Protecting Satellites By Assessing the Density of Earth's Upper Atmosphere

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Scientia

PROTECTING SATELLITES BY ASSESSING THE DENSITY OF EARTH'S UPPER ATMOSPHERE

Earth's upper atmosphere is home to a growing number of satellites. To prevent these valuable instruments from colliding with one another, operators often require accurate information about how the orbits of these satellites are affected by drag. However, due to the Sun's continually changing activity, the density of air found in this region can vary drastically, making it difficult for operators to calculate how adjustments should be made. Using a combination of modelling approaches, a team led by **Dr Daniel Weimer** at Virginia Tech shows how air density throughout the upper atmosphere can be precisely calculated, over a wide range of timescales.

The Thermosphere

If we were to travel directly upwards from Earth's surface, the density of the atmosphere surrounding us would drastically drop. Above just 8,000 metres in altitude, oxygen levels become too low for humans to survive indefinitely. Above 50,000 metres, not enough air is present to scatter the Sun's light, and the blue sky fades into the blackness of space.

This point might appear to provide a clear upper boundary to Earth's atmosphere – but in reality, the body of gas that shrouds our planet extends far further still. Beginning at altitudes of roughly 100 kilometres, and reaching as high as around 600 kilometres, a region named the 'thermosphere' can be found. The density of the atoms and molecules in this region decrease sharply with altitude, but at different rates according to their molecular masses.

Since these molecules have very little atmosphere above them to shield them against the harsh environment of outer space, their properties are heavily influenced by incoming radiation from the Sun. As the very name 'thermosphere' suggests, the absorption of this radiation can heat this gas to extreme temperatures. The temperature at the uppermost limit of the thermosphere is known as the exospheric temperature, which can reach values as high as 2,000°C. Yet due to the temperamental nature of our host star, the properties of this part of the atmosphere can be notoriously difficult to predict.

Unpredictable Orbit Changes

The surface of the Sun is a vibrant and ever-evolving environment. Some features emerge and disappear entirely within just a few hours, while other processes repeat over cycles of several years. Following particularly violent events, such as solar flares or coronal mass ejections, sudden bursts

of charged particles may travel across interplanetary space to interact with Earth's magnetic field.

As this happens, disturbed magnetic fields can themselves generate powerful currents of charged particles in Earth's upper atmosphere. These dramatic events are called 'geomagnetic storms'. While charged particles from the Sun can readily interact with Earth's atmosphere in polar regions – creating

the famous aurora – more severe geomagnetic storms can cause this to happen at far lower latitudes. These natural light displays have occasionally been recorded in the tropics. The auroral currents dissipate heat energy in a conducting layer of the atmosphere known as the ionosphere, which heats the thermosphere.

Because of this extreme variability in solar activity, the temperature of the thermosphere can change drastically and unpredictably on local scales, with potentially damaging implications for many important satellite systems. The problem is that many of the satellites we depend on for navigation, weather forecasting, pollution monitoring, and many other important applications, all orbit within the thermosphere.

If this part of the atmosphere were stable and predictable, this wouldn't be too much of an issue. By simply accounting for the drag experienced by satellites as they pass through the thermosphere, operators could calculate any necessary changes to their paths – ensuring that the instruments remain operational for as long as possible. However, since the thermosphere's temperature is so strongly tied to the Sun's constantly changing radiation, the density of layered gases in this region will vary in turn, making it far more difficult to predict the drag experienced by a satellite at any given time.

Modelling Variations in Density

To overcome this challenge, researchers have aimed to develop models of the evolving thermosphere. In a 2015 study, for example, a team led by Daniel Weimer of Virginia Tech discovered a strong link between thermosphere temperature, and its emission of nitric oxide. Using satellite observations of these emissions, the researchers developed a model which could more accurately predict variations in the density of the upper atmosphere following powerful geomagnetic storms.

Building on this work, Dr Weimer's team used real density measurements gathered by multiple satellites to model temperatures at the thermosphere's upper boundaries. In this study, they used several years of data gathered by the Challenging Mini-satellite Payload (CHAMP) and Gravity Recovery and Climate Experiment (GRACE) satellites and the ESA Swarm mission. From measurements made by the instruments' accelerometers, the researchers calculated how the drag experienced by the satellites varied throughout their observation periods.

Introducing: EXTEMPLAR

To build a model of thermosphere density, Dr Weimer and his colleagues then divided the thermosphere into a spherical geodesic grid of 1,620 similarly-sized triangular cells – arranged in a similar way to the famous architectural structures found in the Eden Project in the UK, or at Epcot in Disney World. The sides of each of these cells represented distances of roughly 800 kilometres.

The team then used data from CHAMP, GRACE, and Swarm to derive equations to calculate the exospheric temperature values for each grid cell on the globe. The required parameters included date, time of day, measured levels of ultraviolet radiation from the Sun at different wavelengths, and measured disturbances in the solar wind far beyond the Earth's magnetic field. From the velocity of the solar wind and the magnetic field carried within this wind, the researchers could calculate the amount of heating in the ionosphere, using a method previously developed by Dr Weimer. The team dubbed their model ‘Exospheric Temperatures on a Polyhedral Grid’ (EXTEMPLAR).

In parallel with EXTEMPLAR, the researchers used a further modelling approach developed by the US Naval Research Laboratory, named the Mass Spectrometer and Incoherent Scatter radar Extended (MSIS) model. This approach calculates both the temperature and density of several different species of atoms and molecules, at varying altitudes throughout the atmosphere, given the exospheric temperatures above each location. Normally, the MSIS model calculates temperatures using geomagnetic indices and solar activity measured at radio wavelengths; EXTEMPLAR provides an alternative approach to calculating the temperatures needed by MSIS to obtain the densities.

Together, these two modelling approaches allowed Dr Weimer’s team to convert the temperature values in each of EXTEMPLAR’s triangular cells into values for density at any altitude in the thermosphere. Altogether, this approach resulted in a global-scale picture of local variations in thermosphere density. In addition, it allowed the researchers to predict how density values would change over timescales ranging from just a few hours, to several years.

Comparisons with HASDM

In their latest study, Dr Weimer’s team evaluated the performance of EXTEMPLAR combined with MSIS using a database developed by the US Air Force, named the High Accuracy Satellite Drag Model (HASDM). This database determines the thermosphere’s density directly by drawing together the measured paths of several dozen calibration satellites, and continually adjusting its parameters to match real-time observations as closely as possible. HASDM’s measurements were taken at numerous altitudes across the thermosphere in 3-hour intervals over a 20-year period, between 2000 and 2019.

The database was a particularly useful benchmark, as it allowed the researchers to directly visualise how the thermosphere’s density was affected by real events, including solar flares, coronal mass ejections, geomagnetic storms, and the cooling that occurred in the thermosphere after these events had ended. On longer timescales, the data also captured a full 11-year solar cycle. This solar cycle is a regularly-repeating period where the Sun dims and brightens, and when the direction of its magnetic field flips around – producing predictable variations in the frequency of solar flares and coronal mass ejections.

To evaluate the performance of EXTEMPLAR and MSIS, Dr Weimer and his colleagues used their required input parameters, collected across the same 20-year period, to model the altitude-varying thermosphere density across the same 3-hour intervals in HASDM. As they hoped, their

predicted values showed excellent agreement with HASDM’s measurements – performing best above altitudes of 400 kilometres, where geomagnetic storms produce the most dramatic changes in density.

Reducing Collision Risks

Based on this success, the team hopes that their modelling approach could soon be used to accurately gauge the continually varying conditions of Earth’s upper atmosphere, even when measurements of the drag experienced by orbiting satellites aren’t being made directly. Such advanced prediction capabilities could have important implications for the operation of satellite-based systems in the future.

With the latest advances in technologies including rockets, wireless communications, and robotics, low-Earth orbit is becoming increasingly accessible to scientists and private companies alike. While these developments are rapidly opening up exciting new opportunities in research and technology, they also mean that Earth’s upper atmosphere is becoming increasingly crowded – creating an ever-growing risk of valuable instruments colliding with each other.

Through their combination of EXTEMPLAR and MSIS, Dr Weimer and his colleagues hope that the operators of these systems will be able to accurately predict the drag that their satellites will experience during their orbits, even as solar activity induces constant variations in the thermosphere’s density. In turn, this will enable them to calculate how these orbital paths should be adjusted to minimise any risk of disastrous collisions.

The researchers will now aim to further improve their modelling approach, such as by fine-tuning the time lags between the auroral heating and the arrival of temperature changes at lower latitudes. The use of ‘real time’ solar wind measurements in a predictive model is under development, along with a collaborative effort to develop a grid-less version of the model incorporating machine learning. These improvements could boost the accuracy of the team’s predictions even further – potentially helping more groups to benefit from the latest advances in satellite technology.

Meet the researcher

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Dr Daniel Weimer completed his PhD in Space Physics at the University of Iowa in 1984. After working at the Air Force Research Laboratory, the University of Alaska, Mission Research Corporation and Solana Scientific Inc, Dr Weimer began his current role in 2008, as a Research Professor of Space Science at the Virginia Tech Centre for Space Science and Engineering Research. He has now worked in space physics for over 40 years, and is well known in the community for modelling several key aspects of the ionosphere – the region of Earth's upper atmosphere where atoms and molecules are ionised by solar radiation. Dr Weimer's current research interests include models for predicting geomagnetic variations on Earth's surface, as well as new techniques to predict changes to the temperature and density of the upper atmosphere due to solar activity.

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FURTHER READING

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