ARLISS Data Logger Project

(Part 2)

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In the first part of this article, I described the need to measure the forces to which rocket payloads are subjected. It also described the measurements made by the AL-016 Data Logger and how the recorded data can help identify events occurring during a flight. This article discusses the more advanced data analysis that is performed to measure rocket flight effects on payloads. (The flight data referenced in this article is from the September 2014 ARLISS Event (www.ARLISS.org). It can be found at www.rafresearch.com/arlissdatalogger/flightdata/ARLISS2014/index.xml .)

Our initial analysis indicated that student payloads are being subjected to acceleration shocks that are larger than we expected, but surprisingly, the huge acceleration spikes (up to 176 g) did not correlate strongly with payload damage data. This was believed to be because the duration of these shocks, and therefore the energy contained within them is small. That drove the development of more advanced post-processing analysis of the data collected by the AL-016 Rocket Data Loggers.

The Spacecraft Payload Environment

After the cold war, the DNEPR project was formed to convert the Russian/Ukrainian multiple-warhead R-36M ICBM into a vehicle to lift commercial payloads into orbit. That vehicle is now being used for many of the student CubeSat launches. The DNEPR Space Launch Systems User's Guide specifies the "spacecraft environment" (including vibration and shock loads) that should be expected by payloads launched into space. It specifies the vibration and shock loads in terms of frequency bands.

Frequency sub-band (Hz)	30-50	50-100	100-200	200-500	500-1000	1000-2000	2000-5000
Maximum Shock Spectrum Values (g) for durations of up to .1 sec.	10	25	100	350	1000	1000	1000

The SpaceX Falcon 9 Launch Vehicle User's Guide provides the following chart as its payload shock specification.

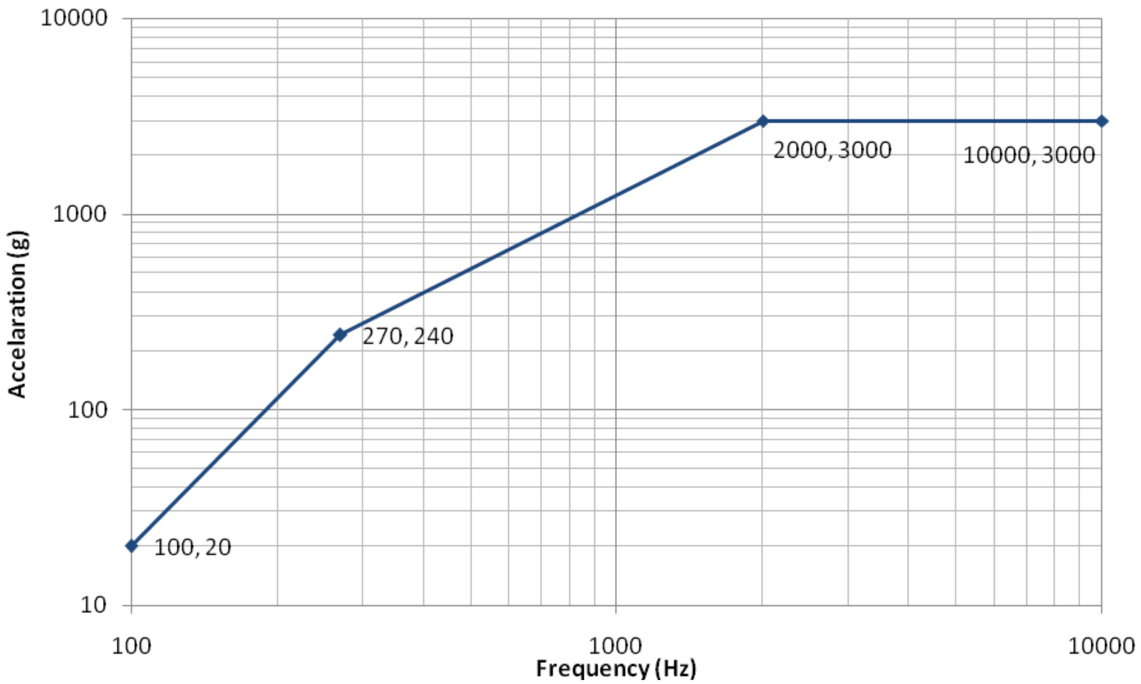

Figure 8. SpaceX Falcon 9 payload shock specification.

Since the ARLISS program is a surrogate for exerting the hostile stresses of space flight upon student payloads, it’s logical to strive to make our ARLISS launch vehicles match these existing commercial standards as closely as possible. To determine how our ARLISS rockets compare, we needed to analyze the accelerometer measurements in terms of frequency bands.

Acceleration Spectral Density (ASD)

The measured accelerations can be mapped from the time domain into the frequency domain by means of Fourier Transformation. ASD analysis performs a Fast Fourier Transformation (FFT) on two windows of flight accelerometer data, the launch window and a second user selectable time window. The windows can be from 48 milliseconds to 12 seconds wide. The longer duration time windows are used to analyze motor burn and coast periods. The shorter windows can be used to zoom in on specific fast occurring events. Figure 8 shows the recorded acceleration of a typical M1419W motor in an ARLISS rocket. Figure 9 shows what those forces look like in the frequency domain.

Note that “Mag” in the legends of the charts refers to magnitude, the length of the vector addition of X, Y, and Z. In a chart, if the magnitude line overlays any of the X, Y, or Z lines, visual priority is given to the X, Y, or Z line.

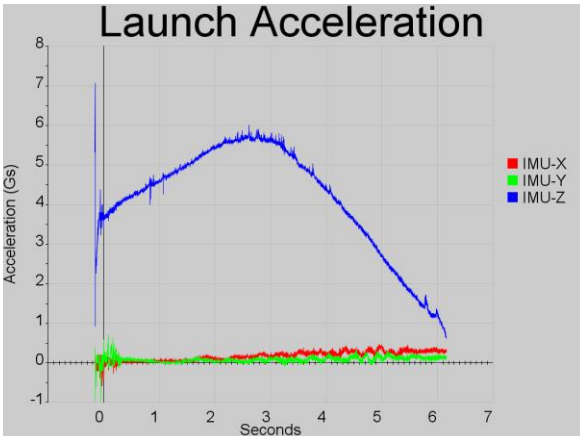

Figure 9

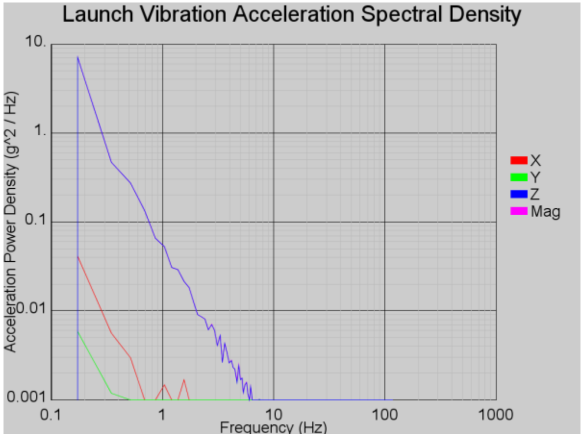

Figure 10

The root mean square acceleration (Grms) is the square root of the area under the ASD curve in the frequency domain. The area under this ASD chart is 13.2g (the square root of the 173.1g^2 value displayed on the web page near the chart). ARLISS motor burn acceleration exceeds the DNEPR standard acceleration the 30-50 Hz band by 32%.

There is a sustained energy release during the entire 6.1 second analysis window. This makes the launch window a good candidate for this type of analysis. The coast window is also a good candidate for ASD analysis, but forces exerted by ARLISS rockets during this window were very small and uninteresting.

Unfortunately, the energy released during deployment window is not sustained, but rather released in very short bursts. The theory behind Fourier Transformations is based upon waveforms that extend to infinity in both positive and negative time dimensions. For the FFT based analysis to be accurate, the analysis period needs to be contained (or nearly contained) within the energy release. The energy bursts of the deployment window are too short to gather a sufficient number of data samples. Accelerometer sampling rates need to significantly improve before Fourier Transformation based analysis should be used to analyze deployment and pyro-shock events.

ASD is primarily used for vibration analysis, not short interval shocks. Several resources are available to help understand vibration and vibration measurements. I recommend Harris' Shock and Vibration Handbook, by Cyril Harris.

Shock Response Spectrum (SRS)

The preferred method of measuring shocks (short duration impulse or vibration events) is to use a Shock Response Spectrum (SRS). The calculation of a SRS requires that the recorded accelerations be "played back" into an array of single degree-of-freedom (SDOF) systems.

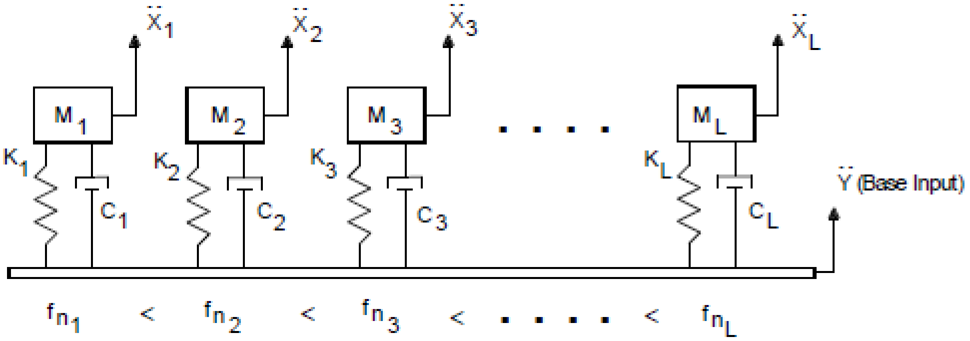

Figure 12. SRS array of SDOF systems, each with a unique Natural Frequency

All of the SDOFs in the array have the same 5% damping factor, but widely distributed natural frequencies. (To produce results that can be read well on a logarithmic plot, we modeled six SDOFs per octave throughout the frequency range to be analyzed.) During the “play back” of the sample data, the peak response of each SDOF is captured and plotted.

The below SRS chart is from a CO_2 deployed payload that measured only 28.4g of peak acceleration. This was one of the softest deployments of the ARLISS launch event.

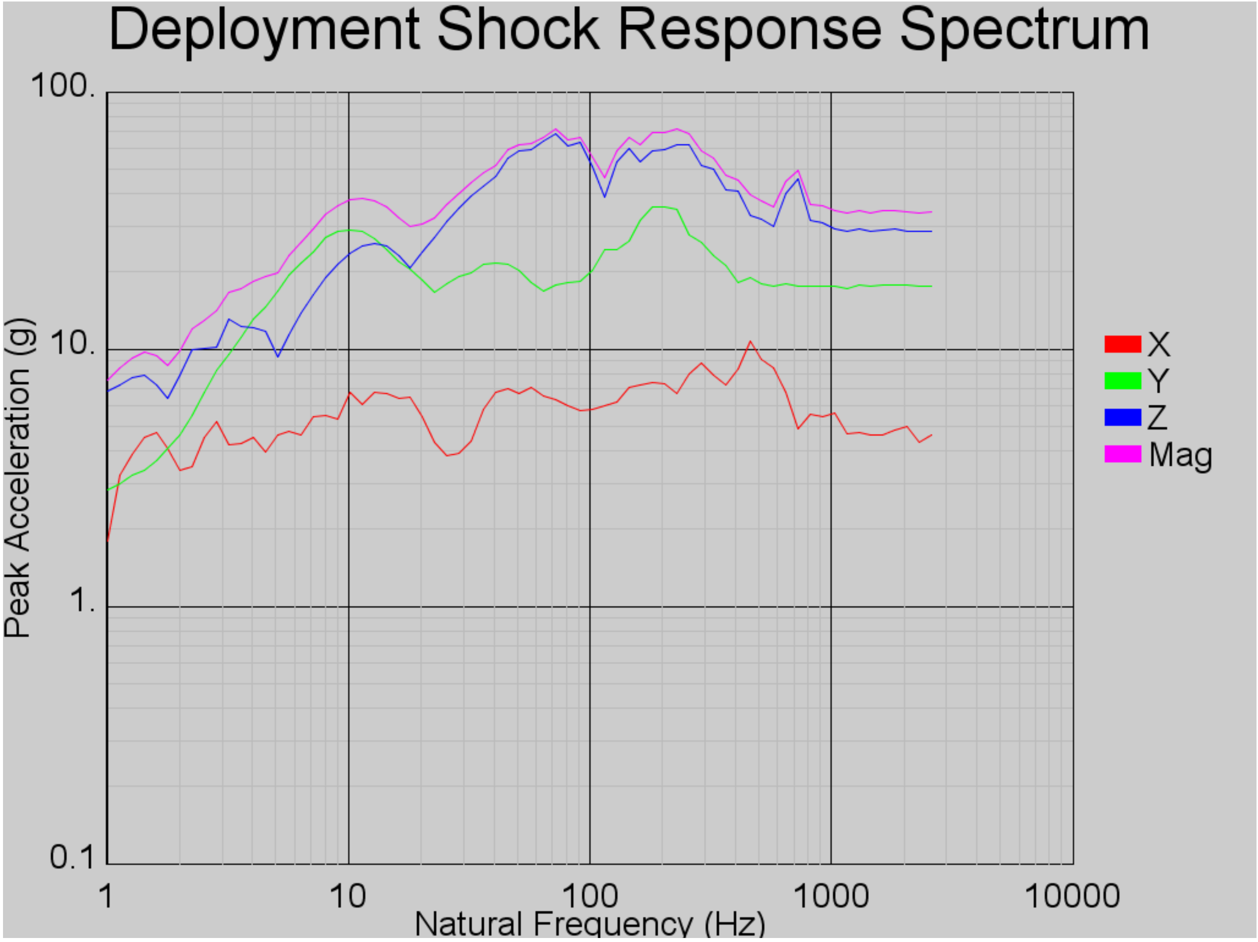

Figure 13. Deployment window events of a 28.4g flight (no payload damage)

This SRS chart is easily compared to the Spacecraft Payload Environment specifications. At frequencies less than 100 Hz, acceleration shock should be limited to 20-25g. Even this CO2 deployment, one of the softest recorded deployments, exceeded the lower than 100Hz band shock limit by 300%. The magnitude of the deployment shock of this flight reached 70g at 70Hz. SRS is called a maxi-max analysis. It computes the "worst case" scenario as it assumes that worst case acceleration on each axis occurred at the same instant in time. But, even the Z-axis only SRS reaches near 70g.

Let's compare the above flight to a flight of that same rocket made later in the week during light winds. Since the payload's objective was to land then drive its way back to a designated GPS point, we decided to deploy the payload upwind. That way the wind would blow the payload's parachute toward the GPS target rather than away. To achieve this we angled the launch rail about 3 degrees into the wind.

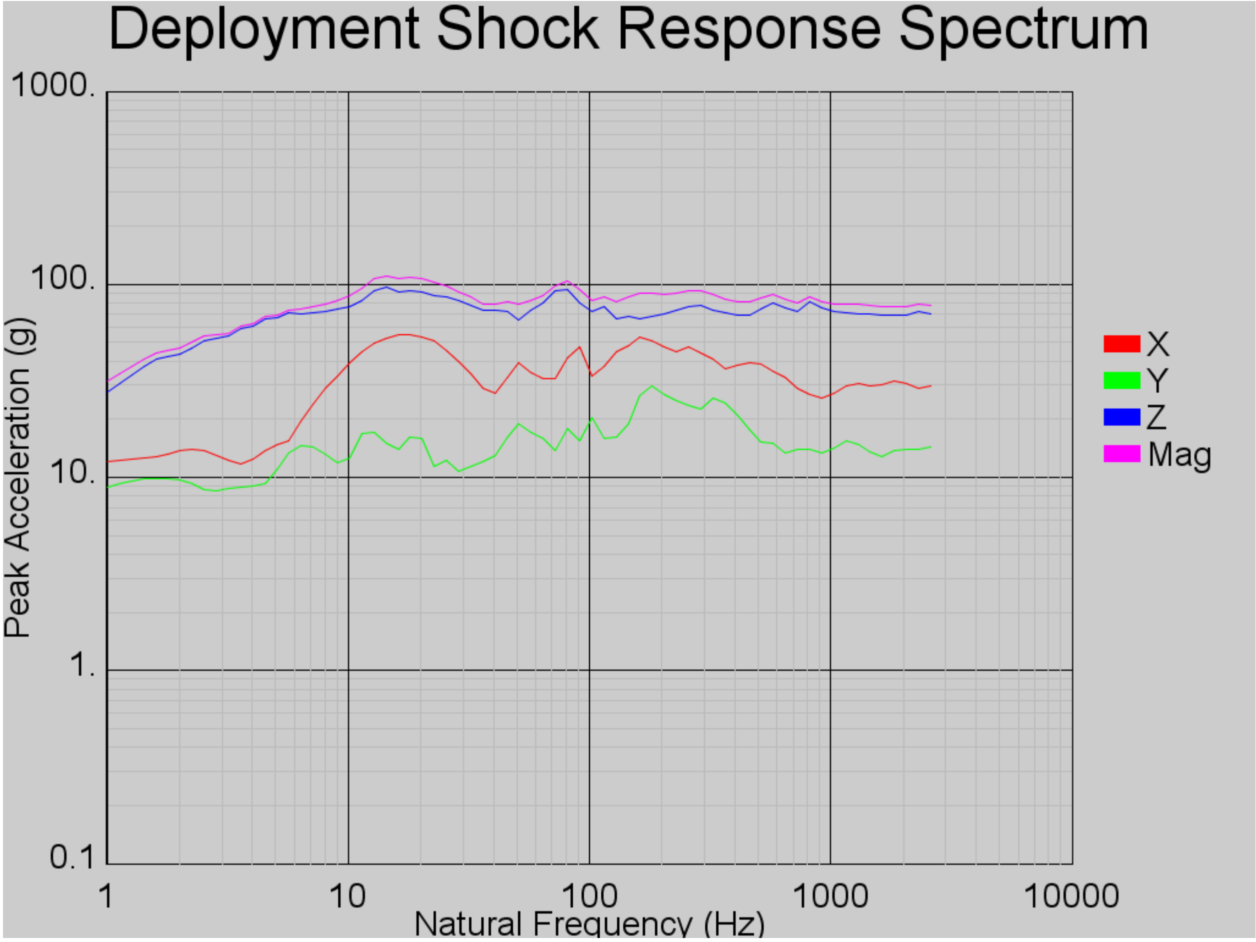

Figure 14. SRS chart of the "Into the wind" flight.

The angled launch combined with the natural weather-cocking of the over-stable rocket resulted in a deployment that occurred several hundred yards upwind. The wind blew the payload back toward the target point as planned, but deployment shock broke parachute shroud lines resulting in a hard landing. The damaging shock was not caused by the deployment pyro event, but rather the inflation shock of the parachutes.

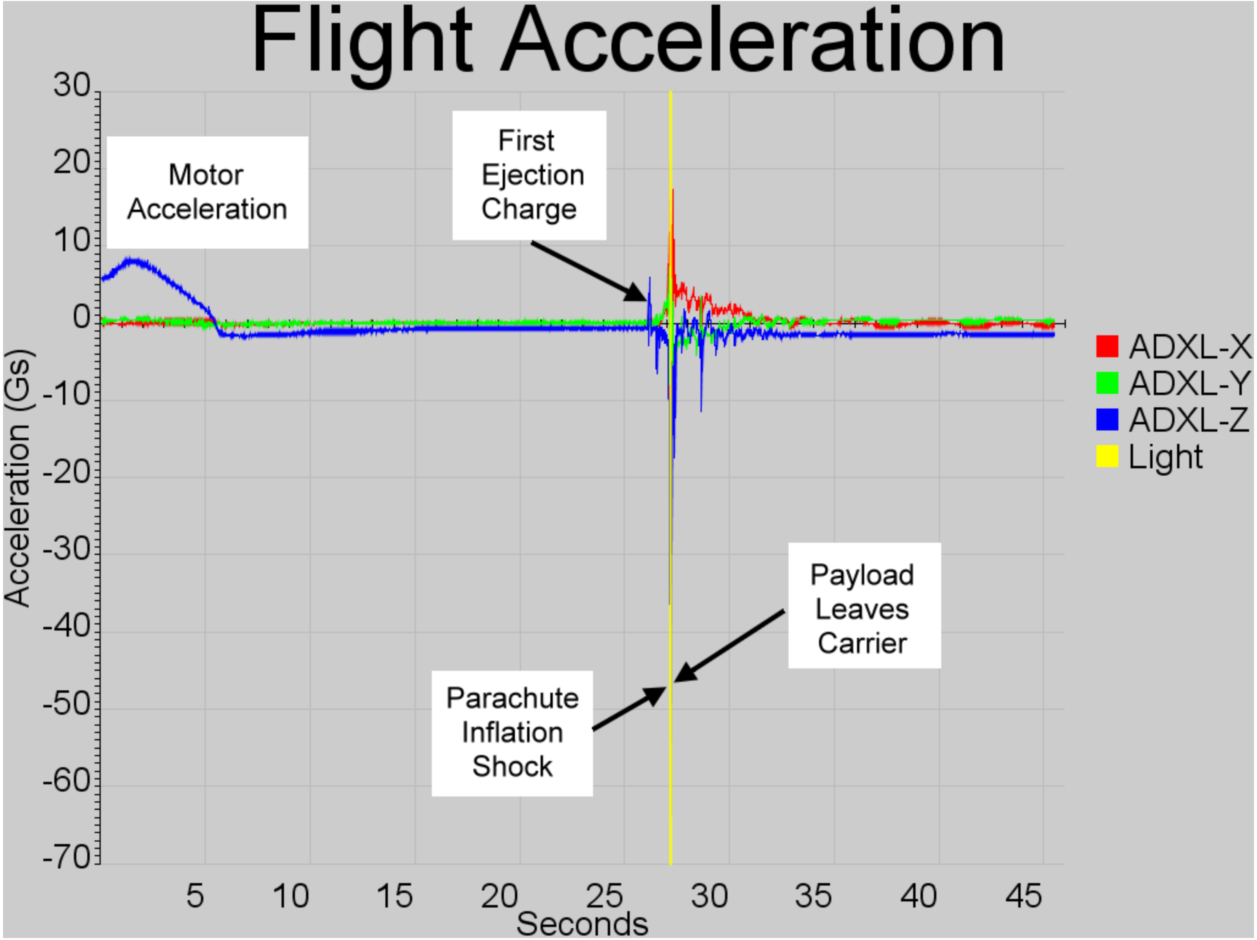

Figure 15. Time domain measured acceleration of the "Into the wind" flight.

The "first ejection charge" separated the rocket and deployed the main parachute at apogee. However, apogee just means that the vertical velocity has zeroed, because of the angled launch and weather-cocking, the rocket still had a substantial horizontal velocity. The rocket's main parachute inflated suddenly causing a -65g shock. This shock was strong enough to prematurely deploy the payload. (The "Light sensor" detected payload deployment at the instant of main parachute inflation). If the payload was ejected with roughly the same horizontal velocity as the rocket, then it also would have experienced the same parachute inflation shock as the rocket. It is not surprising that some of its parachute shroud lines broke.

Examining the SRS (Figure 14) of this flight more closely, we can see that not only that the peak acceleration values exceeded 100g, but that also the frequency of the peak moved down to 11Hz. This exceeded the DNEPR standard by a factor of 1000%.

Again I recommend the above referenced Harris book for more information regarding the SRS and shock measurement, especially Chapter 26, Part II which deals with pyroshocks.
One important characteristic of pyroshock is the knee in the SRS curve. If the acceleration sensors are very close to the pyrotechnic charge, they will make a "near field" recording. Further away, they will make a "far field" recording. The characteristics of a "near field" recording are

data series that generally increase left to right across and off the chart. A “far field” recording contains a knee where acceleration starts to reduce with higher frequencies. A pyro-charge produces energy across a very large frequency range. However, energy at the higher frequencies drops off very quickly with distance. If the SRS chart does not show this a knee, then the frequency response of the acceleration sensor is not adequate for measuring the recorded shock. Since all SRS charts from the ARLISS event showed a knee in the SRS plot occurring below 100 Hz (less than 1/10th the sampling frequency of the AL-016’s accelerometer), the frequency response of the Logger’s accelerometer has proved more than capable of handling the shock events of high power rocketry.

Conclusions

Both the ARLISS motor burn (M1419W) and payload deployment create shocks in excess of the commercial payload standards. ARLISS motor burn acceleration exceeds the DNEPR guideline acceleration the 30-50 Hz band by 32%. However, modern commercial payload rockets use nozzle thrust vectoring rather than fins to stabilize the flight of a rocket. Since high power rockets use fins, it is important that our rockets reach an aerodynamically stable speed before they leave the launch rail. Reducing motor thrust could bring us into alignment with the DNEPR standard, but at the cost of longer launch rails and perhaps a smaller margin of safety.

Payload deployment, by far, is worse of the two problems. Deployment shocks exceeded the DNEPR guidelines by 300% for softer deployments and 1000% for the rougher deployments. CO_2 deployments typically resulted in lower peak shocks than black powder deployments, but the magnitudes of pyro-shock in general did not seem to be strongly correlated to reported payload damage. All of the reported payload damage involved damage to the payload mechanical structure. Pyro-shock, because of its high-frequency content rarely mechanically damages payload structures. Pyro-shock is known to cause intermittent (contact bounce) and permanent (solder ball fracture) failures in electrical components. I believe that some of the strong pyro-shocks may have caused payloads to malfunction, but because of the unknown cause of the malfunction and because some payloads were overly fragile, the payload teams did not want to cast blame on the rocket’s deployment system.

Damage Reports: (# of flights)

12	Payload disposition reported “No damage”.
32	Unknown. (No payload disposition filed.)
1	Damage believed to be caused by payload being dragged across ground by parachute.
1	Damage believed to be caused by payload deploying while the rocket has significant horizontal velocity.
1	Payload got tangled with rocket’s parachute. Both came down hard. Severe damage.
1	Payload’s wire hub broke on landing. (No further info available)
1	The carrier deployed, but the payload got stuck in payload carrier. (Too tight of a fit.)
1	Rocket deployed neither parachutes nor payload. Rocket, payload, and Logger destroyed.

At launch, a section of the flight card was to be given to the payload team, filled out after they recovered their payload, and returned to an ARLISS coordinator. This failed to occur on over 60% of the flights. We know nothing about the payload damage that may have occurred during these flights.

Most importantly, the AL-016 Data Logger has provided a measurement capability that creates a basis for better understanding what is occurring during rocket flights. The data enables rocket builders to observe the stresses generated by their flights, formulate experiments, and ultimately to improve our ability to provide a more consistent and less stressful flight for payloads. Payload designers can see the stresses that their projects need to be designed to withstand. As new theories and analysis methods are developed, the published flight information provides a historical database for back-testing and data-mining.

More information on the AL-016 Rocket Data Logger is available at http://www.rafresearch.com/rocketdatalogger/ .