Deep Space 1 Spacecraft Vibration Qualification Testing

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The environmental qualification program for the Deep Space 1 spacecraft included a force-limited random vibration test in two axes. A semi-empirical force limit procedure was used to derive force limits for the test. The results of the test show that the acceleration inputs measured near the feet of a number of spacecraft mounted instruments reached their assembly random vibration test specifications. Also, several major structural elements of the spacecraft reached their flight limit loads during the spacecraft vibration test. Test results, as well as lessons learned, from those tests will be discussed in this article.

The Deep Space One (DS1) spacecraft, as illustrated in Figure 1, is NASA's first New Millennium Program deep-space mission involving an asteroid flyby. The main objective of the DS1 mission is to space validate many advanced payload technologies that hold promise for enabling desired 21st century space science missions for low cost flights. DS1 is the first spacecraft with ion propulsion as its primary propulsion system. The mission is managed for NASA by the Jet Propulsion Laboratory (JPL). The spacecraft was launched on October 24, 1998 on a Delta II launch vehicle from Cape Canaveral. During a highly successful primary mission, it tested 12 advanced technologies in the environment of space. The launch weight of the DS1 spacecraft is 1070 lbs. DS1 flew by the asteroid Braille on July 28, 1999 and is currently on its extension mission that will include encounters with two comets.

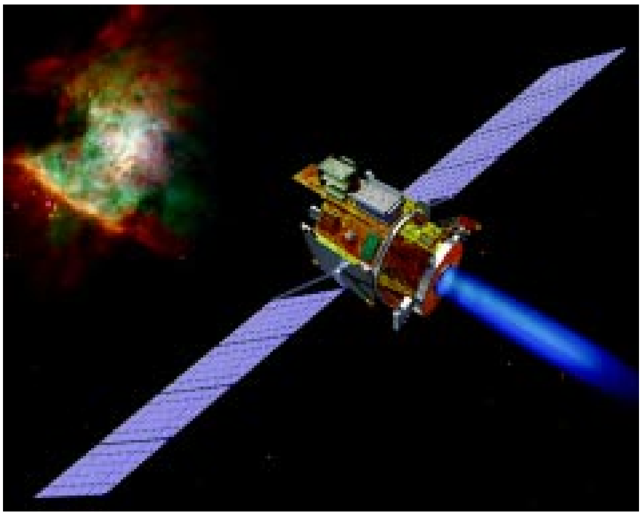

Figure 1. DS1 spacecraft deployed configuration in flight.

DS1 Spacecraft Random Vibration Test

The environmental test program for the DS1 spacecraft included a force-limited random vibration test in two axes. The spacecraft vibration test demonstrated design qualification and workmanship verification of the assembled flight spacecraft for the transmitted vibration environment encountered in launch. The DS1 flight spacecraft, with a test Payload Attachment Fitting (PAF) but no thermal blankets installed, mounted on the shaker for the vibration tests is shown in Figures 2 and 3. Figure 2 illustrates the vertical vibration test setup and Figure 3 shows the lateral vibration test setup. For lateral axis vibration tests, the DS1 spacecraft was positioned on the slip table in such an orientation that the shake direction was at a 45° angle to the spacecraft X- and Y-axes. In these two tests, two mass simulators were used in place of Scarlet Solar Arrays. The weight of the DS1 spacecraft with test PAF was 765 lbs, which is less than the weight at launch because for the test the tanks were loaded with stabilization pressure instead of fluids. The DS1 spacecraft bolts to the shaker head adapter at twenty-four (24) attachment points. 24 triaxial force transducers were installed between the test PAF and the shaker head for force limiting. In addition, more than 150 accelerometers were installed on the spacecraft for test response monitoring and limiting to ensure spacecraft safety. The test was conducted at JPL in November of 1997.[1] The spacecraft was powered and operated in the launch mode during the testing.

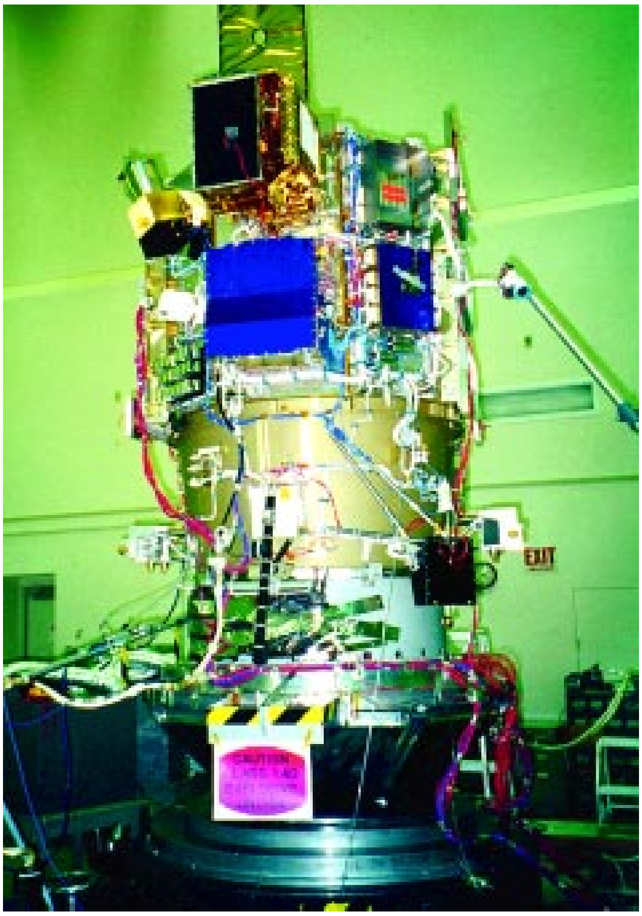

Figure 2. DS1 spacecraft on shaker for vertical vibration testing.

Random Vibration Test Requirements

The spacecraft vibration test frequency range was 10 to 1600 Hz with 0.02 g^2/Hz input acceleration level from 20 to 200 Hz. The test duration requirement for each test axis was 60 sec. This specification, as shown in Figure 4, was derived from the results of an extensive finite element model (FEM) pretest analysis, which indicated that excessive notching would be required to maintain the spacecraft's structural integrity with a higher-

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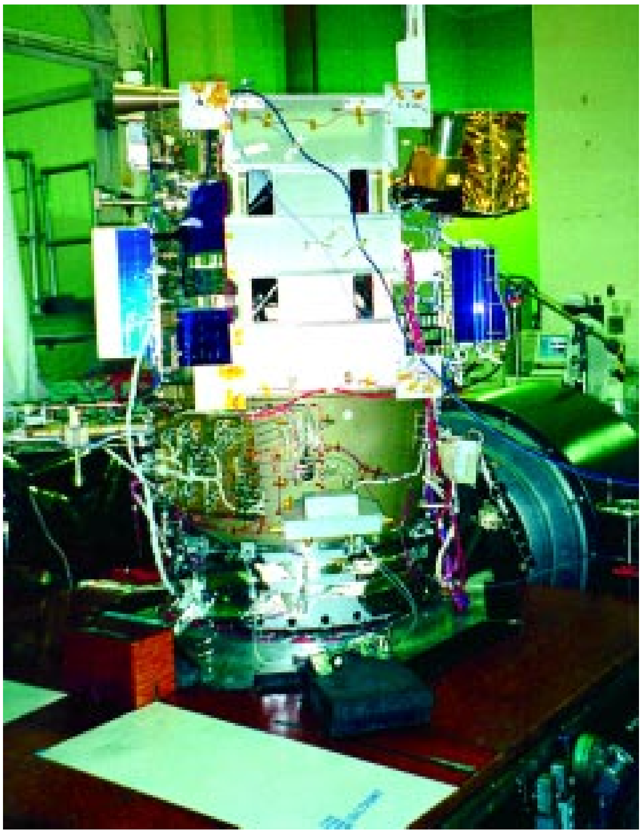

Figure 3. DS1 spacecraft on shaker for lateral vibration testing.

level input. The 0.02 g^2/Hz specification enveloped payload interface accelerations from previous launch vehicle specifications and launch data. Figure 5 shows the force specification required for the full-level DS1 spacecraft random vibration test. The force specification was derived semi-empirically by multiplying the acceleration specification in Figure 4 by the squared weight of the test spacecraft and by a factor of two. This semi-empirical force prediction method was also used in the Cassini flight spacecraft vibration test, which is discussed in Reference 2. The choice of the C^2 factor equal to two was selected on the basis of the pretest analysis and in order to keep the vibration test loads below the spacecraft design limit loads. During the test, it was not necessary to modify or update the force limit specified in the test procedure. Only the summed force of each test direction was needed in the controller feedback to notch the acceleration input.

Test Control and Operations

The vibration acceleration spectrum was controlled from the spectral maximum of the two test axis control accelerometers (approximately 180° apart). Figure 6 shows a close-up view of the test PAF mounted on top of the shaker head adapter. In this photo one of the force transducers, which is located under the test PAF at each of the 24 attachment positions, as well as one of the test control accelerometers, are visible. Another monitoring accelerometer mounted near the control accelerometer for test verification and two cross axis accelerometers mounted on the shaker head adapter plate for evaluation can also be seen in this photo. The m+p international shaker control system at JPL can handle 48 active channels. Approximately 40 channels of the DS1 spacecraft responses were installed as quick-look data channels to monitor each test run. In addition to the force limiting channels, some of these channels were used as response control channels in the control system to ensure that the spacecraft flight limit loads were not exceeded. Response controls were specified at several critical locations on the spacecraft, such as the Magnetometer Attachment, the Thruster Bracket, the Star Tracker and the Miniature Integrated Camera Spectrometer (MICAS) Radiator.

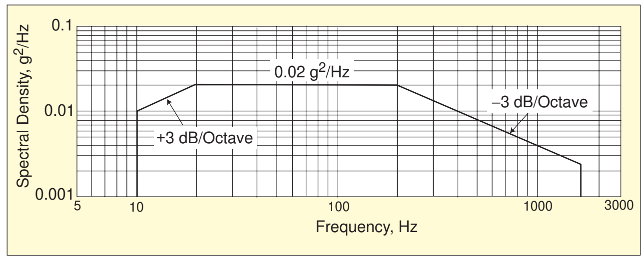

Figure 4. DS1 spacecraft random vibration acceleration specification – 3.5 g RMS overall, 60 sec test duration.

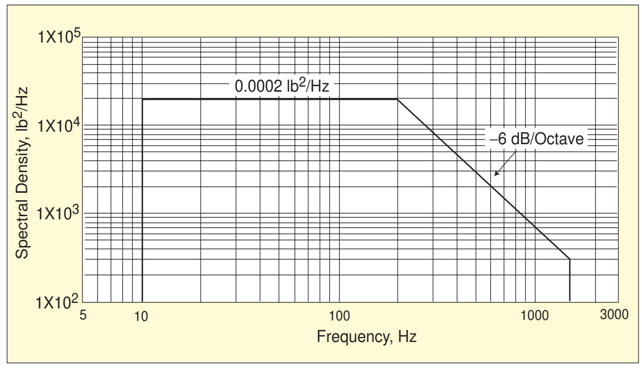

Figure 5. DS1 spacecraft random vibration force limit specification.

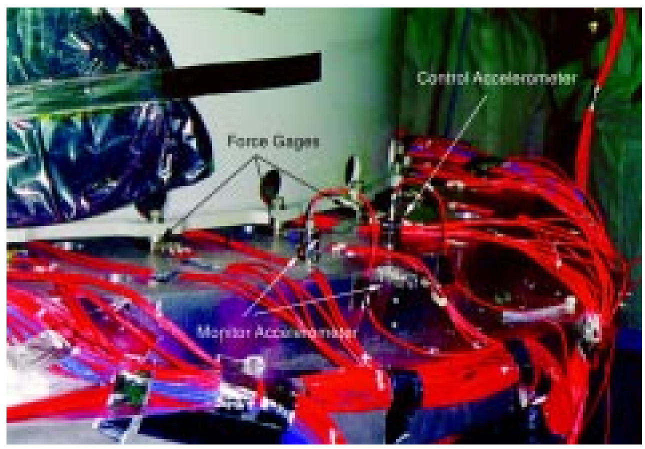

Figure 6. Force transducers and control accelerometers for DS1 vibration test.

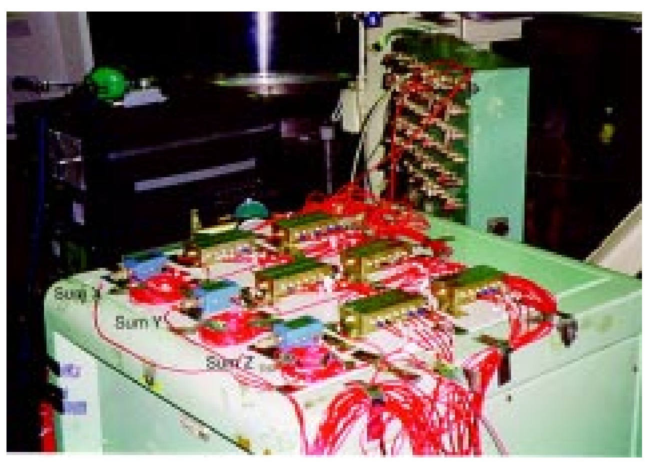

Figure 7. Summing of 24 force measurements in X, Y and Z directions.

Figure 7 shows the force signal summing hardware setup. One summing box collected the first 12 channels of force signals from each measured direction and another box collected the remaining 12 channels of the same direction. For each force component, two summing boxes are then joined together by a third box to form the final force control signal. All three com-

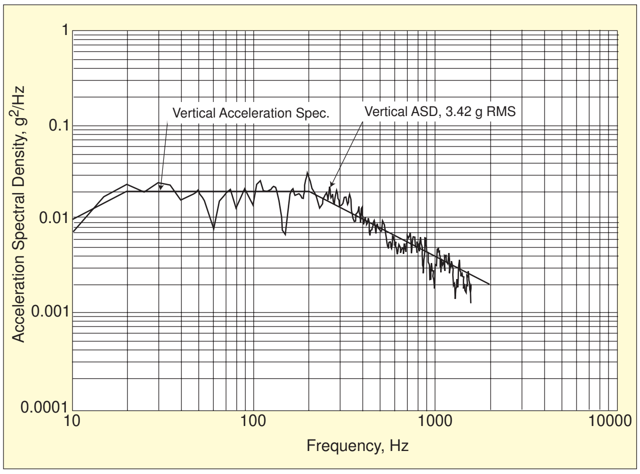

Figure 8. Full level input acceleration spectral density in DS1 spacecraft vertical random vibration test.

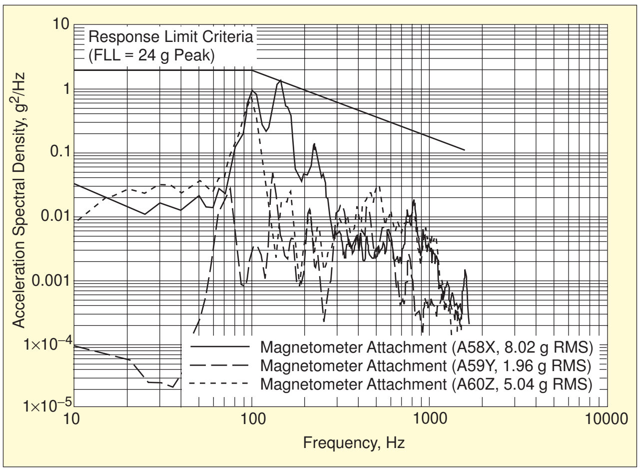

Figure 10. Magnetometer attachment response spectral density in DS1 spacecraft vertical random vibration test.

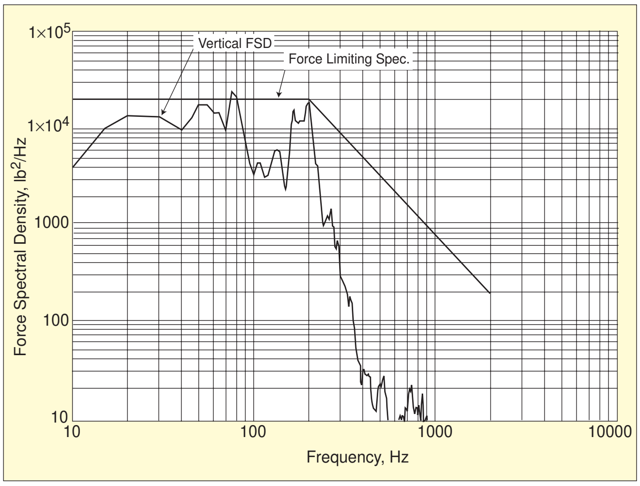

Figure 9. Total vertical force measured in DS1 spacecraft vertical random vibration test.

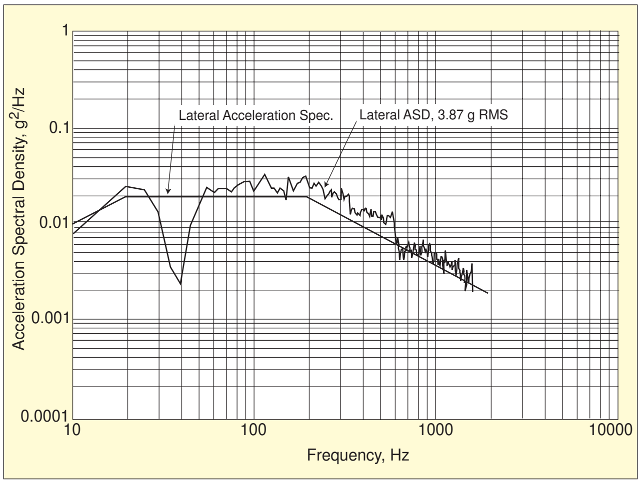

Figure 11. DS1 spacecraft full level input acceleration spectral density for lateral vibration test.

ponents of the total force vector were used in the controller feedback to notch the acceleration input. During the DS1 spacecraft pre-vibration calibration testing, the force measurements at the test PAF were consistently lower than the actual DS1 test spacecraft weight. These differences in measurement are attributed to the fact that both the attachment bolt and the force gage react to the interface loads at each attachment. The ratio of the load carried by the transducer verses the load carried by the bolt is dependent on their relative stiffness. Factors of 1.4 (increased by 40%) and 1.2, respectively, were used to correct the force measurements in the spacecraft vertical and lateral axis tests.

Test Results

Figures 8 and 9, respectively, show the input acceleration and force spectra measured in the actual full-level vertical random vibration test of the DS1 spacecraft. Due to the large number of channels used in the control system, the accuracy of the vibration control spectrum was degraded to an extent that the upper- and lower-test tolerances were nearly reached. Nevertheless, comparison of the measured acceleration input with the specification, as illustrated in Figure 8, shows notching of ~4 dB at 60 Hz and ~5 dB at 150 Hz. The first notch was due to force limiting and the second notch was due to response control at the Magnetometer attachment. Figure 10 shows the response limit spectral density along with the measured response levels. Control response reached its limit at about 150 Hz where notching occurred in the input acceleration. The lateral acceleration input spectrum for the full level test run is presented in Figure 11. The notch in the acceleration input spectrum, the ~10 dB notch at 40 Hz, was due to X-axis force limiting.

Figure 12 shows the acceleration levels measured near the Low Gain Antenna (LGA) interface. Comparison of these measured data with the assembly random vibration test specifications, which are also shown in Figure 12, verifies that many of the components in the spacecraft vibration test reached their assembly random vibration test specifications. In addition, several major structural elements of the spacecraft including attachment structure for the Magnetometer, the Star tracker and the Thruster reached their flight limit loads during the spacecraft vibration test. No structural damage was evident as a result of the test; pre- and post-low level sine survey verified that the spacecraft's structural integrity was maintained. However, several spacecraft anomalies were discovered either during or after the spacecraft vibration test. The summary of the hardware failures is as follows:

- A hydrazine liquid service valve opened prematurely.
- The Spherical Langmuir Probe fell off the bottom of the Remote Sensing Unit.
- Three screws in the Power Processing Unit (PPU) loosened. One screw backed out part way and two fell out.
- The Star Tracker bracket left chatter marks and scratches on the shear panel due to the loosening of the bracket fasteners.

All the above equipment failures were identified as 'workmanship' problems and were corrected by the DS1 project office before launch.

Conclusions

1. Force limiting was used in the vibration tests of many of the DS1 flight experiments and spacecraft components and on

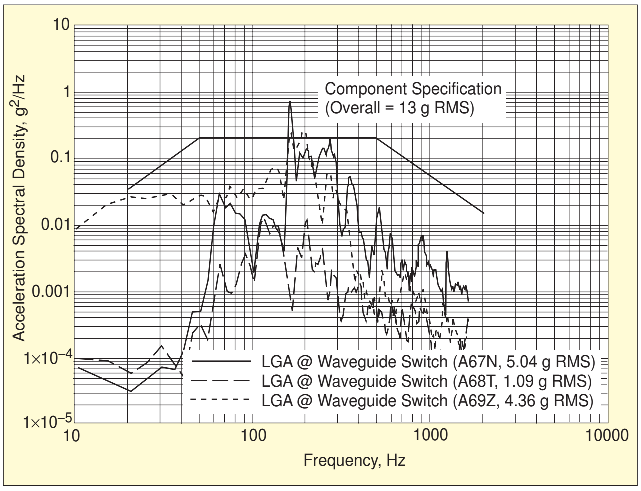

Figure 12. Acceleration inputs to LGA interface in DS1 spacecraft vertical random vibration test.

the assembled spacecraft and was extremely beneficial in avoiding unrealistic test failures. In all cases, the use of force limiting reduced the degree of over testing, without compromising the test objectives. In the DS1 spacecraft system test, the use of force limiting greatly simplified and expedited the conduct of the complex vibration test and also improved test safety.

2. All three components of the total input force vector, as well as the responses at over a hundred critical positions on the spacecraft, were monitored during the test. But only the total in-axis force signal and one response limit acceleration were needed in the controller feedback to notch the acceleration input. The force limits were derived using the semi-empirical method together with an extensive pretest analysis. The force specification in the test procedure was used without any modifications during the test.
3. During the DS1 spacecraft full-level vibration tests, the flight limit loads were achieved at a number of critical locations on the spacecraft and the instrument responses were similar to those in the assembly random vibration tests.
4. The system level random vibration test was very effective in identifying the equipment workmanship and problems on the assembled spacecraft. Therefore corrective actions to close out those problems could be taken to avoid launch and/or flight problems.
5. Poor input spectrum control can arise in force and response limited vibration tests. In the DS1 test, it was caused by the slow servoloop response time associated with the large number of limit channels employed in the multiple control strategy.

Acknowledgments

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References

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2. K. Y. Chang and T. D. Scharton, "Cassini Spacecraft and Instrument Force Limited Vibration Testing," Proceedings of the Third International Symposium on Environmental Testing for Space Programmes, ESTEC, Noordwijk, Netherlands, 24-27 June 1997.

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