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

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ABSTRACT

At low and middle latitudes, wavelike 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. However, 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 is a 6U CubeSat mission with team members from ASTRA, AFRL, UTD, COSMIAC, and Boston College. The SORTIE spacecraft is designed to approach the complex challenges in discovering the wave-like plasma perturbations in the ionosphere. SORTIE will provide the initial spectrum of wave perturbations which are the starting point for the RF calculation, provide measured electric fields which determine the magnitude of the instability growth rate near where plasma bubbles are generated, and will provide initial observations of the irregularities in plasma density which result from instability growth. The SORTIE mission is slated to launch in late 2017, and will provide a timely overlap with NASA's ICON mission scheduled to launch in the 2017 timeframe. The baseline operational plan will be a year of on-orbit lifetime orbiting at a low to middle inclination orbit near 350-400 km altitude.

MISSION MOTIVATION AND OBJECTIVES

Wave-like perturbations in ionospheric plasma density echo wave-like perturbations in the background neutral atmosphere that couple to the ionosphere through various mechanisms. Winds may mechanically move the ionospheric layer vertically through collisions. Alternatively, 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.

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 the AFRL sponsored Communications/Navigation Outage Forecasting System (C/NOFS) orbit. These measurements show the wide range of spatial scales and correlations that exist between the plasma density 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. Equatorward motions are upward and will increase the plasma density above the F-peak, while poleward motions are downward and will tend to decrease the plasma density above the F-peak.

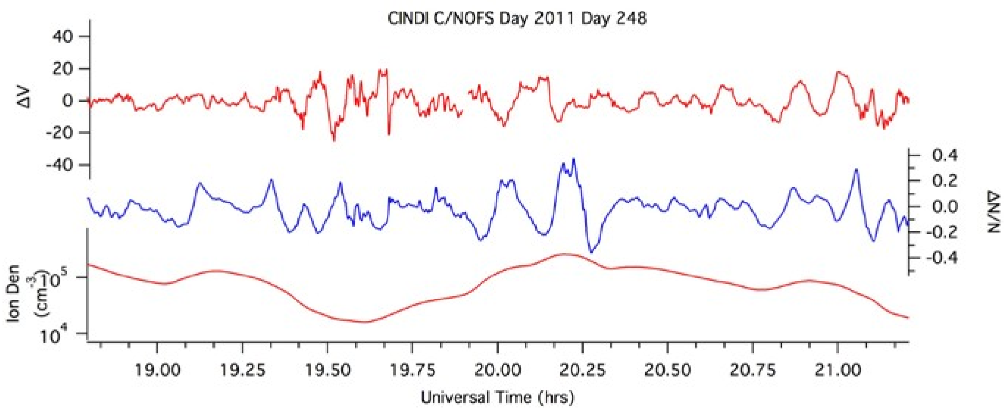


Figure 1. Vertical ion velocity and plasma density perturbations from a C/NOFS orbit.

and the plasma velocity. Traveling ionospheric disturbances (TIDs) have also been routinely measured in the bottomside ionosphere via HF sounders [1], and the sounder data confirm the assertion that waves are pervasive features in the F-region ionosphere, but that they rarely exist as continuous wave trains. Like C/NOFS, the HF sounder data also reveals that multiple waves can be present at the same time.

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

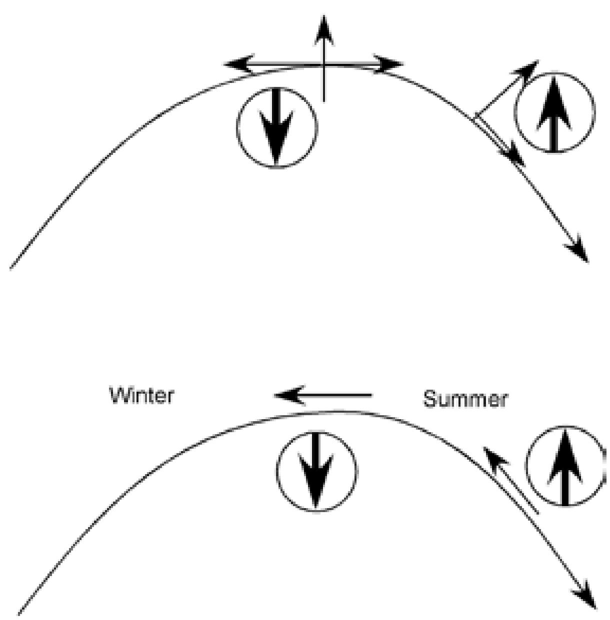


Figure 2. Parallel and perpendicular plasma drifts geometry.

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 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

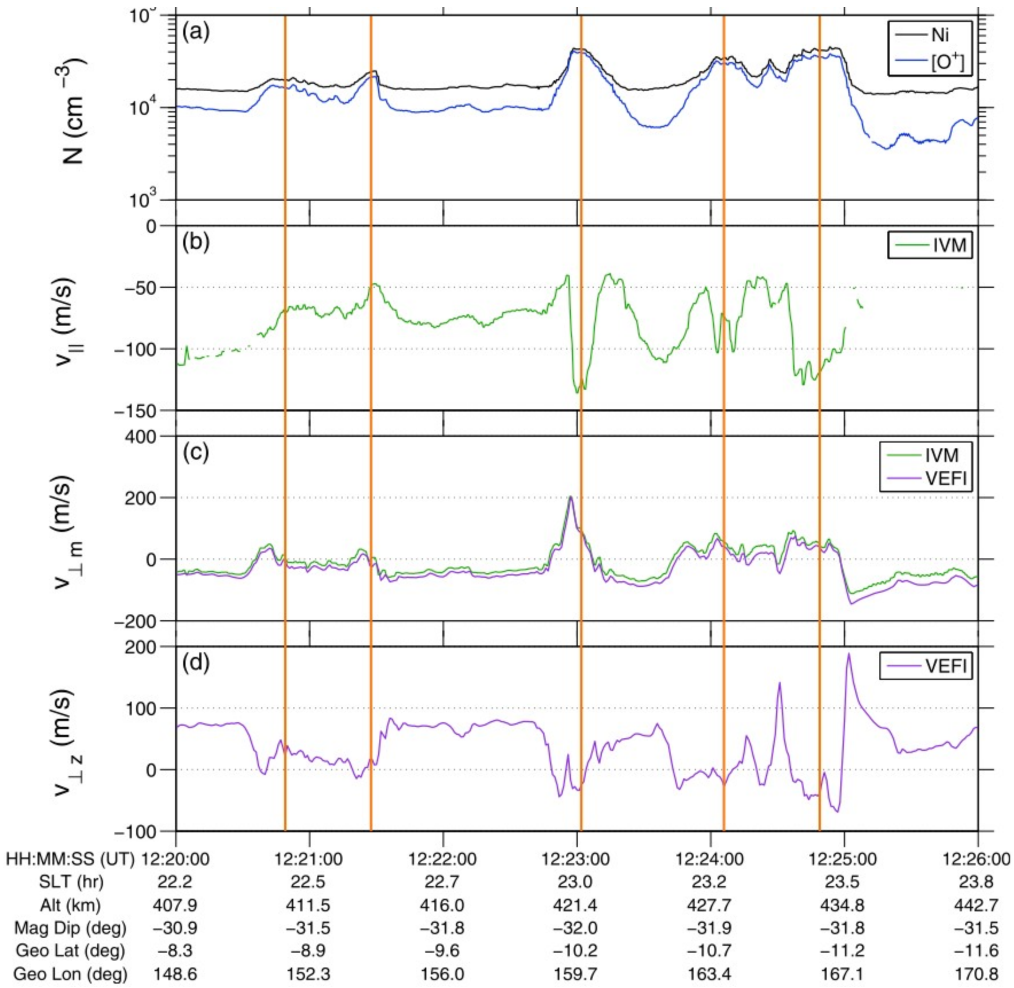


Figure 3. C/NOFS Data from 26 June, 2009.

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 observed across a plasma density enhancement in the topside ionosphere. The top panel clearly identifies plasma density enhancements, and the vertical lines 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 $\boldsymbol{E} \times \boldsymbol{B}$ 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 RT calculation; (2) measured electric fields which determine the magnitude of the RT growth rate near the region where 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 predictive models 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

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

Science Traceability Matrix

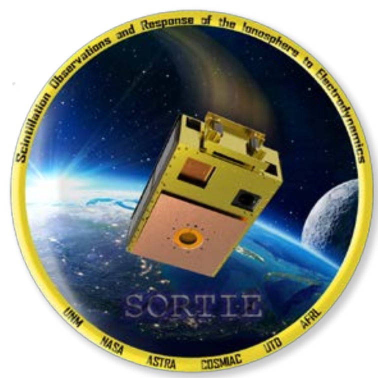
Mission Goal

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*



variability in concert with the 2017 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 6 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.

MISSION DESIGN

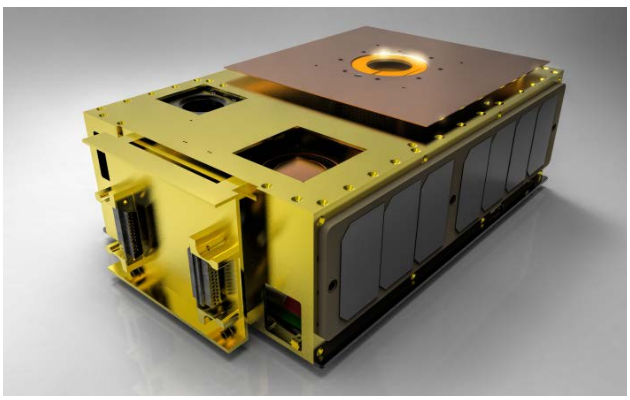
Spacecraft

The SORTIE spacecraft, supplied by COSMIAC and 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 SORTIE spacecraft has sufficient power and telemetry budgets to measure the plasma drifts and densities with a 100% duty cycle. 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). Note that aside from the communication antennas, the SORTIE spacecraft has no deployables. The SORTIE CubeSat will be inserted into orbit from a 6U deployer. UHF antenna dipoles (located above the mIVM sensor in Figure 4) will be deployed after launch, using a pre-determined commissioning sequence that ensures a safe LV-spacecraft separation distance prior to antenna deployment. The spacecraft will then continue with the commissioning sequence, which will include de-tumble and alignment to the RAM vector.

Sensor Suite

The SORTIE sensor suite consists of two components; a 1) micro Planar Langmuir probe (μPLP) and a 2) mini Ion Velocity Meter (mIVM). The μPLP is provided by AFRL and the mIVM is provided by UTD. The μPLP instrument consists of a Langmuir probe, mounting structures, and electronics system. The μPLP design is a miniaturized planar Langmuir probe 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 mIVM is a simple adaptation of similar sensors that have flown on satellite missions starting with Atmosphere Explorer, in the 1970's and presently on the C/NOFS and Defense Meteorological Satellite Program (DMSP) programs. The mIVM is mounted to view approximately along the spacecraft velocity vector in the ram direction, 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 and the second 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 that are approximately in the local vertical and the local horizontal.



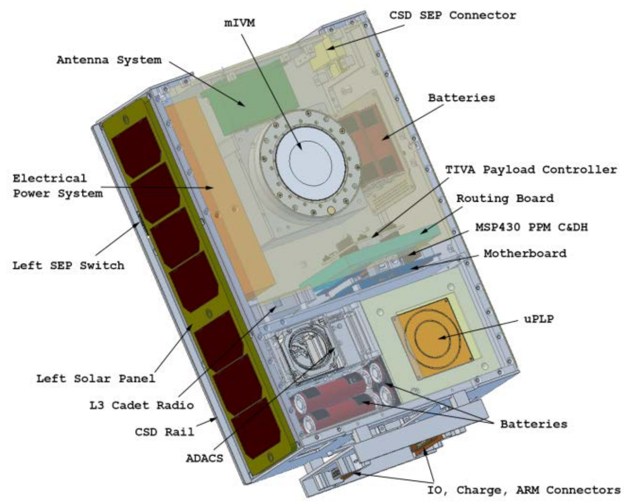


Figure 4. SORTIE Observatory Configuration

Observatory

The SORTIE observatory, a combination of the spacecraft with the integrated sensor suite, is shown in Figure 4. The observatory specifications are shown in Table 5.

Table 2: SORTIE Observatory Specifications

Observatory Property	Value
Mass/Volume	8 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	

Mission Operations

The primary SORTIE ground station will be located at the NASA Wallops Flight Facility (WFF) and utilize a ~ 20 m UHF dish site. Software defined radios at WFF will be remotely controlled from the Mission Operations Center (MOC) located at COSMIAC/UNM in Albuquerque NM. The status of the MOC to ground station link is monitored 24/7. The MOC will be led by a mission operations manager, and will perform mission operations planning, command generation, and data acquisition and management. The MOC staff is composed of trained operators who have performed data downlinks from the ISS as well as the University of Michigan RAX CubeSat. SORTIE will communicate in UHF government bands for both uplink and downlink. The radio is a CadetU UHF, capable of 3 Mbits/s FEC encoded downlink at 460-470 MHz and 9.6 kbits/s uplink (450 MHz). The mission operations system configuration is shown in Figure 5.

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.

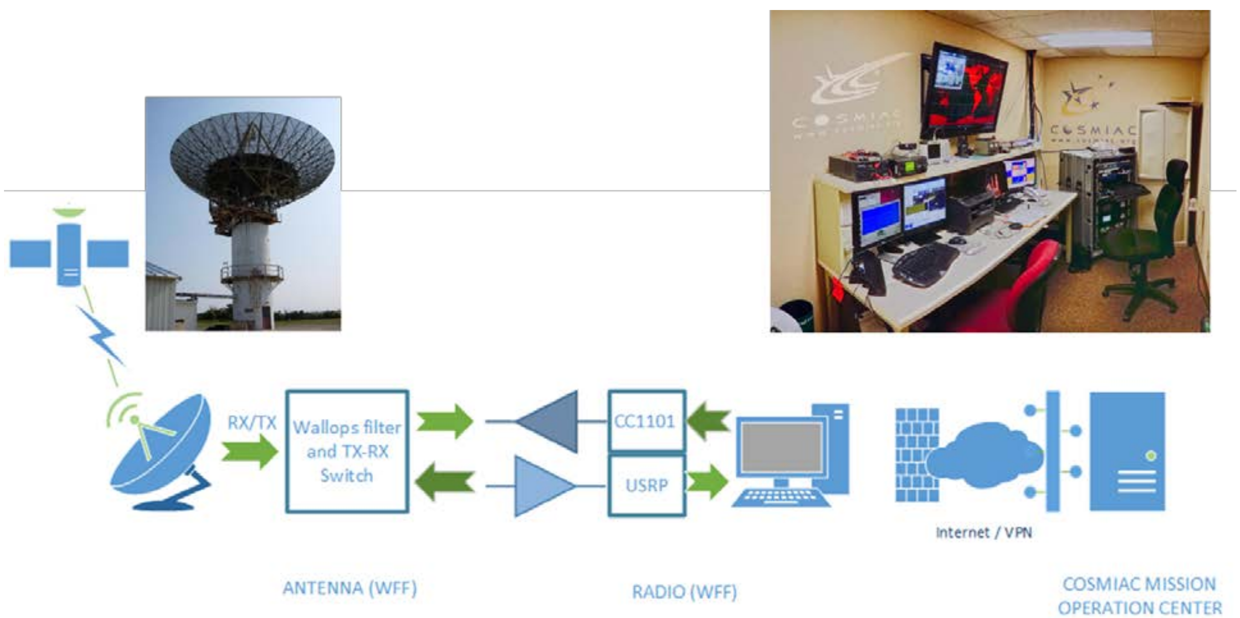


Figure 5. SORTIE Mission Operations Schematic

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.

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. The SORTIE science objectives will be achieved via in-situ ion-drift and plasma density measurements with spatial resolution < 100km from a 6U spacecraft that will launch in 2017.

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