

Winds at the Edge of Space

In that section of space closest to the Earth but some 100 km in altitude, known as geospace, powerful winds and a complex of physical, chemical, and electromechanical phenomena dominate a dynamic region through which we travel, navigate, and communicate. Geospace winds (from a hurricane force 100 m/s to an incredible 800 m/s), in particular, can alter satellite trajectories and induce ionospheric electric fields, making an understanding of those winds of high value. This article explains what we know about geospace wind and describes the Naval Research Laboratory activities aimed at improving modeling of geospace winds and in developing new sensors to illuminate this important geospace parameter.



Wind at the Top of the Atmosphere

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At an altitude of 100 km (62 miles), above 99.99997% of the atmospheric mass, pilots and passengers become astronauts. This altitude can be defined as the lower boundary of geospace. The notion that the space around our planet is vast and empty, however, is far from true. In fact, this environment, in which the satellites that we rely on for communication and navigation operate, can vary significantly on short time scales and is governed by complex physical, chemical, and electromechanical phenomena. One such phenomenon is wind. Wind in geospace alters satellite trajectories and induces ionospheric electric fields. Typical wind speeds are 100 m/s (greater than those of a category 5 hurricane) and can reach up to 800 m/s during geomagnetic storms. In this article, we review what we know about wind at the top of the atmosphere, and we describe Naval Research Laboratory activities in improved modeling and the development of new sensors that are shedding more light on this basic geospace parameter.

WHAT DRIVES GEOSPACE WINDS?

The wind we experience near the Earth's surface is primarily driven by gradients in air pressure and is steered by the Coriolis force. These two forces also shape wind patterns in the thermosphere (above 90 km), where large, solar-driven day–night differences in temperature (and thus pressure) create wind speeds of ~100 m/s that diverge from the subsolar region and converge on the nightside, as shown in Fig. 1. However, other, more complex forces also drive thermospheric winds and create unique modeling challenges. First, atmospheric waves and tides propagate up from the lower atmosphere to produce thermospheric wind variations on kilometer scales to global scales; semidiurnal oscillations in the lower thermosphere (~90 to 180 km) are a prominent consequence of this connection with the lower atmosphere. Second, as the atmosphere becomes thinner with increasing height above 100 km, its viscosity becomes very large (due to the increase in mean free path), thereby inhibiting vertical gradients and dissipating upward-propagating waves. Finally, the motion of the ionized portion of the thermosphere (the ionosphere) is constrained by geomagnetic and electric fields. Collisions between ions and neutrals can thus

act as either a retarding force or a driver of the neutral wind. The latter behavior occurs most dramatically at high latitudes, where strong electric fields (generated by the interaction between the solar wind and Earth's magnetosphere) drive a polar convection pattern of ions, which in turn spins up the neutral wind. During severe geomagnetic storms, such as the one that occurred in October 2003, shortly after solar maximum, thermospheric wind speeds in excess of 800 m/s were observed.

WHY STUDY GEOSPACE WINDS?

In addition to being a basic environmental parameter, accurate knowledge of thermospheric winds is important for at least two critical civil and military applications: radio wave propagation and satellite orbit prediction.

Winds induce a complex pattern of electric fields and currents in the ionosphere because of the motion they impart to ions and electrons relative to the geomagnetic field. As the “equatorial plasma fountain” in Fig. 2 illustrates, these electric fields fundamentally shape the total amount and distribution of ionization, which in turn affects the propagation of radio waves

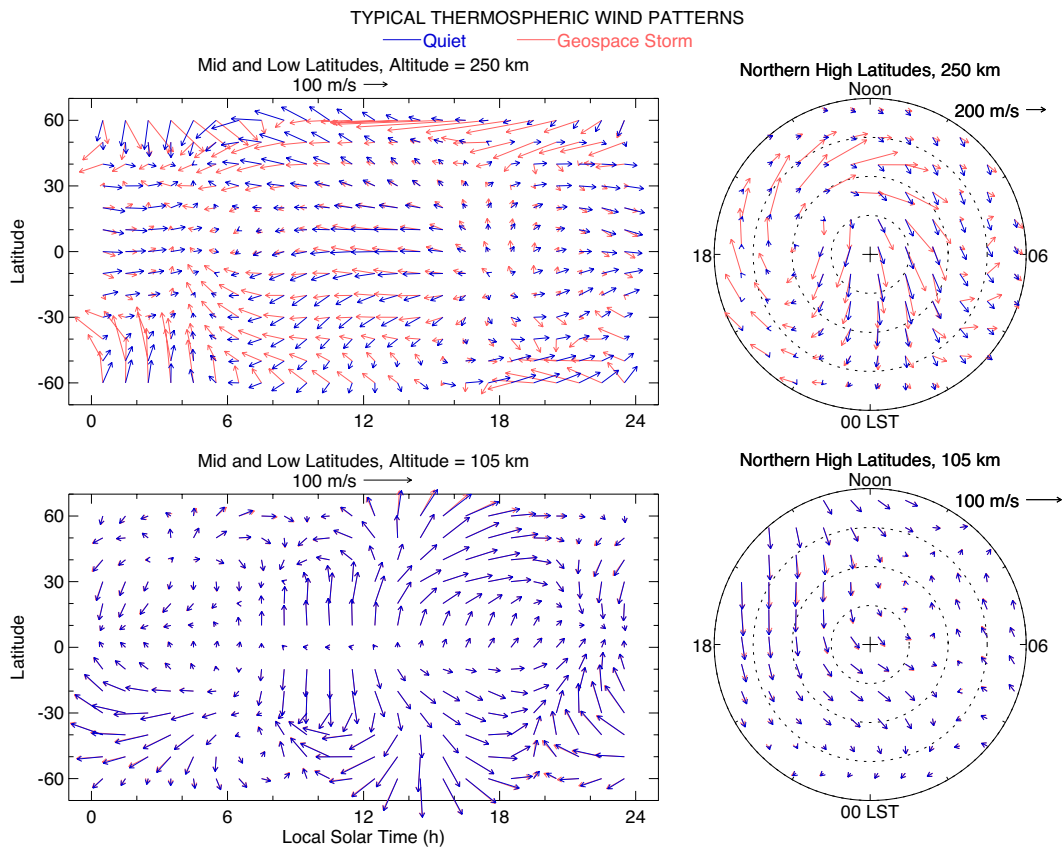


FIGURE 1 Typical wind patterns in the lower thermosphere (bottom panels) and upper thermosphere (top panels). The left panels show winds at mid and low latitudes, and the right panels show winds over the northern polar region (the outer ring is 50°N). Blue arrows show patterns under quiet space weather conditions; red arrows show typical patterns during fairly strong (Kp index of 7) geospace storms. The winds shown are from NRL's Horizontal Wind Model (HWM07).

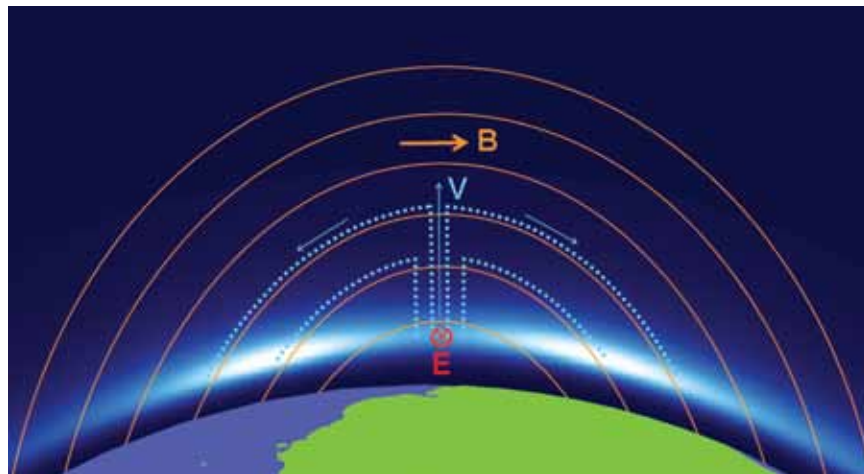


FIGURE 2 The equatorial plasma fountain: an example of how winds influence the distribution of ionization. Wind in the lower thermosphere induces an eastward electric field (E) near the geomagnetic equator. This field, combined with the southward geomagnetic field (B), causes ions and electrons to drift upward (V) to high altitudes. From there, the plasma diffuses downward, under the influence of gravity, along magnetic field lines, creating regions of enhanced ionization ~15° away from the equator. The blue shading in the figure represents low (dark blue) to high (white) ion densities.

incident on the ionosphere. For example, the ionosphere typically causes a phase delay in GPS signals that amounts to a range error of several meters; wind-induced electric fields cause this range error to vary by ~50% to 100%. Neutral winds can also create and trigger ionospheric instabilities and irregularities, which scatter radio waves and render portions of the radio wave spectrum useless for communication.

The thermosphere exerts a drag force that is the largest source of uncertainty for the prediction of satellite trajectories in low Earth orbit. Since the direction of drag is along the relative motion between the satellite and atmosphere, winds are a key variable for predicting orbital paths and reentry times and locations, particularly for satellites with large surface areas such as those with deployable solar panels. Typical wind speeds of ~100 m/s are a non-negligible 1.3% of orbital speed, increasing to 10% during severe geomagnetic storms.

Despite the importance of geospace winds, there are currently no routine operational observations of this parameter. To compensate for this deficiency, the Naval Research Laboratory's Space Science Division (SSD) is pursuing a two-pronged research and development effort.

HISTORICAL WIND MEASUREMENTS AND EMPIRICAL MODELS

The first component of SSD's effort is to compile historical measurements of geospace winds starting in the 1970s and encapsulate them into a single empirical, climatological model. This global model, known as the Horizontal Wind Model (HWM),¹ extends from the ground to 600 km altitude. HWM incorporates observations made with a wide range of techniques, including in situ satellite data, optical remote sensing data, and data from active techniques such as ground-based lidar (light detection and ranging). Figure 3 summarizes the height coverage afforded by the various methods of measuring geospace winds. HWM uses a vector spherical harmonic expansion to represent the winds as a function of altitude, latitude, local time, longitude, solar activity, and geomagnetic activity. It provides a condensed view of over a million wind observations spanning more than four decades. The most important thermospheric data set in the model is from the Wind Imaging Interferometer (WINDII), a Michelson interferometer on board the Upper Atmosphere Research Satellite (UARS) that

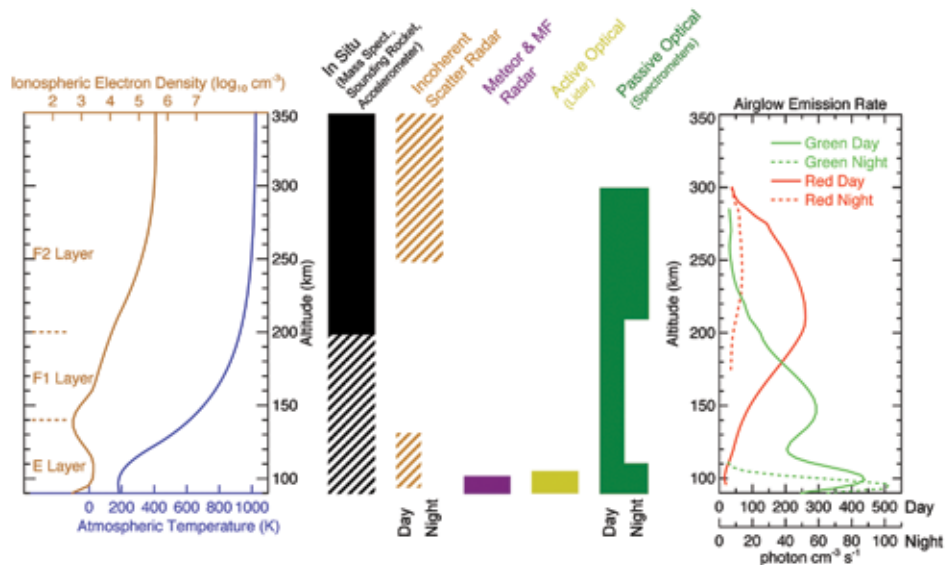


FIGURE 3

Altitudinal coverage of thermospheric wind measurement techniques. Hashed regions indicate limitations of the technique. For in situ techniques, the region below 200 km is difficult to access routinely, due to strong atmospheric drag on orbiting probes in this region. Inference of winds from incoherent scatter radars (ISRs, which probe ionospheric composition and plasma drift), requires significant physical assumptions; additionally, only the north-south component is derivable in the upper thermosphere. Meteor radars and other medium frequency (MF) radars measure winds in the lower thermosphere by tracking ionized meteor trails or ionospheric irregularities, respectively (below ~100 km, the plasma moves with the neutral wind). Passive optical techniques rely on naturally occurring airglow emissions, which are very weak at night between 100 and 200 km; consequently, little is known about nighttime winds in this region. The plot in the right panel shows typical airglow brightness profiles (from NASA's UARS/WINDII instrument) for two important emissions: 557.7 nm (green line) and 630.0 nm (red line), both of which are from atomic oxygen. The left panel shows typical electron density and neutral temperature profiles.

measured winds between 90 and 275 km altitude from 1991 to 1997.² WINDII is the only significant source of wind data in the critical ionospheric dynamo region between 110 and 200 km, and SSD's analysis and modeling of this data have greatly improved the accuracy of empirical wind predictions in this region.

SSD's analyses of wind data have also greatly advanced understanding of how geospace storms affect global wind patterns. Geomagnetic activity, caused by the interaction of the solar wind with the upper atmosphere, modifies quiet-time wind patterns in two ways. First, as mentioned above, enhanced convection of high-latitude ions spins up the neutral wind. Second, heating at high latitudes by dissipation of electrical currents creates pressure gradients that drive equatorward winds. At lower latitudes, the equatorward perturbations are steered westward by the Coriolis effect (and in the process generate an electric field known as the disturbance dynamo). These effects are quantified in HWM07, which provides the best available empirical representation of winds during geomagnetic storms. Figure 1 illustrates how the wind patterns are influenced by geomagnetic storms.

HWM07 is widely used in the upper atmospheric research community for several critical purposes: (1) as a benchmark for validating new observations and measurement techniques against past data; (2) as an initial or boundary condition for physics-based models of the atmosphere; and (3) as an a priori specification of neutral winds in ionospheric models (such as NRL's SAMI3 model of the ionosphere³) and of background winds in simulations of small-scale atmospheric waves.

Although HWM07 is an indispensable tool and probably the best available predictor of winds for specified geophysical conditions, it is not an ideal model of thermospheric weather. At a given epoch, measured winds typically deviate from climatological averages by ~30 m/s. These day-to-day and hour-to-hour fluctuations are due in part to lower atmospheric waves percolating up into the thermosphere, which can, for example, produce rapid global-scale transport of lower thermospheric constituents.⁴ To specify and forecast such fluctuations requires an assimilative model of the whole atmosphere, including the thermosphere. NRL's SSD, along with the NRL Remote Sensing Division and the NRL Marine Meteorology Division, have pioneered the development of high altitude assimilative models (e.g., Ref. 5). However, due to lack of data, these are limited to below the base of the thermosphere (~90 km). A dense network of timely observations will be needed to achieve accurate thermospheric wind forecasts, and so SSD's second component of geospace wind research has focused on the development of innovative instruments to measure winds both in situ and remotely.

NRL IS DEVELOPING NEW TECHNIQUES TO MEASURE WINDS

The NRL Space Science Division is developing two complementary, innovative types of thermospheric wind sensors for future space missions. One is an optical, remote sensing technique called DASH (Doppler Asymmetric Spatial Heterodyne) spectroscopy, which features advantages of state-of-the-art remote sensing techniques, relaxed fabrication tolerances, and reduced instrument complexity. DASH can measure winds and temperatures between ~90 and 350 km, using the Doppler shift and broadening of airglow emissions. The other sensor is an in situ instrument consisting of an extremely compact suite of instruments to measure density, temperature, neutral wind, plasma drift, and the composition of neutrals and ions. The Winds-Ions-Neutral Composition Suite (WINCS) instrument was designed and developed jointly by NRL and NASA/Goddard Space Flight Center for ionosphere-thermosphere investigations in orbit between 120 and 750 km altitude.

The DASH concept is based on the spatial heterodyne spectroscopy (SHS) technique and is optimized for the measurement of thermospheric winds.⁶ The advantages of remotely measuring winds include the capability of measuring at low altitudes (90 to 250 km) where short satellite orbit lifetimes hamper the use of in situ instrumentation. In addition, wind vector profiles can be measured over extended altitude ranges and with an altitude resolution of several kilometers.

Following the conception of the DASH technique in 2005 (U.S. Patent 7,773,229), NRL SSD led an effort that resulted in the first monolithic DASH interferometer, shown in Fig. 4(a), and the first DASH ground-based measurements of thermospheric winds.^{7,8} In 2011, NASA selected a DASH satellite instrument design (shown in Fig. 4(b)) as part of the Ionospheric Connection Explorer (ICON) mission proposal led by the University of California, Berkeley, for a detailed mission study and potential 2013 selection for flight as a NASA Explorer mission.

The WINCS design (U.S. Patent Application 13/247,168) is shown in Fig. 5 and features extremely small size ($7.6 \times 7.6 \times 7.1$ cm), low weight (0.75 kg total mass), and low power (about 2.0 W). The true benefit of WINCS is the ability to measure space weather parameters with an extremely small and low-cost instrument that could be flown on almost any spacecraft, e.g., as the primary instrument on a nanosatellite or as a secondary instrument on a much larger spacecraft. Utilizing WINCS in this way will allow multipoint measurements of the ionosphere-thermosphere (IT) system, resulting in more complete data sets. The most effective employment of WINCS would be on an IT

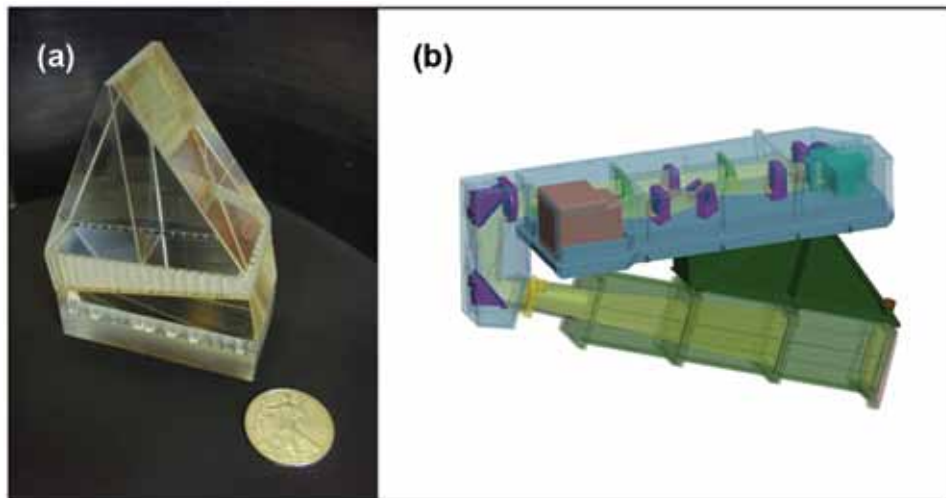


FIGURE 4

(a) The first monolithic DASH interferometer. This interferometer was successfully used for ground-based thermospheric wind observations in preparation for future satellite applications. (b) Instrument concept for a space-based, remote-sensing instrument using the DASH technique to measure altitude profiles of thermospheric wind and temperature.



FIGURE 5

The WINCS payload (7.6 cm × 7.6 cm × 7.1 cm) for the SENSE program (top cover removed).

constellation mission, which would revolutionize our understanding of the IT system dynamics. Such a constellation would test our ability to simulate the dynamics of the ionosphere and thermosphere on a global scale. The WINCS instrument is manifested on four upcoming flights over the next two years: the U.S. Air Force's Space Environment Nano-Satellite Experiment (SENSE, a CubeSat), two Department of Defense Space Test Program (STP) missions supported by the Office

of Naval Research (STPSat-3, a small free-flyer satellite, and STP-H4 on the International Space Station), and the CubeSat investigating Atmospheric Density Response to Extreme driving (CADRE), a National Science Foundation CubeSat to be flown by the University of Michigan.

[Sponsored by ONR]

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THE AUTHORS



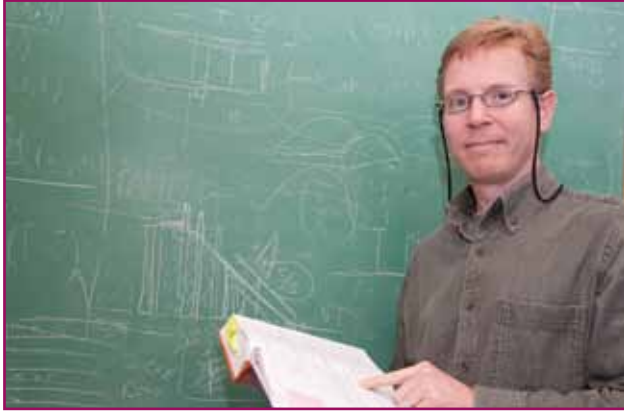
CHRISTOPH R. ENGLERT received his doctorate degree in physics from the University of Bremen in Germany in 1999. He was a National Research Council postdoctoral fellow at NRL until 2001, when he joined NRL as a research physicist. He currently serves as the branch head of the Geospace Science and Technology Branch. Dr. Englert has worked on spatial heterodyne spectroscopy instrumentation and data analysis and interpretation since 1999; for example, he was the project scientist of the SHIMMER-MIDDECK instrument, which flew on the STS-112 Space Shuttle mission in 2002, and the principal investigator of SHIMMER on STPSat-1, which was launched in 2007. Together with Dr. Harlander he is a co-inventor of the DASH technique to measure atmospheric winds. He received a NASA Group Achievement Award, a Department of the Navy Top Scientists and Engineers of the Year Award, two NRL Alan Berman Research Publication Awards, and an AIAA Space Systems Award.



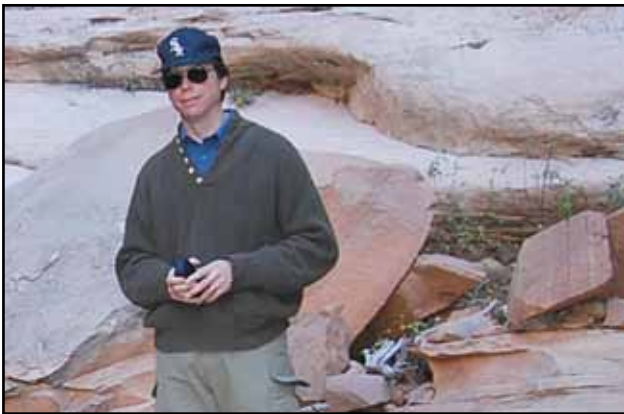
CHARLES M. BROWN received his Ph.D. in chemical physics from the University of Maryland in 1971. Since that time he has been at NRL, first as a National Research Council postdoctoral fellow, and later as a physicist in the Space Science Division. Dr. Brown's specialty is spectroscopy, and he has enjoyed over 40 years of laboratory and space flight experience involving spectroscopic instruments. He has contributed to the design, building, testing, and calibration of flight instruments including MAHRSI for STS-66 and STS-85 on the Space Shuttle, BCS on the Yohkoh satellite, and EIS on the Hinode satellite. Over the years, Dr. Brown has also conducted high resolution laboratory research on spectroscopy of atoms and high-temperature plasmas and has analyzed data from solar space experiments. Dr. Brown is currently working with SHS instruments such as REDDI and DASH to measure upper atmospheric winds.



DOUGLAS P. DROB received his B.S. in engineering physics with a minor in applied mathematics from Embry-Riddle Aeronautical University in 1991. He received his Ph.D. in atmospheric and space sciences from the University of Michigan in 1996. He joined the Upper Atmospheric Physics Branch of the Naval Research Laboratory as a National Research Council postdoctoral fellow to pursue research on ultraviolet remote sensing of the upper atmosphere. Dr. Drob was the primary developer of the next-generation HMW07 empirical thermospheric wind model, as well as a codeveloper of the NRLMSIS-00 neutral density, composition, and temperature empirical thermospheric model. Dr. Drob's research involves the computational aspects of the analysis of available satellite- and ground-based upper atmospheric observations, in conjunction with first-principles general circulation modeling, to address basic research questions and engineering challenges related to ground-to-space low-frequency acoustic propagation, ionospheric physics, and satellite drag.



JOHN T. EMMERT received a B.S. in astronomy from the University of Arizona in 1989. After serving in the U.S. Navy for several years, he earned a Ph.D. in physics at Utah State University in 2001. For his graduate research, he studied the behavior of wind patterns in Earth's thermosphere. He began working in the NRL Space Science Division as a National Research Council postdoctoral fellow, studying the long-term response of the thermosphere to increasing atmospheric concentrations of carbon dioxide, and continued this work as a research faculty member at George Mason University. He joined the Space Science Division in 2005, where his research focuses on the climate and dynamics of the thermosphere, using a variety of geophysical databases and models.



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ANDREW NICHOLAS is a research physicist in the NRL Space Science Division's Solar Physics Branch who designs, develops, characterizes, operates, and analyzes spaceflight experiments to study the thermosphere and ionosphere using both in situ and remote sensing. He is the principal investigator of the Atmospheric Neutral Drag Experiment microsatellite missions and PI of Special Sensor Ultraviolet Limb Imager sensors for the Defense Meteorological Satellite Program block of satellites. He earned his B.S. from Embry-Riddle Aeronautical University in 1991 and an M.S. in space physics from the University of Alaska in Fairbanks in 1993. In 2009 Mr. Nicholas received the Dr. Delores M. Etter Top Scientists and Engineers of the Year Award for his work on spaceflight sensors.



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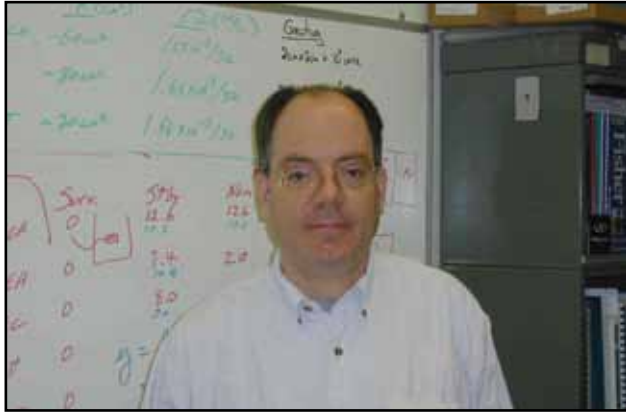


ANDREW W. STEPHAN received his M.A. and Ph.D. in astronomy from Boston University in 1997 and 2001, respectively. He received his B.S. from the University of Wisconsin with a double major in physics and mathematics in 1993. He joined NRL in 2001 first as a contractor with Computational Physics Inc. before becoming a member of the Space Science Division in 2002. His primary research interest is in the remote sensing of the composition and winds of planetary atmospheres, with an emphasis on the ultraviolet airglow and aurora produced in the terrestrial ionosphere and thermosphere. He is currently project scientist for the Remote Atmospheric and Ionospheric Detection System (RAIDS) that is operating as part of the HICO-RAIDS Experiment Payload (HREP) on the International Space Station. Dr. Stephan received the NRL Award of Merit for Group Achievement in 2009 for his work on RAIDS. He is a member of the American Geophysical Union and has served on the Science Steering Committee for the National Science Foundation (NSF) Coupling

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JOHN M. HARLANDER received his Ph.D. in physics from the University of Wisconsin-Madison in 1990. In 1991, he joined the Physics Department at St. Cloud State University (MN) where he currently holds the position of professor. Professor Harlander has been collaborating with NRL's Space Science Division on space-based remote sensing instruments for 20 years. He is co-inventor, with Christoph Englert at NRL, of the DASH technique for measuring upper atmospheric winds.



KENNETH D. MARR received his B.S. in physics from Principia College in 1999 and his Ph.D. in plasma physics from MIT in 2010. While at MIT, he worked at the Plasma Science and Fusion Center (PSFC) under the supervision of Dr. B. Lipschultz, using spectroscopy to study the edge rotation of the fusion plasmas created in the Alcator C-Mod tokamak. After graduation he worked briefly as a postdoctoral researcher and as a contractor for Fusion Research Technologies, continuing his research and optimizing the performance of the spectroscopy equipment at the PSFC. In 2011, Kenneth was awarded a National Research Council grant to join Dr. C. Englert at the Naval Research Laboratory to work on the development and characterization of Doppler Asymmetric Spatial Heterodyne (DASH) instrumentation with the ultimate goal of future spaceflight missions to measure the motion of the upper atmosphere. He is also involved in similar projects using ground-based systems to measure wind speeds and temperatures in the thermosphere.