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Equatorial ionospheric specification and forecasting with HF beacons, radar,  
and simulation

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We review the accomplishments of the Cornell effort to study and forecast equatorial spread F in the Peruvian sector. Equatorial spread F (ESF) is a phenomenon associated with plasma convective instability in the postsunset equatorial F-region ionosphere. Convective instability can disrupt ground- and space-based radio communication, navigation, and imaging systems. While the effects have been known about for 80+ years, they remain difficult to predict and mitigate. Our forecast strategy incorporates a novel AFOSR-supported numerical ionospheric instability model which includes both 1) nonequipotential field lines and 2) complete transport in the (E), valley, and F regions. It can be initialized and forced solely with data from the Jicamarca Radio Observatory. The model has been shown to be able to reproduce, qualitatively and quantitatively, plasma density irregularities observed at Jicamarca during campaigns conducted under a range of background conditions. This has been demonstrated in an extensive series of AFOSR-supported experimental campaigns. While the simulation code does not produce false alarms, it occasionally fails to predict irregularities. These failures could be due to causes outside the ionospheric region visible to Jicamarca. To investigate this shortcoming, we deployed a network of HF beacon transmitters and receivers in the Peruvian sector under this award.

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Final Report: Equatorial ionospheric specification and forecasting  
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## Abstract

We review the accomplishments of the Cornell effort to study and forecast equatorial spread  $F$  in the Peruvian sector. Equatorial spread  $F$  (ESF) is a phenomenon associated with plasma convective instability in the postsunset equatorial  $F$ -region ionosphere. Convective instability can disrupt ground- and space-based radio communication, navigation, and imaging systems. While the effects have been known about for 80+ years, they remain difficult to predict and mitigate. Our forecast strategy incorporates a novel AFOSR-supported numerical ionospheric instability model which includes both 1) nonequipotential field lines and 2) complete transport in the  $E$ , valley, and  $F$  regions. It can be initialized and forced solely with data from the Jicamarca Radio Observatory. The model has been shown to be able to reproduce, qualitatively and quantitatively, plasma density irregularities observed at Jicamarca during campaigns conducted under a range of background conditions. This has been demonstrated in an extensive series of AFOSR-supported experimental campaigns.

While the simulation code does not produce false alarms, it occasionally fails to predict irregularities. These failures could be due to causes outside the ionospheric region visible to Jicamarca. To investigate this shortcoming, we deployed a network of HF beacon transmitters and receivers in the Peruvian sector under this award. The beacons use PRN coding and provide measurements of group delay (pseudorange), Doppler shift (time rate of change of optical path length), and amplitude. From the beacon data, the regional electron density can be estimated in three dimensions. Estimates are available once per minute.

We report here on results obtained during this, the final year of the project. The beacon data analysis code was further refined and streamlined and tested on new campaign data. A paper describing the analysis code in detail and demonstrating its performance was published in 2021, and experimental results, including forecast results, were presented in several conferences and workshops. One final experimental campaign was conducted in September of 2021, and the results are being analyzed and prepared for dissemination now.

The HF beacon network in Peru has been expanded beyond its original design specification and is now composed of three transmitting stations and six receiving stations. We will continue to maintain and exploit the unique resource and develop its space weather forecast potential under other auspices now that this award has concluded.

## Introduction

This is the fifth and final report on our project to study irregularities in the low-latitude  $F$ -region ionosphere due to equatorial spread  $F$  (ESF). It is well known that these irregularities degrade communication, navigation, and imaging systems based on the ground and in space. With support from AFOSR, the Cornell team developed a special 3D numerical simulation of the underlying plasma physics. Our simulation differs from others in some important ways. For one, it solves the electrostatic potential fully in three dimensions. For another, it solves the ion transport equations fully in all ionospheric strata including the valley region. This allows it to reproduce the evening vortex, the dominant dynamical feature in the postsunset equatorial ionosphere, and to simulate the instabilities and irregularities that emerge from it.

We have conducted a number of campaign studies based at the Jicamarca Radio Observatory, using campaign data to predict ESF phenomena “after the fact.” Overall, the numerical simulations have been able to reproduce the ionospheric irregularities seen by the radar insofar as their occurrence, morphology, and rates of development. Our simulation does not produce false alarms, implying that there are no necessary conditions for instability being neglected. Some missed detections have occurred, however, implying that the simulation may be unaware of sufficient conditions for instability, i.e., disturbances caused externally to the experimental domain propagating into it. Such events are the main remaining obstacle to reliable forecasts.

This project had the overall goal of specifying the  $F$ -region ionosphere, stable and unstable, in the vicinity of Jicamarca and not just the volume directly over the radar. With the help of the Jicamarca staff, we deployed HF beacon stations across Peru. While HF beacons are not novel by themselves, ours are unique in that they employ PRN binary phase coding. Our beacon receivers decode the signals and infer their group delay, Doppler shift, and amplitude. Other observables including the polarization and bearing of the received signal can be deduced as well, although we do not yet exploit this capability. The beacon data are furthermore invertible and can be used to estimate the regional electron density in a 3D volume around Jicamarca. While the beacons only interrogate the bottomside, the ISR gives information about the topside directly overhead, and the picture is supplemented by GNSS TEC data acquired over a broad range of zenith angles.

This project had three specific objectives. The first was to expand our experimental database through regular campaigns at Jicamarca. We acquired data spanning a broad range of seasonal, solar flux, and geomagnetic conditions than was previously available. The second was to maintain and exploit the beacon network. The network surpassed its design goal and now includes nine stations (three transmitters and six receivers). The network has been highly reliable and continues to function at the present time. The third objective was to demonstrate the utility of the network for regional remote sensing and forecasting. For this purpose, we formulated and reformulated an analysis code which reconstructs the ionosphere regionally on the basis of the HF data for the purpose of initializing our numerical forecast code. The two codes together constitute an incisive instability forecast tool which could be made operational relatively easily.

## Accomplishments

The main accomplishments of our project are itemized below.

- ▷ The analysis code we use for reconstructing the regional ionosphere from the HF beacon data and the related signal chain is in place, functional, and quite usable. The code can incorporate data from GNSS receivers in addition to data from sounders and the incoherent scatter radar. It can use biquintic B-splines for horizontal representers now as an alternative to bicubic splines. It can make use of multiple electron density profile parametrizations as options. Finally, it includes variational sensitivity analysis for inferring focusing and absorption from amplitude data. This is a novel development which has not seen much attention in the literature. Over the last year in particular, this part of the code was extensively tested and simplified. Development work continues, and the analysis code is now being augmented to incorporate sensitivity analysis in a more efficient adjoint framework. This work will continue past the threshold of this AFOSR award.

- ▷ Additional campaigns have been conducted at Jicamarca. The list of campaigns conducted under this award now stands at:

March 29 – April 1, 2017

July 24, 25, 2017

July 31 – Aug 3, 2017

December 16–20, 2017

January 10–13, 2018

April 2–6, 2018

October 1–4, 2018

March 22–27, 2019

June 10–11, 2019

December 2–5, 2019

September 21–24, 2020

September 21–25, 2021

Note that the Jicamarca Radio Observatory was closed on two occasions in 2020 and 2021. This is the reason for some of the larger gaps later in the schedule.

- ▷ The HF beacon network stands at nine stations (see Figure. 1). Maintaining the stations in the era of COVID-19 has been challenging, but all stations are presently functioning, and an enormous dataset has been acquired. The network is a tremendous resource for space weather surveillance and forecasting and will be incorporated in forecast activities and campaigns under other auspices going forward.
- ▷ Results from the beacon network were presented most recently at the Fall 2020 AGU, at CEDAR 2021, and at the URSA GA in Rome in 2021 and will be revisited in the Fall 2021 AGU.
- ▷ Data from the ALTAIR radar acquired during the NASA WINDY campaign in August, 2017, and the Too-WINDY campaign in June of 2019 were processed and incorporated in this work to which they are highly relevant. Results were published in two recent publications.

- ▷ Overall, our forecast strategy seems to be successful and stands at the verge of being operational. What is required now is the development of an assimilative framework for coupling the beacon network data with the ionospheric DNS. Support from other agencies for this effort is being sought.

## Biography

The following papers were published under this award:

Hysell, D. L., Baumgarten, Y., Milla, M. A., Valdez, A., & Kuyeng, K. (2018). Ionospheric specification and space weather forecasting with an HF beacon network in the Peruvian sector. *Journal of Geophysical Research: Space Physics*, 123, 6851–6864. <https://doi.org/10.1029/2018JA025648>

Hysell, D. L., Milla, M. A., & Kuyeng, K. (2019). Radio beacon and radar assessment and forecasting of equatorial F region ionospheric stability. *Journal of Geophysical Research: Space Physics*, 124, 9511–9524. <https://doi.org/10.1029/2019JA026991>

Hysell, D. L., Rao, S., Groves, K. M., & Larsen, M. F. (2020). Radar investigation of postsunset equatorial ionospheric instability over Kwajalein during project WINDY. *Journal of Geophysical Research Space Physics*, 125, e2020JA027997. <https://doi.org/10.1029/2020JA027997>

Hysell, D. L., Rao, S., & Larsen, M. F. (2020). Equatorial F-region plasma waves and instabilities observed near midnight at solar minimum during the NASA Too WINDY sounding rocket experiment. *Journal of Geophysical Research: Space Physics*, 125, e2020JA028408. <https://doi.org/10.1029/2020JA028408>

Hysell, D. L. (2020). From Instability to Irregularities, *The Dynamical Ionosphere*, Massimo Materassi, Biagio Forte, Anthea J. Coster, and Susan Skone (Eds), Elsevier, <https://doi.org/10.1016/B978-0-12-814782-5.00011-X>

Hysell, D. L., Rojas, E., Goldberg, H., Milla, M. A., Kuyeng, K., Valdez, A., et al. (2021). Mapping irregularities in the postsunset equatorial ionosphere with an expanded network of HF beacons. *Journal of Geophysical Research: Space Physics*, 126, e2021JA029229. <https://doi.org/10.1029/2021JA029229>

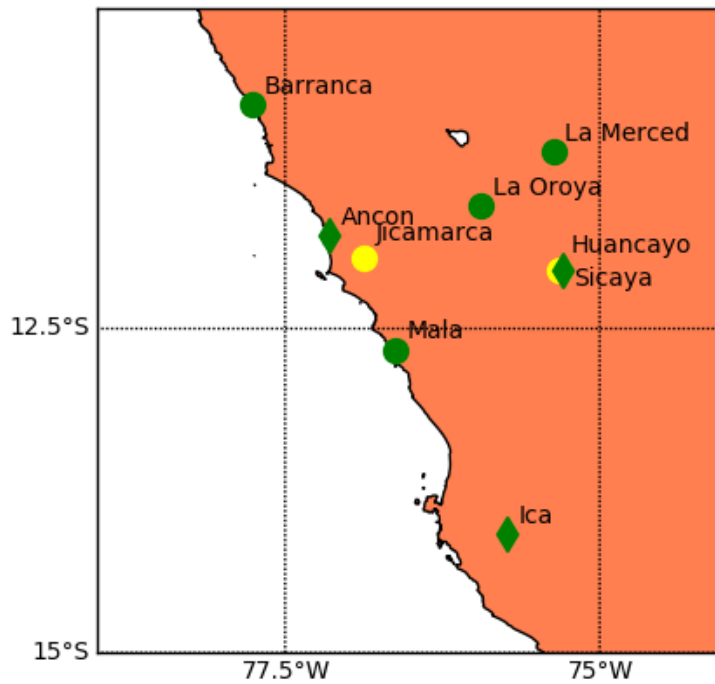


Figure 1: Sites for beacon stations in the Peruvian network. Transmitters are located in Ancon, Ica, and Huancayo. Receivers are at Barranca, Jicamarca, Mala, Sicaya, La Oroya, and La Merced. Pairs of receive stations are deployed at Jicamarca and Sicaya which can be used for interferometry or dual-polarization studies.