High-latitude and Equatorial Ionospheric Scintillation Based on An Event-Driven Multi-GNSS Data Collection System

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Abstract

This paper describes an event-driven ionosphere and space weather monitoring system and presents some observations of high-latitude and equatorial scintillation characteristics based on data collected at several high and low latitude locations. The backbone of this system is an array of wideband software-defined radios (SDR) synchronized by a common low phase, noise-timing device and controlled by custom decision software that continuously evaluates measurements generated by a commercial ionospheric scintillation monitoring (ISM) receiver. The IF samples collected by the SDR have been post-processed using a variety of receiver signal processing algorithms to minimize loss-of-lock and carrier cycle slips. The results are helping to shed new light on the GNSS signal propagation effects during space weather events, providing a wealth of test data for the development of robust GNSS receivers, and enabling studies of the dynamic ionosphere.

1. Introduction

Being a weakly ionized plasma bathed in the Earth's magnetic field, the ionosphere is an unavoidable pathway through which all space-based radio signals must travel. Sandwiched between the neutral atmosphere and outer space, the ionosphere serves as a critical link in the Sun-Earth system and is home to space weather events. Understanding the ionosphere's effects on radio signal propagation and using radio waves to study the ionosphere have been active research areas for many decades. These subjects have gained renewed interests in recent years because of our societies' increased dependence on satellite technologies, such as the Global Positioning System (GPS) and its extended family of Global Navigation Satellite Systems (GNSS). For GNSS users, the ionosphere is characterized by spatial irregularities, which interfere with its signal propagation, potentially disrupting applications such as aviation, intelligent transportation, precision agriculture, surveying, tracking, and communications that have grown to rely on GPS.

The popularity of GNSS has also led to its recognition as a powerful and versatile means for ionospheric remote sensing and space weather monitoring because of their well-defined signal structures, global coverage, and distributed and passive nature. A number of GPS and GNSS networks have been established for such purposes and have contributed to our understanding of ionospheric effects on satellite navigation and space weather climatology at different geomagnetic regions. However, these legacy GPS networks lack the accuracy, robustness, and spatial and temporal resolution to enable studies of smaller-scale ionosphere plasma structures, which are the causes of the ionosphere's day-to-day variability. Understanding the seeding sources and electrodynamic mechanisms responsible for creation and evolution of these small-scale structures holds the key to space weather forecasting.

These legacy ionospheric scintillation monitoring receiver networks also fall short in providing a high quality and truthful description of GNSS signal distortions when traversing ionospheric structures. This is because GNSS receiver-generated signal parameters estimations are convoluted outputs of disturbed signals inputs and receiver processor transfer functions. Additionally, legacy GPS and even current state-of-the-art ionospheric scintillation monitors often lose signal lock or generate numerous carrier phase cycle slips during strong ionospheric space weather events. Moreover, most of the existing ISM receivers either work with only two GPS civil signals (L1 and L2C), or a limited number of international GNSS signals, which are constrained by on-board computing resources. Such a limitation prevents full utilization of the ever-evolving signals in space. Unprocessed, raw signals across GNSS frequency bands are needed to allow careful processing and analysis of the ionospheric effects on GNSS signals.

To overcome these issues, we developed reconfigurable wideband software radio data collection systems to sample GNSS signals for extensive post-processing to remove non-scintillation error effects and to maintain signal lock (Peng and Morton, 2012). Continuous collection of full wideband, multi-constellation, multi-frequency GNSS signals is not sustainable because of the prohibitive amount of data storage that would be required. Since it is only necessary to collect data during actual space weather events, an event-driven system was developed in which wideband radio front ends record data when space weather event indicators, computed from a continuously operating ISM receiver, surpass a pre-set threshold value (Pelgrum et al, 2011; Taylor et al, 2012). This paper describes the architecture of this data collection system and deployment history, and presents example findings of high latitude and equatorial scintillation characteristics based on processing and analysis of the data collected by the system.

2. Event-Driven Multi-GNSS Data Collection System Description

Figure 1 shows the current schematic block diagram of our continuously evolving, event-driven, multi-GNSS data collection system. A wideband antenna receives the signals within the entire GNSS family of constellations and its outputs are split eight ways to input to a commercial, off-the-shelf, multi-GNSS ISM receiver, such as the Septentrio PolaRxS or the Novatel GPStation-6, and seven software-defined radio (SDR) radio front (RF) ends. These low-cost, reconfigurable SDR RF front ends are Ettus universal serial radio peripheral (USRP, model N210) devices, driven by the same external low-phase noise, oven-controlled, crystal oscillator (OCXO) onboard the ISM receiver to ensure time and frequency synchronization across the entire system. The seven SDR front ends samples GPS L1, L2C, L5, GLONASS L1 and L2, Galileo E1, E5a, E5b, and BeiDou B1 and B2 signals at 25MHz and up to 14-bit resolution. The results are temporarily stored in the circular buffer of the data collection server. Sample ISM measurements are used to establish baseline characteristics based on amplitude and carrier phase scintillation indices (S_4 and σ_ϕ), carrier-to-noise ratio (C/N_0), carrier-minus-code (CMC) measurement multipath indicators, and visual inspection at each antenna site. Space weather event threshold values are then determined based on these baseline characteristics. A software trigger mechanism will then signal the contents of circular buffers to be stored permanently to a local RAID storage array if the ISM measurements surpass the threshold values. This process continues until after the event subsides to normal quiet conditions. The data collection server communicates with the data center at our home institution via a virtual private network (VPN) connection to the Internet, allowing remote re-configuration of the RF front ends, monitoring of the status of the system's operation, and retrieval of sample measurements.

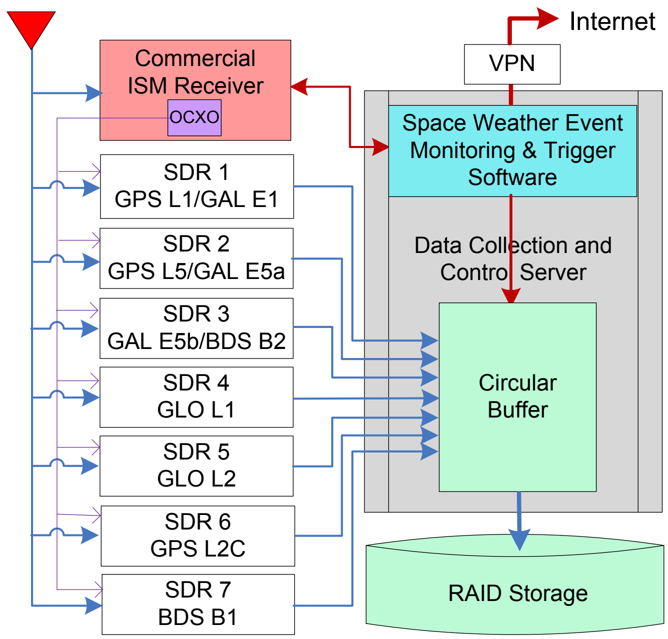

Figure 1. Schematic block diagram of an event-driven, multi-constellation, multi-frequency wideband GNSS data collection system.

To date, well over 120TB of high quality raw GNSS signal samples containing various levels of ionospheric disturbance signatures have been captured by this unique network of data collection systems at high and low latitude stations, as shown in Figure 2. The USRP front ends samples are post-processed using custom GNSS receiver acquisition and tracking algorithms designed to handle deep signal fading and high carrier dynamics typically associated with ionospheric scintillation signals. In addition to providing a wealth of resources to observe and study ionospheric scintillation phenomena, these data have played a critical role in supporting and testing the development of robust and accurate GNSS receiver carrier-tracking algorithms (Carroll et al, 2014; Yin et al, 2014; Xu and Morton, 2014, 2015; Kassanbian and Morton, 2013, 2014). In this paper, we will only focus on highlighting some of the characteristics of scintillation signals without going into the details of the receiver processing algorithms.

3. Example Characteristics of High Latitude and Equatorial Scintillation.

We present several characteristics observed from the data collection systems described above. These characteristics are: the time distribution of scintillation occurrence, the relationship of scintillation to solar activity, and correlation of scintillation with geomagnetic activity.

The occurrence frequency of scintillation events, defined as the number of scintillation events recorded during a certain time interval, is an important indicator in scintillation climatology studies. The knowledge that the occurrence frequency is dependent on the time of day and the seasons can help to predict the periods when scintillation is most likely to occur. Figure 3 shows the scintillation hourly occurrence probabilities at the three data collection sites with respect to hours after local sunset. Although scintillation events at the three locations mostly occurred during local night time, the distribution at high latitudes is much broader than those at low latitudes where the events are mostly concentrated between 1-2 hours post local sunset and midnight. Statistics show that more than 98% of the scintillation at Jicamarca and Ascension Island was observed from one to six hours after sunset, which is consistent with the previous findings of numerous researchers [*Basu et al.*, 2002; *Cervera and Thomas*, 2006; *Beniguel et al.*, 2009].

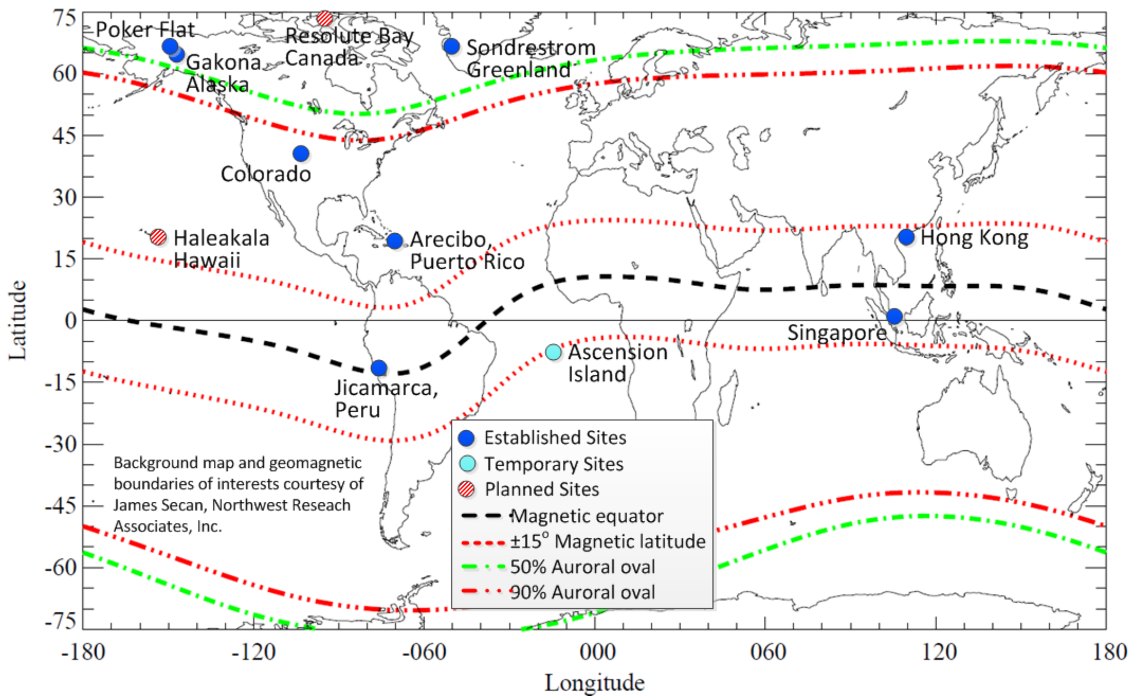

Figure 2. Locations of multi-GNSS, multi-frequency data collection systems deployed since 2009.

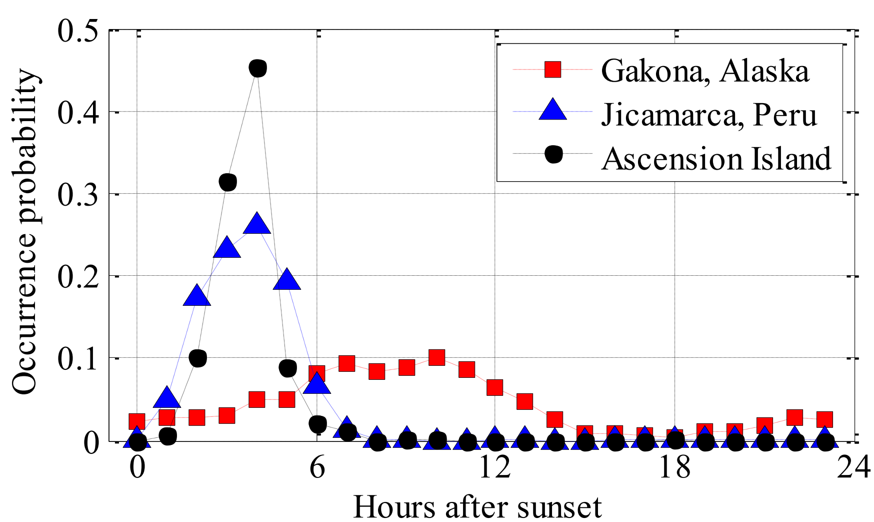

Figure 3. Scintillation occurrence frequency on L1 with respect to hours after local sunset.

In addition to solar radiation, scintillation occurrence is also affected by the Earth's orientation and the Sun-Earth magnetic field interaction, which is partly reflected in the seasonal pattern of scintillation. Figure 4 illustrates how scintillation occurrence frequency at Gakona and Jicamarca was affected by solar activity and seasons. The four seasons are defined as: spring (SP) – March to May; summer (SU) – June to August; fall (FA) – September to November; winter (WI) – December to February. The intensity of solar activity is indicated by the seasonal sum of the monthly sunspot number shown as black dots. Due to the limited datasets available from these two sites, it is difficult to make a clear-cut comparison until more data is processed. Nevertheless, several phenomena can be observed from the individual datasets. At Gakona, Alaska, the trend of scintillation occurrence frequency was largely affected by solar activity. Scintillation was observed more frequently around equinoxes (spring and fall) than adjacent solstices (summer and winter). In contrast to the half-a-year cycle at high latitudes, scintillation occurrence frequency at Jicamarca more closely follows a one-year cycle as described in previous research [*Akala et al.*, 2011], and largely decreases in the summer.

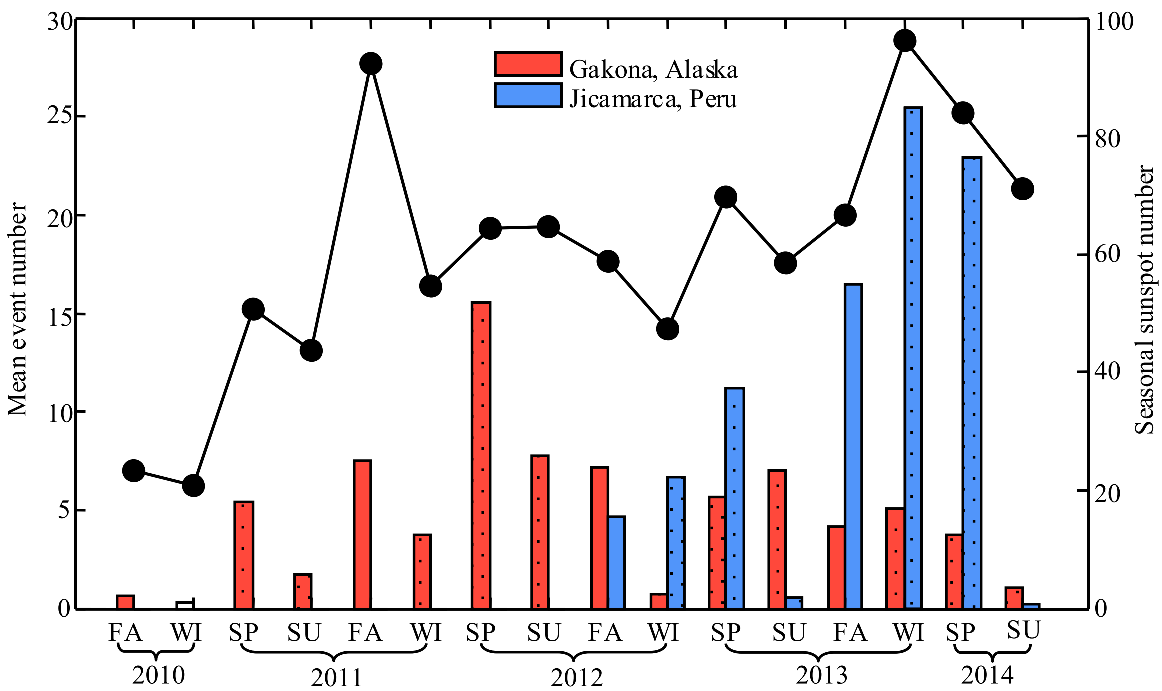

Figure 4. Seasonal scintillation occurrence frequency on L1 and sunspot number.

Figure 5 illustrates the relationship between ionospheric scintillation and geomagnetic disturbances observed at high-latitude using data collected on July 15, 2012 in Gakona, Alaska. The top panel shows variations of the *H*, *D* and *Z* components of the local geomagnetic field. The middle and bottom panels represent the total number of satellites above the elevation mask (blue), the number of satellites affected by either amplitude or phase scintillation events (black), and the percentage of satellites affected at a given epoch (red). This result is characteristic of many high latitude events. Figure 6 shows quantitative numerical relationships between the occurrence probability of phase scintillation events with maxσ_f index larger than 30 degrees, and the variation and deviation in the geomagnetic field. These results indicate that scintillation and local geomagnetic field activities are strongly correlated in Alaska. In contrast, scintillation at our equatorial sites is much less correlated with geomagnetic activity in most events.

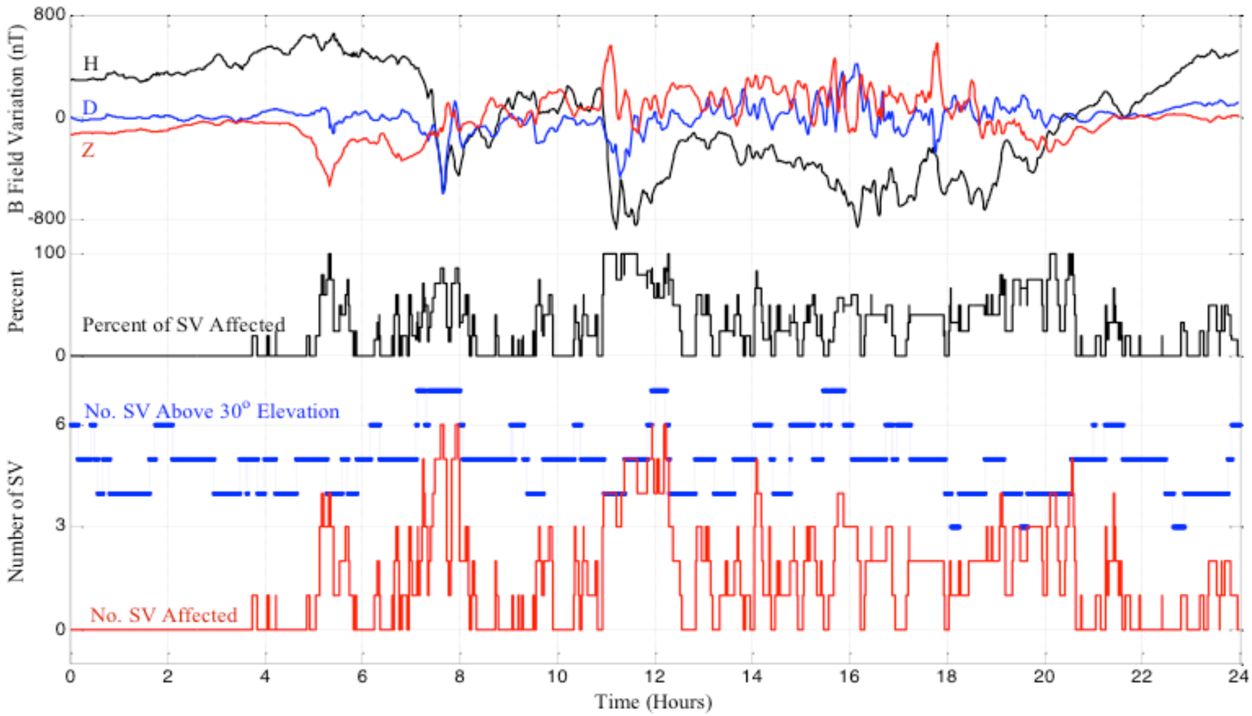

Figure 5. Magnetic field variation, and number and percentage of GPS satellite (SV) signals experiencing scintillation simultaneously on 7/15/2012 at Gakona, AK (Jiao et al, 2013).

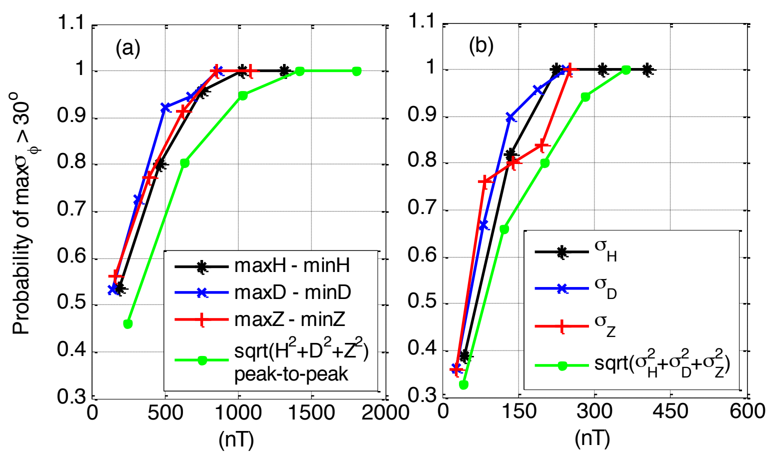

Figure 6. Occurrence probability of maxσ_f> 30° on L1 with respect to (a) variations in geomagnetic field amplitudes and (b) standard deviations in geomagnetic field components in Alaska.

4. Conclusions

This paper describes an event-driven, multi-GNSS, data collection system for ionospheric scintillation monitoring and studies. Several such systems have been deployed at high and low latitude areas and over 120TB of wideband multi-GNSS scintillation data have been collected at these sites. These data has been used to support the development of next generation GNSS receiver-tracking algorithms and study the characteristics of ionospheric space weather phenomena. Several example observations of high and low latitude scintillation characteristics are presented in the paper to demonstrate the usefulness of the data collected.

References:

[1] Akala, A. O., P. H. Doherty, C. E. Valladares, C. S. Carrano, and R. Sheehan, Statistics of GPS scintillations over South America at three levels of solar activity, Radio Sci., 46, doi: 10.1029/2011RS004678, 2011.

[2] Basu, S., K. Grovesa, Su. Basu, and P. Sultana, Specification and forecasting of scintillations in communication and navigation links: current status and future plans, J. Atmo. Solar-Terr. Phy., 64, 1745-1754, doi: 10.1016/S1364-6826(02)00124-4, 2002.

[3] Beniguel, Y., V. Romano, L. Alfonsi, M. Aquino, et al., Ionospheric scintillation monitoring and modelling, Annals of Geophysics, 52, 391-416, doi: 10.4401/ag-4595, 2009.

[1] Carroll, M., Y. Morton, E. Vinande, "Triple frequency GPS signal tracking during strong ionospheric scintillations over Ascension Island," Proc. IEEE/ION PLANS meeting, Monterey, CA, May 2014.

[2] Cervera, M. A., and R. M. Thomas, Latitude and temporal variation of equatorial ionospheric irregularities determined from GPS scintillation observations, *Ann. Geophys.*, *24*, 3329-3341, doi:10.5194/angeo-24-3329-2006, 2006.

[3] Kassabian, N., Y. Morton, "Extending integration time for Galileo tracking robustness under ionosphere scintillation," Proc. IEEE/ION PLANS meeting, Monterey, CA, May 2014.

[4] Kassabian, N., Y. Morton, "Galileo tracking performance under ionosphere scintillation," 4th Int. Colloquium Sci. Fundamental Aspects Galileo Prog., Oct. 2013

[5] Pelgrum, W., Y. Morton, F. van Graas, P. Vikram, S. Peng, "Multi-domain analysis of the impact on natural and man-made ionosphere scintillations on GNSS signal propagation," Proc. ION GNSS, 617-625, Portland, OR, Sept. 2011.

[6] Peng, S., Y. Morton, "A USRP2-based reconfigurable multi-constellation multi-frequency GNSS software receiver front end," GPS Solutions, DOI: 10.1007/s10291-012-0263-y, 2012.

[7] Taylor, S., Y. Morton, Y. Jiao, J. Triplett, W. Pelgrum, "An improved ionosphere scintillation event detection and automatic trigger for a GNSS data collection system," Proc. ION ITM, 1563-1569, Newport Beach, CA, Feb. 2012.

[8] Xu, D., Y. Morton, S. Taylor, "Algorithms and results of tracking Beidou signals during strong ionospheric scintillation over Ascension Island," Proc. ION ITM, San Diego, CA, Jan. 2014.

[9] Xu, D., Y. Morton, "GPS signal fading and carrier phase variations revealed by vector processing," Proc. ION ITM, Dana Point, CA, Jan. 2015.

[10] Yin, H., Y. Morton, M. Carroll, E. Vinande, "Implementation and Performance Analysis of A Multi-Frequency GPS Signal Tracking Algorithm," Proc. ION GNSS+, Tempa, FL, Sept. 2014.