1.12 DASI: DISTRIBUTED ARRAYS OF SMALL INSTRUMENTS FOR SPACE WEATHER RESEARCH

John C. Foster
MIT Haystack Observatory, Westford, Massachusetts

1. INTRODUCTION

Recent ground-based upper-atmospheric research has revealed space weather storm fronts which sweep across the Americas during strong geomagnetic disturbances. Mesoscale and spatially and temporally localized processes and effects play a significant role in the interconnection between the high-altitude magnetosphere and Earth's ionosphere and lower atmosphere. In order to address the physical causes and characteristics of such space weather phenomena, a means of providing high spatial and temporal resolution observations of Earth's upper atmosphere is needed. In recognition of this need, the NAS Solar and Space Physics Decadal Survey has recommended that the next major ground-based instrumentation initiative for space science research be the deployment of widely-distributed arrays of small instruments. Analogous to the meteorological arrays which support terrestrial weather research, modeling, and predictions, space weather arrays will provide continuous real-time observations of Earthspace with the resolution needed resolve mesoscale phenomena and their dynamic evolution. Ground-based DASI instrumentation will address the need for observations to support the next generation of space weather data-assimilation models and will push our understanding of the physical processes which interconnect the spheres of Earthspace to a new level. Planning for the deployment of DASI will involve the development of miniaturized and robust instruments and instrument clusters and the ability to communicate with them in real time and to distribute their data to a wide variety of users.

The NAS Committee on Solar and Space Physics (CSSP) has undertaken a study of the scientific underpinnings for the development of such arrays, the infrastructure needed to support and utilize them, and an implementation plan for their deployment. Community input has been solicited and a workshop to address the scientific goals and issues involved in DASI has been held in mid 2004. A CSSP workshop report is in preparation, whose emphasis will be the scientific motivation for DASI. Input from and collaboration with the meteorological community is sought as the space weather community develops its plans for distributed arrays of small instruments.

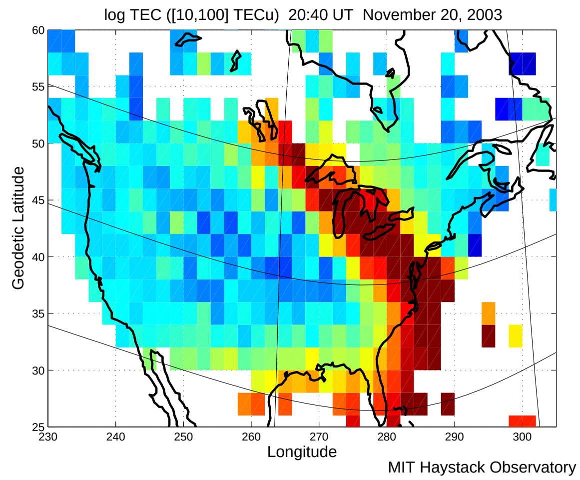

Figure 1. Distributed observations of GPS TEC depict the intense storm-enhanced density plume which can form at mid latitudes during major disturbances.

2. SPACE WEATHER AND DASI: AN EXAMPLE

During geomagnetic storms, sharply-increased total electron content (TEC) can occur at mid latitudes, over continental North America (cf. Figure 1). Based on Millstone Hill radar observations, Foster (1993) first described the continuous plumes of SED at the equatorward edge of the main ionospheric trough. Steep density gradients [Vo and Foster (2001)] are formed along the edges of the SED plumes and these are responsible for adverse Space Weather effects on both navigation and communications systems.

Storm-induced electric fields penetrate the inner magnetosphere where they uplift and redistribute the plasma of the low-latitude ionosphere. Eastward electric fields near dusk produce a poleward displacement of the equatorial anomalies (EA) and enhancements of TEC in the post-noon plasmasphere and mid-latitude ionosphere. Strong magnetospheric electric fields are generated as storm-injected energetic particles fill the enhanced ring current. These SAPS (subauroral polarization stream) electric fields [Foster and Burke (2002)] erode the plasmasphere boundary layer [Carpenter and Lemaire (2004)], producing plasmaspheric drainage plumes which carry the high-altitude material towards the dayside magnetopause [Foster et al. (2004)]. The near-Earth footprint of the plasmaspheric erosion events is seen as the mid-latitude streams of storm-enhanced density (SED) which sweep poleward across the North American continent [Foster et al. (2002)]. These processes produce storm fronts of dense thermal plasma which extend continuously from low latitudes into and across the polar regions.

2.1 *Distributed-Array Observations of Space Weather Storm Fronts*

Considerable effort has been expended in addressing the space weather problems of the dynamic atmosphere-space interface. The expanding network of GPS TEC receivers in the US sector has provided an important example of the use of distributed small-instrument arrays to capture the extent and dynamics of ionospheric Space Weather disturbances. In this instance, the effects of the dynamic atmosphere-space interface, namely the ionospheric plasma variability, present the single largest source of error in global positioning when using affordable single-frequency GPS receivers.

A network of more-costly dual-frequency GPS receivers has been globally deployed to support high precision geodetic and geophysical measurements, particularly for the study of earthquake hazards, tectonic plate motion, plate boundary deformation, and meteorological processes. These same receivers can be utilized to measure the ionospheric total electron content (TEC). Using WWW-accessible data from these GPS arrays, the ionospheric research community, for the first time, has been able to describe the extent and severity of stormtime ionospheric variability.

Figure 1 presents observations of the intense increase in TEC over the continental US and concurrent erosion plume of storm enhanced density imaged by an array of greater then 450 North American GPS receivers during the November 20, 2003 superstorm. TEC gradients and associated scintillations during this event led to widespread Space Weather outages in communications and navigation systems. TEC gradients of ~ 100 TECu/deg latitude were associated with the SED plume shown in Figure 1. GPS TEC observations have been used to analyze a number of similar space weather events as reported by Foster et al. (2002; 2004) and Coster et al (2003).

The satellites of the GPS constellation are in 12-hr circular orbits with orbital inclination ~55˚. The GPS satellites have apogee near 20,000 km (L~4) and the vertical TEC determined is the combined contribution of the ionosphere and overlying plasmasphere. In the above examples of the use of DASI-type techniques to address Space Weather concerns. The existing array of distributed ground-based GPS receivers provides the means of mapping the overlying ionospheric perturbations in near real time. DASI would field both widespread and regionally-concentrated arrays of clustered instruments to provided needed data, spatial coverage, and real-time monitoring across the coupled spheres of geospace research.

3. DASI WORKSHOP COMMON THEMES

Sponsored by the NSF and coordinated by the NRC/CSSP, a DASI Working Group meeting was held at Woods Hole, MA in June 2004. Representatives of the thermosphere, ionosphere, magnetosphere, and solar-heliosphere research communities discussed the scientific underpinnings of the distributed small instruments program described in the NRC Space Physics Decadal Survey [NRC (2003)]. A number of recurrent themes arose during these discussions.

3.1 *Insufficient Observation*s

Observational space physics is data-starved, producing large gaps in our ability to both characterize and understand important phenomena. This is particularly true for Space Weather events, which often are fast-developing and dynamic, and extend well beyond the normal spatial coverage of our current sensor arrays. A strong motivation for DASI is to provide the wide-ranging, continuous, high-resolution datasets needed to guide the development of theory and models which will better describe and predict the characteristics and dynamics of Earth's space environment. Low-cost instrumentation, widely deployed and running continuously, can provide the spatial and temporal coverage needed to capture the evolution and characteristics of the weather in geospace.

3.2 *Geospace as a System*

Geospace processes involve significant coupling across atmospheric layers and 'altitude boundaries', as well as coupling across multiple scale sizes from global (1000s km), to local (10s km), to micro-scale (meter-scale and smaller). Many of the associated phenomena have been studied extensively - but often at a sub-system level. It has become apparent that a systems approach - addressing geospace as a coupled whole - is needed to make significant progress in understanding the space weather environment. A combination of the multiple points of view provided by clustered DASI instruments will give greater understanding than the individual measurements taken in isolation.

Section 2, above, described the system-wide Space Weather significance of the prompt global effects of disturbance electric fields and the redistribution of thermal plasmas in the ionosphere and magnetosphere. An appreciation of geospace as a system also indicates that continuous long-term distributed measurements are needed to advance our understanding of the coupling of the neutral atmosphere and the overlying space environment. We cannot consider the neutral upper atmosphere in isolation - the thermosphere-ionosphere are symbiotically connected. The neutral upper atmosphere is also profoundly affected by the lower atmosphere (dynamical coupling via planetary waves, tides, gravity waves). An unanswered question is the extent to which the quiescent global variability pre-conditions the thermosphere-ionosphere response to space weather events.

DASI should provide both the coordinated multi-technique observations needed to characterize these intercoupled processes simultaneously, and a means of digesting and disseminating this information to a variety of users. The multiple scale sizes involved suggest that a variety of DASI instrument array configurations will be needed.

3.3 *Real-Time Observations*

The magnetosphere-ionosphere-thermosphere (M-I-T) system is a highly dynamic, coupled, and nonlinear system that can vary significantly from hour to hour at any location. The coupling is particularly strong during geomagnetic storms and substorms, but there are appreciable time delays associated with the transfer of mass, momentum, and energy between the different domains. It is now becoming clear that a significant fraction of the flow of mass, momentum, and energy in the M-I-T system occurs on relatively small spatial scales and over a wide range of temporal scales. Consequently, the elucidation of fundamental coupling processes requires continuous real-time measurements from a distributed array of diverse instruments as well as physics-based data assimilation models. The DASI initiative will establish the required program.

The ionosphere routinely causes Space Weather disturbances including satellite communications denial, GPS navigation errors and outages, and tracking inaccuracuries for space objects. Space weather nowcasting involves monitoring and modeling a distributed, structured, and highly variable medium. Whereas a basic understanding of physical processes can be derived in detailed post processing of the observational data sets, Space Weather forecast and nowcast requirements indicate a real need for real-time data and the means to communicate them promptly to the user.

4. SIGNIFICANCE OF DASI INITIATIVE

DASI is the culmination of decades of discipline-related local instrument development that pursued science at the sub-system level. With the advent of the internet and affordable high speed computing, these local deployments can become elements of a global instrument. When different instrument techniques are then combined to observe all aspects of the system, the DASI concept is realized. DASI presents the opportunity to build an observational network which is capable of addressing fundamental questions about the dynamics and characteristics of our geospace environment.

DASI will complement and extend the capabilities of the next generation of space-based research and Space Weather instruments by providing a global context within which to understand in-situ and remote sensing observations (cf. Immel et al. (2004)).

DASI science will be the proving grounds for the next generation of space scientists and the new breed of atmospheric-space researchers. The multiple parameter and global distribution of these data streams will challenge our ingenuity to view the atmosphere-space interface as a coupled inhomogeneous single system. The dynamic couplings in this global system are not understood, although their consequences are significant. For example, the Sun drives the Earth's atmosphere and near space environment, but to what extent the lower atmosphere's dynamics modifies or tunes the atmosphere-space interface remains unknown. The magnetosphere causes geomagnetic storms that drive the ionosphere-thermosphere, but to what extent the ionosphere-thermosphere pre-conditions the magnetosphere for its storage and release of energy is still to be discovered. None of these couplings or feedbacks are local but, more precisely, they reach across the system boundaries connecting regions from low to high latitudes and altitudes between the mesosphere, the thermosphere, the ionosphere, the plasmasphere, and the magnetosphere. This system is coupled electrically, energetically, as well as by mass flows.

DASI addresses these outstanding voids of knowledge by simultaneously measuring the key parameters, both the drivers and state variables, on the global scale. Composed of many and varied distributed instruments, DASI becomes a single instrument that generates a single data steam. Such observations will challenge our best researchers, but hold the key to resolving the physics of the dynamic atmosphere-space interface.

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