Abstract

The Galileo spacecraft has been subjected to the charged particle environment around Jupiter since 1995. There have been numerous system failures attributable to radiation effects. We summarize those failures, their causes and any associated fixes.

The Radiation Effects on Galileo Spacecraft Systems at Jupiter

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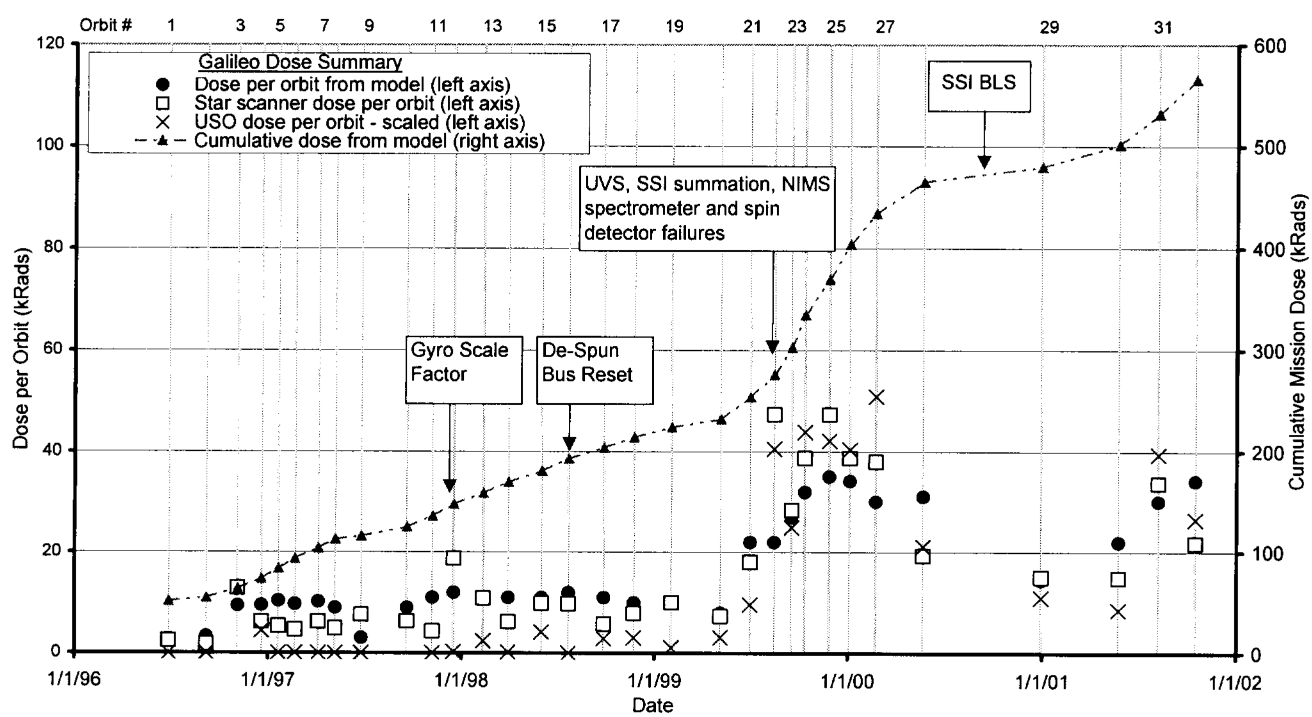
The Galileo spacecraft was designed to only make 11 orbits through the harsh radiation environment near Jupiter. To date, it has completed its 33rd orbit and has survived a dose equal to four times the design limit. Nevertheless, the spacecraft has experienced many system problems such as:, increased detector noise, part failures such as leakage current due to total dose effects, power glitches probably due to arcing dielectrics, IESD noise, Cerenkov and Florescence radiation in optical elements, oscillator frequency shifts, and other effects. Due to the flexibility of the spacecraft design and an excellent flight control team, many of the failures have been rendered impotent and the spacecraft continues returning high quality science observations from 10 of 11 instruments.

It is the intent of this paper to document the system failures caused by the radiation environment and the response of the Galileo flight team to it. We also categorize the strength of the connection between the failure and its proposed radiation-related cause and, where possible, identify the failed part.

Much of the pre-flight modeling of dose estimates were based on a model environment [1] which provides particle fluxes between 1 and 16 Jovian Radii. Because Galileo was not endowed with a calibrated dosimeter, independent checking of the model environment has had to proceed through less direct means such as integrating flux as measured by onboard particle detectors. The indications are that as of late January 2002 the spacecraft has received 600 krads behind 2.2 g/cm^2 [2]. Most systems were only designed to survive to 150 krads and in fact serious spacecraft failures began to appear at approximately this dose. Figure 1 shows the modeled cumulative flux for the mission through the I32 orbit. The other markers represent the dose taken per orbit as predicted by the model, and as data from several flux-measuring instruments scaled to approximate the model. Several important spacecraft anomalies are also noted.



A selected few of the major spacecraft anomalies that are known to be radiation related will be discussed here. It helps to understand that the orbit of Galileo spends roughly a day or two near Jupiter in the radiation belts followed by months at a high altitude apoapsis far beyond the belts [3]. During the long apoapsis portion of the flight it is possible to diagnose the spacecraft and recover from problems. Also, some annealing of damage has been consistently measured during this period.

Gyro problems: Galileo carries a pair of rate-integrating gyros to sense spacecraft motion. Near the end of the nominal 11-orbit mission, the gyros began to exhibit errors between the real and perceived angular slew. The spacecraft attitude control computer can take this erroneous data as an indication that the vehicle needs to be autonomously repointed – an action that is dangerous considering Galileo's weak, slow and delayed communication link to Earth. Additionally, the proper pointing of science instruments can be seriously affected. The bias problem is at its worst just after a Jovian periapsis pass and gradually anneals by 5% to 30% over the next months. A circuit analysis traced the probable failure to some DG-181 solid state switches. Further work has shown that part-to-part variation in radiation tolerance as measured in ground testing prior to flight, and amount of shielding, can explain the in-flight data. The Galileo team has devised a procedure where the radiation-induced error generated in one 2-day pass through the belts is measured, and a correction factor is determined and uploaded so that the next pass near Jupiter is accomplished with an acceptable gyro performance. The gyro correction factor is re-determined once every orbit.

Bus Reset Problem: Almost all data from the 16th, 18th and 33rd orbits were lost due to the spacecraft entering safe-mode after falsely believing it had received a "Power-on reset" signal. This false signal was traced to 2 of 48 slip-rings between the spinning and non-spinning portions of the spacecraft. Specifically, an arc seems to be occurring in the vicinity of the slip-rings which then triggers the anomaly. This only happens near periapsis and after absorbing a set amount of integrated electron flux as measured by onboard particle detectors. The troublesome rings are directly below a cut-out in the metal shielding of the entire slip-ring assembly so that intense electron flux is probably preferentially charging nearby insulator parts in this area.

Quartz Oscillator Problem: An ultra-stable quartz crystal oscillator exhibits a transient frequency shift during and shortly after the pass through the belts, and it anneals within a few days. It is not yet known if the drift is caused by the quartz or by the oscillator electronics, or both.

Other Problems: Almost all of the science instruments and several of the engineering systems suffer from problems caused by increasing noise when pushed deep into the Jovian particle environment. The star scanner, which provides the ultimate source of attitude reference for Galileo, has also proven to be an adept if accidental instrument for measuring >1.5 MeV electrons [4]. The electron multiplier tube in the star scanner is an excellent dose-rate monitor that measures dose-rate to its first cathode. A few instruments suffer periodic memory upsets due to unknown causes, and others have lost a portion of their suite of detectors. A dual FET in a single ungrounded case picks up charge which can cause Galileo's optical camera to produce useless white images.. One instrument, an ultraviolet spectrometer, has failed entirely due to a failure of an LED or photocell measuring position within an optical grating assembly. In all, 12 failures that are definitively radiation induced are documented in the paper while another 13 with a likely or possible connection to radiation are noted.

Equally important with the failures are the successes. The attitude control computer contained bipolar integrated circuitry and was found in pre-flight testing to be extremely susceptible to SEUs. A crash course was instituted to replace the bipolar with CMOS equivalents [5]. To date, not a single SEU has been observed in this computer. No failure related to spacecraft surface charging has been noted and onboard measurements indicate that the spacecraft remains at +/- 10 volts in sunlight. All data bus cabling was well shielded and grounded and there has been no indication of any bus problems noticed in six years of operation at Jupiter. Surface charging-related problems were not observed and few, if any SEUs have occurred. Pre-launch attention to detail in these areas paid off.

Although this summary paper is far to short to detail the rationale, some of the major lessons learned are presented here.

It is now obvious that a few simple dosimeters should have been instrumented on the spacecraft. They would have allowed one to better determine the accuracy of the dose estimates obtained from the Jupiter environment model. Having better estimates of the dose in spacecraft at Jupiter would, perhaps, allow for more aggressive design of future Jovian spacecraft. Although Galileo carried radiation spectrometers, the level of uncertainty in their data, and especially the choice of energy channels, do not allow for significantly improved estimates of dose-depth on Jovian spacecraft. .

A very elliptical orbit with a period measured in weeks or months and with an apoapsis far from the radiation belts has proven to be extremely important. The long apoapsis allows time to diagnose and correct problems before they can begin to compound.

A part at the center of a spacecraft is not necessarily well shielded.

At Jupiter, there is significant variability in the outer magnetospheric environment, although perhaps less than seen at Earth. It may be possible to predict the worst times by looking for spikes of high-energy electrons in the middle magnetosphere and possibly monitoring Io in the infrared for volcanic outbursts.

Although most radiation related anomalies occurred at lower altitude, within the orbit of the moon Ganymede, being outside this marker was not an absolute guarantee of safety. Performing the majority of science activities inbound to Jupiter is preferable to outbound as some problems show a predilection to occurring just after periapsis due to the accumulation of flux.

As predicted, the spacecraft began to suffer major anomalies just as it was exceeding its radiation design dose, but only in a small portion of the circuits that might have failed at this dose. Less predictably, human operators were able to figure out methods to work around the anomalies, thus greatly extending mission life and utility.

Although some systems failed "on schedule" most systems have multiple layers of hidden margin and have yet to fail. A cheaper, although less long-lived spacecraft might have been designed by keeping tighter rein on all the various design margins, some of which are not normally quantified.

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