Ionospheric Mapping Software Ensures Accuracy of Pilots' GPS

NASA Technology

To permit safe and reliable aircraft navigation over North America using the Global Positioning System (GPS), the Federal Aviation Administration (FAA) has developed the Wide Area Augmentation System (WAAS), which improves the accuracy, availability, continuity, and integrity of GPS positioning enough to ensure its safe use by pilots to determine their locations. The early development of WAAS relied on software developed at NASA's Jet Propulsion Laboratory (JPL), particularly the GPS-Inferred Positioning System (GIPSY) and the Global Ionospheric Mapping (GIM) software packages. The former has been licensed by hundreds of commercial and noncommercial organizations (*Spinoff* 1999 and 2010).

More recently the continued development of WAAS has relied on companion software also developed at JPL. The SuperTruth and IonoSTAGE packages allow the system to address the threat to accurate positioning posed by code delays and phase advances due to refraction in Earth's ionosphere.

More than about 50 miles above the planet's surface, electrons can be separated from atoms, resulting in positive ions and free electrons. Ionization of the upper atmosphere is much more active in the daytime since it's largely driven by the sun's ultraviolet radiation and the solar wind, which rip electrons off of neutral particles. Earth wind patterns and electrodynamics in the atmosphere help make the electron distribution irregular and patchy, resulting in "space weather" that can interfere with signals.

GPS signal delays caused by activity in the ionosphere are measured in meters, with large delays being on the order of 40 meters, says Lawrence Sparks, senior technologist with the Ionospheric and Atmospheric Remote Sensing Group at JPL. While it doesn't take long for signals traveling at the speed of light to cover 40 meters, he says, even a delay of a small fraction of a second can make a significant difference in determining the position of a fast-moving plane. "It is crucial to bound the positioning errors accurately for landing an aircraft safely in fog, for example."

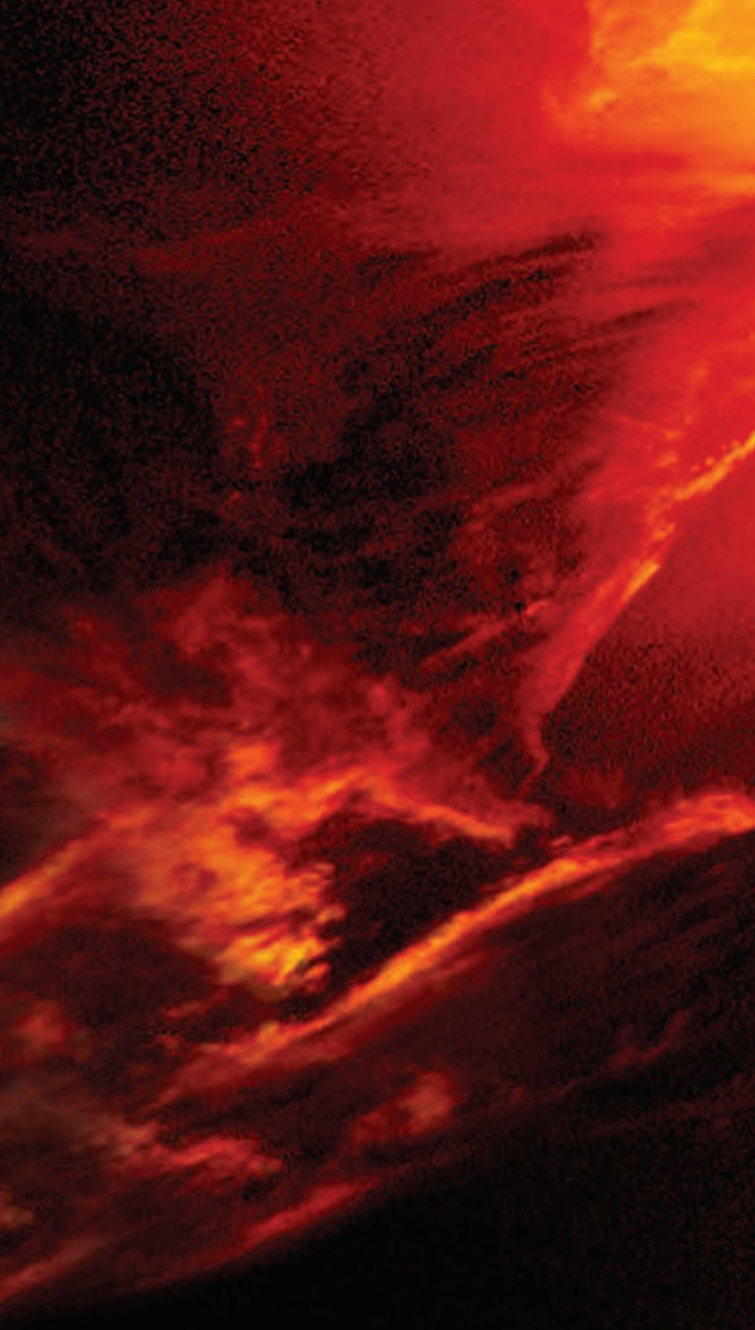
GIM allows Raytheon Corporation, the prime contractor of the system, to map ionospheric disruption in real time by processing the delays between GPS satellites and the 38 WAAS reference stations around North America. Each signal includes a sort of time stamp, making it possible to determine how long it took to travel from the satellite to the receiver, Sparks says. WAAS broadcasts vertical ionospheric grid delays for regularly spaced points across the coverage area.

The observations are also used to calculate and broadcast the grid ionospheric vertical error (GIVE) for those same points. The GIVEs bound the range of possible error in pilot positions derived from GPS—that is, they let users know how reliable the information provided by WAAS really is.

"Only part of the ionosphere is sampled by WAAS at any given time," Sparks explains. "A disturbance can be overlooked because its location hasn't been sampled. To protect the user from such errors, WAAS relies on an ionospheric threat model."

The threat model—one factor in calculating GIVE—is constructed from a sort of worst-case scenario based on historical data generated by SuperTruth, including records of severe ionospheric storms. "We try to quantify what kinds of ionospheric disturbances the system could have possibly missed," Sparks says. "For every possible satellite configuration, we determine the worst-case errors we've ever seen." These are usually caused by coronal mass ejections—huge bursts of solar wind and magnetic fields on the surface of the sun that can cause dramatic increases in the number of ions in Earth's upper atmosphere.

Sparks designed and wrote the computer code comprising the Ionospheric Slant TEC Analysis Using GNSS-Based Estimation (IonoSTAGE) software package,



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— Larry Sparks, Jet Propulsion Laboratory

The sun emits a constant stream of charged particles, ultraviolet radiation, and x-rays, which generate activity in Earth’s ionosphere by ripping electrons away from molecules to create more charged particles, or ions. Solar flares or coronal mass ejections such as the one seen here cause the most dramatic “space weather,” which interferes with radio signals and electrical systems.

Smaller aircraft and smaller airports especially benefit from the Federal Aviation Administration's Wide Area Augmentation System, which operates on software pioneered by NASA. For example, most small airports don't accommodate enough traffic to justify the cost of more than $1 million to install an instrumented landing system, but the cost to inspect and commission an approach procedure that can be navigated with the help of GPS is about 90 percent less.

Global Positioning System (GPS) satellites, such as this one from the Block IIR series, not only transmit data to and from GPS units on earth, but they are also used to determine the extent to which those signals are being delayed by activity in Earth's ionosphere.

wherein TEC signifies total electron content between a GPS receiver and satellite, and GNSS stands for global navigation satellite systems. JPL uses the program to compute the ionospheric threat model and corroborate Raytheon's calculations of ionospheric delay and the maximum possible error in those calculations.

To generate the threat model, IonoSTAGE calculates electron density in the ionosphere between any given satellite and reference station—a figure known as total electron content—and the signal delay it's causing. The software's computation of the ionospheric threat model has proven to be a critical contribution to WAAS, Sparks says, noting that Raytheon and JPL have relied on completely independent code packages to arrive at the same model, allowing IonoSTAGE to validate Raytheon's results.

SuperTruth plays a critical role in providing high-precision measurements for generating the ionospheric threat model by IonoSTAGE. The new and improved SuperTruth algorithm provides a fast and more advanced approach to processing ionospheric measurements under adverse solar and geomagnetic conditions, explains JPL's Attila Komjathy, chief architect of the SuperTruth software. "After transferring the code base, Raytheon personnel reported to us an average of about 30 percent improvement in data volume over the early version of the processing algorithm comprising GIPSY and GIM alone."

Technology Transfer

Since WAAS was commissioned in 2003, FAA spokesman Paul Takemoto says, more than 73,000 planes have been outfitted with the capability to use the system for navigation and landing assistance. Because big airliners generally have other onboard navigation systems that can serve the same functions, and because these planes tend to travel exclusively between major airports outfitted with instrument landing systems, he says, WAAS finds most of its users among individual aircraft owners, business jets, emergency transporters, and an increasing number of regional airlines across North America. These often land at airports that don't have enough traffic to justify purchasing an instrument landing system.

With WAAS, no navigational equipment is required at the airport, although infrastructure requirements such as runway markings or lighting, for example, may still need to be met to gain the full benefit of WAAS for landing. Furthermore, no consideration needs to be given to the placement of a navigation facility, maintenance of clear zones around the facility, or access to the facility for maintenance.

Since the advent of WAAS, the FAA has created almost 4,000 "localizer performance" approach procedures, each enabling the use of the system for landing on a specific runway end, Takemoto says, adding that the agency has a goal of writing procedures for every airport that qualifies for them.

In late 2013, the first commercial licenses for SuperTruth and IonoSTAGE were issued when NEC, an international company based in Japan, with US headquarters in Irving, Texas, licensed the entire suite of WAAS-enabling software for use in Japan. The company says it plans to use the technology to provide its clients with more reliable calculations of ionospheric delays.

Benefits

WAAS is especially useful for landing in low visibility, and Sparks says this is a critical function.

Before WAAS, he says, small planes required an airport with an instrument landing system to land under low-visibility conditions. “It was only at larger airports that an aircraft had the capability to land under extremely adverse conditions. Smaller airports were simply not available.”

Using GPS with no augmentation to land at airports without an instrument landing system, aircraft may have no vertical guidance for approach, says Jason Burns, space segment lead for WAAS at the FAA. “WAAS provides additional safety by providing vertical guidance where there otherwise would be none.”

With WAAS providing greater assurance as to the aircraft’s actual position, the same plane can now drop to altitudes as low as 200 or 250 feet without runway visibility.

In addition to assisting with landing, Burns says, WAAS also is beneficial when flying point to point. Before satellite navigation, a plane would fly from one ground radio beacon to the next when visibility was limited. This did not always result in a straight path to the desired destination. With WAAS, aircraft can fly the most direct path. This can also be accomplished with GPS, but only if appropriate procedures are followed to ensure GPS will be reliable for the entire length of the flight. WAAS provides this integrity.

Sparks says the system seeks to strike a balance between providing ranges of possible errors that are wide enough to guarantee that they bound the actual error but narrow enough that the information is useful for positioning.

If a signal error were ever greater than the bound calculated by WAAS, Sparks says, that would constitute what NASA and the FAA call HMI, or hazardously misleading information. WAAS specifications require that this not happen more than once in 10 million landings. “That’s the spec we’re all trying to meet, and so far, we have,” he says. “In 11 years, we’ve never had a single instance of HMI recorded.” ❖

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The most visible ionospheric activity comes in the form of aurorae, such as the aurora borealis, pictured here. These occur when Earth’s magnetic field pulls electrons in the ionosphere down toward the poles, where they collide with atoms lower in the atmosphere, releasing energy. Ions in the solar wind can also contribute to aurorae.

Image courtesy of the US Air Force