122nd ASEE Annual Conference & Exposition
June 14 - 17, 2015
Seattle, WA
Making Value for Society
Paper ID #12391

Global Navigation Satellite Systems GNSS as an Effective Tool for Engineering Education

Prof. Wayne A Scales, Virginia Tech

Wayne A. Scales is a Professor of Electrical and Computer Engineering and Affiliate Professor of Aerospace and Ocean Engineering at Virginia Tech. He is also the Director of the Center for Space Science and Engineering Research. He currently teaches graduate and undergraduate courses in the areas of electromagnetics and radio wave propagation, plasma physics, computational physics, upper atmospheric space science, and Global Navigation Satellite Systems GNSS. He received his PhD at Cornell University in Electrical Engineering and Applied Physics. He has received several Dean's citations for teaching excellence during his years at Virginia Tech.

Dr. J Michael Ruohoniemi
Dr. Geoff Crowley,

Geoff Crowley is the Founder and Chief Scientist of Atmospheric & Space Technology Research Associates (ASTRA). He is also a co-founder of the American Commercial Space Weather Association (ACSWA) and serves on the Executive Committee. He has published over 100 scientific papers as lead author or co-author. His interests include measuring the ionosphere from the ground and from space. He led the 'CASES' GPS receiver development project, and development of the 'TIDDBIT' HF sounder, and he leads several instrument teams developing instruments for small satellites. He was PI on the DICE Cubesat mission, and leads the recently selected NASA SORTIE mission. He is well known for modeling and simulation of the ionosphere and thermosphere, and his experimental work on Traveling Ionospheric Disturbances. He received his PhD in Ionospheric Physics from Leicester University in the UK.

Global Navigation Satellite Systems GNSS as an Effective Tool for Engineering Education

W. A. Scales, J. M. Ruohoniemi
Bradley Department of Electrical and Computer Engineering
Virginia Tech
Blacksburg, Virginia, USA
G. Crowley
Atmospheric & Space Technology Research Associates, LLC
Boulder, Colorado, USA

Abstract: Applications of Global Navigation Satellite Systems (GNSS) are ubiquitous in today's society. Their number is expected to grow rapidly for the foreseeable future and well-trained engineers will be needed to exploit the full potential of this technology. GNSS encompasses a broad range of engineering and science disciplines and provides an excellent opportunity to effectively train students on state-of-the-art applications, a broad spectrum of engineering and science fundamentals, and the interrelationships between multiple engineering disciplines. We describe our experience and lessons-learned in teaching an advanced undergraduate-level GNSS capstone design course in the department of Electrical and Computer Engineering at Virginia Tech over the past 15 years. We report on the objectives of the course, the topic selection, the capabilities of laboratory hardware, approaches to GNSS data extraction and analysis, and the importance of the accompanying teaching laboratory. Student perceptions of specific measurable learning objectives are provided which underscore the importance of a hands-on laboratory component in teaching a successful GNSS course.

Introduction

Global Navigation Satellite Systems (GNSS) have revolutionized both the defense and consumer product industries, and their applications have become ubiquitous in today's society. In the near future, more satellites and constellations, more broadcast frequencies, more advanced signal structures, and better ability to take into account the impact of the earth's upper atmosphere will allow unprecedented accuracy and open the door to even more uses. Currently operational GNSS constellations include the United States' Global Positioning System (GPS) and the Russian Federation's GLObal NAvigation Satellite System (GLONASS). Two other global GNSS systems are expected to be fully operational by 2020 at the earliest: the European Union / European Space Agency satellite navigation system (Galileo) and China's global navigation satellite system (BeiDou/Compass). France, India, and Japan are in the process of developing regional navigation systems. Once all these regional and global systems are working the GNSS technology will provide a user with access to positioning, navigation and timing signals from more than 100 satellites. The impact of the new capabilities will extend from basic science to more practical engineering and technology including geophysical exploration, airline and spacecraft tracking, surveying, precision agriculture, and unmanned vehicles. As a result, a growing number of employers are seeking hires with understanding and experience of GNSS. The emerging nexus between education, research, and industry in this critical area presents an opportunity for a joint effort to help prepare the next generation of engineers with early, direct, and stimulating access to GNSS science and technology. A relatively broad range of engineering and science disciplines is required to understand the GNSS-associated technologies that enable this spectrum of applications. These include orbital mechanics, signal processing and communication system theory, computational mathematics, statistics, radio wave propagation, upper atmospheric space physics, and even relativity theory.

Not only has GNSS revolutionized modern technology, it has begun to be used effectively for a broad range of educational purposes. Kindergarten through 12th grade (K12) educational programs based on GNSS have been developed to teach fundamental science and engineering concepts, the principles of engineering design, and the impact of modern technology on society [1]. The teaching of geography is particularly enhanced by consideration of GNSS and considerable efforts are being made to incorporate Geographic Information System (GIS) and GNSS concepts into K12 educational technology [2]. Also for K12, there are approaches in technology education assessment theory that use the so-called GPS-analogy to 'locate' students and move them forward on their learning journey [3, 4]. Another general educational approach, called 'GPS trails', is location-based learning which utilizes GPS receivers and gaming strategies to increase the effectiveness and excitement of learning facts, interrelationships, and other educational content [5].

The training of engineering students at the undergraduate level in GNSS technology, the general subject of this report, has seen a variety of teaching approaches. These have often been based on application training within specific engineering disciplines rather than acquisition of detailed firstprinciples understanding. The training is often provided as needed in a module within the offering of a core course. For instance, in Civil and Environmental Engineering (CEE), GNSS technology is incorporated into construction engineering and management curricula for training students to use spatial construction data for various applications that include surveying, construction planning, and scheduling [6]. Aerospace Engineering (AE) curricula place emphasis on technology applications related to air and space navigation, traffic control, and pilotless aircraft and aerospace technologies, such as atomic clocks, that enable GNSS [7]. In general, undergraduates appreciate applications of GNSS and design projects that are effective in giving some insight into fundamental GNSS principles [8]. These approaches, however, do not address learning GNSS from first principles and so do not convey the depth of understanding that is necessary to work with a broad spectrum of GPS technologies and to design new applications. Educational approaches in Electrical and Computer Engineering (ECE) that utilize GNSS signals collected at the raw level and which replicate the detailed computations performed inside actual GNSS receivers have begun to be more commonplace [9]. This latter approach is very effective at teaching fundamental principles and is considered in the following discussion.

We report on our experience in teaching a laboratory-based ECE capstone design course on GNSS theory and design applications. The course has been taught for the past 15 years at Virginia Tech and has evolved with advances in GNSS technology and on-going assessment of instructional effectiveness. The range of technical disciplines associated with GNSS provides a rich interdisciplinary educational experience that can be leveraged to effectively train a broad range of engineering students. The GNSS learning experience brings together fundamental concepts utilized in many lower division engineering courses and therefore solidifies the students' understanding of working on real world engineering problems and systems that require multiple disciplines. The course has benefited a broad cross-section of students from a number of engineering departments outside of ECE that include aerospace and ocean, mechanical, civil and environmental, and mining. It consists of a theoretical component that explains the inner workings of GNSS and an innovative hands-on laboratory component that uses state-of-the-art equipment to give students practical training and the opportunity to work on more extensive design projects. Students are trained in how to operate GNSS receivers, decode data and to ultimately progress to work on more extensive final design projects, as described below.

Course Content

As previously described, competencies over a relatively broad range of engineering and science topics are required for understanding GNSS. The course contents are listed in Table 1 for a fourteen-week semester course. The theory of GNSS is presented during lectures that occur three times a week for 50 minutes at a time with a generous allowance for in-class discussion. A laboratory project is assigned each week that reinforces understanding of the theory. The laboratory component is open-access with on-site tutorial help available one day per week. Each student team (generally consisting of two students) is assigned a Lab station with their own GNSS equipment for the duration of the semester.

Topic	**Lectures**
1. Fundamental Concepts, Coordinate and Time Systems	6
2. Satellite Orbit Theory	6
3. Concept of Ranging and GNSS Observables Determination	3
4. Navigation Solution Calculation	4
5. Error Sources and Accuracy Determination	6
6. Atmospheric Effects and Associated Scientific Measurements	3
7. Signal and Communication System Theory	4
8. Discussion of Course Projects	6
9. Differential GPS (*e.g.*, SBAS/WAAS)	2
10. GNSS Modernization	2
Total	**42**

Table 1. GNSS course contents

It can easily be seen that the conceptual basis of the course extends over many engineering and science topics including vector analysis, linear algebra and matrix theory, probability and statistics, Kepler orbit theory, radio wave propagation and electromagnetics, and signal and communication system theory. Concepts of atmospheric science (ionosphere and troposphere) are also discussed and applied including Total Electron Content (TEC), scintillations (S_4, σ_ϕ), and occultation. Typically few undergraduate students, even upper level ones, have strong capabilities across all these disciplines. For instance, aerospace engineers may have a solid understanding of satellite orbit theory but not electromagnetics or signal theory while electrical engineering students may have contrasting skills. Some students may have competencies in vectorial and matrix mathematics but not in probability and statistics theory. We have found that teaching GNSS using a first-principles approach is highly effective for imparting functional competencies across this broad range of topics for both upper level undergraduates and beginning graduate students.

Teaching Laboratory

An accompanying laboratory is the critical component of the course that provides hands-on experience to reinforce the detailed theory behind the topics first presented in the lectures. Our approach to integrating hands-on laboratory exercises has some similarities to other recently described approaches to GNSS engineering education [9]. There are three principal capability 'components' to a complete GNSS teaching laboratory. The first is the capability to tap the raw GNSS data streams. This may be very low level data from the receiver Radio Frequency (RF) front end by which students can investigate tracking and acquisition theory in detail as well as the navigation solution. However, in our experience the typical undergraduate student does not have a sophisticated background in RF signal theory and it is better to allow the non-specialist to have direct access to the higher level data that is more easily converted to standard GNSS results. These higher level data include GNSS satellite ephemeris and GNSS observables (i.e., pseudorange, carrier phase, and Doppler shifts). The direct-access approach is utilized in the course described here, as shown in Figure 1. This allows students to quickly move to the stage of understanding and implementing the detailed calculations for satellite positions, ranging information, and ultimately the GNSS navigation solution. The second component of an effective laboratory is the capability of students to work with the computer codes that process GNSS data and to replicate the calculations performed inside GNSS receivers that determine positions, velocities, and possibly related scientific measurements. A typical desktop or notebook computer is sufficient for this task. The computer language utilized in the course described here is MATLAB which is a standard in ECE departments in the U.S. The calculations are also applied to investigate the various sources of uncertainty and the accuracy of the solutions. The final component of the lab is the capability to compare the results with some reference. The laboratory described here typically uses commercial GNSS receivers for this purpose. Students gain confidence when the results of their calculations match those of the laboratory receivers.

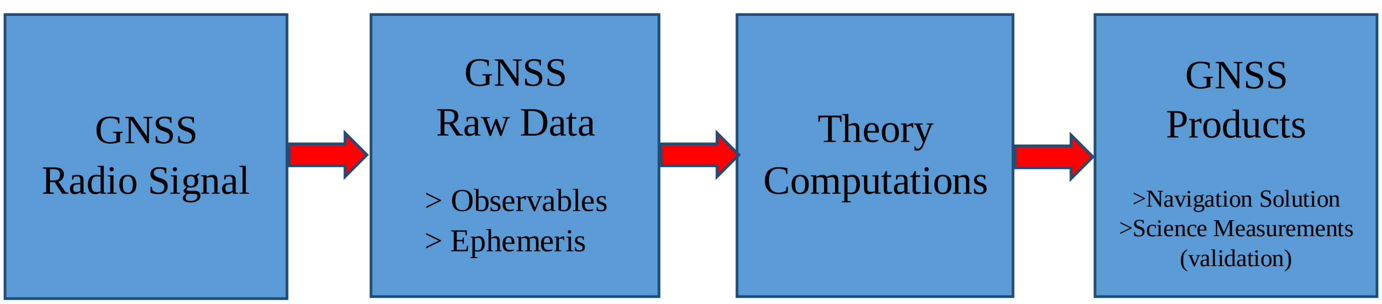

Figure 1. Basic design of a GNSS course laboratory component which emphasizes student computations of GNSS raw data products to reproduce GNSS receiver products (navigation solutions and science measurements).

There are a number of ways to obtain raw GNSS data. One way is to utilize GNSS receivers that allow the user access to the raw data stream. Some of these receivers also allow access to GNSS satellite ephemeris. For receivers that do not provide ephemeris, there is the option of obtaining GNSS satellite ephemeris from various websites such as **ftp://cddis.gsfc.nasa.gov**. If GNSS receivers are used to obtain such live data, the choice of receiver can be tailored to the objectives of the laboratory. For the Virginia Tech laboratory, the Connected Autonomous Space Environment Sensor (CASES) dual frequency L1/L2 GPS receiver has been found to be quite effective for this purpose. The CASES receiver was jointly developed by Cornell, UT Austin, and Atmospheric Space Technology Research Associates (ASTRA), and is sold commercially by ASTRA (**www.astraspace.net**). The CASES receivers are cost-effective and utilize a general purpose digital signal processor (DSP) to perform all the data acquisition, tracking operations, and science and navigation operations. Table 2 summarizes various data streams available from the CASES GPS receiver. In addition to the requisite navigation solutions (column 5 in Table 2), which are provided at 1 Hz cadence, the CASES GPS receiver also provides three additional data streams. These additional data streams include the low and high data rate raw GPS observables and ionospheric scintillation parameters. All of the parameters shown in Table 2 are computed onboard the CASES GPS receiver in real time, and no external computer is required. All data stream rates can also be reconfigured by the user.

Data Type	**Per Channel High Rate Data**	**Per Channel Low Rate Data**	**Per Channel Scintillation Parameters**	**Other**
Default Data Rate	100 Hz	1 Second	60 Seconds	1 Second
Configurable Rate?	Yes, 50 or 100 Hz	Yes, ≥ 1 Second	Yes	Yes, ≥ 1 Second
Available Parameters	> Integrated Carrier Phase > In-Phase Accumulation > Quadrature Accumulation > GPS Time > Receiver Time	> Pseudorange-based **TEC** > Phase-based delta **TEC** > Pseudorange > Integrated Carrier Phase > GPS Time, Receiver Time > Doppler Frequency > SV Elevation, SV Azimuth > C/N_0 > Data Validity Flag, Cycle Slip Flag > Signal Acquisition Status > PRN, SV Health	> S_4 > σ_ϕ > τ_0 > Scintillation Power Ratio > GPS Time > Reference Channel Status > PRN	> Receiver X/Y/Z Position > Receiver X/Y/Z GPS Time > Receiver Time > Velocity > Receiver Clock Error > Receiver Clock > Error Rate > Navigation Solution Flag

Table 2. Summary of CASES GPS receiver data products.

The low rate data is continuously sent at a maximum of 1 Hz (1 sample per second) and provides pseudorange, phase, C/N_0, Doppler shift, receiver position, and velocity. The high rate data are recorded typically at 100 Hz (100 samples per second). Data types included in the high rate data are the in-phase accumulation (I), quadrature accumulation (Q), and phase. The full specifications and characteristics of CASES receiver are described in detail in [10].

Amongst other outputs, the CASES receiver provides the ability to obtain raw GNSS data (*e.g.*, L1, L2 phase observables and range observables) and also data for accessing atmospheric effects (*e.g.* TEC, individual channel carrier to noise power (C/N_0), amplitude scintillation index (S_4), and standard deviation of phase scintillation (σ_ϕ)). This suite of scientific data allows students to thoroughly investigate the impact of the upper atmosphere (ionosphere) on GNSS signals as well as space weather effects. The CASES receiver enables the student to work through the GNSS data from either the raw or direct-access level and to compare the results of his/her computations against those provided by the receiver itself. Importantly, the dual-frequency CASES GPS receiver provides students with an awareness of the ongoing GNSS modernization signals and techniques. The software architecture of the CASES GPS receiver allows students to test, modify, and implement various DSP algorithms for satellite acquisition and tracking, and to investigate their effects on navigation and science data products. Amongst the many re-configurable parameters, students have the ability to change the bandwidth of phase, frequency, and delay locked loops (PLL, FLL, DLL). Students can design their own algorithms to estimate GPS observables and implement them on the CASES GPS receiver to gain valuable hands on experience.

If a GNSS receiver is used to provide raw data for student calculations, there are interesting options for the source of the GNSS radio signal shown in Figure 1. The most obvious choice is to use signals from a GNSS antenna. While straightforward, the subsequent analysis then pertains to a stationary situation. More applications can be explored by allowing the location of the receiver to vary, either physically or virtually, as would be realized in practice with vehicle systems (automotive, aircraft, spacecraft). For such applications, a virtual analysis based on a GNSS RF hardware signal simulator is ideal. An RF GNSS simulator emulates the environment of a GNSS receiver on a dynamic platform by modeling vehicle and satellite motion, signal characteristics, and atmospheric effects, allowing the receiver to actually navigate according to the parameters of the scenario. While such hardware signal simulators are typically expensive, they open up a large range of opportunities for training students. With a GNSS simulator, students can model effects that impact GNSS receiver performance, such as atmospheric conditions, obscuration, multipath reflections, antenna characteristics, and interference signals. They can also run scenarios for many different kinds of tests, with full control of all aspects of the GNSS operating environment. At Virginia Tech., hardware signal simulators produced by Spirent Communications are currently being used for developing raw data streams for the course described here. They allow for various scenarios of vehicles as well as atmospheric and propagation effects on the GNSS constellations (GPS, GLONASS, Galileo, and BeiDou). A GNSS simulator is combined with a spectrum analyzer to demonstrate the spread spectrum concept in addition to the signal structures for different GNSS systems. Students can control the content and characteristics of the GNSS constellation signals and test how GNSS receivers would perform if various GNSS constellation signal errors occurred. Signal simulators have been used for a number of years during the evolution of the teaching laboratory.

We have found that a basic turn-key solution for enabling state-of-the-art GPS engineering practicums described in this paper can be based on the ASTRA receivers. A **CASES GPS Lab Educational Package (**solutions@astraspace.net) can be customized to fit various classroom sizes and coursework requirements. Typical components include: software programmable radio front ends; GPS receivers and antennas; software; and visualization tools. Pricing ranges from a starter package for less than $20k, through advanced packages beginning at $70k. Educational discounts for individual receivers are also available.

Note that these modest costs do not include the cost of the Spirent hardware simulators (www.spirent.com) that we use in the more advanced, optional segments of the course and projects. The cost of simulators is highly variable ($50-500K) depending on the options offered by Spirent, such as frequency bands (e.g., L1, L2, L5) and number of constellations (e.g., GPS, GLONASS, Galileo, BeiDou). Also, spectrum analyzers and oscilloscopes are found to be useful to demonstrate the GNSS signal structure.

Course Projects

Design projects form a critical and defining part of the course. The individual course topics and the associated laboratory exercises are chosen to build up students' core knowledge of GNSS so that they may complete a larger, more extensive design project by the end of the course. The projects require a comprehensive report and oral presentation. Projects over the years have included the development of algorithms for vehicle navigation including automobiles, aircraft, and spacecraft, assessment of propagation effects such as multi-path, and assessment of the impact of the space environment (space weather) on GNSS as well as scientific measurements to characterize the space environment. The application of hardware signal simulators to model atmospheric and propagation effects has primarily been used for research purposes [11]; this type of modeling is also an excellent educational tool that may serve as a basis for laboratory exercises as well as design projects. For the course project, regardless of topic, students typically have to collect and work with raw GNSS data and develop algorithms for processing and analyzing the data. Several of the projects have been expanded and refined for the purpose of exposing new students in summer Research Experience for Undergraduates (REU) programs to research with GNSS.

Student Assessment

Student critiques of the course and other associated feedback have been useful over the years particularly their comments on the laboratory component. The current measurable learning objectives, which describe expected student competencies at the end of the course, are as follows:

- Fundamental GNSS theory and concepts
- Satellite orbit theory and satellite position calculations
- Navigation solution concepts and computational techniques
- GNSS error sources and GNSS accuracy
- Differential GPS

Figure 2 shows an average of four years of data (2010-2014) collected on student perceptions of their degree of mastery of the learning objectives. These are rated on a scale that extends through four levels articulated as *poor*, *fair*, *good* and *excellent*. The perception level on all the learning objectives is *good* or better which is within an acceptable range for the course. It is important to note that the perception on mastery of Differential GPS (DGPS) is acceptable although it is the weakest level of the five learning objectives. This can be directly traced to the fact that due to time constraints there is currently no laboratory component for DGPS in the course. All four of the other learning objectives have one or more laboratory assignments. This appears to underscore the importance of the hands-on laboratory exercises as an essential aspect of the learning experience. In general, student perceptions closely track performances on quizzes and exams. Unfortunately, the data available do not allow further detailed comparison between theoretical and practical approaches, however, such comparison would be very enlightening and will be performed in the future.

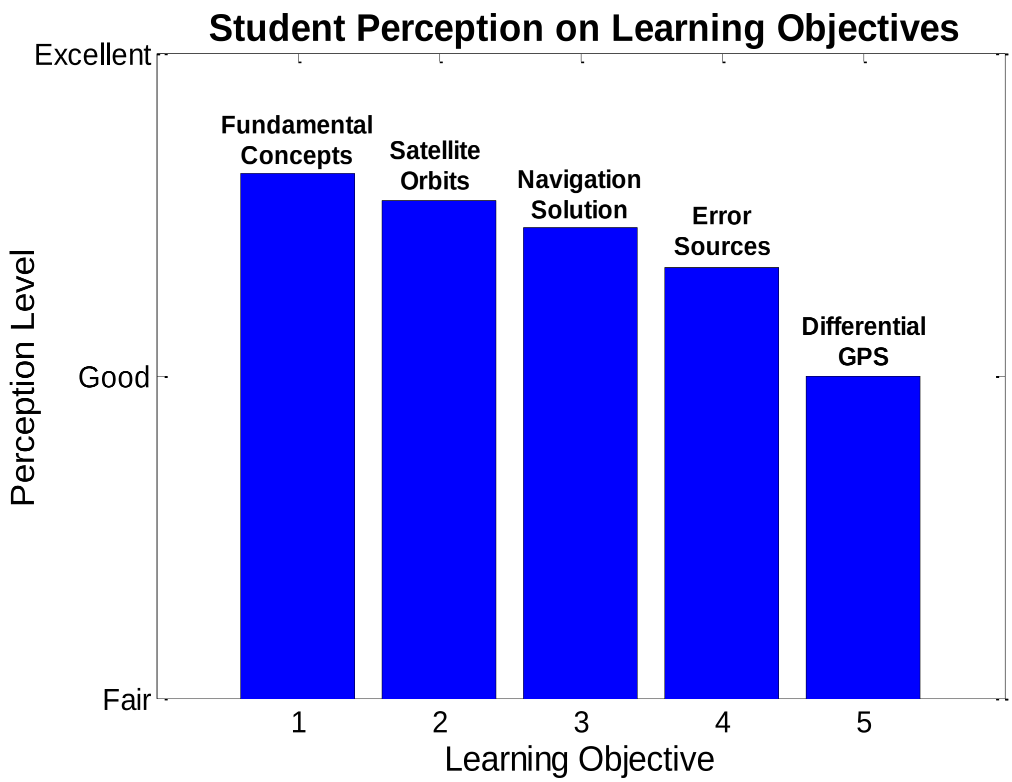

Figure 2. Student perceptions of mastery on major learning objectives.

Future Outlook and Conclusions

Opportunities will continue to grow for well-trained engineers in the area of GNSS design and application of GNSS technology for the foreseeable future. Here, we have described a comprehensive course for senior undergraduates and beginning graduate students that integrates theory and laboratory instruction to promote first-principles understanding of GNSS and competencies in related technical areas and in GNSS analysis and design. As described here, a state-of-the-art laboratory component greatly enhances the instructional value of such a course. The ongoing modernization of GNSS includes the development of a number of new satellite constellations and their accompanying frequency bands and signal structures. This will require an even broader scope of training involving large, international engineering systems. Teaching programs will need to expand to take into account the new GNSS constellations and the applications associated with the expanded services. The new opportunities and teaching requirements will encompass K12 education as well as education and training at the university level. In summary, just as GNSS has revolutionized our society through technological advances over the past few decades, the future is bright for instructors and students to transform education and research experiences with GNSS.

References

[1] Find it with GPS!, Developed by IEEE as part of TryEngineering (www.tryengineering.org).

[2] Bednarz, S. W., and R. H. Audet (1999),The status of GIS technology in teacher preparation programs, *Journal of Geography*, *98*(2), 60-67.

[3] Hartell, E. (2010), GPS-performance in technology education, In *Knowledge in Technology Education: Volume one Proceedings* (pp. 171-177), Griffith University.

[4] Hartell, E. (2012), GPS-Performance in Technology Education Part II, In *Explorations of best practice in Technology, Design & Engineering Education, Volume One* (pp. 141-148), Griffith Institute for Educational Research.

[5] Zecha, S. (2014), Outline of an Effective GPS Education Trail Methodology, 352-361.

[6] Walters, R., and Z. Gao (2006), Strategy to incorporate GIS and GPS applications into construction education, In *2006 ASEE Annual Conference & Exposition: Excellence in Education*.

[7] Wicks, F. (2003), Aerospace Engineering Division" Teaching the Global Positioning System Principles and Applications", ASEE 2003-2271, In *2003 ASEE Annual Conference & Exposition: Staying in Tune with Engineering Education*.

[8] Monemi, S., and Z. Aliyazicioglu (2008), Teaching and using GPS/GIS in electrical engineering projects, AC 2008-2072, In *2008 ASEE Annual Conference & Exposition: New Trends in ECE Education II.*

[9] Phuong, X. Q., G. Povero, and G. Belforte (2010, October), Work in progress—GnssEduPack: An innovative approach to education and training in the field of Global Navigation Satellite Systems, In *Frontiers in Education Conference (FIE), 2010 IEEE* (pp. T4C-1). IEEE.

[10] Crowley, G., G. Bust, A. Reynolds, I. Azeem, R. Wilder, B. W. O'Hanlon, M. L. Psiaki, S. Powell, T. E. Humphreyes, and J. A. Bhatti (2011), CASES: A novel low-cost ground-based dual-frequency GPS software receiver and space weather monitor*, in Proceedings of the 24th International Technical Meeting of The Satellite Division of the Institute of Navigation (ION GNSS 2011)*, pp. 1437–1446, Portland, OR, September 2011.

[11] Dautermann, T., M. Sgammini, and S. Pullen (2013), Ionospheric threat simulation for GNSS using the Spirent hardware signal simulator, *GPS Solutions*, 1-9.