The South Atlantic Anomaly seen by MOPITT instrument

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***Abstract*-This paper reports on Device Single Events (DSE) occurring in the MOPITT (Measurements Of Pollution In The Troposphere) accelerometers, correlation with radiation environment and solar activity.**

Introduction

The MOPITT instrument aboard the Terra spacecraft has collected two years of data since launch on Dec. 18, 1999. It is in a sun-synchronous polar orbit and has an orbital period of 98.88 minutes (with an exact repeat period of 16 days), altitude of 705 Km, an inclination of 98.2°, descending node crossing time 10:43am.

During daytime the satellite flies on a descending pass from the North Pole to the South Pole and crosses the equator at 10:43 am. During nighttime it flies on an ascending orbit.

The MOPITT instrument is an infrared gas correlation radiometer [Drummond, 1996]. It operates with eight channels, four CO thermal channels at a fundamental wavelength of 4.7 µm, two CO solar channels at 2.3 µm and two CH_4 solar channels at 2.2 µm.

For optimal performance, that is maximum signal-to-noise ratio, the detectors need to be cooled to < 105 K.This is achieved by using a pair of 50-80 K mechanical Matra Marconi Stirling Cycle Coolers. The compressors as well as the displacers are mounted back to back in order to minimize the axial vibration. The cooler z-axis, the piston axis, is perpendicular to the spacecraft velocity vector and to the nadir direction. The vibration level in three directions is given by two sets of piezoelectric accelerometers

(Kistler Instrumente AG) mounted on the compressor and displacer. Each accelerometer uses a unique shear mode sensing element made of quartz. It is in fact a multi-component force transducer, which consists of a stack of quartz discs or plates and electrodes. Each quartz disc has been cut in a definite crystal axis, and the orientation of the sensitive axes coincides with the axes of the force components to be measured. An internal circuit Piezotron (built-in charge-to-voltage converter) provides a low impedance output. The units are hermetically sealed and are constructed of titanium. Compressor vibrations are less than 0.25 Newtons (N) for x and y directions and less than 0.2 for z direction The vibration level for displacer is less than 0.18 N for x direction and less than 0.3 N for y and z direction. These parameters are within the normal operating range of the transducer, and are well characterized.

During normal operation periods, there are short fluctuations (spikes, one telemetry point only) which apparently increase the normal level of vibration by more than 4 sigma (see fig 1 for an example). These spikes, or accelerator anomalies, occur much more often for the z-direction compressor vibrations. Anomalies for other directions and for the displacer are less than 1% of all accelerometer anomalies. Their intensity distribution is well described by a decreasing power-law function of apparent vibration intensity (Fig.1, bottom panel).

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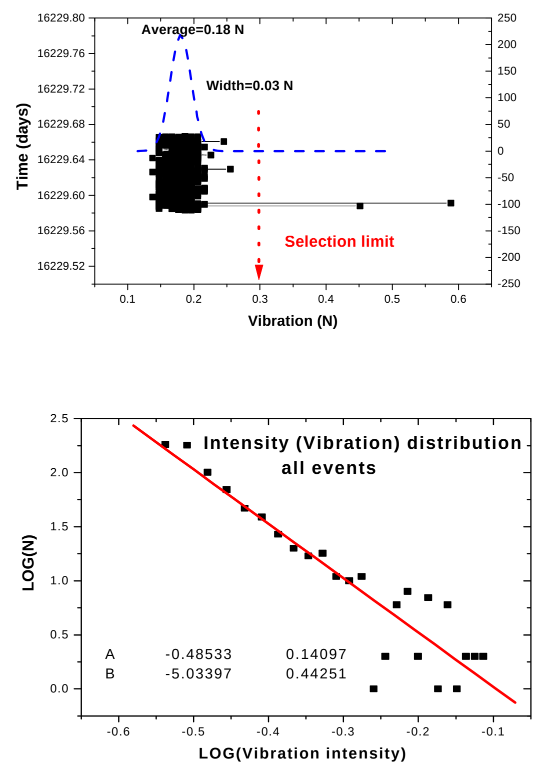

Fig. 1. Example of vibration time distribution shown by Compressor Accelerometer(top panel) and intensity distribution (bottom panel).

DSE Location

During the period, from March 2000 to June 2002 we received more than 800 accelerometer anomalies which is a large enough set to apply a statistically meaningful analysis. The strong localization of these events (see Fig.2) in the South Atlantic Anomaly (SAA) (for a similar case see for example Heirtzler,2002). and polar regions demonstrate that these Device Single Events, DSEs, are caused by the radiation environment (energetic particles). For a recent discussion of space radiation environment (space weather) and its effects on technological systems in space see Brautigam,2002 for CRRES and Gubby and Evans,2002 for Telesat.

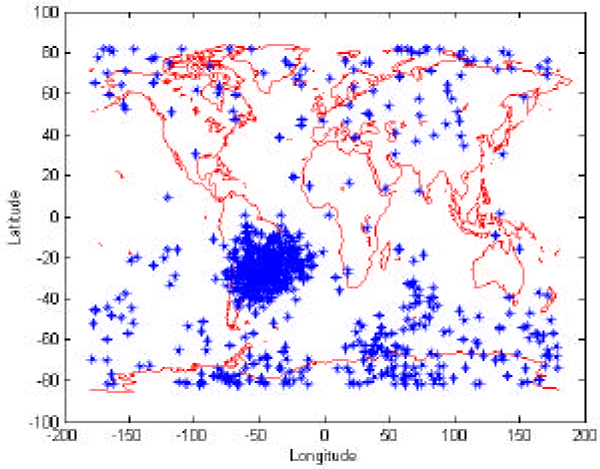

Fig.2 Mopitt-Acc anomaly sites.

The MOPITT DSE occur mainly in SAA and Polar regions as a consequence of two main source of radiation: trapped radiation and Solar Particle Events (SPE). The small fraction of background events not connected to SSA or Polar regions are probably due to Galactic Cosmic radiation (GCR).

SAA

The SAA is an area of anomalously weak geomagnetic field strength caused by an offset of the geomagnetic dipole axis towards the northwest Pacific. This weak field allows trapped radiation particles to reach lower altitudes before bouncing back to the northern hemisphere.

The latitude and longitude distributions of DSE in the SAA region (56.2% of all events) can be well fitted with a gaussian form giving the location for SAA:

Latitude = -25.9 width = 16.4

Longitude = -47.0 width = 29.7

A DSE map over the SAA is provided in Fig. 3, giving the intensity contour for anomalies at 705 km altitude.

The overall Day/Night asymmetry ratio is 0.88 (with 0.77 for events over SAA). As gyro radius of trapped particles can be very large, the lower rate of DSE (43.6 %) during the day side of the earth can be the effect of the neutral atmosphere expands during the day compared to the night (the radiation belts are eroded due to increased interaction with neutral constituents).

Table 1. SAA location :

	Day	Night
Latitude (degree)	-26.12 Width=14.4	-25.65 Width=17.8
Longitude (degree)	-47.13 Width=29.3	-47.06 Width=29.4
%	43.6 %	56.4 %

The same effect can cause the lower latitudinal width of SAA gaussian form on the day side (see Table 1).

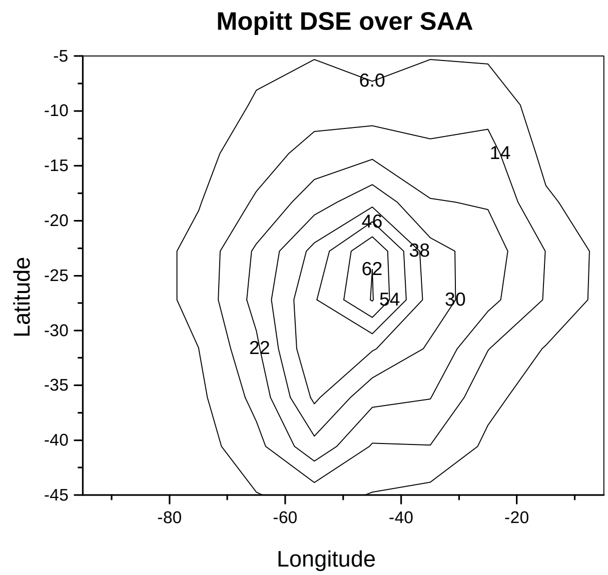

Fig. 3 Intensity contour of Mopitt DSE over SAA region. (The number on the contours state for the number of events)

Polar regions:

There is an evident asymmetry between North and South poles regions with more DSE in the South hemisphere and an evident concentration of events in a wide region around –60, 100W (Fig. 2).

If we consider the polar regions (> 70N and > 70S) , the polar DSE received from Mopitt accelerometer is 18% of the total with 70% of them in the Southern hemisphere. The Day/Night asymmetry ratio for DSE received over the polar regions is more than 2x which indicates that most of the high energy particles causing accelerometer anomalies are not trapped particles, but are likely sourced from solar wind injected via poles.

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Correlations with Solar Activity

Many of relevant particle sources are modulated during the course of the solar cycle. The effect of solar activity is to increase the loss of protons due to the expand atmosphere during solar maximum and so to decrease the trapped radiation doses in LEO [Heinrich,1994]. The same anti-correlation for the integral GCR flux and solar activity is due to increase of the interplanetary magnetic field (IMF) generated by the sun [Ahluwalia 2002]

The time distribution of the Mopitt DSE monthly average daily rate shows an increase more than 2x, for the time period of Nov 2001 – Feb 2002 suggesting a direct connection with solar activity.

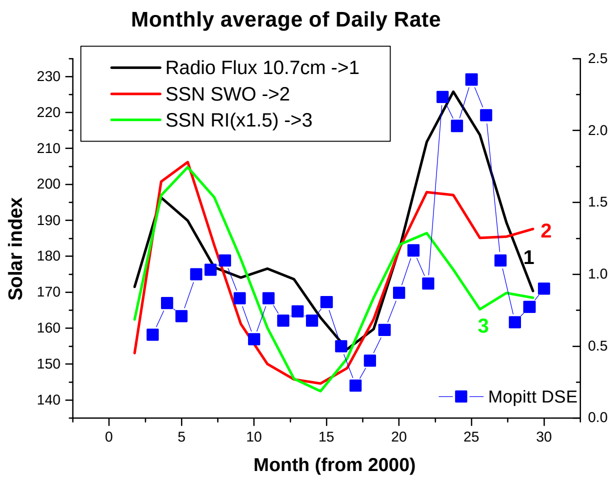

Fig. 4 Monthly average of Mopitt-Acc anomalies Daily Rate and Solar Activity .

The lines in fig. 4 are our polynomial fit to monthly average Solar indexes : SSN SWO , sunspot number provided by SEC Space Weather Operation, SSN RI SSN (scaled by 1.5) provided by S.I.D.C. Brussels International Sunspot Number and the F10.7 index (10.7 cm radio flux values in sfu units) provided by Penticton, B.C. Canada [1].

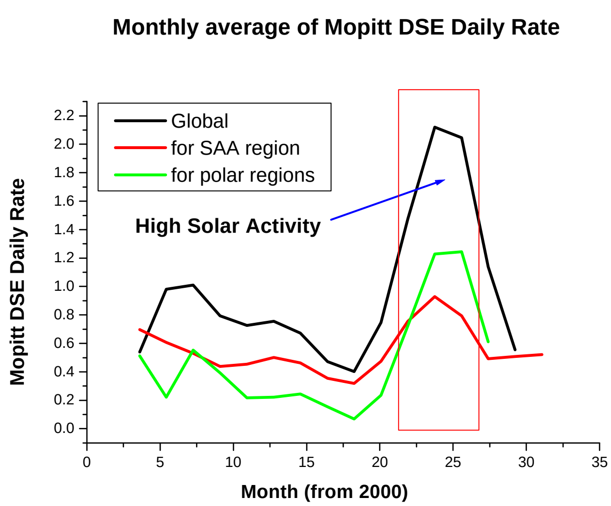

Fig. 5 Monthly rate of Mopitt-Acc anomalies Daily Rate for different regions(Polynomial smooth)

Inspection of Fig 4. shows a similarity in the Mopitt monthly average DSE Daily Rate and the solar activity as characterized by the sunspot number and 10.7 cm Radio Flux. There is a general trend of decreasing from a moderate activity at the beginning of 2000 to a minimum at the beginning of 2001 and a sharp increase in the period of Nov/2001 to Mar/2002. This direct correlation with the solar activity and is present for events located in SAA and those in the polar regions (see Fig 5). Due to the small time scale and probably due to higher altitude (705 km) of the spacecraft the anti-correlation with solar activity expected during the eleven solar cycle is not observed.

During the High Solar Activity Period (Fig. 5) the DSE rate over the poles increase more than the SAA rate as a consequence of injection of direct high energy particles at the poles (the overall percentage of events occurring over SAA, decrease to 42% during this 4 months period of high Solar Activity).

Solar Proton Events

Very large particle events with large fluxes of high energy particles which reach the earth occur during so called Solar Proton Events (see for example [Tranquille, 1994]).
These SPE are normally associated with eruptive prominences, large solar flares and coronal mass ejections (CME) [Baker, 2000]. Even though their frequency is low over a long period of time, a single SPE can have the most extreme effects on low-Earth orbit space systems as well as on the Earth's atmosphere[Jackmman et al ,1999; 2001].
For the full time period, the daily rate of Mopitt DSE has an average value of 0.98 events/day but during a short time interval, usually one or two days, the rate can increase dramatically. These high daily rates, as is shown below, are caused by high intensity SPE.

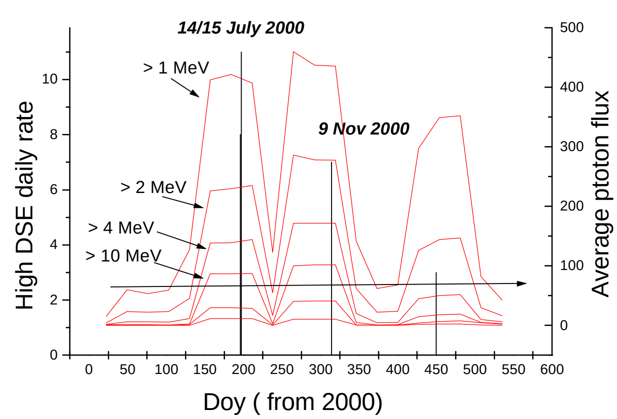

Fig.6 "Near-Earth" energetic proton fluxes averaged for 27days provided by OMNIWeb[3] and high Mopitt anomalous event daily rate during April 2000 to April 2001

Using data provided by OMNIWeb [2] we plot the proton fluxes near the earth (one 'solar day' averaged) over our high daily DSE rate. Fig.6 suggests that accelerometer anomalies signals are produced by energetic protons with energies larger than 10 MeV.

From the list of SPE affecting the Earth Environment prepared by NOAA-Space Environment Center [1] we select SPE for which the proton flux at >10MeV is larger than 10000pfu (1pfu=1p/sq.cm-s-sr). Time series of Mopitt DSE daily rates and high-flux SPE are shown in fig. 7. There is a perfect coincidence with 3 big SPE. There are two high flux SPE near the solar event of 6 Nov 2001 with no relevant consequences on Mopitt accelerometer and, near the beginning of 2002 (a High Solar Activity period of time, see Fig.5), three days of high DSE daily rate without any SPE correspondence. (see the box in Fig 7).

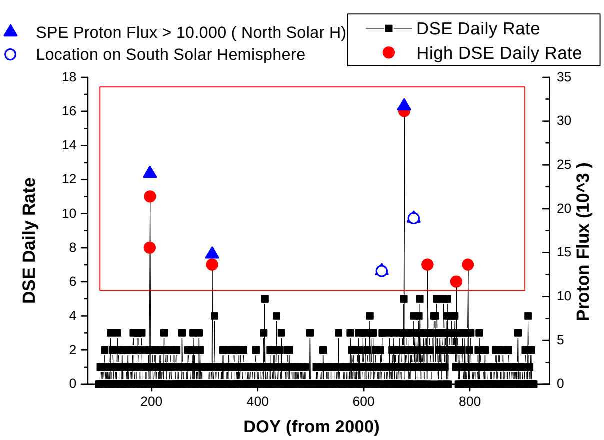

Fig.7 Mopitt high DSE daily rate (SPE and proton fluxes from [2])

The last inconsistency can be explained by the general increase of DSE rate due to High Solar Activity by the end of 2001 and beginning of 2002 (in Fig.7 is seen for this period of time a general increase of DSE daily rate).

In a close inspection of high flux SPE event we found that the two 'quiet' SPE (those which don't induce a high daily rate for Mopitt DSE) are different from the those other three SPE which have great impact, in several respects :

-Both quiet SPE have associated CME, flare or active region located in South hemisphere of the solar disc while all the others are in the North hemisphere (see Fig 7). We notice this, but probably is not relevant for our case.

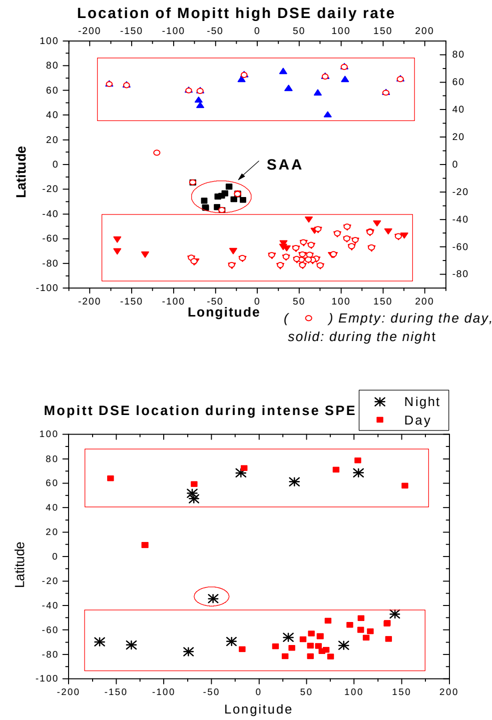

Fig.8 Location of high DSE daily rate. Top panel: all DSE events from the box of Fig.7.Bottom panel: DSE coincident with intense SPE.

-The two 'quiet' SPE have a flatter increase of particle flux (from GOES proton flux plots [3]). The proton flux rises from pre-SPE level to a high value in a short time (~1hour) for the three significant SPE, while for the two 'quiet SPE' the rise time to maximum proton flux take 5-6 hours.

-The energy spectrum of these two types of SEP differ in respect of the high energy component. The two quiet SPE have comparable proton flux for particles with energy .>10 MeV, but less intense proton fluxes for particles with energies > 50 MeV [3]. A similar conclusion, that the Mopitt accelerometer is sensible to particles with energies > 50 MeV, can be obtained from SOHO spacecraft. The Proton Monitor (PM) on the SOHO Spacecraft respond to ions with incident energies > 50MeV and to electrons with incident energies > 2 MeV. The largest particle flares since Jan 1996 observed by PM on SOHA were only those we named 'intense SPE' and which induce a high daily rate for Mopitt DSE.

The Mopitt DSE daily rate is direct correlated with the intensity of the event. Fig 9 shows the linear dependence between the DSE daily rate and the proton flux of the SPE event (5-minute averages for energies > 10 MeV measured by GOES spacecraft in geosynchronous orbit)

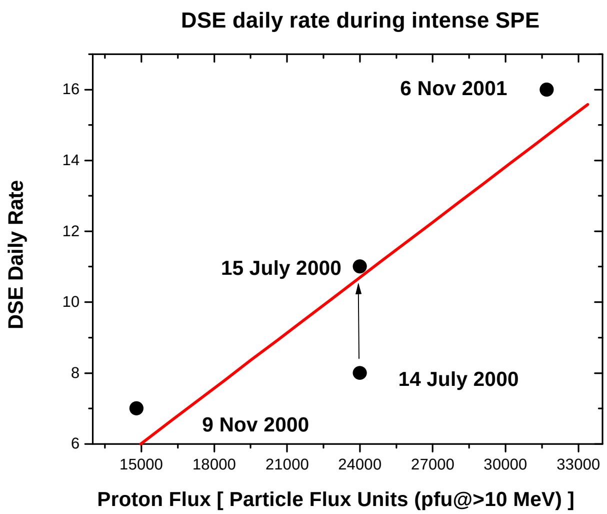

Fig. 9 Correlation between Mopitt DSE and the proton flux during intense SPE. (DSE events coincident with SPE ,see fig.7)

CONCLUSIONS

During more than two years period of time the Mopitt accelerometers recorded satellite anomalies by showing short, high intense signals well correlated with high energy radiation environment. Analysis of anomalous accelerometer signals shows a direct correlation of DSE daily rate with solar activity, a Day/Night asymmetry caused probably by interaction of trapped particles with the neutral atmosphere and a direct correlation with high intensity solar proton events. The high energy particles – the source of anomalous accelerometer signals- are localized mainly in SAA region. The polar regions are also regions (there is a North/South asymmetry) of high risk for satellites mainly during intense SPE.

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[2] nssds.gsfc.nasa.gov/omniweb/
[3] www.sec.noaa.gov/ftpdir/plots/ : GOES Proton fluxes.
[4] umtof.umd.edu/pm/flare/ : SOHO Proton monitor .

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