Development of Space Weather Monitoring System and Statistical Study of GPS Scintillations

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***Abstract*—Autonomous Adaptive Low-Power Instrument Platforms (AAL-PIP), containing several space weather instruments, were recently deployed in Antarctica. Among the instrumentation on the platforms are magnetometers for measuring magnetic activity and Connected Autonomous Space Environment Sensor (CASES) Global Positioning System (GPS) software-defined receivers for measuring ionospheric scintillation. However, no reasonable monitoring system for the AAL-PIP stations exist. As a result, the majority of recorded data has not yet been analyzed. In this project, we develop a Graphical User Interface (GUI) that displays daily magnetic activity and GPS scintillation events, as well as housekeeping data to monitor system health. Also, we conduct a statistical study to reveal a correlation between the disturbances in the ionosphere and GPS signal fading. In this study, we find general patterns of the relationship in the recorded data from 24 January 2012 through 7 May 2012 utilizing different sets of data from the AAL-PIP system and reputed solar storm indices.**

I. Introduction

The sun emits a continuous flow of charged particles that permeates throughout the solar system. This emission is known as the solar wind. Its direct interaction with the the Earth's magnetic field creates a unique environment called 'magnetosphere' and often cause the magnetic fields to fluctuate. The effects of the energy coupling between the Sun and the Earth are visibly evidenced by Auroras on both South and North Poles, brilliant natural light displays in the sky caused by the collision of energetic particles with atoms in the high latitude atmosphere. However, due to the large variation of magnetic flux in the magnetosphere by the solar winds, the resulting Geomagnetically Induced Current (GIC) may cause damage to the electrical power system. It is, thus, vital to monitor such fluctuations.

The geomagnetic activity can be measured with a device known as magnetometer. Two types of magnetometers are regularly utilized, fluxgate and search-coil. According to [1][2], the fluxgate magnetometer is typically used to measure the DC magnetic fields. It is capable of keeping track of a vector field which always points in the same direction and maintains the same magnitude. On the other hand, search-coil magnetometer (also known as induction magnetometer), only picks up AC field. The DC field, static magnetic field, is actually the magnetic flux density of the Earth's internal field. The AC field, change in the magnetic activity, is the sum of all of the geomagnetic activity. This isolates the measurement to the fluctuating activity in the field caused by the solar wind [1][2][3].

In conjunction with the geomagnetic activity, the solar wind causes fluctuations in the electron density of the Earth's ionosphere. These ionospheric irregularities interfere with traversing radio signals transmitted by Global Position Systems (GPS). A signal refracts as it passes through the irregularities causing a distortion of its phase and amplitude. These distortions, as observed in the received signal, are referred to as ionospheric scintillations. As a result of the scintillations, GPS signals may suffer fading and even loss of lock with its receiver.

Scintillations occur most often at the equatorial and high latitude regions. Many scintillation studies have been performed for the low and mid-latitude regions, as a greater number of scintillation receivers are available in those locations [4][5][6]. However, due to the necessity of signal continuity in GPS, it is important to study the effects of the high latitude scintillations. In the past decade, several scintillation analyses were performed in the Arctic regions. However, due to the absence of civilization and extreme environment, the Antarctic regions were impractical settings to perform any sort of research.

As part of a collaborative project funded by the National Science Foundation (NSF), the Polar Experiment Network for Geospace Upper-atmosphere Investigations (PENGUIn) team assembled six Autonomous Adaptive Low-Power Instrument Platforms (AAL-PIP) systems in the polar regions to measure space weather, the changing environmental conditions in the space between atmospheres of the Earth and Sun. Four of these AAL-PIP systems contain, along with both fluxgate and search-coil magnetometers, Connected Autonomous Space Environment Sensor (CASES) GPS receiver, as explained in [7][2].

The CASES receivers deployed on AAL-PIP stations are custom designed to monitor GPS scintillations in Antarctica. CASES is a dual frequency GPS antenna/receiver that tracks L1C/A and L2C signals and measures the phase and amplitude scintillations in the ionosphere. It contains a cognitive engine that can trigger low rate data (up to 10Hz) or high rate data (50-100Hz) collection based on scintillation activity. CASES incorporates software defined radio technology which provides

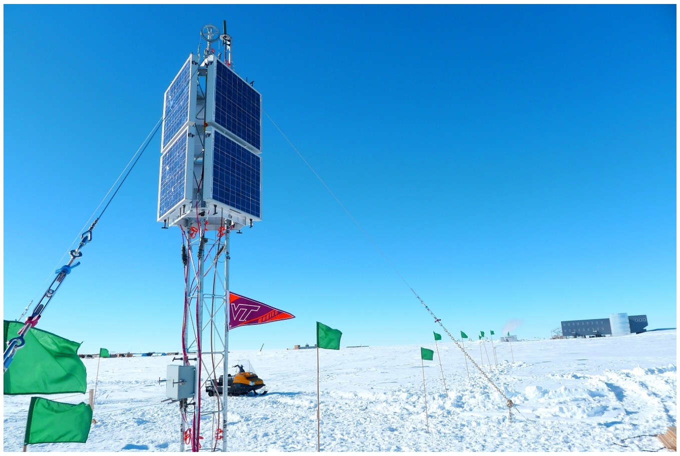


Fig. 1. An AAL-PIP system deployed in Antarctica at the United States South Pole station.

the ability to make updates, change various power saving modes and collect data remotely. However, CASES requires post-processing outside of the AAL-PIP system.

AAL-PIP still requires a remote user interface, and data recorded thus far (72 days of data between 24 January 2012 and 7 May 2012) has yet to be analyzed. It has been our goal to produce a monitoring system displaying space weather data and system health of AAL-PIP, as well as to analyze recorded data to explore the relationship between solar storms and GPS scintillations.

II. AAL-PIP Monitoring System

Currently, the instruments on AAL-PIP in Antarctica are controlled from a server located at University of Michigan, Ann Arbor. Data from the instruments is also downloaded to the server daily. We developed a new Graphical User Interface (GUI) to track Virginia Tech remote stations in Antarctica, and new software to download the fluxgate magnetometer (FGM), search-coil magnetometer (SCM), GPS CASES receiver (GPS) and system health, or housekeeping (HSKP), data. This data is displayed on the screen automatically on a daily basis to be utilized as an "AAL-PIP System Monitoring System" and "Space Weather Monitoring System" at Virginia Tech. Figure 2 is a block diagram showing the work cycle process from the initial retrieval of raw data from AAL-PIP to the final display of the data on the GUI.

The on-board computer on the AAL-PIP take different data sampling rates. For example, fluxgate magnetometer takes at rates of one sample data per second, Search-coil takes at 10 samples per second [2], housekeeping takes at 4 samples per minute and GPS takes at low sampling rate 10 samples per second and at high sampling rate 50 samples per second. Housekeeping, Seach-coil, and GPS cases data files are stored in various binary formats, while the Fluxgate data is in ASCII text format.

To download, track, and backup files on Linux systems, the Rsync program is utilized. Rsync is a software application and network protocol for Unix-like and Windows systems that synchronizes files and directories from one location to another while minimizing data transfer and is widely used for backups and mirroring and as an improved copy command for everyday use. It behaves in much the same way as rcp, a command on the Unix operating systems that is used to remotely copy to copy one or more files from one computer system to another. But, Rsync has several more advanced options and uses the rsync remote-update protocol, which greatly speeds up file transfers when the destination file already exists. To automatically download all the files on Windows systems, NcFTP or PSCP is run via the operating systems task scheduler. Ncftp provide a powerful and flexible interface to the Internet standard File Transfer Protocol (FTP). PSCP is a freeware SCP (Secure Copy) program for the Windows command line processor. PSCP proves to be the best at handling SFTP (Secure File Transfer Protocol) remote connections. To track, backup, and synchronize files, Delta Copy, an open source program, is utilized. On first use it will backup all selected files then it will only copy the part of file that has actually been modified.

To process the data from a particular instrument like the search-coil, fluxgate, and CASES GPS, as well as the House-keeping, we developed MATLAB programs that individually and automatically run on schedule. To process the obtained instrument data, we applied our MATLAB scripts and routines to display the data in a visually comprehensible format. By using these scripts, we created different statistical analysis tools and different types of plots.

The MATLAB scripts for processing the instrument data are run independently of the GUI. They are executed on a 24 hour time interval to grab the raw data files once downloaded from the Michigan server. The codes decompress each instrument data and convert them to formatted ASCII (text) files that are easy to manage. Data parsing is also utilized to place all of the instrument data together without shifting the time results. On occasion, the time sampled data contains empty results. In

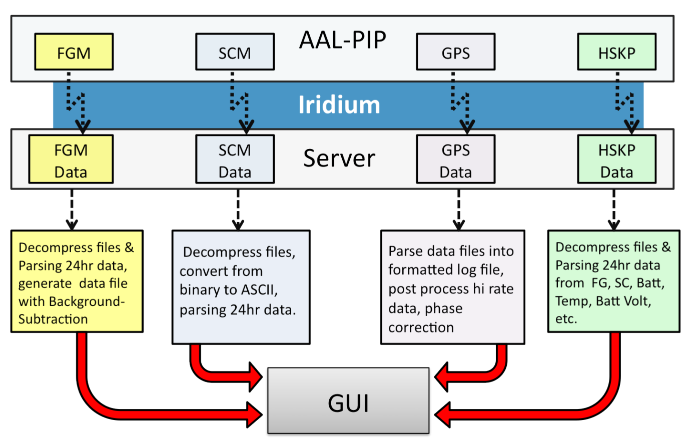


Fig. 2. Block Diagram of the overview of the work cycle, the file transfer, data handling, and display in the Graphical User Interface.

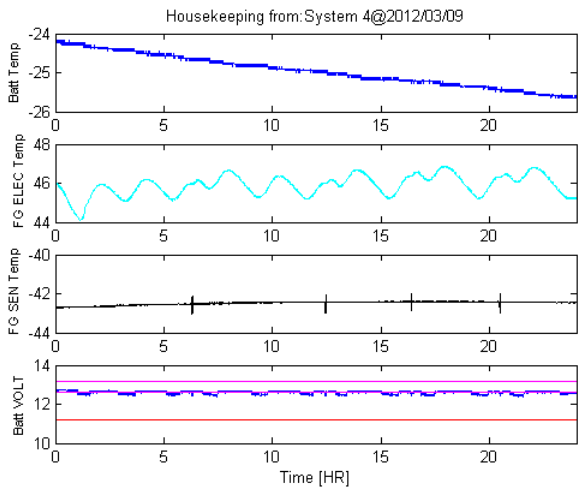


Fig. 3. Sample generated plot of the AAL-PIP Housekeeping (system health) data.

these cases, interpolation is utilized to fill in the missing data smoothly. After parsing, all processed data is saved for future analysis and plot images are generated for display.

The housekeeping data is used to display the health conditions of the AAL-PIP. It contains temperature readings from the fluxgate sensor, electronics box, and battery box, battery voltage levels, and on/off states. This data is pre-parsed and can be plotted immediately. Figure 3 is the produced housekeeping plot.

The fluxgate data samples must be processed, before plotting. Because the main interest is to obtain the variation of magnetic fields (the sum of all magnetic field minus the field generated by earth), we then subtract the DC fields by taking the average (the mean) of all day samples and subtracted to

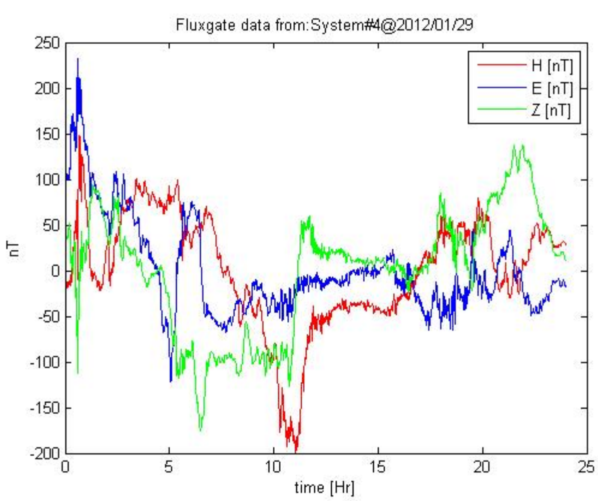


Fig. 4. Sample generated plot of the AAL-PIP Fluxgate Magnetometer data.

the original raw data results. Figure 4 is the produced fluxgate magnetometer plot.

The search-coil sensor on the other hand, picks up only the changes in magnetic flux density (AC magnetic components) due to the physics involved in the sensor. The data files are 10 times larger than those from the fluxgate magnetometer, and files are not in text format but in binary. We obtain from the AAL-PIP 2 channel measurements, the X component and the Y component.

The ability to compare the GPS scintillation rates with magnetic activity recorded by the magnetometers is of vital importance in the GUI, as the possible correlation between the two is of great interest. However, the GPS data recorded by CASES receiver require even more further post processing than the magnetometer data because a certain degree of phase correction is necessary to resolve oscillator noise errors.

The independent processing scripts provides the GUI with the freedom to handle the graphs display without wasting resources in the analysis. The front end of the GUI is a simple format such that most users could understand from first impression how to use it. Figure 5 is a screenshot of the final product of the GUI. With this interface, selected plots are shown in such a way that data can be more easily interpreted, managed, compared and printed.

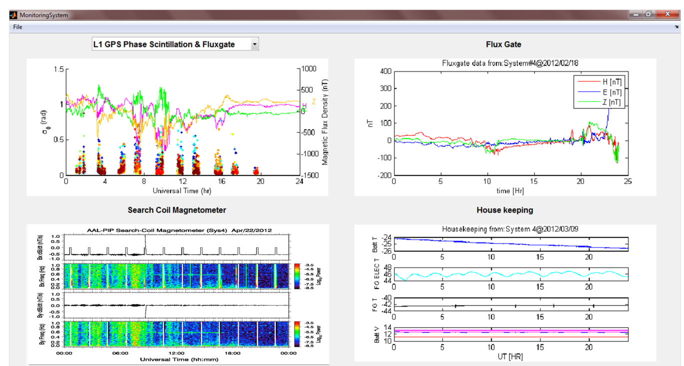
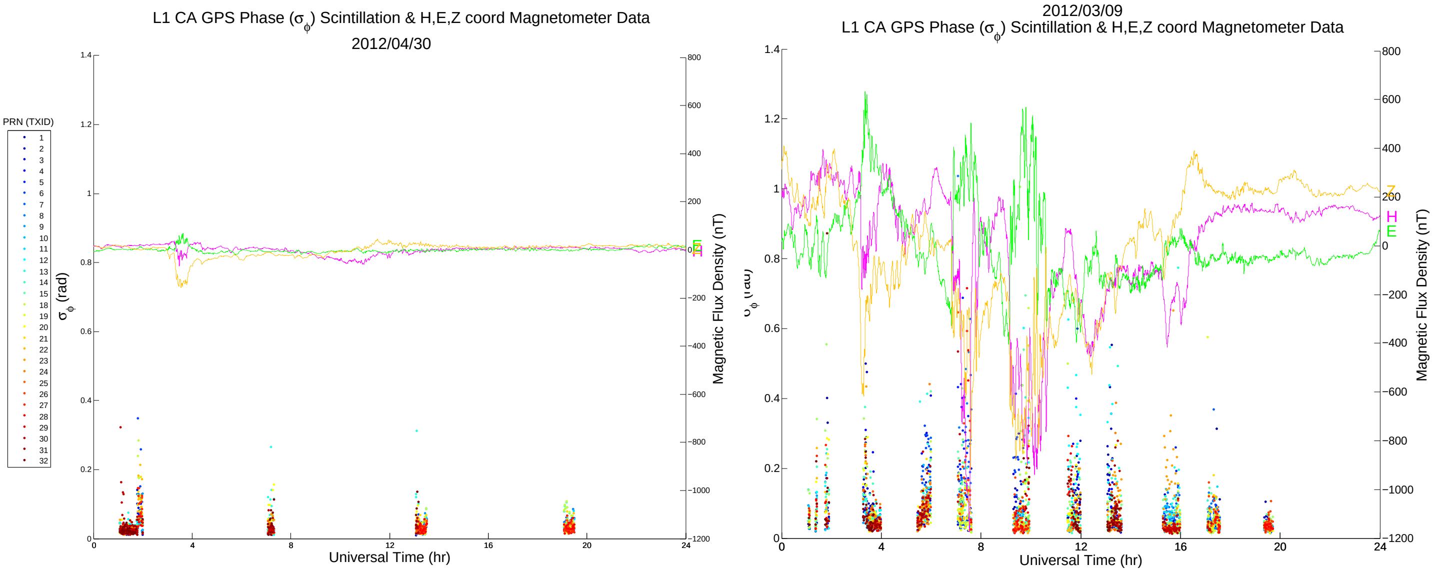


Fig. 5. Screenshot of the final product of the GUI for a sample day.

III. Statistical Study of GPS Systems

GPS scintillation is distortion of a GPS signal caused by the diffraction produced as it passes through the ionospheric irregularities with fluctuating electron density distribution. Distortion and fading to a GPS signal can be observed in both the phase and amplitude of the signal.

We study GPS scintillation in order to learn more about how the events occur, and when they occur the most. Previous analysis has indicated that GPS scintillation is most prominent in the equatorial and high latitude regions. In our studies, we observe data from one of the AAL-PIP systems, System 4, stationed in South Pole, Antarctica. We are able to examine two scintillation parameters from the recorded data: amplitude scintillation index (S4) and standard deviation of detrended phase (σ_ϕ). Although, for purposes of our study, we focus



(a) (b)

Fig. 6. Geomagnetic activity on fluxgate magnetometer and low rate GPS phase scintillation on CASES recorded at the AAL-PIP South Pole Station 4 during (a) a 'quiet' day and (b) a storm day.

more on phase scintillation because at high latitudes, more profound fluctuations occur in phase scintillations than in amplitude scintillations [6].

The CASES GPS receivers record data for two major frequencies during measurements: L1CA (GPS L1 legacy civil code) and L2CL (GPS L2 civil L code) [8]. Scintillation is measured in both frequencies, but useful high rate data is most detected only on L1CA. Thus, for our study, we generally focus more on data in the L1CA GPS signal frequency.

The time period for the study begins 24 January 2012, as this was the start of AAL-PIP System 4's operation. The end of the period is 7 May 2012, which is when the AAL-PIP system went into hibernation mode until the return of sunlight to the south pole. However in this time period, there are only 72 days of scintillation data. This is due to the data limits of system upload/download. Only 13 MB of GPS data can be sent to the Michigan server each day. In normal mode operation, the CASES receiver collects low rate data (up to 10 Hz sampling) and triggered-high rate data (50 - 100 Hz sampling) until the daily memory limit is reached. However, if a major incoming solar storm is detected, CASES can switch to storm mode, in which the receiver is operated on a 1 hour ON and 1 hour OFF schedule for 24 hours, as described in [9].There is no limit on the amount of data stored. However, in order to send the data back, it must be transmitted via the allotted 13 MB/day as priority over data from days deemed less important. For this reason, the scintillation data of those non-storm days are not stored on the AAL-PIP system. In the case of our time period, 33 days of GPS scintillation data were removed.

In our initial analysis of the 72 day dataset, we plot daily low rate GPS scintillation from the CASES receiver with magnetic activity from the fluxgate magnetometer to see any general correlations. For example, Figure 6a is the plot for April 30 2012, a quiet day, or a day of low geomagnetic activity, while Figure 6b is the plot for March 9 2012, a storm day, or a day of high geomagnetic activity. In both, higher number of scintillations occur in conjunction with fluctuations in magnetic activity. Of course, smaller fluctuations in magnetic activity are in conjunction with smaller rises in scintillation, while greater fluctuations are in conjunction with greater rises. This pattern is common throughout the full time period.

To further explore this relationship, we examine the high rate scintillation data. However, prior to its analysis, the high rate scintillation requires a certain degree of post processing. This is due to the fact that the CASES receiver uses temperature-compensated crystal-oscillator (TCXO) as a reference oscillator. Noise from the oscillator is prevalent in phase scintillations. It is, therefore, necessary to remove this noise to avoid false detection of phase scintillation [9].

In order to analyze the high rate data, we modify a previously developed program designed to perform the post processing correction [9]. Our modifications recursively run through each day of the scintillation data, and, after post processing, determines the daily maximum scintillation and the daily number of scintillations. Using this selected data we are able to perform macro-analyses.

We observe the distribution of recorded ionospheric scintillations throughout the day to find the common patterns of occurrence. Specifically, we look at the relationship of the recorded scintillations with the daily geomagnetic storm and substorm times, the times during the day in which the solar wind is most directly and most indirectly hitting the location respectively. To do so, we convert to a Magnetic

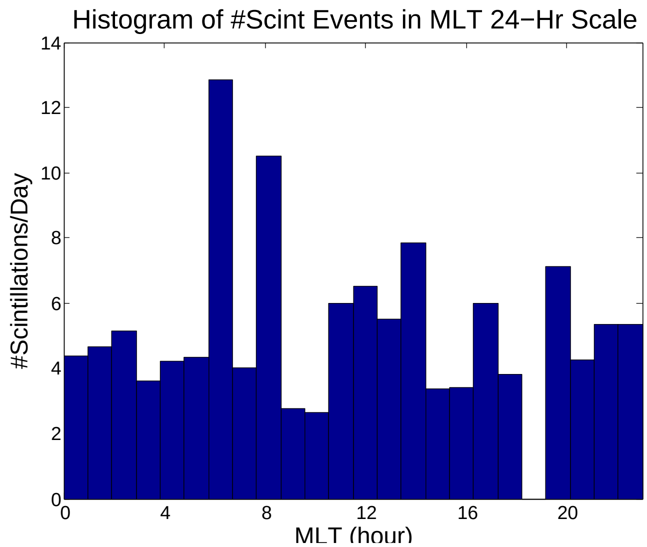


Fig. 7. Cumulative number of scintillations per hour during high rate collection for the test period

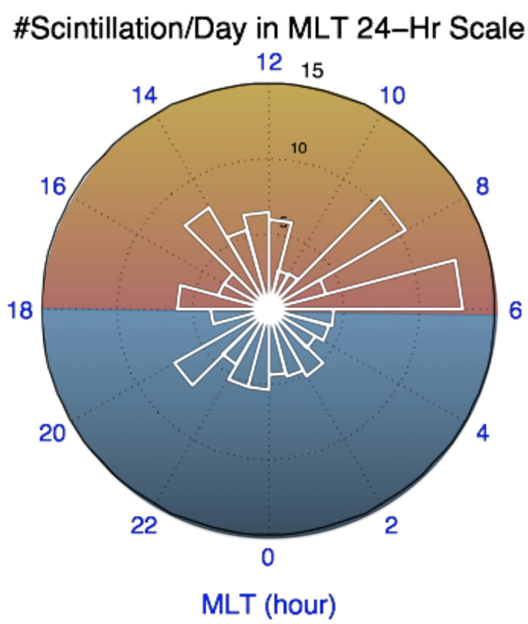


Fig. 8. Cumulative number of scintillations per hour during high rate collection for the test period

Local Time (MLT) scale. MLT is a time-zone system based on true geomagnetic coordinates. At the south pole there is a 3.6 hour offset from Universal Time. This means, for instance, that 0:00 MLT is 3:36 UT. In MLT, the daily geomagnetic storms typically occur in the dayside while substorms in the nightside. Due to data limit and power consumption constraints, no days have full 24- hour data. Certain days have data at particular times, while others do not. In order to compensate for this, the cumulative number of scintillation events in each hour is normalized by the total number of days in which those scintillation events occurred. This produces a normalized distribution of number of scintillations per day per hour. Figure 7 and 8 displays such a distribution for the time period. From Figure 8, it is clear that, during the period, there were more scintillation events recorded during the daytime, with the most occurring at geomagnetic dawn, around 6:00 MLT.

We also compare scintillation for the period with indicators from external sources. Kp, Dst, and AE are reputed storm indexes whose scales are derived from global geomagnetic readings from ground-based magnetometers. Kp index is an estimated 3-hour interval indicating storm-level geomagnetic activity between 1 - 9 where 1 indicates quiet activity and 9 indicates extreme storm time [11]. Dst index monitors magnetic storm-level in a world wide scale in units of nano Tesla; negative indicates that there is a storm, more negative harsher the storm [11]. AE index describes the auroral electrojet activity in the auroral zone [11]. The number of sunspots is a phenomenon that is closely related to the sun's magnetic activity [12]. We plot both daily index plots like the plot in Figure 9, and a large-scale plot as shown in Figure 10, which displays the number of scintillations per day along with the max daily Kp and Dst index values and number of sunspots from 24 January to 7 May 2012. In the latter the similar

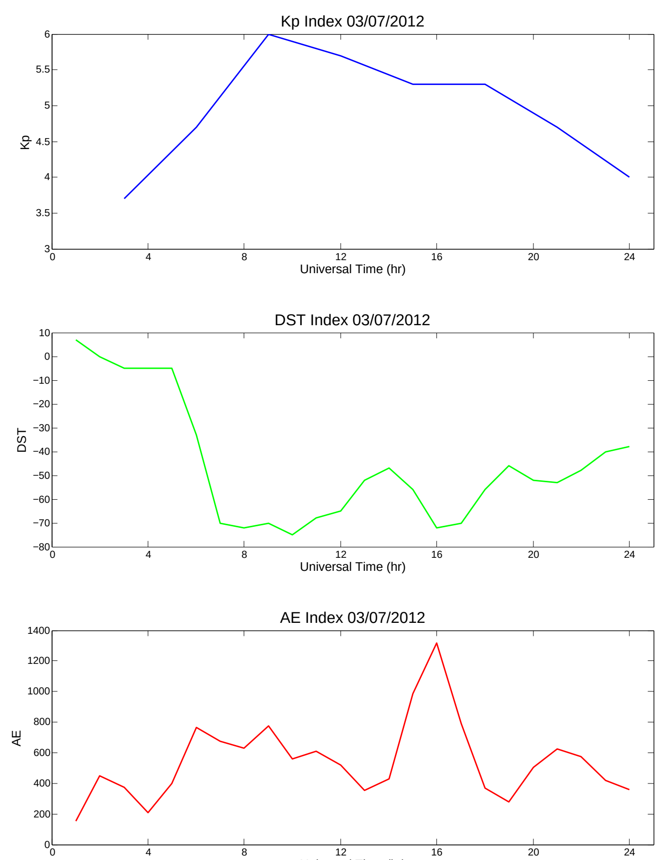


Fig. 9. Sample day plot of Kp, Dst, and AE indexes

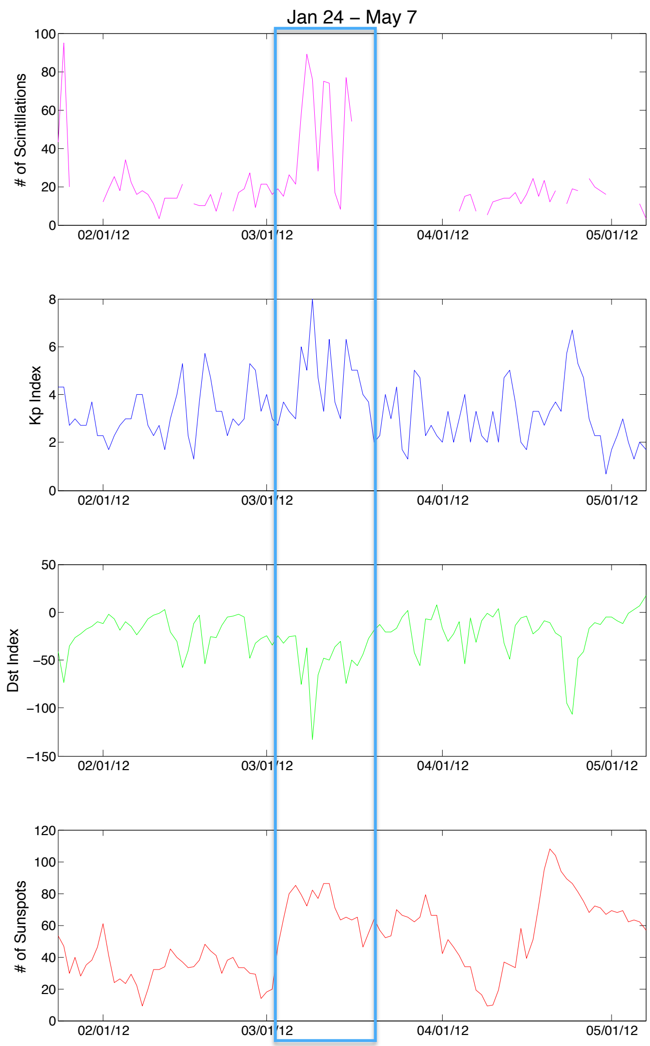


Fig. 10. Comparison of daily number of scintillations with daily max Kp and Dst storm indices, as well as daily number of sunspots over the period of time.

incidents of activity between all, indicate a strong correlation between ionospheric scintillation and solar magnetic activity.

IV. Conclusion

We have developed an AAL-PIP Monitoring System GUI that can be utilized to monitor day to day activity, as well as tools to further analyze GPS scintillation. The monitoring system and the analytical tools can be used in conjunction with each other and even integrated for the use of analytical studies. The monitoring system displays daily readings from the fluxgate magnetometer, search-coil magnetometer, and GPS CASES receiver, along with AAL-PIP housekeeping data.

In the statistical analysis of GPS scintillation from 24 Jan - 7 May 2012, a higher number of scintillation events occur during the magnetic local daytime, with the most occurring around dawn. The study also revealed a close relationship between the recorded GPS scintillation and magnetic activity caused by solar winds.

Both the GUI and scintillation analysis tools will be utilized to continue further research of space weather activity from Antarctica.

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