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Mars Science Laboratory Parachute Inversion Phenomenon and Flight Risk Assessment

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During full-scale wind tunnel testing of the parachute for the Mars Science Laboratory two of the test parachutes experienced an inversion. These were unexpected occurrences and required an analysis of the phenomenon as observed in test and an assessment of what risks it may imply for flight on Mars. The test conditions and the inversion morphology are discussed as they relate to the wind tunnel tests and the impacts on the test effort. The timeline for the formation of the inversions is described and compared to the timeline expected in flight. Differences between the physics and behavior in test and flight are discussed as they relate to the threat of inversion. Mitigating actions are described as well as arguments used in determining the final configuration for use in flight.

Nomenclature

D_o	=	parachute reference diameter
DGB	=	disk-gap-band parachute
M	=	Mach number
MD	=	mortar deployment
SD	=	sleeve deployment

I. Introduction

THE Mars Science Laboratory (MSL) mission will use a 21.5 m reference diameter (D_o) Viking scaled disk-gap-band (DGB) parachute as a critical component of its entry, descent, and landing system. Structural testing of the MSL parachute was performed in the 80'x120' test section of the National Full-Scale Aerodynamics Complex (NFAC) operated by the Arnold Engineering Development Center (AEDC) at NASA's Ames Research Center, Moffett Field, California. These developmental tests were conducted in five different tunnel entries over a ten month period from October of 2007 through July of 2008, while the final flight lot qualification tests were conducted in April of 2009. During the second tunnel entry in December, 2007, the parachute that was used in the second of three planned mortar deployment (MD) tests inverted below the band of the canopy. This was the first time that a DGB parachute had ever inverted in any nominally executed test which includes all wind tunnel, low altitude, high altitude, subsonic, supersonic, and Mars flight condition deployments.

Following the MD2 inversion a Risk Assessment Workshop (RAW) was convened in January, 2008, at Pioneer Aerospace in South Windsor, Connecticut, to discuss possible mitigations to the inversion phenomenon both for NFAC testing as well as for flight. The historical flight and test experience was reviewed and a number of options were considered before a down selection exercise reduced the design space to two modifications which were implemented for the third NFAC entry in March, 2008. The two modifications were shown to have no ill effects on the mortar deployment of two 21.5 m and two 23 m parachutes and all four of the openings were observed to be within expectations.

Observations made during the second and third tunnel entries showed that the weakest point in the design was at the suspension line to band joint and this junction could fail under certain conditions during test. In order to build some added strength margin into the parachute the suspension line material was changed from Kevlar-29 to Technora-T221 which necessitated a fourth tunnel entry to verify the new material margins. In addition, the testing

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technique for performing multiple inflation load cycles, a requirement levied on the parachute to account for test observed supersonic behavior, had not been determined and the fourth entry provided an opportunity to develop a new sleeve deployment technology that had been designed and constructed during the spring of 2008.

During MD8, which was the first mortar deployment of the June, 2008, test series (the fourth tunnel entry), the parachute again inverted below the band in much the same manner as was observed in MD2. The test series was halted and an intense Tiger Team investigation was launched to study the problem and to determine what fundamental physics were at work behind the inversion and whether these physics presented a risk to the flight deployment at Mars. The charter of the Tiger Team involved several key fronts. How does our understanding of MSL flight risk posture change as a result of the two parachute inversions at the NFAC? Is Mars flight more risky than we thought? Is the MSL parachute more risky than we thought? What is our best assessment of the at Mars risks?

The overall mission risk was assessed following two primary paths. In the first path the parachute would stay on the planned course with a focus on the understanding of the risk to flight, in particular, the physics of supersonic flight versus subsonic testing; how can the test risk assessment be used and how can the flight risk be bounded? In the second path design changes were considered, in particular, the implementation of "anti-inversion" netting at the bottom of the band and an assessment of the associated implementation risk.

This paper summarizes the NFAC test observations and provides a discussion of the physics believed to be responsible for the inversion behavior. These physics are compared to historic data obtained in supersonic testing and to the conditions expected at Mars in order to assess the overall risk during flight. Conclusions of this exercise are summarized, and a final recommendation is presented, that were used by the MSL team in determining the flight design and configuration.

II. Problem Description and Test Observations

The planned approach for structurally qualifying the MSL parachute for flight was to test the parachute in the NFAC 80'x120' wind tunnel[1] in a manner similar to that used to qualify the parachute for the Mars Exploration Rover (MER) program[2]. A special strut was constructed in the wind tunnel test section to accommodate the enormous loads generated by the MSL parachute and to provide an anchor point on the tunnel centerline. The strut was equipped with a launch arm that had both azimuth and elevation angle rotational degrees of freedom thus allowing the parachute to move across the test section freely without generating moments in the strut or launch arm. Pin-type load cells were used to attach the parachute triple bridles to the mortar fixture which was in turn attached to the launch arm using a second set of facility load cells thus providing a redundant load measurement. This test set-up is shown with a fully inflated parachute in Fig. 1. Two parachute handlers are visible in Fig. 1 below and on either side of the parachute who, along with the exit door near the center of the image, help to provide a sense of scale. Note that the parachute blocks approximately 25% of the tunnel cross-section and extends well beyond the normal tunnel test section.

The most realistic way to deploy the parachute, and functionally the most straightforward, is through a mortar deployment. For this type of test the launch arm is set at an elevation of approximately 10° above horizontal and is held in place with a break tie. Once all the camera and data recording equipment is made ready, the tunnel is brought onto condition and the mortar is initiated, launching the parachute into the wind stream. This was done for the first time on December 3, 2007, without incident. However, during the next test which was conducted the following day the parachute inverted which quickly led to a catastrophic failure of the canopy. Parachute inversions are known to be a risk for other applications[3,4] but no disk-gap-band (DGB) had ever inverted prior to this incident so this was very much an unexpected turn of events.

The video coverage for the test was set-up to provide global inflation information for use in loads reconstruction and the limited information available was inadequate to clearly identify the root cause of the inversion. Nevertheless, the basic features of the inversion were evident from the available MD2 videos and are illustrated in Fig. 2. The need for high quality videographic data was evident in the face of the newly realized threat of canopy inversion. Thus, in order to proceed with the last mortar deployment planned for the second tunnel entry, two high speed cameras were enlisted to help provide better coverage for the MD3 test. This test was conducted on December 11, 2007, with a nominal outcome and while the high speed video demonstrated the complexity of the early deployment stages, no evidence of what might have caused the inversion on MD2 was detected.

Following the conclusion of the second NFAC entry the MSL team decided to convene a Risk Assessment Workshop (RAW) at Pioneer Aerospace in January, 2008, in order to examine the available data and to determine if any measures could be taken to minimize the likelihood of its reoccurrence. Many different options were considered and debated at length during the RAW that primarily focused on controlling the extraction of the parachute from the deployment bag (Dbag) and providing tension in the suspension lines to reduce the chances for an inversion. In the end it was recommended that three modifications be made to the parachute packing procedure: 1) elimination of the S or Z-fold in favor of a flat-fold to reduce the pack complexity and to better accommodate the mortar geometry, 2) the addition of line ties connecting the suspension line bites to the Dbag in order to help tension the suspension lines during deployment, and 3) the addition of a canopy compartment to help ensure the canopy does not deploy early.

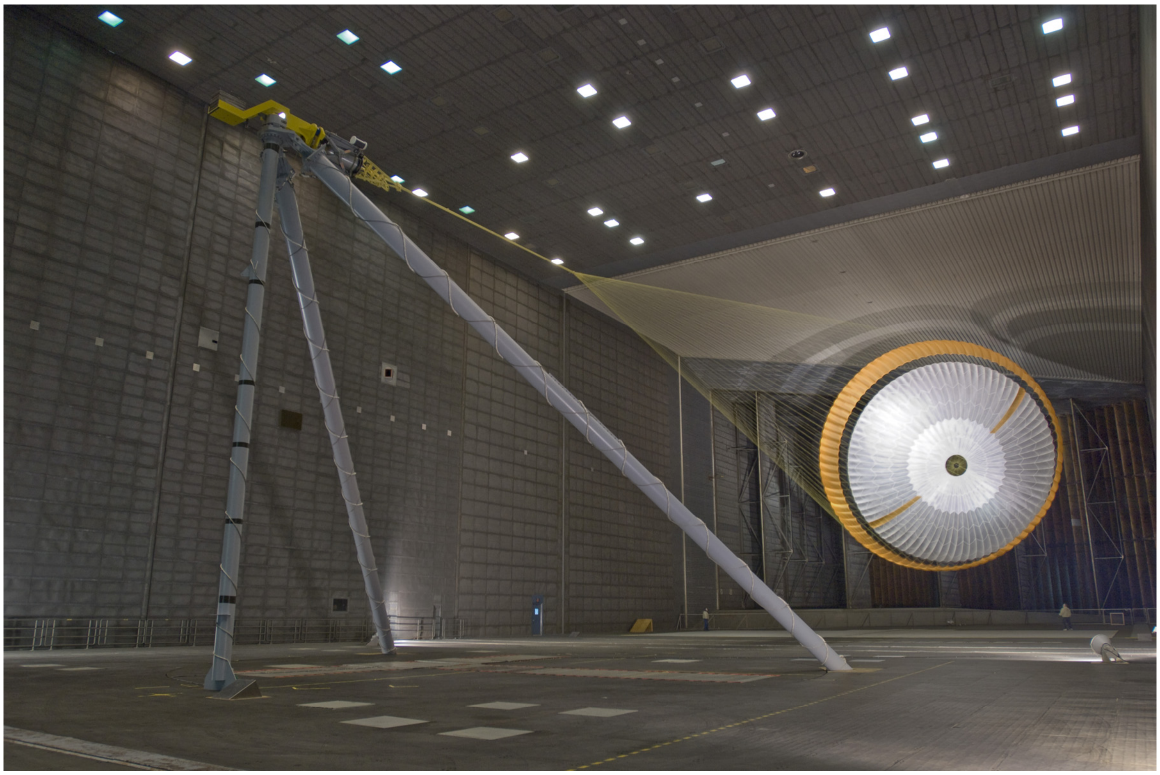

Figure 1. NFAC test set-up overview showing the test strut and launch arm with a 21.5 m MSL parachute.

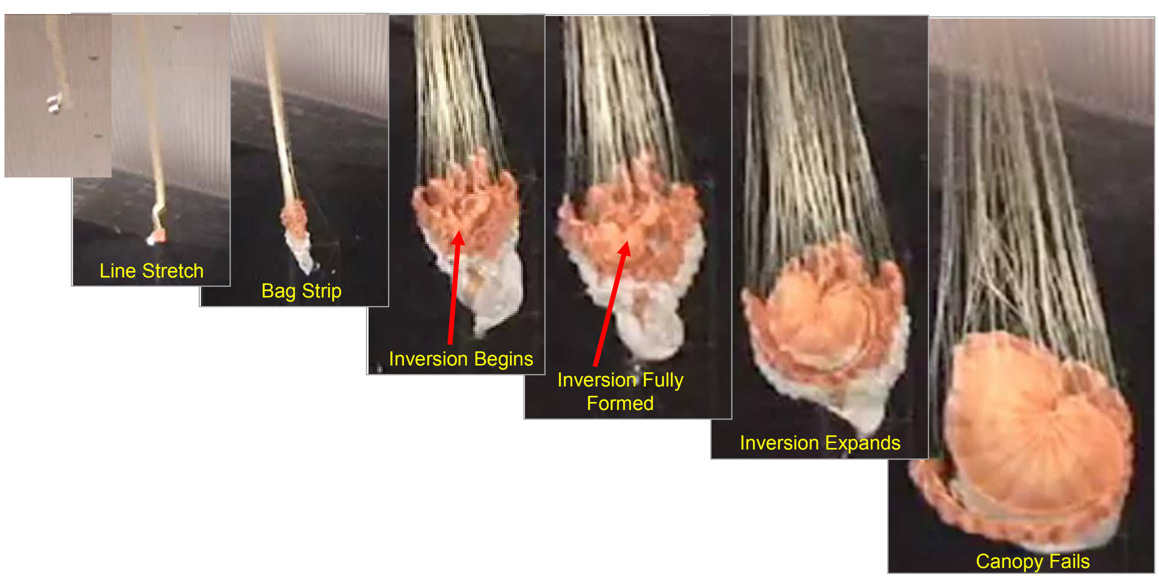

Figure 2. Development of the band leading edge inversion during the second mortar deployment of a 21.5 m reference diameter DGB in the NFAC 80'x120' wind tunnel.

A third NFAC tunnel entry was conducted in March of 2008 in order to evaluate the RAW recommendations. The video coverage for these tests was expanded to include a total of three high speed cameras as well as professional video cameras and a number of camcorders. The high speed cameras were positioned on the lower left, the lower right, and in the ceiling of the test section such that their fields of view were roughly evenly spaced every 120° around the tunnel centerline. This was an unprecedented level and quality of video coverage for a parachute test and provided a powerful tool for detecting any risks of parachute inversion as well as determining the effects of the RAW modifications. All four of the mortar tests MD4-MD7 went smoothly and provided the highly sought after video data which detailed the initial parachute deployment. Ultimately when the data were analyzed from these and other future tests it was determined that the additional tension provided by the line ties had a negligible effect so this feature was dropped from the flight packing procedure although the canopy compartment and flat-fold pack were retained.

Experience from reefed deployment tests conducted in the December entry indicated that the weakest point of the parachute design was the suspension line to band hem joint. In a bid to maximize the parachute structural margin a decision was made to manufacture two additional 21.5 m parachutes using Technora-T221 for the suspension lines in place of Kevlar-29. This was virtually a 1:1 switch as the Technora lines were purchased with exactly the same braid pattern and Technora-T221 has nearly the same modulus as Kevlar-29. The plan was to leverage the experience gained in the December and March test series in order to help qualify the new Technora parachutes during a fourth tunnel entry in June, 2008. In addition, in response to the area oscillations requirement[1], a new sleeve deployment (SD) technique was to be tested in an effort to address the need to deploy the parachute multiple times in test.

With these goals in mind, the team assembled once again for the fourth NFAC entry in June of 2008. Unfortunately, the new Technora lined parachute tested in MD8 experienced an inversion at the bottom of the band leading to catastrophic failure in a manner that was assessed to be nearly identical to the MD2 inversion. This time, however, the high speed and high resolution still cameras trained on the test captured the incipient inversion and provided a rich source of information surrounding its formation, a portion of which is shown in Figs. 3 and 4.

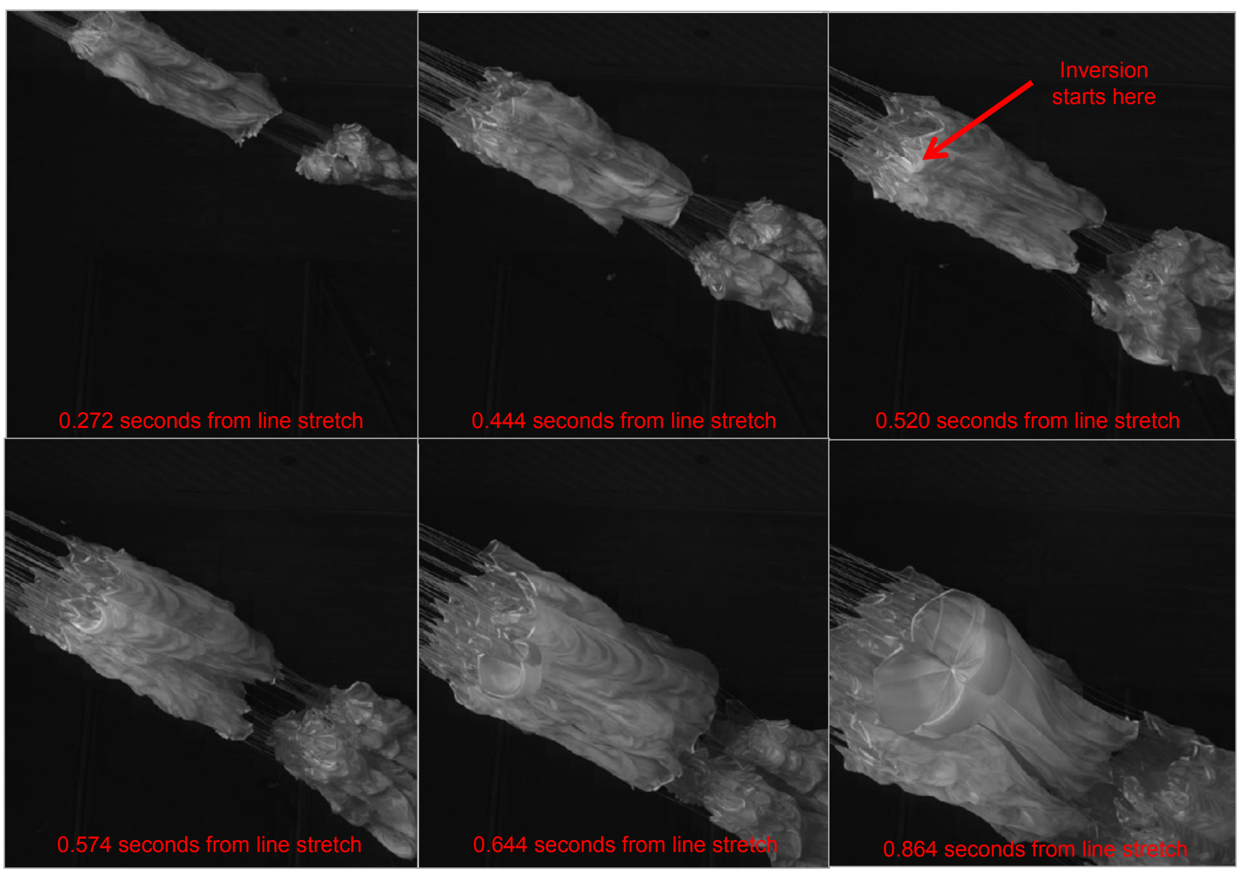

Figure 3. High speed photography capturing the onset of a band leading edge inversion on MD8.

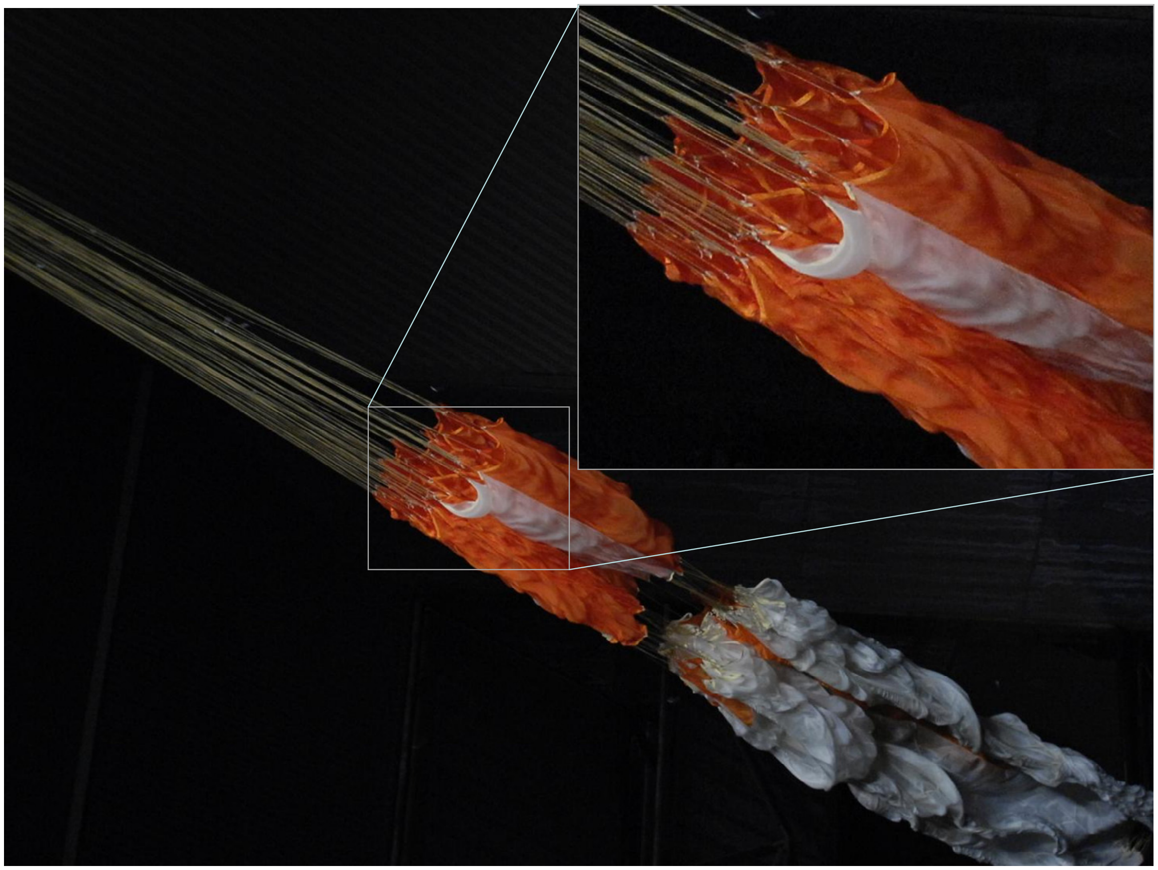

Figure 4. Initial stage of the MD8 inversion evident as the air scoop shape or sail shape in the white gore.

III. Leading Edge Cross-overs

One of the observations made during the period between the third and the fourth NFAC test series was that the leading edge of the band could "cross-over" and form a stable geometric shape or "scoop" without actually inverting the parachute. This behavior was initially overlooked due to the rapid and chaotic motion of the parachute during the deployment which tends to mask their appearance. However, once the feature was known to exist and having learned what to look for, a leading edge cross-over (LEC) could be easily detected in the high speed and still camera image data and were subsequently found to be a relatively common occurrence.

Ultimately two different types of LECs were identified which were termed "simple" and "compound" depending on the number of gores that participated in the LEC's localized inversion. The basic forms of a simple and a compound LEC are illustrated in Fig. 5 where the difference between the number of participating gores is evident. At the time of this discovery there were a total of five mortar deployments MD3-MD7 where high speed video had been taken. Once the LEC phenomenon had been identified, a review of all of the available video data was conducted wherein it was determined that LECs were commonplace and at least one LEC was identified in every mortar deployed test. Figure 6 shows an example of a number of simultaneous LECs that developed on the leading edge of the band during MD7.

Compound LECs are much more dangerous and are, in fact, miniature inversions that if they become unstable, will usually lead to a full canopy inversion. Nearly all of the LECs detected were on the bottom or side of the parachute as it was deployed in NFAC but never on the top. This is the case for MD7 as shown in Fig. 6 and was found to be universally true. This bias is a strong indicator that gravity plays a roll in the LEC formation; the mechanism for this is that the horizontal deployment results in a cross wind condition as the strut supports the bridles on the upwind side while the canopy descends across the wind stream on the downwind side. In addition it was noted that, during the early post-bag-strip period, groups of lines from the top-side portions of parachute could fall between the suspension lines on the bottom-side resulting in the more dangerous compound LEC. Hence gravity's effect was twofold in contributing to the formation of LECs and exacerbating their effect once formed.

Historically three leading causes of parachute inversions have been identified: 1) random movement of the parachute skirt, 2) cross wind deployments, and 3) an uneven canopy skirt[3]. From this discussion it is evident that all three of these components are present in the horizontal wind configuration to some degree: there is clearly random motion of the skirt of the band, gravitational effects produce a cross-wind component, and the top side – bottom side feature of the horizontal deployment can result in a somewhat uneven canopy skirt.

A LEC becomes unstable when the drag force of the scoop exceeds the flag drag tension generated by the band and disk. This delicate force balance is conceptually illustrated in Fig. 5. Once this imbalance condition is met the LEC will quickly grow and form a full leading edge inversion. It should be noted that one exception to this occurred in the ninth sleeve deployment test SD9 conducted as part of the fifth NFAC entry in July of 2008, where a compound LEC was observed forming on the disk leading edge. This case, shown in Fig. 7, was highly unusual as it was both the only time a disk LEC was ever observed and also the only time that an initially unstable LEC motion was arrested and corrected with the eventual outcome being a nominal inflated shape with no detectable damage to the parachute.

During the Tiger Team exercise the observation was made that the timing of the LEC is very important in determining if the LEC will propagate into a full blown inversion. Figure 8 shows the time relative to line stretch that the LECs were first observed on the first eight mortar deployments. While the precise time at the start of the MD2 inversion is not known (it is indicated as a range in Fig. 8) it is clear that it was very early in comparison to the majority of the cataloged LECs. The MD8 inversion is the earliest recorded occurrence of a LEC in any MD test. Of course the mere presence of an early occurring LEC does not guarantee that the parachute will invert, however, the risk of inversion is much greater during these early events. The primary reason for this is straightforward; the longer the parachute is exposed to the flow the more restoring force will be generated by the inflating disk section and hence, the more difficult it is for a LEC to overcome this force to form an inversion. The timing of the inversion is discussed further with regards to flight risk in Section IV.

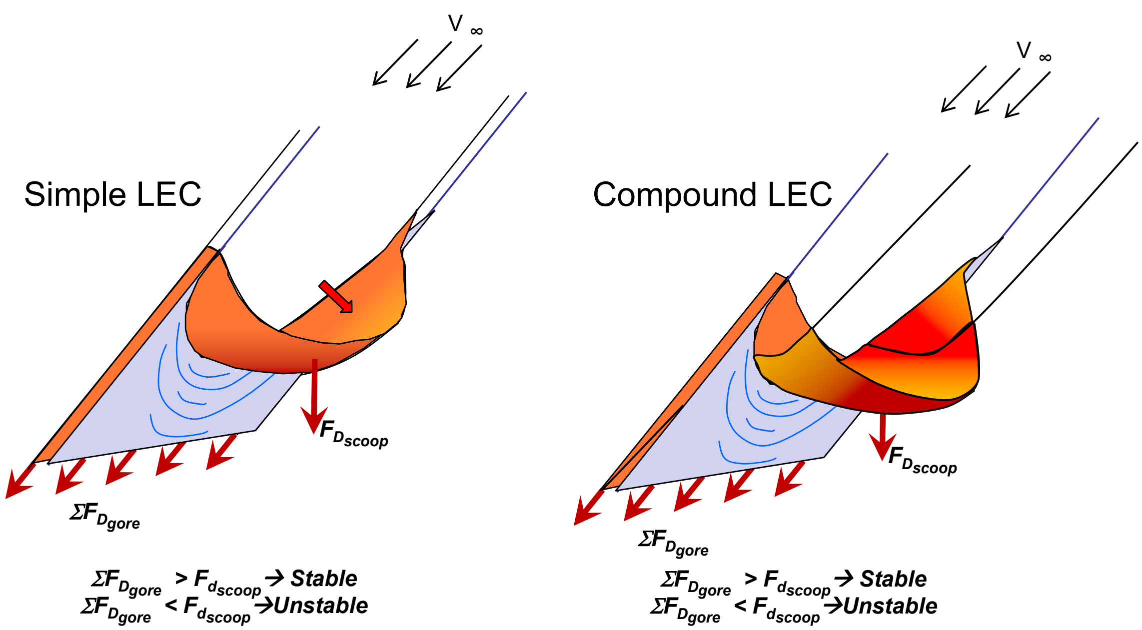

Figure 5. Simple and compound LECs illustrating the force imbalance that can lead to instability. Simple LECs have only one gore cross-over whereas compound LECs involve more than one gore and have at least one line that crosses-over as well.

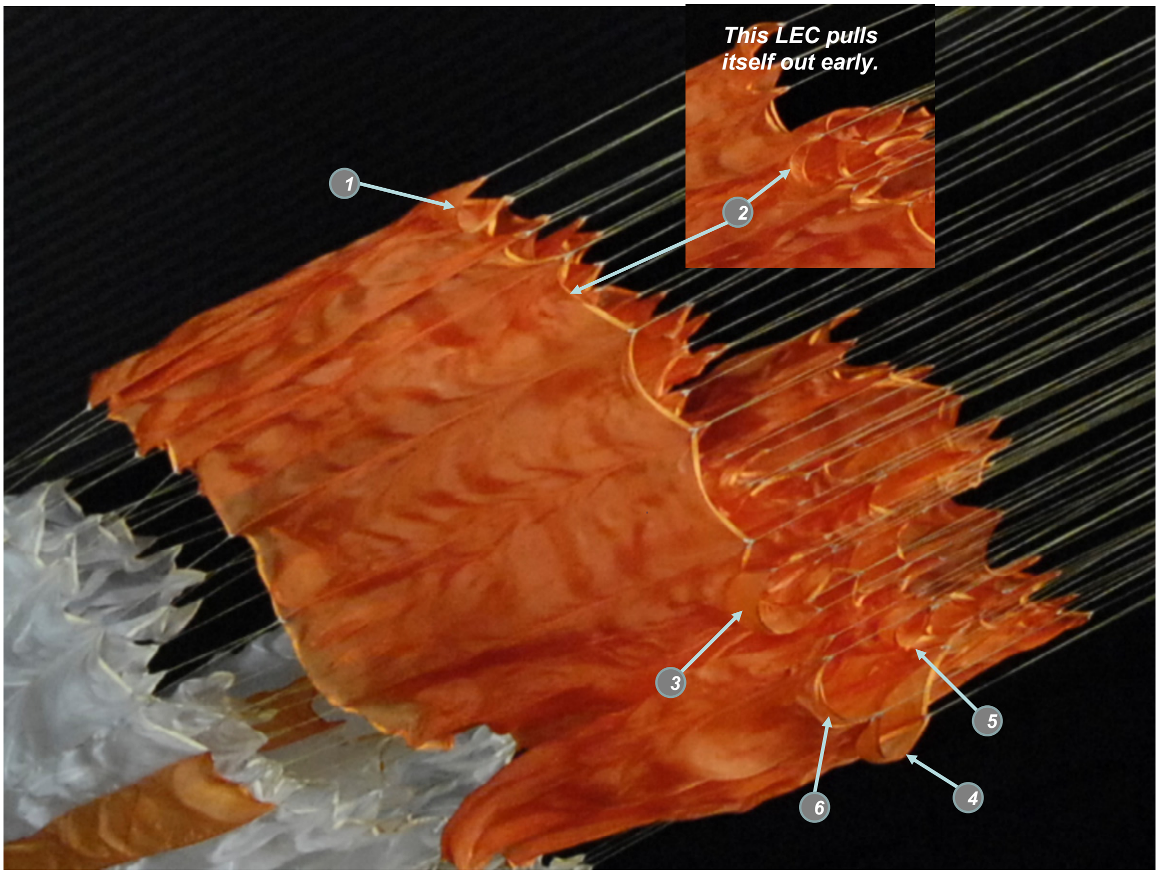

Figure 6. LECs identified during the MD7 deployment of a 21.5 m DGB. Most LECs are simple but the LEC labeled as number 3 is compound and is less stable.

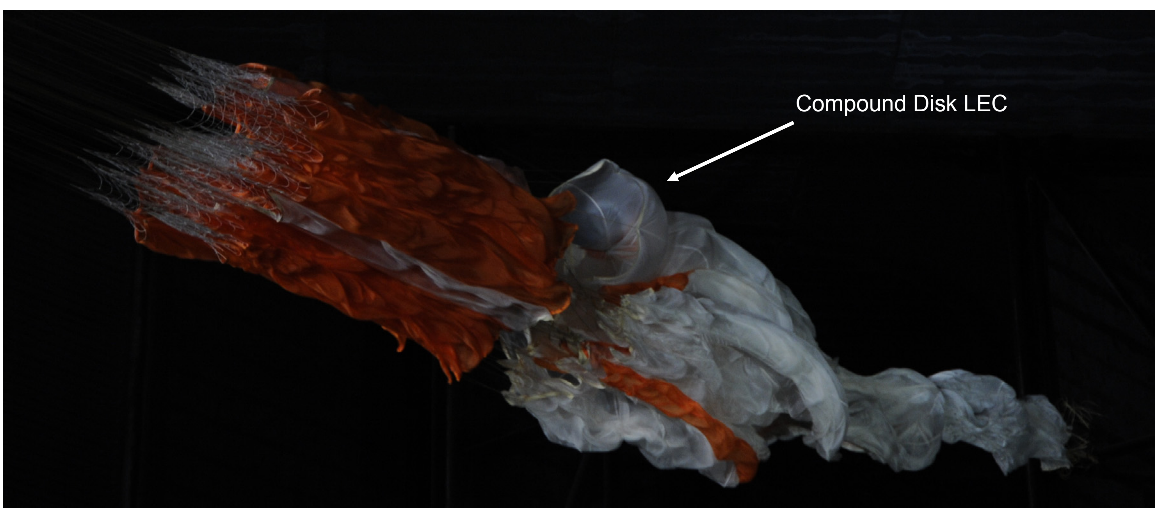

Figure 7. The compound disk LEC observed during SD9. This was the only time a LEC was seen on the disk skirt and also the only time that an initially unstable LEC was arrested and corrected.

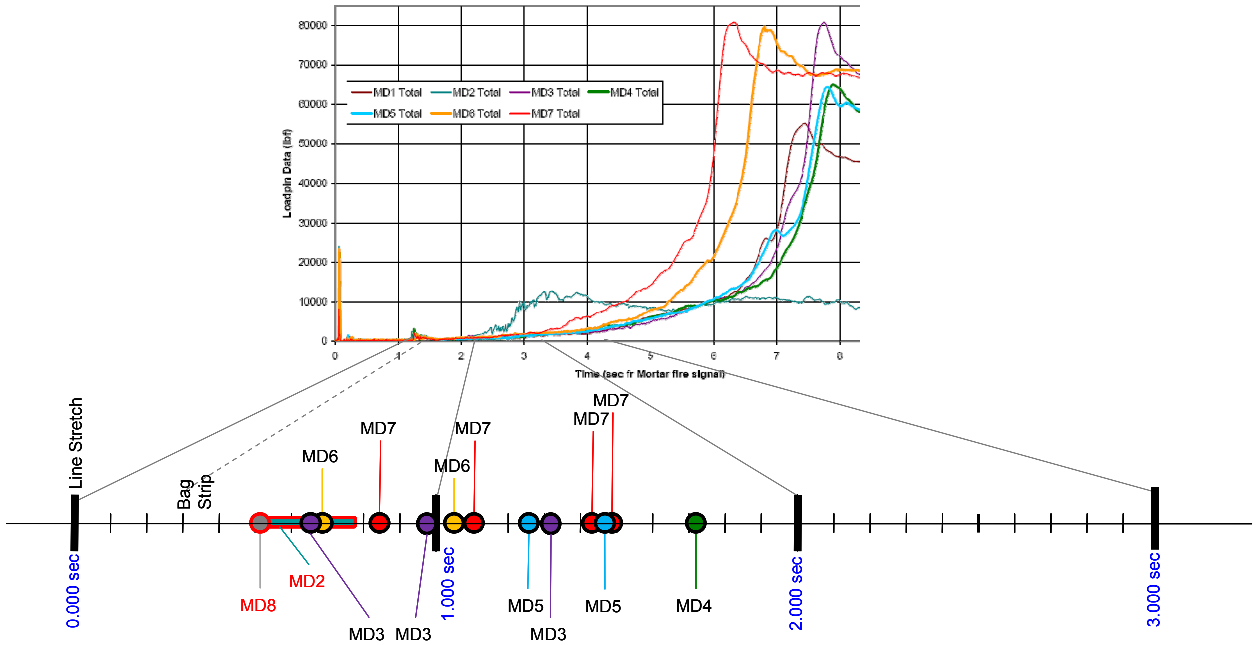

Figure 8. Timing of LECs relative to line stretch for different MD tests illustrating that LECs that occur late in the deployment timeline are benign but the two earliest LECs detected both led to parachute inversions.

IV. Supersonic and Subsonic Physics and Parachute Opening Morphology

In comparing the subsonic and supersonic parachute openings it is apparent that the two different velocity regimes display a fundamentally different opening geometry. This is illustrated in Fig. 9 where a side-by-side comparison is made between the PEPP 19.7 m parachute inflation[5] on the left and a low altitude subsonic MSL inflation from NFAC on the right. The high altitude supersonic inflation initially opens radially outward with a quasi-circular geometry forming at the mouth of the band and evolves with a continuously expanding canopy. In contrast, the low altitude subsonic inflation initially opens with a collapsed multi lobed canopy and inflation evolves with in-folds and lobes until sufficient internal pressure exists to force the parachute open. This fundamental difference in opening morphology is captured in Fig. 10 which shows the band geometry at a number of time normalized equivalent stages of deployment. I.e., the start and end times are determined by line stretch and full open and the geometry is captured at uniform intervals between these two points.

The concern over LECs and the observation of the radical difference in opening morphology led the Tiger Team to ask two important questions. First, is the NFAC test initial inflation dynamically similar to Mars flight? And second, how could the observed NFAC behaviors be reflected at Mars?

The answer to the former is that the NFAC inflation process is not dynamically similar to the supersonic inflation at Mars. Although the forces have some degree of similarity to flight due to the fact that the dynamic pressures are matched to some level, the volume filling time scales, driven by flow field velocities, are an order of magnitude different and the inertia ratio between the canopy and the entrained air mass differs from flight by two orders of magnitude. The NFAC test is not constructed to be dynamically similar, but rather is used to stress the canopy at full inflation to load levels representative of flight. This lack of dynamic similarity suggests that NFAC test dynamics are significantly different than those in flight.

In regards to the latter, the NFAC differs from flight most notably in that the LEC forces are thought to be close to flight like because they are driven by dynamic pressure. The restoring forces that reduce the size of an LEC bloom are driven by volume filling processes where inflation is inversely proportional to the flow velocity. At NFAC the restoring forces evolve an order of magnitude more slowly than the LEC propagating forces evolve. The net result is that an LEC is more likely to evolve into a full scale inversion at NFAC than in flight. In summary, analysis of the relative times scales of the inverting and restoring time scales concluded that the inversion process observed in NFAC was very unlikely, if not impossible, to occur in flight.

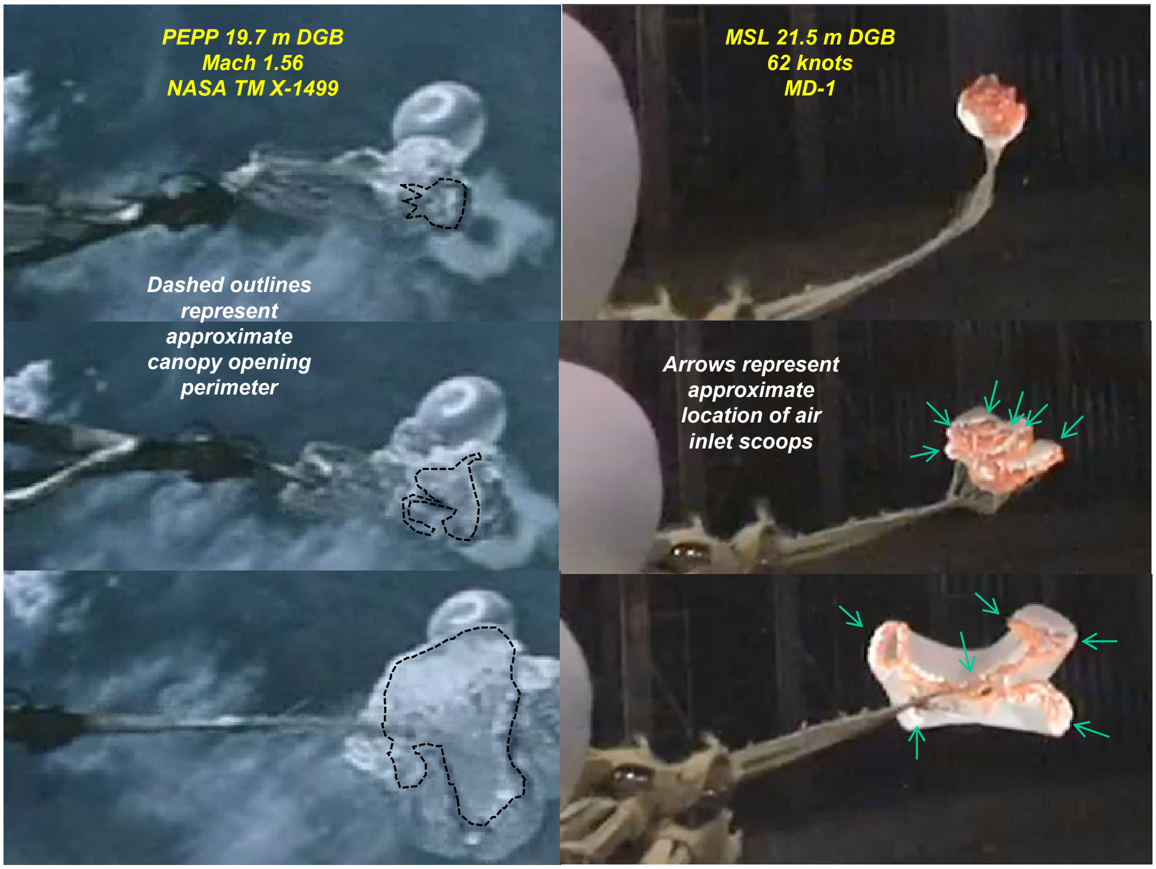

Figure 9. Video frame comparison of the parachute band opening profile between the PEPP 19.7 m DGB supersonic high altitude deployment and a MSL 21.5 m DGB subsonic sea level deployment. The images shown are at similar times following mortar deployment.

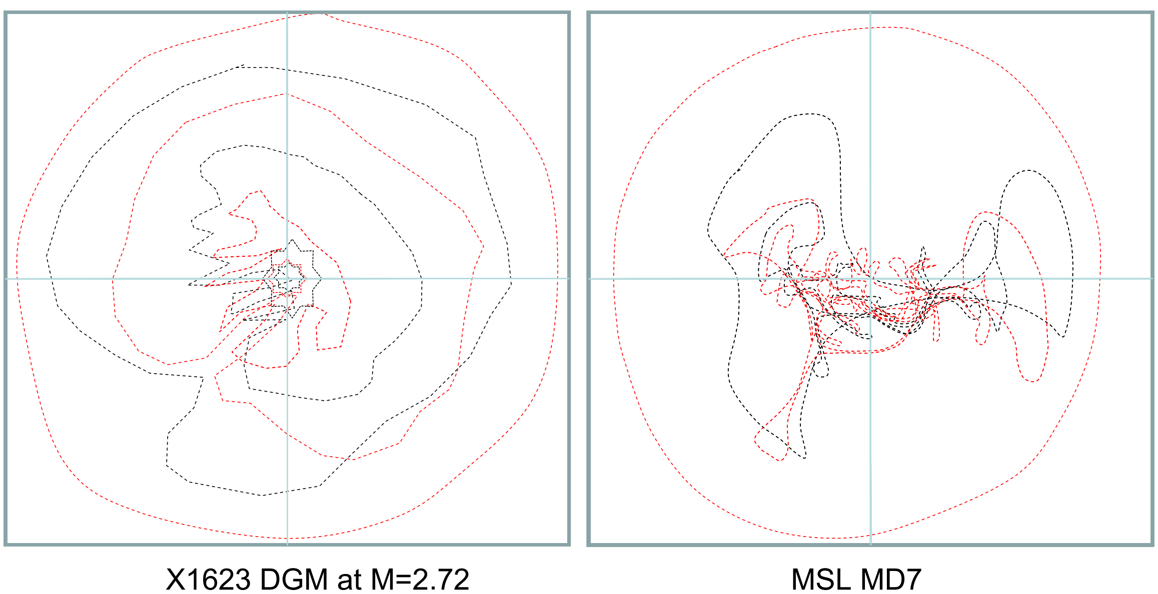

Figure 10. Comparison of the parachute band geometry between supersonic and subsonic deployments. Each line represents an equivalent time step normalized to the time required to reach full inflation. The supersonic deployment opens very quickly and in nearly uniform steps whereas the subsonic deployment opens very late.

The difference in the two flight regimes can also be illustrated by considering the time scale of the events. The earliest onset of a leading edge cross-over at NFAC was on MD8 and yet, as shown in Fig. 11, it still occurs well after the flight and high altitude test loads indicate that the parachutes are well into the opening process. The inflation times for a number of supersonic DGBs at different velocities are summarized in Fig. 12 with all of them being approximately an order of magnitude faster than the observed deployment times for the MSL 21.5 m D_o parachute in NFAC. This shows that the subsonic timing which holds the parachute in a dangerous tightly packed configuration in a cross-wind environment is vastly different from the supersonic timing where the band opens almost immediately. The result of this is that it is unlikely that the physics leading to an inversion in the NFAC tests can be repeated on the timescale associated with flight.

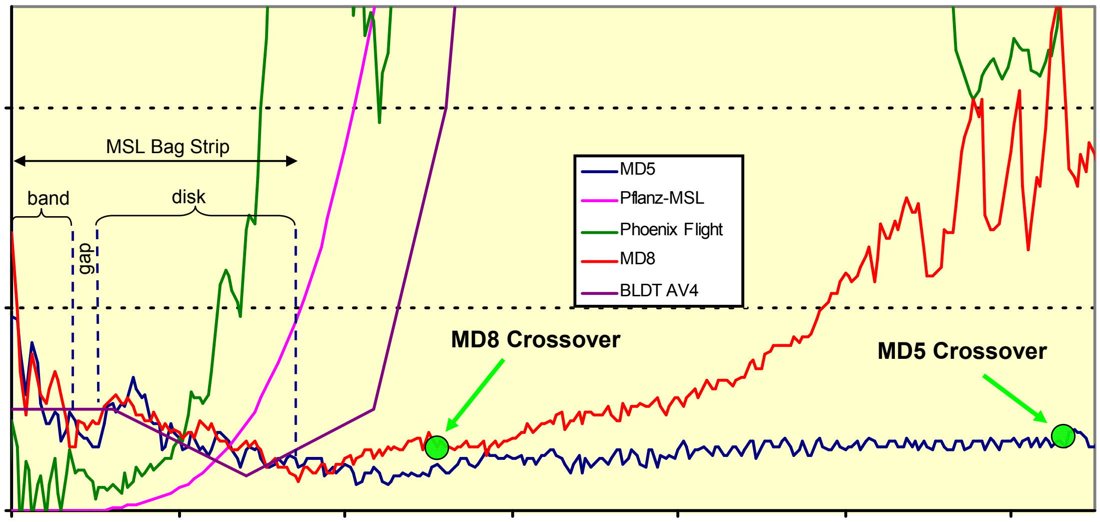

Figure 11. Comparison of inflation profiles from MD5, MD8, Phoenix flight data, BLDT AV-4 test data, and a Pflanz MSL inflation model.

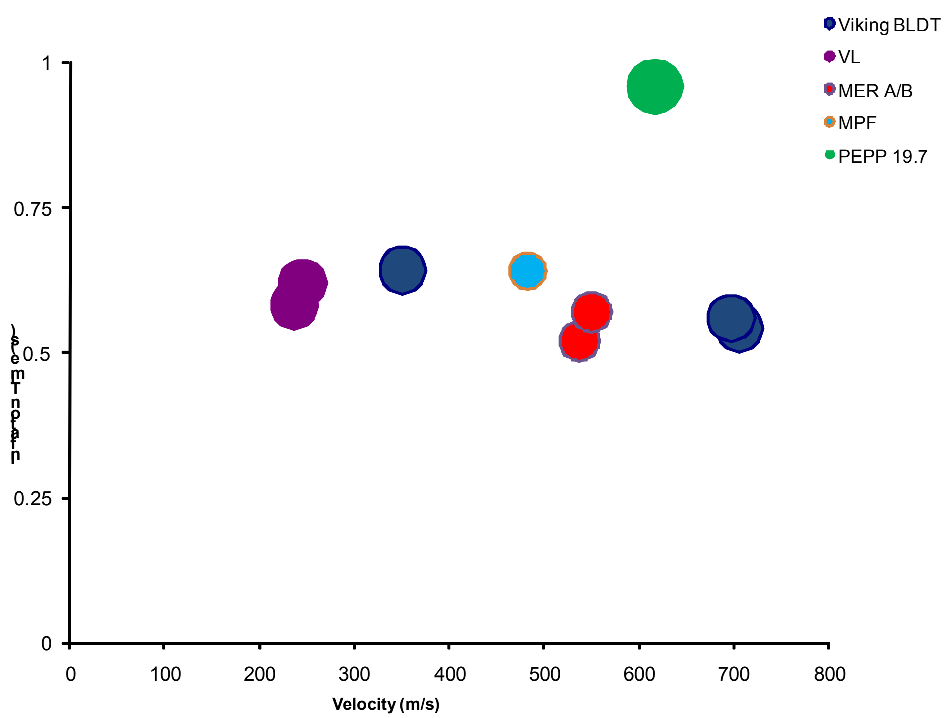

Figure 12. Summary of the DGB inflation times for Viking BLDT, the Viking Landers, MER, MPF, and the PEPP 19.7 m parachute.

V. Mitigating Actions for Test and the Flight Design

One of the most successful solutions to the problem of parachute inversions on terrestrial parachutes is the use of anti-inversion nets. In response to the MD8 inversion, commercially available netting was added to the second Technora parachute as well as the remaining 21.5 m and both 23 m Kevlar development parachutes. The nets are shown on a fully deployed canopy in Fig. 13 and are also visible in Fig. 7 during the early stages of a sleeve deployment. While the anti-inversion netting was successful at preventing inversions it did lead to a different type of structural failure mode which was observed on SD17 when a suspension line failed at the bottom of the netting. It is not clear whether this was the result of damage caused by sewing the netting to the suspension lines, by cumulative damage associated with the sleeve deployments, or possibly by a stress concentration due to the change in stiffness where the net is attached. Regardless the SD17 line failure further sensitized the MSL team to the potential for unforeseen and complex interactions associated with the anti-inversion nets in the high stress region at the skirt of the band.

For flight it was determined that the risk associated with loss of heritage to previous experience in adding anti-inversion nets outweighed the potential benefit as the likelihood of an inversion was found to be so low. In the end the only modifications of significance made to the MSL parachute system were the incorporation of a canopy compartment in the deployment bag and the change to a flat-fold pack to promote a more orderly deployment.

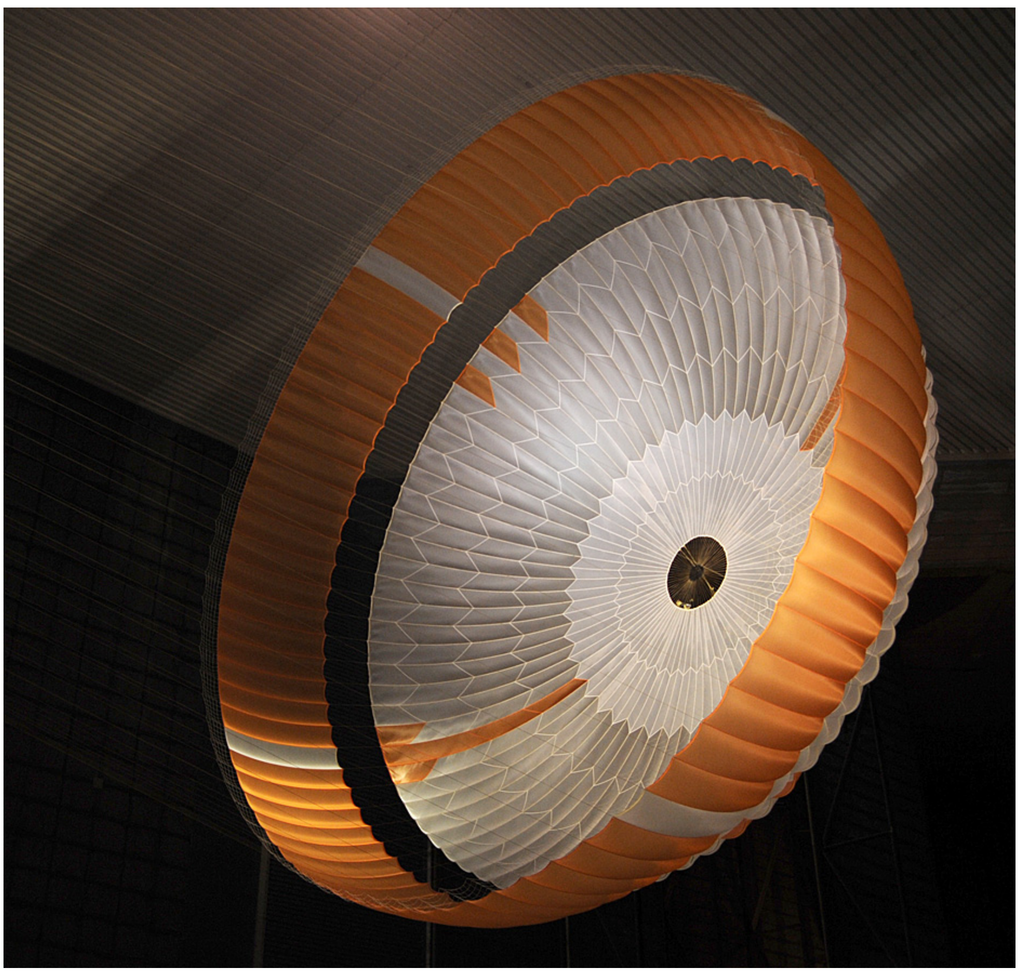

Figure 13. MSL 21.5 m DGB augmented with anti-inversion netting fully deployed at NFAC.

VI. Conclusion

Although the consequence of an inversion in flight is catastrophic the conclusion reached through this effort is that the flight physics are sufficiently different from those in the NFAC tests that the LEC and inversion phenomenon is not a risk to flight. This conclusion was reached based on the understanding of the source of the LECs in NFAC as being related to the test set-up as well as the significant differences in the physics of supersonic and subsonic deployments. In particular, the time scale required for an inversion to form in NFAC is sufficiently long that it could not form if it occurred on the same scale in flight. Only minor changes were made to the deployment bag and parachute packing procedure to help promote an orderly deployment and it is not clear that these changes have any effect on the risk of an inversion in flight. Following MD8 all parachutes tested in NFAC were augmented with an anti-inversion net. This preventative measure was highly successful and no other inversions occurred throughout the balance of the test and qualification program. Some consideration was given to adding anti-inversion nets to the flight parachute but this was rejected as it was a departure from flight heritage and represented an unquantified risk.

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