Enabling Space Science at Mid-latitudes with a Wallops Island Geophysical Observatory

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Executive Summary

The purpose of this white paper is to motivate a significant expansion of the Wallops Geophysical Observatory to enable next generation studies of the mid-latitude ionosphere-thermosphere. Such an expansion might ultimately include an increased use of the rocket range, a network of mid-latitude instrumentation to provide meso-scale observations, and a multi-static Geospace Radar network capable of high performance incoherent scatter measurements. This combination will provide detailed plasma diagnostics complementary to in-situ observations. Expanded experimental capabilities are critical to address many open scientific questions related to the mid-latitude ionosphere and thermosphere.

Introduction

As one of two active rocket ranges in the continental United States and home of the NASA sounding rocket program, the Wallops Flight Facility (WFF) is a critical location for the development of an expanded mid-latitude Geophysical Observatory. This network would leverage the existing incoherent scatter class Millstone Hill Geospace Radar to the north, develop existing range assets where possible to enable multi-static capability, and could ultimately motivate the development of advanced array radars on mobile ocean platforms. Such platforms are very ambitious to construct but would enable measurements in optimal relationship to rocket trajectories. NASA WFF has the personnel capable of maintaining and operating such instrumentation and has extensive experience in the deployment of assets to support rocket launches and in-situ observations. Moreover, the NASA WFF already supports many other instruments, including a Digisonde ionosonde, VIPIR HF radar, SuperDARN, all sky imagers, and magnetometers. Wallops is additionally well-placed to be included in larger scale networks of all-sky imagers (MANGO), GNSS TEC, and other instrumentation located on the eastern half of the continental US.

The mid-latitude ionosphere is an exciting domain for space science research with frontier questions developed over the last several decades of research. While many research efforts have focused on equatorial and high latitudes, a large number of critical systems rely on a highly detailed understanding and specification of the ionosphere at mid-latitudes. As one example, high frequency radio wave propagation controls the performance of over-the-horizon radar systems. These systems have to contend with the variable effects of traveling ionospheric disturbances, sporadic-E, and storm time phenomena such as sub-auroral polarization streams. Our ability to detect, quantify, and forecast such phenomena are very limited and this directly impacts our ability to model radio propagation and to assess operational system impacts.

Key physical mechanisms related to phenomena at mid-latitudes are not fully understood. One example lies in sporadic-E - one of the oldest mysteries since the earliest days of radio science. However, community understanding remains insufficient to produce accurate models at even a moderate level of fidelity. Sporadic-E layer formation occurs with rapid changes in electron density. However, the details of the process by which these changes occur, and the physical mechanisms involved, contain many unanswered questions.

Due to incomplete understanding, mid-latitude experimental and theoretical investigations are needed for appropriate incorporation into improved ionospheric models. Because of the complex interplay of plasma physics with neutral atmosphere dynamics and chemistry, it is necessary in particular to study mid-latitude phenomena using coordinated sets of instrumentation and observations. Instrumentation used at mid-latitudes needs to combine detailed plasma and neutral atmosphere measurements in selected regions with the meso-scale fields of view necessary to specify boundary conditions. Scientific progress requires co-located networks of instrumentation that include both ground based assets, orbital platforms, and in-situ measurements made using rocket instrumentation.

A Wallops Island Geophysical Observatory, organized around the rocket range and complemented by existing and future ground based Geospace radar systems, distributed radio sensors, and optical instrumentation, holds the key to making significant progress towards expanding our knowledge of mid-latitude space science.

Successful examples of this approach exist at other locations. At high latitudes, the Poker Flat Incoherent Scatter Radar, located next to the Poker Flat Research Range, has been indispensable in understanding of ionospheric state parameters and preconditioning during many sounding rocket launches, and provided critical data to assist with the interpretation of the in situ rocket observations. This has maximized scientific return by providing background plasma conditions, which are combined with high resolution in situ observations from suborbital launches. Substantial progress on scientific questions at mid latitudes will also occur if the most powerful ground-based observing techniques are co-located with a rocket range. A network of incoherent scatter capable radars that can be configured in an optimal manner to support rocket range in-situ measurements would be an extraordinarily powerful tool for making progress in our study of mid-latitude space science.

Scientific Motivation

A workshop was held at WFF in May 2022 that generated many compelling, open scientific questions at mid-latitudes. This meeting was attended by approximately 25 members of the community, and included program officers from NASA, NSF and ONR. Table 1 is a science traceability matrix showing critical space science questions that emerged from the meeting, along with the resulting requirements for measurement of key plasma and neutral physics parameters.

Combined with the discussions at the workshop, it quickly became clear that high capability joint experimental measurements, beyond what can be achieved with a single instrument, are needed to make progress. These questions can be addressed using a network of instrumentation that is anchored by a combination of multi-static incoherent scatter capable Geospace Radar and the in-situ capabilities provided by the rocket range. One key mid-latitude state parameter that is necessary for the closure of many scientific questions is the neutral wind. The sounding rocket-based chemical tracer technique remains a critical method to provide this measurement. Combining measurements of thermospheric winds, additional in situ observations of the plasma, and ground-based observations closes scientific questions at mid-latitudes both regionally and beyond.

A few important scientific topics are particularly compelling. One of the foremost questions is understanding coupling between the E-region and the F-region at mid-latitudes. Previous studies have found similar propagation directions between medium scale traveling ionospheric disturbances (MSTIDs) in the F-region and sporadic E in the E-region, but the causal connection between both of these mechanisms, if it exists, has yet to be conclusively observed. This sort of scientific question requires in situ sounding rocket observations, but also simultaneous observations of the background state of both the E- and F-region electron density along the magnetic flux tube. Such observational needs are ideally suited for a measurement using a properly positioned network of incoherent scatter capable radars.

Other compelling scientific topics included understanding plasma instabilities at mid-latitudes, structures associated with the storm time sub-auroral ionosphere (SAID, SAPS, etc), and other large scale thermodynamic and electrodynamic effects during geomagnetic storms. Additionally, an expanded Wallops Geophysical Observatory would provide a useful testbed for non-traditional experiments. For example, it is possible to generate enhanced VLF emissions from large rocket motor burns, which enhances particle precipitation that can only be measured by instrumentation at an ionospheric footpoint. Such experiments lead to enhanced and altitude/time-dependent electron density and plasma temperature best diagnosed with an incoherent scatter radar. These non-traditional experiments would use expanded Wallops centered radar capabilities to provide critical information regarding the ionospheric response.

Recommendation

The Wallops Flight Facility is an ideal location for future infrastructure to address compelling midlatitude ionospheric and thermospheric science. **We recommend a significant expansion of the Wallops Geophysical Observatory to enable next generation studies of the mid-latitude ionosphere-thermosphere.** Given the previous example provided by the Poker Flat Research Range, there is a significant scientific return provided by co-located ground-based instrumentations near/down range from a sounding rocket range. Configurations of this type allow fine scale to meso-scale studies required to close compelling mid-latitude scientific questions which e.g. rely on detailed, multi-scale knowledge of the plasma dispersion relation and electrodynamic coupling. We recommend that enhanced infrastructure be placed at/near the Wallops Flight Facility with instrumentation including, but not limited to, multistatic incoherent scatter radars, coherent scatter radars, multistatic meteor radars, additional high frequency radio wave propagation experiments, all sky imagers, Fabry-Perot interferometers, ground-based VLF receiver, a high density network of GNSS TEC receivers, and other appropriate instrumentation developed by the community. Complementary small satellite missions should also be considered within the overall Geophysical Observatory framework. The scientific motivation for this expanded instrumentation network and associated measurement requirements are summarized below in Table 1.

Table 1 : Science Traceability Matrix for a Wallops Island Geophysical Observatory	
Category: Plasma Instabilities at Mid-Latitudes	
Specific Questions	Measurement Requirements
Which instabilities are dominant in the midlatitude ionosphere? Gradient Drift? Temperature gradient? (modified) Perkins Instability?	Gradient scale sizes of electron density, electron and ion temperature
What are the sources of free energy for the instabilities?	ISR and coherent radar observations in common volumes; in situ observations of plasma parameters
What role does E-F coupling play in the generation of plasma instabilities?	Common volume coherent radar observations and simultaneous E- and F-region ISR observations along similar magnetic flux tube
Category: Mid-Latitude Sporadic E	
What is the connection between midlatitude sporadic E and traveling ionospheric disturbances?	Nearly simultaneous observations of electron density in the E- and F-region, along a similar magnetic flux tube. Ionosonde observations of sporadic E.
What are the relative roles of the plasma instability and neutral instabilities in the generation of sporadic E?	Observations of ionospheric state parameters and in situ neutral wind and electrodynamics. Mesoscale meteor radar observations of neutral winds.
What are the characteristics of the wind shears associated with sporadic E?	ISR observations of E-region electron density, coherent radar observations of common E-region volume, and in situ rocket observations of neutral winds.
Category: Traveling Ionospheric Disturbances	

What is the relative role of atmospheric gravity waves versus instability processes (Perkins instability) in the generation of traveling ionospheric disturbances (TIDs)?	ISR observations of F-region electron density regionally and near rocket trajectory, colocated ionosonde observations, in situ observations of neutral winds and electrodynamics. Mesoscale meteor radar observations of neutral winds.
Does the response observed in the electron density correspond to an externally driven response or a response caused by an instability?	ISR observations of F-region electron density regionally and near rocket trajectory, colocated ionosonde observations, in situ observations of neutral winds and electrodynamics
What is the connection between TIDs and TADs (traveling atmospheric disturbance) and the impacts on the upper atmosphere?	ISR observations of F-region electron density, plasma drift, F region neutral winds
Category: Subauroral Polarization Streams (SAPS)/Subauroral Ionization Drifts (SAID)	
What is the vertical structure of a SAPS/SAID?	ISR observations of the F-region of electron density, plasma drifts and ion temperature; in situ observations of plasma parameters including electric fields and ion temperatures
What plasma instabilities are associated with a SAPS/SAID channel?	ISR observations of the F-region of electron density, plasma drifts and ion temperature; in situ observations of plasma parameters including electric fields and ion temperatures. Regional observations of electron density gradients.
Category: Storm Response of the mid-latitude ionosphere	
How does a penetration electric field affect the vertical plasma density structure?	ISR observations of regional plasma drifts; in situ observations of plasma parameters including electric fields.
What are the dependencies that exist between plasma instabilities and enhancements due to stormtime effects?	ISR observations of regional plasma drifts; in situ observations of plasma parameters and composition measurements.
What is the role of the midlatitude thermosphere in high latitude-low latitude coupling during storm time?	ISR observations of the ionosphere conditions; neutral wind and temperature measurements
Category: Ionospheric variability and impacts on radiowave propagation	
What is the connection between lower	Mesoscale meteor radar observations of

atmospheric forcing and ionospheric variability during quiet-times and disturbed conditions? What impact does this variability have on radiowave propagation?	neutral winds; ISR observations of electron densities and plasma temperature; in situ observations of electrodynamics; HF radar and ionosonde observations of the electron density; ground-based VLF observations of D-region response to solar and geomagnetic activity
What are the characteristic scale sizes of ionospheric variability? Does ionospheric variability have a longitudinal dependence, beyond typical diurnal variability?	ISR observations of electron densities; in situ observations of electrodynamics; HF radar and ionosonde observations of the electron density
What is the response of the electron density over land versus over the ocean? Do effects from ocean waves impact the ionospheric electron density?	Mesoscale meteor radar observations of neutral winds; ISR observations of electron densities; in situ observations of electrodynamics; HF radar and ionosonde observations of the electron density
Category: Non-traditional Experiments	
How does the Neutral and Plasma density affect Rocket Exhaust Drive Amplification (REDA) of VLF waves? What is the impact of enhanced D-region absorption produced by artificial precipitation of radiation belt electrons from amplified VLF/whistler signals?	ISR measurements of D-region electron density near magnetic footpoint; observations from HF riometer; observations from ground-based and rocket-borne VLF receivers; ionosonde observations. In situ observations of electromagnetic fields.
What is the ambient plasma density and plasma drift velocity during a chemical release experiment? What field aligned irregularities are produced by the chemical release?	ISR observations of electron density, ion drifts, and ion temperatures. Coherent scatter radar observations along common volume; in situ observations of plasma parameters.
What is the ambient plasma density at the altitude of satellites in low earth orbit? What is the impact of plasma waves on radar tracking of space debris?	ISR observations of electron density, ion drifts, and ion temperatures. Coherent scatter radar observations along common volume; in situ observations of plasma parameters.
How do large rockets (e.g. Antares) launched from WFF affect the atmosphere and ionosphere?	ISR observations of waves in the ionosphere, Lidar wind measurements, coherent scatter