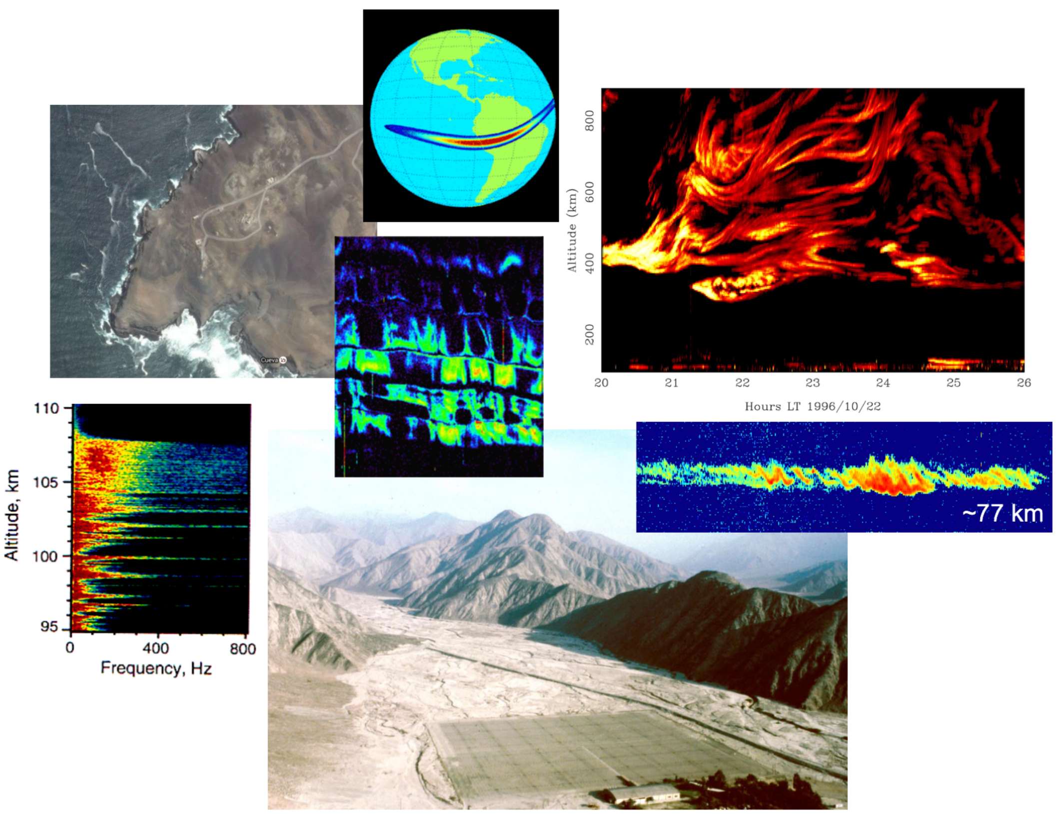
A NASA Sounding Rocket Campaign in Peru --

Unprecedented, Preeminent Science at a Unique Observing Site



A White Paper

Prepared by Members of the International Space Science Community

January 25, 2018

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Executive Summary

A sounding rocket campaign in Peru is proposed which presents an opportunity for NASA and NSF to carry out unique, pre-eminent scientific space research at the magnetic equator. The main motivation for the campaign is to carry out fundamental scientific research of natural processes in the earth's ionosphere and upper atmosphere which are unique to the low latitude region of geospace, and specifically to the near-space region that includes the earth's magnetic equator. Examples of such processes include the equatorial electrojet, the daytime "150 km" echo region, regions of nighttime ionospheric turbulence known as equatorial "spread-F", the equatorial anomaly region, and the equatorial mesosphere. These phenomena (as well as many others) include major unanswered questions that would be investigated by scientific instruments carried aloft into the equatorial ionosphere on sounding rockets while detailed, simultaneous observations are carried out by ground-based instrumentation, notably the Jicamarca radar in Peru. Although theoretical progress has been made toward understanding some of these phenomena, many critical questions remain. Indeed, the lack of detailed measurements remains the single greatest obstacle towards making progress in our understanding. This proposed campaign would remedy this situation by gathering the necessary observations of key, targeted geophysical phenomena using probes launched on sounding rockets flown in conjunction with radar and other ground-based observations.

In addition to scientific understanding, the natural phenomena to be investigated with this rocket/radar campaign attack many space weather problems unique to the low latitude ionosphere. These include the need to predict the large scale disruption of radio waves that wreak havoc on communications and navigation systems which results from the disturbed nighttime ionosphere at the equator. From the standpoint of both scientific understanding and space weather applications, a consensus has evolved that fundamental measurements are needed to make progress and that the necessary data are best obtained from focused sounding rocket research missions.

The campaign would notionally consist of 10-14 sounding rockets to be launched at the existing rocket range at Punta Lobos, Peru, which is operated by the Peruvian space agency, CONIDA, and is ideally situated to carry out these scientific investigations. Punta Lobos has been used previously for two major NASA rocket campaigns (Antarqui, 1975; Condor, 1983) and could easily accommodate the proposed "standard" NASA sounding rockets envisioned here. Furthermore, the launch location is near the world-renowned, largely NSF-funded Jicamarca radar which would provide essential observations for all anticipated investigations.

Advances in scientific instruments, payload configurations, radar modes, and ground observing systems promise to provide significant new scientific data and discoveries that go far beyond the achievements of previous NASA rocket campaigns. The new observations are particularly welcomed as theoretical and modeling work has advanced significantly in the many decades since the previous campaigns. Peruvian scientists, primarily at the Jicamarca radar, would be fully engaged in the rocket/radar investigations including data analysis and interpretation. The Peruvian space agency, CONIDA, has indicated, at least informally at this time, that they would enthusiastically welcome such a campaign. The campaign proposed here promises to significantly advance our knowledge of a number of important, critical processes that characterize the earth's ionosphere and upper atmosphere that only exist at the equator.

I. Introduction

Ever since the earliest days of space research, the combined ionosphere/upper atmosphere at the Earth's equator has been identified as the seat of spectacular natural phenomena which represent important physical processes unique to this region of space. At the equator, the horizontal magnetic field lines help characterize an ionosphere that is very different than that which is found in the high latitude auroral zone and polar cap, regions influenced by energetic particles, field-aligned currents, and electric fields that originate in the magnetosphere and map down along the nearly vertical magnetic field lines. At low latitudes, rather, this largely "self contained" region of the ionosphere/upper atmosphere gives rise to systems of intrinsic currents, electric fields, and neutral dynamics that produce a host of waves and turbulence that vary markedly with altitude and range and cover spatial distances from planetary scales to wavelengths of less than a meter.

It thus is no surprise that Earth's low latitude geospace region has captivated the international space community since the earliest days of the space age, solidly engaging the experimental, theoretical, and modelling community. Indeed, dedicated satellites such as the San Marco and C/NOFS satellites as well as a host of NASA sounding rocket campaigns carried out since the early 1960's have focused their research on understanding the many important processes unique to the low latitude ionosphere and upper atmosphere. Further, the world's largest ionospheric radar, the Jicamarca Radio Observatory in Peru, was built expressly to probe the ionosphere above the magnetic equator, where it has operated continuously for over 50 years, supported primarily by the National Science Foundation.

In recent years, the importance of understanding the many space weather problems unique to the low latitude ionosphere has been identified as a top priority, particularly the need to predict the large scale disruption of radio waves that wreak havoc on communications and navigation systems which results from the disturbed nighttime ionosphere at the equator. From the standpoint of both scientific understanding and space weather applications, a consensus has evolved that fundamental measurements are needed to make progress and that the necessary data are best obtained from focused sounding rocket research missions.

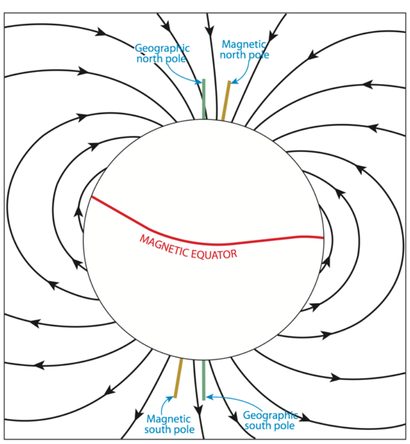

Figure 1. Earth's dipole magnetic field is offset from the geographic poles.

The proposed sounding rocket campaign described here will examine the region of geospace near the earth's magnetic equator where the magnetic field lines are exactly horizontal. The magnetic equator is offset from the geographic equator because the earth's dipole magnetic field is offset from the earth's geographic poles, as depicted in Figure 1. As described herein, a large number of unique geophysical phenomena in the near-earth region of space occur only at or near the magnetic equator. These processes constitute some of the most important and spectacular phenomena in space physics represent the core of the proposed research to be addressed with the sounding rocket investigations discussed in this document.

There are two driving requirements for the proposed campaign: (1) it must take place within 1 degree of the magnetic equator which is where a number of key geophysical phenomena to be explored with the rocket probes take place (see discussion below); and (2) it must be supported by a very capable set of ground-based instrumentation, including an incoherent scatter ionospheric radar. Fortunately, there exists a very well-suited rocket range at Punta Lobos, Peru near the state-of-the-art Jicamarca Radio Observatory very near the magnetic equator in Peru that is ideal for the "rocket/radar" campaign envisioned here, as shown in Figure 2. Indeed, NASA has carried out a number of previous, very successful rocket/radar campaigns in Peru, as described in the next section.

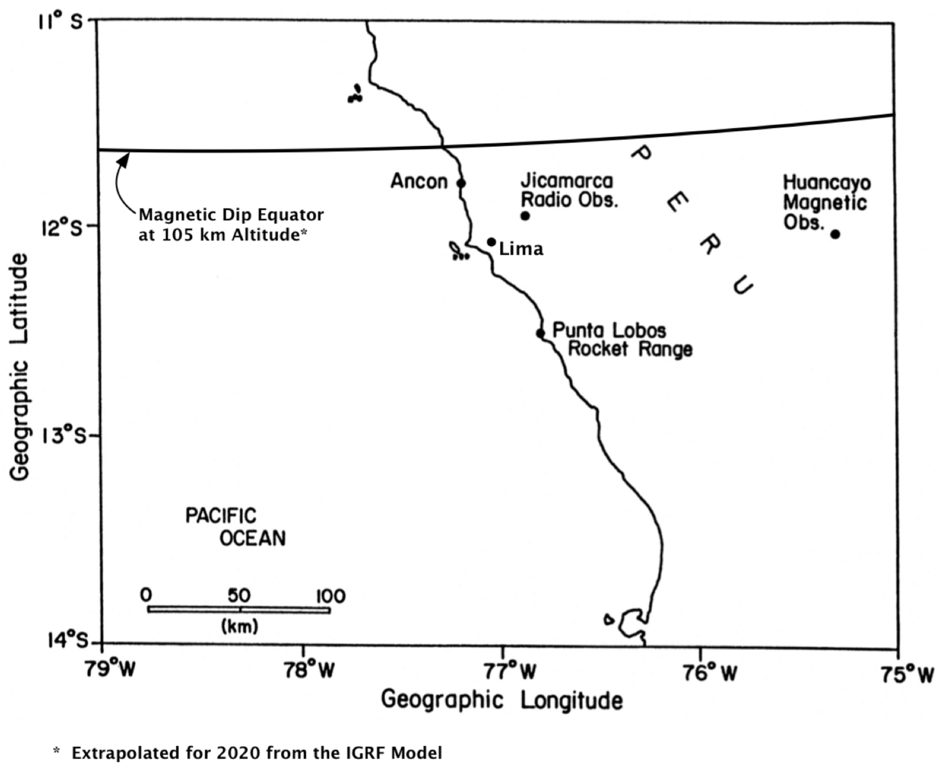

Figure 2. Map showing the location of the Punta Lobos Rocket Range, the Jicamarca Radio Observatory, the Huancayo Magnetic Observatory, and the magnetic equator.

The Punta Lobos rocket range continues to be operated today by CONIDA, the Peruvian space agency. The basic infrastructure at the range is in place, and NASA's familiarity with the range makes many aspects of the campaign planning and operations much easier. Furthermore, the range extends out on a prominence over the Pacific, permitting launches of rockets along azimuths to the west and south, ideal for the experiments envisioned here.

The scientific community has had two "community-wide" meetings at the NSF-sponsored CEDAR conferences in June, 2016 and June, 2017. Participants in the workshops included experimentalists, theorists, and modelers with interests in equatorial aeronomy, space plasma physics, and space weather, as well as representatives from NASA Headquarters (HQ) and the

Peruvian scientific community. The sounding rocket and the incoherent scatter radar experimental communities were well represented. Moreover, the audience included participants from outside these two groups, drawn by growing community interest in global space weather modeling, opportunities for deploying supporting instrumentation, and synergies between a low-latitude rocket campaign and the impending launches of the NASA satellite instruments that comprise the ICON and GOLD missions. At both meetings, a series of presentations was provided that highlighted examples of new, important scientific research that could be carried out in a future rocket/radar campaign. After consultation with NASA HQ, it was decided that a "white paper" (this document) would be written by members of the scientific community documenting the many different research problems that could be addressed, and resolved, with a future rocket-radar campaign. This white paper serves to document not only the scientific importance, but also the feasibility of carrying out such a campaign.

For planning purposes, this white paper puts forward a notional campaign, in order for the various agencies to understand the scope of the proposed investigations, at least at this time. Essentially, it is anticipated that a campaign of 10-14 sounding rockets will be supported by the NASA Sounding Rocket Program Office at the Wallops Flight Facility in Virginia where the rocket payloads will be designed, built, tested, and managed. The campaign would take place in 2022 and include an anticipated launch window that would encompass ~8-10 weeks. It would be carried out at the Punta Lobos launch range in Peru and would be a joint US-Peru scientific research program. The main focus would be on understanding unique and important processes in the ionosphere and upper atmosphere that only exist at the equator.

Indeed, the Peruvian space agency, CONIDA, has indicated, at least informally at this time, that it would welcome such a joint US-Peruvian campaign. NSF researchers have also shown strong enthusiasm for a future rocket/radar campaign involving Jicamarca and other ground-based instruments that it supports in this region. Indeed, this campaign presents an ideal opportunity to achieve common inter-agency scientific research important for both NASA and NSF, as well as an opportunity to enable important US-Peruvian scientific cooperation in space research.

An outline of this white paper is as follows: We begin with an overview of past NASA campaigns at the magnetic equator, notably in India, Peru, and Brazil. We then present a scientific justification for the campaign, using examples of the many important pressing scientific problems that can only be addressed with sounding rockets launched at the equator in conjunction with a powerful science research radar. We then provide an overview of the Jicamarca radar and other ground-based instruments in South America that can be expected to participate in this campaign, followed by a brief description of the existing rocket range at Punta Lobos, Peru. This is followed by a top level outline of a "notional" campaign with respect to the number of rockets, duration of the campaign, etc., for initial planning purposes. We conclude with a summary.

This document is a starting point for what is anticipated to be a critically important research campaign that is certain to advance our understanding of the equatorial ionosphere and upper atmosphere by a significant degree.

II. Remarks on Past NASA Campaigns at the Magnetic Equator

In this section, we briefly review past NASA rocket campaigns that have been carried out at the magnetic equator since 1964.

In Figure 3, a map shows the existing launch sites within 1 degree of the magnetic equator at which NASA rocket campaigns have been carried out. As listed in the table below, this includes launches at Thumba, India, Punta Lobos, Peru, and Alcântara, Brazil. In addition, a number of launches took place in 1965 from a ship, the USS Croatan, which also included simultaneous observations from ground-based scientific equipment in Peru.

NASA Sounding Rocket Campaigns at the geomagnetic equator:

- 1964 India (Thumba) -- 4 rockets
- 1965 USS Croatan (off coast of Peru) -- 10 rockets
- 1970 India (Thumba) -- 6 rockets
- 1972 India (Thumba) -- 2 rockets (w/Germany)
- 1975 Peru (Punta Lobos) -- 19 rockets
- 1983 Peru (Punta Lobos) -- 18 rockets
- 1994 Brazil (Alcântara) -- 13 rockets
- 2022 Peru (Punta Lobos) -- ??

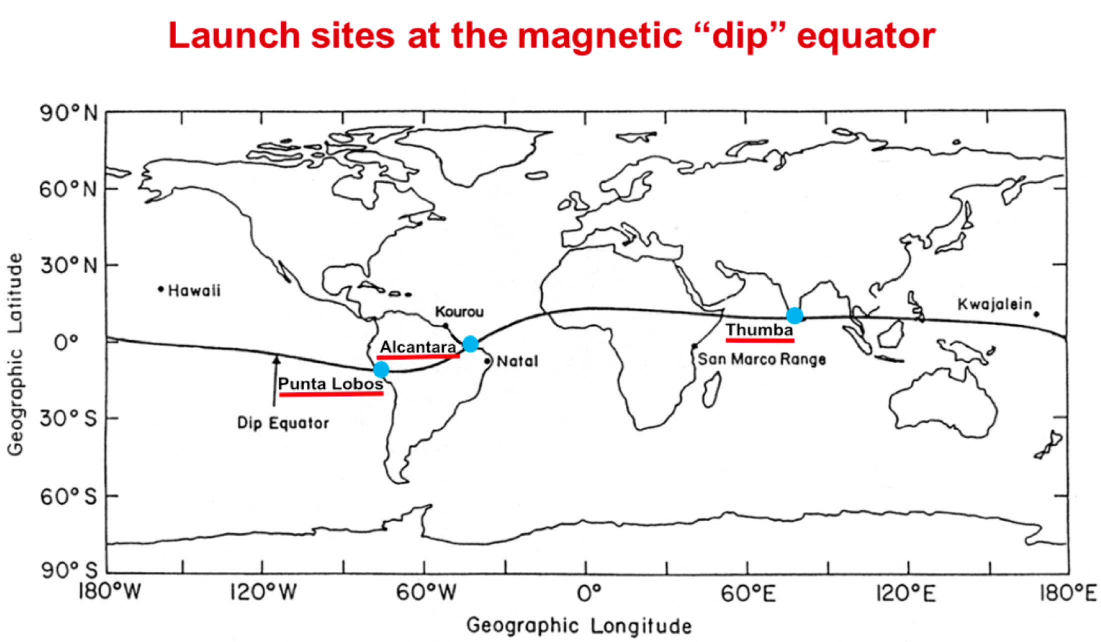

Figure 3. NASA launch sites near the magnetic equator where rocket campaigns have been carried out.

The most recent NASA campaigns at the equatorial equator were the Condor Campaign in Peru in 1983 and the Guará Campaign in Brazil in 1994. Both were enormously successful with a number of significant results that advanced our understanding of the equatorial ionosphere. Indeed, each had a strong publication record and fostered a number of graduate students and PhD theses. [For the Condor campaign, see, in particular, the special sections of the *Journal of Geophysical Research* that featured 6 papers on F-region results published in 1986; 4 papers on the Critical Velocity Effect results published in 1986; and 3 papers on Electrojet results published in 1987. For the Guará campaign, see, in particular, the special issue of *Geophysical Research Letters* published in 1997 that included 14 papers highlighting results from this campaign.]

An additional US campaign, Project EQUION, consisted of a single rocket which was launched in 1974 from Punta Lobos and was led by the Aerospace Corporation with instrumentation from the University of Texas at Dallas and included important involvement from the NSF-sponsored Jicamarca radar. The Wallops Flight Facility provided assistance and advice, particularly in the range planning. In fact, the Sounding Rocket Program Office at Wallops used the same Punta Lobos location for the NASA/Antarqui campaign which took place a year later. The science results of the EQUION project are published in Morse et al. [1977].

Fortunately, the Punta Lobos range in Peru is not only available, it is still being used for Peruvian rocket launches (see section V below). We anticipate another very successful NASA sounding rocket campaign to be carried out in Peru in 2022.

III. Scientific Justification for the Campaign

A rocket/radar campaign from Peru would enable NASA and NSF researchers to explore space physics phenomena found only at Earth's magnetic equator for the first time in several decades. In this section, we discuss several science research topics that illustrate some of the critical unknown processes in geospace that exist only at the magnetic equator and which would be particularly well-suited to be addressed by a dedicated sounding rocket/radar campaign. A list of candidate science "focus" areas, which is by no means inclusive, includes:

- Equatorial Electrojet Electrodynamics and Instabilities (Day and Night)
- Daytime "150 km" irregularities
- Spread-F plasma depletions and associated instabilities and turbulence
- Large scale vortices, shears, and enhanced winds/electric fields at sunset and sunrise
- Nighttime low latitude valley region
- Equatorial Temperature and Wind Anomaly
- Topside ionospheric studies
- Mesospheric turbulence, gravity waves, and instabilities

Beyond fundamental scientific research, understanding the equatorial ionosphere is vitally important for space weather research as its intrinsic irregularities and turbulence disrupt space-to-ground radiowave communication and navigation transmissions such as GPS more frequently and more dramatically than any other region of the ionosphere except the storm-time auroral ionosphere. Indeed, this region exhibits enhanced wave growth and turbulence because here the Earth's geomagnetic field is horizontal and charged particles travel along these fields for hundreds of km in relatively homogeneous conditions. In turn, this geometry forces the development of waves in order to dissipate energy. Irregularities associated with various processes in the equatorial ionosphere readily appear in radar echoes as illustrated in Figure 4.

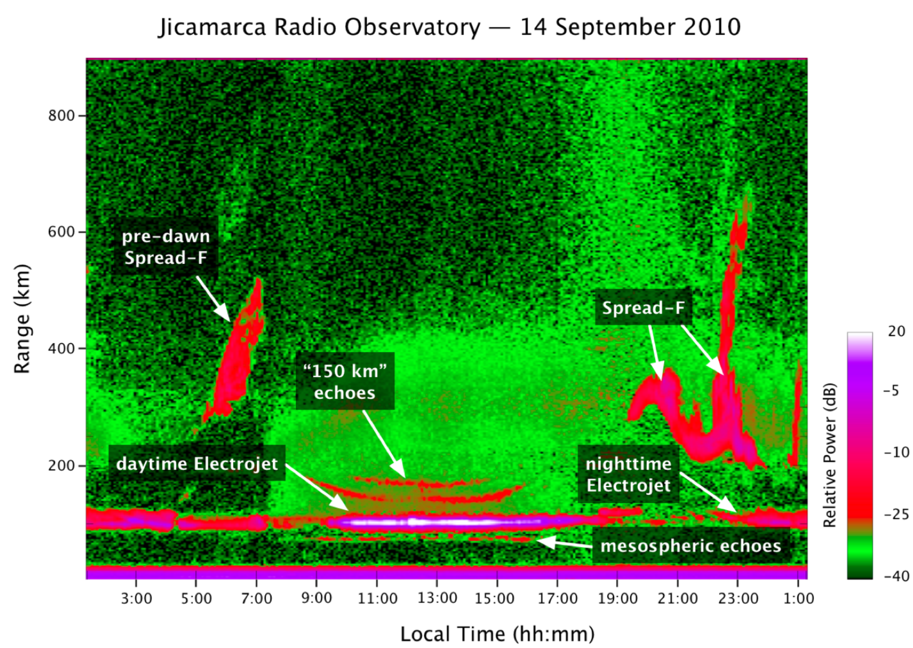

Figure 4. Observations over a 24 hour period from the Jicamarca Radar in Peru illustrating many different sources of irregularities that create radar backscatter echoes in the equatorial ionosphere.

Equatorial Electrojet and its Instabilities (Day and Night):

Electrojet Electrodynamics. The strongest current that comprises the world-wide system of currents in the lower ionosphere driven by the atmospheric dynamo is the equatorial electrojet (see Figure 5). This current system exists as a result of both the dynamo action at all latitudes and the enhanced conductivity set up precisely at the magnetic equator by the horizontal magnetic field geometry. At this location within the altitude range of 95-115 km, a vertical polarization field, **E**, creates a horizontal $\mathbf{E} \times \mathbf{B}$ electron drift which drives a current (since the ions are collision dominated) that reinforces the small, existing dynamo current thus creating the strong electrojet current. This current has been observed by ground-based magnetometers, such as at the Huancayo Observatory in Peru, for almost a century.

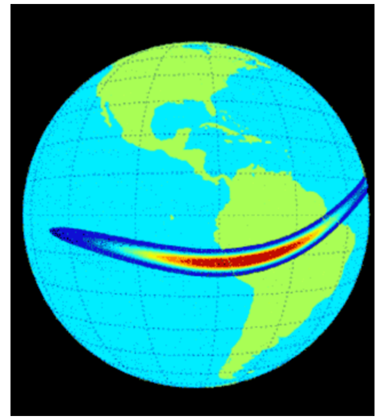

Figure 5. Daytime electrojet based on model of Alken and Maus [2007] [B. A. Carter, personal communication.]

An example of simultaneous measurements of the polarization electric field, current, and plasma density measured on a sounding rocket launched in the daytime electrojet from Brazil is shown in Figure 6 [Pfaff et al., 1997]. In this figure, the resulting electrojet plasma drifts (see panel on the right) are calculated independently using both the measured electric fields (i.e., the $\mathbf{E} \times \mathbf{B}$ drift) and the measured current and plasma density. The discrepancy between these two drift profiles might be due to the neutral wind contribution which was not measured. At night, the electrojet

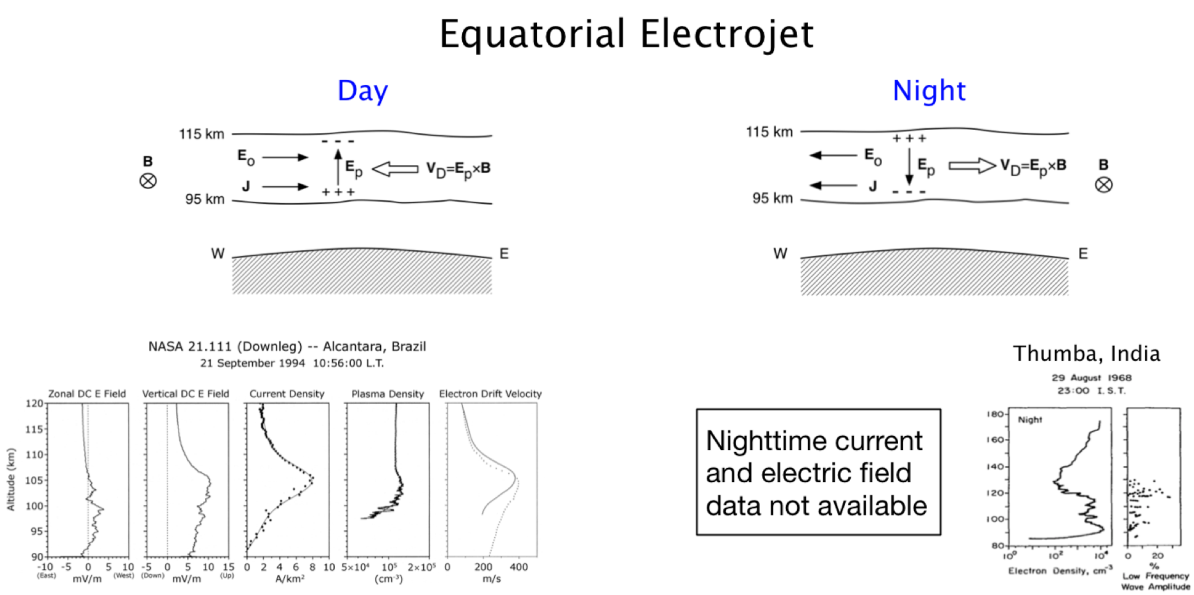

Figure 6. Schematic (top) showing how the electric fields and currents reverse direction between the daytime and nighttime electrojet. Example (lower left) of NASA rocket measurements of DC electric fields, current, and plasma density measured in the daytime equatorial electrojet [Pfaff et al., 1997]. No such comprehensive electrodynamic measurements have been gathered in the nighttime electrojet where the electric field and currents reverse direction, nor at sunset or sunrise, where the fields may be particularly intense. Structured electron density profiles at night should profoundly affect the electrodynamics, as indicated in the density data gathered on an Indian rocket shown in the lower right. [Prakash et al., 1972].

current is expected to reverse direction and, accordingly, the polarization electric field is expected to be directed downward. The magnitude of the nighttime current densities is much lower than during the daytime due to the greatly reduced ambient electron density. However, the structured plasma density expected in the nighttime electrojet should have profound effects on the polarization electric field and resulting currents, as evidenced by the highly variable electrojet instability signatures at night, as discussed below. *No nighttime measurements of either the reversed electrojet current or downward polarization electric field have ever been measured, let along the associated neutral winds*. (The failure of one electrojet rocket in the 1994 NASA campaign in Brazil precluded the nighttime experiment.)

Future electrojet rocket measurements would be expected to focus on measuring the complete electrojet electrodynamics both in the daytime and nighttime including the ambient winds, DC electric fields, and vector current measurements revealing components in the vertical and field-aligned directions. In addition, the electrodynamics of the afternoon “counter-electrojet” have never been measured.

Electrojet Instabilities. In addition to the electrodynamics of the equatorial electrojet, this strong current is also the seat of intense waves and turbulence generated by local plasma instabilities. Indeed, among the most common and largest amplitude waves found anywhere in geospace are the equatorial electrojet waves that occur daily at the Earth’s magnetic equator. These waves derive from the gradient drift, Farley-Buneman, and meteor instabilities from which their basic physics has been explored experimentally (primarily using rocket probes and radars), theoretically, and using simulations. However, the actual physical system that creates these waves mixes all these processes together. Researchers studying this turbulent region have had a wealth of radar data but only limited multi-instrumented *in situ* studies that would enable them to fully understand the complex physical processes that govern this turbulent region.

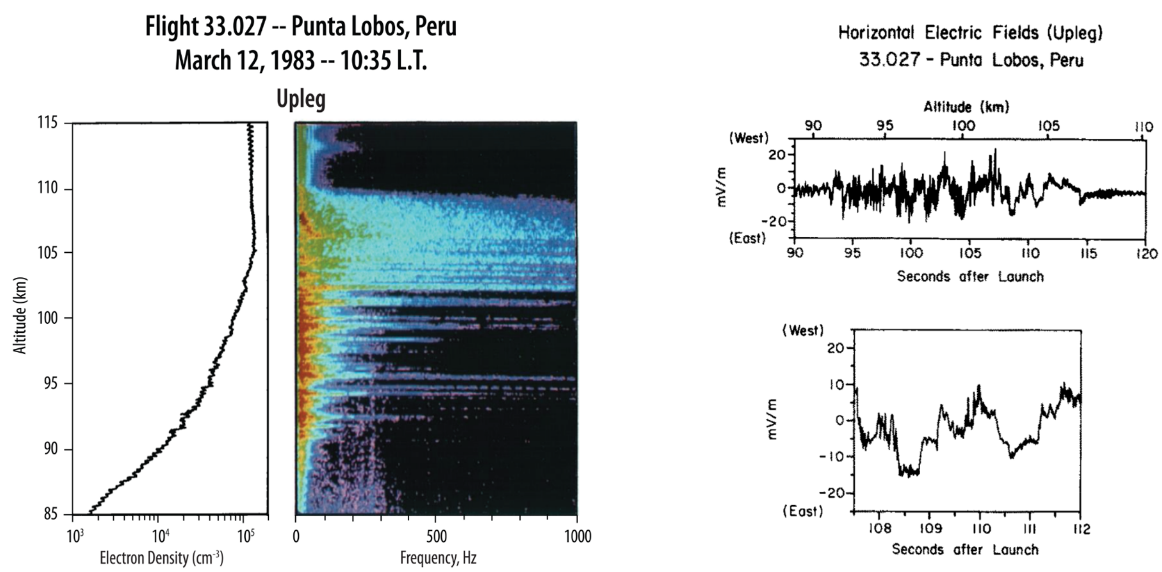

Figure 7. (left) Rocket observations in the daytime electrojet in Peru showing the density profile and associated electric field irregularities, representing two-stream and gradient drift waves; (right) Zonal electric fields during the same flight showing large scale, steepened structures [Pfaff et al., 1987].

When the relative electron-ion drift speed exceeds approximately the acoustic velocity, collisional two-stream waves are excited, as illustrated by the broadband emissions extending to higher frequencies between 102 and 110 km in the altitude spectrogram in the left portion of Figure 7, where the instability threshold conditions are met. The upper portion of this region, where "pure" two stream waves are driven, is also the seat of intense vertically driven, meter scale waves routinely observed by radars that still elude our understanding.

At lower altitude, large amplitude, longer wavelength (lower frequency) waves are observed that are driven by the gradient-drift instability and are set up by the vertical (positive upwards) DC electric field in concert with the upward ambient plasma gradient. The lower edge of the daytime ionosphere (below 105 km) is unstable at long wavelengths in the electrojet region, as evidenced by structure in the plasma density and the electric field data shown on the right side of Figure 7. The square-wave nature of the electric fields and sharp corners suggest local steepening processes at work and may explain the saturation of vertical two-stream wave phase velocities at these altitudes [Pfaff et al., 1987]. Distinct, km-scale waves dominate the spectrum when the gradient-drift instability is active, propagating zonally along the electrojet. Jicamarca radar interferometer data have shown how these waves change directions between daytime and nighttime conditions as the ambient polarization electric field changes sign [Kudeki et al. 1982, 1987].

At night, the equatorial electrojet not only reverses direction, but the region becomes, at times, even more highly unstable. Examples of Jicamarca radar observations of irregularities are shown in Figure 8 [Swartz, personal communication; See also Farley et al., 1994]. Notice the large scale structures above about 105 km in the lowest panel, presumably propagating zonally and due to the gradient drift instability discussed above, in this case operating at sunset. The uppermost panel shows intense waves near 108 km that might be due to primary two-stream waves or intense irregularities associated with steep plasma gradients. All three panels depict irregularities near 96-98 km that may represent a tidal layer that is frequently present even if the corresponding electrojet echoes are weak.

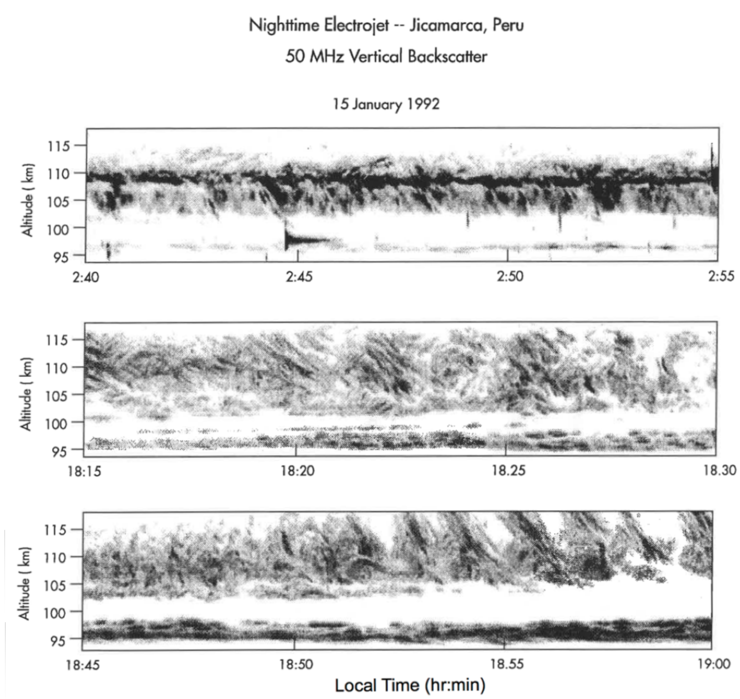

Figure 8. Jicamarca observations of irregularities associated with the nighttime electrojet for three 15 minute intervals on the same night.

An additional example of electrojet echoes from Jicamarca covering the entire nightside period is shown in Figure 9. Notice here how the electrojet instability amplitudes strengthened after around 16:30 LT and extended to higher altitudes. Then, at 19-20 LT, near the time of local sunset, the backscatter was greatly reduced, yet extended to higher and lower altitudes. After about 21 LT, the echoes returned in concentrated packets, becoming strongest just before dawn where the polarization electric fields are believe to have increased. The detailed plasma waves at night in conjunction with DC electric fields, currents, and winds, have never been measured *in situ* at night.

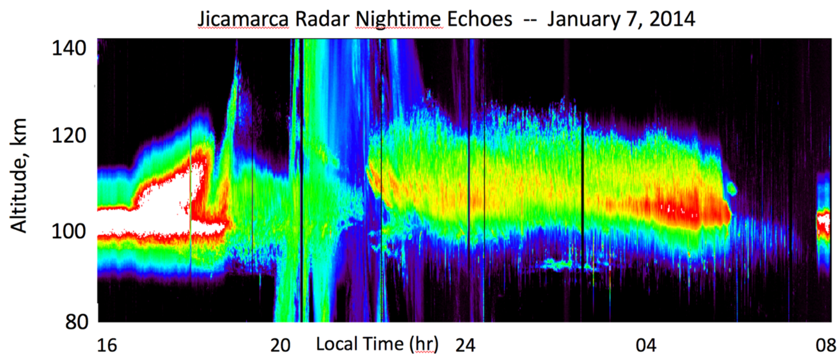

Figure 9. Continuous nighttime electrojet echoes observed at Jicamarca from well before sunset to dawn.

Finally, we emphasize that the Jicamarca radar has developed extensive imaging techniques that enable it to quantify the dynamics and several non-linear aspects of the electrojet turbulence as a function of altitude within the layer, particularly at night. We can expect such powerful, advanced radar techniques to be available in full force in a future rocket/radar campaign, gathering simultaneous measurements in conjunction with the rocket experiments. The nighttime electrojet electrodynamics and instabilities are expected to be a prime target of a future rocket campaign in Peru.

Daytime "150-km" echoes

Surprisingly, the daytime ionosphere at the equator above the electrojet region, between roughly 130 km and 170 km, is the seat of a unique and remarkable physics revealed by observations with powerful ground-based radars led by the Jicamarca Observatory in Peru, as well as subsequent theory and modeling efforts. Although a very small number of rockets with very limited instrumentation has sampled this region, a modern rocket campaign with comprehensive instruments would greatly enhance our knowledge of this region and unlock the mysteries of why the ionosphere at these altitudes behaves in such a distinctive way.

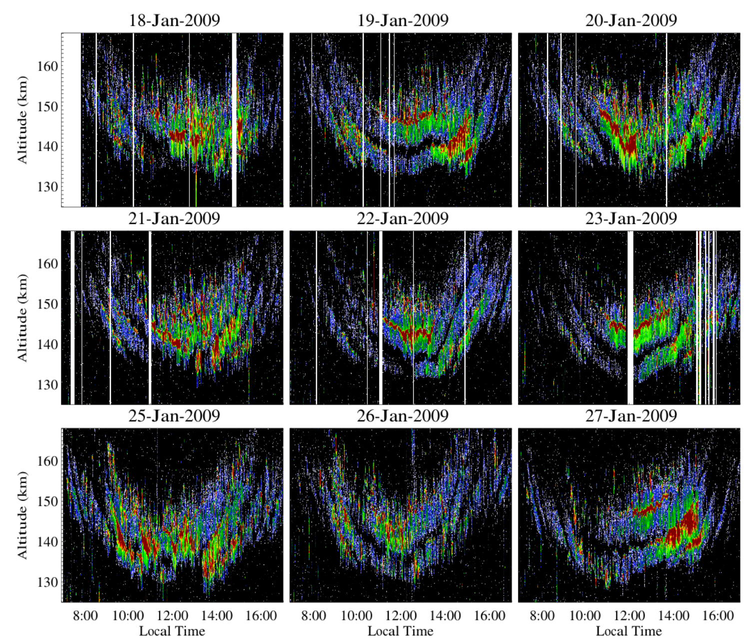

Figure 10. Examples of daytime valley echoes over Peru. Note the day-to-day variability in terms of strength, number of layers, small periodicities, etc. [after Chau and Kudeki, 2013].

Figure 10 shows the altitude-temporal behavior of upper E-region daytime radar echoes, usually called "150-km echoes", for nine days in January 2009, observed with Jicamarca VHF radar. These echoes that occur in the daytime ionosphere between 130 and 170 km have been studied for more than 50 years, but an explanation of the underlying drivers has been elusive. Note that the echoes are arranged in multiple layers presenting a necklace shape (i.e., higher altitudes around sunrise and sunset and lower around noon), the signals show periodicities ("pearls") that repeat every few minutes, and their day-to-day variability is significant. Indeed, the large scale modulation suggests a gravity wave modulation of the layer, as shown in Figure 11, for which detailed inspection reveal what appear to be enhanced and forbidden layers within the echo layers, forming checkerboard and fishbone patterns [e.g., Kudeki and Fawcett, 1993; Lehmacher, personal communication].

Characteristically similar echoes have been observed at other longitudes, but always at latitudes at or close to the magnetic equator. The annual characteristics of these echoes show different patterns at different longitudes. For example, in the central Pacific Ocean the echoes are stronger during the June-August months, while in Peru and India, they are present all year long. A summary of the characteristics of daytime echoes can be found in *Chau and Kudeki* [2013] and references therein.

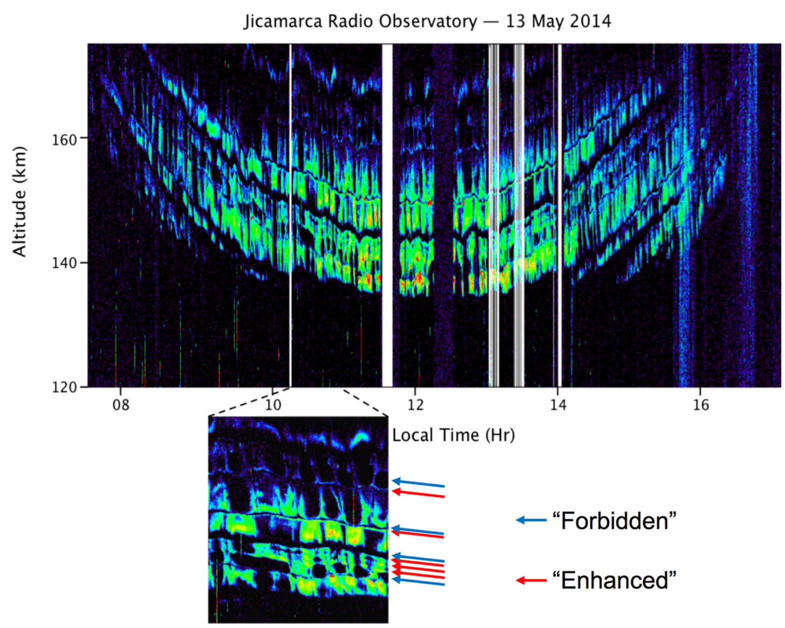

Figure 11. Echo patterns showing gravity wave modulation, forbidden and enhanced regions, and checkerboard patterns [Lehmacher, personal communication, 2016].

Recently, *Oppenheim and Dimant* [2016] suggested that daytime echoes may result from photoelectron-induced waves. They use large-scale simulations to reproduce the enhanced incoherent scatter 150-km echoes, the necklace shape, and the main features during solar flares and solar eclipses. However, the origin of features such as the pearls, layer details, day-to-day variability, and the longitudinal and seasonal dependence, still require explanation. The latter features suggest a strong connection to lower atmospheric forcing, possibly related to a mix of local and non-local (via magnetic field lines) drivers.

Importantly, these echoes serve another very important purpose: They produce a clear signature of the vertical velocity of the ambient plasma and hence are used to derive, on a routine basis, the zonal electric field associated with this vertical **E** x **B** velocity [e.g., Chau and Woodman, 2004.]

We note that there have been a few observations of plasma density irregularities near 150 km in the daytime gathered by sounding rocket probes flown at the magnetic equator in India [e.g., Prakash et al., 1969] and Peru [e.g., Smith and Royrvik, 1985]. These measurements have provided important insight regarding the density spectra of the irregularities and have prompted considerable theoretical discussion. The lack of complementary measurements on the payloads, for example of the neutral density structure and winds, DC and wave electric fields, composition, currents, suprathermal electrons, etc., precluded definitive answers regarding their origin. Future rocket measurements of daytime 150 km echoes with comprehensive instrumentation launched in conjunction with simultaneous radar measurements promise to significantly advance our understanding of this puzzling feature of the earth's daytime ionosphere.

Spread-F plasma depletions and associated instabilities and turbulence

Equatorial spread F (ESF) is a common, spectacular, and disruptive space weather phenomenon that occurs in the nighttime equatorial F-region ionosphere during both geo-magnetically quiet and disturbed times, often with planetary scale proportions. ESF is caused by convective plasma instabilities driven by the free energy in the post-sunset configuration of the ionosphere. This phenomenon may be characterized by a series of depleted magnetic flux tubes or wedges that stretch between magnetic conjugate locations in the northern and southern hemispheres. Sometime referred to as "bubbles", these elongated plasma depletions typically have internal, eastward electric fields of 5–20 mV/m (although sometimes much greater) and hence undergo significant upward $\mathbf{E} \times \mathbf{B}$ motions at speeds much greater than those of the background, ambient plasma [e.g., Aggson et al. 1992]. The seat of the depleted flux tubes is well established to be the base or lower ledge of the nighttime F-region plasma (e.g., near 250 or 300 km). When fully developed, however, these depletions can rise to altitudes of over 1000 km and extend significantly in latitude, sometimes beyond the mid-latitude ionization anomalies. In some cases, plasma enhancements, instead of depletions, are observed [e.g., Le et al. 2003].

Examples of equatorial spread-F are shown in the Jicamarca backscatter radar map for 3-m irregularities in Figures 12 and 13. The strong radar backscatter shown in Figure 12 near 400 km at 20 LT presumably corresponds to the F-region ledge, elevated in altitude due enhanced vertical drifts of the background ionosphere. Notice that the radar echoes, in this example, are strongest at the onset, and that the irregularities appear to "erupt" into apparent interleaved layers of irregularities that extend to much higher altitudes. In Figure 13, the spread-F occurs at lower altitudes and attains its strongest amplitudes later in the evening near 21:45 LT.

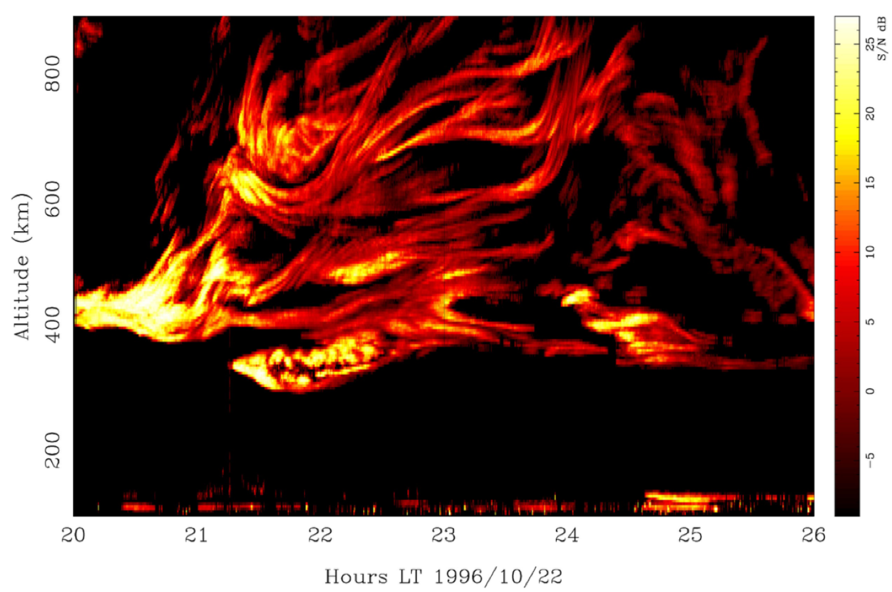

Figure 12. Example of equatorial spread-F observed by Jicamarca Radio Observatory from 20 L.T. to 02 L.T.

A key feature of the plasma depletions is that they themselves are unstable, and give rise to plasma density irregularities spanning scale sizes from tens of centimeters to hundreds of kilometers or more. The irregularities interfere with trans-ionospheric radio signals and pose a hazard to communication, navigation, and imaging systems. ESF is visible to a number of different ground-based instruments which can be used to monitor irregularity occurrence and associated plasma flows.

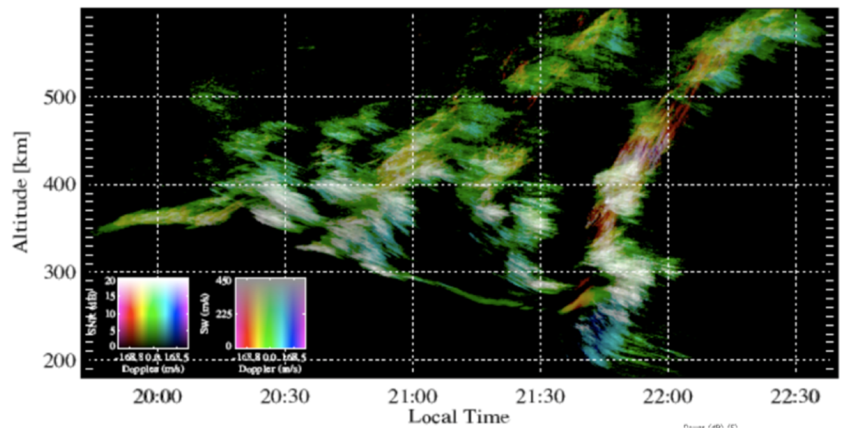

Figure 13. Another example of spread-F measured by Jicamarca in which color scales are used to show the amplitudes and phase velocities.

The theory of plasma instabilities and irregularities in equatorial spread F has expanded greatly since the era of Project Condor. Zargham and Seyler [1989] distinguished between interchange instability in the inertial regime, which is the electrostatic form of the Rayleigh-Taylor instability, and instability in the collisional regime, which is essentially the **E** x **B** instability with gravity and vertical winds augmenting the background, driving current. Zargham and Seyler [1987] analyzed the collisional interchange instability in detail, taking into account the effect of the finite depth of the bottomside F region, which introduces a long-wavelength cutoff. The short-wavelength cutoff is due to diffusive dissipation. Sultan [1996] reformulated the collisional instability problem using flux tube-integrated quantities, deriving growth-rate estimates still widely used today. Krall et al. [2010] determined the conditions that control the terminal altitude of ESF plumes. Dynamic and thermodynamic aspects of the instability in three dimensions were predicted by Huba et al. [2008]. Dao [2013] studied the electromagnetic properties of the instability, simulating how quasi-equipotential magnetic field lines are actually maintained by reflecting shear Alfven waves. The main nonlinear effect in the collisional interchange instability is wave steepening whereas the inertial interchange instability is thought to support inertial-range turbulence.

Recent developments with sounding rocket technology afford series of multiple sub-payloads to be launched by a single rocket. Sampled within an appropriate volume, such a well-instrument constellation would resolve space/time ambiguities and enable the evolution of the irregularities to be ascertained. State-of-the-art instrumentation includes electric field, magnetic field, and plasma density wave instruments and interferometers with high telemetry rates routinely available.

Large scale vortices, shears, and enhanced winds/electric fields at sunset and sunrise

In concert with understanding the characteristics and evolution of equatorial spread-F irregularities, a critical question concerns determining the conditions that actual give rise to the unstable conditions for spread-F in the first place. Indeed, the electrodynamics of the equatorial ionosphere at sunset has commanded considerable attention among experimentalists, modelers, and theorists since the earliest days of space research. In particular, the motions of the ionospheric plasma at sunset have been studied extensively ever since ionosondes and radar measurements revealed that the equatorial ionosphere often rises rapidly near the dusk terminator [e.g., Fejer, 1981; Fejer and Scherliess, 2001]. This strong vertical plasma motion is associated with enhanced eastward zonal electric fields and is believed to be an important factor in the initiation of large scale plasma depletions associated with equatorial spread-F. Moreover, in the last 20 years, the horizontal motions of the plasma have also been identified as playing a key role in the electrodynamics of the sunset ionosphere, led in particular by Jicamarca radar observations [Kudeki and Bhattacharyya, 1999] and satellite observations [Eccles et al., 1999] of plasma vortices at sunset.

In addition to highly variable plasma drifts in the sunset equatorial ionosphere, neutral upper atmospheric motions or winds are also believed to be an essential ingredient in the overall electrodynamics picture, although direct measurements of the winds at F-region altitudes at sunset have been elusive. Importantly, Kudeki et al. [2007] demonstrated that differences in the wind and ion drift vectors alone were sufficient to instigate large scale plasma instabilities in the equatorial ionosphere, such as those believed responsible for initiating spread-F. Such conditions are likely encountered at sunset near the magnetic equator, particularly in the presence of vortex motions in which the neutral gas motions are not expected to mirror those of the coincident plasma. An example of the vortex motion in the plasma drift detected by the Jicamarca radar at sunset at the onset of spread-F initiation is shown in Figure 14 [Kudeki and Bhattacharyya 1999].

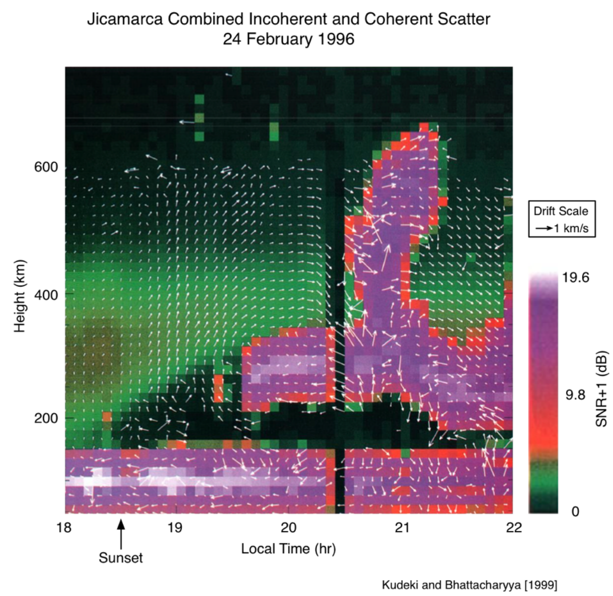

Figure 14. **E** × **B** drifts (*white arrows*) and Jicamarca backscattered power map for the early evening hours of February 24, 1996 [Kudeki and Bhattacharyya 1999]. The scattered power corresponds to incoherent scatter (*brown* and *green shades*), and shows how the lower edge of the ionosphere rises after sunset, which occurred at 18:32 LT. The stronger scatter (*red* and *purple shades*) correspond to coherent scatter of the spread-F and E-region irregularities. Notice the vortex pattern in the **E** × **B** *arrows* prior to the onset of the high altitude plume that begins near 20:30 LT.

Shear instabilities also have been suggested to create the large-scale undulations that ultimately seed the Rayleigh-Taylor growth of spread-F [e.g., Hysell and Kudeki 2004]. This shear in the zonal plasma drift at the base of the F-region was observed in altitude profiles of the vertical electric field measured on sounding rockets flown from Kwajalein Atoll, as reported by Hysell et al. [2006]. Finally, we mention that other seeding mechanisms have been proposed as possible explanations for the initiation of spread-F, such as gravity waves [e.g., Fritts et al., 2008]. Rocket instruments that measure neutral and plasma gas properties and their associated velocities and fields will be able to detect the presence of gravity waves and test these ideas as well.

Although much less explored compared to the sunset theater, the electrodynamics at dawn is also of keen scientific interest, again because of the vertical and horizontal gradients expected in both the plasma and neutral gases. Indeed, satellite measurements of the dawn equatorial ionosphere have revealed enhanced vertical drifts, as discussed by Aggson et al. [1995] and Kelley et al. [2014] from which an example is shown in Figure 15. Vertical profiles of the winds and electric fields are needed to fully understand the possible sunrise counterpart to the sunset plasma (and wind?) vortices discussed above. Note also that sometimes spread-F is also triggered near dawn, as shown previously in Figure 4.

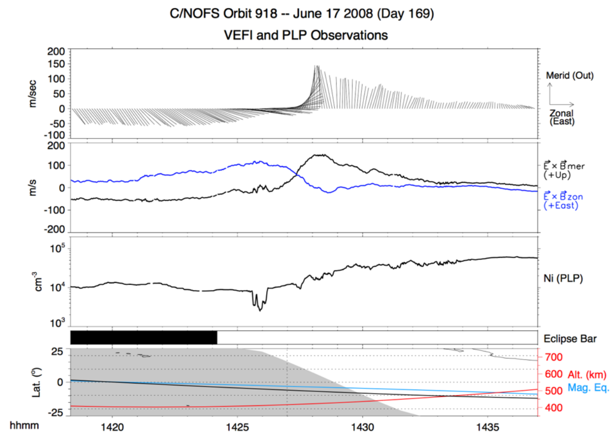

Figure 15. Satellite observations of vector **E** × **B** drifts revealing large vertical motions just after dawn [Kelley et al., 2014]. The horizontal black bar shows when the satellite was in eclipse and the grey shading in the lowest panel depicts the ground shadow.

Today, theory and modelling are ahead of observations, and the ability to test the theory using ground-based instruments is limited. The aforementioned theoretical conclusions require *in situ* testing and verification in order for work to progress. The most persistent problem in ESF is in the area of forecasting. Toward that end, a combined experimental mode has been developed at Jicamarca designed to acquire all accessible information about the state of the ionosphere prior to the onset of ESF as well as characteristics of the subsequent plasma irregularities. The mode measures electron number density, electron and ion temperature, vertical, and horizontal plasma drift profiles. Plasma irregularities are characterized using coherent scatter radar imaging. The datasets are more comprehensive than what can be acquired using the ALTAIR radar on Kwajalein which cannot measure plasma drifts nearly as accurately as Jicamarca and has no imaging capability.

While details vary, most contemporary theories of ESF formation and variability emphasize the role of neutral winds and/or gravity waves and the variability they exhibit. Sounding rocket measurements of state parameters in the twilight ionosphere at Jicamarca, particularly neutral wind measurements, would allow an assessment of different forecast models and strategies and allow us to resolve this long-standing problem in space weather. The synergy between such experiments and NASA's ICON mission, which seeks to quantify ionospheric dynamo theory and the influence of thermospheric winds on the low-latitude ionosphere, is obvious and compelling. Sounding rockets could also measure wave parameters inaccessible to ground-based instruments and allow us to connect, for example, macroscopic ESF features with the specific detrimental effects on navigation and communications systems.

Sounding rockets are ideal platforms to gather the necessary data to carry out this scientific research. Not only do they provide largely vertical profiles on relatively slow-moving vehicles, but also they can be launched directly into regions of desired geophysical conditions in conjunction with detailed ground-based radar measurements.

The nighttime low latitude valley region (LLVR)

Less well known than the daytime 150-km echoes are layers of coherent scatter seen in the equatorial valley region at night. The layers are observed at altitudes as high as about 170 km, well above the electrojet. They occur less frequently than 150-km echoes, electrojet irregularities, and even equatorial spread F. They remain sparsely documented and poorly understood. That the nighttime valley echoes differ essentially from daytime 150-km echoes is an important clue to their respective causes.

A vivid example of nighttime valley-region echoes observed at Jicamarca is shown in Figure 16 [Hysell, personal communication]. Below about 115 km altitude, the echoes depicted in the figure correspond to irregularities excited by instabilities in the equatorial electrojet discussed previously.

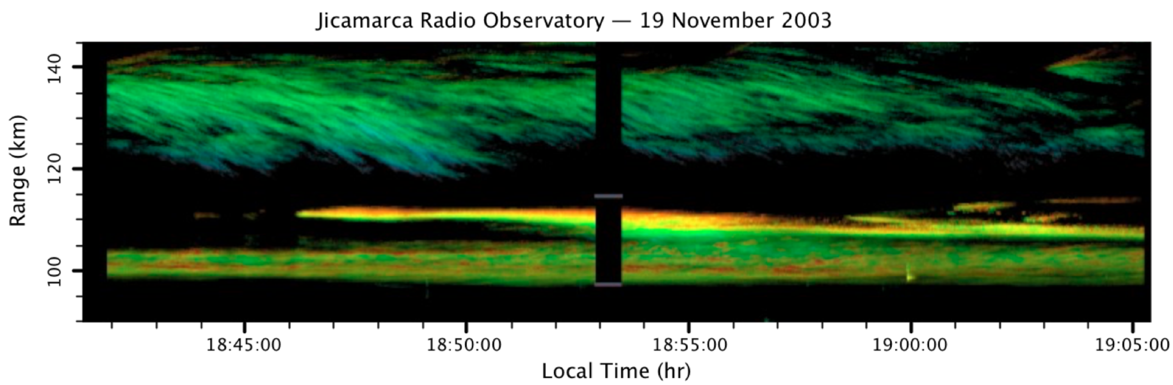

Figure 16. Echoes observed by the Jicamarca Radio Observatory in the nighttime valley region between 120 km and 145 km.

The main features of interest here are the echoes above about 120 km altitude. They exist in the plasma density "valley region", above the electrojet but beneath the bottomside of the F region in strata where the ions are nearly magnetized. They are generally not as strong as echoes from the electrojet and have smaller Doppler shifts and spectral widths. Indeed, the echoes depicted here have spectra that are slightly blue shifted and very narrow.

The nature of the irregularities underlying the valley echoes and the instability that produces them, the state of the background ionosphere in the nighttime valley region, the ultimate source of free energy for instability, and the impact of the valley irregularities on the overall ionospheric state are poorly understood. The layers are a relatively recent discovery and have never been probed by spacecraft. A comprehensive investigation combining space- and ground-based measurements of the background state and wave parameters in the nighttime valley region is required. The layers are too low to be probed by satellites and are ideal for sounding rockets.

Another type of nighttime irregularity possibly related to the valley echoes shown in Figure 16 is that of quasi-periodic equatorial echoes, as shown in Figure 17 and discussed in *Woodman and Chau* [2001]. These are the strong echoes under the F-region ledge shown in the figure. Clearly, the large scale dynamics of these lower altitude echoes appear to be coupled in some fashion with that of the higher altitude spread-F. Similar to their daytime counterparts, the morphology and origin of the nighttime echoes at these altitudes are poorly known. Characteristics of these echoes are described in *Woodman and Chau* [2001], *Chau and Hysell* [2004], and *Patra et al.* [2007]. Moreover, *Patra et al.* [2007] presented a comparative anatomy of the nighttime and daytime echoes as observed over India. Efforts to understand both daytime and nighttime echoes have been carried out using mainly radar data. In both cases, a deep physical understanding remains limited.

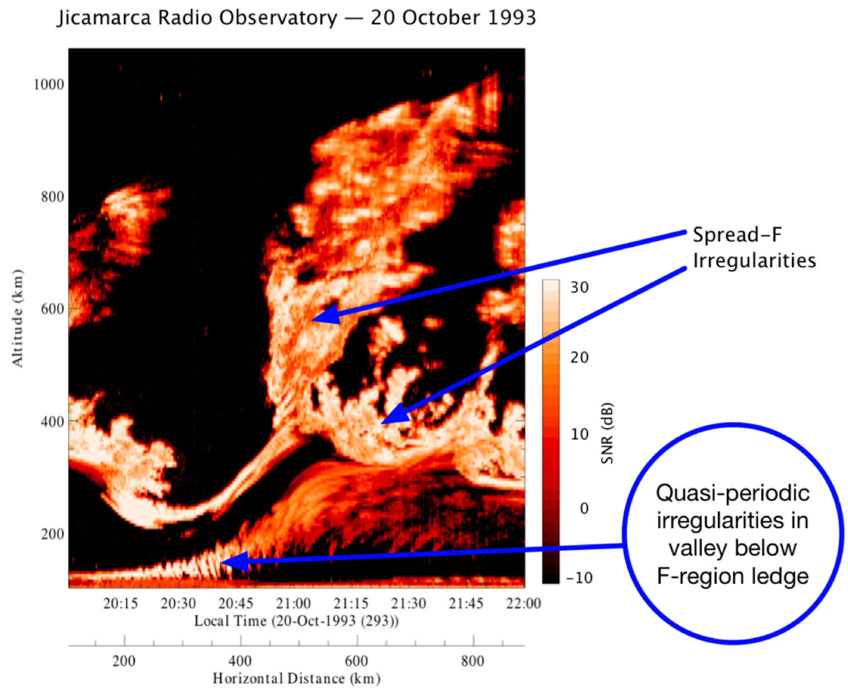

Figure 17. Example of nighttime echoes observed over Peru. The echoes above ~200 km are the so-called Equatorial spread-F (ESF) echoes. The valley echoes occurred below the ESF echoes (adapted from *Woodman and Chau* [2001]).

Efforts to understand both daytime and nighttime echoes have been carried out taking advantage of mainly radar data. In both cases, a deep physical understanding remains limited. Among other parameters that appear to be needed to understand these echoes are: (a) local and lower gravity waves and tides, (b) local and lower winds, (c) local and field-aligned conductivities, (d) composition, including metallic ions, (d) electric fields, (e) field-aligned currents, and (f) electron densities (profiles and perturbations). Such instrumentation will help reveal both the large scale, and short scale physics that create, and govern, the irregularities responsible for these echoes. Ultimately, a multidisciplinary approach including sounding rockets and radars, as well as theory and modelling, is needed to advance our knowledge and understanding of these unexplained geophysical phenomena.

Some of these parameters will be available for the first time from the upcoming ICON satellite mission and others might come from whole atmosphere models with and without data assimilation schemes. Among other parameters, ICON will measure remote sensing profiles of winds, composition and temperatures between 90 and 300 km, and *in situ* electric fields and electron densities. Almost simultaneously, the GOLD mission will provide composition and temperature measurements around 160 km over South America. These observations, combined with high-resolution electrodynamics simulations that are constrained at the larger scales by whole atmosphere models and/or observations, present an opportunity to provide new insights into the observed low latitude valley echoes at night as well as the puzzling daytime 150 km echoes.

Equatorial Temperature and Wind Anomaly

Ever since its original identification in satellite data several decades ago [Raghavarao et al., 1993], a significant outstanding research question involves understanding the equatorial temperature and wind anomaly (ETWA). The earth's low latitude plasma density enhancements at approximately 10 degrees of either side of the magnetic equator are a regular feature of the earth's ionosphere as shown in the TEC simulations from the SAMI2 model in Figure 18. Recent satellite data [Clemmons et al. 2013] using neutral density measurements gathered with the polar-orbiting STREAK mission have revealed wind structures along the meridional direction associated with the anomaly, as shown in Figure 19 in plots versus latitude and longitude. These features are strongly tied to non-migrating atmospheric tides, which act to modulate this ion-neutral coupling phenomenon. Several competing physical mechanisms [Raghavaro et al., 1993; Fuller-Rowell et al., 1997; Maruyama et al., 2003; Clemmons et al. 2013] have been advanced to attempt to explain these features, but none has been tested to satisfaction due to lack of a data set that contains all of the needed measurements. Comprehensive measurements on a sounding rocket with a large horizontal velocity launched south from Punta Lobos (see arrow on Figure 18) will reveal the origins of the structuring.

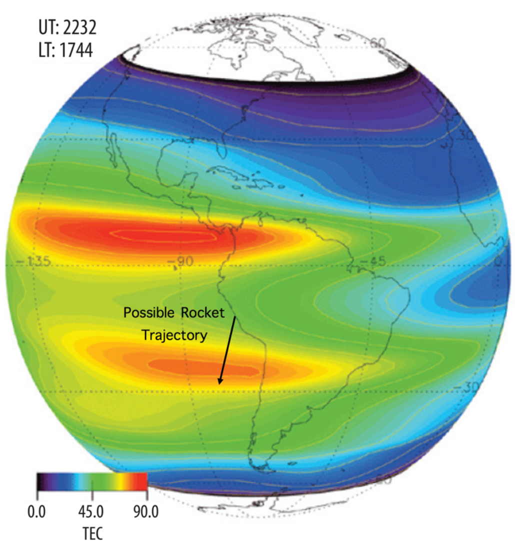

Figure 18. TEC model results showing equatorial anomaly enhancements in the late afternoon. Center of globe correspond to 17:44 L.T. (Figure courtesy Joe Huba, 2012.) A possible rocket trajectory is overlaid.

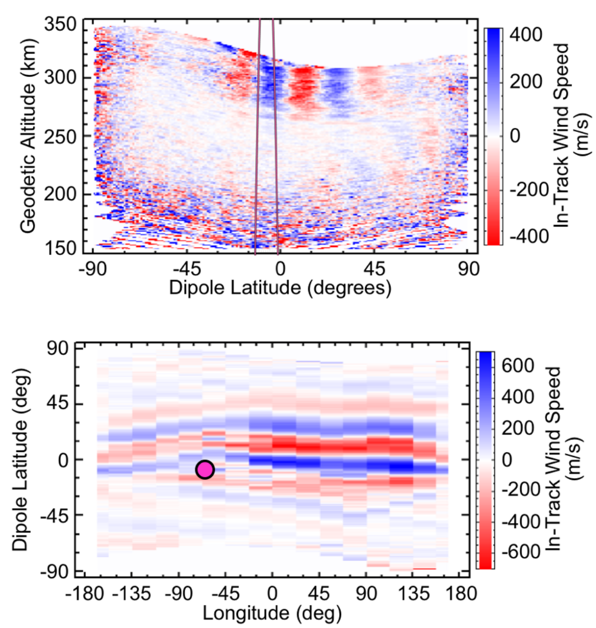

Figure 19. Neutral wind variations along polar-orbiting STREAK mission trajectory [Courtesy, Jim Clemmons, 2013]. Shown are a possible rocket trajectory through wind field and the position of the Punta lobos launch site.

"Topside" ionosphere studies

The topside is that part of the ionosphere above the F2 peak (about 450 km) and below the protonobase. As in the E-region, it here where multiple ion species exist and where chemistry competes with transport in determining composition. Heat transport dominates local heating and cooling in the topside and includes both thermal conductivity and energetic electron transport. (Below the F peak, chemical production and loss and heating and cooling essentially balance locally.) At low latitudes, the topside ionosphere is confined to the inner plasmasphere whereas at middle and high latitudes it resides in the outer plasmasphere and in the polar cap, respectively.

The properties of the equatorial topside ionosphere are strongly influenced by the geomagnetic field which inhibits vertical transport locally. Since the magnetic field does not appear in the plasma Hamiltonian, it cannot affect the equilibrium configuration of the ionosphere. It can, however, retard the approach to equilibrium and effectively prevent it from being reached. Stark differences between the topside at equatorial and middle latitudes is evidence of their effect.

A new experimental mode at Jicamarca is capable of measuring plasma number density, ion composition, and temperature throughout the topside ionosphere. The main features observed in campaign studies include a regular, sawtooth-like diurnal variation in the H^+/O^+ transition height, the appearance of weak helium ion layers just below this height, and drastic elevations in electron and ion temperatures at sunrise followed by depressions around local noon.

While many of the features in the Jicamarca datasets have been recovered through modeling, significant discrepancies persist, indicating fundamental deficiencies in our understanding of equatorial aeronomy, particularly in the area of heat transport, particularly around sunrise. In order to close the gap between theory and observations, detailed measurements of density, temperature, and composition profiles in the F-region and topside are required. Most importantly, the energetic electron population needs to be characterized. This need can only be fulfilled by sounding rockets. To our knowledge, the energetic electron spectrum has never been measured by rockets at low geomagnetic latitudes.

Mesospheric turbulence, gravity waves, and instabilities

The Jicamarca Radar is the world's largest Mesosphere-Stratosphere-Troposphere (MST) radar. Scattering from 3-meter irregularities in the daytime D region/mesosphere, which occur every day, allows a detailed view of horizontal and vertical winds, gravity wave breaking, instabilities, and turbulence in the region between about 60 to 85 km unmatched by any other radar. An example is shown in Figure 20.

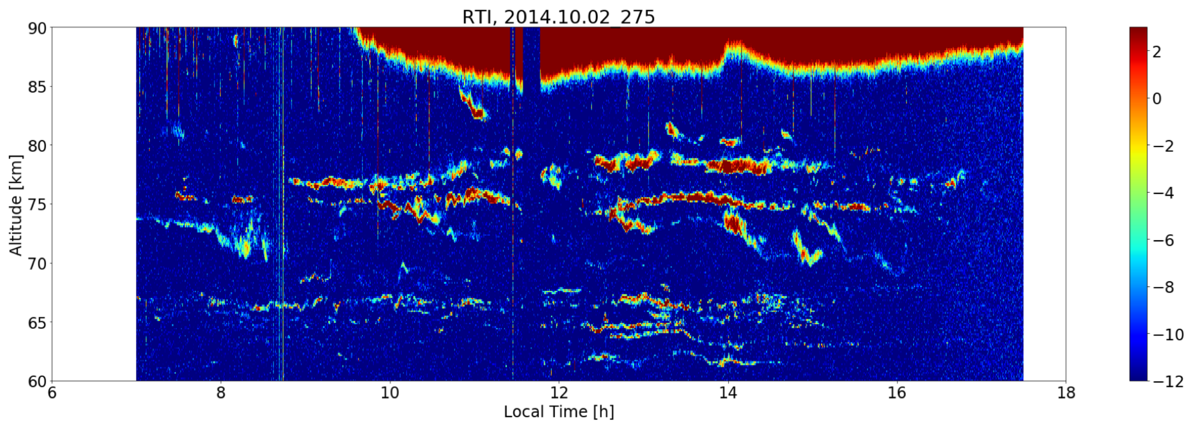

Figure 20. Height-Time-Intensity diagram for one day of daytime mesospheric echoes. Range resolution is ~150 m and time resolution is ~8 seconds.

The location and strength of the layers is thought to be determined by many factors including electron density, electron density gradient, density fluctuations, temperature gradient, and level of turbulence. However, there has been no coincident set of in situ measurements to date that would determine some or all of these parameters during the presence of these echoes.

While there have been two rocket campaigns measuring the electron density fine structure near Jicamarca (Klaus and Smith, 1978; Røyrvik and Smith, 1984), none of these measurements showed a clear correspondence to echoes in the main region of 70 to 80 km. Klaus and Smith observed a major layer of density fluctuations near 75 km, but no simultaneous echoes were observed; Røyrvik and Smith observed a narrow layer of fluctuations near 85 km, while the radar showed weak echoes from 79 to 82 km in 3-km range gates.

Mesospheric echoes can also be routinely observed with the VHF radar in Gadanki, India; however, with much lower sensitivity and resolution. Simultaneous in situ measurements of electron density fluctuations have been reported from an Indian rocket experiment (Chandra et al., 2008; Das et al., 2009); however, the horizontal distance was more than 100 km and the height of the fluctuation layer did not match the height of the echo layer.

Low latitude *in situ* measurements of electron density fluctuations have also been made from Brazil (Goldberg et al., 1997; Lehmacher et al., 1997) and Kwajalein (Lehmacher et al., 2006). Neither case showed significant layers of turbulence, however, some strong electron density gradients were present. Neither experiment included a radar that could detect mesospheric echoes.

In many past studies, the echoes have been divided in weakly turbulent below 70 km and strongly turbulent above 70 km. The finer resolution data obtained since 2004 have challenged this picture. Instead, a broad, but weakly scattering region capped by thin sheet of strong scatterers appears to be more common. In these cases, the low intensity echoes are spectrally wide, i.e. turbulent, while the thin sheet is spectrally narrow, suggesting structures that mimic convective regions capped by a stable inversion layer. Only detailed temperature and electron density measurements can confirm or reject this idea.

Finally, we show an example of strong scatter at 77 km in Figure 21 that lasted for about an hour and closely resembles a Kelvin Helmholtz wave train. *In situ* measurements into stable layers such as this one will reveal both the characteristics of the scattering layer as well as the possible drivers of such phenomena, such as neutral wind shears.

The nature of such strongly scattering regions in the mesosphere is largely unknown. Partial reflection is a possible explanation, but the presence of meteoric smoke, the abundance of water and water cluster ions in this region, and similarities to polar mesospheric summer echoes, opens up questions for compelling, new science investigations.

In summary, only a series of dedicated mesospheric rocket soundings, optimized for low D region plasma densities and (relatively) high mesospheric neutral densities, during the presence of significant mesospheric echo activity monitored by the Jicamarca radar, can be expected to significantly advance our understanding of radar scattering and turbulence in the mesosphere.

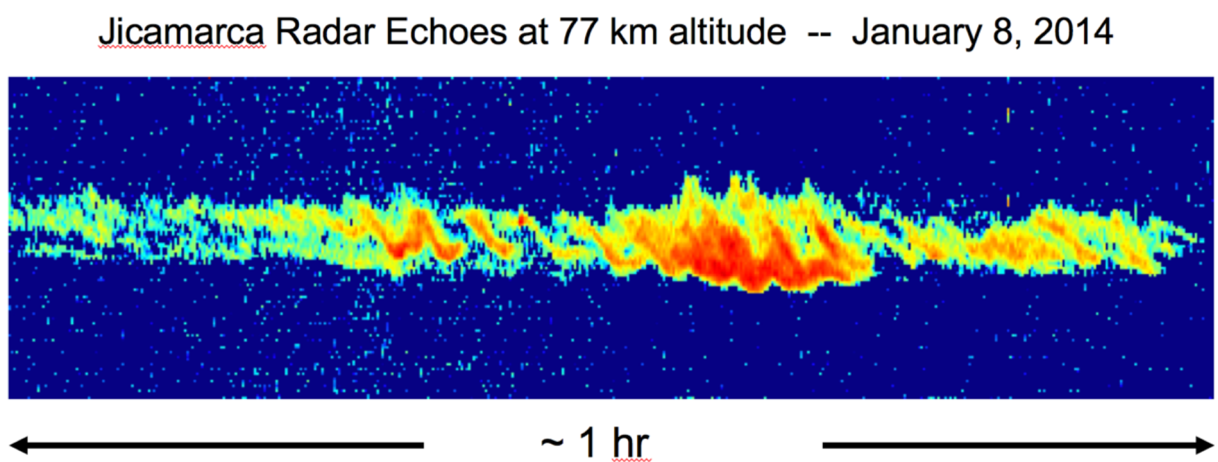

Figure 21. Jicamarca radar echoes showing evidence for Kelvin Helmholtz waves near 77 km that lasted for approximately 1 hour.

IV. Jicamarca Radio Observatory and other ground-based instruments

Jicamarca Radio Observatory. Since the last NASA scientific rocket campaign in Peru (CONDOR campaign) in 1983, the Jicamarca Radio Observatory (see Figure 22) has increased significantly its capabilities to observe the upper atmosphere. Different parts of the 50 MHz incoherent scatter radar at Jicamarca have been upgraded to modern technology and new observational modes are now possible. The main radar now operates with a solid-state transmitter in the first stage of amplification providing a more reliable and stable pulsed waveform to excite the following stages of amplification. All four high-power transmitters were upgraded and are fully operational for very demanding experiments. An electronic antenna beam steering system for the main Jicamarca array is under implementation at the observatory. This system will allow the antenna beam position to be changed within a second allowing the possibility of interleaving different radar beam positions for improved observations of ionospheric phenomena. Solid-state TR switches were also developed at the observatory and implemented in the switchyard in order to use the full bandwidth of the antenna array. In this way, high-resolution experiments show a better performance. Reception lines have also been upgraded and now each polarization and antenna quarter can be acquired using digital receivers developed at the observatory.

Figure 22. Recent picture of the antenna array of the Jicamarca incoherent scatter radar in Lima, Peru.

All the upgrades and improvements mentioned above have allowed the implementation of new modes of ionospheric observation. In particular, a multi-beam incoherent scatter radar mode is now our most commonly run radar experiment during the World Day international campaigns. This mode is a mixture of 3 typical modes at the observatory (east-west drifts, double pulse Faraday rotation, and radar imaging). This combo-mode allows the simultaneous estimation of electron densities, electron and ion temperatures, and vertical and zonal drifts of the equatorial F-region ionosphere. In addition, the same mode enables observations of Spread-F plumes at nighttime applying a radar imaging technique. This mode will be suitable for the proposed rocket/radar campaign because it would allow to monitor ionospheric state parameters before the occurrence of Spread-F irregularities. In addition, since the early 90´s, a low-power mode for ionospheric irregularities observation has been running at the observatory for about 4000 hours every year. This mode is named JULIA (Jicamarca Unattended Long Term investigations of the Atmosphere) and utilizes different sectors of the Jicamarca antenna array to observe electrojet and 150-km echoes during daytime hours and Spread-F events at night. This mode also includes a radar imaging mode to observe Spread-F plumes. The measurements conducted in this mode have facilitated the development of climatology studies regarding the occurrence of ionospheric irregularities in the Peruvian sector.

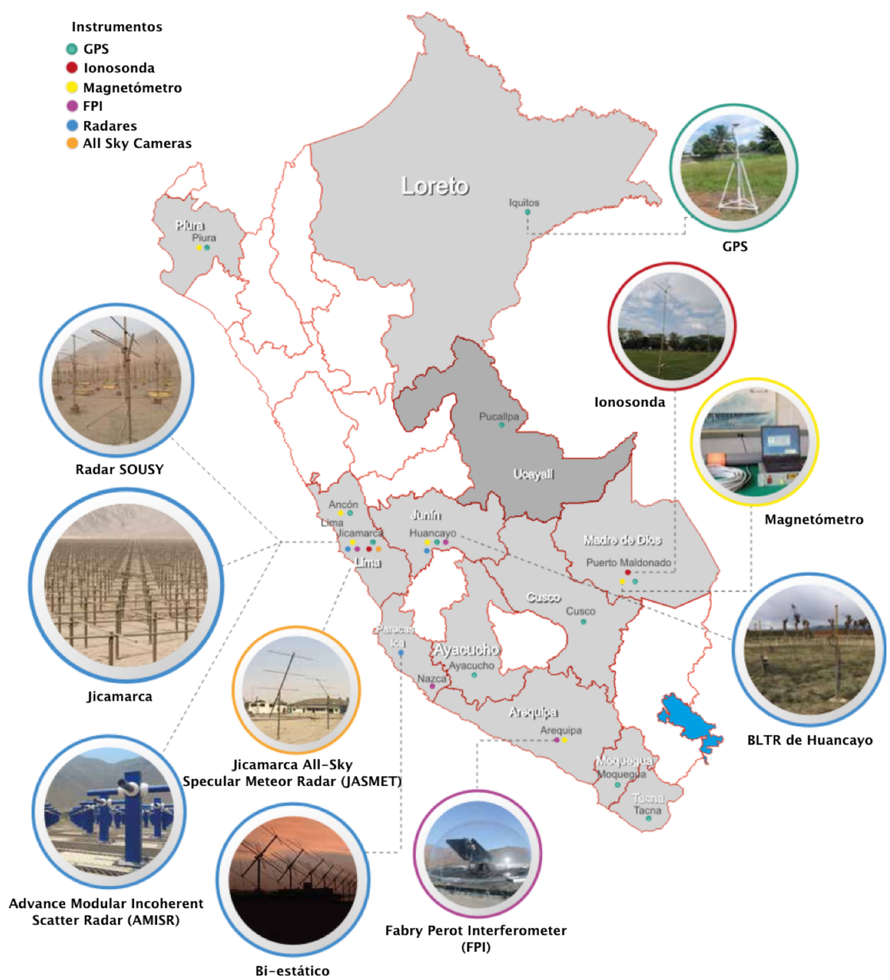

Figure 23. Cluster of instruments deployed in Peru for ionospheric and upper atmospheric studies

In addition to the radar upgrades and new modes of observation, the Jicamarca radio observatory also operates and maintains a variety of geophysical instruments to monitor and observe the upper atmosphere and ionosphere. Such instrumentation, as shown in Figure 23, can be used for a series of studies in conjunction with the rocket observations.

Low Latitude Ionospheric Sensor Network. Jicamarca staff members also help manage the Low Latitude Ionospheric Sensor Network (LISN), a project in collaboration with Dr. Cesar Valladares (University of Texas at Dallas). LISN is a network of 35 GPS receivers, 6 magnetometers, and 4 VIPIR ionosondes deployed in South America, as shown in Figure 24. Data are sent in real time to the LISN main server located at the IGP headquarters in Lima. These instruments, in particular, the VIPIR ionosonde at Jicamarca and the magnetometers and GPS receivers in Lima and surrounding area, can be used (and relocated if needed) to support the rocket campaign.

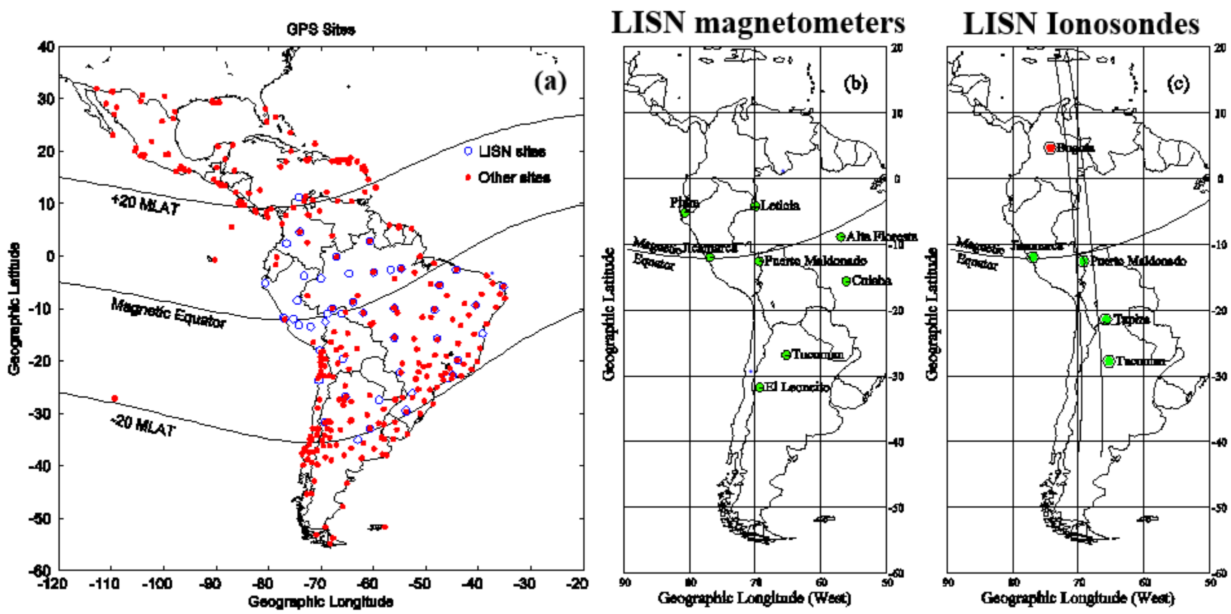

Figure 24. (a) Locations of LISN GPS receivers in blue and GPS receivers that belong to other networks in red, (b) LISN magnetometers and (c) VIPIR ionosondes.

In addition, Jicamarca helps manage a network of Fabry-Perot interferometers located in Jicamarca, Nazca, and Arequipa. This network usually operates in a Common Volume mode in order to measure thermospheric winds and temperatures at night. Furthermore, Jicamarca also operates two all-sky airglow cameras located in our optical station next to the observatory. One of these cameras is used for the observation and study of gravity wave activity in the mesosphere, a project conducted in collaboration with Dr. Gary Swenson and Dr. Fabio Vargas at University of Illinois at Urbana-Champaign. The second camera is mainly used to study Spread-F depletions; this is an effort in collaboration with Dr. Carlos Martinis at Boston University. All of these optical instruments can also be operated in support of the rocket experiments.

Even further, Jicamarca is in charge of a series of other radar systems deployed in different regions of Peru (mainly at Jicamarca, Ancón, and Huancayo observatories). One of these radars is a small

AMISR system composed of 14 panels that have been recently deployed at Jicamarca. The system operates at 435 MHz and can deliver a peak power of 224kW. This radar is mainly used to observe ionospheric irregularities (equatorial electrojet and spread-F). This system is very flexible and can switch antenna pointing directions from pulse to pulse. Spread-F studies using Jicamarca radar and AMISR are being conducted in collaboration with Dr. Fabiano Rodrigues at University of Texas at Dallas. This instrument can be relocated to a location closer to the rocket launch site in Punta Lobos in order to monitor, in real time, the formation of irregularities towards the west (over the ocean) and thus help determine when to launch the rockets.

A multi-static HF sounder system composed of multiple transmitting and receiving stations is being implemented in the central part of Peru. This is a project led by Dr. Dave Hysell (Cornell University) with the goal of monitoring the space-time variation of the ionosphere before the occurrence of Spread-F events. The idea is to perform multiple HF links between different stations at different frequencies and using pseudo random codes in order to obtain electron density estimates of the bottom part of the ionosphere in 3-dimensions applying a refraction tomography technique. The network stations are being deployed and we expect to have at least 3 TX stations and 4 RX stations in the next year. This system can also be part of the tools that could be used to support the rocket launches.

In addition to the geophysical equipment currently available in Peru to monitor the ionosphere, specialized instrumentation to support the rocket campaign can also be brought to Peru. For example, a version of the meteor radar system MMARIA (multi-static multi-frequency agile radar for investigations of the atmosphere) developed by Dr. Jorge Chau in Europe to study the mesosphere and lower thermosphere could be implemented in Peru. In fact, a system-like MMARIA with different stations between Punta Lobos and Trujillo (500 km to the north of Lima) could be used to estimate mesospheric wind fields. Such measurements will be important, for example, to support a rocket mission to study the 150-km region. Magnetic field lines link the mesospheric activity above Trujillo and the ionospheric activity at 150 km altitude above Lima (located at the magnetic equator). An experiment of this type will be useful to understand the physics behind the generation of the 150-km irregularities.

V. Punta Lobos Rocket Range

The origin of the Peruvian Space Agency CONIDA (Comisión Nacional de Investigación y Desarrollo Aeroespacial) is related to the first NASA rocket campaign in Peru conducted in 1975 at Punta Lobos (see Figure 25). At that time, CONIDA was created and, together with NASA, implemented a rocket range site in Punta Lobos next to Pucusana, a small town 50 km south of Lima. The same rocket range was used later, in 1983, for the CONDOR campaign. After these campaigns, CONIDA continued using this site and developed its own rocket program. The name of this program is Paulet and was started in 2004. In 2006, the first rocket developed by CONIDA was launched reaching an altitude of ~20 km. Since then, different versions of the Paulet rocket have been developed and are currently under test. The goal of the program is to develop a rocket capable of reaching the ionosphere at altitudes beyond 100 km. Thanks to the development of the Paulet program, the rocket range at Punta Lobos has been maintained in good condition and its installations for payload and motor integration are currently being modernized. Although the available rocket launchers might need some modifications to support some of the NASA rockets (and, indeed, NASA may be expected to bring in its own temporary launchers for the campaign), this range offers both the available land with launch capability over the ocean and some basic structures needed to conduct the proposed rocket campaign in Peru.

Figure 25. CONIDA Scientific Base for rocket launchers at Punta Lobos.

For example, the infrastructure available at Punta Lobos for the previous NASA campaigns included a vehicle assembly building, a payload assembly building, a blockhouse, and pads for telemetry and radar vans as well as for launchers. The launch pads used in the Condor campaign are shown in Figure 26.

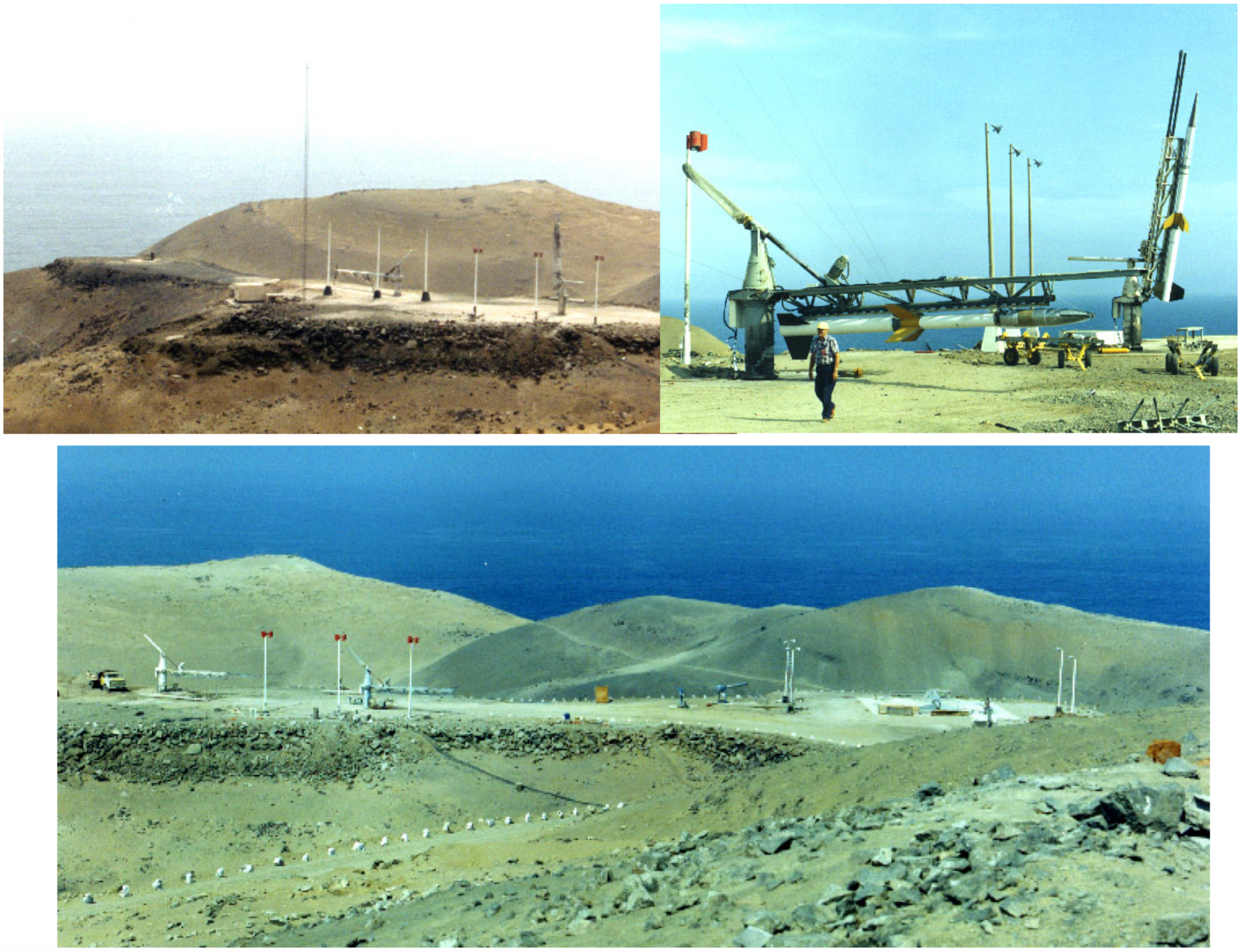

Figure 26. Launch pads at Punta Lobos used during the NASA Condor campaign in 1983.

A key feature of the Punta Lobos rocket range is that it permits launches over the ocean with a large range of azimuths. Launching along different azimuths may be important for some investigations. As shown in Figure 27 (left), the horizontal path of three different rockets launched during the Antarqui and Condor campaigns are depicted. Notice that launches were along the magnetic equator to the west, as well as slightly to the north and south of the magnetic equator. On the other hand, Figure 27 (right) shows the trajectories of two rockets launched along more southerly azimuths during the Condor campaign.

It is also noteworthy that such southerly azimuths are of great interest for sounding rocket experiments that carry astrophysics telescope payloads that may wish to come to Peru in order to observe celestial sources in the southern hemisphere.

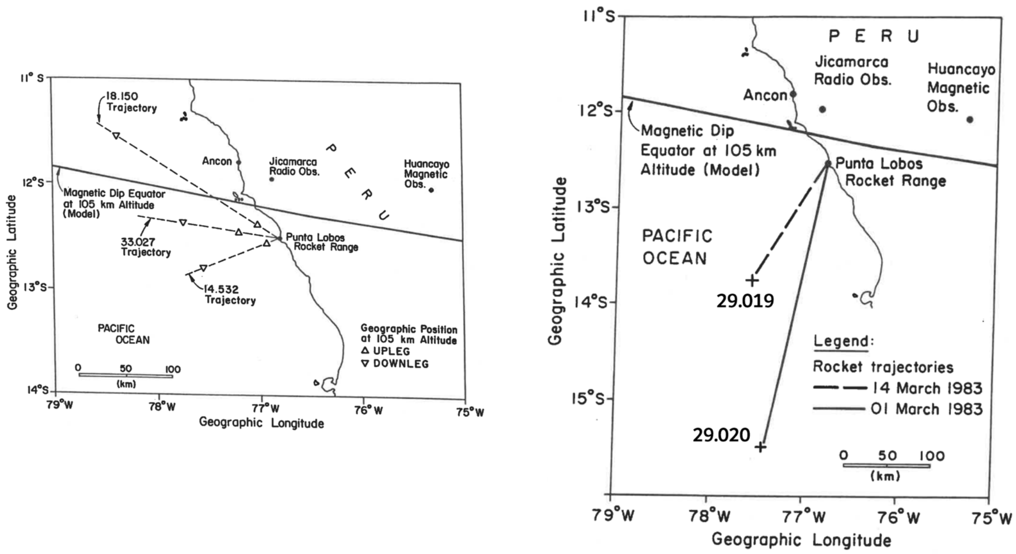

Figure 27. Examples of different launch azimuths for assorted rockets launched from Punta Lobos during the Antarqui and Condor campaigns.

In addition to the rocket range, recently, CONIDA built a modern facility that houses the ground control segment of the Peruvian Satellite System, which includes the Peru Sat-1 satellite, the first of its kind carrying on-board a very high-resolution optical instrument for Earth observation. The new complex is named CNOIS (National Center of Operations of Satellite Images) and it is located in the vicinity of the Punta Lobos rocket range near Pucusana (see Figure 28).

Figure 28. National center of operations of satellite images (CNOIS) located next to Punta Lobos.

The CNOIS facility includes a main control room where all satellite orbits and manuevers are monitored and controlled, a multiband transmitting and receiving ground station, an image processing lab where the image products are prepared for delivery, as well as fully equipped meeting and conference rooms (with a capacity of 90 people.)

Given its location, CNOIS could be the perfect place to manage the logistics of a rocket campaign at Punta Lobos. In fact, scientists and rocket operators could stay there during the campaign as lodging for 8 people is currently available inside this complex. Also, a special room with computers and high-speed internet access could be conditioned to be used as the center of operations for the rocket launches. Meeting and conference rooms at the complex could also be made available as they might be needed during the rocket campaign. The facility can also support the installation of additional equipment or instrumentation, e.g., a tracking radar, communication stations, etc. In conjunction with the Punta Lobos rocket range, these facilities are well equipped to support a rocket campaign in Peru.

VI. A Proposed "Notional" Campaign for Initial Planning Purposes

The proposed rocket campaign will most likely include a mix of large (multi-stage) and smaller (single stage) rockets, depending on the different scientific investigations, driven to a large extent by the altitude and range (horizontal distance) requirements as well as the number of sub-payloads per rocket, etc. For planning purposes, we anticipate that 5-6 proposed investigations might be selected, with Principal Investigators represented by educational institutions, industry, and government. Such investigations might each include several rockets. Hence, the entire campaign might include 10-14 sounding rockets, or perhaps more. In some cases, depending on the science investigation, one rocket might be launched nearly simultaneously (within a few minutes) of another rocket.

The notional campaign window would likely be scheduled for 8-10 weeks, with additional time needed prior, and after, the launch window to build up and dismantle any NASA hardware brought on site.

The preferred season would most likely be February/March or October/November, based on historical data of the most intense "seasons" of nighttime ionospheric turbulence (i.e., equatorial spread-F) in Peru, although the actual launch window season would be revisited by the selected investigations in conjunction with the Wallops Sounding Rocket Program Office schedule. For example, experiments that seek to understand the effects of stratospheric warmings on the upper atmosphere would presumably require launches in January when this effect is dominant.

There is likely no required solar cycle dependency, although some investigations might benefit from increased geomagnetic activity. For a few investigations, there may be a lunar phase requirement based on either science (e.g., lunar influence of the electrojet) or lighting conditions such as optimal viewing for certain nighttime experiments including ground-based Fabry-Perot observations.

All of the rockets that are anticipated to be flown consist of proven rocket motors and sub-systems, with respect to telemetry, power, attitude control, and attitude and trajectory knowledge. Furthermore, based on the examples of science investigations presented herein, all of the experiments would use scientific instruments that are well-proven and can be designed, built, and tested within the framework of standard NASA sounding rocket investigations (typically, 3 year grants).

It is anticipated that the NASA rocket investigations would be selected based on standard procedure of peer-review of proposals and would be administered by the Science Mission Directorate at NASA Headquarters. It is further anticipated that the rocket payloads, motors, and operations would be managed by the Sounding Rocket Program Office at the NASA/Wallops Flight Facility as part of the regular NASA sounding rocket program.

VII. Summary

We have described a proposed sounding rocket campaign in Peru which presents an opportunity for NASA and NSF to carry out unique, pre-eminent scientific space research at the magnetic equator. The main motivation for the campaign is to carry out fundamental scientific research of natural processes in the earth's ionosphere and upper atmosphere which are unique to the low latitude region of geospace, and specifically to the near-space region that includes the earth's magnetic equator. Examples of such processes include the equatorial electrojet, the daytime "150 km" echo region, regions of nighttime ionospheric turbulence known as equatorial "spread-F", the equatorial anomaly region, and the equatorial mesosphere. These phenomena (as well as many others) include major unanswered questions that would be investigated by scientific instruments carried aloft into the equatorial ionosphere on sounding rockets while detailed, simultaneous observations are carried out by ground-based instrumentation, notably the Jicamarca radar in Peru. Although theoretical progress has been made toward understanding some of these phenomena, many critical questions remain. Indeed, the lack of detailed measurements remains the single greatest obstacle towards making progress in our understanding. This proposed campaign would remedy this situation by gathering the necessary observations of key, targeted geophysical phenomena using probes launched on sounding rockets flown in conjunction with radar and other ground-based observations.

In addition to scientific understanding, the natural phenomena to be investigated with this rocket/radar campaign attack many space weather problems unique to the low latitude ionosphere. These include the need to predict the large scale disruption of radio waves that wreak havoc on communications and navigation systems which results from the disturbed nighttime ionosphere at the equator. From the standpoint of both scientific understanding and space weather applications, a consensus has evolved that fundamental measurements are needed to make progress and that the necessary data are best obtained from focused sounding rocket research missions.

The campaign would notionally consist of 10-14 sounding rockets to be launched at the existing rocket range at Punta Lobos, Peru, which is operated by the Peruvian space agency, CONIDA, and is ideally situated to carry out these scientific investigations. Punta Lobos has been used previously for two major NASA rocket campaigns (Antarqui, 1975; Condor, 1983) and could easily accommodate the proposed "standard" NASA sounding rockets envisioned here. Furthermore, the launch location is near the world-renowned, largely NSF-funded Jicamarca radar which would provide essential observations for all anticipated investigations.

Advances in scientific instruments, payload configurations, radar modes, and ground observing systems promise to provide significant new scientific data and discoveries that go far beyond the achievements of previous NASA rocket campaigns. The new observations are particularly welcomed as theoretical and modeling work has advanced significantly in the many decades since the previous campaigns. Peruvian scientists, primarily at the Jicamarca radar, would be fully engaged in the rocket/radar investigations including data analysis and interpretation. The Peruvian space agency, CONIDA, has indicated, at least informally at this time, that they would enthusiastically welcome such a campaign. The campaign proposed here promises to significantly advance our knowledge of a number of important, critical processes that characterize the earth's ionosphere and upper atmosphere that only exist at the equator.

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