Studie of Ionospheric Irregularities: Origins and Effects

Steven P. Powell  
School of Electrical and Computer Engineering  
321 Rhodes Hall, Cornell University  
Ithaca, NY 14853  
phone: (607) 255-4551  fax: (607) 255-9072  email: sp35@cornell.edu  

Mark L. Psiaki  
Sibley School of Mechanical and Aerospace Engineering  
206 Upson Hall, Cornell University  
Ithaca, NY 14853  
phone: (607) 255-9100  fax: (607) 255-1222  email: mlp4@cornell.edu  

Award Number: N00014-09-1-0295  
http://gps.ece.cornell.edu  ; http://gps.mae.cornell.edu

Special Notes:  1. Paul M. Kintner was the original principal investigator for this award  
   until he passed away in November 2010.  
   2. This award terminates on 30 September 2015, so this report will serve as both an  
   annual report for FY2015 and also a final report for this award. Therefore, it is  
   somewhat longer than a typical annual report.

LONG-TERM GOALS

We have two long-term goals. The first is to understand the electrical properties of the upper  
atmosphere and space environment to better assist designers and users of space systems and  
technology. The second is to educate the next generation of leaders in space science and engineering.

OBJECTIVES

The scientific objectives of the project are:

(1) To investigate space weather and its effects on GPS, including the characterization of L-band  
   scintillations and scintillation effects on GPS signals and receivers;

(2) To investigate the origin of ionospheric irregularities, which lead to ionospheric scintillation  
   storms, through deployment of GPS scintillation receivers at equatorial latitudes (regionally in  
   South America), at mid-latitudes (Hawaii, Ithaca, Puerto Rico, Utah), and at high latitudes  
   (Norway, Alaska);

(3) To develop GNSS receivers (WAAS, Galileo, and modernized GPS) that can assess the effect of  
   scintillations and space weather on modernized GNSS signals;
(4) To develop space-based GPS receivers for sounding rocket and satellite applications that can remotely sense the ionosphere, thermosphere, and mesosphere.

Our research focuses on the study of space weather and the impact of space weather on GPS and GNSS receivers. Our approach is primarily experimental, and we have a reputation for producing cutting-edge instrumentation and for developing successful experiments. The vast majority of the universe exists in a plasma state and we focus on our own upper atmosphere and ionosphere as natural laboratories for studying space weather and as an environment that affects satellites and their signals. This yields a mix of applied and curiosity-driven research. By primarily employing sounding rockets and ground-based instrumentation, graduate students are able to participate in the full range of research and to develop into future leaders. For example, Cornell University’s development of a GPS receiver for measuring fast amplitude scintillations has led to a global program with receivers deployed at multiple sites across South America, Africa, and China. Several Ph.D. students and postdocs from Cornell and Brazil have been trained using these receivers. This receiver not only monitors ionospheric scintillation but additionally measures ionospheric drifts. This effort also leverages our development of GPS software receivers and space-based GPS receivers.

The scientific significance of this work is an increased understanding of the physics of ionospheric irregularities and other space weather phenomena. The naval significance is the improved ability to design radio navigation equipment and other RF satellite signal receivers that are less susceptible to space weather-based outages, as well as an increased understanding of and capability to predict outages when space weather events overwhelm the capabilities of existing and improved systems.

**APPREACH**

The methods used to carry out this project can be classified into three categories. The first is the development of GPS/GNSS receiver hardware and software suitable for space weather data collection. The second is the deployment and operation of these receivers and the archiving of collected data. The third is the analysis of collected data.

GPS/GNSS receiver hardware is being developed because of the difficulty of using COTS GNSS technology for space weather monitoring. COTS GPS receivers do not produce the needed data products at the needed sample frequencies, nor do they have the required tracking robustness to maintain signal lock and return data during the most severe space weather events, which are the ones of greatest interest. Some manufacturers allow firmware upgrades/modifications that could, in theory, provide the needed performance, but the cost of such upgrades is large, and the process of defining, requesting, and receiving upgrades is cumbersome.

In-house development avoids these pitfalls. Two additional benefits of in-house receiver development are the education of students in GNSS receiver technology and analytical researchers, be they students, staff, or faculty, about the characteristics and limitations of GNSS-based space weather data.

Various Cornell GNSS receivers were and are currently being used to collect space weather data. Two general strategies are being pursued for collecting space weather data in a variety of significant places around the globe. One strategy is to loan equipment to colleagues, who then place the equipment in strategic places, provide infrastructure for operating the equipment, and share the resulting data with
Cornell. To date, the locations covered in this manner include Antarctica, Brazil, China, Eritrea, Hawaii, Japan, Norway, Peru, Puerto Rico, Utah, and, of course, Ithaca, NY.

The second space weather receiver-deployment strategy has been to send Cornell researchers and receivers to a location where interesting space weather is likely to occur. Recent campaigns have focused on equatorial spread-F/scintillation data in South America, with campaigns conducted in Brazil in 2007 and 2009, and at the Jicamarca Radio Observatory (JRO) in Peru in March 2011. The latter campaign involved deploying five CASES receivers and two digital storage receivers in an array with a 2.7 km east/west extent and a 1.1 km north/south extent.

To date, analyses of space weather data have concentrated on two phenomena: equatorial scintillation and solar radio bursts. The types of analyses vary from calculating simple correlations to using data in sophisticated fitting algorithms that couple physics-based radio signal propagation models and ionospheric models with computer algorithms to solve the resulting inverse problems.

Correlation analyses have been used to study the geometry and drift of scintillation and to demonstrate that solar radio bursts can severely impact GNSS receivers.

Model inversion work has been carried out, largely under a related NSF grant. It is mentioned here because that work is highly dependent on the data collected as part of this project, and the requirements of that effort have been used to design the data collection campaigns to make their results more useful in model inversion studies. Model inversion involves the fitting of amplitude and phase scintillation data to models of ionospheric irregularities and diffractive L-band GNSS signal propagation through the irregularities. Model-inversion analysis and the data collection campaign design should be coupled to maximize the observability of underlying ionospheric irregularities.

In 2014 and 2015 we teamed up with the Naval Research Laboratory to develop a GPS radio occultation system to be used as part of the GROUP-C (GPS Radio Occultation UV Photometer-Collocated) experiment for the International Space Station (ISS). The GROUP-C experiment will be sent to the ISS in 2016 as part of the STP-H5 palette of experiments. Please refer to the Work Completed and Results section of this report for additional details on this latest work.

**WORK COMPLETED**

1. We developed a prototype real-time dual-frequency (L1CA//L2C) software GPS receiver based on a DSP chip.
2. We developed a compact and low-power RF front-end for L1CA and L2C.
3. We conducted the first L1CA/L2C measurements of ionospheric scintillation using multiple receivers.
4. We developed a brass board L5 tracking circuit based on an FPGA.
5. We developed an ionospheric scintillation model for use in commercial GPS signal simulators.
6. We authored a cover story in *Inside GNSS* on GPS and scintillation.
7. We developed a GPS spoofer.
(8) We authored a cover story in *GPS World* on GPS spoofing.

(9) We developed new techniques for improving dual-frequency GPS receiver performance for improved ionospheric monitoring and presented the results at conferences and in publications.

(10) We developed a dual-frequency L1/L2C GPS receiver for space-based applications (FOTON), flew it on a sounding rocket, and made the first GPS-based measurements of the vertical electron density profile during an active auroral event.

(11) We upgraded the design of the FOTON dual-frequency L1/L2C GPS receiver for radio occultation measurements, and built two units (a flight unit and a flight spare) to be sent to the International Space Station as part of the GROUP-C experiment.

(12) We developed a multi-element antenna system to be used with the FOTON to mitigate the effects of RF multipath degradation of the dual-frequency L1/L2C GPS signals, and to increase the quality of the radio occultation measurements.

(13) We participated in the integration and test activities of the FOTON GPS receiver and antenna array at NRL and NASA/JSC along with additional elements of the GROUP-C experiment and the entire STP-H5 palette of instruments.

RESULTS

(1) We demonstrated how amplitude and phase scintillation are related. Deep amplitude fades are accompanied by fast half-cycle phase shifts, which has important implications in designing scintillation-resistant receivers.

(2) We developed a dual-frequency GPS receiver operating on a digital signal processing chip. This software is portable and has led to an entirely new family of practical software GPS receivers.

(3) We demonstrated a GPS spoofer based on a GPS software receiver, leading to a cover story in *GPS World*.

(4) We developed and successfully flew a new space-based dual-frequency L1/L2C GPS receiver on a sounding rocket for navigational and scientific purposes, and made the first GPS-based measurements of the vertical electron density profile during an active auroral event.

(5) We developed GPS spoofing detection methods that led to a *GPS World* article.

(6) We developed a spaceflight-ready dual-frequency L1/L2C GPS radio occultation receiver and a complementary multi-element antenna array for the GROUP-C experiment for the International Space Station.

The development of space weather-monitoring GPS/GNSS receivers has resulted in a series of hardware devices that returned much useful data. The current generation of receivers includes CASES (Cornell Autonomous Space Environment Sensor), which has been used successfully in an ongoing data collection effort in Antarctica and in the March 2011 Jicamarca, Peru scintillation campaign; and a digital storage receiver that logs an entire segment of the GPS spectrum or some other spectrum of interest. Digital storage receivers have been used to decipher the Galileo PRN codes.
Scintillation data collection campaigns in Brazil in 2007 and 2009 and in Jicamarca, Peru in 2011 have been used to monitor scintillations on L1 and L2 GPS frequencies, representing the first scintillation observations on the new GPS civilian L2C signals. These campaigns also demonstrated that weak scintillation (in the 0.4 to 0.6 range) on L2 is closely correlated with weak scintillation on L1. This correlation disappears with strong scintillation. Also, scintillation on L2 is stronger than on L1 for the same ionospheric irregularities.

Analysis results include demonstrations of spatial and temporal correlations of equatorial scintillation on the GPS L1 C/A signal, successful model-inversion fits to recorded L1 C/A and L2C signals during weak scintillation, and the demonstrated possibility of severe Solar Radio Burst (SRB) impacts on GPS/GNSS receivers. The SRB results demonstrate that this space weather phenomenon can be a much more serious concern for GPS/GNSS than was originally thought.

In 2012 we developed the FOTON (Fast Orbital TEC Observables and Navigation) space-based GPS receiver. This new receiver is based on the CASES receiver but repackaged for the rigors of space flight (high vibration, high accelerations, large thermal variations). The hardware is arranged in a stacked board configuration, resulting in a CubeSat-compatible form factor. The FOTON software was modified to account for the greater Doppler shifts associated with rocket and satellite velocities. Extensive pre-flight electronic and environmental testing was carried out on the FOTON receiver, including vibration and spin tests and GPS simulator tests. The FOTON receiver was successfully flown on the NASA MICA sounding rocket on February 19, 2012, and reached an apogee of 325 km over Alaska during an active auroral event. The data from the FOTON receiver was of excellent quality, useful for both navigation (position, velocity, and timing) and scientific purposes (TEC and scintillation).

Fig 1. TEC profiles from two GPS satellites from the FOTON receiver on the MICA sounding rocket.
In 2013 we analyzed the FOTON data, along with collaborators at the University of Texas at Austin, and obtained the first GPS-based measurements of the vertical electron density profile during an active auroral event. Figure 1 shows these profiles (courtesy of G. Lightsey, University of Texas at Austin), derived from dual-frequency GPS TEC measurements from the FOTON receiver onboard the MICA sounding rocket. The two separate profiles are from two different GPS satellites at substantially different look angles from the rocket payload: PRN 5 was to the southwest at low elevation angles (≈14° to 18°) and PRN 15 was to the northwest at higher angles (≈31° to 34°). The TEC data time history was combined with the rocket trajectory to obtain these vertical profiles. The two profiles differ substantially, especially between 100-175 km, due to the presence of a highly disturbed ionosphere, primarily to the north and west, with strong auroral arcs during the rocket flight.

Fig 2. The STP-H5 palette with the GROUP-C experiment. The GPS antennas point in the wake direction toward the limb.

In 2014 we upgraded and modified the design of the FOTON dual-frequency L1/L2C GPS receiver for radio occultation measurements, and built two units (a flight unit and a flight spare) to be sent to the International Space Station as part of the GROUP-C experiment. We also developed a multi-element antenna system to be used with the FOTON to mitigate the effects of RF multipath degradation of the dual-frequency L1/L2C GPS signals, and to increase the quality of the radio occultation measurements. The GROUP-C experiment will be sent to the ISS in 2016 as part of the STP-H5 palette of experiments, as shown in the illustration of Figure 2.

The GPS instrument looks toward the limb, in the aft direction, and obtains vertical TEC profiles of the ionosphere by observing the apparent setting of a GPS satellite, taking advantage of the orbital trajectory of the ISS as shown in Figure 3. The GROUP-C experiment will compare and correlate the measurements from the Nadir-looking UV photometer and the GPS sensing of the same ionosphere.
Fig 3. The geometry of the GROUP-C experiment illustrating how the aft-looking GPS instrument will obtain a vertical TEC profile of the same ionosphere that is observed by the Nadir-looking photometer. The vertical TEC profile is obtained over approximately 1 minute as the GPS satellite appears to set, due to the ISS trajectory.

Fig 4. FOTON L1/L2C GPS radio occultation receiver for the ISS GROUP-C experiment, shown mounted to a test plate. This flight unit is mounted inside of an enclosure provided by NRL (see Fig 5).

The scientific results of the GROUP-C experiment will have to wait until it is launched to the ISS in 2016 and begins returning data, but the results of the engineering effort to design, build, and test the FOTON GPS receiver and the multi-antenna array are shown in the photos of Figures 4 through 8.

The FOTON consists of a 3-board stack of electronics: the RFE board (RF Front End), DSP board (Digital Signal Processor) and IIB board (ISS Interface Board). While the RFE and DSP boards have design heritage from the FOTON receiver flown on the MICA sounding rocket, the IIB is a new board that was designed and built in 2014 to provide power and signal conditioning for the ISS interface.
The 3-element patch antenna array is shown in Figure 5. Each antenna is connected to an input port of a 3-way RF switch, with the output of the switch connected to the FOTON receiver. The RF switch sequentially selects each of the antennas, which produces a predictable apparent motion in the phase center of the antenna array. This system takes advantage of the 20 cm spacing of the antennas, and the corresponding predictable effect on the carrier phase of the direct signal (line-of-sight) and multipath signals (reflected off of elements of the ISS) in order to mitigate the effects of the multipath signal on the radio occultation measurements. The multipath mitigation measures will initially be performed by post-processing the FOTON GPS data on the ground. However, the system has been designed so that multipath mitigation algorithms may be implemented onboard (within the FOTON receiver), by uploading new firmware to the experiment once it is on-orbit. This more sophisticated operating mode will only be attempted after the minimum success of the experiment has been achieved.

Fig 5. 3-element patch antenna array used for multipath mitigation for the FOTON GPS radio occultation receiver, shown during vibration testing at NRL. The FOTON GPS receiver is the gold box, lower left. The Aerospace Corporation supplied the patch antennas, and NRL supplied the ground plane.

At the end of FY2014 the FOTON flight unit was delivered to NRL, and in FY2015 the Principal Investigator (S. Powell) travelled to NRL a total of 8 times for a series of hardware and software tests, and for integration with the other elements of the GROUP-C experiment. These tests were devised to test the FOTON receiver and antenna array in as realistic conditions as possible. The tests included vibration testing, thermal cycling in a temperature chamber, and outdoor testing so that the antenna array would be illuminated with realistic GPS signal levels (see Figure 6). This outdoor test was extremely important since the remainder of the testing takes place in controlled laboratory settings, and while similar to the environment expected on orbit, it is extremely challenging to duplicate the outdoor RF environment.
Fig 6. GPS antenna array and FOTON receiver (inside of pink enclosure) shown during outdoor testing on the rooftop of the NRL lab. The objective of this test was to illuminate the antenna array with realistic GPS signal levels and to verify nominal FOTON operation.

Fig 7. Integrated bench-top testing of the GPS antenna array (inside of RF-shielded box on left), FOTON receiver, and GROUP-C electronics inside of the NRL cleanroom. The sensitive LITES instrument is mounted onto the GLIB (GPS/LITES Interface Box) on the right, requiring this test to take place in a cleanroom. A GPS signal is re-radiated inside of the RF-shielded box so that the FOTON can function nominally, and to avoid interference with other nearby GPS receivers.

Cornell Ph.D. Graduate Student B. O’Hanlon travelled to NRL for several days of intensive software testing of the FOTON firmware upload mode, and this mode was tested, and proper operation verified, on the flight hardware that is shown in Figure 7. As mentioned earlier, this firmware upload mode will enable multipath mitigation algorithms to be implemented in the FOTON receiver in the later portion of the ISS mission. A special RF-shielded enclosure for the GPS antenna array was fabricated for this integrated testing of the entire GROUP-C experiment. The testing took place in the NRL cleanroom, and the RF-shielded enclosure enabled GPS signals to be re-radiated indoors to the antenna array, without the risk of interference to other nearby GPS receivers.
In April, 2015, the GPS antenna array, FOTON receiver, and other elements of the GROUP-C experiment, were shipped to the NASA Johnson Space Center for integration with the entire STP-H5 palette of instruments. The PI travelled to NASA/JSC twice in 2015 to participate in these integration and test activities.

Additionally, procurement recommendations and installation advice was provided to STP staff regarding equipment needed for a GPS repeater system for the NASA/JSC lab. Upon arrival at NASA/JSC, the PI trained several of the STP staff on the proper use of this GPS re-radiator system and how to verify that the test levels were comparable to what would be received on orbit. Separately, a second GPS repeater system was procured for use at other key locations during the integrated testing.

The GPS antenna array and FOTON receiver were mounted onto the STP-H5 palette as shown in Figure 8. Basic functional testing of the standalone GROUP-C experiment (including the FOTON instrument) was performed during the first trip to NASA/JSC, and complete end-to-end testing, through the entire STP-H5 data handling system, was performed during the second trip.

As of the end of FY2015, the entire palette of instruments, including the GROUP-C experiment and FOTON GPS system, has successfully completed vibration and EMI testing, and is currently being shipped to the NASA Langley Research Center for TVAC (thermal vacuum) testing. The TVAC is the final major test to be performed before the STP-H5 palette is shipped to the Kennedy Space Center for launch to the ISS in 2016.

**Fig 8. The STP-H5 palette of instruments shown during the early stages of integration and testing at NASA/JSC. The 3-element GPS patch antenna array is clearly visible, and the FOTON GPS electronics box is located in the center-left of the photo, just to the right of the large red square object.**

**IMPACT/APPLICATIONS**

Our work with GPS receivers and space weather is of continuing importance in understanding and predicting the behavior of GPS receivers in the presence of both solar radio bursts and scintillation. In
the future, our receivers will be critical to evaluating the impact of space weather on GNSS signals. Our past work in determining the shape of fade patterns is important to understanding how velocity resonance will occur and potentially produce loss of lock or even loss of navigation in GPS receivers. Our recent work with WAAS signals will lead to understanding the significance of scintillations on this system. Our continued development of software receivers looks to the future, when modernized GPS signals will be available and dual- and triple-frequency measurements of TEC should be inexpensive.

We have demonstrated that scintillation during deep fades has canonical behavior. That is, deep fades are accompanied by half-cycle phase jumps. This phenomenon will lead to new designs for GPS receivers that can track robustly in the presence of scintillation.

We designed and operated a GPS signal spoofer. How easy it was to design is clearly significant. The impact is that, within five years, GPS spoofing is likely to be common, and the fabrication of GPS spoofers by students who have not yet achieved a college degree in engineering will be possible. We have also developed spoofing detection strategies to combat this threat.

The development and successful sounding rocket flight test of the FOTON space-based dual-frequency GPS receiver demonstrates that this new GPS receiver can work in space. We look forward to making this new GPS receiver available as a space weather sensor for small and low-cost satellite missions, such as CubeSats, or as part of a suite of scientific instruments on a larger scientific satellite or the ISS. In 2014 and 2015 we made a significant step toward achieving this goal by including the FOTON GPS radio occultation receiver as part of the GROUP-C experiment that will be launched to the ISS in 2016.

TRANSITIONS

The DSP software technology has been leveraged to win an STTR from the USAF, in association with ASTRA (Atmospheric and Space Technology Research Associates, a small company in Boulder, CO), to develop inexpensive GPS space weather receivers that can be connected in large arrays. In 2012 we collaborated with ASTRA on an SBIR from the USAF to investigate hardware miniaturization, power reduction, and multipath mitigation of CASES GPS space weather receivers. The intent of this SBIR is to transition CASES space weather receivers into a commercially available product.

RELATED PROJECTS

See above.

PUBLICATIONS


