

# Monitoring the geospace response to the Great American Solar Eclipse on 21 August 2017

Shun-Rong Zhang<sup>1\*</sup>, Philip J. Erickson<sup>1</sup>, Larisa P. Goncharenko<sup>1</sup>, Anthea J. Coster<sup>1</sup>, and Nathaniel A. Frissell<sup>2</sup>

<sup>1</sup>Haystack Observatory, Massachusetts Institute of Technology, 99 Millstone Road, Westford, MA 01886, USA;

<sup>2</sup>Center for Solar-Terrestrial Research, New Jersey Institute of Technology, 161 Warren Street, Newark, NJ 07102, USA

**Keywords:** solar eclipse; geospace effect; ionospheric observations; ionospheric radio; citizen science

**Citation:** Zhang S.-R., Erickson, P. J., Goncharenko, L. P., Coster, A. J., and Frissell, N. A. (2017). Monitoring the geospace response to the Great American Solar Eclipse on 21 August 2017. *Earth Planet. Phys.*, 1, 72–76. <http://doi.org/10.26464/epp2017011>

Since ancient times, solar eclipses have fascinated—and sometimes terrified—humankind. Solar eclipses are direct sensory experiences. As the sun vanishes from the sky, birds fall silent during the midday twilight. Modern instrumentation has enabled research into the consequences of this sudden change in irradiation within the upper atmosphere. For the first time in 26 years, a total solar eclipse occurred over the continental United States (CONUS) on 21 August 2017, passing between coastlines in the 16:00–20:00 UT period. Millions of citizens and science enthusiasts lined up from Oregon all the way to the South Carolina along the 150 km wide path of totality to witness moments of amazing surreality during this event, dubbed the Great American Solar Eclipse (Figure 1). Among them were space scientists who took advantage of the unprecedented opportunity to probe atmospheric responses to the eclipse in order to understand fundamental physical processes that link the Sun, Moon, and Earth's neutral atmosphere and ionosphere.

Observational scientists used a number of advanced tools to monitor global and regional upper atmosphere response during the 2017 eclipse. Global Navigation Satellite System (GNSS) receivers have become key ground-based sensors for studying the upper atmosphere. Observations based on dense GNSS receiver networks have revealed some important ionospheric disturbance structures, including ionospheric mesoscale perturbations originating from solar storms as well as meteorological and seismological processes. For 20+ years, scientists at the Massachusetts Institute of Technology (MIT) Haystack Observatory have produced daily global total electron content (TEC) maps with increasing data density as geodetic networks grow. Figure 2 plots the distribution of more than 2,000 GNSS receivers over the CONUS that were used by the MIT team to monitor TEC variations induced by the 2017 solar eclipse. Notice that the TEC data coverage provided by these receivers and corresponding GNSS satellites is much

more dense than the receiver density. The MIT team also set up a few additional specialized GNSS receivers along the path of totality and conducted observations with more sophisticated configurations. Some of these receivers were put in the backyard of fellow space scientists' homes. Figure 3 shows an initial analysis of the GNSS differential TEC map for 18:00 UT when the totality was located in the central US. This was derived after removing some background variations using a sliding 2-hour window. A very clear differential TEC "hole" shown as blue demonstrates obvious eclipse induced photochemical and dynamical changes. This was the first time since the start of eclipse ionospheric effect observation more than 50 years ago that clear eclipse effects were revealed over such a wide geographic region. The high-fidelity and wide-coverage ionospheric observations available for the first time for eclipse ionospheric study will help address scientific controversies regarding wave generation by the supersonic moon's shadow in the ozone layer and propagation for a few hundred kilometers upward into the ionosphere.

MIT Haystack Observatory has a long history of space science studies focusing on ionosphere and magnetosphere research. Since 1960, Haystack scientists have operated a powerful ground-based ionospheric radar, the Millstone Hill incoherent scatter radar (ISR), as a diagnostic of ionosphere conditions, measuring very weak echoes as transmitted radio waves are scattered by the ionospheric plasma. Figure 4 shows the Millstone Hill ISR's 68 m zenith antenna, which has been located on the site since the early 1960s. A highly cited study of eclipse conditions at mid-latitudes on 30 May 1984 occurred using Millstone Hill ISR, and was the last dedicated study using that instrument before 2017. This year's eclipse track caused the radar site to experience a 70% magnitude partial eclipse overhead. The radar also has a 46 m diameter fully steerable antenna, and during the eclipse passage measurements were also made toward a region that was very close to the eclipse's totality. Combined with the vertical (zenith) measurements using the 68 m antenna, Millstone Hill provided critical plasma state information for ionosphere and thermosphere studies. The Arecibo ISR in Puerto Rico, the most sensitive radar of its

Correspondence to: S.-R. Zhang, [shunrong@mit.edu](mailto:shunrong@mit.edu)

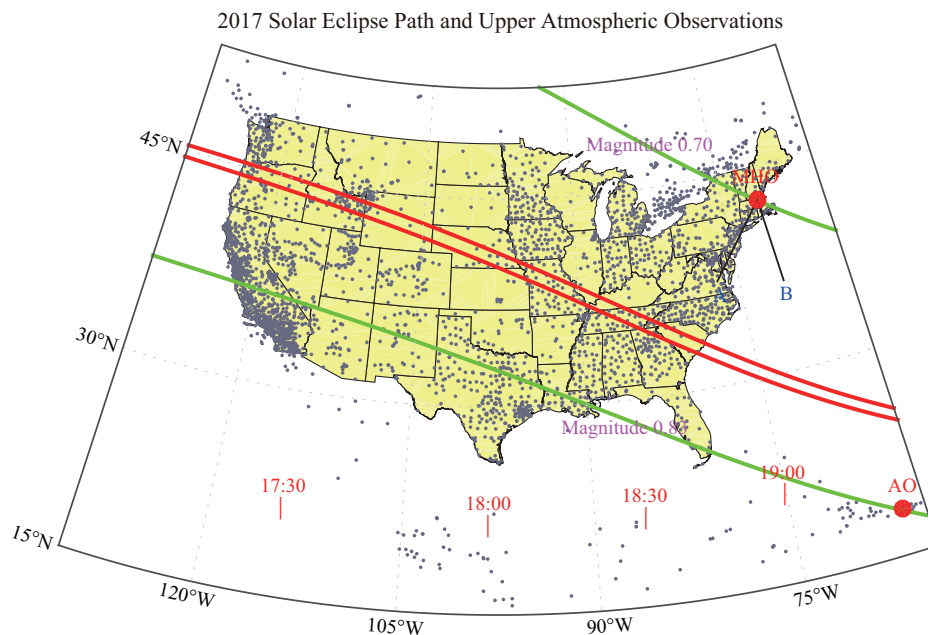
Received 07 OCT 2017; Accepted 08 OCT 2017.

Accepted article online 11 OCT 2017.

Copyright © 2017 by Earth and Planetary Physics.



**Figure 1.** Children were watching the eclipse at MIT Wallace Astrophysical Observatory in Massachusetts. Photo credit: The Sun (Lowell)/John Love.



**Figure 2.** GNSS receiver distribution across the solar eclipse zones in the continental US. Notice that the TEC data coverage provided by these receivers and corresponding GNSS satellites are much more denser than the receiver density shown here. Red lines mark the totality zone. Given also are locations of ionospheric incoherent scatter radars at Millstone Hill (Boston) and Arecibo (Puerto Rico), which are within the partial eclipse region.

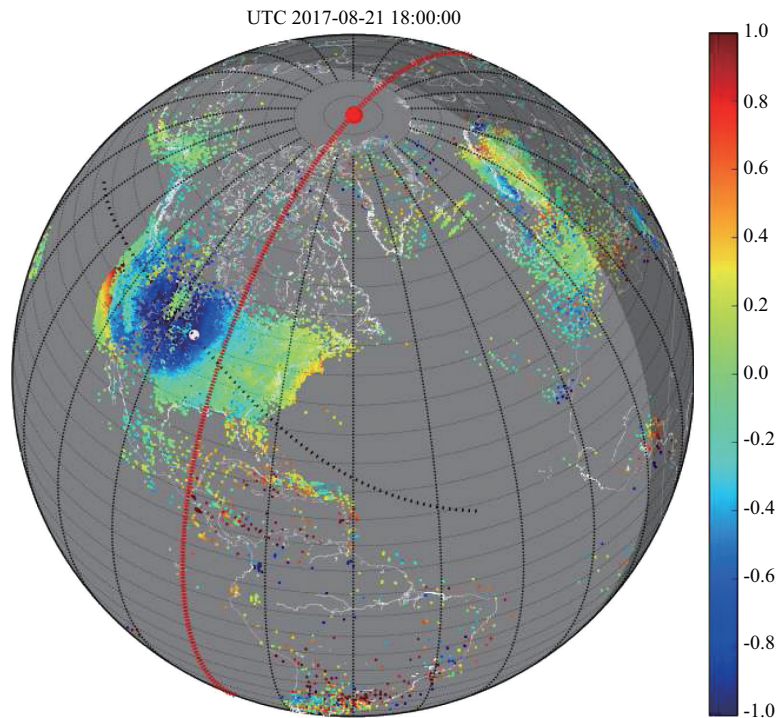
type with a 305 m diameter antenna, also participated in the eclipse observational campaign with the largest antenna system in the world for ionospheric radio remote sensing. Poker Flat ISR near Fairbanks, Alaska is located at the auroral latitude. The site experienced a magnitude of 48% partial eclipse and the ISR also conducted dedicated experiments to study high-latitude ionospheric responses.

Ionospheric radio sounding at HF frequencies is the oldest active technique for observing conditions in the upper atmosphere, having been used for nearly a century. Ionosonde observations have been used for the past 50 years to study important ionospheric physics and chemistry pathways during solar eclipses. Modern

networks of ionosondes, such as the Global Ionospheric Radio Observatory (GIRO) managed by the University of Massachusetts (Lowell), are able to provide near real-time monitoring of ionospheric conditions. Based on a report for the INAG (Ionosonde Network Advisory Group) newsletter on the 2017 solar eclipse effect, the maximum plasma frequency  $f_oF_2$  was reduced by up to 30%, and its corresponding height  $h_mF_2$  dropped by ~100 km.

A solar eclipse also significantly affects radio propagation that is dependent on ionospheric electron density structure at various heights. Radio waves in the HF bands are often used for ionospheric radars, e.g., ionosondes and the SuperDARN distributed radar network, with these frequencies strongly refracted by the E





**Figure 3.** An initial GNSS differential TEC map result for 18:00 UT, derived after removing background variations using a linear function within a 2-hour sliding window. The dotted curve represents the path of the eclipse totality and the white dot the location of the moon shadow. The actual totality width is  $\sim 1.5$  times of the size of the white dot. The red line is the local noon-time meridian.



**Figure 4.** The incoherent scatter radar (ISR) at Millstone Hill, located near Boston, Massachusetts, and operated by MIT Haystack Observatory, is a Class-I large geospace facility funded by the US National Science Foundation. Shown is the larger 68-meter diameter zenith antenna used by Millstone Hill for vertical ionospheric measurements. Using this antenna in combination with a fully steerable 46-meter diameter antenna (not shown), the radar measures multiple ionospheric plasma state parameters over a broad section of the eastern US and a wide altitude range. These parameters include electron density, ion and electron temperatures, and plasma velocity. Millstone Hill ISR conducted experiments during the 2017 eclipse to probe ionospheric changes. Photo by Shun-Rong Zhang.

and F region ionospheric plasma. In the VLF bands and sometimes at LF bands, radio waves are often totally reflected at the

ionospheric D-region boundary, and thus the skywaves can travel for a long distance through the Earth-ionosphere waveguide. The

higher electron density (daytime) in the D-region typically absorbs the LF and VLF signals, but during eclipses the reduced D-region absorption due to reduction in electron density can make long-distance radio propagation possible. Monitoring these radio waves provides very important information on lower ionospheric conditions. A number of universities and research units in the US (e.g., Virginia Tech, Air Force Research Laboratory, University of Colorado at Boulder, University of Houston) conducted extensive VLF, LF, and HF active and passive radio experiments during the eclipse. Figure 5 shows a temporary field site in Lusk, Wyoming that was used by NOAA scientists to host an ionosonde.

The neutral part of Earth's upper atmosphere was also studied using optical techniques. This atmospheric region emits a faint and characteristic glow visible at night as atoms and molecules receive thermal input and later relax to lower energy states. Instruments that monitor this upper atmospheric glow, known as Fabry-Perot interferometers (FPIs), are typically operated only at night due to daytime background conditions caused by Rayleigh scattered sunlight. Other active optical techniques (LIDARs) used a high-power laser pulse to conduct Rayleigh, Mie, and resonance scatter vertical measurements from neutral and metallic species in the upper atmosphere. During eclipses, the dimmed sky brightness significantly eases the task of measuring weak optical signals in the upper atmosphere. Particularly for the 2017 eclipse, LIDAR facilities (Utah State University) and multiple FPIs were turned on to detect upper atmosphere responses and perturbations during the eclipse or/and the post-eclipse period.

In-situ data directly measured by low earth orbiting satellites was also available and is being studied during the eclipse period. In particular, the US Defense Meteorological Satellite Platform (DM-SP) satellite constellation and the NASA Thermosphere, Ionosphere, and Mesosphere Energetics and Dynamics (TIMED) satellite, and the ESA Swarm satellites flew through the moon's shadow and sampled ionospheric and thermospheric parameters during the eclipse.

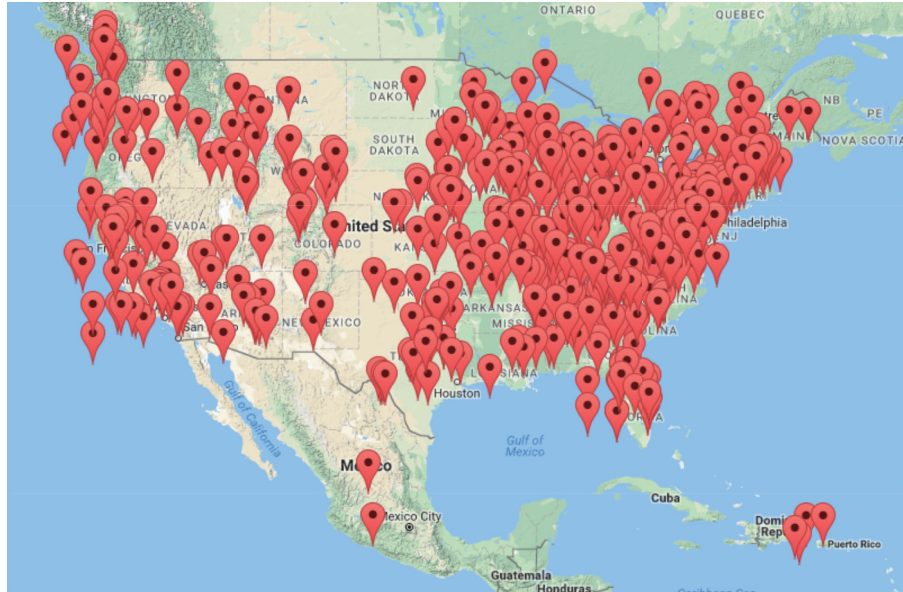
Observations of the 2017 eclipse were complemented by extens-

ive theoretical work, which will be ongoing for some time. In particular, modelers who run sophisticated upper atmospheric first-principle models are conducting significant studies aimed at understanding inherent physical and chemical processes and coupling mechanisms, and will also aid in interpretation of complicated observations during the eclipse passage. Models include TIE-GCM (NCAR High Altitude Observatory, and its domestic and international users), SAMI3 (US Naval Research Lab), GITM (University of Texas in Arlington and University of Michigan), WACCM-X (NCAR High Altitude Observatory), as well as a few dedicated D-region models. The research "orchestra" provided by these models, combined with the extensive observational set mentioned previously, are converging on common goals: through eclipse scenario studies, scientists hope to significantly advance our knowledge of the coupling, dynamics, and energetics of the geospace system.

Finally, in a modern and exciting development, large numbers of citizen scientists are engaged as well in eclipse studies alongside the professional scientific community. Amateur (ham) radio operators routinely use radio frequencies whose propagation characteristics are directly affected by eclipse-induced changes in ionospheric densities. A number of large-scale amateur radio experiments were coordinated by HamSCI, the Ham Radio Science Citizen Investigation (hamsci.org), an organization started by ham operator-space physicists with the goal of fostering collaborations between the amateur radio and professional scientific communities. The HamSCI team at the New Jersey Institute of Technology led three initiatives to study the eclipse ionospheric effects at HF: the Solar Eclipse QSO Party, a radio contest-like event designed to study large-scale changes in propagation; a wideband recording initiative to record the radio spectrum; and a frequency measurement experiment to measure eclipse-induced Doppler shifts on the HF bands. Figure 6 shows a distribution of more than 600 amateur radio stations that contributed their logs to big data-class citizen science observations for eclipse ionospheric research. HamSCI also supported EclipseMob, a citizen science project to study the ionosphere using VLF frequencies.



**Figure 5.** A temporary scientific field site hosted an ionosonde in Lusk, Wyoming. The background shows also the eclipse-watching auto traffic (to the left) lining up on the highway. Photo credit: John Swoboda (MIT Haystack Observatory).



**Figure 6.** Distribution of more than 600 amateur radio stations that contributed their logs to “big data”-class citizen science observations for eclipse ionospheric research. (Source: Map data @ 2017 Google, INEGI; <http://www.hamsci.org/article/more-600-stations-registered-seq>.)

Overall, the 2017 Great American Eclipse provided a modern and fresh “active experiment” opportunity to address some fundamental ionosphere-thermosphere-mesosphere coupling questions at the frontier of space science, and the work continues to draw significant community interest:

- The US Coupling Energetics and Dynamics of Active Regions (CEDAR) scientific association met during their annual summer workshop in early June to discuss coordinated analysis efforts.
- In the US, over a short time frame of less than a few months, a number of general eclipse science news conferences were held (and more are planned) by government funding agencies such as NASA and NSF and professional scientist unions such as the American Geophysical Union (AGU).
- In the US Congress, politicians and science policy makers within the Joint Subcommittee on Research and Technology and Subcommittee on Space held a September 2017 hearing on eclipse observation, research, and public outreach activities.
- In December 2017, AGU will hold its annual fall meeting in New Orleans, and five dedicated sessions will cover a variety of aspects on the 2017 eclipse event, including science results in solar physics and geospace effects, as well as educational and public outreach efforts.

- The AGU journal *Geophysical Research Letters* (GRL) will produce a special section entitled “New understanding of the solar eclipse effect on the upper atmosphere: the 21 August 2017 Solar Eclipse scenario”, containing refereed journal articles on 2017 eclipse studies.

All of these efforts together indicate that the 2017 solar eclipse proved to be an intensely interesting topic both in the science community and for the general public. This interest has also heightened awareness that another solar eclipse on 2 July 2019 will be visible in South America, and in particular that a major solar eclipse on 8 April 2024 will be visible over a great portion of the CONUS. Planning of new efforts for these forthcoming great eclipse opportunities in the coming years is already taking place, among both scientists and the general public.

**Acknowledgements** GPS TEC data products and access through the Madrigal distributed data system are provided to the community by the Massachusetts Institute of Technology under support from US National Science Foundation grant AGS-1242204. For eclipse activities, The eclipse research effort at MIT Haystack Observatory was partially supported by NASA grant NNX17AH71G. SRZ also acknowledges NASA LWS funding support (NNX15AB83G) and the DoD Multidisciplinary Research Program of the University Research Initiative (MURI) project ONR15-FOA-0011. NAF is supported in part by AGS-1552188/479505-19C75.