Project Summary

The Sub-Auroral Polarization Stream (SAPS) is a region of enhanced westward plasma drift observed below the dusk-midnight sector auroral oval during geomagnetic disturbances. The traditional paradigm proposes SAPS to be a manifestation of an active magnetosphere-ionosphere feedback process whereby Region-2 FACs close across the mid-latitude trough, eliciting chemical changes that further reduce ionospheric conductivity while increasing the electric field in a manner that maintains current continuity. However, recent studies show SAPS-like flows can also occur during periods of geomagnetic quiet which cannot be explained by the traditional paradigm. The overarching goal of the proposed work is to determine the extent to which the "traditional paradigm" of SAPS is valid under different geomagnetic conditions and to determine the role of different factors in driving SAPS-like flows, that were overlooked in previous studies. Specific tasks will focus on combining different datasets such as SuperDARN, AMPERE and GPS TEC to develop a statistical characterization of SAPS-like flows, determine the role of different factors such as the substorm current wedge and under-shielding in driving and controlling them and finally determine the dynamics of magnetosphere-ionosphere-thermosphere coupling during such flows.

Intellectual Merit : The intellectual merit of this proposal lies in the prospect of advancing our current understanding of the dynamic coupling between the inner magnetosphere and sub-auroral ionosphere and their response to internal and external driving influences. Specifically, the proposed work is focused on determining the interplay between FACs of magnetospheric origin and ionospheric convection in the vicinity of the mid-latitude trough during SAPS and SAPS-like flows. The project is timely because of the recent improvements in the mid-latitude infrastructure such as the development of mid-latitude SuperDARN network, availability of GPS TEC and AMPERE measurements providing continuous global views of the ionospheric electrodynamics. SAPS is a prominent example of magnetosphere-ionosphere coupling which is long-lasting operates over hemispheric spatial scales, and exerts a controlling influence on the evolution of large scale plasma features such as storm enhanced density and the formation of plasma irregularities. The attainment of a comprehensive, observationally based understanding of the dynamics and drivers for SAPS and SAPS-like flows under different geomagnetic conditions directly addresses goals of the NSF Aeronomy program. Finally, developing a robust understanding of SAPS and SAPS-like flows has been the focus of the "CEDAR GRAND Challenge: Storms and Substorms Without Borders (SSWB) and GEM SIMIC Focus Group".

Broader Impacts : The insights developed on atmosphere-ionosphere-magnetosphere coupling are directly relevant to the NSF Coupling Energetics and Dynamics of Atmospheric Regions (CEDAR) program. The databases of SAPS and SAPS-like flow events developed during the project will serve as modeling challenges to researchers, making the proposal relevant to the Geospace Environment Modeling (GEM) program and the NASA Living with a star (LWS) program. The project is also highly pertinent to the National Space Weather Action Plan since it will help develop bench marks for certain space weather events and ionospheric disturbances such as SAPS and SAPS-like flows. Other broader impacts include career development of an early career scientist and support for undergraduate students on summer research projects. Funds are allocated for the early career scientist to visit other researchers in the field to gain proficiency in multi-instrument data analysis techniques and further develop collaborations.

Project Description

1 Introduction

Determining the dynamics of the coupled magnetosphere-ionosphere-thermosphere system and its response to solar-wind variability is an active area of research directly relevant to the NSF Aeronomy program and highlighted by the National Research Council (NRC) 2013 Decadal strategy for "Solar and Space Physics: A Science for a Technological Society". Specifically the NRC report identifies the following key relevant science goals that need to be addressed : (1) "Determine how global and mesoscale structures in the magnetosphere respond to solar wind forcing" (SWMI goal 1) and, (2) "Determine how magnetosphere-ionosphere-thermosphere coupling controls system-level dynamics" (SWMI goal 7). This proposal will advance our understanding of the dynamic coupling between the inner magnetosphere and the sub-auroral ionosphere and their response to solar-wind variations, by analyzing factors that haven't been fully explored in previous studies. In particular, it will build upon recent studies which have reported observations of Sub-Auroral Polarization Stream (SAPS)-like flows, during geomagnetically quiet times in addition to geomagnetic storm periods [*Kunduri et al.*, 2017; *Lejosne and Mozer*, 2017]. Traditional SAPS driving mechanisms cannot explain the formation of such flows, demonstrating the limitations in our current understanding of the inner magnetosphere and how it couples to the sub-auroral ionosphere-thermosphere. These observations of SAPS-like flows coupled with new insights into the inner magnetosphere and substorms [*Kepko et al.*, 2015; *Mishin et al.*, 2017] have fueled a renewed interest in the topic. The overarching goal of this proposal is thus to test the traditional paradigm of SAPS under different geomagnetic conditions and determine the drivers of the recently reported quiet-time SAPS-like flows observed during non-storm periods. Finally, the proposed research is highly pertinent to the National Space Weather Action Plan which identifies developing benchmarks for various space weather events and ionospheric disturbances as one of it's key goals.

1.1 Sub-Auroral Polarization Streams : The Traditional Paradigm

SAPS are regions of westward directed plasma flows located equatorward of the auroral oval in the dusk-midnight sector. Early measurements of SAPS were predominantly obtained by satellites such as DMSP and Akebono or radars such as the Millstone Hill incoherent scatter radar. A number of terms such as Polarization Jets (PJ) [*Galperin et al.*, 1974], Sub-Auroral Ion Drift (SAID) [*Spiro et al.*, 1979; *Anderson et al.*, 1993, 2001], Sub-auroral Electric Fields (SAEF) [*Karlsson et al.*, 1998] and Substorm Associated Radar Auroral Surges (SARAS) [*Freeman et al.*, 1992] have been used to describe these sub-auroral flows. The term SAPS was coined by *Foster and Burke* [2002] to encompass all these separately reported phenomena which exhibit a certain degree of similarity. SAPS were thus defined as latitudinally broad regions (3°-5° wide) of enhanced westward flows observed in the nightside sub-auroral region. SAID/PJ are latitudinally narrow (∼1° wide) channels of intense westward flows, often exceeding 1 km/s, which are embedded within the SAPS [*Foster and Burke*, 2002]. SAPS are commonly associated with geomagnetic disturbances when the ion Alfvén layer moves closer to the Earth compared to the electron Alfvén layer due to differences in their energy spectra. Such a misalignment can set up strong radially outward polarization electric fields which map into the ionosphere along magnetic field lines in the poleward direction producing SAPS. Moreover, downward Region-2 Field-Aligned Currents (FACs) are generally thought to

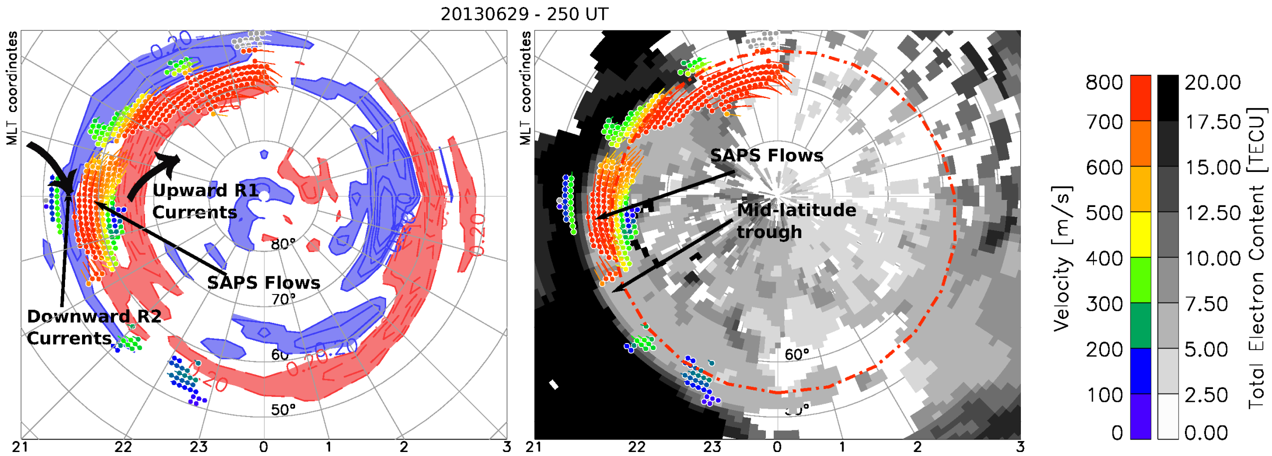

Figure 1: A SAPS event on June 29, 2013 at 250 UT which agrees with the traditional paradigm. The left panel shows Field Aligned Currents (FACs) from AMPERE and velocity vectors from the mid-latitude SuperDARN radars overlaid on a map marked in MLT-MLAT coordinates. The right panel shows GPS TEC measurements and SuperDARN mid-latitude vectors scaled according to the color bar on the right along with the equatorward auroral oval boundary estimated using POES satellite passes.

collocate with the equatorward ion precipitation boundary and close with Region-1 FACs via Pedersen currents. However, when there is a misalignment in the ion/electron precipitation boundaries a portion of the downward Region-2 FACs ($J^{\downarrow}_{R2}$) flows into a region of low ionospheric conductance which hinders current closure thus resulting in the generation of large poleward directed electric fields which drive SAPS. Finally, these poleward directed electric fields can lead to increased collision frequencies and enhanced ion recombination rates resulting in further decrease in conductivity producing a feedback effect that allows the electric fields to grow even more [*Schunk et al.*, 1976]. The ionospheric feedback is expected to play an important role in generating and sustaining SAPS, since the fraction of $J^{\downarrow}_{R2}$ flowing into the sub-auroral latitudes is generally small [*Foster and Burke*, 2002]. Some of the strongest SAPS flows are therefore expected to be collocated with the deepest conductivity gradients. This sequence of events is what we here call the "traditional paradigm of SAPS".

The hypotheses below summarize the drivers and feedback mechanisms for the traditional paradigm of SAPS:

H1. **During geomagnetic disturbances, the ion precipitation boundary moves equatorward of the electron precipitation boundary. The Asymmetric ring current is collocated with the ion precipitation boundary and at least a portion of $J^{\downarrow}_{R2}$ flows into the low-conductivity region setting up strong SAPS associated electric fields.**

H2. **SAPS flows are collocated with the mid-latitude trough and strongest SAPS flows are associated with the deepest gradients in the trough.**

H3. **SAPS produce steeper troughs due to frictional heating, creating a positive ionospheric feedback effect which further increases the SAPS electric fields.**

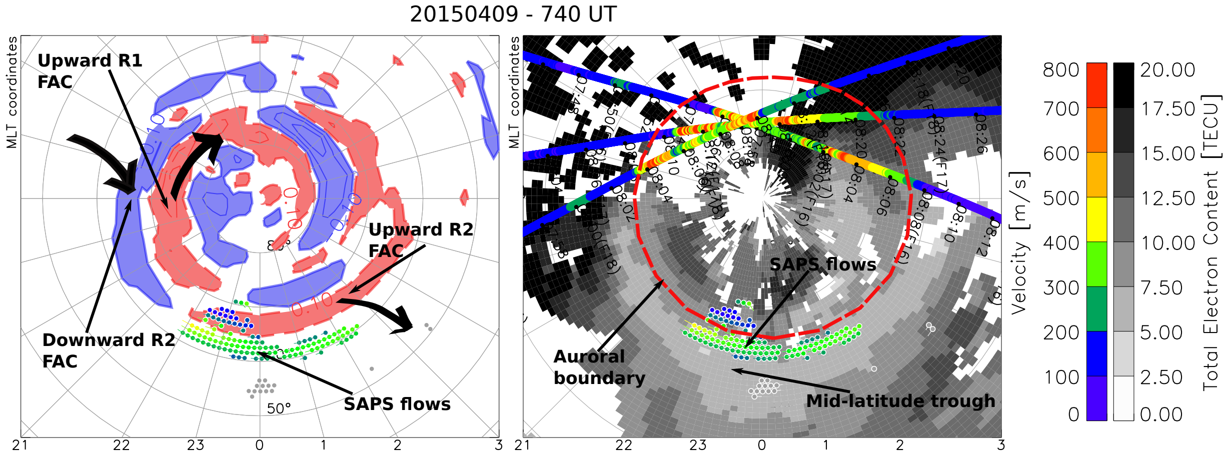

Figure 2: A sample SAPS-like event on April 9, 2015 at 740 UT in the same format as Figure 1

Figure 1 presents an example SAPS event on June 29, 2013 at 250 UT which agrees with the traditional paradigm. It occurred during geomagnetically disturbed conditions when Dst dropped to -100 nT and Kp was 6. In the left panel we present contours of FACs derived from AMPERE along with the ionospheric convection vectors derived from mid-latitude SuperDARN observations. On the right panel a GPS TEC map with SuperDARN vectors overlaid is presented. The red dashed circle presents the auroral oval estimated using POES satellite data [*Kunduri et al.*, 2017]. SuperDARN convection velocities and GPS TEC measurements are scaled according to the color bar on the right. The data clearly show SAPS are located inside the trough and a portion of downward region-2 currents on the dusk side are located equatorward of SAPS inside the trough. This event is thus an example of a "traditional" SAPS observed during geomagnetically disturbed conditions which is consistent with the conventional driving mechanisms (Hypothesis H1-H3).

1.2 New insights into SAPS

Recent studies using mid-latitude SuperDARN data have shown SAPS-like flows are more persistent features of the ionosphere than realized and are observed $\sim 30\%$ of the time (when radars are in the dusk-midnight sector) [*Kunduri et al.*, 2017]. It is important to note that these SAPS-like events showed enhanced velocities and were not associated with the low-velocity Sub-Auroral Ionospheric Scatter (SAIS), which is the commonly occurring type of backscatter that is observed in the night side quite-time mid-latitude ionosphere [*Ribeiro et al.*, 2012]. SAPS-like flows were observed $\sim 15\%$ of the time even during quiet geomagnetic conditions [*Kunduri et al.*, 2017]. Similar reports of SAPS-like observations during geomagnetically quiet conditions (Kp ≤ 2 and $|Dst| \leq 20$ nT) made by the Van Allen Probes were discussed by *Lejosne and Mozer* [2017]. A preliminary examination clearly showed that even though some of these events exhibited similar characteristics to storm-time SAPS, they were clearly not driven by the same mechanisms. For example, they were not located between $J^{\downarrow}_{R2}$ and $J^{\uparrow}_{R1}$ (Hypothesis H1) and the speed was not sufficient to generate frictional heating (Hypothesis H2, H3).

An example of a SAPS-like event is presented in Figure 2 (in the same format as Figure 1). This event occurred on April 9, 2015 at 0740 UT when Dst was $\sim$-5nT and Kp was 3. Note that SuperDARN observations were obtained well below the auroral oval estimated using DMSP SSJ/4 data (not shown) using the methodology described in *Kunduri et al.* [2012] thereby indicating they are sub-auroral and perhaps belong to the SAPS category. Particularly noteworthy is the fact that SAPS-like flows observed during this event are equatorward of $J^{\uparrow}_{R2}$ rather than poleward of significant $J^{\downarrow}_{R2}$. Although the observations presented in this example exhibit characteristics similar to SAPS (in terms of location and flow direction), they do not concur with Hypothesis H1 and thereby the traditional paradigm of SAPS. The question then becomes what is driving these SAPS-like flows and is it appropriate to classify them as SAPS?

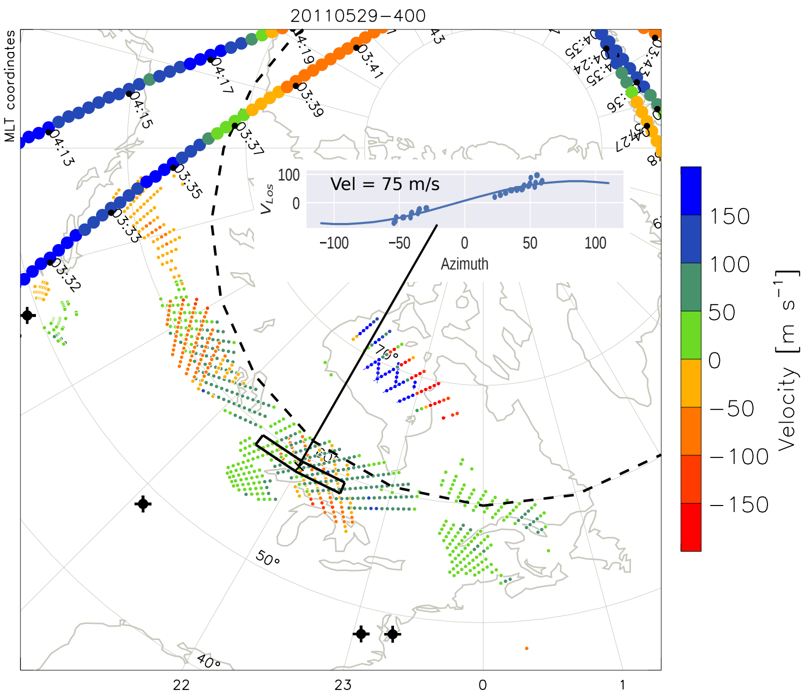

Figure 3: Low velocity SAPS-like event observed in mid-latitude SuperDARN radars on May 29, 2011 at 0400 UT. Line-of-Sight velocities are overlaid on a map marked in MLT-MLAT coordinates with overlaid POES satellite passes and associated best-fit auroral oval boundary. L-shell estimate of velocity [*Kunduri et al.*, 2012; *Clausen et al.*, 2012a] near 22 MLT is shown in the inset.

Another important aspect of "traditional" SAPS is frictional heating and ionospheric feedback in the mid-latitude trough. *Schunk et al.* [1976], using theoretical calculations, showed that electric fields $\geq$ 50 mV/m (speeds in the order of $\sim$1000 m/s) are required to set up frictional heating in the mid-latitude trough (Hypothesis H3). However, some "non-traditional" SAPS-like events seen by SuperDARN exhibit much lower velocities than those required for frictional heating. One such example is presented in Figure 3. This event occurred on May 29, 2011 at 4 UT when Dst was $\sim$-30 nT and Kp was 4. The 2D velocities during this event were estimated using the L-shell fitting procedure [*Kunduri et al.*, 2012; *Clausen et al.*, 2012a] and found to vary between 75 m/s and 150 m/s, indicating that electric fields associated with SAPS were lower than 5 mV/m. This is an order of magnitude lower than the threshold required to produce ionospheric feedback in SAPS.

We thus summarize the following shortcomings of the "traditional paradigm" of SAPS drivers and feedback mechanisms as applied to these SAPS-like events:

S1. **$J^{\downarrow}_{R2}$ are not always observed equatorward of SAPS-like flows.**

S2. **The electric fields associated with SAPS-like flows can be an order of magnitude lower than those needed to generate frictional heating and ionospheric feedback ($\sim$50 mV/m suggested in *Schunk et al.* [1976]).**

The examples presented above demonstrate the limitations of our current understanding of the inner magnetosphere and the factors driving SAPS-like flows. It is clearly necessary to revisit the "traditional paradigm" of SAPS generation mechanisms to develop a better understanding of coupling in the magnetosphere-ionosphere-thermosphere system. Henceforth, we will classify SAPS into two categories, namely, **"traditional" SAPS** and **"non-traditional" SAPS-like** based on their agreement with the current widely accepted model of SAPS driving mechanisms.

1.3 Potential Drivers for SAPS-like Flows

In the previous section, we demonstrated shortcomings in the "traditional paradigm" of SAPS. Motivated by the necessity to re-think SAPS generation mechanisms, we now discuss other types of drivers for SAPS-like flows.

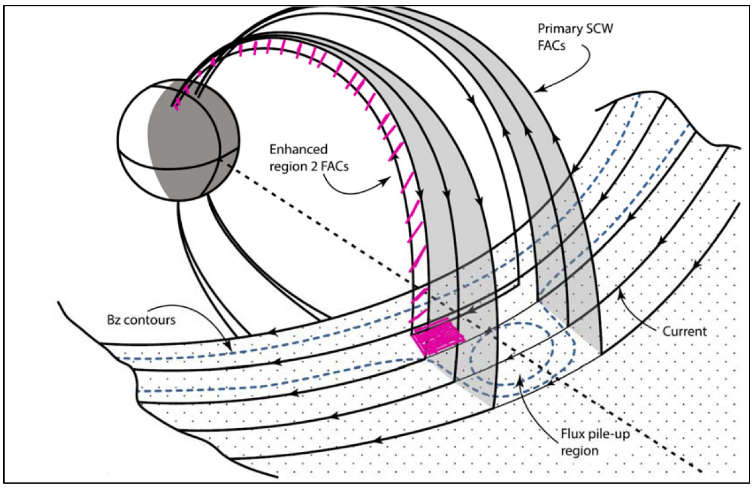

Figure 4: Two loop circuit of substorm current wedge (Image adapted from *Mishin et al.* [2017], supplementary Figure S11). The Region-1 type currents in the SCW ($J^{\uparrow}_{SCW}$) are shaded grey. A new region-2 type current system in the SCW ($J^{\downarrow}_{SCW}$) is shown Earthwards of $J^{\uparrow}_{SCW}$. The region of SAPS-like flows are marked with magenta shading between $J^{\downarrow}_{SCW}$ and $J^{\uparrow}_{SCW}$.

Recent studies have shown the Substorm Current Wedge (SCW) can have a two-loop circuit similar to the upward flowing Region-1 ($J^{\uparrow}_{SCW}$) and Region-2 FAC ($J^{\downarrow}_{SCW}$) system [*Murphy et al.*, 2013; *Kepko et al.*, 2015; *Mishin et al.*, 2017] as shown in Figure 4 (adapted from *Mishin et al.* [2017]). Of particular relevance here is the suggestion that SAPS-like flows could be generated due to the poleward electric field inherent in the two-loop circuit of SCW (formed due to the closure of $J^{\downarrow}_{SCW}$ and $J^{\uparrow}_{SCW}$) [*Mishin et al.*, 2017]. The region of likely SAPS-like flows is marked with magenta shading in Figure 4.

Figure 5 shows a SAPS-like event on May 16, 2011 at 0820 UT which agrees with the scenario presented in Figure 4. The geomagnetic conditions were quiet during this event with Dst ∼-10, AE ∼300 and Kp was 3. The presence of the two loop sub-storm current wedge during the event is confirmed and discussed in greater detail by *Murphy et al.* [2013]. Here, we focus on the SAPS-like flows (inside the trough) between the two loop current system embedded inside the SCW ($J^{\uparrow}_{SCW}$ and $J^{\downarrow}_{SCW}$). We deduce the following hypothesis from Figures 4 and 5:

H4. **SAPS-like flows can be driven by current closure in the SCW.**

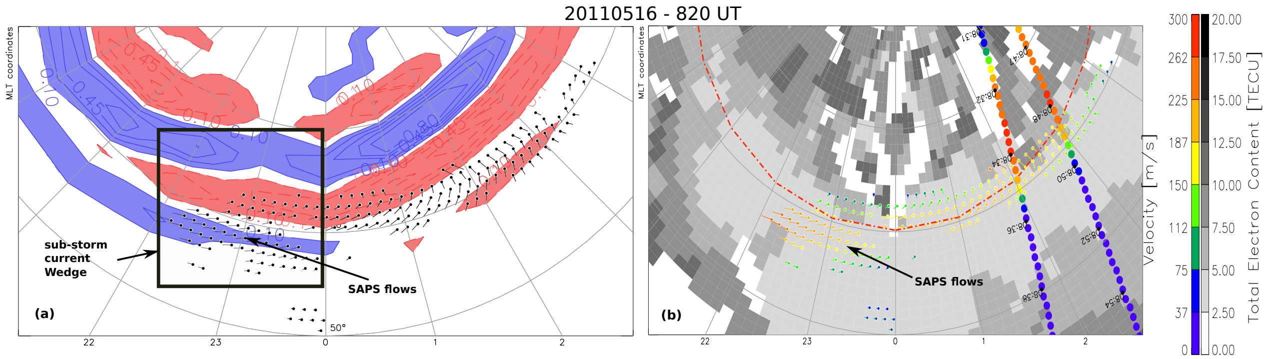

Figure 5: An example SAPS-like event on May 16, 2011 at 820 UT which agrees with the scenario presented in Figure 4. Panel (a) presents AMPERE currents and SuperDARN fitted velocity vectors. The sub-storm current wedge is boxed along with the SAPS-like flow vectors. Panel (b) presents GPS TEC and SuperDARN fitted velocity vectors scaled according to the color bar on the right along with POES satellite passes and the best-fit auroral oval boundary.

Another important factor that can potentially drive SAPS-like flows is under-shielding. During steady state, it is well known that the inner magnetosphere shields the mid and low latitude ionosphere from the electric fields and plasma convection associated with the outer magnetosphere [*Kelley et al.*, 1979; *Wolf et al.*, 2007]. However, during periods of a sudden southward B_Z turning or oscillating B_Z on the order of $\sim$ few minutes, the shielding electric field does not have enough time to develop, thereby allowing the high-latitude fields to penetrate to mid and low latitudes [*Kelley et al.*, 2003; *Fejer et al.*, 2007; *Wolf et al.*, 2007]. Such electric fields can drive SAPS-like flows in the dusk-midnight sector. This potential influence for under-shielding to drive SAPS-like flows in the sub-auroral ionosphere needs to be rigorously investigated. We deduce the following hypothesis on the influence of under-shielding in generating SAPS-like flows:

H5. **SAPS-like flows can be generated due to under-shielding of the inner magnetosphere.**

In summary, we have shown that our current paradigm of SAPS drivers and feedback is limited and cannot explain all SAPS-like flows during all geomagnetic conditions. We have also discussed two potential mechanisms that might explain the generation of SAPS-like flows during substorms and penetration electric field events when the "traditional" paradigm fails. A summary of the hypotheses discussed and their associated shortcomings is presented in Table-1. In the next section, we propose a plan to test the mechanisms against observations and determine the dominant drivers for SAPS-like flows over a broad range of geomagnetic conditions.

2 Scientific Contribution

In the previous sections we discussed several shortcomings associated with our current understanding of SAPS drivers and presented examples of SAPS-like enhanced sub-auroral convection that

Hypothesis	Shortcoming
SAPS are collocated/poleward of $J^{\downarrow}_{R2}$.	Some SAPS-like flows are not observed in the proximity of $J^{\downarrow}_{R2}$ (Figure 2).
SAPS are collocated with the trough and strongest SAPS are collocated with deepest trough gradients (H2).	Not fully validated on a statistical basis.
SAPS produce deeper troughs due to frictional heating creating an ionospheric feedback (H3).	Not fully validated through data and SAPS speeds are not always sufficient to generate frictional heating.
Current closure in the SCW can produce SAPS-like flows (H4).	Not yet fully validated.
Under-shielding of inner magnetosphere can produce SAPS-like flows (H5).	Not yet fully validated.

Table 1: A summary of the hypotheses and their shortcomings

disagree with the traditional paradigm. Moreover, new results on SAPS-like flows [*Kunduri et al.*, 2017; *Mishin et al.*, 2017] demonstrate the short comings in our current understanding of the nature of magnetosphere-ionosphere coupling at sub-auroral latitudes. These inconsistencies make it necessary to divide SAPS into two further sub-categories: (1) SAPS events which agree with the "traditional paradigm" and (2) SAPS-like events which cannot be explained by the traditional drivers. Roughly, we perceive that SAPS/SAPS-like flows may be associated with storm/non-storm conditions, respectively, but this needs to be verified. The proposed work will focus on answering several questions relating to SAPS and SAPS-like flows, to improve our understanding of the coupled inner magnetosphere sub-auroral ionosphere system:

Q1. To what extent is the traditional paradigm of SAPS valid?

  (a) When does the traditional paradigm of SAPS fail?
  (b) What percentage of SAPS-like flows are actually SAPS?
  (c) Under what geophysical conditions are SAPS-like flows observed?

Q2. What are the mechanisms driving SAPS-like flows?

  (a) How often does the substorm current wedge drive SAPS-like flows?
  (b) What is the role of under-shielding in driving SAPS-like flows?

Q3. What is the influence of the mid-latitude trough on SAPS and SAPS-like flows?

  (a) How does the location of SAPS and SAPS-like flows relative to the mid-latitude trough vary with geomagnetic conditions?
  (b) Does the strength of SAPS and SAPS-like flows vary with the magnitude of trough gradients?
  (c) What is the role of ionospheric feedback in producing SAPS and SAPS-like flows?

3 Research Plan

New insights into the inner magnetosphere [*Kepko et al.*, 2015; *Kunduri et al.*, 2017; *Mishin et al.*, 2017] show that previous studies have not completely explored some important factors such as the influence of substorm current wedge and under-shielding in generating SAPS-like flows. Determining the role of these factors is particularly important in explaining the formation of SAPS-like flows and understanding the dynamics of the coupling between the inner magnetosphere and sub-auroral ionosphere, especially during relatively quiet geomagnetic conditions.

The overarching goal of the proposed work is to determine the extent to which the "traditional paradigm" of SAPS is valid and to determine the role of different factors in driving SAPS-like flows, that were overlooked in previous studies. Specific tasks related to the individual science questions (above) are listed below:

3.1 Task 1 : Determine the occurrence statistics of "traditional" SAPS and SAPS-like flows

3.1.1 Background

In *Kunduri et al.* [2017] a database of large-scale SAPS and SAPS-like events, with over 3000 hours of observations made by the US mid-latitude SuperDARN radars was created. An important result of the study was observations of SAPS-like flows during quiet geomagnetic conditions. Several examples from the SuperDARN database (a few presented in previous sections) show the traditional paradigm fails to explain the formation of SAPS-like flows. The first step in the project will be to determine the percentage of SAPS-like events in the SuperDARN database and create a casebook of such events to determine their occurrence characteristics under different geophysical conditions.

The current task is organized towards answering science question Q1.

3.1.2 Focus Points

The major focus points of the first task will be :

- Identify periods of "traditional" SAPS and SAPS-like events from the SuperDARN database. In other words, determine when Hypothesis H1 is valid.
- Determine the occurrence characteristics of "traditional" SAPS and SAPS-like flows under different geomagnetic conditions.
- Determine the average location and velocity characteristics of "traditional" SAPS and SAPS-like flows.

3.1.3 Datasets and Methodology

The primary datasets used in this study will be ionospheric convection velocities obtained from the mid-latitude chain of **SuperDARN** radars and Field-aligned current data derived from the **Active Magnetosphere and Planetary Electrodynamics Response Experiment(AMPERE)**.

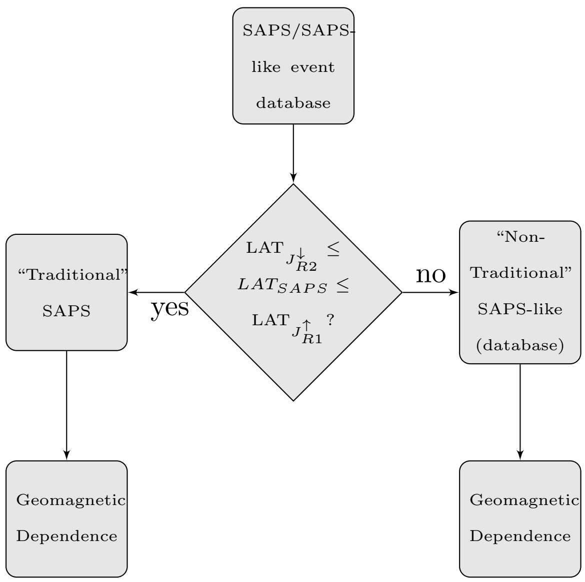

Figure 6: Flowchart describing the methodology of task 1

The task will predominantly use data from the SuperDARN database (∼3000 hours of observations) [*Kunduri et al.*, 2017] and classify the events into SAPS and SAPS-like. The classification of the events will be based on the location of the $J^{\downarrow}_{R2}$ with respect to the flows. When the flows are located between $J^{\downarrow}_{R2}$ and $J^{\uparrow}_{R1}$ the events will be classified as SAPS (for example, Figure 1) and SAPS-like otherwise. The flowchart in Figure 6 summarizes the procedure. Once a casebook of SAPS-like events is developed, the next step will be to derive their occurrence characteristics under different geophysical conditions (parametrized by IMF B_Z, Sym-H, Asy-H and AE indices). Such an analysis will provide insights into the nature of the background geophysical conditions driving them. Finally, the average location (MLAT-MLT) and velocities of the SAPS-like flows will be determined and compared with the average characteristics of SAPS to determine the differences between their occurrence, location and velocities under different geophysical conditions.

3.1.4 Significance of task 1

The first task is important because it will test our current understanding of the coupling within inner magnetosphere/sub-auroral ionosphere system across a broad range of geomagnetic activity. Furthermore, the creation of the database of SAPS and SAPS-like flows will be of great value for other researchers.

3.2 Task 2 : Determine the drivers of SAPS-like flows

3.2.1 Background

In previous sections, we cited two hypotheses discussing potential drivers of SAPS-like flows which have not been fully considered in previous observational studies, namely, (1) Hypothesis H4 : current closure in J_{SCW}, and (2) Hypothesis H5 : under-shielding of the inner magnetosphere. The goal of the current task is to validate these Hypotheses (H4 and H5) using the casebook of SAPS-like flows and to determine the percentage of SAPS-like flows driven by each under different geophysical conditions.

The second task is organized towards answering science question Q2.

3.2.2 Focus Points

The major focus points of the second task will be :

- Determine the percentage of SAPS-like flows that are generated by J_{SCW} (Hypothesis H4).

- Determine the percentage of SAPS-like flows that are generated as a result of under-shielding (Hypothesis H5).

3.2.3 Datasets and Methodology

The primary datasets used in this study are ionospheric convection velocities from mid-latitude chain of **SuperDARN** radars and Field-aligned current data derived from **AMPERE**.

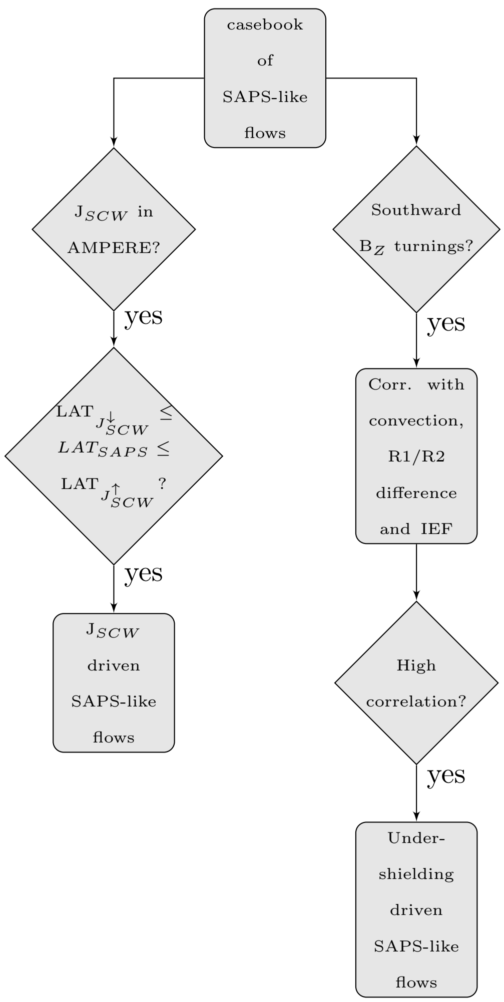

Figure 7: Flowchart describing the methodology of task 2

The task will utilize the casebook of SAPS-like flows developed previously (section 3.1) to determine the percentage of events generated due to J_{SCW} (H4) and under-shielding (H5). We will begin with testing Hypothesis H4. *Murphy et al.* [2013] demonstrated that AMPERE can detect signatures of the two loop structure of J_{SCW} [*Kepko et al.*, 2015; *Mishin et al.*, 2017], even during relatively quiet geomagnetic conditions. We will examine the time period of each individual event from the casebook manually to identify signatures of J_{SCW}. If J_{SCW} is identified in AMPERE and SAPS-like flows are located between the downward flowing ($J^{\downarrow}_{SCW}$) and upward flowing ($J^{\uparrow}_{SCW}$) components of J_{SCW}, the event will be labeled as being driven by the two loop structure of J_{SCW} (for example see Figure 5).

Testing Hypothesis H5 will be somewhat more involved. Under-shielding is typically expected during a sudden southward turning of IMF B_Z, resulting in an increase in the dawn-dusk convection electric field and a lack of similar response in the dusk-dawn electric field shielding the inner magnetosphere. In other words, an imbalance between Region-1 and Region-2 FACs can produce under-shielding [*Fejer et al.*, 2007; *Wolf et al.*, 2007]. To determine if some of the SAPS-like flows are driven by under-shielding, we will shortlist the events when IMF B_Z abruptly turns southwards shortly before or during the event. Electric fields associated with SAPS-like flows during these shortlisted events will be correlated with the IEF, difference in the magnitude of Region-1 and Region-2 FACs (derived from AMPERE) and high-latitude convection (derived from SuperDARN). The events will then be labeled as being driven by under-shielding if a high degree of correlation is observed between these parameters.

The process to determine the validity of Hypotheses H4 and H5 is outlined in Figure 7. Finally, a statistical analysis of the events will be performed to determine the percentage of events generated due to each of the drivers under different geomagnetic conditions. Such an analysis will be particularly useful in forecasting and now-casting the occurrence of SAPS-like flows based on geomagnetic conditions.

3.2.4 Significance of task 2

The task is timely and important because it will test the validity of two new paradigms for explaining SAPS-like flows during non-storm intervals, that have not yet been extensively examined.

3.3 Task 3 : Determine the influence of the mid-latitude trough on SAPS and SAPS-like flows

3.3.1 Background

A crucial factor in the traditional paradigm for the formation of SAPS is the mid-latitude trough and the role of ionospheric feedback (Hypotheses H2 and H3). However, the precise dependence of SAPS location and speed on trough location and depth has not been verified statistically. Furthermore, it is an open question whether SAPS-like flows depend on the trough at all. The goal of this task is to test the statistical validity of these hypotheses as a function of geomagnetic activity level.

The third task is thus organized towards answering science question Q3.

3.3.2 Focus Points

The major focus points of the third task will thus be:

- Quantify the variability in the mid-latitude trough with respect to geomagnetic conditions and season and its impact on the magnitude of SAPS/SAPS-like flows.
- Identify the location of SAPS/SAPS-like flows with respect to trough minimum and the poleward/equatorward boundaries, under different geomagnetic conditions.
- Determine the threshold electric fields required to setup frictional heating and ionospheric feedback. Validate if electric fields ≥ 50 mV/m are indeed required to setup frictional heating as suggested by *Schunk et al.* [1976].
- Quantify the percentage of times frictional heating is generated under different geomagnetic conditions.

3.3.3 Datasets and Methodology

The primary datasets used in this study are ionospheric convection velocities from the mid-latitude chain of **SuperDARN** radars and **GPS Total Electron Content (TEC)** measurements of the mid-latitude trough. Moreover, we will run coordinated experiments with the **Millstone Hill ISR** to determine the interaction between the mid-latitude trough and SAPS/SAPS-like flows.

For this task we will use edge-detection methods (such as canny edge detector or the Laplacian of Gaussian method) to determine the location of the mid-latitude trough from the maps of GPS TEC obtained from the Madrigal Web between 2011 and 2014 (same date range used to create SuperDARN database of SAPS and SAPS-like flows [*Kunduri et al.*, 2017]). In particular, we will extract the location and TEC values of the trough minimum and poleward/equatorward boundaries from each of the maps. Average characteristics of trough locations and gradients, binned by different levels of geomagnetic activity and season will be determined and compared with the average characteristics location and velocities of SAPS/SAPS-like flows presented in *Kunduri et al.* [2017].

Such an analysis will determine the relative location of the flows with respect to the mid-latitude trough and demonstrate whether the strongest flows are indeed collocated with the deepest trough gradients. Furthermore, we will classify the troughs as SAPS-time and non-SAPS time based on whether SAPS/SAPS-like flows are observed by SuperDARN and determine the differences in location and gradients between them for each geomagnetic activity level. Deeper SAPS-time troughs would be indicative of the presence of frictional heating and ionospheric feedback. Finally, a high correlation between flow speeds and trough depth (under similar geomagnetic activity levels) would indicate the presence of frictional heating during SAPS/SAPS-like flows and provide an estimate of electric fields required to setup frictional heating and thereby ionospheric feedback. Finally, we will validate our statistical results by running coordinated experiments with the Millstone Hill ISR under different geomagnetic conditions. The data from these experiments will be used to determine the evolution of the trough (determined from ISR and GPS TEC) to changes in electric fields (determined from ISR and SuperDARN observations) and currents (determined from AMPERE) during the course of the experiment.

3.3.4 Significance of task 3

The third task is important because it will examine the role the of mid-latitude trough in the formation of SAPS/SAPS-like flows and determine the extent to which theoretical formulations of ionospheric feedback in the sub-auroral region are valid.

3.4 Relevant experience

The proposing team has extensive experience working with SuperDARN data and has previously published several studies on SAPS (for e.g., *Kunduri et al.* [2012, 2017]; *Clausen et al.* [2012a]. The team also has experience working with the freely available AMPERE (e.g., *Clausen et al.* [2012b]) and GPS TEC (e.g., *Thomas et al.* [2013]) datasets and have secured commitments from Dr. Brian Anderson (personal communication) and Dr. Anthea Coster (personal communication) to provide validated AMPERE FACs, GPS TEC measurements respectively and associated interpretation in the context of this project. Likewise, the team has a commitment from Dr. Philip Erickson (personal communication) to run coordinated experiments between Millstone Hill ISR and SuperDARN to study SAPS and SAPS-like flows.

3.5 Management Plan

The majority of the data analysis tasks will be conducted by Dr. Bharat Kunduri (PI) at Virginia Tech under the supervision of Dr. Joseph Baker (Co-PI). Funds are also allocated for undergraduate students to assist Dr. Kunduri in these tasks as a summer undergraduate research project thereby gaining valuable hands-on experience in working with space science related datasets such as SuperDARN, AMPERE and GPS TEC.

3.6 Work Plan

In the previous sections the proposed research was divided into three tasks, each addressing a specific science question. We now provide a year by year breakdown of the timeline to complete these tasks :

Year-1 :

1. Identify SAPS and SAPS-like flows in the SuperDARN database.
2. Determine the occurrence, location and velocity characteristics of SAPS and SAPS-like flows as a function of geomagnetic activity.
3. Make the SuperDARN database of SAPS/SAPS-like flows available for public use.
4. Visit the MIT Haystack observatory to collaborate with Dr. Philip Erickson (PI of the Millstone Hill ISR) and run coordinated experiments between SuperDARN and the Millstone Hill ISR.
5. Present results of SAPS/SAPS-like occurrence statistics at the fall AGU meeting and CEDAR workshop. Publish the results in the Journal of Geophysical Research (JGR).

Year-2 :

1. Visit Dr. Brian Anderson (PI of AMPERE project) at Johns Hopkins Applied Physics Lab to collaborate on analyzing AMPERE data.
2. Determine the percentage of SAPS-like flows that are generated by the substorm current wedge and under-shielding.
3. Make the database of substorm/under-shielding SAPS-like flow events available for public use.
4. Continue scheduling experiments with the Millstone Hill ISR to study the behavior of SAPS/SAPS-like flows under different different geomagnetic conditions.
5. Present results of drivers of SAPS-like flows at the fall AGU meeting and CEDAR workshop. Publish the results in the Journal of Geophysical Research (JGR).

Year-3 :

1. Visit the MIT Haystack observatory to collaborate with Drs. Anthea Coster and Philip Erickson on analyzing GPS TEC and data from coordinated SuperDARN and Millstone Hill ISR runs.
2. Analyze the role of the mid-latitude trough in modulating the strength and location of SAPS/SAPS-like flows.
3. Determine the threshold electric field magnitude required to frictional heating in the trough and the extent of ionospheric feedback.
4. Present results of trough influence on SAPS/SAPS-like flows at the fall AGU meeting and CEDAR workshop. Publish the results in the Journal of Geophysical Research (JGR).

A summary of important aspects of the proposed research is presented in Table 2.

Task	Hypotheses Tested	Relevant Science Question	Datasets	Deliverables	Timeline
1	H1	Q1	SuperDARN, AMPERE	1) Journal Paper, 2) Present results in AGU, CEDAR, 3) Database of SAPS/SAPS-like events	year-1
2	H4, H5	Q2	SuperDARN, AMPERE	1) Journal Paper, 2) Present results in AGU, CEDAR, 3) Database of "non-traditional" SAPS-like events	year-2
3	H2, H3	Q3	SuperDARN, GPS TEC, Millstone Hill ISR	1) Journal Paper, 2) Present results in AGU, CEDAR	years-1,2,3

Table 2: Summary of Research Plan

Intellectual Merit

The intellectual merit of this proposal lies in the prospect of advancing our current understanding of the dynamic coupling between the inner magnetosphere and sub-auroral ionosphere and their response to internal and external driving influences. Specifically, the proposed work is focused on determining the interplay between FACs of magnetospheric origin and ionospheric convection in the vicinity of the mid-latitude trough during SAPS and SAPS-like flows. The project is timely because of the recent improvements in the mid-latitude infrastructure such as the development of mid-latitude SuperDARN network, availability of GPS TEC and AMPERE measurements providing continuous global views of the ionospheric electrodynamics. SAPS is a prominent example of magnetosphere-ionosphere coupling which is long-lasting operates over hemispheric spatial scales, and exerts a controlling influence on the evolution of large scale plasma features such as storm enhanced density and the formation of plasma irregularities. The attainment of a comprehensive, observationally based understanding of the dynamics and drivers for SAPS and SAPS-like flows under different geomagnetic conditions directly addresses goals of the NSF Aeronomy program. Finally, developing a robust understanding of SAPS and SAPS-like flows has been the focus of the "CEDAR GRAND Challenge: Storms and Substorms Without Borders (SSWB) and GEM SIMIC Focus Group".

Broader Impacts

The insights developed on atmosphere-ionosphere-magnetosphere coupling are directly relevant to the NSF Coupling Energetics and Dynamics of Atmospheric Regions (CEDAR) program. The databases of SAPS and SAPS-like flow events developed during the project will serve as modeling challenges to researchers, making the proposal relevant to the Geospace Environment Modeling (GEM) program and the NASA Living with a star (LWS) program. The project is also highly pertinent to the National Space Weather Action Plan since it will help develop bench marks for certain space weather events and ionospheric disturbances such as SAPS and SAPS-like flows. Other broader impacts include career development of an early career scientist and support for undergraduate students on summer research projects. Funds are allocated for the early career scientist to visit other researchers in the field to gain proficiency in multi-instrument data analysis techniques and further develop collaborations.

Results From Prior NSF Support

Bharat Kunduri (PI)
Dr. Kunduri has worked on several NSF funded projects as a graduate student and a postdoctoral associate. His work on SAPS has resulted in two journal articles discussing to interhemispheric conjugacy in SAPS [*Kunduri et al.*, 2012] and statistics of SAPS [*Kunduri et al.*, 2017] and another journal article discussing potentials associated with SAPS is under review. Dr. Kunduri presented made several presentations at the AGU Fall meeting, CEDAR and GEM workshops, in particular he actively participated in the GEM focus group : "storm-time inner magnetosphere-ionosphere convection". Dr. Kunduri also received first prize in the student poster competition at the 2013 CEDAR workshop in Boulder, Co. Finally, Dr. Kunduri developed several data processing and visualization tools to analyze SuperDARN, AMPERE and GPS TEC datasets. Several of the visualization tools and processing software developed by Dr. Kunduri are hosted on the VT SuperDARN website.

Joseph B. H. Baker (Co-PI)
Dr. Baker has been PI on three NSF grants. The first is ATM-0924919 (Budget: $194,869, Title: "GEM Postdoc: Characteristics of ULF Waves Associated with Electron Acceleration to Relativistic Energies", Term: 10/1/2009-9/30/2011) which provided support for a post-doctoral fellow (Dr. Lasse Clausen). This grant resulted in two journal articles which analyzed ULF waves [*Clausen et al.*, 2011a] and EMIC waves [*Clausen et al.*, 2011b] during magnetic storms. Two additional papers analyzing a SAPS event [*Clausen et al.*, 2012a] and the motion of the region-1 field-aligned currents [*Clausen et al.*, 2012b] were also published. The second PI grant is AGS-1150789 (Budget: $488,201, Title: "CAREER: Inter-Hemispheric Magnetic Conjugacy of Ionospheric Convection", Term: 3/1/2012-2/28/2017). This grant was the primary support for three separate graduate students and resulted in four student first-author journal articles [*Kunduri et al.*, 2012, 2017; *Joshi et al.*, 2015; *Malhotra et al.*, 2016] and co-author contributions on two additional studies [*Prikryl et al.*, 2013; *Walsh et al.*, 2015]. The third PI grant is AGS-1259508 (Budget: $150,262, Title: "Collaborative Research: Inferring High Latitude Convection Patterns Using SuperDARN, DMSP and ACE", Term: 02/1/2014-01/31/2018) which has provided partial support for a graduate student to study drivers for ionospheric convection. So far, this grant has resulted in one student first-author article [*Maimaiti et al.*, 2017] and one co-authored study [*Eriksson et al.*, 2017]. Finally, Dr. Baker has been a Co-PI on several NSF grants which have funded SuperDARN science and operations activities at Virginia Tech (PI: Dr. Mike Ruohoniemi).

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(a) Professional Preparation:

- Virginia Tech, Blacksburg, Ph.D, Space Science, 2013
- University of Florida, Gainesville, M. S, Atmospheric Electricity, 2010
- Dr. M. G. R. Educational and Research Institute, Chennai (India), B. Tech, Electrical Engineering,2008

(b) Appointments:

- Postdoctoral Associate, Virginia Tech, 2016-current
- Data Scientist, HT Media Ltd., 2015-2016
- Data Scientist, Tilt Video Inc., 2014-2015

(c) Scientific, Technical and Management Activities:

- Received first Prize in Student Poster Competition, 2013 CEDAR Workshop, Boulder, CO.
- Recipient of Pratt fellowship at Virginia Tech.
- Recipient of outstanding academic achievement award at University of Florida.
- Reviewer for Journal of Geophysical Research and Geophysics Research Letters.
- Member, American Geophysical Union (2010-current).
- Developed several web tools and software for the Virginia Tech SuperDARN group.

(d) Publications:

- Kunduri, B. S. R., J. B. H. Baker, J. M. Ruohoniemi, E. G. Thomas, S. G. Shepherd, and K. T. Sterne (2017), Characterizing the electric fields observed by SuperDARN in the sub-auroral ionosphere, J. Geophys. Res., Under Review.
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Postdoctoral Mentoring Plan

One postdoctoral researcher (Dr. Bharat Kunduri) will be funded and will serve as the PI on this project. The postdoc will be mentored by Dr. Joseph B. H. Baker (co-PI on this project). The mentoring program will provide a framework for the postdoc's professional and career development and will include a structured mentoring plan, career planning assistance, and opportunities to build and improve important skills such as writing grant proposals, developing collaborations with other research institutes, assist in mentoring graduate and undergraduate students, writing articles for publication and other communication skills. Specifically the plan will include:

Scientific Leadership

Funds are reserved for the publication of results in established peer-reviewed papers and to travel to scientific meetings and workshops to present results and interact with other scientists. During these trips, the postdoc will represent the VT SuperDARN group and be provided with opportunities to engage in collaborative research activities with scientists at other institutions.

Engineering Fieldwork

The postdoc will assist in the maintenance of existing SuperDARN radars. In this way, he will gain valuable training in engineering fieldwork and become involved in the day-to-day facility support activities of the VT SuperDARN group.

Interdisciplinary Research

The Center for Space Science and Engineering Research (Space@VT) was formed in 2007 and currently counts around 20 faculty members and approximately 30 students. Research interests encompass ground-based and space-based experimental investigations, as well as advanced computational modeling and theory. The rapid growth of Space@VT provides exciting possibilities for the postdoc to grow in new scientific directions under the guidance of a multi-disciplinary group of space scientists and engineers.

Professional Development and Career Counseling

Virginia Tech is a public land-grant university and has the largest enrolment of full-time students in Virginia (over 30,000). The University places great value in its research staff, including postdoctoral associates. Through the Office of the Vice President for Research (OVPR) Virginia Tech provides a robust program of professional development opportunities. In addition to online resources, there is a regular schedule of workshops and tutorials each semester. Topics covered include: export controls, project management, research compliance, grant proposal preparation, and professional integrity. The Virginia Tech Postdoctoral Association also provides networking and community building opportunities. The postdoc will be encouraged to take advantage of these university resources.

Teaching and Graduate Student Mentoring

The postdoctoral associate will assist in the mentoring of VT SuperDARN graduate students and there will be additional opportunities to become directly involved in leading student seminar sessions and teaching the occasional class.

Data Management Plan

Products of Research

This is primarily a scientific data analysis project that will use existing data archived at the Virginia Tech SuperDARN laboratory, Madrigal Web (MIT Haystack) and The Johns Hopkins University Applied Physics Laboratory. Other data will be obtained from various online databases. An important product of the project is the creation of the SAPS and SAPS-like flow datasets. The data will be stored in *netCDF* files and will be made available through the *Virginia Tech SuperDARN website* for the scientific community and general public. The proposal team has strong experience in working the datasets and corresponding software from previous efforts. The results from the research will be published in open-access peer-reviewed journals and shared in conference proceedings.

Data Format

Software will primarily be developed using *Python* and *Interactive Data Language (IDL)*. Data generated from scientific analysis of datasets will primarily be archived in *ASCII* format and *netCDF* files.

Data Access and Sharing

The primary vehicle for sharing the results of the research will be via presentations at conferences, articles published in peer-reviewed journals, and postings of databases, plots and other materials to the Virginia Tech SuperDARN website. Data products and associated software from data analysis and modeling will be available to other interested researchers on request. Those who request data access for the purpose of re-use and production of derivatives will be encouraged to consult closely with the PI to ensure that the data is used and interpreted appropriately.

Data Archiving

The Virginia Tech SuperDARN laboratory maintains a robust system for the storage and dissemination of data obtained from the entire SuperDARN radar network and other space physics datasets. The center-piece for the data archiving system is the RAID-6 array capable of storing 13 TB of data. The system currently contains all SuperDARN data from the radars worldwide dating back to 1993. Both fundamental "raw" data samples and derivative data products are stored on the system. This same system is also used to feed data to the laboratory's analysis computers and external web interface where it provides browse capability for external users. To protect against large scale data loss, a number of protections are in place. At Virginia Tech, the use of RAID-6 device for storage allows for hard drive failures without the loss of data. Additional protection comes from the fact that SuperDARN data is routinely distributed to partner organizations within the collaboration, thus providing ample redundancy. Custom written software and website information are also backed up on a nightly basis to multiple computers within the lab. Each week, a copy of his backup is also uploaded to remote radar sites in Blackstone, VA and Hays, KS.

Costs

All data management costs will be covered under the SuperDARN Geospace Facilities grant.

Facilities, Equipment and Other Resources

- **Laboratory :**
  This research will be carried out in the SuperDARN HF Laboratory at Virginia Tech. This facility contains all of the RF electronics equipment necessary for maintaining operation of the HF radars. The PI also has access to the data products (and the corresponding software to analyze them) from other instruments listed in the project (AMPERE, GPS TEC and Millstone Hill ISR).

- **Clinical :**
  N/A

- **Animal :**
  N/A

- **Computer :**
  All personnel in the SuperDARN HF Laboratory have workstation computers running the Linux operating system for data analysis. Computer resources in the ECE Department at Virginia Tech include a Departmental network specialist and high speed internet connections sufficient to support the proposed project.

- **Office :**
  All personnel have office space at Virginia Tech equipped with standard office furniture.

- **Major Equipment :**
  None required

- **Intellectual and Collaborative resources :**
  N/A

- **Other Resources :**
  Clerical and administrative support at Virginia Tech is provided by the Department of Electrical and Computer Engineering, the Center for Space Science and Engineering Research (Space@VT), and the Office of Sponsored Projects.