatter radar measurements. At that time, the tri-static UHF capability was fully operational, EISCAT Heating was active, and the VHF system was being tested. A decade later a new radar was inaugurated, the EISCAT Svalbard Radar, located under the dayside cusp region at a geographic latitude that allows noon-time airglow measurements in the winter. These systems have provided several solar cycles of key scientific results, due in no small part to continuing advances in pulse coding and data processing techniques. Nonetheless, the limitations of the existing radars are now presenting obstacles to advances in a number of areas.

EISCAT is on the verge of implementing a significant upgrade to its capabilities. The existing mainland facilities are planned to be replaced by an ambitious multi-static incoherent scatter radar system called EISCAT-3D. The new system will use phased array technologies combined with multiple locations and high peak transmitter power to provide rapid, three-dimensional vector measurements of the ionospheric plasma. The arrays will also support multiple simultaneous beams on receive for complete altitude coverage as well as separate subarrays for interferometric imaging within the transmitter beam. These capabilities will be well suited for the next steps in probing the high-latitude ionospheric environment. In addition, the implementation will be highly software-centric and, as such, will support measurements in a wide range of scientific areas.

C. La Hoz
Department of Physics and Technology, University of Tromsø, Tromsø, Norway

### A partial (pun intended) portrayal of Don Farley by a fan and pupil

Don Farley's career, contributions and achievements are outstanding and distinctive. This is a personal and partial narrative of a limited set of achievements and recollections from the perspective of a pupil. As such, one of the qualities that strikes me most is his insight and capacity to explain complicated, often seemingly impenetrable, matters, be it physical, mathematical or technical, in a way that makes their essence comprehensible. Be it in class, in a seminar or in his writings. His two major contributions in physics are in the theory of incoherent scattering of radio waves from a plasma and in the theory of plasma current instabilities in the ionosphere. The former underpins incoherent scattering radar and the latter is still being unveiled with the help of radar techniques Don created (tho simulations are also important). His distinctive abilities range from theoretical brilliancy to masterly technical inventiveness to pedagogic excellence. Don not only made outstanding theoretical contributions. As an enlightened man, he also had to validate by experiment the theories he created. For many of the required experiments he invented novel radar and signal processing techniques. Important advances in ionospheric and atmospheric phenomena are still being possible or motivated by his technical creations. The inspiration that he generates among the younger generation, foremost his students, is remarkable, among others in incoherent scattering theory, ionospheric plasma instabilities, radar coding and radar imaging. I will address concisely his use of the generalized Nyquist theorem, another of his distinctive trademarks, and mention his kind portray of the wave (i.e., Nyquist) and dressed-particle fans as a reflection of the wave-particle duality of the electron. The upshot is that there are many around who owe much to Don, hold him in high regard and, above all, wish him well.

M. C. Kelley
Department of Electrical and Computer Engineering, Cornell University, Ithaca, NY

### A History of Cornell research from a rocket scientist viewpoint

A brief history of how the rocket program began and grew at Cornell. A great aspect of the program was convincing NASA to go to remote locations near Radar facilities. The first of these associated with Cornell was the CONDOR Campaign near Jicamarca. I review what I think were the most important results of this effort. This success led to many other Campaigns of this type in Alaska, Greenland, Kwajalein, Puerto Rico, Brasil, and Wallops Island, most of these were were carried out in multiple years. There is no time to summarize all these results but in brief the two fly-throughs of the Arecibo Heater and Miguel Larsen's work are spectacular.

M. F. Larsen
Department of Physics & Astronomy, Clemson University, Clemson, SC

### Wind measurements at altitudes from the troposphere to the thermosphere

An important advance in our understanding of the dynamics at all levels of the atmosphere, from the troposphere to the middle and upper thermosphere, came about when the so-called MST (Mesosphere/Stratosphere/Troposphere) radar wind measurement techniques were developed in the 1970's and 1980's. In particular, the full range and strong influence of mesoscale fluctuations with time scales of a few hours or less and spatial scales of hundreds of meters to a few kilometers became evident. The strong vertical coupling between atmospheric layers over a broad range of altitudes due to those fluctuations was shown clearly by the new techniques. In addition, incoherent scatter radar measurements provided some of the most extensive neutral wind measurements at ionospheric heights with the exception of some of the satellite missions that came later. Recent developments in analysis techniques for obtaining thermospheric winds from incoherent scatter radar data now offer the potential for obtaining wind profiles at E-region heights with unprecedented time and altitude resolution. An overview of the measurement techniques and some of the implications for our understanding of the associated dynamics will be reviewed, as well as the need for future measurements.

F. D. Lind
MIT Haystack Observatory, Westford, MA
**Next generation geospace radio arrays**

Radio and radar instrumentation plays a key role in the observation of the Geospace environment. Ground based radio instrumentation, and incoherent scatter radar in particular, has provided a sustained record of observation and scientific discovery. Ongoing technological trends, such as the exponential improvement in computing technology, have greatly changed how we operate existing instrumentation and the capabilities which are possible in future designs. Recent efforts have led to the the development of radio arrays which have extraordinary capabilities. To date the majority of these instruments have been developed and used for applications in Radio Astronomy. Radio arrays can be constructed in a wide variety of scale sizes and spatial distributions. When combined with one or more transmitters it is possible to produce active radar systems or passive radars using transmitters of opportunity. This includes incoherent scatter capability if sufficient power aperture is achieved. Advanced radio arrays are digital instruments with measurement techniques implemented as software running on high performance computing systems. This computing capacity is used to control, filter, and interpret the flow of information from the sensor elements. In many cases this information can be used to simultaneously address multiple applications and this ability can be enhanced with appropriate instrument design. When applied to Geospace, advanced radio arrays can provide a wide range of scientific capability and enable measurements from the lower atmosphere, into the ionosphere, through the heliosphere, and to the surface of the Sun. The principles by which we design such instruments are guided by the scientific scope we allow ourselves. This scope determines the potential for enabling future discoveries and is a key element in the overall value of the instrumentation to society. I will discuss future technological trends which will shape the next generation of Geospace radio arrays, define the principles for guiding their development, and highlight examples from on-going work which inform us of their potential.

J. W. Meriwether
Department of Physics & Astronomy, Clemson University, Clemson, SC
**Optics and radar measurements: Complimentary attributes to solving aeronomic problems**

Numerous examples show that the combination of ground-based optical and radar measurements represents a powerful tool in aeronomy for addressing ion-neutral coupling problems relating to the chemistry and dynamics of the upper atmosphere region. The possible problems depend in part on the sensitivities of the optics and the incoherent scatter radar and in part on the location of the observing site whether polar, mid-latitude, or equatorial. As an example, the improvement in the Fabry-Perot interferometer sensitivity provided by the use of a good quality CCD camera has opened new pathways for addressing old ion-neutral coupling problems that had never been resolved.

M. A. Milla[1] and E. Kudeki[2]
(1) Radio Observatorio de Jicamara, Instituto Geofísico del Perú, Lima, Perú
(2) Department of Electrical and Computer Engineering, University of Illinois at Urbana-Champaign, Urbana, Il

## Incoherent scatter theory and the effect of Coulomb Collisions

In 1958, the first incoherent scatter radar measurements were successfully conducted by Kenneth Bowles using a 41 MHz radar system. Soon after this experiment, different scientists, including Don Farley, developed the theory of incoherent scattering of radio waves by plasma density fluctuations. Different approaches were followed, but all arrived to the same results. In particular, Dougherty and Farley [1960] and Farley et al [1961] followed the fluctuation-dissipation or generalized Nyquist noise theorem to develop their theory. At the same time, the construction of the Jicamarca Radio Observatory was taking place near Lima, Peru. First observations using the entire antenna were conducted in 1962; however, the initial results obtained puzzled the research community. The Jicamarca radar was built with the goal of measuring the ion gyro-resonance in the equatorial ionosphere in order to determine plasma composition; the idea was to use Jicamarca as a mass spectrometer for the ionosphere. However, no signatures of the gyro-resonance were observed in the initial F-region incoherent scatter observations at Jicamarca. Soon, the reason for these results was explained. Farley [1964] described that the lack of gyro-resonance signatures on the radar measurements was an effect of Coulomb collisions. This was the beginning of a series of investigations and studies that were conducted in order to understand the different "effects" that the Coulomb collision phenomena had on determining the shape of the incoherent scatter spectra measured with the Jicamarca radar. In this presentation, we will describe the most recent work developed by Kudeki and Milla [2011] and Milla and Kudeki [2011] in studying Coulomb collision effects on incoherent scatter radar signals when radar beams are pointed perpendicular to the Earths magnetic field (B). To study these effects, a procedure to estimate the spectrum of plasma density fluctuations was developed based on simulations of particle trajectories in collisional plasmas. We have recently generalized this procedure to consider the case of multiple ion components in order to study the characteristics of the incoherent scatter spectrum in O+, H+, and He+ plasmas, which is needed for the analysis of topside perpendicular-to-B observations at the Jicamarca Radio Observatory. We will report on the development of this approach and on the characteristics of the spectrum models that were developed. The simulation results show that the ion collision process can be fairly well approximated as a Gaussian motion process, a model that has been previously studied in the literature by different authors. However, in the case of electron collisions, the process is not Gaussian having a complicated dependence on plasma parameters. As it will be discussed, electron collisions have a significant impact on the shape of the incoherent scatter spectrum. The ultimate application of the models that were developed is the simultaneous estimation of plasma drifts, densities, and temperatures of the topside equatorial ionosphere in perpendicular-to-B experiments at Jicamarca.

M. J. Nicolls
SRI International, Menlo Park, CA

## AMISR: Review of results, and planning for the future

AMISR operations at the Poker Flat Research Range are nearing 10 years, and operations at the Resolute Bay Observatory have surpassed 5 years. The major results and contributions from these systems will be presented. With the Poker Flat Incoherent Scatter Radar (PFISR), these include fundamental contributions to our understanding of auroral electrodynamics and substorm initiation, the nature of storm-enhanced density, and ion-neutral coupling in the auroral region. With the Resolute Bay Incoherent Scatter Radar (RISR-N), these include contributions to our understanding of the formation and evolution of polar cap patches and polar cap aurora. Unaddressed and active areas of investigation will be discussed.

AMISR's flexible operations approach has allowed for a new class of operations, where experiments are scheduled and transitioned fast and seamlessly, and where continuous operations are both feasible and cost effective as demonstrated by PFISRs continuous dataset since March of 2007. This approach allows for new studies not possible before, from scheduling short satellite conjunctions, to performing long-term analyses, to sharing radar time amongst multiple users. Suggestions for future areas of development will be outlined.

Technically, AMISR technology requires updating given obsolescence and performance issues especially with respect to the solid state power amplifier and the low-noise amplifier front-end, two key components in the antenna element unit. Plans and progress for updating these components, and other technical development areas, will be outlined.

Finally, recent opportunities will be described as we move toward the process of choosing new sites and new science for AMISR. Thoughts on appropriate strategies will be sketched with the goal of engendering community support.

E. Nossa[1], D. L. Hysell[1], M. F. Larsen[2], and M. P. Sulzer[3]
(1) Cornell University, Ithaca, NY
(2) Clemson University, Clemson, SC
(3) Arecibo Radio Observatory, Arecibo, Puerto Rico

## High time- and height-resolution neutral wind profiles in the daytime E layer based on Arecibo World Day data.

A new method for estimating high-resolution vector neutral wind profiles in the E region has been developed. Using regularization methods and computer optimization, high time- and height-resolution neutral wind profiles can be obtained from datasets collected in the standard World Day mode at Arecibo. MRACF data collected while the feed system is swinging are used to estimate ionospheric electric field though second-order Tikhonov regularization. The estimates are subsequently combined with E-region coded long-pulse data to estimate the neutral wind profiles. The required computations this time are performed iteratively using the method of conjugate gradients and employing sparse math. During the process, the E-region composition is calculated by incorporating an equilibrium photochemistry model in the fitting. Several example datasets will be shown. The features in the estimated wind profiles are broadly consistent with previous experiments involving chemical releases and other methods.

M. M. Oppenheim
Boston University, Boston, MA

### The ongoing saga of the Farley-Buneman instability: from the sun to the lower ionosphere

Over 20 years ago, my Ph.D. advisor, Niels Otani, “suggested” I study an obscure thesis topic: the non-linear dynamics of the Farley-Buneman Instability in the lower ionosphere. He was planting a seed that would grow into a career simulating plasma turbulence, tracking meteors, modeling global Magnetosphere-Ionosphere-Thermosphere coupling, and trying to understand the solar atmosphere. This talk will trace how a thesis developed many branches but never broke off from the original trunk, the study of a plasma instability first understood by Don Farley.

R. F. Pfaff
NASA/Goddard Space Flight Center, Greenbelt, MD

### Key features of the Farley-Buneman instability revealed by sounding rockets flown in the equatorial and auroral electrojets

Don Farley’s seminal discovery and theoretical development of the collisional two-stream instability (known as the Farley-Buneman instability) has proven to be a fundamental process that is a common feature of the earth’s geospace environment - specifically in the lower ionosphere of the auroral/polar cap regions as well as in the equatorial electrojet. Electric field observations launched on sounding rockets in both the two-stream unstable auroral and equatorial electrojets have considerably advanced our knowledge of these waves, including their amplitude and detailed waveforms, spectra, phase velocity, instability threshold and conditions for growth, and non-linear evolution. We provide an overview of some of the key results from numerous rocket experiments and relate them to Don Farley’s original contributions over 50 years ago.

F. S. Rodrigues[1], J. A. Smith[1], M. J. Nicolls[2], R. H. Varney[2], M. A. Milla[3], C. Martinis[4], and J. Arratia[5]
(1) The University of Texas at Dallas, Richardson, TX
(2) SRI International, Menlo Park, CA
(3) Jicamarca Radio Observatory, Lima, Peru
(4) Boston University, Boston, MA
(5) A. G. Mendez University System Student Research Development Center, San Juan, Puerto Rico

### AMISR-14 at Jicamarca: New observations of equatorial spread F

In August 2014, a 14-panel version of the Advanced Modular Incoherent Scatter Radar (AMISR-14) system was deployed at the Jicamarca Radio Observatory in Peru. This temporary installation is part of the preparation for a longer-term deployment of the system in Argentina, which will investigate magnetic conjugate phenomena with the Arecibo Observatory in Puerto Rico. For approximately a week, a few radar modes were attempted in order to test the system and to make coherent backscatter radar observations of field-aligned irregularities associated with equatorial electrojet, 150-km echoes, and equatorial spread F (ESF).

This talk will present results of experiments carried out for observations of ESF. For that purpose, the AMISR-14 system was operated at 445 MHz, and used a 28-bit coded pulse soundings, with an IPP of 4 ms. The digital steering capability allowed us to make interlaced measurements with the beam pointed at seven different directions including 20.8 and 9.6 degrees off-zenith to the West and to the East of the radar site, in addition to vertical observations and observations to the North and South of the site (off-perpendicular to the magnetic field). The setup would allow us to study the dynamics of ESF events in the magnetic equatorial plane with a much wider view (but lower zonal resolution) than possible with the interferometric radar imaging technique.

Pre-midnight ESF events were successfully detected on the nights of August 20 and 21. The 50 MHz Jicamarca Unattended Long-term Investigations of the Ionosphere and Atmosphere (JULIA) was operated alongside the AMISR-14 and confirmed the occurrence and nearly collocation of sub-meter and meter scale irregularities. Echoes at UHF were of the order of a few dB above the noise level. According to JULIA, however, the events were weaker (in terms of SNR values) than fully developed ESF plumes. The multi-beam observations allowed us to track zonal motion of the scattering structures, their vertical development and, at times, their decay. More details about the experiment and results will be described during this presentation.

J. P. St-Maurice
University of Saskatchewan, Saskatoon, SK, Canada

**Farley-Buneman waves at large aspect angles**

It is now well-known that the Farley-Buneman (FB) instability mechanism provides an excellent explanation for the presence of large amplitude plasma waves in the cm to few m wavelength range in the high latitude E region whenever the ambient electric field exceeds 20 mV/m. From linear theory considerations, the structures are expected to be strongly field-aligned, namely, to have wavevectors that are within 2 degrees of perpendicularity. That is to say: no aspect angle greater than 2 degrees away from perpendicularity to the geomagnetic field is expected to grow. However, while cm to m-size structures are, as expected, regularly observed to be very nearly perpendicular to the magnetic field, there are many notable exceptions. These include older Canadian CW experiments at 4 degrees or more off perpendicularity to the magnetic field, EISCAT and COSCAT observations at aspect angles as much as 15 degrees away from perpendicularity, and so-called HAIR echoes detected at close ranges by SuperDARN HF radars. While one way to deal with this situation is to introduce mode-coupling with the background ionosphere acting as a source of modes, a promising approach to explain the large aspect angle observations is based on the fact that the eigenfrequency of FB waves is actually a (weak) function of altitude. One way to deal with this is to shy away from plane wave analysis along the magnetic field and to use an Eikonal approach, where the frequency is the weakly space-dependent derivative of the phase so that the component of the wavevector along the geomagnetic field becomes time-dependent. Calculations indicate that after a time scale of the order of 1 s, the aspect angle becomes so large that the structures can no longer grow. However, this does not mean that they suddenly vanish. Instead, as the aspect angle grows, the structures decay, but gently, at least at first. The larger the amplitude has grown before the aspect angle stops the growth, the wider the range of aspect angles over which large amplitude structures will be seen. It should be noticed that as the aspect angle grows, the phase velocity of the structures also goes down. Indeed all the large aspect angle observations show phase velocities well below the ion-acoustic speed, meaning that if they are related to the FB wave instability mechanism, they should be damped, that is, they are indeed losing amplitude. The basic point, however, is that losing amplitude is not synonymous with being of a negligible amplitude.

C. E. Valladares
Boston College, Boston, MA

**LISN - The distributed observatory for the Jicamarca IS radar**

The low-latitude ionospheric sensor network (LISN) is an array of small instruments that operates continuously as a real-time distributed observatory to understand the complex day-to-day variability and the extreme state of disturbance that occurs in the South American low-latitude ionosphere. The LISN observatory specifies the state of the ionosphere in terms of the TEC values and the initiation and transport of plasma bubbles across the South American continent. To achieve this regional nowcasts, the LISN system includes 45 GPS receivers, 5 flux-gate magnetometers distributed on 2 base lines and 3 Vertical Incidence Pulsed Ionospheric Radar (VIPIR) ionosondes deployed along the magnetic meridian that intersects the magnetic equator at 68° W.

The center (not literally) of the LISN observatory is the Jicamarca IS radar, which provides more precise and complete measurements of the ionosphere and atmosphere. Jicamarca ISR measurements serve to compare LISN results obtained during assimilations runs of the GPS TEC and VIPIR densities. In addition, a team of engineers from Jicamarca oversee normal operations of the LISN network. They are vigilant of data uploads, participate in new installations, and respond promptly for equipment repair. As the success of the LISN project hinges on the Jicamarca ISR, it is necessary to remember the legacy of a small group of scientists from the USA that 50 years ago decided to spend several years working at the Jicamarca ISR and train a cadre of Peruvian scientists and engineers. I will provide a summary of recent instrument installations and new processing algorithms that have been developed under the LISN project.

J. Vierinen
MIT Haystack Observatory, Westford, MA

**New results from upgraded plasma line receivers at Arecibo, Haystack, and Sondrestrom**

Recent upgrades to plasma line receivers at Haystack, Arecibo, and Sondrestrom allow observing the full incoherent scatter spectrum simultaneously. Several examples of interesting plasma line measurements performed recently using these receivers are discussed. Examples include high resolution ionospheric wave measurements, auroral enhancements, high resolution E-region dynamics, and up-down shifted plasma line asymmetry. Several possible future uses for the new receivers are discussed.

R. F. Woodman
Instituto Geofísico del Perú, Lima, Perú

**An Early History of the Jicamarca Radio Observatory: Don Farley's contributions**

The Jicamarca Radio Observatory was conceived and built during the early 1960's, at the beginning of the Space Age as an alternative, using the Incoherent Scatter technique, to the in situ measurements made by means of rocket and satellites. The Sputnik and the Explorer I satellites had been launched. The Incoherent Scatter technique had been proposed by William B Gordon, and. Ken Bowles had proven that it worked. Gordon was expecting that the echoes had a bandwidth corresponding to the Doppler shift of the scattering electrons, but Bowles' experimental results showed that it was determined by the speed of the ions and that their gyrating frequency around the magnetic field lines could be used to determine the ion composition of the ionosphere. This led Bowles to propose the construction of the Jicamarca Radio Observatory were it is located, close to the Magnetic Equator. Its early history. leading to the first results, will be presented, including Don Farley's theoretical and experimental developments which broaden the spectrum of the parameters that could be measured.