Global Ionosphere-Thermosphere-Mesosphere (ITM) Mapping Across Temporal and Spatial Scales

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Overview

In order to fulfill the pressing need for accurate near-Earth space weather forecasts, it is essential that future measurements include both temporal and spatial aspects of the evolution of the ionosphere and thermosphere. A combination of high altitude global images and low Earth orbit altitude profiles from simple, in-the-medium sensors is an optimal scenario for creating continuous, routine space weather maps for both scientific and operational interests. The method presented here adapts the vast knowledge gained using ultraviolet airglow into a suggestion for a next-generation, near-Earth space weather mapping network.

Why the Ionosphere, Thermosphere, and Mesosphere?

The ionosphere-thermosphere-mesosphere (ITM) region of the terrestrial atmosphere is a complex and dynamic environment influenced by solar radiation, energy transfer, winds, waves, tides, electric and magnetic fields, and plasma processes. Recent measurements showing how coupling to other regions also influences dynamics in the ITM [e.g. Immel et al., 2006; Luhr, et al, 2007; Hagan et al., 2007] has exposed the need for a full, three-dimensional characterization of this region. Yet the true level of complexity in the ITM system remains undiscovered primarily because the fundamental components of this region are undersampled on the temporal and spatial scales that are necessary to expose these details.

The solar and space physics research community has been driven over the past decade toward answering scientific questions that have a high level of practical application and relevance. The result of that focus has been the proliferation of research captured under the heading of “space weather.” This phrase is chosen intentionally to highlight the commonality between space physics research and the focused effort of the meteorological community to make weather forecasting comprehensive, accurate, and accessible. Similar to how weather measurements and forecasts affect our daily lives, there also is a need for space weather measurements to inform missions, operations, and assets in the near-Earth space environment that facilitate modern life.

Current measurements are able to connect solar system events to isolated changes in the three-dimensional volume of the near-Earth space weather environment. The understanding of how that connection evolves in space and time is lost as sensors move away from the initial perturbation. Similar problems have been resolved in other areas of solar-terrestrial research. In particular, the solar community has developed results and advances in temporal and spatial imaging of the Sun and its upper atmosphere all the way to Earth. Yet our understanding of ITM space weather, which is needed to connect those solar and interplanetary phenomena to terrestrial effects, is still in its infancy. Recent measurements and models have helped, but to reach the maturity on par with successful meteorological forecasts for rain, wind, and temperature, space weather requires significant, long-term commitment to making the measurements that track the development of the ITM system across temporal and spatial scales to rigorously expose the changes of this medium through which spacecraft, both manned and unmanned, must traverse. With a futuristic vision toward routine travel in the space environment, these forecasts must become as comprehensive, accurate, and accessible as the weather maps of today.

Measurement Approach

There are a wide variety of methods for mapping the ITM system. The measurement concept put forth in this document suggests a two pronged attack to filling the deficiency in making routine space weather maps: (1) a comprehensive, rapid global imaging system from geosynchronous or other high-altitude orbit, and (2) a complement of small, low-Earth orbiting sensors to provide the third dimension for contextual interpretation of the global images. In order to provide the global coverage, a remote sensing technique from a space-based platform is essential. Current data from recent remote sensing missions such as the NASA Thermosphere Ionosphere Mesosphere Energetics and Dynamics (TIMED) mission demonstrate the current state-of-the-art capability. These sensors make measurements of strips of the ITM system over the course of a day that are meshed together to create a global map as the Earth rotates under the satellite orbital plane. At the orbital period of 90 minutes, the sampling rate is not sufficient to properly address changes in the global ITM environment that occur on timescales as small as a few minutes. In addition, the spatial sampling also is limited by orbit characteristics as 15 orbits per day distributed around the globe yield effective zonal sampling of more than 20 degrees. Thus these types of maps are effectively a composite of temporal and spatial changes but produce the illusion of a global measurement. While the data are representative of the high-quality measurements and results that can be achieved, they must be interpreted in the context of various models that are available. Only a combination of comprehensive, dedicated spatial and temporal imaging can provide the same rigor in space weather maps as that found in the meteorological community.

The technique of using ultraviolet (UV) airglow for remote sensing of the ITM is a strong tool for providing the measurements necessary to meet the needs proposed in this document. The UV spectral range from 10-400 nm has many emissions that tie directly to the constituents of the upper atmosphere [Meier, 1991], and background contamination is extremely low in most cases due to absorption of these emissions in the lower atmosphere below 100 km. Indeed, many discoveries about the composition, temperature, and dynamics across the ITM have been made using UV airglow. However, these missions have historically been single-sensor missions that, while continually providing new information about the state of the ITM, are not configured to discern temporal from spatial changes. A sensor suite unifying global and local measurements would work together to provide the imagery necessary to provide routine space weather maps of the ITM system at temporal and spatial resolutions necessary to meet the needs of future users. There are many well-developed alternate techniques for monitoring the ITM and these data will continue to provide complementary information for comparison. However, without delving into the many strengths and weaknesses of these numerous alternate approaches, the combination of UV sensors provides the most complete, proven technique for meeting the comprehensive requirements for measurements that are needed.

First, a global UV imager would provide the means to characterize the temporal changes in the global ITM system, including its response to solar and geomagnetic activity. This sensor could be placed in geosynchronous orbit, at a Lagrangian vantage point, or even on the Moon, with the capability to provide high temporal resolution disk imaging to expose the cadence of the response of the whole ITM system, on timescales of the order of a few minutes. Fittingly, this imager will be a modern implementation of the far ultraviolet camera flown to the Moon during the Apollo 16 mission [Carruthers and Page, 1972, 1976] that demonstrated for the first time the possibility of obtaining such a global ITM image, including auroras, the ionospheric tropical arcs, and even the hydrogen geocorona. This concept was taken to the next level when DE-1 returned over a half a million images of the ultraviolet airglow and aurora, exposing many new surprising results [see Frank and Craven, 1988]. Spectroscopic techniques have advanced significantly since then but no mission has yet been designed to take advantage of this capability. To achieve the desired resolution and cadence for the next generation might require additional innovation in optics and sensor development and the data volume will be large, but the return on investment will be substantial.

Second, small UV sensors will provide essential, targeted information to further define the changes to the IT system on all scales. This is a necessary complement to provide the spatial aspects not resolved with global imaging. Much like local Doppler radar enhances satellite imagery for meteorological purposes, these smaller “field” sensors would provide the second half of this imaging suite. The ITM volume, and the coupling, has important structure in all three dimensions and the users of this information occupy the entire volume. These sensors are an essential cog to put the large-scale maps into context with the vertical structure and interaction that also defines the system. While functionally they would be similar to those already flying on current missions, it is necessary to update these current sensors to meet added demands. A handful of sensors in orbits at key local times would be required to appropriately complement the global images. Naturally a larger fleet would produce an even better data product, so with the high demand for access to space it is beneficial to take advantage of innovative optical designs that improve the possibility of incorporating a sensor into available slots on any mission. Small-scale sensors have already been developed for high-sensitivity UV measurements of the ITM system from a relatively small package [e.g. Cotton, et al., 1994, 2000]. These Limb-imaging Ionospheric and Thermospheric EUV Spectrographs (LITES) use a simple optical design with a single optical element to obtain high-sensitivity limb profiles of EUV and FUV emissions. Low-cost, light-weight, high-sensitivity sensors like LITES would be an ideal complement to the flagship global UV imager.

Application to Science and Society

The measurements obtained by this UV sensor suite would be complementary to many other areas of NASA research. The images would provide key details about the propagation of solar events once they reach the terrestrial atmosphere. Images that extend from the surface of the Sun out into the coronal region and into the near-Earth region are now routinely collected. Likewise, the lower atmosphere receives routine coverage from missions that map changes in the composition as they affect life on Earth. A similar effort has not yet been initiated for the upper atmosphere of Earth where the impacts of these events are realized. The ITM, while effectively ignored in comparison to these two other high-profile areas of study, must now be considered on par with these other solar-terrestrial regions as global lifestyles depend on satellites and space-based platforms for communication and information transfer, and space travel and tourism rapidly raises the commercial and social relevance of this region. This importance is even recognized by the American Meteorological Society that recently added a Space Weather section to its portfolio, in part because of the impact space weather has on transpolar airline flights, the ubiquitous applications for Global Positioning Satellites, and the lifetime and risk assessments for satellites and all space-based assets. The cost to replace these resources, the timeline for development of these replacements, and the inability to easily access these resources for repair, all make the ITM region an equally compelling region to add a routine monitoring capability. While either the global disk imager or the suite of smaller local sensors alone would provide significant gains toward filling this data void, the combination provides an exponential gain that cannot be matched.

References

1. Carruthers, G. R. and T. Page [1972], Apollo 16 far-ultraviolet camera/spectrograph: Earth observations, *Science*, **177**, 788.

2. Carruthers, G. R. and T. Page [1976], Apollo 16 far-ultraviolet imagery of the polar auroras, tropical airglow belts, and general airglow, *J. Geophys. Res.*, **81**, 483.

3. Cotton, D. M., T. Cook, and S. Chakrabarti [1994], A single element imaging spectrograph, *Appl. Opt*., **33**, 1958.

4. Cotton, D. M., A. Stephan, T. Cook, J. Vickers, V. Taylor and S. Chakrabarti [2000], TESS: The tomographic EUV spectrographs, *Appl. Opt*., **39**, 3991.

5. Frank, L. A., and J. D. Craven [1988], Imaging results from Dynamics Explorer I, *Rev. Geophys*., **26**, 249.

6. Hagan, M. E., A. Maute, R. G. Roble, A. D. Richmond, T. J. Immel, and S. L. England [2007], Connections between deep tropical clouds and the Earth's ionosphere, *Geophys. Res. Lett*., **34**, L20109, doi:10.1029/2007GL030142.

7. Immel, T. J., E. Sagawa, S. L. England, S. B. Henderson, M. E. Hagan, S. B. Mende, H. U. Frey, C. M. Swenson, and L. J. Paxton [2006], Control of equatorial ionospheric morphology by atmospheric tides, , *Geophys. Res. Lett*., **33**, L15108, doi:10.1029/2006GL026161.

8. Luhr, H. K., C. Hausler, and C. Stolle [2007], Longitudinal variation of F region electron density and thermospheric zonal wind caused by atmospheric tides, *Geophys. Res. Lett*., **34**, L16102, doi:10.1029/2007GL030639.

9. Meier, R. R. [1991], Ultraviolet spectroscopy and remote sensing of the upper atmosphere, *Space Sci. Rev*., **58**, 1-185.