ULTRA-STABLE OSCILLATORS DEDICATED TO LOW-EARTH-ORBIT APPLICATIONS : BEHAVIOR VS RADIATION

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Abstract— **This paper presents radiation experience-returns of CNES, French space agency, at low-Earth-orbit of on-board ultra-stable oscillators. It shows the current solutions used for reduce radiation sensitivity of such on-board oscillators. And, it summarizes French R&D dedicated to drastically reduce this sensitivity.**

I. INTRODUCTION

Ultra stable oscillators (USO) are widely used in space systems (telecommunication, navigation, precise positioning). And for all space programs need to verify the end-of-life (EOL) frequency stability over the lifetime (from few years up to 20 years), as well as the mid and short-term stabilities and the phase noise. These specifications should be compliant with all on-board environmental conditions, mainly temperature, magnetic fields from earth or spacecraft, and radiations. The present paper is focused on this last issue.

One of major programs concerned by the radiations problem is DORIS (Doppler Orbitography and Radiopositioning Integrated in Space). It is Doppler satellite tracking system developed for precise determination and precise ground location. Its ultimate aim is to achieve an accuracy of one centimetre. The DORIS system was designed by CNES, in partnership with French mapping and survey agency IGN and space geodesic research institute GRGS, to answer to the one centimetre challenge. Since 1990, it is on-board of JASON1 and ENVISAT altimetric satellites and remote sensing satellites SPOT series: 2, 4 and 5. SPOT series and ENVISAT are at 830 km, and JASON1 at 1336 km. Altitudes correspond to low Earth orbit (LEO). It also flew with SPOT3 and TOPEX-POSEIDON. Future DORIS will be embarked on JASON2, PLEIADES, ALTIKa, HY2, CRYOSAT2. Currently, seven DORIS instruments are in orbit, based on a one-way bi-frequency Doppler technique with on-board very accurate measurements from a network of 55 ground transmitters beacons.

This paper highlights radiation experience-returns at LEO of on-board USO. And it proposes short and long -term solutions to reduce this radiation sensitivity.

II. LEO RADIATION EFFECTS

Radiation effects responsible of a frequency shifts on space USO are caused by these main sources: space radiation due to cosmic rays, trapped protons, and electrons in the Van Allen belts or solar flare protons ejected from the sun during solar activity.

A. *Van Allen belts*

The Van Allen belts are toroïdal belts of charged particles surrounding the Earth near the equator. There are two belts: the inner belt, which extends to about 45° North and South geomagnetic latitude and from 800 to 8,000 km in altitude, and the outer belt, which fluctuates in size and intensity with solar activity, but is symmetrical about the equator and extends to about 70° geomagnetic latitude North and South and reaches altitudes up to 130,000 km. Results from previous investigations also showed that cosmic rays consist primarily in high energy protons with too small fluxes to produce radiation effects in quartz crystals [VIG94], [SUT88]. Stassinopoulos and Barth [STA84] showed also that trapped electrons in the Van Allen belts do not contribute significantly to the total radiation dose accumulated by spacecrafts in LEO. Therefore, studies on the susceptibility of quartz crystal resonators to LEO radiation environment focus on proton radiation induced effects.

Van Allen belts effects on on-board USO are determined by several parameters: duration of the mission, orbit parameters… and, finally, a 3-D Monte-Carlo analysis of the geometrical and physical description of the satellite taking into account the equipment and the USO itself [BRU05] is necessary to calculate the radiation sensitivity of the USO.

The protons able to go into the quartz crystal are those whose energy is greater than 60 MeV. Figure 1 gives the spatial distribution of such protons in the inner belt at the JASON1 orbit altitude where the usual SAA (South Atlantic Anomaly) region is visible. Nevertheless, we observed the presence of significant flux in wide intervals of longitudes

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and latitudes after the East and West sides of SAA. The resulting radiation orbital cycle is about 1 rad/h[1] during 10 min to 40 min on a 120 min cycle. At the antipodes of the SAA, the flux is null.

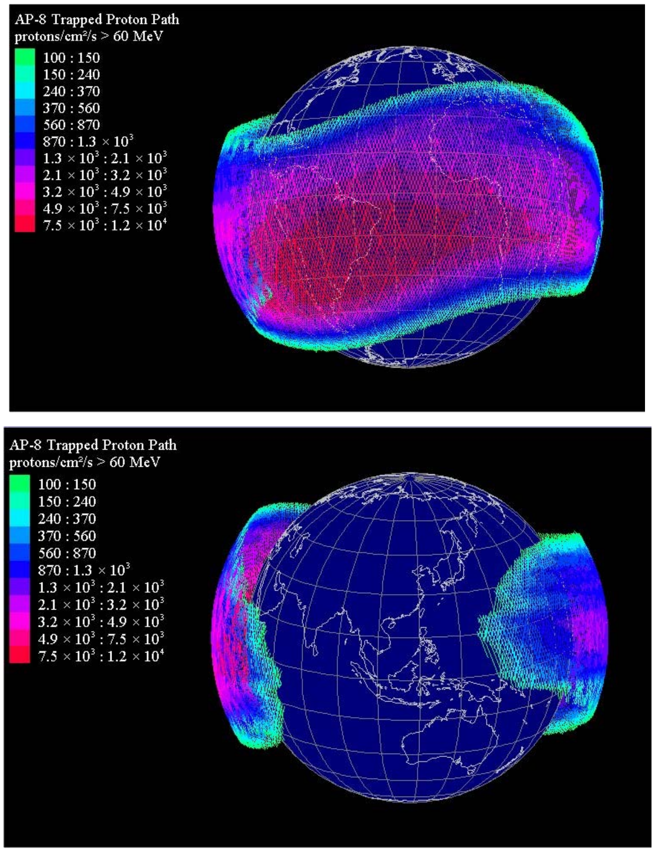

Figure 1. Figures (proton) : Integral protons belt flux for energies greater than 60 MeV in the usual SAA region at the East and the West, and the SAA antipodes view.

All the DORIS USO are in the inner belt. In fact, they are affected by three main effects: the total ionizing dose (TID), the low dose rate (LDR) and the single event (SE).

B. Total ionizing dose

The TID is the main parameter affecting the EOL frequency stability. For example, USO for applications such as telecommunication or precise positioning need respectively an EOL frequency stability of 0.2 to 1 ppm over 20 years and 0.2 ppm over 5 to 10 years.

Using some ground beacons synchronized by an atomic frequency standard, it is possible to determine the on-board USO frequency over one pass with an uncertainty of a few 10^{-12}. The DORIS EOL and mid-term (MT) required performances in orbit are compliant for each USO, except for JASON1, where large frequency variations are observed (Figure 1).

[1] 1 Gy = 100 rad

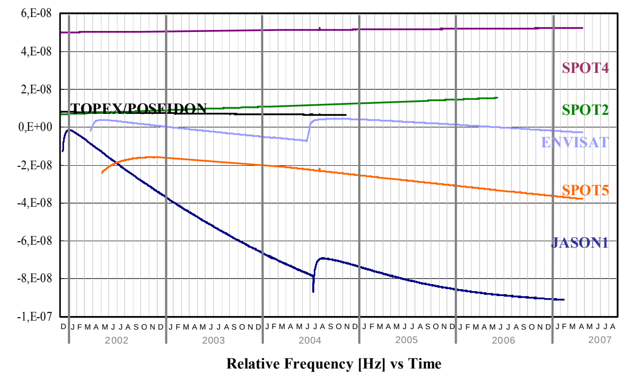

Figure 2. Long-term (LT) frequency instability (aging) of 10 MHz DORIS in-flight USO in LEO: SPOT series (2,4,5) ENVISAT at 830 km orbit altitude, TOPEX-POSEIDON and JASON1 at 1336 km altitude.

In fact, the TID effect is mainly due to the accumulation of LDR of ionizing radiations and single events.

The backup USO has been used for JASON1 and ENVISAT because of anomalies. For JASON1, the anomaly is due to the LDR effects.

C. Low dose rate ionizing radiation

Figure 3 presents the frequency variations of the DORIS USO observed in July 2002 and April 2003 on-board JASON1 satellite over a period of 4 days. The observed discontinuous frequency variations (1 to 6.10^{-11} peak-to-peak) are strongly correlated to the run of the satellite through the SAA. The radiation environment of LEO corresponds to radiation exposures with relaxation periods. The flux of protons during orbit is not continuous. Cycles coincide with transits through the SAA proton belt.

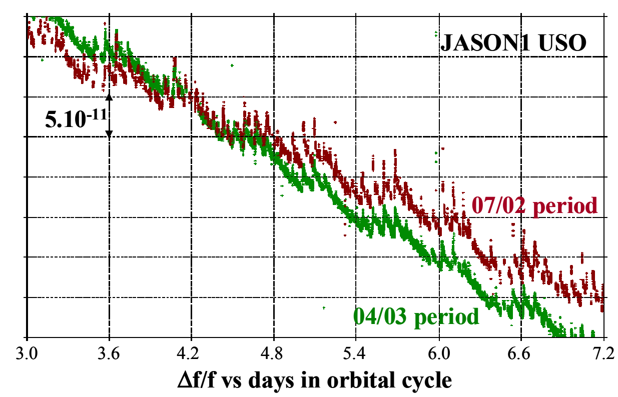

Figure 3. Frequency variations of the DORIS USO observed in July 2002 and April 2003 on-board JASON1 satellite over a period of 4 days.

In june 2004, due to this anomaly (see Figure 2), the Channel 2 has been swapped for the Channel 1. However, the same discontinuous frequency variations of Channel 2 USO have been observed on the Channel 1 USO. Figures 4 and 5 present the frequency variations (without slope frequency) of both USO, Channel 2 and Channel 1, at two dates over a period of one day : in July 2002 and April 2003 for Channel 2, and, in July 2004 and May 2005 for Channel 1.

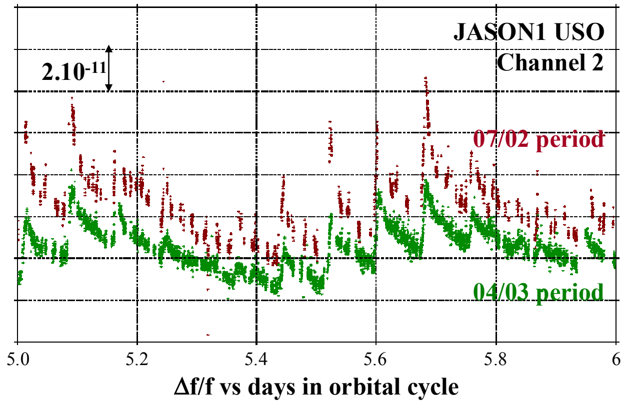

Figure 4. Frequency variations (without slope) of the Channel 1 USO observed in July 2002 and April 2003 on-board JASON1 satellite over a period of 1 day.

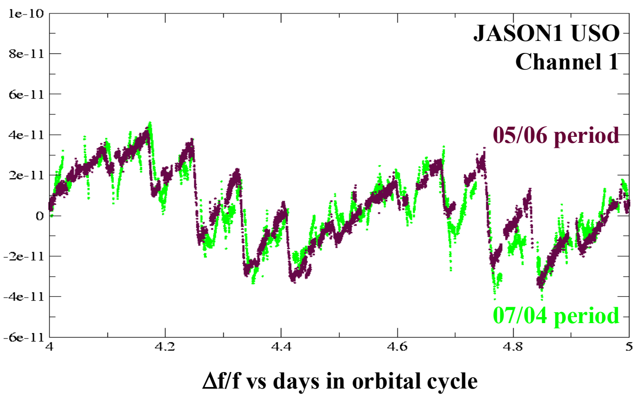

Figure 5. Frequency variations (without slope) of the Channel 1 USO observed in July 2004 and May 2005 on-board JASON1 satellite over a period of 1 day

D. *Single events : Solar flares*

Solar flare protons ejected from the sun during solar activity induce also frequency variations. Figure 6 illustrates the frequency drift of on-board DORIS USO caused by the solar flare observed the 20th of January 2005.

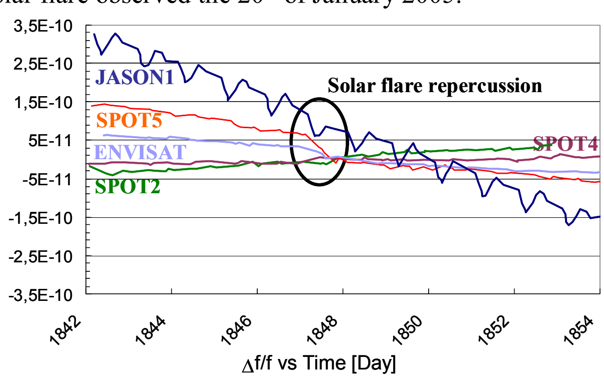

Figure 6. Solar flare on frequency variations of DORIS on-board USO observed the 20th of January 2005.

The high particles rates from solar flare are transitory with intensity peaking of 100 to 10,000 particles $cm^{-2}s^{-1}$.

III. RADIATION EXPERIMENTATION : WHAT PARTICLES ?

Both proton and gamma radiation are forms of ionizing, but gamma is more commonly used to study general trends and signatures of total dose effects in resonators [KIN85]. Theoretical and experimental studies reported in [NOR84], [SUT88] have revealed that energy losses in alpha quartz due to 1.25 MeV gamma rays and protons are indeed similar over the LEO dose and kinetic energy ranges, even though these two forms of radiation differ in their physical interactions with quartz.

Nonetheless, our experiments to verify this similarity between gamma and proton radiation were not also a conclusive. A similarity between both signature and direction of frequency changes has been demonstrated, on the other hand, the magnitude of frequency variation was not the same. These experiments have been realized on a SC 5 MHz PFM USO. Fixed energy of protons particles was about 110 MeV. However, these experiments must be carried on.

However, because the magnitude and direction of frequency changes from low level gamma and proton radiation are nearly identical for a given quartz resonator, and because the magnitude is used for relative comparison, the gamma radiation data for low level radiation exposures can be accurately used to predict the performance of a resonator when subjected to proton radiation.

IV. SHORT-TERM SOLUTIONS

A. *Radiation shielding*

The quartz crystal resonators can be shielded from some radiation characteristics by metals such as aluminium, copper or by composite materials lead but volume, weight and ESD considerations in spacecraft often make the addition of shields prohibitive. Furthermore, high energy protons cannot be effectively shielded.

B. *Specific quartz materials*

Most of works have demonstrated that quartz impurities quantities have a important role in radiation susceptibility (for both low and high radiation levels). A few suppliers (GEMMA, SAWYER, VNIISIMS) and laboratory (EADS-ASTRIUM UK) have dedicated quartz crystals to low radiation sensitivity applications. However, even if these materials present about the same trace elements, the frequency deviation signature and magnitude are not the same. Figure 7 presents the frequency behaviour of some USO manufactured with high quality quartz crystals on-board of TOPEX-POSEIDON, JASON1, and JASON2. A γ-ray beam of 1 rad/h flux was applied during 40mn every 120mn.

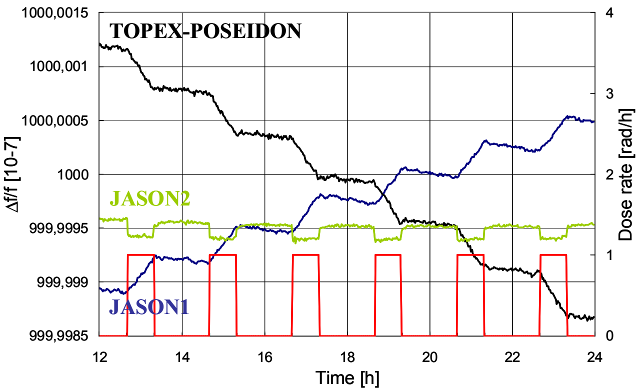

Figure 7. Frequency behaviour of some USO on-board of TOPEX-POSEIDON, JASON1 and JASON2 quartz-lots.

The TOPEX-POSEIDON and JASON1 quartz materials have a similar behaviour. The main radiation mechanisms are due to cumulated dose. Their frequency changes are respectively of 3.10^{-11} and 2.10^{-11} for 1 rad cumulated dose. On the other hand, the quartz foreseen to be used in JASON2 is sensitive to the flux dose ($1.5.10^{-11}$ at 1 rad/h). Contrary to the other batches, JASON2 quartz is unswept. The amount of protons or alkali ions is the same than as-received.

Frequency deviation-signature and magnitude of each quartz lots are almost different. Moreover in the same lot, a non-negligible scattering has been observed:

- TOPEX lot: -8.10^{-11} to -1.10^{-11}
- JASON1 lot: 2.10^{-10} to 5.10^{-12}
- JASON2 lot: 5.10^{-11} to 1.10^{-12}

Such a scattering forces on-board USO manufacturer to evaluate LDR radiation performance of each quartz crystal of a production batch. Furthermore, this heavy operation does not guarantee the low LDR sensitivity.

C. Pre-conditioning

Fortunately, it has been noted that a pre-irradiation of resonators can reduce radiation induced frequency shifts [NOR84]. This pre-irradiation stage consists to saturate quartz crystal material. It involves a strongly decreasing frequency change at low dose rate radiation. Indeed, C-MAC[2] Frequency Products has investigated some high quality quartz materials coming from VNIISIMS, SAWYER, and GEMMA [CAN01]. The authors said that only one type of material seems to be saturated after 150 krad (which has been also swept) whereas the others are satured after only 5 to 20 krad.

[2] RAKON France since 2007

According to these results, the authors decide to apply a 30 krad pre-conditioning on the quartz crystal material (GEMMA) for the next JASON on-board USO generation (JASON2).

The result is translated by an impressive improvement of magnitude of more than one decade (Figure 8). Moreover, the resonators pre-conditioning of quartz crystal lot modify the LDR sensitivity. After this pre-irradiation, the cumulated dose becomes the main cause of frequency drift.

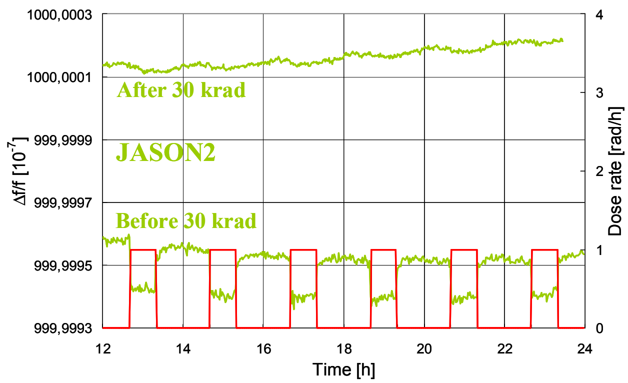

Figure 8. Frequency behaviour of a JASON2 quartz-lots before and after 30 krad radiation

Furthermore, it has been observed that the LDR susceptibility of quartz crystal resonators submitted to 30 krad then 60 krad (30+30 krad) is greatly reduced up to a ratio of 20. But, unfortunately, the first 30 krad irradiation degrades the Short Term stabilities of all oscillators, except one (Figures 9 and 10). Up to now, this degradation has not been explained. The second 30 krad irradiation dose consists in an EOL qualification of the pre-conditionning. It corresponds to about twice the total life ionizing dose in orbit (15 krad) and does not decrease the performances of the USO.

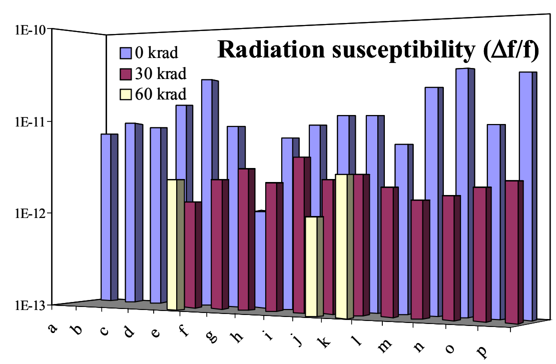

Figure 9. LDR susceptibility of quartz crystal resonators lot dedicated for JASON2 USO before and after 30 and 60 krad irradiation

Even if the pre-conditioning allowed to improve the LDR sensitivity up to one decade and more, this step of the space USO development is very heavy : one pre-conditioning (30 krad), one EOL radiation qualification and three LDR radiation campaigns (before and after 30 krad pre-conditioning, and after 30 krad EOL radiation qualification).

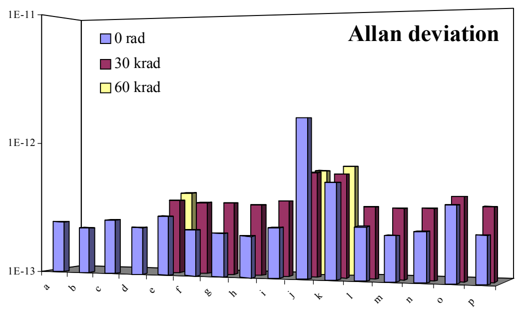

Figure 10. Short term (ST) frequency instability of quartz crystal resonators lot dedicated for JASON2 USO before and after 30krad.

The next step consists now in understanding the main quartz mechanisms inducing frequency shifts and the second part summarizes our investigations to reach these goals.

V. LONG-TERM SOLUTIONS

Previous works have showed that radiation sensitivity of USO is due to the quartz resonator. The frequency fluctuations depend on resonator technology, quartz crystal quality (impurities, dislocations…) and radiation characteristics. Up to now, some works concerned only quartz-material radiation sensitivity and other ones discussed just on resonator/oscillator radiation sensitivity. Nevertheless, few published works have investigated the correlation between both aspects: quartz material and quartz resonator/oscillator radiation-sensitivity. Reference [WEA04] of Applied Physics Laboratory from John Hopkins University summarizes prior works and presents some interesting results.

CNES (French space agency) started at the end of 2004 a R&D study taking into account quartz material and oscillator. French experts in quartz material (GEMMA, ICMCB-CRPAA, LCEP, LPMC), in quartz resonator (C-MAC[3], LCEP), in quartz oscillator (C-MAC[3], LCEP, LPMO) and in radiation (CPO, LSI, ONERA) have been gathered to determine and understand the mechanisms responsible for the radiation sensitivity of material, resonator and oscillator, and to correlate them in order to reduce their susceptibilities.

A. Investigated quartz materials

First of all, we have chosen different kinds of quartz materials to try to obtain a large spectrum of defects with their own environment. So, we introduce in our batch some samples of Natural quartz and synthetic quartz coming from 4 different suppliers: GEMMA (from France), SAWYER (from USA), VNISSIMS (from Russia) and HIRST-ASTRIUM (grown in UK). In each quartz block, samples with the same orientations and the same dimensions have been prepared except for those used in measurements is possible normalized (Y-cut samples for IR spectrometry and X-ray topography).

B. Quartz materials investigations

To understand the interactions between quartz crystal and resonant frequency shift due to irradiations, it is necessary first to know in-depth the quartz crystal itself. For that, we have to qualify and, if possible, to quantify the defects present in the lattice of the crystal. They can be microscopic point or line defects if the macroscopic defects as inclusions, veils or twins do not be taken into account. We have numerous tools to measure first the amount of imperfections in the crystal but also their displacements or recombinations under irradiations.

This variety of analytical techniques is such as chemical analysis (ICP-AES) for metallic impurities, low temperature FTIR, X-ray topography for dislocations [BOY07], dielectric relaxation spectroscopy for charges dynamics [CAM07], EPR measurements for paramagnetic defects, micro Raman spectroscopy, and, last, cathodoluminescence and thermoluminescence [DEM07]. A brief description of each kind of measurements is also included.

This reference [CIB06] summarizes preliminary results of all analytical techniques. More details of each of them are presented at this symposium [BOY07], [CAM07], [DEM07].

C. Oscillator investigations

To correlate these quartz materials investigations and effectively observed frequency variations of resonator, some test USO have been built in the same materials than those studied before, during and after exposure to radiation. The investigations of these oscillators submitted on ionizing radiation will be focused on LDR effects and pre-conditionning.

VI. CONCLUSION

Some solutions have been used to reduce partly USO radiation sensitivity : shielding, specific quartz materials and quartz crystal pre-conditioning. Even if they can be efficient, each of them has a drawback. Shielding does not guarantee total radiation protection (high energy protons) and weight, volume and ESD criteria must be taken into account. Scattering observed on specific quartz materials forces on-board USO manufacturer to evaluate LDR radiation performances of each quartz crystal resonators of a production batch. Furthermore, this heavy operation does not guarantee the low LDR sensitivity. And, if the pre-conditioning operation allowed to reduce this LDR sensitivity, this step of the USO development is consequently heavy.

[3] RAKON since 2007

Because of these drawbacks, CNES and French experts in radiation and in quartz material and oscillator have been gathered to determine and understand the mechanisms responsible of the radiation sensitivity of material and oscillator and to correlate them in order to reduce their susceptibility.

VII. ACKNOWLEDGMENT

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