C/NOFS Thermospheric Research and Reentry EXperiment (T-RREX)

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ABSTRACT

The Air Force Research Laboratory is leveraging an extraordinary opportunity with the Communication/Navigation Outage Forecasting System (C/NOFS) satellite to collect a comprehensive set of low-altitude measurements as the orbit decays. Reentry is expected before the end of this year. C/NOFS is in a 13° elliptical orbit, with apogee currently below 500 km and perigee below 360 km. The primary goals for this last phase of the C/NOFS mission are to advance our understanding of topside/bottomside dynamics and to improve models currently used for trajectory propagation, orbital drag, and uncontrolled reentry predictions.

1. Introduction

The Communication/Navigation Outage Forecasting System (C/NOFS) satellite was launched on 16 April 2008 carrying a full suite of instruments to monitor the equatorial ionosphere. Together with a network of ground stations and a suite of ionospheric models running in the C/NOFS Data Center, its mission was to characterize and forecast the conditions that degrade communication and navigation capabilities. The initial orbit was elliptical at a 13° inclination, with an apogee of 850 km and perigee of 400 km. Although designed for solar maximum conditions, C/NOFS was placed into orbit during a solar minimum with the lowest levels of activity recorded during the space age. This was in turn followed by a ‘mini’ solar maximum with few significant solar storms. It was not until 17 March 2015 that C/NOFS experienced a storm with Kp values as high as 8 and Dst values below -225 nT.

The benign space environment has been turned to advantage. The dedicated payload and science teams have published more than 130 papers to date in refereed journals that have added significantly to our knowledge base and virtually rewritten the book on the equatorial ionosphere in solar minimum. The satellite and its instruments have performed remarkably well with a rate of data return exceeding 95%. C/NOFS remains fully operational, a tribute to the scientists and engineers who designed and built it and the operations teams that have maintained it so well.

C/NOFS has now completed seven successful years on orbit. Table 1 lists the C/NOFS satellite instruments, parameters measured, and the principal investigators. The strong partnerships forged during the C/NOFS mission have been a significant factor in its success.

Table 1. *C/NOFS instruments, measurements and principal investigators (PIs)*

Name	**Instrument**	**Measured Parameters**	**PI and Organization**
PLP	Planar Langmuir Probe	- Ion density - Electron temperature - Power spectral densities	Patrick Roddy AFRL
IVM	Ion Velocity Meter	- Vector ion drift velocities - Ion temperature - Ion composition	Rod Heelis U. of Texas at Dallas
NWM	Neutral Wind Meter	- Vector neutral wind velocities - Neutral composition	Rod Heelis U. of Texas at Dallas
VEFI	Vector Electric Field Instrument	- Vector DC & AC electric fields - Magnetic fields - Relative plasma density - Optical lighting emission	Rob Pfaff NASA GSFC
CERTO	Coherent Electromagnetic Radio Tomography	- Space-to-ground scintillations - Ne reconstruction	Paul Bernhardt NRL
CORISS	C/NOFS Occultation Receiver for Ionospheric Sensing and Specification	- Ne profiles - Line-of-sight TEC - Space-to-space scintillation - Stratospheric refractivity	Paul Straus Aerospace Corp.

Orbital parameters of the C/NOFS satellite remained relatively stable for several years but, as expected, when solar activity levels increased in 2011, the orbit gradually began to change as well (Figure 1). C/NOFS began flying below the peak of the F-layer as the perigee altitude continued to fall. Then, for about six months from June to October 2013, C/NOFS was placed in safe mode while scientists in the Space Weather Center of Excellence at the Air Force Research Laboratory (AFRL) sought funds to continue operations. By the time C/NOFS was brought out of safe mode in October 2013 to support AFRL's Conjugate Point Study (CPS), apogee altitude had fallen below 700 km and perigee was below 380 km. During the next year of CPS operations, apogee altitude fell about 10 km/month and perigee about 1-2 km/month.

By the end of CPS in September 2014, the now rapidly changing orbit and the sound state of health of the C/NOFS satellite and sensors provided the impetus for AFRL to take advantage of an extraordinary opportunity. This final phase of the C/NOFS mission is dedicated to the Thermospheric Research and Reentry EXperiment (T-RREX) to collect an unprecedented set of space environment data as the orbit continues to decay and the satellite reenters. These low-altitude measurements have great potential to advance our understanding of topside/bottomside dynamics and bottomside specification, and to improve trajectory propagation, orbital drag and reentry prediction models (Figure 2). C/NOFS operations to support T-RREX began on 1 October 2014.

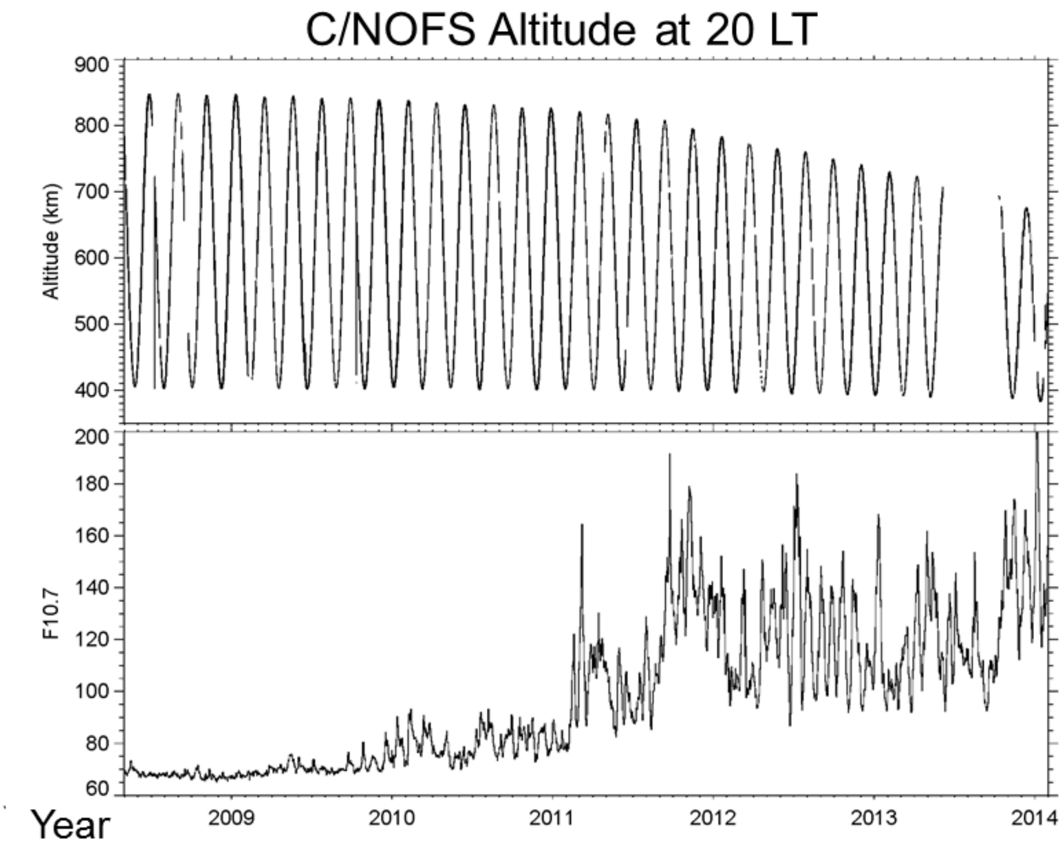

Figure 1. *C/NOFS orbit (top) vs solar EUV flux (bottom). The gap indicates when C/NOFS was in safe mode for ~6 months in 2013.*

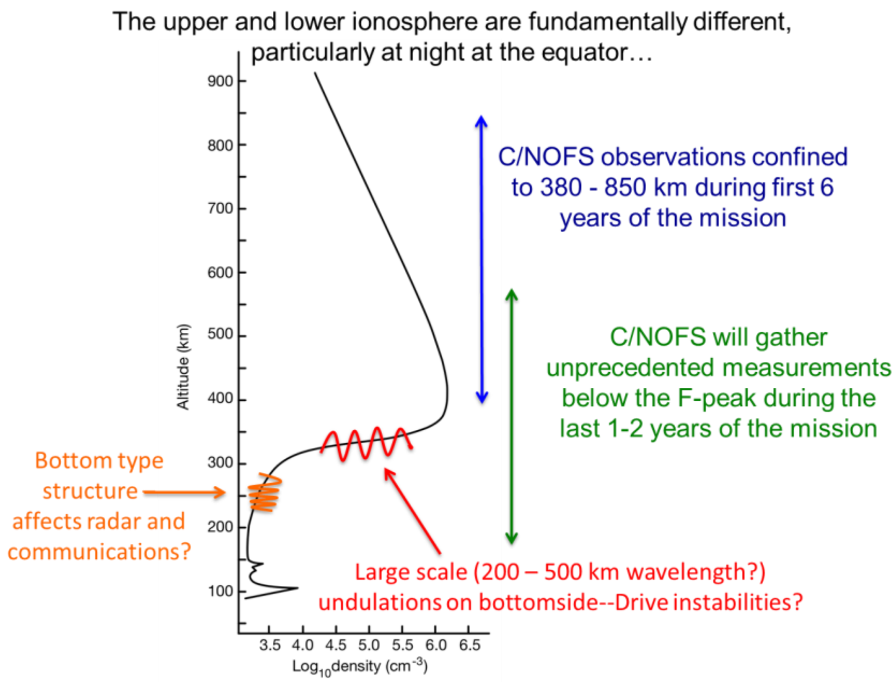

Figure 2. *Diagram of the electron density profile variations C/NOFS has observed.*

2. T-RREX Initial Observations

One of the challenges for T-RREX is power management. Although all sensors are fully operational, it is not always possible to keep all sensors on throughout eclipse. Currently, the CERTO beacon has been off for several months and the PLP power cycles in sunlight and eclipse. The IVM uses little power and is on continuously. VEFI regularly observes bottomside structures as C/NOFS flies below the peak of the F-layer. CORISS provides accurate position, navigation and timing. In the early stages of the mission at higher altitudes and in deep solar minimum conditions, the NWM did not gather much data. With C/NOFS now at lower altitudes, the NWM Cross-Track Sensor (CTS) was turned on in June 2014 and has operated well since then. The NWM CTS has now collected the first long-term data set of neutral density and winds in the equatorial region.

2.1. Neutral Wind Meter (NWM)

Neutral winds are the primary force that drives instabilities in the bottomside ionosphere. However, monitoring neutral winds at thermospheric altitudes is a difficult task and *in situ* measurements are rare. Ground-based Fabry-Perot interferometers offer the most accurate measurements, but they are sparsely deployed and located only on land sites. The C/NOFS NWM provides the most extensive information about wind structures at F-layer altitudes. The utility of the NWM grows as the spacecraft's apogee falls. When conditions are favorable, the Ram Wind Sensor (RWS) will also be turned on.

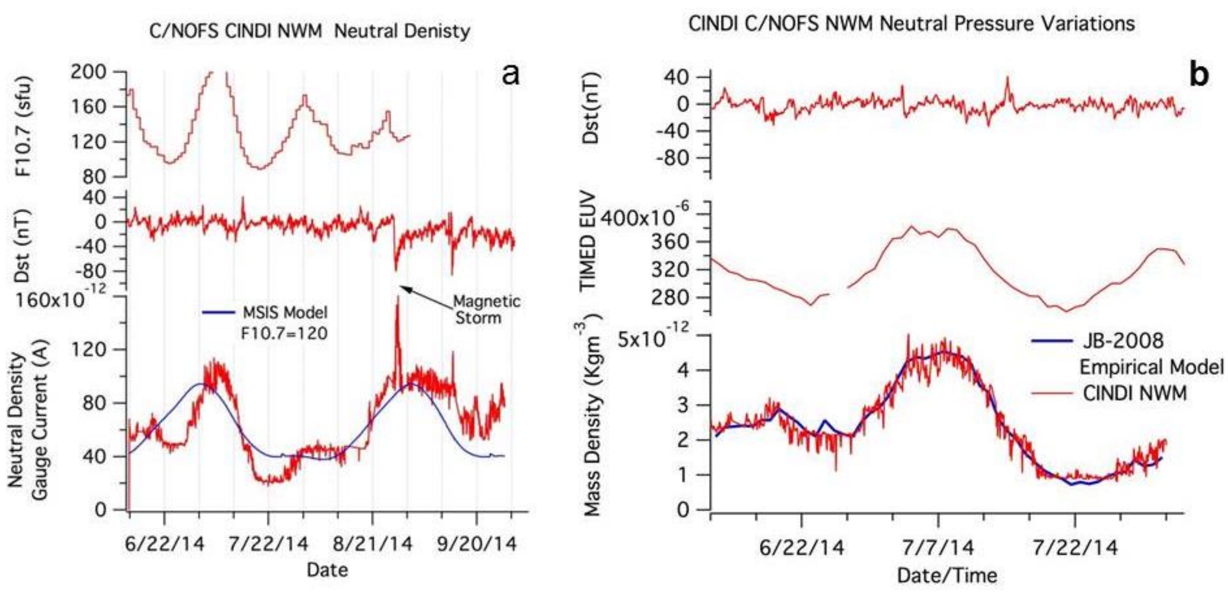

Figure 3. *NWM measurements vs (a) MSIS and (b) JB-2008.*

Figure 3 shows some preliminary results from the NWM CTS during its first few months of operation in the summer of 2014. The plot on the left shows neutral density vs F10.7 (top), the Disturbance Storm Time Index (Dst) (middle), and the empirical Mass Spectrometer and Incoherent Scatter radar data (MSIS) model [*Picone et al.*, 2002] of the neutral atmosphere (bottom). Over the course of the three months, F10.7 ranged from 80 to more than 200 sfu. Conditions early in the time interval were quiet; Dst varied between +/- 40 nT until a storm occurred in late August. Dst quickly fell to ~-80 nT, the recovery phase lasted several days, and Dst remained below 0 nT until late September. The MSIS model was normalized to the sensor current and assumed no changes in magnetic or solar activity. Consequently, the diurnal variation predicted by MSIS is very smooth with no perturbations over the course of the time interval. In general, the trends in NWM density track fairly well with MSIS, but there are differences. The NWM peak in density at the end of June is later and higher than the model predictions, and the minimum on 22 July is significantly below the MSIS values. Further, the observed neutral densities show definite responses to both solar and magnetic activity. NWM exhibits a significant spike during the August storm that MSIS does not. The solar activity variations are associated with the 27-day solar rotation and the appearance of two magnetic storms as indicated by the Dst index.

The plot on the right shows the first couple of months (June-July) of the same quiet time interval when Dst remained between +/- 40 nT. The middle plot is the solar EUV flux measured on the Thermosphere Ionosphere Mesosphere Energetics and Dynamics (TIMED) spacecraft. The bottom plot indicates that the NWM neutral pressure variations correlate very well with the EUV trace and match the Jacchia-Bowman 2008 (JB-2008) operational model for orbital drag extremely well. This example confirms that the NWM measurements and data algorithms are robust, but keep in mind that this is just one example for a very quiet time interval. There is much more analysis to be done under varying solar conditions.

Figure 4 presents an example of NWM density measurements vs Dst for two weeks in March 2012, a time interval when three small solar storms occurred, as marked by the arrows. The density data are highly structured and clearly respond to the geomagnetic activity indicated by the Dst variations. Note that in each case, the density increases rapidly with storm onset and the high density persists for a day or more, well into the recovery phase of the storm. Reentry predictions may be off by 20°– 40° in latitude if such low-altitude neutral density variations are not incorporated into predictive models.

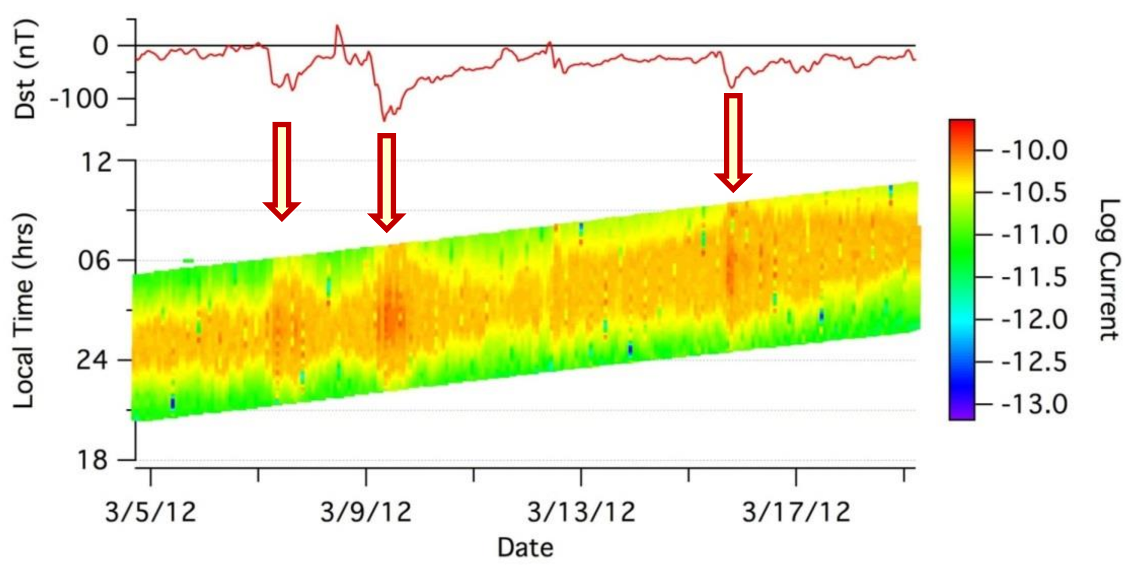

Figure 4. *NWM neutral density measurements vs Dst during three small storms in March 2012.*

2.2. VECTOR ELECTRIC FIELD INSTRUMENT (VEFI)

As C/NOFS spends more and more time below the peak of the F-layer, VEFI regularly observes a variety of wave structures and irregularities in the bottomside ionosphere. One example from September 2014 is shown in Figure 5.

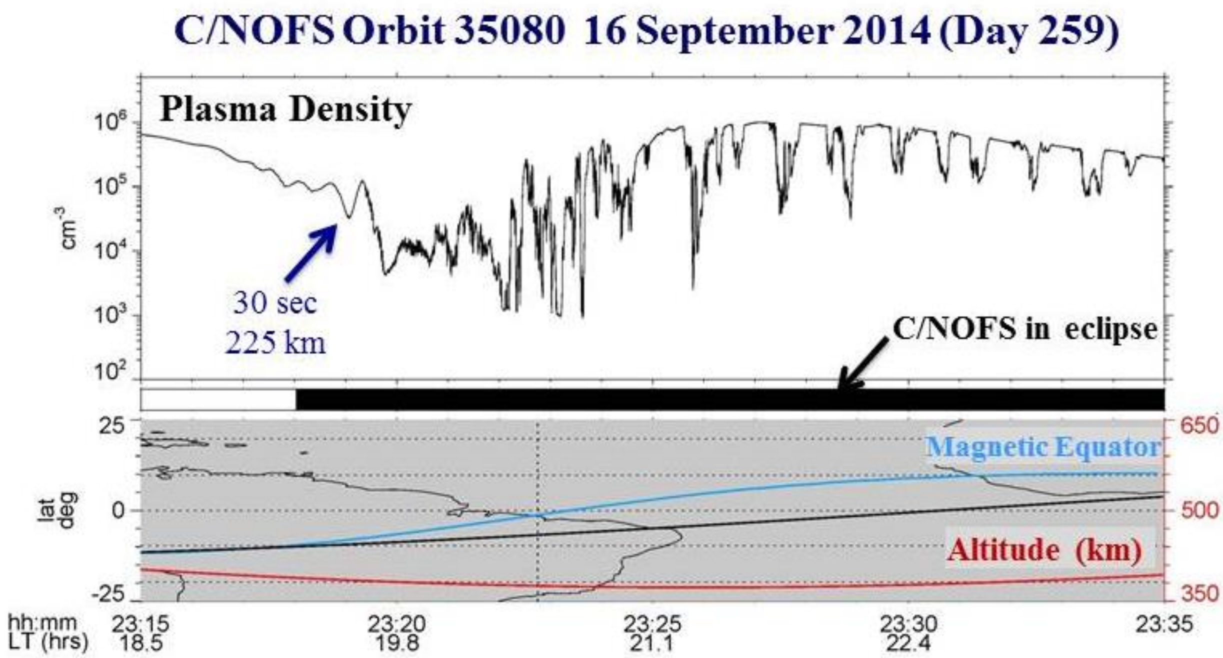

Figure 5. *VEFI observations of irregularities in the bottomside ionosphere.*

The bottom plot shows the C/NOFS location (black) and altitude (red) at the time of the observations on 16 September 2014. Note that C/NOFS was at or near perigee throughout this time interval. The black bar in the center indicates when C/NOFS was in eclipse. The top plot shows a broad density depletion that occurred when the satellite was near the magnetic equator. Superposed on this depletion and extending beyond it are wave-like structures that appeared after sunset, indicating the presence of plasma density irregularities that exist over a wide range of scale sizes.

Figure 6 shows additional bottomside observations from VEFI for three orbits in January 2015 in the same format as Figure 5 with the addition of plasma drift measurements (top plots). Similar to the observations presented in Figure 5, the three passes all show large depletions when the satellite is near the equator and a variety of smaller scale structures that follow or are superposed on the broad depletions. Analysis of these bottomside observations revealed a consistent pattern: the plasma density perturbations are associated with perturbations in the ion velocities. In particular, the density depletions appear to be highly correlated with the direction of the ion drifts, with the depletions occurring when the direction of the ion drift is westward. These results are being investigated further with a larger data sample.

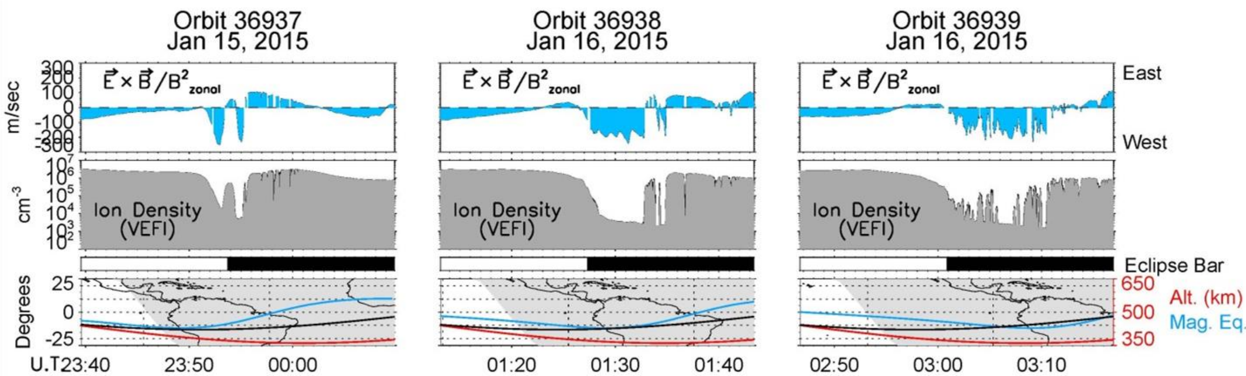

Figure 6. *VEFI observations of plasma density and drifts in the bottomside ionosphere.*

3. C/NOFS Reentry Predictions

Accurately predicting date, time, and location for uncontrolled reentry of space vehicles and orbiting debris still presents many challenges. Current models incorporate a variety of atmospheric density estimates and solar activity predictions, but are still woefully inadequate. C/NOFS reentry predictions provided by three different sources have varied greatly in the past six months, but the mean values are now beginning to converge. Initial estimates based on Two-Line Elements (TLEs) of 1 July 2014 ranged over a six-month interval between September 2015 and February 2016. Updated predictions based on 1 October 2014 TLEs closed the range to four months with the earliest date 24 October 2015 and the latest 20 January 2016. Predictions from January of 2015 brought a surprising change and closed the range to about one month, with the mean reentry predictions now centered around October - November 2015. The effects of the 17 March 2015 solar storm were reflected in the latest set of estimates done on 15 April 2015. Although each prediction comes with a window of ~3-4 months depending on solar activity levels, the mean values continue to cluster around October 2015.

Tracking the C/NOFS reentry affords an opportunity to test models against measurements. The C/NOFS satellite has no propulsion so it will experience an uncontrolled reentry, but it does have the CORISS GPS receiver. CORISS provides accurate position, navigation, and timing information that should permit tracking C/NOFS quite accurately as the orbit decays.

4. Summary

With the decrease in perigee and an increase in solar activity, C/NOFS is poised to gather significant observations at low altitudes in the low-latitude ionosphere – measurements we have never had before. These data will advance our understanding of ionospheric coupling above and below the F peak and fill the gaps in ionospheric models, providing a far more complete and realistic picture of the low-latitude, low-altitude ionosphere. Initial results are quite promising, but there is still much work to be done in understanding the mechanisms that couple the topside and bottomside of the ionosphere. We have never had this opportunity before, and we may not have it again in the foreseeable future. We invite and encourage any collaborations that will leverage the results from this unique data set.

Acknowledgments

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