A Study of Van Allen Belt Signatures of Nuclear Weapon Tests for Future CTBT Technologies

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One of the methods of enforcing the Comprehensive Test Ban Treaty (CTBT) involves complementary measurements of seismic signals. Data from low Earth orbit satellites show that seismic events can result in particle bursts which can be detected by sensors on board of satellites. There is strong evidence for precipitation of charged particles in the van Allen belts caused by seismic events. Coincident particle bursts in satellite-borne detectors have been observed with a > 5-sigma significance with earthquake activity at the corresponding location in SAMPEX/PET, MARIA/SALYUT–7, GAMMA–1 [1], and DEMETER [2]. The mechanism responsible for particle precipitation can be linked to acoustic gravity wave causing Ultra Low Frequency (ULF) charge oscillation in ionosphere coupling to the magnetosphere through travelling Alfven waves around the Earth's dipolar field [3]. This same mechanism is also expected for underground nuclear tests. The main objective of this project is to study the signatures of nuclear weapon tests performed by North Korea in 2006, 2009, 2013 and 2016, and ultimately to discern natural earthquake phenomena from nuclear tests.

INTRODUCTION

The mechanism leading to particle bursts (PBs) is believed to be caused by the Ultra and Extra Low Frequency (ULF and ELF) waves emissions. These waves are believed to be caused by a range of preseismic sources such as local deformation of field electro-kinetics, piezo-magnetism and piezo-electricity and many others [3]. Both *Sivadas* and *Aleksandrin* propose that these low frequency waves become trapped in a geomagnetic field tube (specific channel made by L–shell corresponding to the earthquake) on altitudes between $300 - 500$ km. They then travel as magneto–hydrodynamic Alfven waves along the given L–shell interacting resonantly with particles trapped within that region (depending on frequency of the emission these are bounce resonance or cyclotron resonance interactions). This ultimately results in particles precipitating and circulating within their given L–shell for up to 12 hours (ciatation needed).

The data for this project comes from Los Almost National Laboratory and was collected by 23 GPS satellites between 1st January 2001 and 1st January 2017. The satellites were equipped with with Burst Detector Dosimeters IIR (BDD-IIR) [4] and Combined X-Ray sensor and Dosimeters (CXD) [5] and travelled along a path with a period of approximately 12 hours, taking measurements every 240s. Figure 1 shows trajectories of some of the GPS satellites.

Particle detectors took measurements of rates and fluxes for both electrons and protons as well as recorded geographic locations, magnetic fields and L–shell values. In this analysis we foucsed mainly on electron rates and their variation in time and within L–shells.
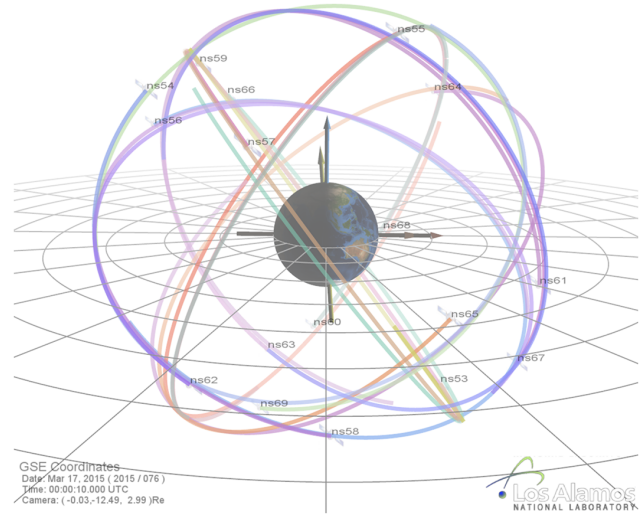

FIG. 1. Trajectories of satellites equipped with CXD instruments [6].

in our data. In our analysis we attempted to reproduce the results presented by *Aleksandrin et al.* by imporoving his analysis method.

The data was analysed in two–year chunks and PBs were defined as reading exceeding the average by at least four σ. Subsequently, PBs were matched to earthquakes (obtained from U.S. Geological Survey website) based on the following conditions: PB occurs within 12 hours before or after the earthquake and the relationship between the earthquake L–Shell (L_{EQ}) and burst earthquake (L_{PB}) can be described by

$$\Delta L = L_{EQ} - L_{PB} < 0.07 \tag{1}$$

Since precipitated particles remain trapped witin a given L–Shell for up to 12 hours (citation needed), we assume that detection of PB depends only on the L–Shells the satellite is traversing regardless of its geographic locatin.
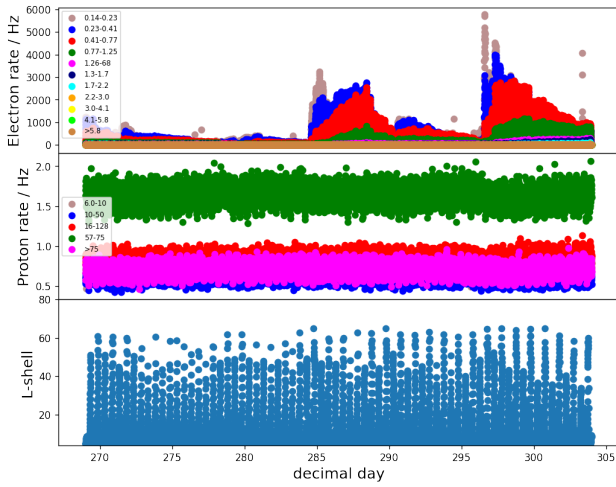
METHOD

Correlated particle bursts and surrogate seismic events

In this part of the project we investigated whether the observations made by low–Earth–orbit satellites can also be found

FIG. 2. Figure to show L–Shell, proton and electron rate readings between 24th Sept and 31st Sept 2010.

Energy spectrum cross–correlation analyis

This method involved investigating normalised cross–correlation coefficients (NCC) between various electron energy channels.

$$NCC = \frac{\sum_{n=0}^{N} x(n) \sum_{n=0}^{N} y(n)}{\sqrt{\sum_{n=0}^{N} x^2(n) \sum_{n=0}^{N} y^2(n)}} \qquad (2)$$

Figure 2 shows a typical weekly set of readings. By investigating NCCs for 2–week periods over 16 years of data, overall 'distribution' can be obtained in order to use this population as the baseline for comparison with periods of nuclear activity.

RESULTS

Figure 3 shows data collected around one of the nuclear tests. An example of temporal histogram is shown in Figure 4. The peaks are representing particle bursts detected by the satellite. The coupling between the earthquake and PB usually occurs around $4 <$ L–shell < 5. By increasing the allowed values of ΔL the features become much less distinguishible as seen in Figure 5. These patterns show findings described in literature.

Method of energy spectrum cross–correlation analysis appeared to be succesfull in discerning between nuclear tests from 2006, 2009 and 2013 and naturally occuring phenomena. Figure 6 shows a histogram of how a set of NCCs for a particular test from 25th May 2006 compare to the overall population and table I gives the set of p–values for all the channels for this test.

It would appear, that particle energies within bursts, in time and spatial coincidence with nuclear tests, are much less correlated than natural sources, resulting in nuclear tests showing as outliers using this detection method.
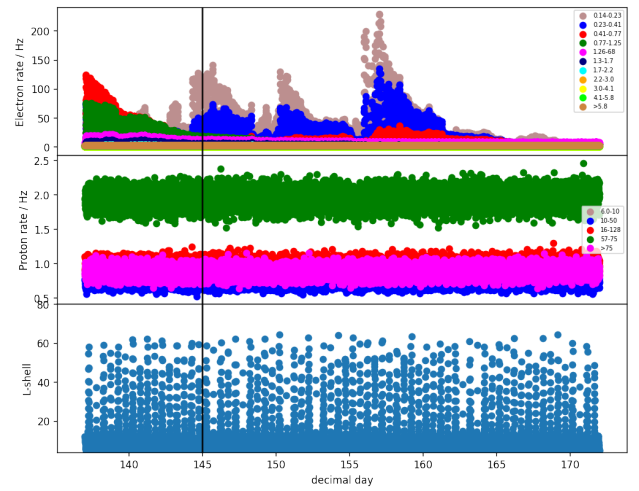

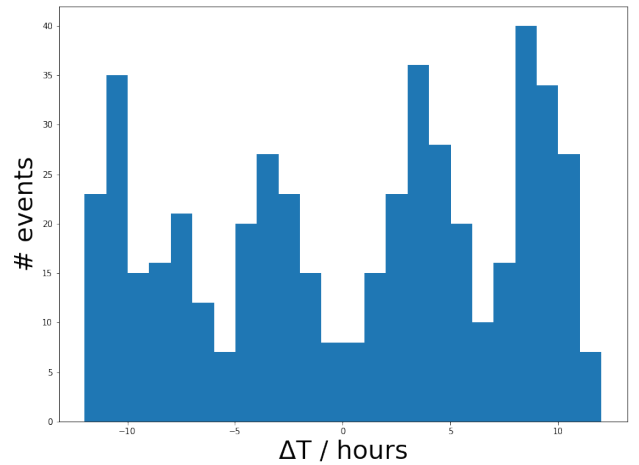FIG. 3. Electron and proton rates for the test on 25th May 2006 (marked by black vertical line).

FIG. 4. Temporal correlation histogram for satellite ns56 under the condition ΔL < 0.07.
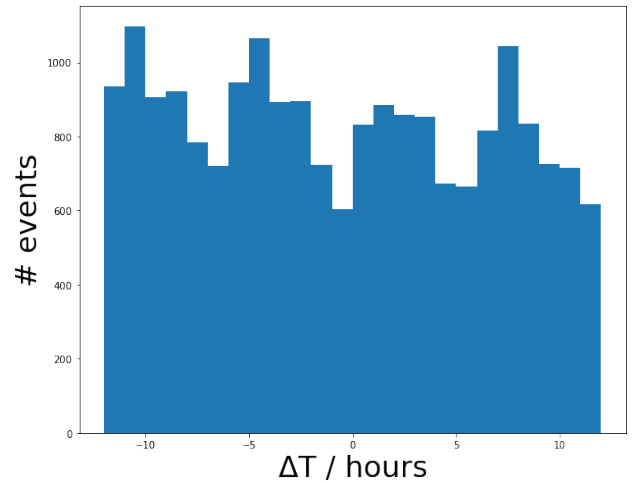

FIG. 5. Temporal correlation histogram for satellite ns56 under the condition ΔL < 1 .
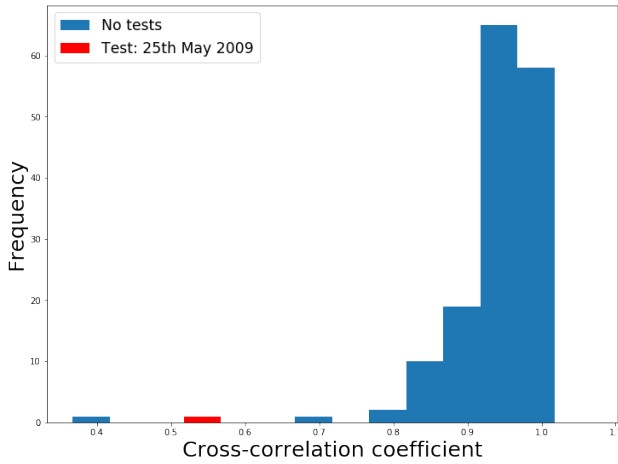
FIG. 6. NCC between channels 2 and 4 for a test performed on 25th May 2006 as compared to the values calculated for 16 years of data.

Channel	0	1	2	3	4	5	6	7	8	9	10
P–values	0.49	0.72	1.00	0.01	0.01	0.04	0.04	0.07	0.05	0.03	0.03

TABLE I. Table of P–values for NCCs from the test performed on 25th May 2006.

DISCUSSION

Temporal correlation method appears to produce results confirming previous observations from a low–Earth–orbit satellites metnitioned earlier. The energy spectrum cross–correlation analysis requires more time and focus to either confirm or refute its usefulness. If correct, it could be a very useful tool are already included in NCC values. The alternative approach to the problem would involve gaining a better understanding of the signal in terms of background and effects of seismic activity on electron and proton rates.

The results obtained in this project are based on electron rates and therefore investigating other properties such as fluxes or magnetic fields could be helpful in discovering some other signatures useful in differentiating between seismic events and nuclear tests. Some publications focus on pitch angles analysis [2], however the data available in this project is not pitch angle resolved [7][8] (*Morley* only discusses the range of pitch angles sampled by the satellites).

CONCLUSIONS

The main conclusions can be summarised in the following points:

- The GPS satellite data show particle bursts coinciding with earthquakes, which has not been observed before at these altitudes.

- Multiple peaks in the temporal correlation analysis are

likely to be due to GPS satellite motion in and out of the particle bursts.

- Character of energy correlations within particle bursts associated with nuclear tests are quantitatively different than natural causes of particle bursts.

The results obtained from temporal analysis confirm previous observations while energy spectrum cross–correlation analysis requires further investigation and improvement.

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