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An unusual spread-F-like event over Arecibo

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Abstract

We describe an apparent mid-latitude spread-F-like event identified with the Arecibo Observatory (AO) incoherent scatter radar (ISR) but also observed using a newly introduced software-defined HF radar and via analysis of Global Positioning System-Total Electron Content (GPS-TEC) data. We show that this event was in fact non-local and appeared, as seen in delta-vTEC Keogram results to be propagating from west-to-east and back to the west crossing over AO twice. We suggest that this event, while indistinguishable from similar long ISR-observed events, has strong non-local properties. The combination of observations, from multiple instruments of this unique event helps tie its development and progression. The Penn State Ionospheric Radar Imager (PIRI), essentially a single frequency ionosonde, was deployed near AO (18.36° N, 66.75° W, 46.5° dip-angle, and $f_o = 4.42$ MHz), Puerto Rico. The apparent PIRI-observed range spread of the event exceeds 400 km — a likely indication of spread-F viewed with an ionosonde. We also compare PIRI results with ISR and GPS-TEC results. ISR range-time intensity plots show rather a calm ionosphere, with exception of a major upwelling, that seems to include kilometer-scale layered structures, in the F-region. In contrast, the HF radar observations reveal that the ionosphere is disturbed by Perkins-like large scale instability structures. The data set is exceptional, consisting of simultaneous fixed frequency, wide-beam high frequency (HF) radar observations, ISR power intensity maps, and delta-vTEC measurements. These joint data sets characterized the nighttime ionosphere F-region and offer new insights into the ionospheric processes leading to what is observed by the very narrow-beam ISR.

1 Introduction

Following their first detection on ionograms[1, 2], ionospheric spread-F phenomenon has been under investigation for nearly a century. Since then, its morphology, occurrence rate and origins have been subject to a great deal of research using radio science tools such as ionosondes, coherent and incoherent radars, and satellites along with theoretical analysis [3, 4, 5, 6]. Spread-F theory and observation have been carried out at all latitudes. In equatorial regions, geomagnetic field lines are near horizontal where they support the ionosphere against gravity. At high latitudes the ionosphere is contingent upon strong forcing from the magnetosphere [7]. For middle latitudes neither the horizontal or vertical field line approximation is applicable which leaves many questions to be answered regarding the mid-latitude spread-F (MSF) phenomenon. Limited access to high frequency (HF) radars in mid-latitude sector leaves most MSF research dependent on relatively sparse ionosondes and ISRs. In this summary paper we present a mid-latitude spread-F-like event observed by the software-defined HF radar, PIRI (18.36° N, 66.75° W, 46.5° dip-angle, and $f_o = 4.42$ MHz), in high temporal and spatial resolution for the first time with, uniquely, parallel ISR and GPS delta-vTEC observations. Recent technological advancements in SDR technology permit MSF studies at very high range and time resolution. The wide-beam PIRI observations are compared with narrow-beam 430 MHz AO ISR result. The considerable difference between HF and ISR are evidence of a highly unstable ionosophere. To better understand the context of the ISR and HF radar we include GPS-TEC results available from the Puerto Rican region. These results are presented in Keogram form [9] using the approach developed by Dinsmore [10]. The paper mainly consists of three sections; Introduction, Multi-instrument Observations, and Data Interpretation.

2 Multi-instrument Observations of a Spread-F like Event

Multiple instruments were used to observe and trace the unusual MSF structure reported herein. The first instrument that is used in the paper is a newly introduced software defined HF radar, PIRI. In March 2017, this radar was deployed near the Arecibo Observatory in order to utilize the new Arecibo ionospheric heater during the March 2017 HF heating campaign. The HF radar setup was identical to the system described in [11] with the exception of its operating frequency and transmit front end. An inverted-V type dipole antenna, which is common in amateur radio community, was used for transmitting. The center frequency of the antenna is 4.42 MHz, and the voltage standing-wave ratio of the antenna is less than 1.2 over a 50-kHz bandwidth. Half-power beamwidth of the antenna in the elevation plane is 120.1° at $\phi = 0°$, 101° at $\phi = 45°$, and 80° at $\phi = 90°$. The transmitting antenna beam points vertically upward, and it is horizontally polarized. A popular ham radio amplifier, Ameritron AL-811H, is used in the final stage of the ampli-

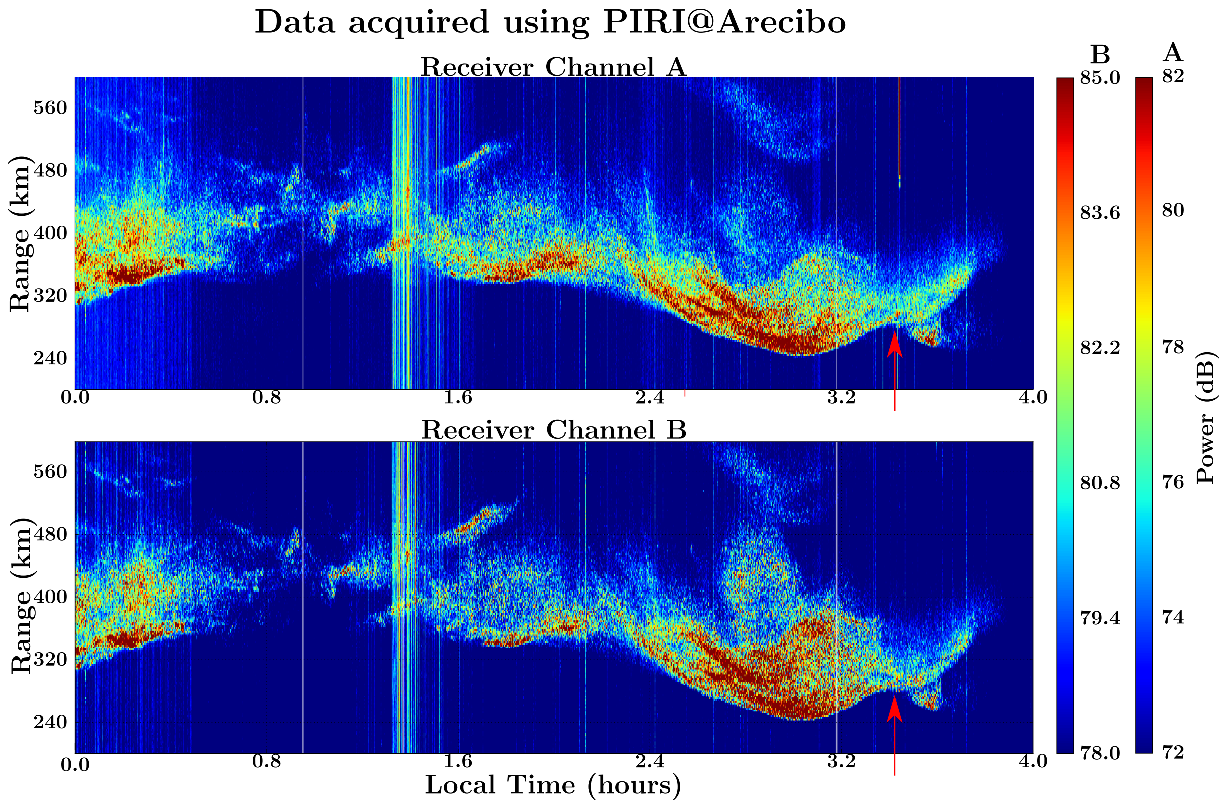

Figure 1. The spread-F-like event captured by PIRI. As seen with PIRI, this event occurs over the 2.4 - 3.2 AST time-frame. The peak of the ISR-defined event (Fig. 2) occurs at 3.3 AST suggesting the strong role of HF propagation from off-vertical in this event. Note that "heater-on" PIRI pulse-returns have been removed due to strong arcing interference. Displayed total power in the two orthogonal channels has been adjusted relative to the individual noise levels. The Barker codes are decoded by sidelobe-free decoding algorithm [8].

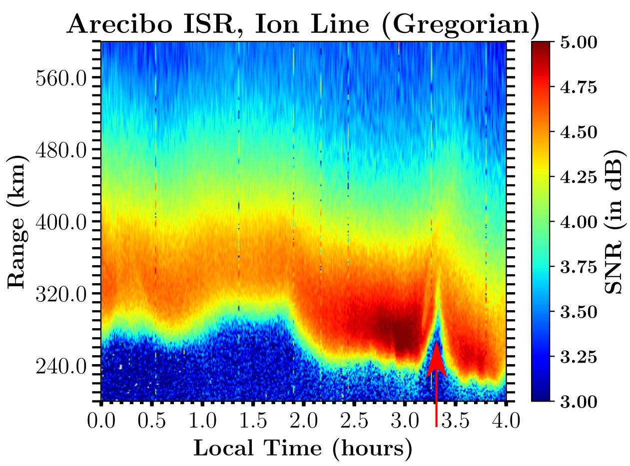

Figure 2. Range-time ISR power intensity observation during Spread- F-like event characterized by the strong up-welling as indicated at 3.3 AST. Strong up-welling F-region features have long been observed at AO [7].

fication and was able to provide 625 W peak power. PIRI has two crossed-dipole active antennas for reception allowing circular polarization analysis. A more comprehensive description of the system can be found in [12]. The second instrument result that is used in this work is the AO 430 MHz ISR which has been in operation for decades and is extensively reviewed in the literature [13, 14]. Until the recent collapse of the Arecibo Observatory, the 430 MHz system was the largest and most sensitive incoherent scatter radar [7, 15]. The AO ISR has a 1/6 degree pencil beam and, via theory of incoherent scattering, parameters such as electron concentration, wind velocity, ion neutral collision frequency [16]. In the observations presented here, both the linefeed and Gregorian T/R systems were used. For these observations, the gregorian was pointing vertically upwards while the linefeed was pointed 11° magnetic south. Only results from the Gregorian receiver is given in this summary paper. Results from the third and final instrument being used in this study, are Global Positioning Satellite Total Electron Content receivers. A network of GPS-TEC receivers are available over most non-oceanic latitudes and longitudes thus providing a global picture of ionospheric processes such as medium or large scale traveling ionospheric disturbances [17]. All GPS-TEC data utilized for this paper is available from the Madrigal website [10].

3 Data Interpretation

On March 15 2017, the PIRI HF radar was operating to test its D-region capabilities so that the Arecibo HF heater

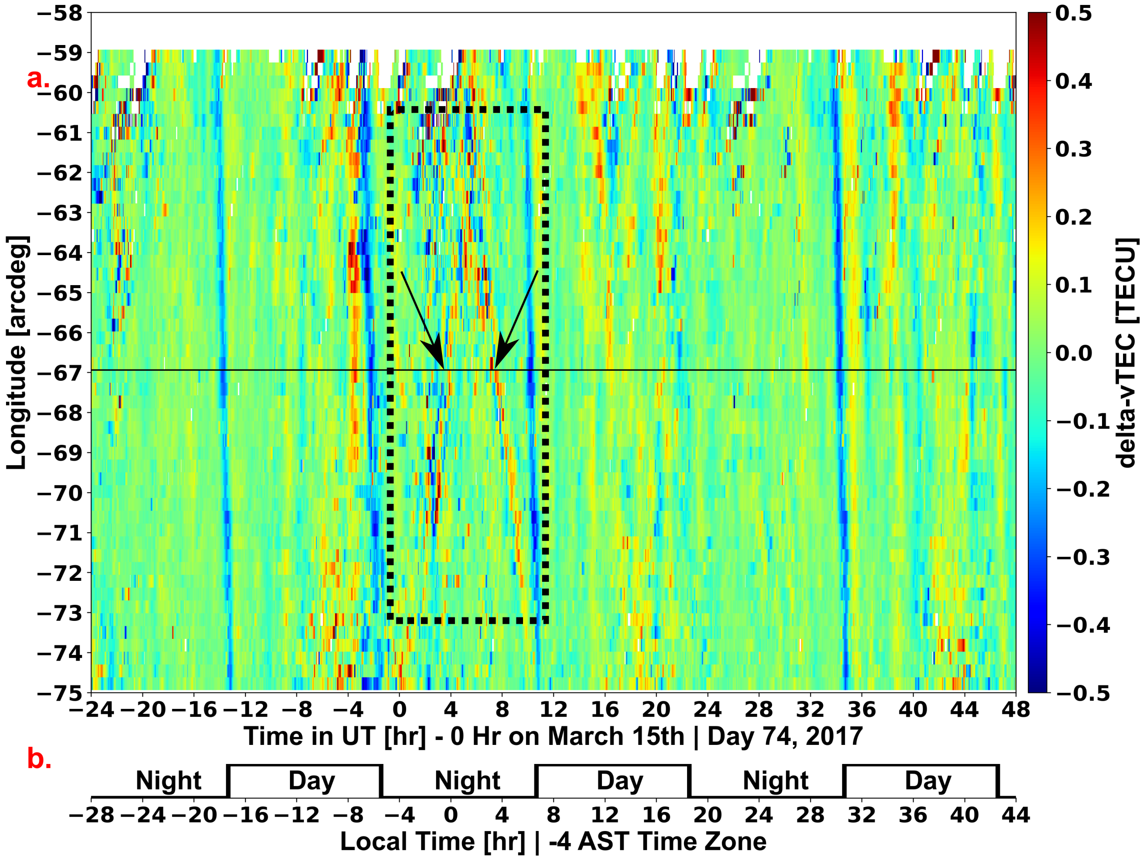

Figure 3. Delta-vTEC Keogram with longitude slicing +/- (east/west) 8 degrees around AO located at -67 degrees longitude as indicated by the black center line. Each longitude "slice" is 0.32 arc-degrees or 36 km in width with north-south extent from South America to well out in the Atlantic. The inverted V structure between -4 to 7 AST is observed as it passes over AO as indicated by the arrows. The full longitude vertical stripes are due to day/night boundary crossings.

Table 1. PIRI and Arecibo ISR Radar Parameters

	Operating Frequency	IPP	Pulse Compression	Pulse Width	Peak Power
Probing (HF Radar) Configuration	4.42 MHz	6 ms	Barker-13	195 us	600 W
Disturbing (Heater) Configuration	5.125 MHz	12 ms	None	1 ms	300 kW
Arecibo Incoherent Scatter Radar	430 MHz	10 ms	Coded Long Pulse	440 us	430 kW

was heating the ionosphere at 5.125 MHz. However, according to a closeby ionosonde at Ramey, PR (18.5°N, 67.1°W), the critical frequency of the ionosphere was below the heating frequency (foF2 < 5 MHz). As indicated in Fig. 1, PIRI showed strong ionospheric plasma instabilities that might be identified as spread-F if they were viewed by an ionosonde. The range extent of the event exceeds 400 km. We originally attempted to attribute this to HF-heating modification of the ionosphere. But, as the HF radar has a wide beam (> 80°), it seems plausible that this structure was observed to the side of the very narrow ISR beam results given in Fig 3.

The narrow beam 430 MHz AO ISR result is given in Fig. 2. As opposed to the HF radar, the ISR range-time intensity plot shows a smooth ionosphere. The only exception is the strong upwelling—often observed at AO—which might normally be attributed to a local Perkins instability induced event induced, in this case, by ionospheric heating [18].

Given the complexity of the Fig. 1 results relative to the apparently straightforward ISR results, we introduced GPS-TEC mapping on the mesoscale surrounding AO to establish the context of the event. Due to the relative sparsity of GPS-TEC receivers in the Puerto Rican region, we utilized delta-vTEC Keogram analysis (Fig. 3) to produce "movies" of this event in the full context of several days. The delta-vTEC (fluctuations around the running mean of the vertical projection of TEC along satellite-receiver geographic tracks at the F-region “pierce point” altitude.) “movies” average sparse data in the north-south dimension yielding the Fig. 3 result. That is, to produce these movies, delta-vTEC is averaged over longitude/latitude-narrow but latitude/longitude wide strips plotted versus time over the geographic map of the region. These maps are formed by cordoning a given geographical region into thin rectangles and averaging all GPS-TEC data points within each segment for each averaging time window. The time averaging process is repeated for multiple time intervals to create a plot that, in principle, demonstrates the progression over time of TEC features in each geographically rectangular cell. Again, this data-display mode is known as a Keogram and, in the event presented herein, this approach proves revealing.

In conclusion, the event in question was clearly observed in the ISR results and initially thought to be an HF-heating induced F-region instabilty structure (upwelling) that would appear as spread-F on an ionogram. The PIRI results were more ambiguous as the complex HF event occurred before the ISR event. Given the wide HF beam, this suggested an ionospheric structure moving over AO from the side and that this structure was not the result of HF heating modification of the ionosphere. In order to establish the context of the radar observations, we turned to available GPS-TEC results which we present in the form of a Keogram with narrow longitudinal slices and wide latitudinal extent. These results point to a propagating ionospheric structure tha first appears to the west of AO, moves over AO to the east, and then passes back over AO (appearing as the very narrow in time upwelling feature in Fig 3), and moves to the west. This is not consistent with a local Perkins instability in the F-region and, thus, points to complex electrodynamics that may prove to involve both equatorial and auroral oval processes.

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