A Comprehensive, First-principles Model of Equatorial Ionospheric Irregularities and Turbulence

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Introduction

Post-sunset ionospheric irregularities in the equatorial $F$ region were first observed by Booker and Wells (1938) using ionosondes. This phenomenon has become known as equatorial spread $F$ (ESF). During ESF the equatorial ionosphere becomes unstable because of a Rayleigh-Taylor-like instability: large scale (10s km) electron density ‘bubbles’ can develop and rise to high altitudes (1000 km or greater at times) [Haerendel, 1974; Ossakow, 1981; Hysell, 2000]. Attendant with these large-scale bubbles is a spectrum of electron density irregularities that can extend to wavelengths as short as 10 cm [Huba et al., 1978]. Understanding and modeling ESF is important because of its impact on space weather: the associated electron density irregularities can cause radio wave scintillation that degrades communication and navigation systems. In fact, for this reason, it is the focus of of the Air Force Communications/Navigation Outage Forecast Satellite (C/NOFS) mission [de La Beaujardiere, 2004].

The impact ESF can have on operational systems is shown in Fig. 1 [Makela, private communication, 2005; Kelley et al., 2002]. The top panel is a composite of optical images at 7774 Å from Mount Haleakala; the darker areas are regions of low electron density (i.e., ESF plasma bubbles). Note that these bubbles can have complex structures (i.e., tilts, bifurcations). Overlaid on this figure are the orbits of three GPS satellites; the actual satellite locations at this time are denoted by the symbols. Of note is the ‘blue’ satellite. The path of the GPS signal from this satellite to the ground receiver passes through the plasma bubble. The signal is strongly scintillated as shown in the lower left panel where $S_4 \sim 1$ (the $S_4$ index is a normalized measure of the standard deviation of the GPS satellites’ received signal power as seen on the ground). In this case it is very
significant because it causes a complete loss of signal as shown by the break in the blue line at 22:45 LT in the relative TEC measurement in the bottom right panel.

Theoretical [Sultan, 1996] and computational [Zalesak et al., 1982; Huba and Joyce, 2007; Huba et al., 2008; Retterer, 2010] models have been developed to describe the large-scale bubble development shown in Fig. 1; an example is shown in Fig. 2. However, these models are decoupled from the global electrodynamics of the earth’s ionosphere. Only recently has a model been developed that can capture both large-scale global ionospheric dynamics (∼ 1000s km) and small-scale bubble dynamics (∼ 10s km) [Huba and Joyce, 2010]. Although this model provides a new capability to understand the day-to-day variability of ESF, it falls far short of modeling the spectrum of irregularities associated with ESF and the small-scale turbulence (∼ 100s m) that is responsible for scintillating radio wave signals. The purpose of this white paper is to propose a comprehensive theoretical and modeling program to address this deficiency.

Scientific and Computational Challenges

The major computational challenge is to seamlessly couple different, spatially overlapping, physics models. These include (1) thermospheric models that describe neutral dynamics associated with tidal motions, planetary waves, and gravity waves [Fritts et al., 2009; Fritts and Lund, 2010], (2) global ionospheric models that describe the neutral wind dynamo and bubble development [Huba and Joyce, 2010], (3) sub-grid electrostatic fluid models that capture electron density turbulence on scales 10s m to 100s m [Hysell, 2000], and finally (4) hybrid and particle-in-cell codes that model small-scale turbulence below the ion Larmor radius (10s cm to 10s m). This is a daunting challenge since it covers a spatial range spanning 8 orders of magnitude and a temporal range spanning 6 orders of magnitude.

As a first step in this challenging project, existing thermospheric, ionospheric, and electrostatic fluid turbulence models can be coupled to improve current modeling capabilities and to identify computational difficulties that need to be overcome in developing a comprehensive, integrated model. However, there is also a need to improve and extend existing models. One example is the electrodynamics of the ionosphere/thermosphere (IT) system. All global models of the IT system

Figure 2: Electron density [Huba et al., 2008] and temperature [Huba et al., 2009] structure of an equatorial plasma bubble.
assume that the geomagnetic field lines are equipotentials; this assumption reduces the potential equation to two dimensions. This assumption is nominally considered valid for global scale sizes \( L \gtrsim 1 \text{ km} \) because of \( \sigma_\parallel >> \sigma_\perp \) where \( \sigma \) is the conductivity of the plasma [Farley, 1963]. However, recent simulation studies by Aveiro and Hysell (2010) suggest this simple scaling argument may not be valid and that 3D electrodynamic model are required. Thus, to accurately describe the self-consistent coupling of large scale to small scale electron density irregularities it is necessary to have a fully three-dimensional electrodynamic model. This will require the solution to a 3D electrostatic potential equation. It will be necessary to have a 3D solver that is robust, efficient, and uses parallel processing on a nonuniform grid. A second example is the need to include finite Larmor radius effects in electrostatic fluid turbulence models [Hysell, 2000]. The oxygen ion Larmor radius is \( \sim 3 \text{ m} \) and the spectrum of ionospheric turbulence is altered on this scale [Huba and Ossakow, 1979].

**Proposed Program**

A comprehensive modeling program is proposed to attack this difficult and important problem. Resources are needed (1) to develop new numerical algorithms to improve both the physics and efficiency of existing models, (2) to develop potentially new models of IT system and sub-system, and (3) to couple existing and new models seamlessly into a comprehensive framework. This effort requires long term, stable funding involving several research groups. A nominal program would be a 5 year effort at $2M/year for a total of $10M. This is consistent with the type of programs suggested by the Advanced Computational Capabilities for Exploration in Heliophysical Science (ACCEHS). In addition to model development, the program also needs to include an data/model comparison component to ensure that simulation results are consistent with experimental observations.

**References**


