# Annealing Displacement Damage in GaAs LEDs: Another Galileo Success Story

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## Abstract

A recent failure of Galileo's magnetic recorder was identified as LED degradation. Annealing the culprit OP133s proved successful and the irreplaceable data was recovered. Test data and modeling results calibrate an understanding of this incident.

### Introduction

The Galileo mission to Jupiter has been very successful in spite of a number of technical obstacles. These range from the impact of the Challenger explosion (delaying launch and causing major propulsion-systems re-designs) to the failed unfurling of the high gain antenna (efforts to maximize data delivery over the low gain antenna were fruitful) and the sticking tape in the magnetic data recorder (slower speed work-arounds were developed). Now in its second mission extension and having far exceeded expectations for delivering invaluable science data about the Jovian system, the aging spacecraft is showing signs of impending failure of critical electronics due to the cumulative effects of the harsh trapped radiation belts in which it operates [1].

Currently, Galileo is on its final orbit which will culminate in its destruction in Jupiter's atmosphere this September 21st. During its next-to-last orbit while recording data during its first and only encounter with the moon Amethea, data collection stopped abruptly about ten minutes after closest approach and the spacecraft entered its "safe" configuration due (most likely) to a single-event upset in the attitude control system. These events have occurred before and while, not unexpected, they are definitely inconvenient. Fortunately, almost all of the primary-goal data and much of the secondary-goal information had been recorded on tape. However, efforts to playback this data after exiting the safehold revealed that the recorder would not work and this time it was not because the tape had stuck again. Because the Amethea encounter brought the spacecraft deeper into the trapped electron and proton belts than ever, radiation was immediately suspected as the proximate cause of the problem. This paper tells the story of the investigations that followed and how an understanding of the specific failure allowed an effective annealing scheme to be carried out in flight. Thus, this story has a happy ending: the collected Amethea data was successfully downlinked to Earth.

### Failure of the Recorder

The Galileo magnetic tape recorder was manufactured by Odetics and is shown in the photograph in Figure 1. We will give only a brief discussion of the recorder here; the full paper will have more details. On the top face, one of the tape reels can be seen (the other is immediately underneath) as well as the winding tape path around the four read/write heads. The capstan drive motor's axis is perpendicular to the plane of the reels and has encoder wheels attached near the bottom face. Telemetry revealed that, during playback attempts, the motor was drawing all the current available to it, a signature that clearly reveals that this is not the same tape-sticking problem previously encountered. Rather the source of the problem was identified as the drive electronics not moving through the sequence of energizing the motor's three windings, but rather was stuck on energizing only one. This could happen if (a) the armature were unable to move into alignment with the energized winding, or if (b) the

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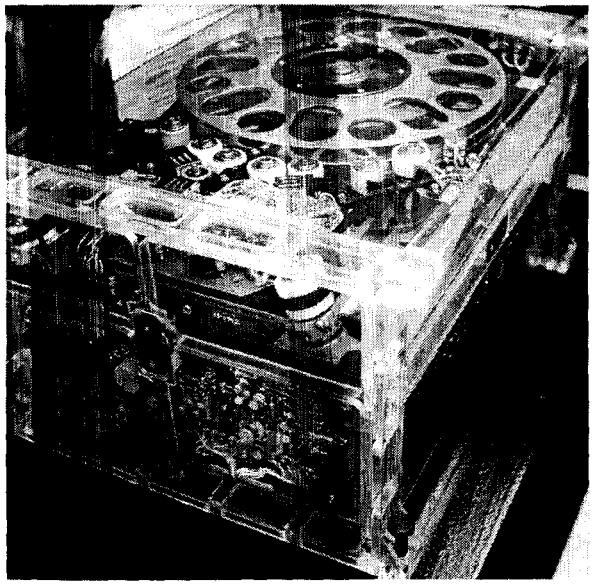

Fig. 1. Photograph of the tape recorder used on Galileo

position encoder wheel were not moving with the armature, or if (c) the electronics were not reporting the encoder wheel position correctly. Both of the former two mechanical events were deemed unlikely because the telemetry indicated that the tape position was exactly the expected one, that is, that the recorder was operating properly up to the safehold occurrence which would shut down the recorder's supply. Thus, scrutiny turned naturally to the latter possibility.

The encoder wheel position is detected by three LED-phototransistor pairs. If any one of the three phototransistors does not detect its LED's illumination when a window in the encoder wheel is in position, then the sequence would stop - exactly the symptoms observed. Radiation could cause this by causing (a) a drop in LET light output, (b) a drop in the phototransistor's gain, or (c) darkening of the elements in the optical path, i.e. the LED and phototransistor lenses and/or the "transparent" wheel material. The latter possibility is thought to be unlikely because of the extremely high doses needed for significant darkening of most transparent materials. We plan to test the specific materials for the full paper. The LED is an OP133 made by Optek and the phototransistor is a silicon device, the MD300 from Motorola; both have focusing lenses built into their package. The LED is an amphoterically doped GaAs diode (wavelength = 935 +/- 35 nm). Previous work with this type of LED [2] has shown that, although the light output is relatively insensitive to ionizing dose, the output is very sensitive to displacement damage. Previous work with optocouplers made from amphoterically doped LEDs and Si phototransistors indicates that the phototransistor contribution to reduced optocoupler gain resulting from proton irradiation is real, but small in comparison with the LED's contribution (<10%). Thus, displacement damage to the OP133 LED was identified as the prime suspect in causing the recorder failure.

**The Radiation Environment Encountered**

Although protons usually dominate the radiation environment in earth-orbiting spacecraft, the Jovan environment has an electron environment with much higher energy. Thus, in most of the orbits near the extended belts of Jupiter the largest contribution to total dose is from high-energy electrons. Displacement damage from the energetic electrons can be a significant problem, particularly for amphoterically doped LEDs, which are extremely sensitive to displacement damage effects [2,3].

In the limited space available for the summary we have described the electron environment in terms of 50-MeV protons, using GaAs NIEL values from Ref. 4 and 5 to determine the relative damage. A more thorough description of the environment and the way that this equivalence was established will be provided in the complete paper.

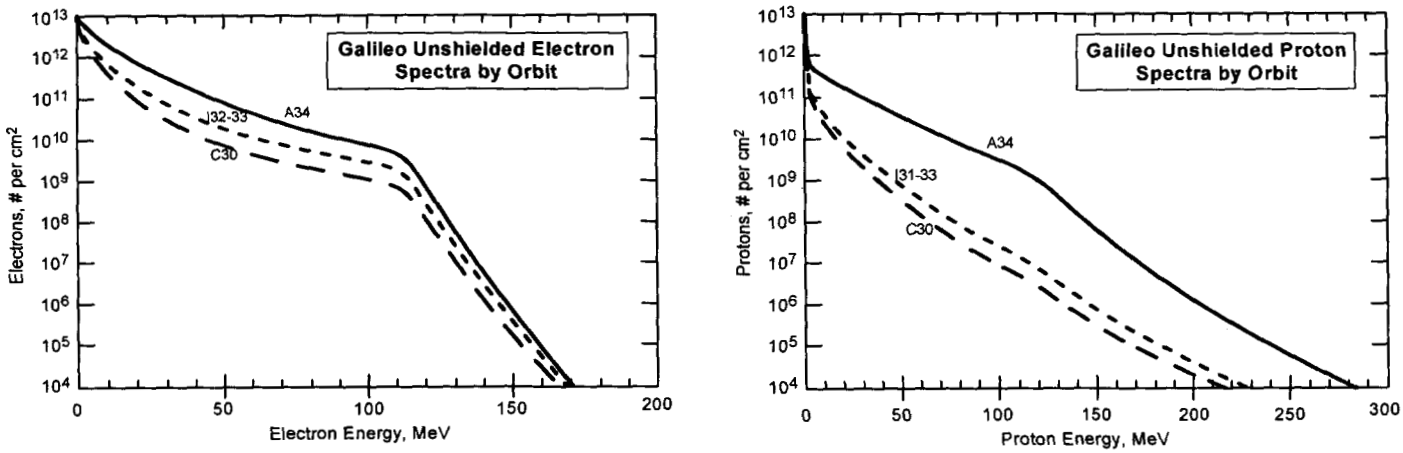


Figure 2. Unshielded spectra for electrons (left) and protons (right) for the last five orbits of Jupiter [1]. Orbit C30 encountered Calisto, orbits I31-33 the moon Io, and A34 included the Amethea encounter where the recorder stopped functioning. Note that A34 has the harshest environment for both, but has particularly increased numbers of trapped protons.

Galileo has made 34 different orbits around Jupiter, most with moon encounters. With the exception of the pass near Amethea, the mean equivalent fluence (99% from high-energy electrons) is 6 x $10^9$ p/cm$^2$ for each pass. Thus, the total equivalent fluence for the preceding 33 passes is 2 x $10^{11}$ p/cm$^2$. This is a sufficiently high fluence to severely degrade the LED. However, the design approach used for Galileo was conservative. The last pass towards Amethea required a different orbit. That orbit not only increased the fluence of electrons, but also went through a region of the Jovan belts with much higher proton fluence. The equivalent fluence produced by this pass was 4.5 x $10^{10}$ p/cm$^2$, with about 60% of the damage produced by protons. Thus, this pass increased the damage by 20% compared to the cumulative damage from the preceding 33 passes.

**LED Damage**

Damage in Optek OP130 LEDs, from the same family of GaAs LEDs used in Galileo, was reported in Ref. 2 and 6. These types of LEDs are quite sensitive to displacement damage. The amount of damage produced by displacement effects is greater at low current compared to the damage that occurs at higher currents, even when pulsed measurements are used to minimize injection-enhanced annealing. Thus, it is important to use LED characterization data that is taken at about the same current used in the application. Using test data at 1 mA for an application at 20 mA will overestimate the damage by a considerable factor.

However, some of the damage will anneal afterwards, provided current flows through the LED after it is irradiated. After irradiation with protons, it takes a total charge of approximately 10 coulombs for ½ of the recoverable part of the damage to anneal. Annealing continues as current is applied, but nearly all of the damage recovers after approximately 1000 coulombs have been applied to the device.

Displacement damage is difficult to deal with unless one can define a parameter that changes linearly with fluence. Damage in amphoterically doped LEDs is *superlinear* with fluence. Rose and Barnes showed that the damage could be linearized by using the relationship [3]

$$[\,(I_o/I)^n - 1\,] = K\,\Phi$$

where $I_o$ is the initial light output, I is the reduced light output after irradiation, n = 2/3 for an LED operating at constant current, K is the damage constant, and $\Phi$ is the particle fluence. This equation was used to evaluate damage from Optek OP130 LEDs, and extend the data by approximately a factor of two because the maximum fluence used for earlier radiation tests was lower than the equivalent proton fluence experienced on Galileo.

Figure 3 shows the dependence of damage (as defined by the above equation) on fluence for OP130 LEDs at three different currents. At the highest current, negligible damage occurs at the lower fluences, and the apparent nonlinearity at low fluence is simply the result of measurement uncertainty.

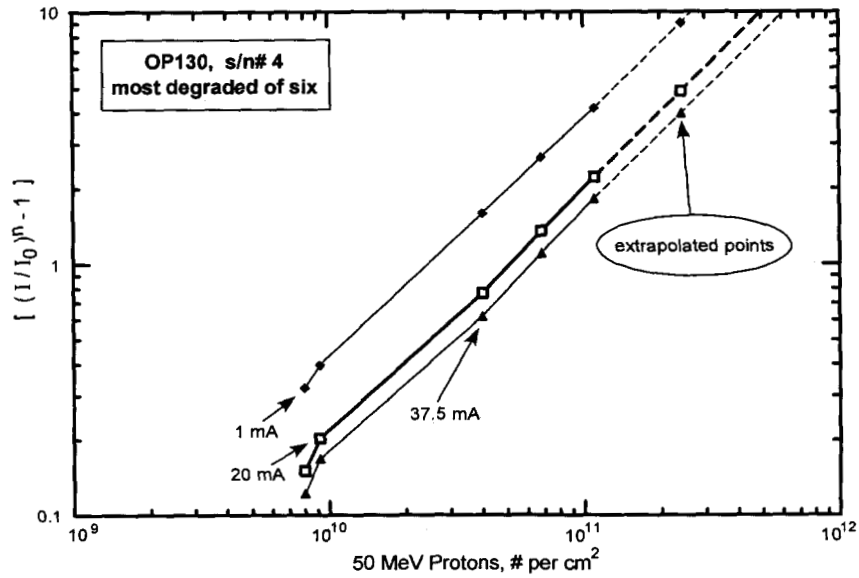


Fig. 3. Linearized damage function vs. proton fluence for the OP130 LED. This relationship was used to extrapolate the damage to higher fluences.

The values in this figure were used to determine the net change in light output at the higher equivalent fluence encountered by Galileo.

This approach is reasonable to estimate damage to the LED in this environment. However, no recent work has been done on electron damage in LEDs, and the NIEL concept may not be accurate because electron damage is dominated by vacancy-interstitial pairs, not cascade damage. Therefore it is important to investigate electron damage and annealing effects from electrons for these devices because most of the damage on the total mission has been caused by electrons. These results will be included in the final paper.

**Recovery of the Recorder**

A special operating mode was utilized that allowed current to be continually applied to the three LEDs without actually attempting to move the motor. After six hours of current-enhanced annealing of the LEDs, the recorder was commanded to move the tape. The tape moved for only ½ second but this was an improvement compared to the totally non-operating condition that occurred before the annealing was attempted. The recorder recovered more after another six hours of current-enhanced annealing, and this time tape motion persisted for 1.8 seconds. This series of annealing and operational sequences was continued for more than 100 hours, as shown in Fig. 4. Each time the recorder operating period was longer, and after the next-to-last annealing cycle, it was able to function for more than one hour, which was sufficiently long to allow most of the data to be recovered.

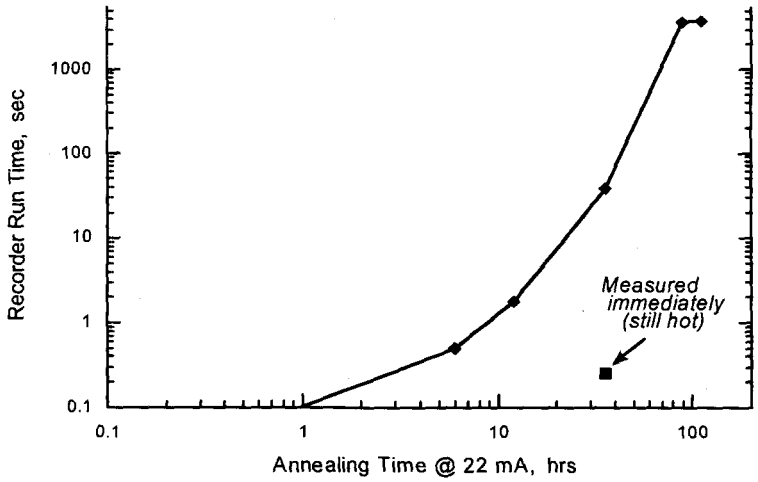


Fig. 4. In-flight annealing is shown by the increasing times that the recorder motor moved after successive intervals when the LEDs were operated continuously in order to cause current-enhanced annealing.

The normal operating current in the LED is 22 mA, which is sufficiently high to raise the temperature in the LED due to self-heating. The LED output decreases about 0.75% per degree C, and this is the most likely reason that the recorder cannot operate indefinitely. Thus, it is likely that the percentage of damage that recovered was only a small amount above the threshold condition required in the circuit. Earlier work on annealing in the OP130 showed that only a fraction of the total damage would recover [6], so the annealing approach has diminishing returns after current has passed through the LED for extended time periods. Diminishing returns are seen in Fig. 4 where the last anneal period only produced a small incremental improvement in recorder run time.

## Conclusions

The rapid and successful response to the Galileo recorder failure required (1) identification of the recorder components and circuit elements capable of causing the failure signature, (2) recognition of the role of radiation damage, and (3) development and deployment of remote repair operations. When the LEDs rose to the top of the suspect list and current-enhanced annealing was identified as a possible solution, it was not clear whether or not too much damage had occurred for that strategy to work. The identification of a mode of recorder operation that would fairly conveniently and unintrusively run current through the LEDs allowed annealing to begin as an in-flight "experiment." Early hints of some success encouraged continued annealing. Fortunately, the recovery hit diminishing returns at a point where recorder operation was restored to a reasonable operating regime.

## References

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