On-Orbit Measurement of JFET Leakage Current and its Annealing as Functions of Dose and Bias at Jupiter.

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Abstract
Controlled bias vs. dose is being used to: induce radiation-annealing, minimize charge in depletion zones and thereby keep a JFET within acceptable operating limits during flight.

DG181 Ground Test
Radiation is known to be the primary cause of the degradation of the inertial gyro electronics on the Galileo Spacecraft at Jupiter. Although much of the electronics has exceeded the mission-design dose limit (usually 150 krads), only one device type, the DG-181 JFET switch, has been proved to be degrading in the inertial gyro electronics. The detailed quantitative degradation in leakage on four DG-181 devices is being monitored, almost in real time. The detailed degradation of specific operating parameters of most other devices throughout the spacecraft cannot be monitored.

Ground tests indicate (Table 1.) that under operating bias during radiation the source leaks current to "ground" or to the drain.[1] Whether the leakage path is parasitic or in the channel is not known. The small gate bias applied in ground tests appears to play only a small role, indicating that parasitic leakage outside the channel may be active. Of the four devices tested: the best device degraded only slightly and the worst device was marginal for the mission. Note that device degradation varied by nearly a factor of ten among the four tested devices.

Table 1. Leakage Current Vs. Accumulated Dose In Ground Tests Of Four DG-181 JFET Devices.

Dose k-Rad	Gate Bias During Irradiation, V	Source Leakage, MicroAmps		
		BEST	MEAN	WORST
62	0	0	0	0
62	-1	----	----	----
112	0	.06	4.3	13
112	-1	.05	2.8	8
250	0	1.9	9.3	16
250	-1	1.9	9.0	22

In-Space Leakage Data
In space at Jupiter, the dose to the DG181 devices has been estimated, and the leakage current has been monitored. The Galileo spacecraft has a number of ways to monitor its accelerations such as by the star scanner and by knowledge of its thruster performance. The spacecraft operators are able to determine the error in the gyro scale factor allowing them to reprogram and correct the gyro with a correction factor. [2] A gyro scale factor error of 10% indicates a leakage current of 18 microamperes in its DG181.[3] Dose estimates are based on knowledge of Galileo's location in the Jovian radiation belts.[4]

The existing model of the Jovian environment combined with the NOVICE radiation transport code and the mass-model of the spacecraft have been used to estimate the dose received by the four sensitive DG-

181 devices. The gyro electronics box is shown in Fig. 1. Leakage in the +1X , +1Y, +2X and +2Y devices does not generate a gyro electronics problem.

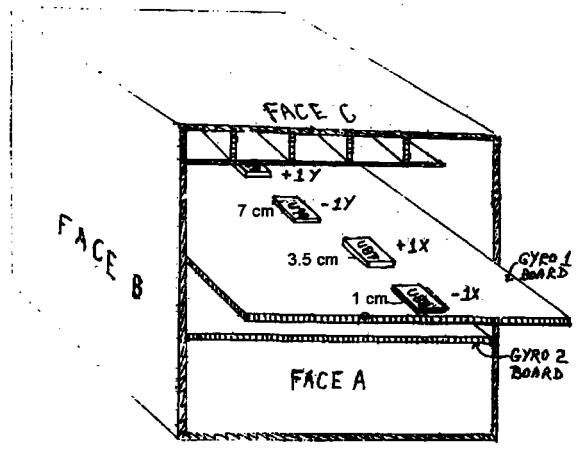

Fig. 1. The Gyro Electronics Box. In this view, face A of the aluminum box is removed and the circuit board for gyro #1 is pulled from the box to show the layout of the four DG-181 devices. Radiation from Jupiter's environment impacts faces A, B and C after passing through thermal control surfaces and thin structural plates. The other three faces are well shielded by the bulk of the spacecraft. The –1X axis DG181 is closest to the irradiated face A and thus receives the most intense radiation. The –2X and –2Y devices lie on a similar board just below the –1X and –1Y devices.

Through twelve orbits, the doses at the devices are predicted to be: -1X = 250 krads, -1Y= 215 krads, -2X = 215 krads and, -2Y = 175 krads. Although the uncertainty of the transport alone is at least 20%, the relative doses among the four devices are more accurate. Further uncertainty results from possible disparity between the actual radiation belts and the model belts. After 12 orbits the change in scale factor indicates leakage currents of: -1X = 18, -1Y = 5, -2X = 4, and –2Y = 2 microamperes. These data are plotted in Fig 2. along with the ground test data.

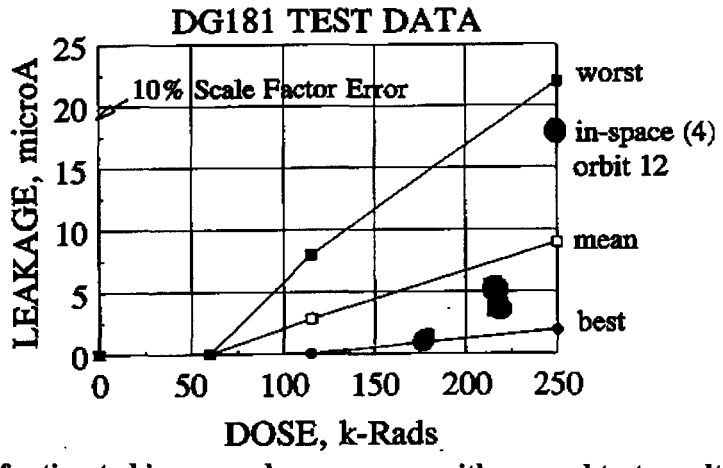

Fig. 2. Comparison of estimated in-space dose response with ground test results. The ground test data are connected with the lines. The in-space data for the four devices after orbit 12, the first measurement of in-space leakage, are shown by the four dark circles.

It seems that the four devices tested on the ground varied in dose-response in a manner similar to the four devices flown in space. There is a factor of 10 variance from the worst to the best device in each group of four.

Damage Annealing
It is important to understand that Galileo orbits Jupiter with highly elliptical orbits. Typically, an orbit consists of perhaps two days of "encounter" where data such as optical observations of the Joivian system are obtained. Within the two-day period is the point of closest approach where Galileo experiences the radiation belts over a period of roughly twelve hours. The remaining part of the orbit consists of perhaps two months far from Jupiter when data is transmitted to Earth, the spacecraft performance is evaluated, and plans for the next encounter are fine-tuned.

The scale factor is usually measured twice per orbit: once prior to the two-day encounter and once after. Unfortunately, the exact timing of the measurements is at the convenience of the spacecraft operators, and does not always provide the best data for measurement of annealing. Furthermore, there are two kinds of annealing with a synergism between the two. Finally, the added dose at encounter varies significantly from one orbit to the next.

Normal Thermal Annealing
Dose at a two-day encounter adds some damage (charged centers in insulator or depletion zone). The scale factor is measured after encounter and again prior to the next encounter during which time some of the damage can anneal. The measurement time spans have varied from ten days to 77 days. Fig. 3 describes the fraction of leakage generated in the most recent encounter that anneals during a time span (10 to 77 days) after that encounter. This was done for 19 orbits. That the measured amount of damage annealed during each orbit was always positive is evidence for the high precision of the scale factor measurement. The temperature of the gyro electronics remained stable at the spacecraft temperature. It is noteworthy that no annealing data was reported in ground tests, despite the fact that annealing improves the performance of devices.

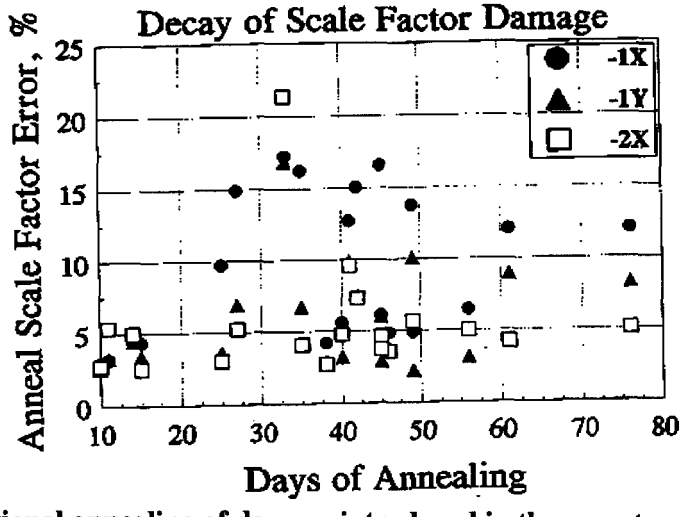

Fig. 3. Measured fractional annealing of damage introduced in the recent encounter for each of 19 encounters.

Radiation-Induced Annealing
It is known that recombination of electrons and holes, generated by radiation, can be used to anneal active charge centers and either move them out of sensitive volumes [5] or change them [6] into less active charge centers. But the recombination rate as a function of position in a device is minimum in its depletion zones and therefore accumulation of active defects is most rapid there. [6] Depletion zones are, on average, both most depleted and widest under full bias so that more defects may accumulate in a biased device under radiation than in an unbiased device. Furthermore, defects once generated in a wide and biased depletion zone can be "annealed" by reducing bias so that the defect is no longer in the

depletion zone, and subsequently injecting electron-hole pairs (by irradiation) in order to anneal the now-exposed defects.

Through orbit 13, the DG181 devices remained fully biased at all times. Afterwards the bias was usually turned off during radiation belt transit, and turned on when outside the belts. Figure 4 shows the results. Note that the scale factor error, DG181 leakage, increased most dramatically when bias power was on. Especially note, for device –1X, that on orbits 14-16, 21, 22 during zero-bias the radiation actually annealed more damage than it introduced, presumably by electron-hole recombination-induced annealing.

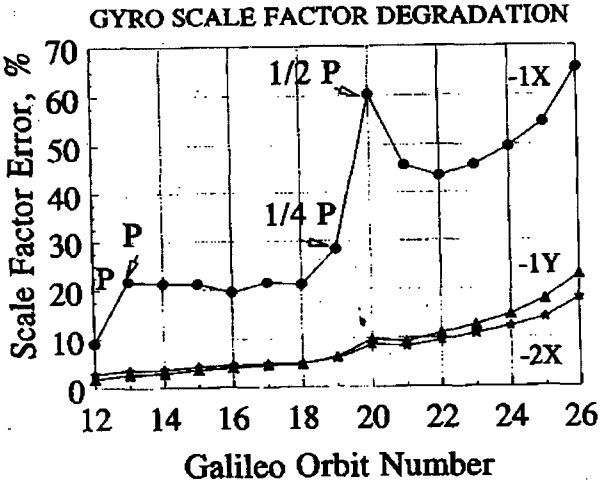

Fig.4. History of scale factor error in three channels. The letter "P" in the graph indicates orbits where bias was on. 1/4P indicates power left on during a fourth of the radiation belt pass, etc.

Further Data and Implications of the Results

It is encouraging that understanding of the mechanisms of point defect generation and annealing allowed us to alter operational pattern of the spacecraft in order to benefit the mission. A companion paper describes the overall Galileo Spacecraft problems due to radiation. Various measures of the radiation belts are available in that paper. Comparison of the DG181 data with other radiation effects on the spacecraft and with the radiation belt intensities on each pass are interesting.

Ground testing did not report a bias sensitivity, yet space testing found it to be very important. If, prior to spacecraft design, one had known that bias could be used to control the level of radiation damage, the mission could have taken advantage of the effect and saved operational expenses. It was only by luck that the ground data was near worst case and that a device in flight was not significantly worse than ground test data.

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