Scintillation Observations and Response of The Ionosphere to Electrodynamics (SORTIE) Mission First Light

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ABSTRACT

At low and middle latitudes, wave-like plasma perturbations are thought to provide the seeds for larger perturbations that may evolve non-linearly to produce irregularities, which in turn have deleterious effects on HF communications and global positioning systems. Unfortunately, there is currently no comprehensive atlas of measurements describing the global spatial or temporal distribution of wave-like perturbations in the ionosphere. The SORTIE mission, a CubeSat experiment with team members from ASTRA, AFRL, UTD, and Boston College, was designed to help map and further understand the wave-like plasma perturbation distributions throughout the ionosphere. The SORTIE 6U CubeSat sensor package measures key in-situ plasma parameters, and includes an ion velocity meter and a planar Langmuir probe. SORTIE will provide (1) the initial spectrum of wave perturbations which are the starting point for plasma instabilities; (2) measured electric fields which determine the magnitude of the instability growth rate near the region where plasma bubbles are generated; (3) initial observations of irregularities in plasma density which result from plasma instability growth. The SORTIE spacecraft was deployed from the ISS in February 2020 and began data collections shortly after orbit insertion. The measurements are expected to continue for at least a year. In this presentation we present the "first light" results of the SORTIE mission, as well as reviewing the science objectives and providing an overview of the spacecraft and instruments.

MISSION MOTIVATION AND OBJECTIVES

Wave-like perturbations in the plasma density echo wave-like perturbations in the background neutral atmosphere that couple to the ionosphere through various mechanisms: (1) winds may mechanically move the ionospheric layer vertically through collisions, or; (2) neutral atmosphere perturbations may be imprinted on the ionosphere through the dynamo action of winds at low altitudes. Regardless of the mechanism, a wave-like perturbation in the ionosphere will result.

In order to connect the plasma density perturbations to wave-like sources it is first necessary to characterize when and where the waves exist, statistically. While waves are pervasive features in the F-region ionosphere, they rarely exist as continuous wave trains. Figure 1 shows the vertical plasma velocity perturbations, the plasma density perturbations, and the plasma density measured continuously around a C/NOFS orbit. These measurements, taken by the ion velocity meter on C/NOFS, show the wide range of spatial scales and correlations that exist between the plasma density and the plasma velocity. Travelling Ionospheric Disturbances (TIDs) have also been routinely measured in the bottomside ionosphere by HF sounders (e.g., ASTRA's TIDDBIT sounder [1]); the HF sounder data confirm the assertion that waves are pervasive features in the F-region ionosphere. However, they rarely exist as continuous wave trains; like C/NOFS, an HF sounder also reveals that multiple waves can be present at the same time.

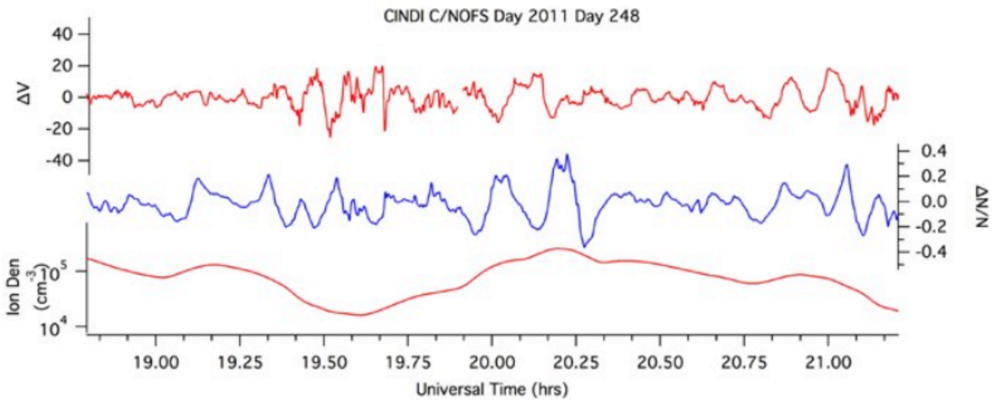


Figure 1. Vertical ion velocity and plasma density perturbations from a C/NOFS orbit.

Inspection of the data shown in Figure 1 reveals areas where the correlation between the vertical plasma drift and the plasma density is high. It also shows areas where the spatial correlation is weak. The action of a neutral wind is to drive plasma perpendicular to the magnetic field under the action of a wind dynamo, or to drive plasma parallel to the magnetic field under the action of collisional forces. Plasma motions parallel and perpendicular to the magnetic field will affect the plasma density in different ways, depending on geographic location.

Near the magnetic equator the action of vertical drift perpendicular to the magnetic field will move plasma into a larger flux tube volume and thus tend to reduce the plasma density in the topside in a signature commonly called the equatorial anomaly. Away from the magnetic equator the upward drift induces diffusive motions parallel to the magnetic field and transport away from the magnetic equator that can locally increase the plasma density. Field-aligned plasma motions induced by neutral winds may move the plasma parallel to the magnetic field, either toward the pole or toward the equator. Equator-ward motions are upward and will increase the plasma density above the F-peak, while pole-ward motions are downward and will tend to decrease the plasma density above the F-peak.

The top panel of Figure 2 schematically shows the associated drifts parallel and perpendicular to the magnetic field, and the corresponding changes in the topside plasma density are indicated by the circled arrow. The lower panel shows the density perturbations associated with plasma motions parallel to the magnetic field. Changing the direction of the perpendicular and parallel drifts changes the sign of the associated density perturbation. The point to be emphasized is that the expected relationships between plasma density and plasma drift require that the components of drift parallel and perpendicular to the magnetic field must be considered, as well as season, and location with respect to the magnetic equator. Recently the appearance of so-called plasma blobs and their associated plasma dynamics have been investigated in the topside ionosphere. Occurring away from the magnetic equator, an upward drift perpendicular to the magnetic field is invoked. However, the transverse propagation of wave-like drift perturbations has been invoked to account for a phase difference between local maxima in the plasma drift and the plasma density [2].

Figure 3 shows the plasma density and drift variations observed across a plasma density enhancement in the topside ionosphere. The top panel clearly identifies plasma density enhancements, and the vertical lines

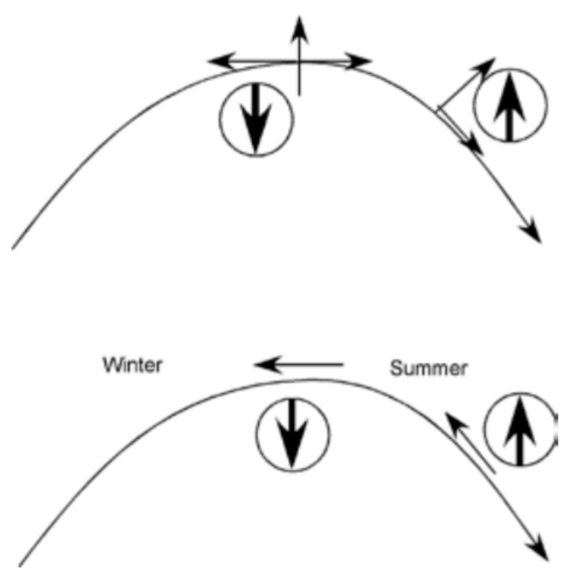


Figure 2. Parallel and perpendicular plasma drifts geometry.

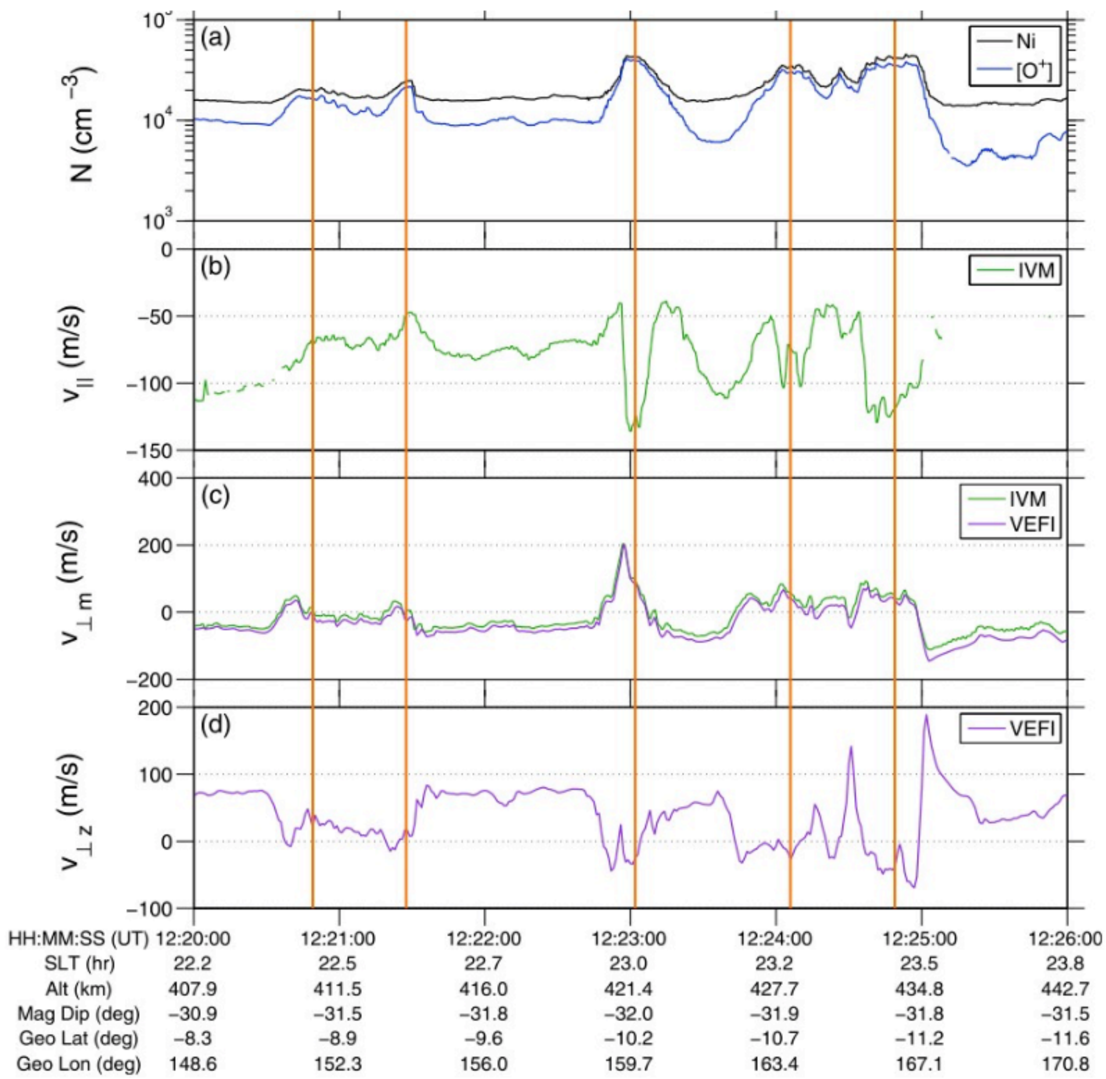


Figure 3. C/NOFS Data from 26 June, 2009.

indicate the times of simultaneously observed plasma drifts in the directions parallel and perpendicular to the magnetic field. The second panel shows a peak near 12:23UT in the parallel plasma velocity that is aligned with the plasma density peak at the same time. However, the third panel shows that the peak in the upward drift perpendicular to the magnetic field is displaced to the west of the plasma density peak. This observation serves to emphasize two features. First the upward drift in the southern hemisphere is accompanied by antiparallel downward drift along the magnetic field, as expected. Second the displacement of the peak upward vertical drift perpendicular to the magnetic field and plasma density peak signal the presence of an electrodynamic feature that is propagating to the west such that the ionosphere continues to rise until the propagating feature has passed.

One final attribute of the ionosphere near the F-region peak, is the fact that it has a built-in memory of the previously applied dynamics. Thus, in the topside ionosphere a previously lifted ionosphere will show an increase in the plasma density at a fixed height compared to an ionosphere that is not lifted. Thus the presence of wave-like signatures in the plasma density is possible even in the absence of a corresponding plasma drift feature.

Describing these prevalent signatures of ion-neutral coupling is the key to understanding the role they play in the formation of plasma density gradients that affect radio propagation paths in operational systems, and potentially as the seed for plasma instabilities that can produce intense radio scintillation. However, ***there is currently no comprehensive atlas of measurements***

describing the global spatial or temporal distribution of wave-like perturbation in the ionosphere. Thus, the objectives of the SORTIE mission are:

> Q1) Discover the sources of wave-like plasma perturbations in the F-region ionosphere, and
>
> Q2) Determine the relative role of dynamo action versus direct mechanical forcing in the formation of wave-like plasma perturbations

OBSERVATIONS AND IMPACT

Examination of Figure 2 and Figure 3 indicates the data gathering and analysis procedure that must be followed to establish the dominant mechanisms for production of plasma density perturbations. We first note that while a vertical drift perturbation will produce a corresponding perturbation in the plasma density, the opposite is not true. Thus there can exist plasma density perturbations, indicative of a previous perturbation in the plasma drift that is no longer observed.

An applied velocity perturbation can also "undo" an existing plasma density perturbation and thus the data set must first be divided into two groups: (a) those that show correlations and (b) those that do not. Those that do not show correlations can still provide valuable additions to Objective 1. Those with correlations are used to establish the dominant causative mechanisms. As noted in our discussion of Figure 3 it is necessary to first establish a phase delay between the velocity components parallel and perpendicular to the magnetic field and the plasma density perturbation. Following this registration, we are able to apply the simple rules shown in Figure 2; anti-correlation between the velocity components and positive correlation between the perpendicular drift and the density indicate the dominance of dynamo ***E x B*** motion. Positive correlation between upward parallel drifts and plasma density indicate the dominance of mechanical forcing of the plasma along the magnetic field. By these means we will produce closure on the second science objective.

While there have been many disparate studies of ionospheric irregularities and the resulting scintillation on GPS and other radio signals, <u>this is the first time that an 'atlas' of ionospheric perturbations will be made for all local times, and multiple seasons for a range of latitudes from the equator to the inclination of the satellite</u>. There are two aspects to equatorial instability: initial seeding, and subsequent evolution of wave perturbations. To date, no investigation has attempted to cover both aspects. SORTIE will provide (1) the initial spectrum of wave perturbations which are the starting point for the Rayleigh-Taylor (RT) calculation; (2) measured electric fields which determine the magnitude of the RT growth rate near the region where Equatorial Plasma Bubbles (EPBs) are generated; (3) initial observations of irregularities in plasma density which result from RT growth. The proposed work is significant because:

1) It advances our understanding of ionospheric irregularities and the roles of various drivers in their formation

2) It will result in an improved predictive capability of ionospheric irregularities

3) We anticipate that the proposed work will eventually lead to the production of forecasts that will be able to predict the location and intensity of scintillation on various radio signals.

The selection by NASA of the Ionospheric Connection Explorer (ICON) underscores the importance of the coupling between the thermosphere- ionosphere system, and understanding all the factors that lead to variability in the ionosphere. ICON's goals are to understand the source of strong ionospheric variability, and to quantify the effects of geomagnetic forcing on the ionosphere. SORTIE seeks to advance our understanding of the sources of ionospheric variability in concert with the flight of the ICON mission.

The SORTIE objectives will be achieved via in-situ ion-drift and plasma density measurements with spatial resolution < 100km. The SORTIE instrument suite will enable the study of the various forcing terms that are critical to understanding the plasma environment. A low to mid latitude near-circular precessing orbit is needed, so that all local times can be covered over the span of the approximately 12-month mission. A portion of the SORTIE science traceability matrix is shown in Table 1.

Orbital inclination is a key consideration in determining mission science return. A low inclination orbit is preferred such that similar magnetic apex heights can be revisited several times each day – however this is not a hard requirement, and it seems unlikely that such a launch opportunity will exist. The mission can be performed near or below station orbit. The mission concept is to sample all local times within 6 months.

Table 1. SORTIE Science to Measurement Functionality Requirements Traceability Matrix.

Science Traceability Matrix

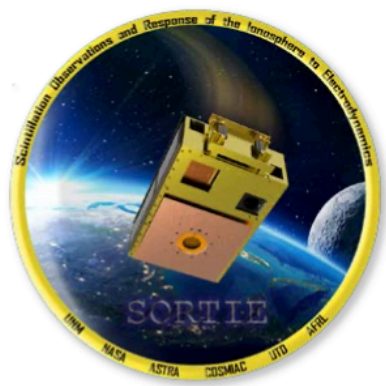
Mission Goal

Generate an atlas of ionospheric density and vertical drift fluctuations with wavelengths < 100km at or below the F-region peak.

Science Objectives		Top Level Requirements			Measurement Requirements			
No.	**Description**	**No.**	**Description**	**Src.**	**No.**	**Description**		**Src.**
Q1	Discover the sources of wave-like plasma perturbations in the F-region	T1	SORTIE shall observe low and mid-latitude* plasma density in and below the F region with sufficient resolution to observe plasma features measuring <100km in length along the orbit.	Q1	MR1	SORTIE shall make plasma density measurements	Measurement: ion densities Spatial Resolution: <100 km Range: $1x10^2$ - $1x10^7$ cm^{-3} Resolution: 10% or 100 cm^{-3} (choose smaller) Noise/Accuracy: 10% or 100 cm^{-3} (choose smaller) Instrument: uPLP	T1 T2
		T2	The SORTIE science team shall correlate plasma density fluctuations observed at and below the F-region with AGWs.	Q1				
Q2	Determine the relative role of dynamo action and more direct mechanical forcing in the formation of wave-like plasma perturbations.	T3	SORTIE shall observe vertical ion drifts in the equatorial* and mid-latitude* F region with sufficient resolution to observe plasma features measuring <100km in length along the orbit.	Q2	MR2	SORTIE shall make ion drift measurements	Measurement: DC Ion-Drifts Spatial Resolution: <100 km Range: -500 to +500 m/s Resolution: 1 m/s Noise/Accuracy: <20 m/s** Instrument: Mini-IVM	T3 T4

**measurements made between ±60° geographic latitude (±15°)*

***instrument allocation: 13 m/s, adcs allocation: 7 m/s, 5 m/s margin, RSS=20m/s*



MISSION DESIGN

Spacecraft

The SORTIE 6U CubeSat spacecraft, developed and qualified by ASTRA, is designed to provide its ram-facing plasma sensing instruments with a large equipotential surface. The equipotential surface minimizes stray electric fields within a Debye distance of the apertures allowing the trajectories of ions to be traceable from the ambient plasma (minimizes local spacecraft effect on the incoming plasma). The ram-facing surface normal will be aligned to within 5° of the velocity vector. Post-processing of the science data will determine spacecraft attitude to < 0.05° (1σ, 3-axis). Aside from the communications antenna, the SORTIE spacecraft has no deployables; the solar panels are body mounted.

Sensor Suite

The SORTIE sensor suite consists of two components; a 1) micro planar Langmuir probe (µPLP) and a 2) ion velocity meter (IVM). The µPLP is provided by AFRL and the IVM is provided by UTD.

High resolution plasma density and temperature is measured by the uPLP. The µPLP instrument consists of a Langmuir probe, mounting structures, and electronics system. The µPLP design is a miniaturized sensor optimized for use on small satellite platforms and combines lessons learned from the successful 5+ year C/NOFS PLP mission and from the development of the

SPLP instrument for the operational SSAEM/COSMIC-II satellite constellation. The μPLP, shown in Figure 4, consists of an inner circular conductive plate and an outer annular conductive plate mounted in a chassis (~ 95 x 85 mm) on the spacecraft ram surface. The inner plate is the collecting area for the plasma, while the annulus serves as a guard ring. The probe conductor connects to the μPLP log electrometer, which is based on the C/NOFS PLP and SSAEM SPLP electrometer designs. The mechanical aspects of μPLP account for the mounting of the sensors and electronics, RF and background radiation shielding, thermal management and internal electrical routing.

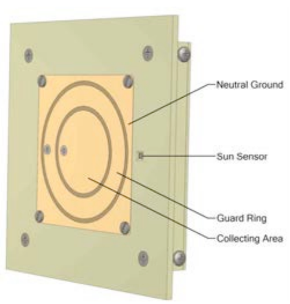


Figure 4. SORTIE μPLP physical configuration.

The temperature, composition and vector velocity of the ionospheric plasma is measured by the CubeSat Ion Velocity Meter (IVM) [3], shown in Figure 5. The IVM is mounted to view approximately along the spacecraft velocity vector and performs two functions. The first function is a planar retarding potential analyzer (RPA), which determines the energy distribution of the thermal plasma along the sensor look direction. The second function is a planar ion drift meter (IDM), which measures the arrival angle of the thermal plasma with respect to the look direction in two mutually perpendicular planes. The SORTIE IVM is the first sensor to perform the IDM and RPA functions using a single planar aperture sensor.

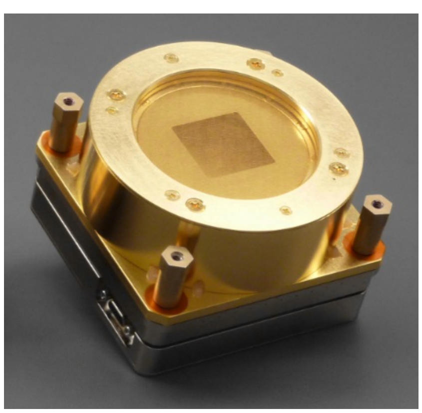


Figure 5. SORTIE IVM (w/o Aperture Plane).

The IVM sensor provides a 1 to 4 second cadence for measurements depending on the instrument mode of operation. The IVM aperture is surrounded by an extended aperture plane that features a SenPot reference plate. This reference plate is electrically isolated from the spacecraft and instrument and floats to a potential driven by the plasma. The aperture plane and sensor bias follow this reference potential to keep internally applied potentials relevant to the incident plasma. The biased aperture feature provides an ideal environment for measuring properties of the thermal plasma, making the sensor tolerant to a range of spacecraft bus bias conditions.

A schematic cross-section of the internal grid structures that are utilized to perform the required functions in the sensor is shown in Figure 6. Two grids, suppressor and repeller, labeled "S" and "R" respectively, are biased, while others are grounded to confine potentials inside the sensor and provide a field-free drift space across which the ions drift supersonically before impacting the segmented collector. The ratio of the currents on adjacent halves of the segmented collector provides a direct measure of the arrival angle of the plasma [4]. For energy distribution measurements (RPA mode) the repeller grid is stepped through a series of discrete positive potentials, or Retarding Voltages (RV), which determine the energy of the ions given access to the collector. Ion density, composition, temperature and drift are extracted by using a least-squares fitting technique on the collected currents as a function of RV.

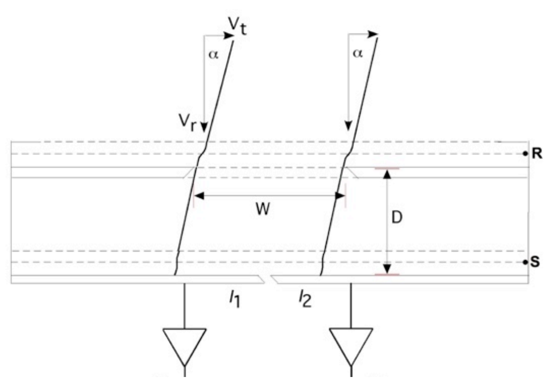


Figure 6. IVM Grid Stack Schematic.

Currents collected by the 4 collector plates behind the grid stack are measured by four ranging linear electrometers, similar to those used for RPAs in past IVM instruments. Simultaneous horizontal and vertical drift measurements are possible by sampling the four quadrants simultaneously. Commandable instrument modes allow for operation in quad-electrometer mode, reverting to legacy horizontal/vertical switching modes or to a legacy RPA mode by connecting all collector plates to one electrometer. The current values are converted to voltages by extremely low-leakage electrometers and digitized by four independent 16-bit analog-to-digital converters. Data products are derived through ground processing that incorporates spacecraft attitude, position and velocity information.

The SORTIE data products derived from the IVM data are provided in Table 2. The SORTIE mission level data product requirements from IVM are limited to Vertical Ion Drift at 100 km cadence (12-second period) near the magnetic equator, 20 m/s precision with a dynamic range of +/- 500 m/s. The deployed SORTIE system is expected to exceed these requirements with margin.

Data Product	**Range**	**Prec**	**Rate**
Ion Drift	+/- 1000 m/s	15 m/s	1 Hz
Ion Composition	O+/H+, 0 to 1	5%	1 Hz
Ion Temperature	400 to 8000 K	50 K	1 Hz
Ion Density	3×10^3 to 3×10^7 cm^{-3}	1%	1 Hz

Table 2. SORTIE IVM Derived Data Products

The resource requirements of the delivered SORTIE IVM are provided in Table 3. The size, weight and power represent significant reductions compared to dual-aperture sensors recently deployed for the NASA ICON and NOAA COSMIC-2 missions.

Table 3. SORTIE IVM Technical Resources

Size	96 x 96 x 75mm + Aperture Plane/SenPot
Weight	718 g
Power	0.38 W
Data Rate / Interface	4,096 bps / UART

Following on-orbit measurements, initial results are available soon after receipt of the first data due to the use of a generalized IVM software package that reflects the history of IVM processing at the Center for Space Sciences at UTD. The SORTIE IVM processing software couples into the general package using mission and instrument specific software packages. This same general IVM package is used to process measurements from both the COSMIC and ICON missions, a design that minimizes the potential differences in geophysical outputs across platforms. The SORTIE IVM hardware differs from the IVM on ICON and COSMIC and this layer for SORTIE processing is still in development. The partial implementation likely has an impact on current results.

The generalization and feature-set of this fundamental IVM instrument package was achieved by building the software using Python and other open source technologies [5], including the Python Satellite Data Analysis Toolkit (pysat) [6], which designed to provide a layer of abstraction between science data and the files that data comes from, freeing users from file and data management. This abstraction, along with other pysat features, directly enables the development of generalized instrument processing software. The conversion of the ion drifts measured in the instrument frame into a geophysical frame most suitable for analysis will use Orthogonal Multipole Magnetic Basis Vectors (OMMBV) [7]. The location of the spacecraft in magnetic coordinates will be determined using the quasi-dipole system implemented in apexpy [8]. The use of pandas [9] as an underlying data format ensures data between the instrument and spacecraft are properly aligned along reported times. Scipy [10], general scientific computing tools, and f2py [11], a tool that enables Fortran calls from python, provides the Levemberg-Marquardt [12; 13] non-linear least squares fitting. numpy [14] provides for a range of math operations, matplotlib [15] supports the figures, and iPython [16] provides for an interactive code environment geared towards research needs.

Observatory Configuration

The SORTIE observatory configuration, a combination of the 6U CubeSat spacecraft with the integrated sensor suite, is shown in Figure 7. The observatory specifications are listed in Table 4.

Table 4. SORTIE Observatory Specifications

Property	Value
Mass/Volume	11 kg / 6U
Power Generation	>10 EOL WOAP
Attitude Control	< 1°, 3-axis stabilized
Attitude Knowledge	< 0.003° for 2 axes, < 0.007° for third axis (1-σ)
Communications	3 Mbps down (10E-5 BER) 9.6 kbps up (10E-6 BER)
EOL = End of Life, OAP = Orbit Average Power	

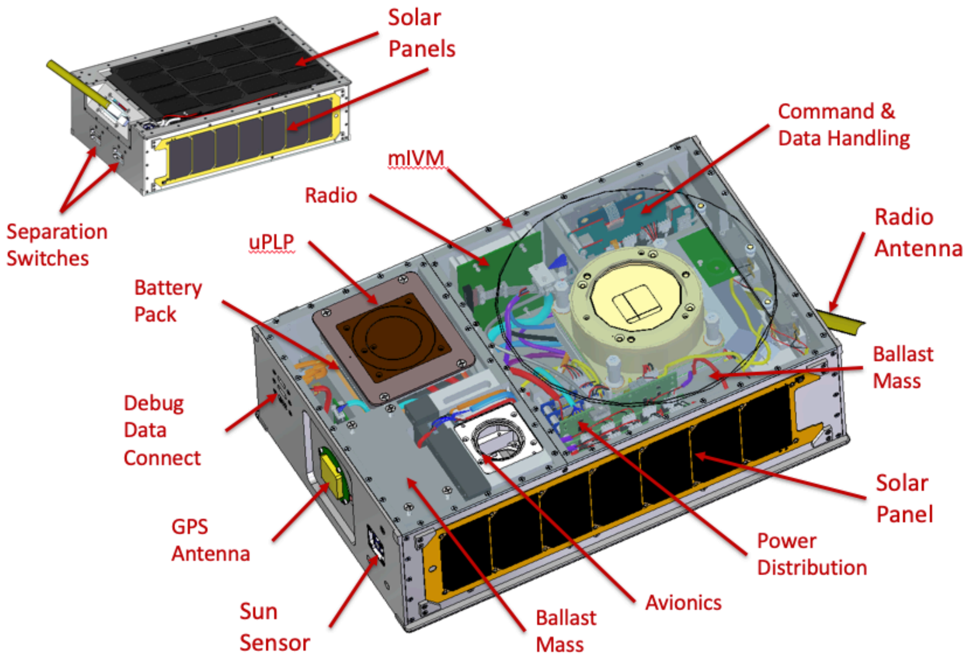


Figure 7. SORTIE Observatory Configuration.

Mission Operations

The primary SORTIE ground station is located at the NASA Wallops Flight Facility (WFF) and utilizes a ~20 m UHF dish site, leveraging heritage program successes such as DICE and Dellingr. Leveraging NASA's recently upgraded hardware set at the WFF site, the Mission Operations Center (MOC) located at ASTRA's facilities in Louisville, CO is able to remotely interface with the site, sending commands to and receiving telemetry from the SORTIE spacecraft. SORTIE operations are staffed for multiple satellite overpasses per day, 7 days a week to maintain the science data collection and downlink on the system. The SORTIE radio is a Cadet-U UHF radio, capable of 3 Mbits/s FEC encoded downlink at 460-470 MHz and 9.6 kbits/s uplink (450 MHz).

A high-level overview of the nominal science operational scenario is shown in Figure 8. SORTIE science observations will target orbit locations between ±30 ° latitude. During those conditions, the observatory

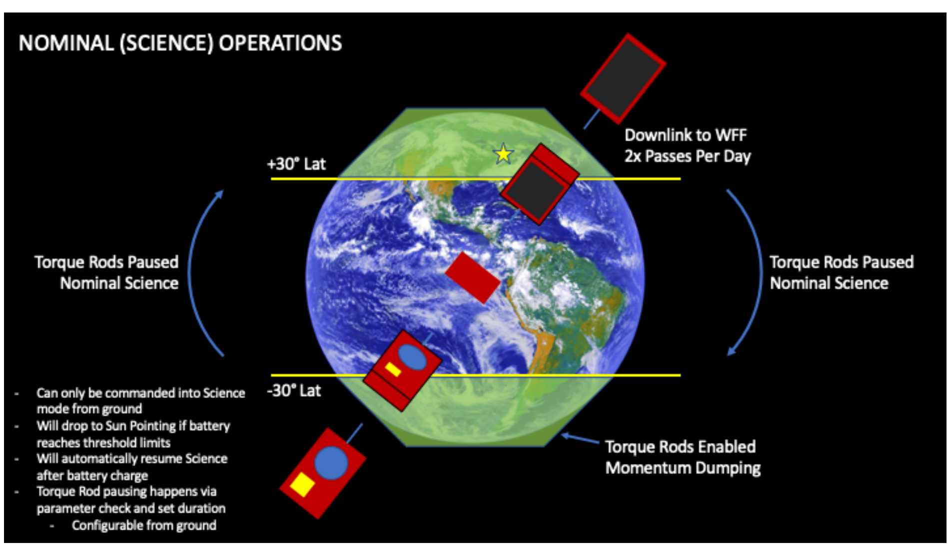


Figure 8. SORTIE Nominal Science On-orbit Operational Scenario.

will fly with the instruments in the RAM velocity direction, with the spacecraft torque rods paused to minimize noise and magnetic contamination. The rods are re-enabled at higher latitudes to permit momentum dumping. Downlinks to Wallops are expected to occur at least twice a day, with four times a day the nominal cadence.

Ground AI&T

SORTIE underwent full integration and testing activities to bring together all of the major subsystem components into an operational observatory. This effort started with subsystem assembly and testing, followed by FlatSat functional testing, then integration of the major subsystems into the full assembly.

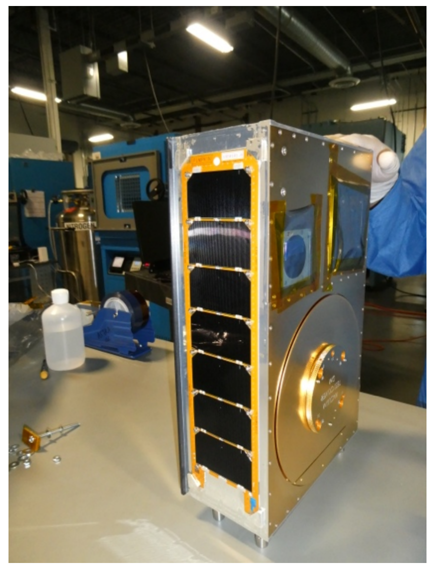
Integration of the µPLP sensor occurred at ASTRA, in collaboration with AFRL. Functional testing of the instrument was also performed to ensure functionality post-integration, including data collection over temperature. Integration of the IVM sensor occurred at UTD, with the ASTRA team travelling with the spacecraft to Dallas, TX. After integration, the sensor and spacecraft underwent stimulation testing and alignment calibration activities to ensure proper functionality and alignment knowledge of the IVM after integration.

ASTRA travelled to the NASA WFF to perform ground station compatibility testing on-site with NASA's UHF small satellite ground station. The team brought the Engineering unit of the SORTIE spacecraft with the EDU flight computer, EDU radio, and flight UHF antenna to WFF for the testing. With the support of the WFF operational team, ASTRA was able to functionally verify the entire RF and Mission Operations chain, starting with commands being generated at the ASTRA MOC, transmitted via the internet to the WFF ground station, broadcast over the ground station TT&C link over the air to the spacecraft, then having the spacecraft respond with telemetry data back through the WFF system, over the internet, and back to the ASTRA MOC.

The full observatory assembly then underwent functional testing, environmental testing, and instrument calibration to bring the observatory to a ready-to-deliver state. System level vibration testing occurred in collaboration with Nanoracks test engineers. Bringing their vibration test deployer, Nanoracks joined ASTRA in integrating the spacecraft into the canister, performing the vibration testing (see Figure 9), and performing a post-test verification of the assembly at ASTRA.

System level TVAC and thermal testing occurred on multiple occasions to validate the thermal response and performance of the observatory. Pictures from the TVAC activity are shown in Figure 10.

Figure 9. SORTIE System Level Vibe Testing.



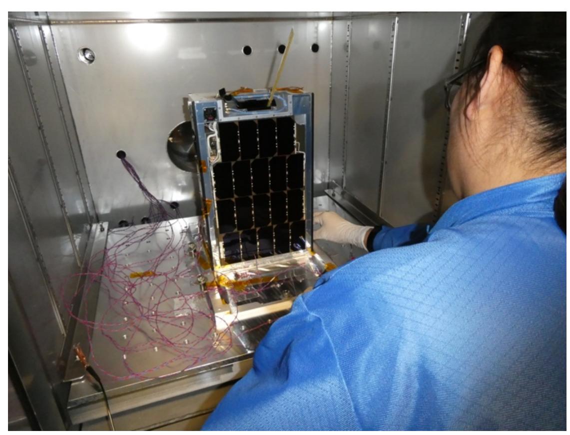


Figure 10. SORTIE System Level TVAC Testing.

LAUNCH

The SORTIE mission was launched aboard the SpaceX CRS-19 Dragon mission to the ISS on Thursday, 5 December 2019 (17:29:24 UTC). SpaceX launched its CRS-19 mission from the Space Launch Complex 40 at Cape Canaveral.

DEPLOYMENT FROM ISS

The SORTIE spacecraft was deployed from the ISS on February 19, 2020 at 17:40:00 UTC. The UHF antenna monopole was deployed 45 minutes after orbit insertion from the ISS using a pre-configured commissioning sequence, ensuring a safe separation distance from the ISS prior to antenna deployment. Shortly after deployment, the spacecraft entered its commissioning sequence, which included de-tumble and sun-pointing of the spacecraft to charge batteries.

SORTIE "FIRST LIGHT"

The SORTIE observatory has been gathering data since its orbit insertion in early 2020. Checkout of observatory functionality (e.g., pointing, communications, power generation, thermal stability, heater functionality) has been completed. Prior to the commencement of nominal operations, the science team is completing the check-out phase of the science sensor performance, followed by commissioning. The uPLP is operating nominally. The IVM is operating nominally. The following highlights the activity of the IVM team to date as part of the check-out (early ops) phase –

IVM On-Orbit Check-Out

At the time of publication of this Small Satellite Conference paper, the IVM team is in the initial check-out phase which includes verification of instrument health, verification of instrument functionality, preliminary science data evaluation and instantiation of ground data flow and algorithms. During the commissioning phase, the IVM team will establish the optimal instrument operating mode which depends on the plasma conditions and operating environment. During nominal operations, on-orbit validation will be performed to evaluate instrument performance and to evaluate the end-to-end SORTIE system as a platform for on-orbit plasma characterization.

The first available set of IVM science data covered a 33-minute time span on May 11, 2020. From this data set the team was able to verify that all internal IVM state-of-health monitors are normal, instrument temperature is normal, data, telemetry and timing interfaces are functional, and science channels are producing reasonable signals. Preliminary review of the science channel outputs indicate that sensor bias and grid biases are functioning normally. The initial data set indicates that the SenPot bias may be operating at or near its maximum operating limit, but subsequent data revealed that this is a periodic feature of the data which needs further review.

Nearly 60 hours of IVM on-orbit data have been made available to the IVM team for processing and analysis at the time of this publication. Before proceeding to the commissioning phase, ground data paths and algorithms must be established and refined, including the processing of raw data to engineering parameters and the processing of ancillary data such as spacecraft time, position, velocity and orientation. While the SORTIE team is in the process of refining the ground systems, the IVM team has reviewed preliminary science outputs of the instrument.

Level-1 engineering parameters are shown in Figure 11. Figure 11(a) shows the currents measured at each RV as the instrument progresses through its sweep. Measurements are robust throughout the data segment and reach currents as low as a few pA at the default maximum RV value of +8V. The largest currents are observed at RV=0. The small spread in curves indicates a plasma that is predominantly O+. H+ has a lower ram energy than O+ due to a lower ion mass. Thus, it is retarded in the first few volts, while O+ is not retarded until near +5V.

The measured arrival angles are in Figure 11(b). Both the raw measurements along with a centered running mean are shown. Magnetic torque rods are firing throughout the data segment (torque rod disengagement and science measurements had not been coordinated at this point in the mission yet), altering the magnetic field around the spacecraft, and thus the measured arrival angle. The rods fire at a high cadence introducing a variance to the signal. The running mean arrival angle (2 seconds) demonstrates a smoothly varying underlying signal. The observed standard deviations of the raw, unfiltered 16 Hz arrival angles are ~8.5 m/s. Near the magnetic equator the vertical ion drift is overwhelmingly provided by the outputs of the DM alone, thus the instrument is meeting requirements.

The SORTIE IVM geophysical observations of the ionosphere are in Figure 12. The density in Figure 12(a) is generated using the measured current at RV=0, known instrument parameters, and the derived plasma velocity in Figure 12(d). The spacecraft passes across the magnetic equator near 13:30 LT and observes a clear density signature of the Appleton Anomaly peak in the first panel, the two density peaks near 13:00 and 14:00 LT, a structure formed due to the presence up upward drifts at the magnetic equator. The rising plasma at the equator falls back down along geomagnetic field lines, moving poleward, producing an increase in density away from the equator. The observed standard deviation is 2E3 N/cc, < 1% of the background signal.

The composition in Figure 12(b) is predominantly O+, an expected outcome for an orbit altitude near 420 km. H+ has a larger scale height than O+, due to the lower ion mass, thus is spread over a larger range of altitudes. The instrument shows a high degree of precision in resolving the H+/O+ composition over the data segment, with observed standard deviations less than 0.2%. Reliably obtaining all parameters from an RPA analysis requires accurate knowledge of composition so that optimized choices may be made during the non-linear least squares fitting.

Temperatures in Figure 12(c) vary between 1,000-1,500K, typical values for the daytime ionosphere. There is a general anti-correlation between temperature and density as is generally observed. Regions near the magnetic equator, with higher densities, have temperatures near 1,000 K while at higher latitudes, and lower densities, temperatures rise to 1,500 K. Temperatures remain near 1,500 K through the end of the data. As the spacecraft is near its northern latitudinal extreme, and the summer solstice is less than a month from away from observations, sunset occurs at later local times. The observed standard deviation for the segment is 18 K.

The ram ion velocity in Figure 12(d) is obtained through a non-linear least-squares fitting of measurements to the Whipple equation [3]. The ion velocity as directly observed by the instrument is shown which includes components from the spacecraft motion, co-rotation, as well as the motion of the plasma itself. Conversion of the raw instrument outputs illustrated here to a geophysical ion velocity relative to co-rotation using spacecraft attitude and ephemeris is underway. Despite this temporary limitation, the values obtained are consistent with expectations generated by previous missions and are expected to produce valid geophysical outputs suitable for scientific analysis. The overall observed standard deviation for the data segment is ~40 m/s. This error reflects the performance of both the hardware and software.

Note in the beginning of the data segment in Figure 12(d) the ram velocities are very close to the running average, with a standard deviation of ~30 m/s between 12:00-13:00 LT, while densities are below 4E4 N/cc. The same density conditions apply between 16:00-17:00 LT yet the standard deviation is larger, ~50 m/s. Since density

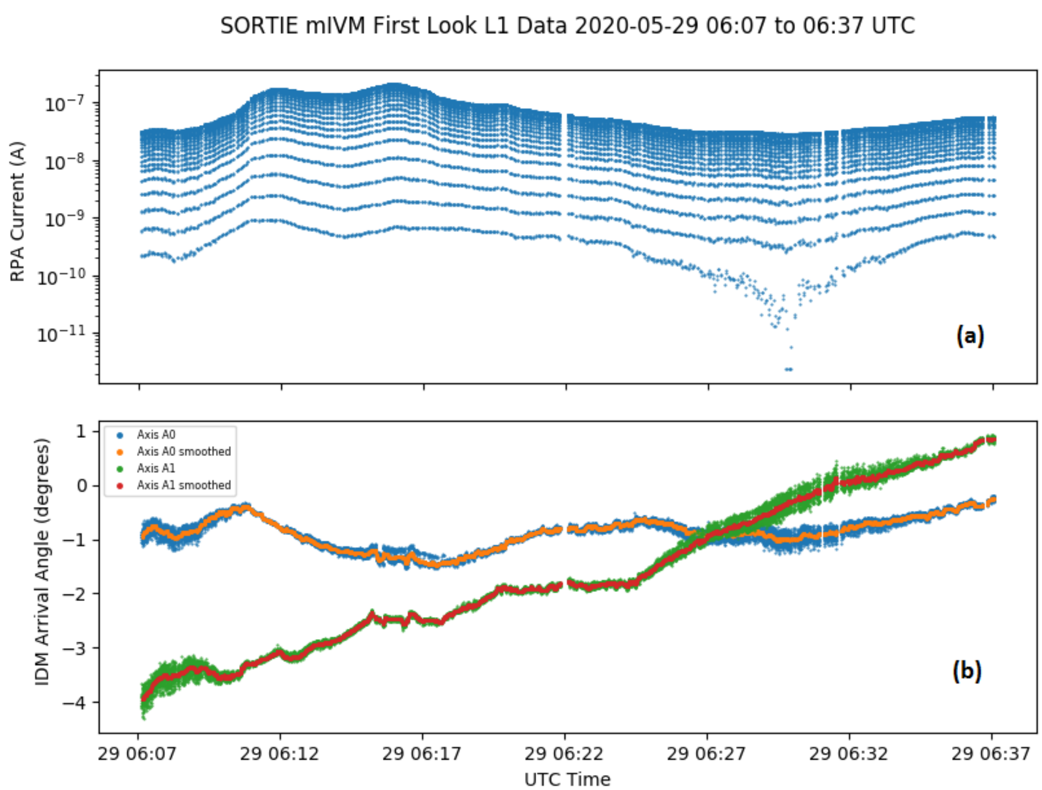


Figure 11. SORTIE IVM Preliminary L1 Data Sample.

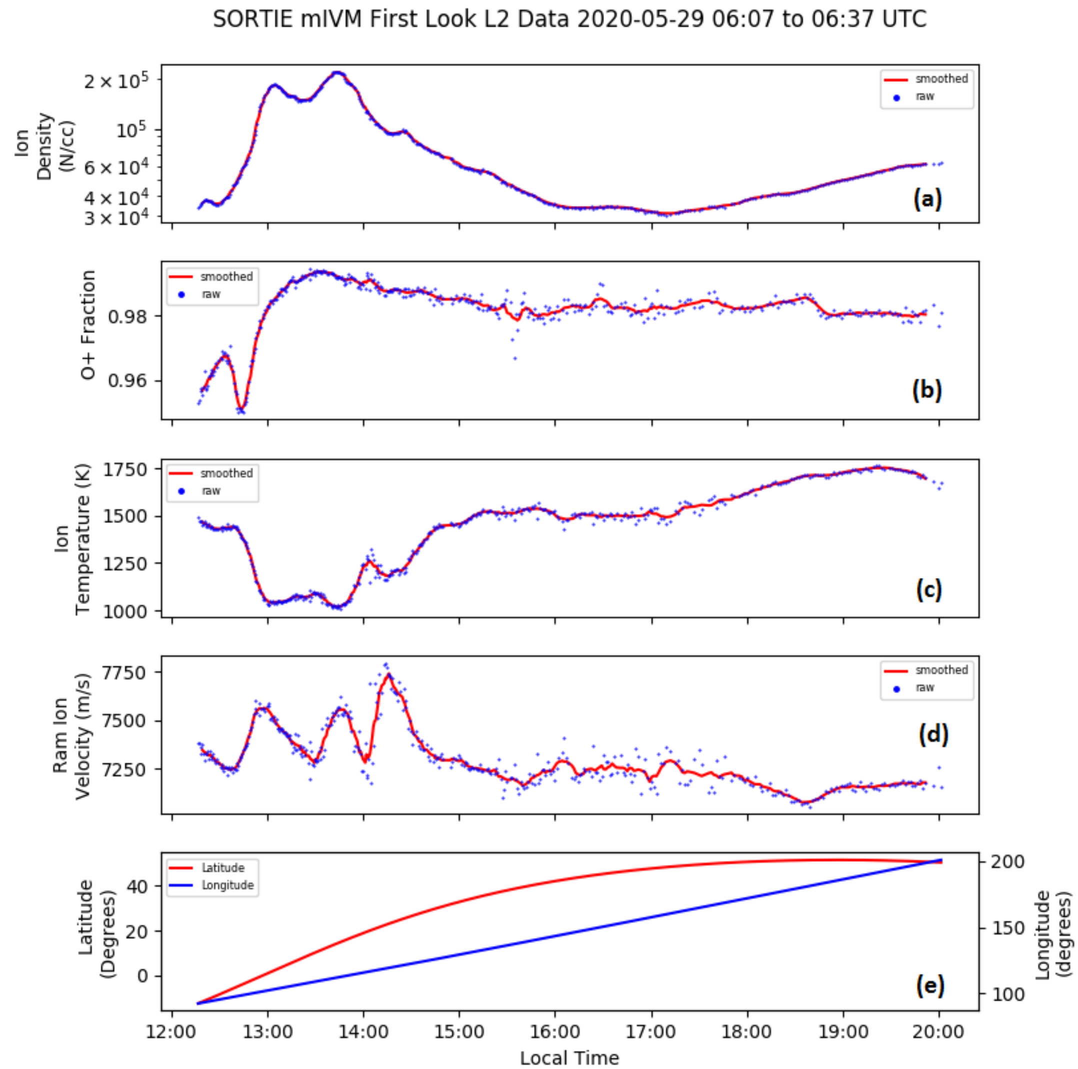


Figure 12. SORTIE IVM Preliminary L2 Data Sample.

levels are the same between local times the relative noise levels of the curves are expected to be the same. The difference between these curves could reflect the difference in O+ composition, <97% vs 98%. Between 13:00-14:00 LT the IVM is in the highest density conditions, and the highest O+ concentration, and has a drift standard deviation of ~40 m/s. The impact of the relative increase in O+ is likely mitigated by the increase in density which reduces the relative noise levels in the currents, improving the ability to resolve smaller contributions by H+.

The IVM resolves ion drifts most accurately when there is a 50%/50% mixture of H+ and O+ [3]. The partially implemented software instrument layer makes resolving the H+ contributions to the measured currents during low H+ concentrations an additional challenge in the non-linear fitting process. Planned improvements to the layer to better reflect instrument operation are expected to improve the software's ability to geophysically interpret the measurements when fitting low H+ contributions.

Despite some limitations in the current ground processing software, the obtained geophysical parameters are consistent with expected values and clearly demonstrate that the SORTIE IVM measurements are suitable for a characterization of thermal plasma in the ionosphere.

SUMMARY

Perturbations in the ionospheric plasma density most frequently appear in the form of discrete regions of waves. At low and middle latitudes, these perturbations are thought to provide the seeds for larger amplitude perturbations that may evolve non-linearly to produce irregularities that are collectively called spread-F. The scintillation of radio waves that result from the presence of these plasma irregularities can be particularly deleterious to communications and navigation systems. Thus a better understanding of the distribution of the initial wave-like plasma perturbations and the conditions under which they can be related to intense plasma instabilities is a key to mitigating their effects.

Wave-like plasma density perturbations are pervasive features in the F-region that are produced by similar perturbations in the neutral atmosphere. Winds may mechanically move the ionospheric layer vertically through collisions. Or neutral atmosphere perturbations may be imprinted on the ionosphere through the dynamo action of winds at low altitudes. No matter what the mechanism, a wave-like perturbation in the ionosphere will result.

Describing these prevalent signatures of ion-neutral coupling is the key to understanding the role they play in the formation of plasma density gradients that affect radio propagation paths in operational systems, and potentially as the seed for plasma instabilities that can produce intense radio scintillation. However, *there is currently no comprehensive atlas of measurements describing the global spatial or temporal distribution of wave-like perturbation in the ionosphere.* The objectives of the SORTIE mission are to (a) to discover the sources of wave-like plasma perturbations in the F- region ionosphere, and (b) to determine the relative role of dynamo action versus direct mechanical forcing in the formation of wave-like plasma perturbations.

The SORTIE mission is now fully underway on-orbit. The SORTIE observatory is functioning and collecting science data. The first light results of the IVM in-situ ionospheric measurements have been presented in this paper. SORTIE will soon move into nominal science observations and initiate global mapping of wave-like ionospheric perturbations.

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