TIME FREQUENCY ANALYSIS AND HILBERT-HUANG TRANSFORM (HHT) OF SINGLE EVENT UPSET (SEU) IN FORMOSAT-2 AND FORMOSAT-3 MISSIONS

Tsung-Ping Lee [*1], Chen-Chou Fong [2], Shan-Kuo Yang [3], His-Mao Tseng [4], Cheng-Chung Huang [5], Way-Jin Chen [6], Chao-Yen Chen [7], I-te Lee [8] and Jann Yeng Liu [9]

[*1] Associate Researcher, Product Assurance, National Space Organization, 8F, 9 Prosperity 1st Road, HsinChu Science Park, HsinChu 30078, Taiwan; Tel: + 886-3-578-4028#1256; E-mail: kevinkohila@nspo.narl.org.tw

[2] Researcher, System Engineering , National Space Organization, 8F, 9 Prosperity 1st Road, HsinChu Science Park, HsinChu 30078, Taiwan; Tel: + 886-3-578-4028#9202; E-mail: cjfong@nspo.narl.org.tw

[3] Engineer and Section Head, Satellite Operations Control Center, National Space Organization, 8F, 9 Prosperity 1st Road, HsinChu Science Park, HsinChu 30078, Taiwan; Tel: + 886-3-578-4028#1561; E-mail: edyang@nspo.narl.org.tw

[4] Assistant Engineer, Product Assurance, National Space Organization, 8F, 9 Prosperity 1st Road, HsinChu Science Park, HsinChu 30078, Taiwan; Tel: + 886-3-578-4028#2266; E-mail: tseng@nspo.narl.org.tw

[5] Researcher, Product Assurance, National Space Organization, 8F, 9 Prosperity 1st Road, HsinChu Science Park, HsinChu 30078, Taiwan; Tel: + 886-3-578-4028#9205; E-mail: arthur@nspo.narl.org.tw

[6] Researcher and Section Head, Product Assurance, National Space Organization, 8F, 9 Prosperity 1st Road, HsinChu Science Park, HsinChu 30078, Taiwan; Tel: + 886-3-578-4028#1312; E-mail: wjin@nspo.narl.org.tw

[7] Research Assistant, National Space Organization, 8F, 9 Prosperity 1st Road, HsinChu Science Park, HsinChu 30078, Taiwan; Tel: + 886-3-422-7151#65759; E-mail: cychen@jupiter.ss.ncu.edu.tw

[8] Ph. D. Student , Institute of Space Science, National Central University, No. 300, Jhongda Rd., Jhongli City, Taoyuan County, 32001, Taiwan; Tel: + 886-3-422-7151#65780; E-mail: 956203001@cc.ncu.edu.tw

[9] Professor and Chief Scientist, National Central University and National Space Organization, 8F, 9 Prosperity 1st Road, HsinChu Science Park, HsinChu 30078, Taiwan; Tel: + 886-3578-4028#9172; E-mail: tiger@nspo.narl.org.tw

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ABSTRACT: Taiwan's second satellite, the FORMOSAT-2 (FS-2), is a high-resolution remote sensing satellite. FS-2 has operated successfully for over 7 years since May 21, 2004. The FORMOSAT-3 (FS-3)/COSMIC (Formosa Satellite No. 3 / Constellation Observing System for Meteorology, Ionosphere, and Climate) mission consisting of six Low-Earth-Orbit (LEO) satellites is the first constellation demonstrating near real-time Numerical Weather Prediction (NWP) using radio signals from the Global Positioning System (GPS) satellites. The FS-3 satellites have performed successfully for over 5 years since their launch on April 15, 2006. Over 300 satellite reboot and reset events have been recorded during the FS-3 mission, and similar Automatic Reconfiguration Order (ARO) events have been recorded on FS-2. Over 2,000 Star Tracker Lost Bytes (LB) events have occurred on FS-2 caused by single event upset (SEU). In this study, we have found that FS-2 ARO and star tracker data lost bytes (LB) are positively correlated with space weather, which influences the satellite mission due to several major space weather parameters: the Kp-index of Earth's magnetic field, proton density, electron density and 10.7 cm radio flux (RF). Also, FS-3 computer resets are correlated with Proton Density, Kp-index, Radio Flux F10.7 and X-Ray. Both the Hilbert-Huang Transformation (HHT) and time-frequency analysis methods are used to analyze non-linear, unstable space satellite trending system data. This paper will show the preliminary results of our recent studies.

1. Introduction

An ARO will disturb a satellite mission for at least one day. Out of 34 AROs that occurred on the FS-2 between May 21, 2004 and the present, 10 were due to SEUs. On the FS-3, more than 300 satellite computer anomalies have been designated as SEUs. This tells us that we must put more effort for understanding the cause of SEUs in space. Using the data from the National Oceanic and Atmospheric Administration (NOAA), Taiwan Analysis Center for COSMIC (TACC) and the Quality Information System of National Space Organization (NSPO), we have employed time and frequency methods to obtain an initial result. Relevant technical terms are explained below:

- SEQ_CYCLIC_OVERRUN: This error message reflects the single occurrence of the system being unable to handle all of the cyclic tasks requested by the Star Tracker or Imager of Sprites on the Upper Atmospheric Lightning (ISUAL) within 250 milliseconds.
- SEQ_CYCLIC_OVERLOAD: This error message indicates that two consecutive SEQ_CYCLIC_OVERRUN errors have occurred.
- Lost Bytes: While the FS-2 satellite is operating in standard mode, if the telemetry data that the Star Tracker sends to the Flight Software (FSW) fails the cyclic redundancy check (CRC), then the entire 152-byte is discarded, hence “Lost Bytes”.
- Automatic Reconfiguration Order (ARO): ARO occurs when the satellite computer has received the restart command in order to protect the satellite mission and the satellite body from permanent harm. The restart command can be triggered by high energy particles, which may induce parity changes in the transistor or related electrical components.

1.1 Tools and Study platform

We have used the time-frequency analysis tool Visual Signal by AnCAD (http://www.ancad.com.tw/). Our experimental platform is a PC with Intel Dual Core T7300 processor and 4 GB of RAM running Windows Vista.

1.2 Methodology

The Hilbert-Huang Transform method (HHT) (Norden E Huang, 2005) (Yuping Zhang, 2006) has been used to separate data into sub-data, and the Hilbert Transform (HT) (Norden E Huang, 2005), a sub-algorithm within HHT, has been used to transform data from the time domain to the frequency domain. Then a matrix correlation method has been used to calculate the covariant correlation coefficient, R, between space weather and SEUs.

2. Analysis Processes

The HHT method can deal with non-stationary and non-linear data. Since the Star Tracker Lost Bytes data from FS-2 is not continuous in sampling daily data (zeros are received when no AROs occur), we have summed the data by month. Table 1 show the data format of partial data as listed below:

Table 1: Input Source Data

year	month	LB	RF	KP	PD1	PD100	XR_BG	XR
2004	5	8	1123	1664	2760000	31900	219	36
2004	6	34	2923	4255	8695000	86900	491.6	51
2004	7	25	3679	5899	5.58E+08	89900	1352	1084
2004	8	53	3412	4530	61130000	115800	1138.1	572
2004	9	41	3094	3957	6.48E+08	98000	610.7	75

(LB Source: FS-2 satellite from 2004/5 to 2010/12)

In this table, LB refers to start-tracker lost bytes, RF refers to radio flux of F10.7, KP refers to Kp-index of geomagnetic field, PD1 refers to Proton Density for particle energies between 1 MeV and 100 MeV, PD100 refers to Proton Density for particle energies exceeding 100 MeV, XR_BG refers to X-Ray Background, and XR refers to X-ray.

2.1 Data Analysis

To find the correlation from LB and space weather, we have used HHT to separate source data into intrinsic mode functions (IMF) and used a correlation formula to compare the correlations. Figure 1 shows the calculation design flow:

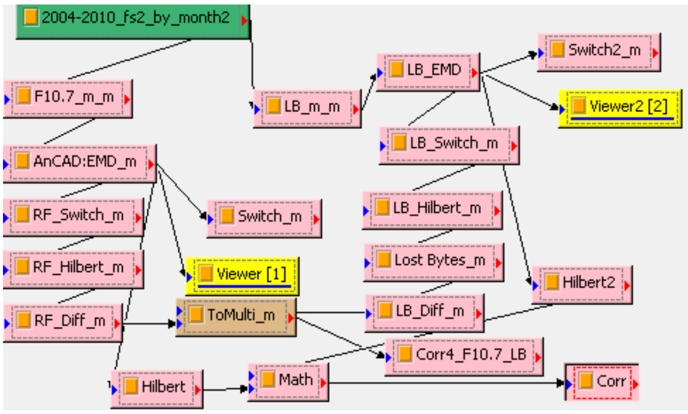

Figure 1: Calculation Flow for correlations

In Figure 1, the input data "2004-2010_fs2_by_month" are shown in green; 18 processes are shown in pink and 2 plotted reports are shown in yellow. On the lower-left side of Figure2, five main calculation processes are described below (we call this the "data process phase"):

- Process F10.7: This is the fourth column from Table 1, and the raw data is from the space weather web site http://www.spaceweather.com/.
- Process AnCAD:EMD_m: In this process, the empirical mode decomposition (EMD) method was adopted to separate F10.7 data to several channels by iteration until the residual value is exceeds 0.3 standard deviations. The final channel of residual value is the trending of F10.7.
- Process Hilbert and RF_Hilbert: Hilbert method was used for frequency tracing.
- Process Diff: The differential math method takes the instantaneous time derivative of frequency.
- Process LB_m_m : This is the third column from Table 1, and the LB means star tracker lost byte summed monthly.
- Process LB_EMD calculation model is the same as process AnCAD:EMD_m.
- Process LB_Hilbert and Hilbert2: Those processes are the same as process Hilbert and RF_Hilbert.
- Process LB_Diff is the same as process Diff; in this case, the differential math method is applied to LB.
- Process Math can bundle data from F10.7 and Lost Byte, in order to satisfy single input of Process Corr.
- Process Corr and Corr4_F10.7_LB are used to calculate the covariance correlation R from LB and other space weather parameters.

2.2 Data Output

After the EMD process, the original data of Lost Bytes and Radio Flux have been plotted as Figure 2.

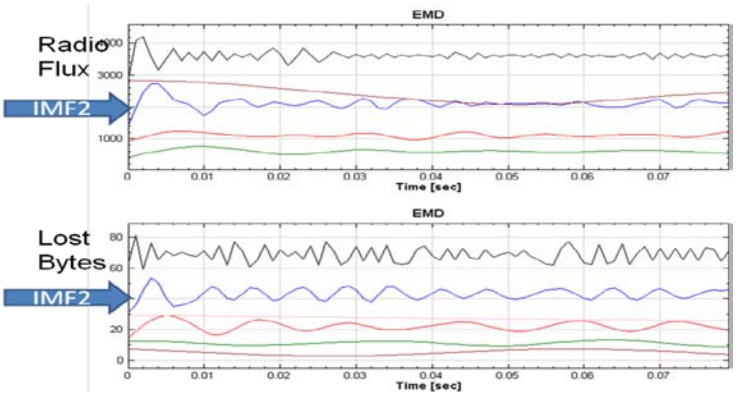

Figure2: RF and LB IMFs after EMD

The IMF2 between RF and LB are similar: the correlations between them can be calculated. We perform the Hilbert Transform on the IMFs and the Math function can be used to bundle the IMFs from RF and LB. Finally, the matrix correlation table has been calculated and is shown in Table 2.

Table 2: LB and RF correlation matrix

Channel	LB1	LB2	LB3	LB4	LB5	LB6
RF1	0.2996743	0.7832614	0.6690542	0.0121828	0.0042704	0.5679098
RF2	0.4039159	0.9108597	0.7753924	-0.0473708	-0.03885	0.603209
RF3	0.098951	0.5346318	0.3689806	0.0793982	0.2207596	0.3743429
RF4	0.2869226	0.7420215	0.859436	-0.3420909	-0.0596783	0.8572747
RF5	0.3022593	0.698167	0.7608352	-0.3211271	-0.2556666	0.7619076

In Table 2, the highest correlation is between the IMF2 of LB and the IMF2 of RF, which are named LB2 and RF2, respectively. It shows that LB and RF may have some certain relationship. An Excel spreadsheet has been used to produce a histogram in Figure 3.

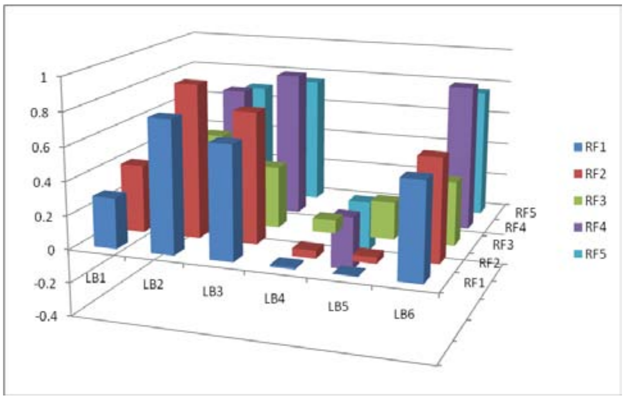

Figure 3: LB and RF histogram

We have compared correlation coefficients between LB and KP, PD1, PD100, XR_BG, and XR (shown in Figure 4).

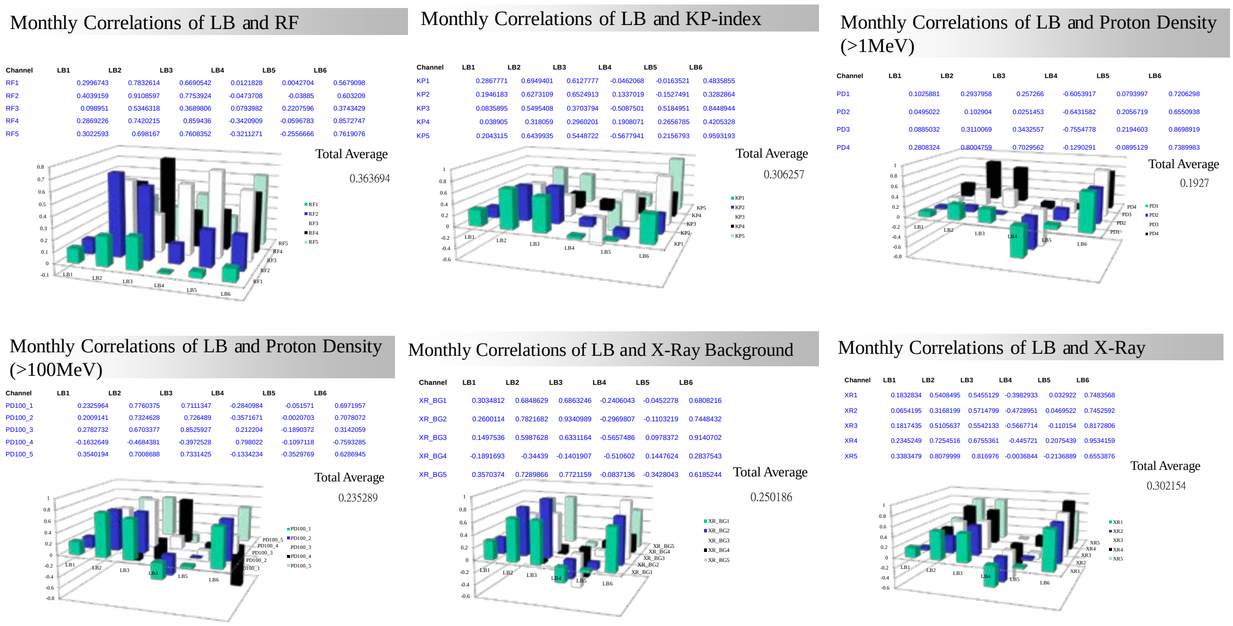

Figure 4: The correlations between LB and space weather

2.3 Time and Frequency

We use daily data and perform a Fast Fourier Transform (FFT) to find that for both radio flux F10.7 and Kp-index, there is a peak at frequency 0.0317 cycles per day (shown in Figure 5).

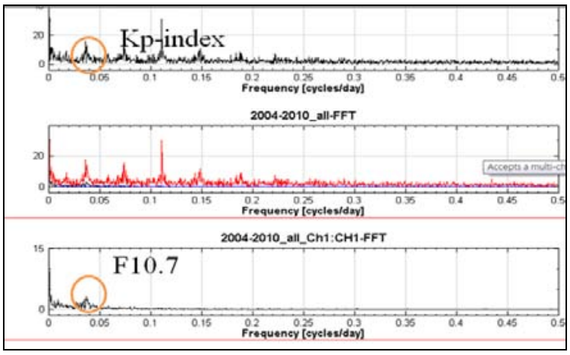

Figure 5: Kp-index and Radio Flux of F10.7 have the same frequency at 0.0317 cycles per day.

This may show that certain relationship exists between F10.7 and Kp-index. An article about the Tsubasa satellite experiment (H. Koshiishi, 2007) has demonstrated that trapped protons make a significant contribution to satellite SEUs.

3. SEU event

Out of 34 AROs that occurred on the FS-2 between May 21, 2004 and the present, 10 were due to SEUs. Out of these, 15 occurrences were located in the South Atlantic Anomaly (SAA) and Polar Regions, and 7 of them were SEUs. Out of 393 computer resets of the FS-3, 274 occurrences were located in the SAA and Polar Regions. We would like to note that the FS-2 satellite is shielded with aluminium (Al), but the FS-3 is not. Figure 6 shows FS-2 ARO locations.

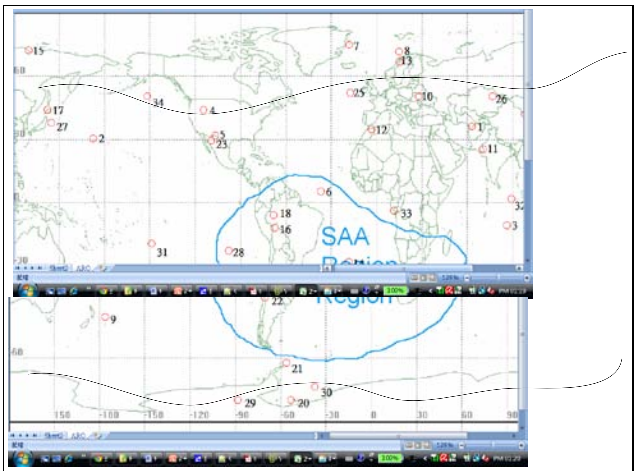

Figure 6: FS-2 ARO Locations

The occurrence numbers of FS-2 AROs are labeled in Figure 6. Figure 7 shows the FS-3 satellite computer reset locations which are designated by asterisks.

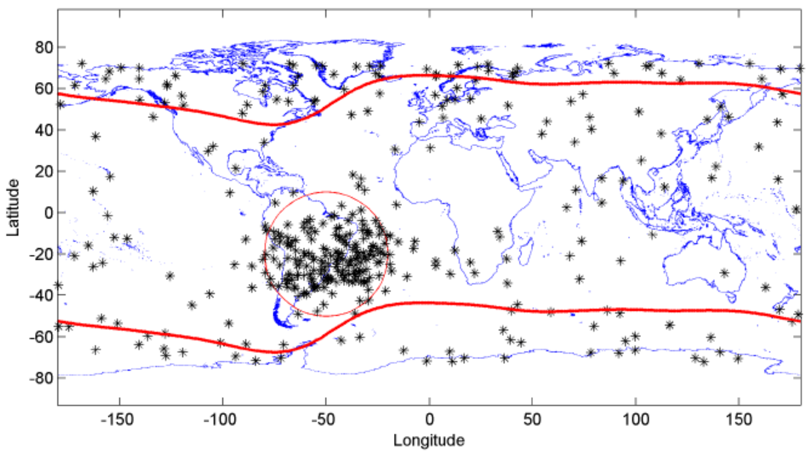

Figure 7: FS-3 Reset Locations

It is clear that the density of resets in the SAA is highest in Figure 7.

4. Conclusion and Future Works

The experimental result showed that FS-2 LB is more strongly correlated with Radio Flux (N. V. Kuznetsov, 2010) (V.F. Bashkirov, 1999) than with Kp-index, X-ray, or Proton Density, which confirms the findings by Koshiishi et al. Furthermore, FS-3 reset is more strongly correlated with Kp-index (N. V. Kuznetsov, 2010) (V.F. Bashkirov, 1999) than with Proton Density, Radio Flux, or X-ray. In the near future, we will combine seasonal parameters and location to study the correlations. Another possible study may be the lead time between LB and ARO; there may be certain relationships between them.

In our study, particles with different energies have different correlations with satellite SEU. This study can lead the way to the implementation of a more accurate graded-Z shielding, with material thicknesses weighted by the energy distributions of the particles encountered along the orbit trajectory. In the near future, the studied results can provide proper-shielding in FORMOSAT-5 and other satellites.

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