V-Band Separation Shock Characteristics

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The V-band systems have been widely used in the aerospace industry for securing spacecraft inside the launch vehicle payload fairing. Separation is initiated by firing pyro-devices to rapidly release the tension bands. A significant shock transient is expected as a result of the band separation. The shock environment is defined with the assumption that the shock events due to the band separation are associated with the rapid release of the strain energy from the preload tension of the restraining band.

This paper discusses the pyroshock characteristics and environments based on various test measurements conducted on several JPL spacecraft programs. Different from previous assumptions, the measurements show that shock at the payload interface is generated primarily by high-speed impacts between the spacecraft and the V-band after separation. Shock levels will be attenuated much quicker with distance since this shock source is a point contact rather than a linear distributed source as assumed.

INTRODUCTION

V-Band Assemblies provide the connection mechanism and the structure between two adjoining main systems and have become industry standard parts. The V-band systems, or so-called clamp bands, have been widely used in the aerospace industry for securing payloads inside the launch vehicle payload fairing and have been used for separation of spacecraft or satellites from the launch vehicles. These systems offer excellent structural properties; very simple, reliable operation; and extensive flight history. However, V-band systems are typically released by operation of pyrotechnic devices such as bolt cutters or separation nuts that holds the clamp band in its preloaded state for the launch phase of the mission. This system has high strength and stiffness when clamped and releases quickly when operated. As a result, considerable high shock is generated after separation that could have a deleterious effect on the structure or equipment located nearby. Several JPL spacecrafts have utilized the V-band assembly for their launch vehicle/payload attachment and have performed launch separation tests during ATLO. The objective of the separation test was to verify the design of the fully assembled spacecraft for the flight shock environment generated by the pyrotechnic actuation event. The shock environment associated with the V-band actuation was also measured in order to verify of the adequacy of assembly pyroshock qualification tests. This paper describes those JPL spacecraft separation tests, discusses the test results as well as subjects related to the V-band pyroshock characteristics and environments, and offers conclusions.

V- BAND ASSEMBLY

V-band is a ring-shaped tension clamp. V-band assemblies come in a variety of styles, using sheet metal V-band clamps, sheet metal V-band flanges or machined flanges. A typical V-band used in the Mars Exploration Rover (MER) program is shown in Figure 1. Generally, the separation band system used in the aerospace industry consists of three main parts: an upper ring, a launch vehicle adapter including lower ring, and a clamp band. The upper attachment ring is installed on the bottom of the spacecraft adapter permanently and serves as the upper surface of interface plane. On the top of the launch payload adapter, the lower ring is installed and serves as the lower surface of interface plane. The clamp band is manufactured in two identical halves and connected together at their ends by pyrotechnic lock devices. In addition, four (4) or six (6) catchers dependent on the ring diameter size are fixed to the payload adapter's ring, to guide, catch and park the band within the allowed volume after band released. The clamp band has a peripheral length shorter than that of the upper ring and the launch vehicle adapter; therefore the clamp band can only be installed in tension. A release mechanism containing pyrotechnic devices is used to release the band.

Figure 1. MER V-Band Assembly after Separation

Often the largest sources of shock in a deployment system is the rapid release of stored strain energy. This preload of the tension strap results in strain energy stored in the release elements as well as the sections of the structure in the preloaded load path. Historically bolt cutters or separation nuts release this strain energy in a very short time, typically less than 0.5 millisecond. Rapid release of energy tends to lead to higher shock. A second aspect of this stored strain energy release is that it occurs within the structural elements of the system and, hence, the shock has a good transmission path to nearby components. A higher level of separation shock environments is specified at the payload attachment for the design of the spacecraft equipment and secondary structures to survive those launch separation events. The shock environment is defined with the assumption that the shock due to the band separation is associated with the rapid release of the stored strain energy from the preload tension of the restraining band acting along a line of contact between two structures being separated.

SPACECRAFT LAUNCH SEPARATION TESTS

Separation tests of V-band release conducted in this study include three JPL spacecrafts which all use the Delta II 37-inch diameter V-band clamp assembly to induce separation of payload attachment. The 1st test article was the Deep Space (DS) 1 flight spacecraft with a 3712C test Payload Attachment Fitting (PAF). The DS1 test configuration before the V-band clamp separation is illustrated in Figure 2. The spacecraft was suspended by a bridge crane. A PAF catcher was placed on the floor below the test article with approximately 2 inches clearance between the top of the catcher and the bottom surface of the test PAF. The PAF catcher was used to catch and to gradually absorb all the energy of the falling test PAF (after separation) without allowing a hard impact. Three repeat firings were performed for determining possible flight-to-flight variation (Reference 1). The 2nd and 3rd test articles were the MER flight spacecrafts attached with the same test PAF.□Their test configuration for the V-band clamp separation is presented in Figure 3. Both MER spacecrafts were tested in the same configuration with the spacecraft supported by the cruise stage support ring on the back shell assembly cart standoff (References 2 and 3). One firing was carried out for each spacecraft. The PAF catcher was placed on the floor below the test article to catch and to gradually absorb all of the energy of the falling test PAF.□

In those spacecraft test configurations, selective sets of tri-axial accelerometers were installed on the test article to measure the shock response levels during the firings of the pyrotechnic device. High shock accelerometers were stud mounted near the shock source on the spacecraft side and on the test PAF to characterize the shock environment and its effect on the nearest assembly. The measurement locations for those tests are shown in the photographs in Figures 4, 5 and 6. A high-speed camcorder (2250 frames per second) was also used to record the actual separation of the V-band assembly for each test firing.

All test spacecrafts were powered, operated, and monitored in the launch configuration. Those separation shock tests were conducted by actual firing of the pyrotechnic devices. The pyro event was initiated from a portable power supply/pyro switch. During the V-band separation, the tension bands jettisoned the test PAF leaving the spacecraft. Gravity accelerated the test PAF into the test PAF catcher that cushioned its shock impact. After each test firing a visual inspection of the test hardware and instrumentation system was performed. Each post test inspection, including review of the high-speed video, showed that the V-band had separated properly, releasing the test PAF completely. There was no visible evidence of spacecraft structural damage or deformation noted as a result of testing.

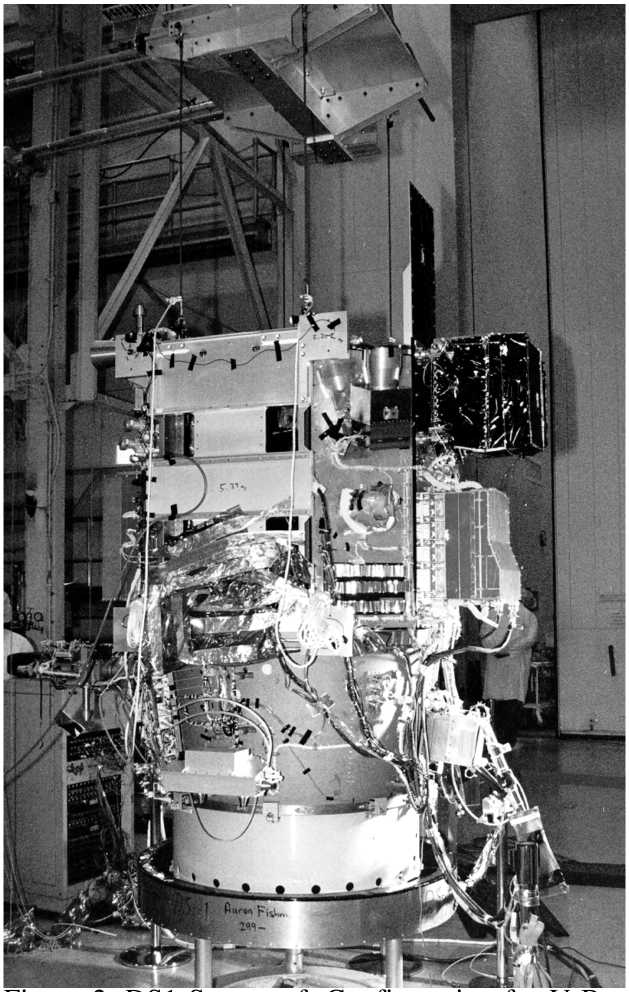

Figure 2. DS1 Spacecraft Configuration for V-Band Separation Test

Figure 3. MER Spacecraft Configuration for V-band Separation Test

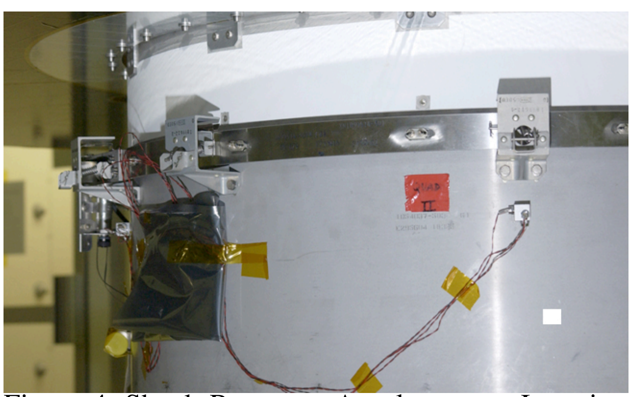

Figure 4. Shock Response Accelerometer Locations for MER#2 V-Band Separation Test (Response Accelerometers Mounted above V-Band in MER#1 Launch Separation Test)

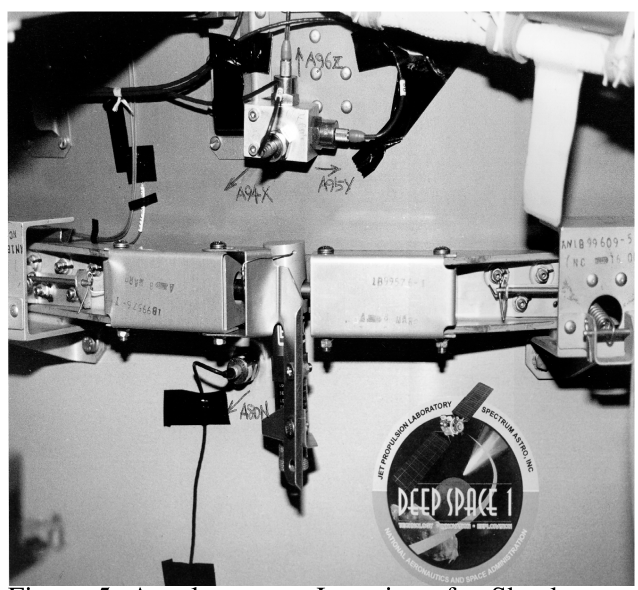

Figure 5. Accelerometer Locations for Shock Measurements in DS1 V-Band Separation Test

TEST RESULTS AND COMPARISONS

Tests were successfully accomplished and all accelerometer inputs were recorded and analyzed. In the following comparisons, the shock response spectrum (SRS) is used to define the shock environment for various measurement locations. Shock measurements made on the test PAF are presented first and are compared with the maximum shock environment provided by Boeing (Reference 4). Measurements made at the spacecraft interface near shock sources are discussed next. Shock measurements made at equipment located short distances away from the V-band are also compared with the spacecraft interface levels. Final, the characteristics of the shock pulses measured at both sides of V-band interfaces are discussed and compared.

Shock Levels Measured at PAF

Figure 7 shows the shock response spectra measured on the test PAF near the bolt cutter during the second and the third of the DS1 spacecraft test firings. (No measured data was obtained for the first firing.) The accelerometer located below the V-band right next to the bolt cutter is illustrated in Figure 5. The test measurements along with the maximum expected interface shock environment as specified in the Boeing document (Reference 4) are plotted in the same figure for comparison. The test data was observed to be quite repeatable during the two firings and are virtually identical to the maximum shock environment provided by Boeing.

Figure 8 shows the shock spectrum levels measured on the test PAF during the MER#2 V-band separation. Two (2) sets of tri-axial accelerometers were used to measure the shock responses in the MER separation tests; one was mounted at the location just below the bolt cutter and near the spacecraft/PAF interface, and a secondary one was mounted at 90 degrees apart below the V-band catcher. The actual measurement locations can be seen in Figure 1 and Figure 4. As shown in Figure 8, the measured shock levels due to the MER spacecraft separation at most frequency regions are slightly below the Boeing imposed shock requirements. Since one firing was performed, no statistical variation could be estimated to obtain the maximum expected flight shock level. Nevertheless, no flight equipment is located on the PAF; the results shown here are only used as a reference base to characterize the source shock levels of the V-band separation.

Shock Levels Measured at Spacecraft Interface

Two sets of tri-axial accelerometers at two locations, 90 degrees apart, were used to measure the shock environment on the spacecraft near the spacecraft/test PAF interface in both DS1 and MER#1 tests. Their respective locations are illustrated in Figure 5 and Figure 6 for the DS1 separation test. The shock levels measured at the DS1 magnetometer and DCIU equipment rails near the spacecraft interface for all firings are plotted in Figure 9. The shock response spectra measured tri-axially at these two locations are independent of measurement direction and similar in response levels. Figure 10 again shows the shock spectrum levels measured at two locations on the spacecraft interface during the MER#1 separation test. The maximum expected spacecraft interface shock environment as specified by Boeing (Reference 4) are also plotted in the same figure for comparison. As shown in these two figures, the maximum measured shock levels due to the V-band separation at most frequency regions can be enveloped by a level which is at least 10 to 12 dB (or 4 times) less than the Boeing imposed shock requirements.

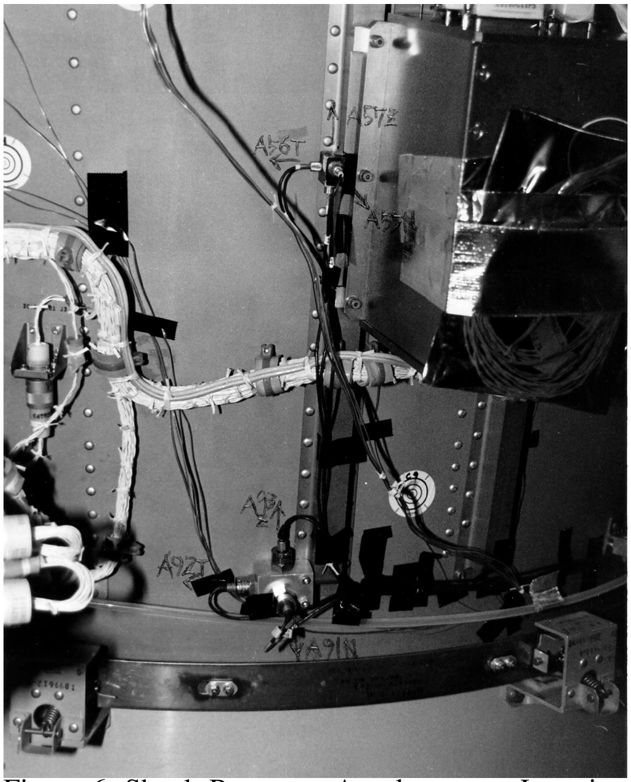

Figure 6. Shock Response Accelerometer Locations for DS1 V-Band Separation Test

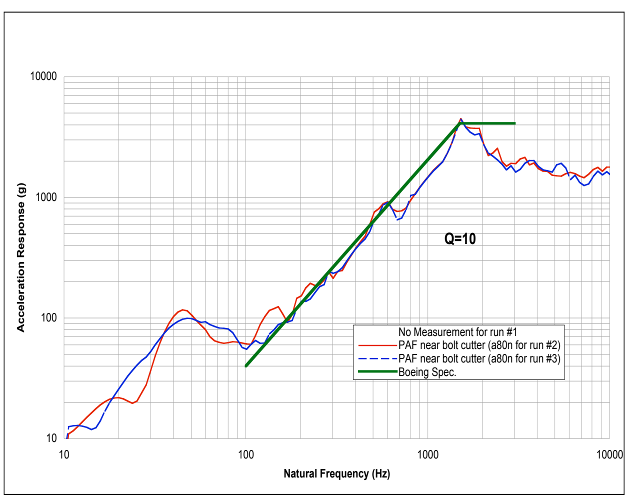

Figure 7. Shock Environment Measured at Test PAF from DS1 V-Band Separation Tests

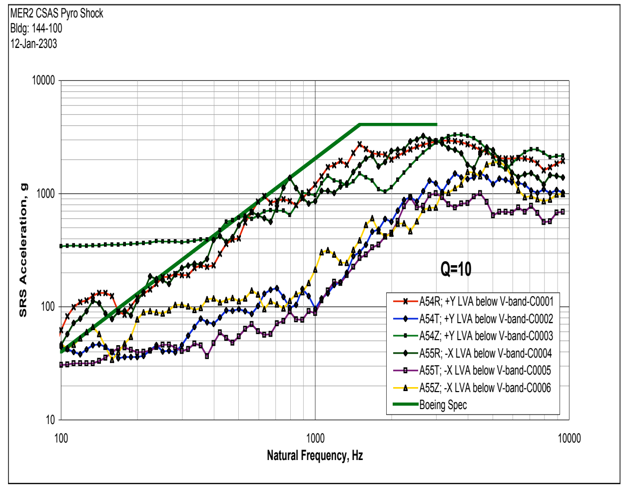

Figure 8. Shock Environment Measured at Test PAF from MER#2 Spacecraft Separation Test

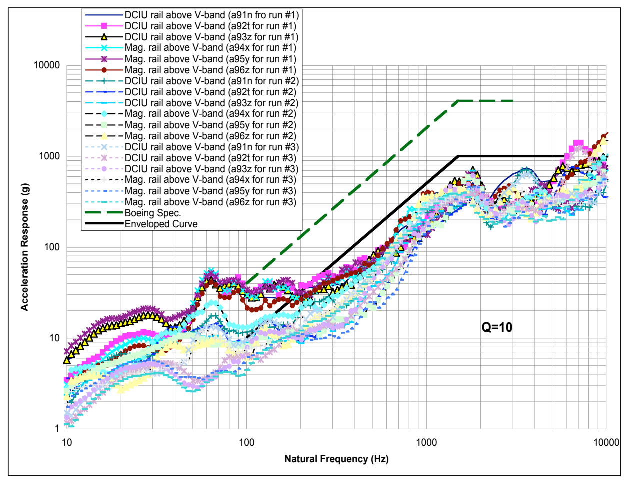

Figure 9. DS1 Spacecraft Interface Shock Environment from V-band Separation

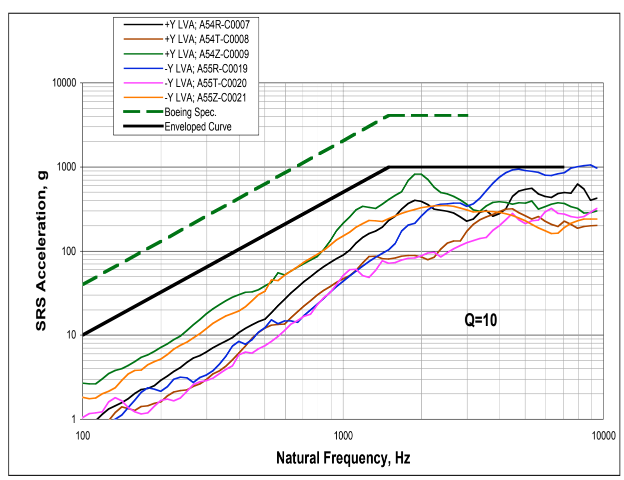

Figure 10. MER#1 Spacecraft Interface Shock Environment from V-band Separation

Shock Levels Measured at Distance from V-band

Two sets of tri-axial accelerometers mounted at two locations, less than 12 inches away, were used to compare the shock environment at equipment locations. Their respective locations are illustrated in Figure 6. Figure 11 shows the z-axis SRS levels measured at these two locations of the DCIU equipment rail for all three DS1 separation firings. The shock response spectra measured tri-axially are independent of measurement direction and similar in response level. As illustrated in the plot, only small variations in shock level for all frequencies in all three firings are observed at each measurement location, except at low frequencies where larger variations are due to instrumentation dynamic range restrictions for the first test firing. However, significant shock attenuation was observed in the frequency range from 400 Hz to 4000 Hz between two measurement locations. The reduction at the DCIU equipment in the same frequency range even reaches a factor of 4 to 5 times less than the spacecraft interface shock input, which is unexpected for a linear shock source of a circular band: distance usually does not produce significant shock reduction or virtually no decay over short distance on a cylinder-type structure. This result is inconsistent with the expectation that the release of tension in restraining band is a direct contributor to the high frequency shock at the spacecraft interface.

Shock Characters of V-band Separation

Figure12 presents the shock waveform measured at the test PAF from DS1 Run# 2 and 3 test firings. Their corresponding SRS values are plotted in Figure 7. Figure 13 presents the shock transients in the radial direction at two different locations measured at the test PAF during MER#2 test firing. These measurements are the highest recordings in all three orthogonal axes. The intensity of the shock pulse as well as the waveform and duration for all four measurements are similar to each other. However, the pulse duration is close to 100 msec, which is much longer than the near-field shock generated from a pyrotechnic device (typically less than 10 msec). The shock levels measured at the PAF are as predicted and the shock character is also as expected, which is primarily due to the rapid release of the stored strain energy from the preload tension of the restraining band acting along a line of contact between the band and the lower adapter ring being separated.

Figures 14a and 14b present typical shock measurements near the DS1 spacecraft interface. Figure 15 shows the shock measurements at two immediate locations near the MER#1 spacecraft interface. Multiple shock pulses were observed at the spacecraft interface during spacecraft separation from the V-band. This result is contrary to expectation. This phenomenon can only be explained that repeated impacts were occurring rather than the waveform being generated from a single band shock or line source during separation. The character may be attributed to the high-speed contacts between the clamp band, the band’s catchers and the spacecraft attachment ring after separation. This result was also noticed from the review of high-speed video films recorded during each separation test.

CONCLUSIONS AND RECOMMENDATIONS

All three spacecraft V-band separation tests were successfully completed and the acceleration data obtained from these tests have provided qualitative information of the V-band shock environments. Based on the test results, the following statements are concluded.

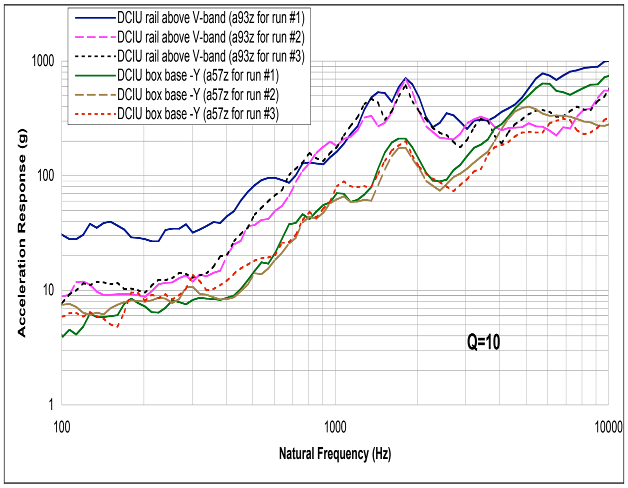

Figure 11. Comparison of Shock Environment Measured at Short Distance from V-band

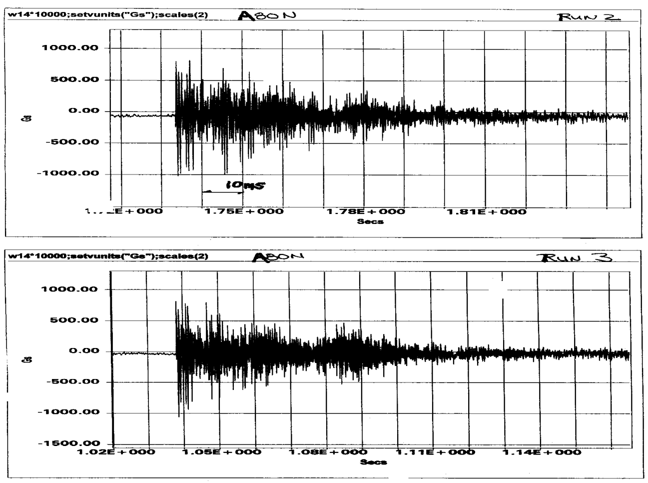

Figure 12. Shock Measurements at PAF below V-Band from DS1 Separation Firings

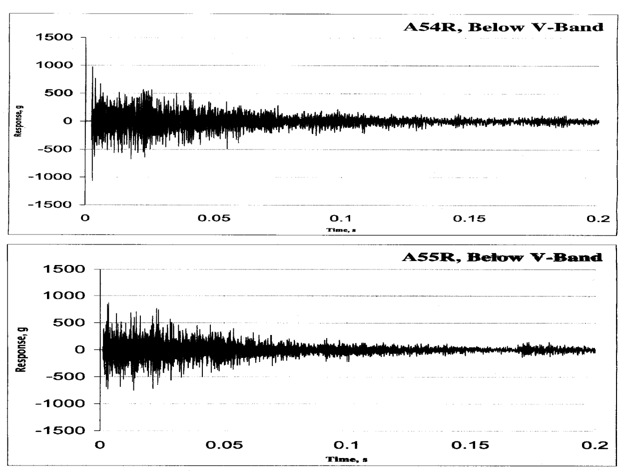

Figure 13. Shock Measurements at Two Different Locations on PAF from MER#2 Test

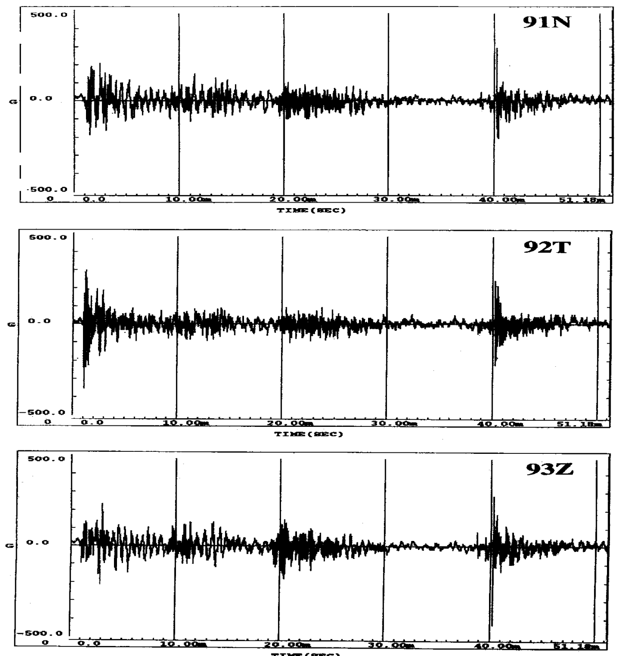

Figure 14a. Typical shock Measurements near Spacecraft Interface from DS1 Separation

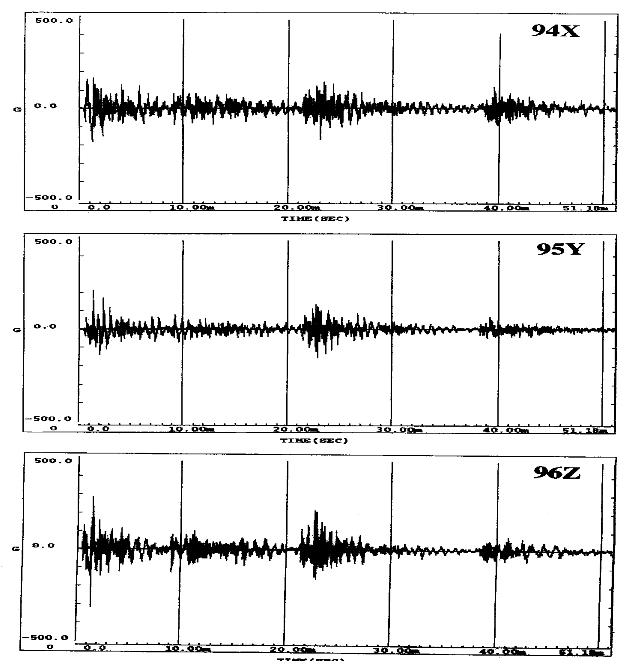

Figure 14b. Typical shock Measurements near Spacecraft Interface from DS1 Separation

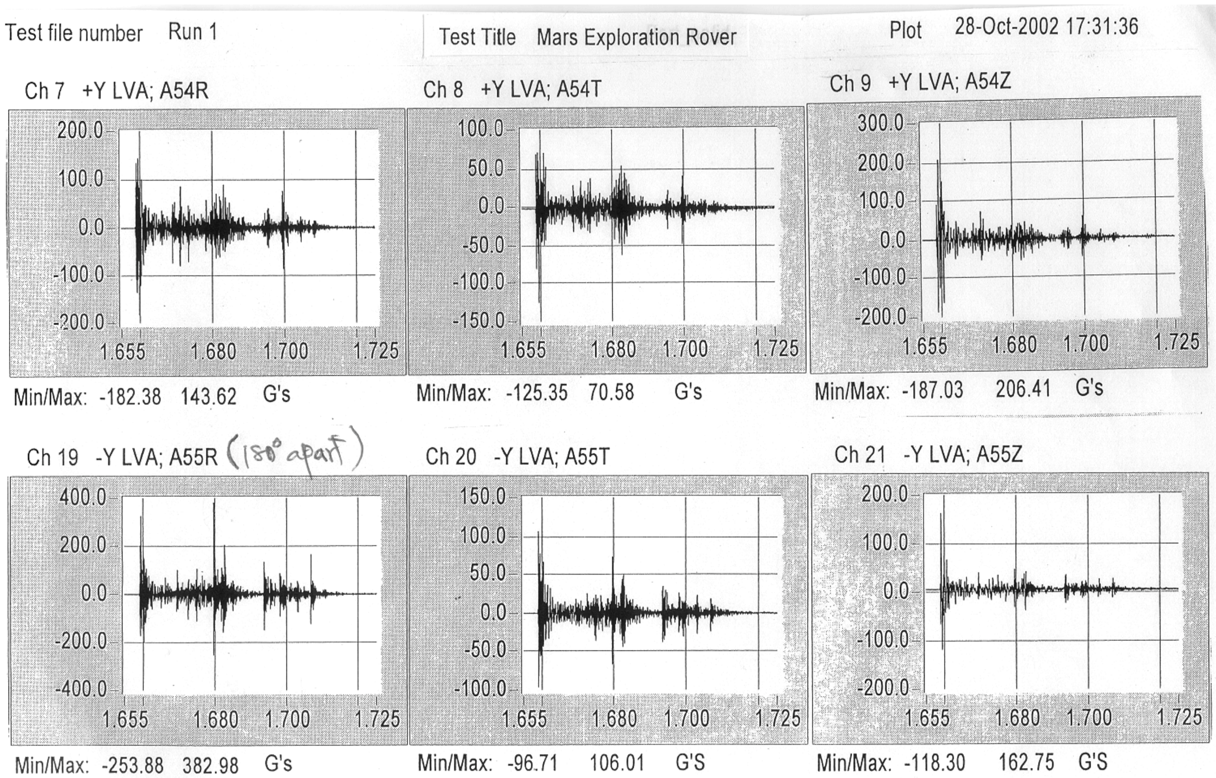

Figure 15. Shock Measurements at Immediate Vicinity of Spacecraft Interface from MER#1 Separation Test

- The shock levels measured at the launch payload adapter are quite repeatable and are virtually identical to maximum shock environment predicted by Boeing for the V-band separation. The shock is primarily due to the rapid release of the stored strain energy from the preload tension of the restraining band acting along a line of contact between the band and the lower adapter ring being separated.

- The maximum shock levels measured at the spacecraft interface above the V-band are at least 10 to 12 dB lower than the imposed shock requirements based on the Delta II payload planner's guide. Also, the shock levels dissipate rapidly with short distance away from the V-band interface. The relatively low shock generated on the spacecraft in comparison with the payload guide specification can allow spacecraft designers and operators more latitude in science instrument placement as well as a reduction in the need from shock analysis and equipment shock qualification testing.

- Multiple shock pulses were observed at the spacecraft interface during the spacecraft separation from the V-band. This character may be attributed to high-speed impacts between the V-band and the spacecraft attachment after separation. This result was also noticed from the high-speed video film. It is concluded that the rapid release of the band's strain energy is not a direct contributor to the high frequency shock at the spacecraft side of the interface. Shock levels will be attenuated much quicker with distance since this source is a point contact shock rather than a linear distributed source as previously assumed.

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