Long Cable Deployments during Martian Touchdown: Lessons Learned

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Abstract—The launch of NASA/JPL's next generation Mars rover is planned for the fall of 2011. The landing scheme chosen for this rover represents a step forward in unmanned payload delivery. The rover will be lowered from a rocket powered descent stage and then placed onto the surface while hanging from three bridles. During this touchdown event, the communication between the rover and descent stage is maintained by an electrical umbilical cable which is deployed in parallel with the structural bridles.

During the development of the deployment device for the electrical umbilical, many obstacles were identified and overcome. Many of these challenges were due in large part to the helical nature of the packing geometry of the umbilical cable. And although none of these issues resulted in the failure of the design, they increased both development and assembly time. Many of the issues and some of the benefits of a helical deployment were not immediately apparent during the trade studies carried out during the deployment selection process. Tests were conducted upon completion of the device in order to characterize both the deployment and separation characteristics of the cable. Extraction loads were needed for inputs to touchdown models and separation dynamics were required to assess cable-rover recontact risk. Understanding the pros and cons surrounding the deployment of a helically packed cable would most certainly influence the outcome of future trade studies surrounding the selection of cable deployment options.[1 2]

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1. INTRODUCTION

The launch of NASA/JPL's next generation Mars rover is planned for the fall of 2011. The entry, decent, and landing (EDL) design for Mars Science Laboratory (MSL) is unlike previous missions. After atmospheric entry and parachute deceleration, a powered descent vehicle (PDV) will be released. The PDV consists of a descent stage and the attached Mars rover. The descent stage is a rocket powered vehicle whose sole purpose is to fly the rover to the Martian surface. After parachute separation, the descent stage will fly the rover to a specified altitude, lower it on a set of three-7.5 m structural bridles, and then place it on the surface of Mars. This process was dubbed "skycrane". Throughout this flight, it will be the rover which actively controls the descent stage by way of a deployable data cable (umbilical). After the rover has been placed on the surface, all soft-good connections (structural bridles and umbilical) to the descent stage will be severed at the rover deck. The descent stage will then fly away, crashing some safe distance from the rover.

The umbilical cable used during the skycrane event was designed to be stored in a helical shape within the descent stage prior to deployment. While separating from the descent stage, the rover will pull the cable straight from its stored configuration. This helical packing geometry was initially appealing due to the requirements set forth for the mechanism. The initial concept did not require large numbers of break-ties to restrain the cable during launch and was able to contain a long length of cable in a relatively small space. Additionally, the minimum bend radius of the cable was never violated, as was done in previous designs.

Although the benefits of a helically packed cable did help in meeting many of the requirements for the device, there were significant challenges in the implementation. The twist developed in the cable during the deployment required extensive design to mitigate the application of tension on the individual wires. Additionally, the packing of the cable proved difficult between deployments due to the cable twist. The twisted cable was also challenging to manage after deployment, both in slack management and separation. Solutions were found to all design hurdles encountered

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[1] 978-1-4244-2622-5/09/$25.00 ©2009 IEEE.
[2] IEEEAC paper #1204, Version 8, Updated January 9, 2009

relating to the twisted cable which allowed for the implementation of the helical packing geometry.

Tests were carried out in which the umbilical was extracted from its deployment device and its extraction loads were measured. These test showed a cable which deployed readily and smoothly over the deployment regions when break-ties did not restrain the cable. The restraining ties did cause momentary increases in load but dissipated a relatively insignificant amount of energy during the rover deployment.

One major uncertainty in the development of this cable deployment scheme was the dynamics of the cable upon separation from the rover deck. Recontact between the cable and the rover had to be minimized during the descent stage's flyaway event. This required knowledge of the cable's motion after separation in order to identify rover hardware at risk of impacts from the umbilical. Testing was performed in order to understand the risks to the rover. Using a pairs of high speed cameras, the tip of the cable was tracked during simulated separation events. A separation envelope was developed for the cable based on this data and the recontact risk posture was quantified.

Although the helically packed umbilical cable was used and helped to meet the performance characteristics required for the mechanism, the design was difficult to practically implement. Solutions were developed for all issues resulting from the packing geometry and should be considered when implementing this type of design in the future.

1.1. MSL Touchdown Overview

As previously mentioned, the skycrane landing architecture is new to NASA's EDL repertoire. The details of the skycrane sequence surrounding the umbilical deployment begin at the moment the rover separates from the descent stage. When released, the rover will deploy 7 m below the decent stage in approximately 5 s. During this time the umbilical cable will be extracted from its helically packed shape within the descent stage. A small line deployed from a retraction mechanism will be attached to the umbilical cable 3 m from the descent stage at full deployment. This line will deploy in parallel with the umbilical as seen in figure 1.1. This line and mechanism apply tension to the cable after full deployment and during the touchdown event. Maintaining tension on the umbilical is critical during the touchdown event to prevent cable slack from accumulating on the rover and snagging during the descent stage flyaway event.

Once the rover has been offloaded from the descent stage by the ground, the descent stage will continue a slow descent for approximately 1 s in order to confirm that the rover is on the ground. Once confirmation is complete, the bridles and umbilical will be cut at the rover deck. The descent stage will then begin its acceleration away from the rover at 5.79 m/s^2 - 8.47 m/s^2. Despite being cut, during the initial stages of the descent stage acceleration away from the rover, the umbilical will be tied to the rover deck with a light-duty break-tie. At the moment that the retraction line becomes fully deployed, this break-tie will be loaded beyond its breaking strength and will release the umbilical. The

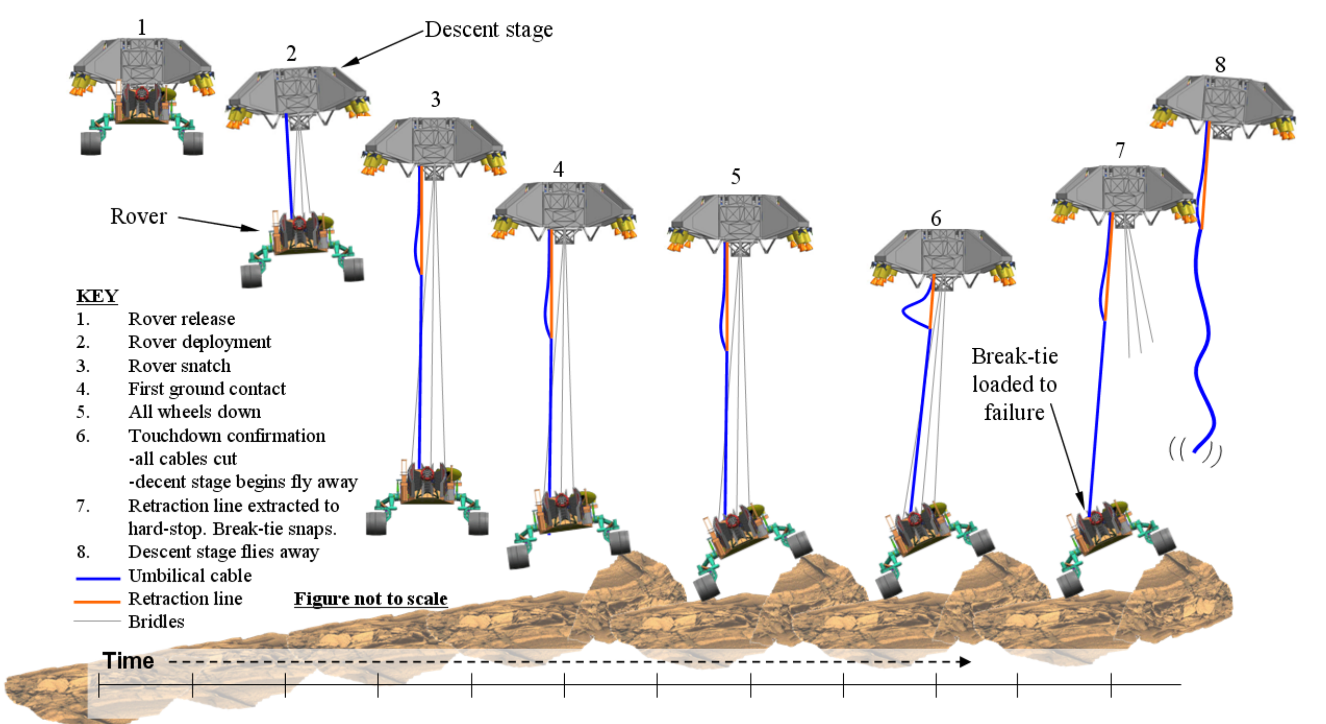


Figure 1.1: Touchdown sequence for MSL.

sequence for rover touchdown can be seen in figure 1.1.

The advantage of keeping the umbilical tied to the rover during the initial portion of the descent stage acceleration is that the descent stage is given an opportunity to develop some velocity away from the rover before the umbilical is allowed to swing across the rover deck. This vertical velocity of the descent stage is imparted to the umbilical at the moment the break-tie fails. It is this velocity which aids in the motion of the cable away from the rover deck and thus prevents gross recontact.

1.2. Umbilical Deployment Major Requirements

The major requirements for the umbilical deployment device are listed below.

1. Deploy the umbilical between the rover and descent stage.
2. The umbilical shall not recontact the rover nor descent stage during the deployment, prior to the cutting event of the umbilical.
3. The umbilical shall not recontact the descent stage after being cut at the rover.
4. The region of the rover at risk for recontact with the umbilical after the umbilical is cut shall be minimized and identified.
5. After deployment, the tension applied between the rover and descent stage from the umbilical deployment device shall not exceed 100 N.

An additional requirement which existed initially dictated that no debris was to be produced during the deployment of the cable. This requirement was imposed because of the large amounts of debris produced during the Mars Exploration Rover (MER) landing event. This requirement influenced the selection of the deployment scheme despite later being struck from the requirement list due to the inability to conclusively prove that absolutely no debris was produced.

1.3. Initial cable deployment trades

Two initial concepts were considered for the deployment of the umbilical cable. The first was similar to one used on MER. The S-box design lays a flat ribbon style cable back and forth in a box as shown in figure 1.2. Although being an efficient way of packing large amounts of cable, there were two main drawbacks to the S-box design. This device produced a large amount of debris during the MER deployments as a result of the break-ties used to secure the ends of the cable. This material rained down on the MER rovers and the Martian surface during the deployment. This debris generation was considered a detriment to this design due to the initial requirement for MSL that no debris be produced.

The second main drawback for the S-box design was gross violation of the wires' minimum bend radius at the fold points. MSL required multiple test deployments of the umbilical system on the flight unit prior to the Martian deployment. Concerns about wire fatigue at the fold locations drove the team away from this design.

Figure 1.2: MER bridle box with loaded bridle

The helically packed umbilical concept appeared to solve the problems associated with the S-box design. By coiling the cable and constraining the cable between two cans, the minimum bend radius could be maintained and the number of break-ties required would be greatly reduced. The packing geometry did require more volume than the S-box design but was within the allocated volume for the device. The first double cone concept can be seen in figure 1.3. This prototype proved that the cable would deploy easily and uniformly, but demonstrated that some type of rate limiter would be required to reduce the ability of the cable to simply fall out of the can.

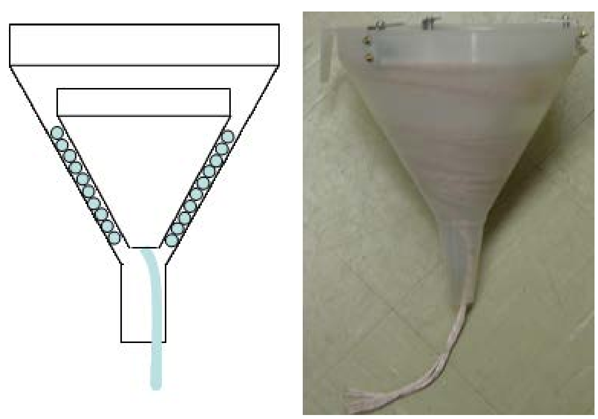


Figure 1.3: Initial double-cone deployment concept.

The initial concept for a rate limiter for the umbilical was a lip and brush setup as can be seen in figure 1.4. This lip and brush would be placed on the lower end of the can. The lip would support the loads of the cable along the axis of the can while the brush would limit the ability of the cable to deploy under its own weight. In prototyping this configuration, it was found that at least the initial first few coils of umbilical had to be exposed to allow for a relatively low force deployment. The reasoning for this can be seen in figure 1.5.

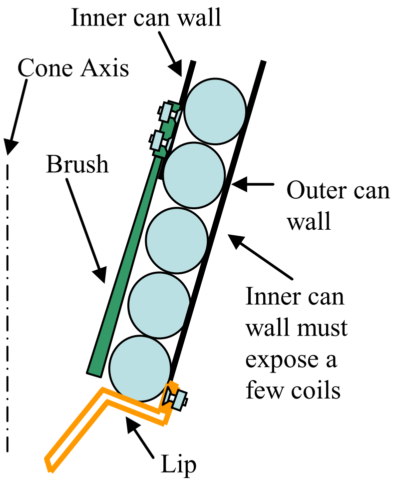


Figure 1.4: Umbilical rate limiter concept.

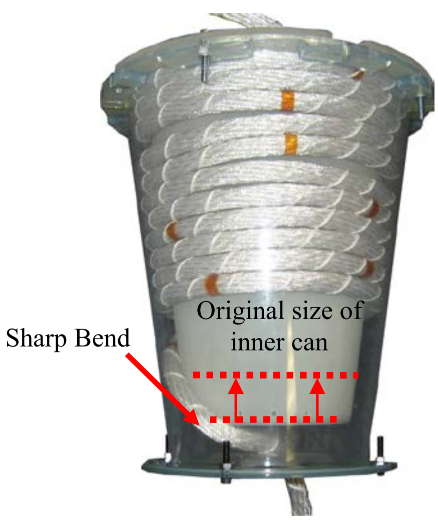


Figure 1.5: Umbilical Deployment device stereolithography prototype.

In figure 1.5 it can be seen that with only one coil exposed, the cable must make a sharp bend around the edge of the inner can. This bend resulted in high cable drag and high required extraction forces.

While the lip proved to be a good way of managing the cable loads along the axis of the cone, the brush proved difficult to implement. The main problem with the use of the brush was that, because the first three coils had to be exposed, the brush had to retrain all of that cable during the launch environment. Initial tests showed the brush concept could not control three coils of cable during launch loads and alternate rate limiter concepts were pursued.

Break-ties were then considered as a replacement for the brush concept. It was thought that if the break-ties could be tied in a way which reduced debris shedding, they would be a viable substitute. Also, it was at this time that the debris shedding requirement was changed from a hard requirement to a best-effort "desirement" due to the difficulty in definitively proving that no part of the system produced any debris during the deployment.

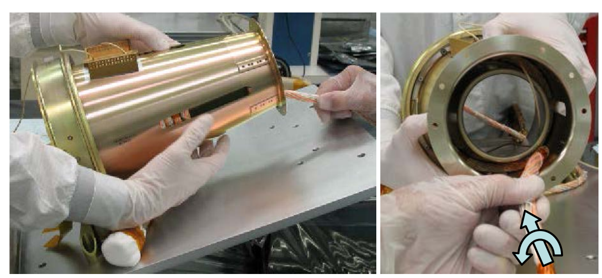
The final concept selected was a helical cable packed between two conical cans with the inner can exposing the first three coils of the cable. Additionally, those first three coils would be retrained through the used of break-ties.

2. HELICAL CABLE DEPLOYMENTS

Despite being initially attractive as a storage and deployment concept, the helical cable geometry was difficult to implement due to nuances involved with cable twist. Reliable solutions were found for all of the encountered challenges, but had these difficulties been known prior to the implementation of this design, alternate concepts may have been explored.

2.1. Packing Issues

The act of packing the umbilical cable into the two cans proved to be difficult because the cable had to be twisted to be coiled. This most easily understood when thinking about the way in which one might coil an extension cord. To have the cable coiled properly, each time a loop is created, the cord in that loop must be twisted 360° about its own axis. This can be seen in figure 2.1. This allows for a nearly stress free cable when in the helical geometry.



(a) **(b)**

Figure 2.1: Umbilical packing side view (a) and end view (b)

The design for this system required that both cans be mounted during the packing of the cable which necessitated packing the cable from one end of the assembly as seen in figure 2.1. This way of packing proved not only difficult and time consuming, but was also not repeatable. The amount of cable left at the end of the device after packing varied by as much as 5 cm. In order to reduce this variation, prior to each packing, the cable was completely extracted and untwisted in order to return to a known untwisted state. This process was time consuming and not totally repeatable. A more robust design would allow for the outer can to be removed, allowing the inner can to be spun to draw in the cable. This would be similar to a garden hose reel. The result would be a tighter and more consistently packed cable around the inner can.

2.2. Cable twist and wire loading

The cable twist which caused the challenges in packing of the cable also allowed for the possibility of tension being applied directly to the wires. The cable construction technique which employs a central rope core with the wires helically wrapped around that core was chosen so that the core could take tensile loads. It was extremely important that in packing the cable, the direction of the helical wrapping of the wires about their rope core be considered. As discussed in "Passive Management of Deployable Cordage During and After MSL Touchdown" [1], if the wire helix about the rope core and the packing helix share the same direction, as the cable is extracted, high tensile loads will be placed on the wires rather than the central rope core. The cable packing helix direction must be in the direction such that when the cable deploys, the wires are put into compression.

2.2. Break-ties

As was previously mentioned, break-ties were required to restrain the last three coils of the umbilical cable. In an attempt to reduce the amount of debris which would rain down on the rover during the deployment, two viable systems of break-tie management were developed. although only one was implemented. The concepts centered on permanently attaching the ties to either the cable or the wall to which the cable was tied. The implemented solution, as seen in figure 2.3, was to tape the ends and knots of the ties to the umbilical deployment device such that when broken, the tie would remain on the device. The initial concept, as seen in figure 2.2, was to tie the break-tie to the cable so that when broken, it would remain on the cable as it deployed.

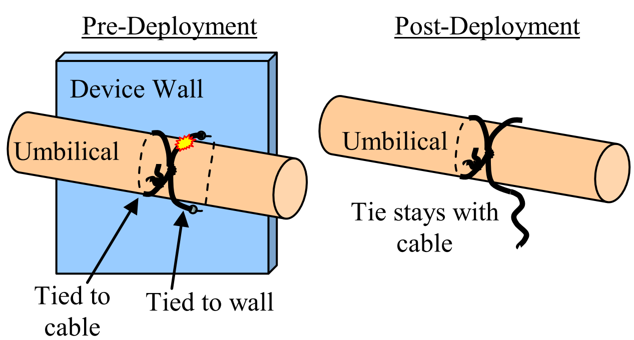


Figure 2.2: Break-tie concept. Tie stays with cable.

Testing proved that both of these solutions limited large pieces of break-tie from being released during the deployment. The taped solution was used for the final design because it facilitated knot tying. Due to the limited access to the interior of the can, tying the ties to the cable proved difficult, but may be useful in other designs.

2.3. Attached Lines

It was mentioned that the umbilical cable, when deployed, would have an attached retraction line deployed in parallel with the cable to keep tension on the cable during the touchdown event. The deployment of this attached line proved to be one of the most challenging portions of the design. The chief reason for this resided in the twist present in the helical cable.

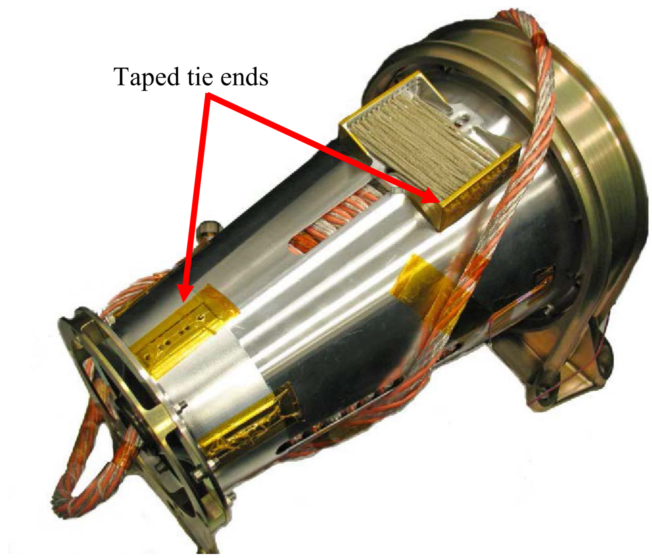


Figure 2.3: Implementation of break tie debris mitigation

The mechanism which provided tension to the retraction line resided within the inner can of the cable deployment device. This resulted in the retraction line deploying down the axis of the helical cable. Upon retraction, the cable would be pulled back up within the helix, causing the cable to tangle and invariably inhibit retraction. This is best understood as seen in figure 2.4 (red arrow). Initial test with the retraction line pulling from within the helix reduced the expected cable retraction capacity by ~25-50%.

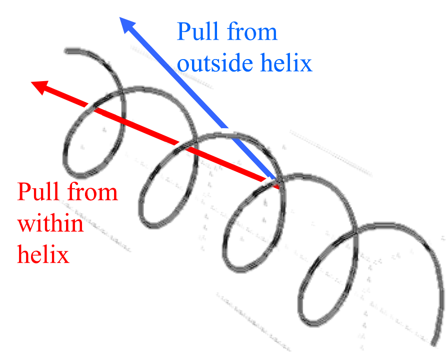


Figure 2.4: Difference in locations of retraction line relative to deployed cable

An alternate retraction method of a helical cable is to pull the cable from the exterior of the helix as shown in figure

2.4 (blue arrow). This allows the helical cable between the retraction point and the mechanism to fall to the side of the retraction line and allow for a full retraction.

To implement this retraction solution in a design in which the retraction mechanism was already placed within the helix proved challenging. The majority of the retraction line was stored on the outside of the outer can and then passed back into the can at the location where the line would have originally attached to the cable. This, along with the original configuration can be seen in figure 2.5.

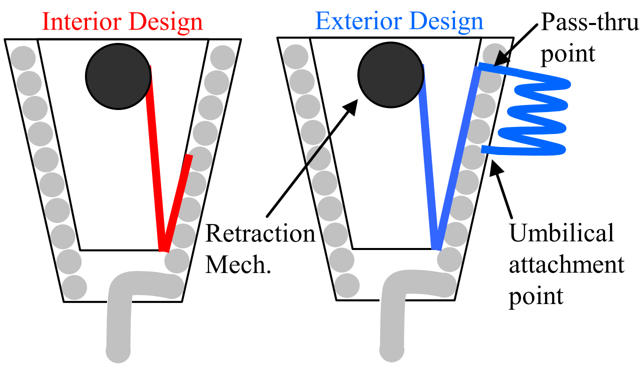


Figure 2.5: Retraction line routing within deployment device.

Figure 2.5 shows that in the new design, the majority of the retraction line must be stored on the outside of the deployment device. Solving one problem required an additional piece of hardware be attached to the device. This length of retraction line was eventually stored on a bracket which can be seen on the front of the device in figure 2.3. The cable was tied to the bracket using more break-ties which were taped to the bracket to prevent debris shedding.

It should be noted that in such a design, it is incredibly important to thoroughly understand the retraction line on the exterior of the device with respect to the umbilical cable length when deployed. The amount of umbilical between the attachment point and the pass thru point must be matched to the amount of retraction line on the exterior of the device.

3. Deployment Testing

Tests of the rover deployment system were conducted to characterize the performance of the system. These tests investigated the deployment times, speeds, bridle loads, and loads seen the umbilical cable as it was extracted. In these tests the umbilical deployment device was mounted to a descent stage simulator which was lifted into place. A mock rover was released from this descent stage simulator and lowered by the bridle deployment device. The umbilical cable was attached to the mock rover by way of a loadcell, and the cable extraction loads were recorded. The cable was extracted at ambient conditions and at -65°C to understand the effects of low temperature on deployment characteristics. The regions of focus in the deployment sequence are the deployment of first three coils of the cable, the deployment of the retraction line, and region between these two.

3.1. Deployment of First Three Coils

The first three coils of the cable were restrained by 18 individual light-duty break ties. The tension required to break these ties can be seen, along with the rest of the deployment sequence, in figure 3.1. In the ambient plot in figure 3.1, it can be seen that the load required to rupture the break-ties varied by nearly a factor of three. The average failure load was 102 N with a standard deviation of 42 N. In

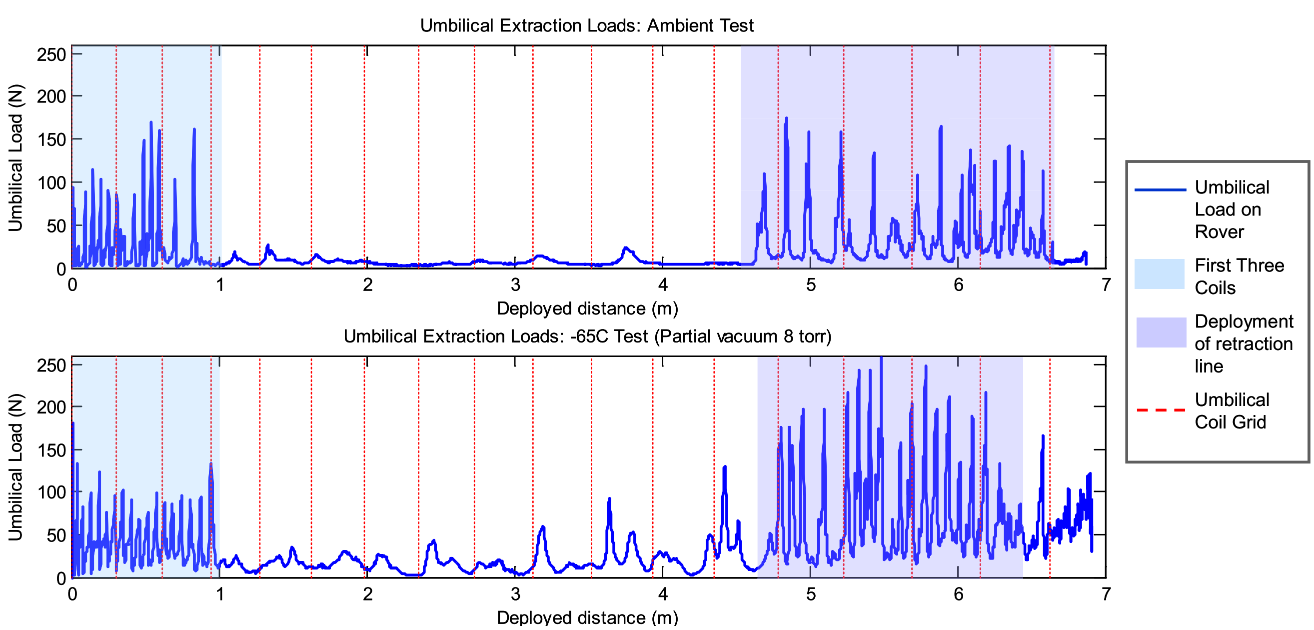


Figure 3.1: Umbilical loads as measured from drop item. Note peaks of individual break ties and peaks between break tie regions. Red dashed lines represent coils of umbilical deployed

contrast, the cold deployment test had a much more consistent failure load with an average of 96 N and a standard deviation of 19 N. The similarity in average failure loads suggests a break-tie which is relatively unaffected by temperature. It is believed that the major cause of load fluctuation in the ambient data is a result of variations in tangential load sharing between ties. This type of load sharing can be seen in figure 3.2.

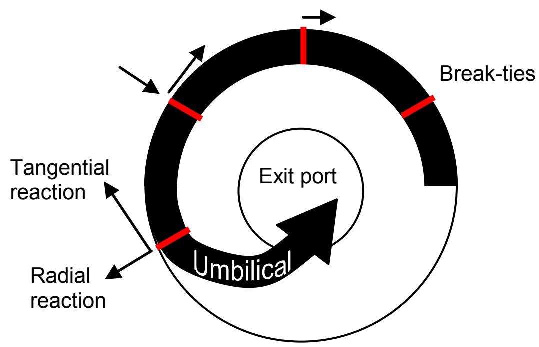


Figure 3.2: Break-tie load sharing. Top view of deploying cable

In this figure, it can be seen that as the cable is extracted, the most highly loaded break-tie does not take the full tension of in the umbilical. The load tangential to the coil can partially pass to ties down the line. The percent of load transfer decreases if the break-ties are extremely tight, but inconsistencies in the tying tension in these ties allowed for varying amounts of load transfer from knot to knot. This load sharing was observed in prototype testing where entire coils would slightly shift upon the loading of each break-tie. Furthermore, a stiff cable would allow for less load sharing which explains the more consistent result observed in the cold extraction data. The load sharing geometry also explains why the recorded failure loads of the break ties were approximately twice the expected breaking strength for the tie material used.

3.2. Mid-Range Deployment

The load recorded between the initial and final break-tie sets were those required to solely extract the umbilical. There was an observable difference between the two extraction cases in this range as a result of increased cable stiffness. Both cases showed small load peaks in this range, but those of the cold case were much more pronounced. These peaks were observed to be a result of the bending radius of the cable during the deployment. The peaks were seen in initial prototype (see figure 3.3) testing and were expected.

3.3. Deployment of Retraction Line

The load peaks present during the final stages of the umbilical deployment were a result of the break-ties used to manage the retraction line. Unlike the initial load spikes in the data set, the average values of these peaks correspond well to the break-tie's ultimate strength. Despite the relatively high magnitude of these peaks when compared to the deployment's average, the distance over which they occur was too small to have any effect on rover deployment time. Additionally, they were predicted to have only minor effects on the descent stage motion.

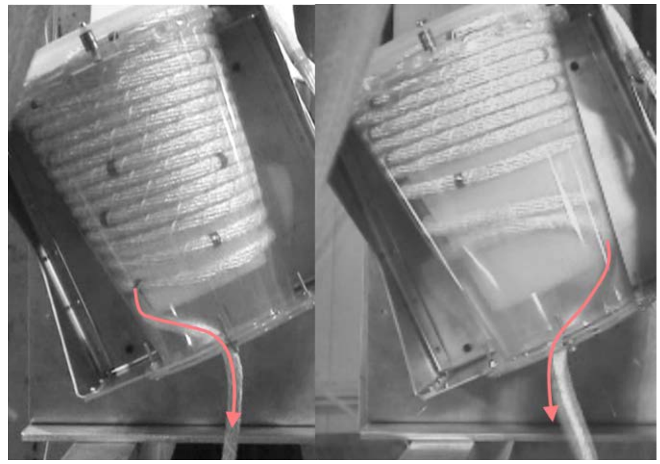


Figure 3.3: Deployment stills of increase bend angle as a result of mounting angle

When the ambient load spikes in this deployment region are compared with those of the cold deployment, it can be seen that the average peak load increased from 120 N to 190 N. With the knowledge that load sharing in this range was not possible and that temperature had little to no effect, the apparent increase in tie failure load can be attributed to the cable drag seen in the mid range data. The faint signature of the superposition of these fluctuations on top of the break-tie peaks can be seen in the ramping oscillation of the load peaks between the final few coil markings in the cold data (see figure 3.1).

4. Cable Separation Envelope Development

MSL's electrical umbilical will unwind and swing from the descent stage after separating from the rover deck during the descent stage acceleration away from the rover. As previously mentioned, upon the start of the descent stage acceleration away from the rover, the umbilical will be cut at the rover deck but will still be tethered to the deck with a light-duty break-tie. When the descent stage reaches the position away from the rover in which the umbilical cable is completely extended, this tether will be loaded to failure and the cable will begin to move up and away from the rover. It was imperative to understand the path of the cable away from the rover to determine what deck hardware was at risk of recontact by the umbilical cable.

4.1. Cable Separation Overview

Using both umbilical separation testing results and Monte Carlo results for descent stage motion during the fly-away event, an envelope was developed which encompassed all expected umbilical profiles away from the rover during this period. Due to the rate of descent stage acceleration combined with the gravity on Mars, Earth based separation testing was possible which provided flight like results. The descent stage vertical position data from simulation results was superimposed onto these testing results and an envelope was developed for the umbilical profile. When the rover tilt due to touchdown geometry was considered, this envelope was shown to interfere with the Ultra High Frequency (UHF) antenna. Although the envelope cleared this piece of hardware with a horizontal rover deck, certain deck angles presented the possibility for recontact. When the descent stage drift and the deck angle probability were considered, the probability of recontact with the UHF was bounded to be no greater than 1.2%

4.1. Pre-Flyaway/Initial Conditions

During the touchdown event, the descent stage may drift horizontally. This horizontal motion, along with rover set-down motion, causes the bridles and umbilical to develop an angle with respect to global vertical. While this angle depends greatly on the terrain on which the rover is placed, as well as the magnitude of the horizontal drift velocity, it should not exceed 15° off vertical at the moment of bridle cut assuming a maximum final deck angle of 36° off horizontal. Although umbilical angle is not exactly equal to that of the bridles, in all cases it will be less extreme. And although this angle will be reduced upon the descent stage fly away prior to umbilical/rover separation (because of the initial near vertical acceleration of the descent stage), this 15° angle was used as an initial angle during testing to add conservatism to the predictions of the swinging of the umbilical.

The descent stage acceleration away from the rover after the umbilical is cut was not finalized at the time of this testing but was to be no less than $5.79\ m/s^2$ [3]. This minimum acceleration along with the perceived acceleration provided by the Martian gravity created a local acceleration of anything on or attached to the descent stage of $9.5\ m/s^2$. With the perceived acceleration on earth of $9.81\ m/s^2$, testing of the umbilical/rover separation event could be done on earth using a static descent stage with relatively little error due to the gravity difference. Because the initial acceleration of the descent stage is nearly vertical, its z-positions could be superimposed onto the profile of a cable released while hanging from a static point in order to create a flight-like umbilical path away from the rover. In order to better assess the possibility of rover recontact by the umbilical, separation tests were conducted to characterize the umbilical motion.

4.2. Testing Setup

The separation event of the umbilical was recorded with high speed video cameras in two orthogonal directions. The video recorded with these two cameras was used, with post processing, to develop a time history of the cable in three dimensions. A 7.5 m length of umbilical was hung from a crane and the crane was positioned such that the cable was hung at 15° and 0° off vertical for two trials each. The cable was then tied to a bracket and the crane was then slowly raised until the cable released from the bracket. The configuration of the testing setup can be seen in figure 4.1.

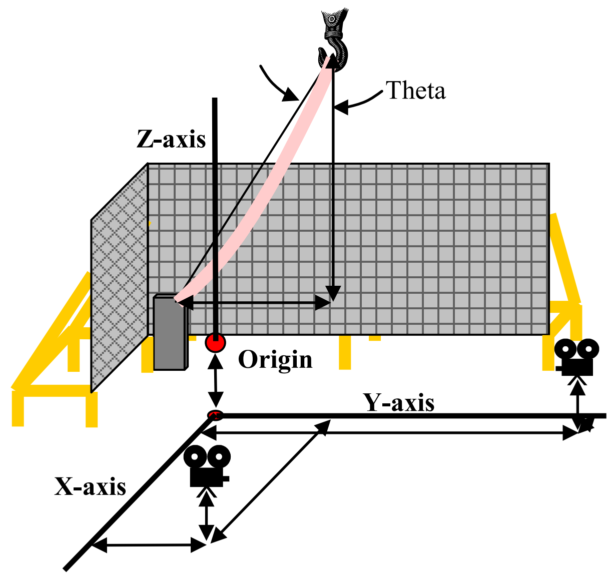


Figure 4.1: Umbilical separation testing setup

4.2. Testing Results

The results of this test showed a cable that, because of its torsion strain, would always jump away from the tie down point upon the break-tie failure and would take longer than 0.4 s to begin moving back down. A series of stills from the high speed camera can be seen in figure 4.2.

The images in figure 4.2 were taken from one of the trials in which the umbilical started at 15° off vertical and light-duty nylon thread as the break-tie material. Although qualitative, it should be noted that similar cable motion was observed in other trials where no break-tie was used (held by hand and then released), suggesting the motion is mostly independent of the tie used.

After these tests were run, the simultaneous and orthogonal video data stets were processed to develop a position history of the cable in 3D space through the first 0.35 s of travel.

4.3. Assumptions

A series of assumptions were made in the creation of the flight-like umbilical profiles. These assumptions are listed below.

4.3.1. Acceleration differences—The difference in perceived

[3] Assuming 4 engines at 70%.

acceleration between flight and earth gravity (0.31 m/s^2) would not contribute greatly to error in the path of the umbilical. It is important to note that the acceleration used is the absolute minimum and was calculated using the heaviest descent stage with the minimum thrust. The actual acceleration of the descent stage will likely be greater than 5.79 m/s^2 and could be up to 8.47 m/s^2.

4.3.2. Time to break-tie loading— The amount of time from the moment that the umbilical is cut to the time at which the break-tie breaks is 0.5s. This is the minimum amount of time for the descent stage to get from its closest approach to the rover to a distance of 7.5 m away. This is the distance at which the umbilical is fully deployed and the break-tie can be loaded to failure. This minimum time of 0.5s was used so that the smallest possible velocity was selected for the descent stage at the moment of the umbilical release. This added conservatism to the analysis. The time to full umbilical deployment could be up to 0.76s.

4.3.3. Neglecting horizontal motion—The horizontal motion of the descent stage over the period from umbilical release to the umbilical being clear of the rover is not large enough to grossly affect the calculated envelope and any errors from this motion can be taken into account in the factor of safety applied to the umbilical envelope. Figure 4.3 shows a plot of descent stage fly-away profiles taken from a Monte Carlo simulation. The plot shows only the profiles from 0.5s after umbilical cut to 0.9s. The lower bounds of this time range was selected for reasons described by assumption 4.3.2 while the upper bounds was selected because the umbilical, in all cases, would be clear of the rover after this point in time. In this figure, the relative horizontal motion as compared to the vertical motion can be seen to be minimal and that no abrupt horizontal motion is seen which might cause wave motion in the umbilical. The range of horizontal drift can be seen to be on the order of 0.5 m while the magnitude is never greater than ~0.35 m.

4.3.4. Neglecting Atmospheric Differences—The difference in ambient atmospheric conditions between the testing conditions (Earth ambient) and that of Mars would not cause the results to be any less conservative. The drag due to local atmosphere was not considered substantial enough to have any effect on the motion of the cable and was thus ignored.

With respect to temperature differences, the colder environment in flight will result in a stiffer cable. This increase in stiffness will cause the twisted cable to move away from the rover more quickly than what was seen in testing as it tries to return to its unstressed state. As such, the ambient conditions in which the test was conducted were considered to make the results more conservative.

4.4. Testing Results

Upon completion of the umbilical separation tests, the data was processed to obtain the 3D profiles. The Z position data of the descent stage fly-away profiles was then superimposed on to the test profiles. The umbilical profiles which were created through this method were then plotted in order to understand the trajectory of the umbilical. An example of one of these profiles can be seen in figure 4.4.

In the quest to define an envelope of which the umbilical would not violate, a small radius circle centered about the exit point of the umbilical was defined as the base of a truncated cone which would become the envelope. From this starting section, a cone with a ½ cone angle of 25° off vertical was defined. This cone encompassed the test data with all descent stage runs. A 1.5 uncertainty factor on the position of the cable tip was applied because of the assumptions made and the fact the analysis is based on only two test trials.

The tilt of the rover deck at touchdown was considered and incorporated into the recontact analysis. To facilitate the recontact assessment in the CAD model of the rover, rather

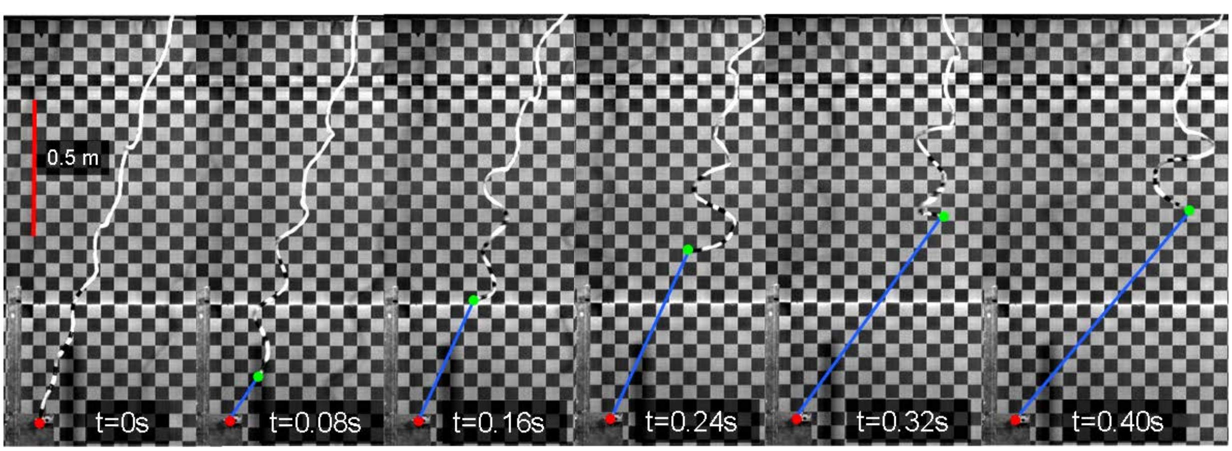


Figure 4.2: Video stills of typical umbilical separation

than hold the envelope constant and rotate the rover by its deck angle to understand what might recontact, the umbilical's envelope was rotated by the deck angle while the rover remained fixed. A rover deck angle probability table was created and these angles were added to the level-ground umbilical envelope.

The deck angle probabilities shown in table 4.1 were calculated through a Monte Carlo analysis by placing the rover on a 15° slope at a uniformly distributed azimuth with respect to the slope (slope was fixed at 15° and was always present). The Golombek-Rapp rock distribution model [2] was used to determine the occurrence of rocks and their sizes under each wheel. This model was anchored in the flight system requirement of 0.25% occurrence of a 0.55m rock within any sampled $2m^2$ area. Once the existence and size of rocks under the wheels was determined, the mobility was articulated to conform to the rocks. The deck angle was then measured relative to horizontal. The amount to which the deck angles shown in the table increased the umbilical envelope can be seen in the figure 4.5.

The envelopes shown in figure 4.5 were inserted into the CAD model of the rover to investigate the potential for recontact. It was found that the only piece of hardware which was at a statistical risk of recontact was the UHF antenna. It should be noted that the low gain antenna was also identified as violating the envelope, but its interference with the envelopes did not begin until considering the 99.99^{th} percentile case. The interference of the UHF with the umbilical envelope began when considering the 80^{th} percentile case for rover deck angle.

Deck angle (°)	Deck Percentile
13.5	10
14.8	20
15	30
15	40
15	50
15	60
15	70
15.6	80
16.9	90
18.3	95
22.2	99
23.8	99.5
25.6	99.7
28.81	99.87
33.4	99.99

Table 4.1: Deck angle probability

It is important to consider that hardware interference with the envelope meant that there was a *potential* for recontact. In addition to the rover landing at the specified deck angle, the descent stage must also drift in the direction of that hardware during the touchdown event for the recontact to

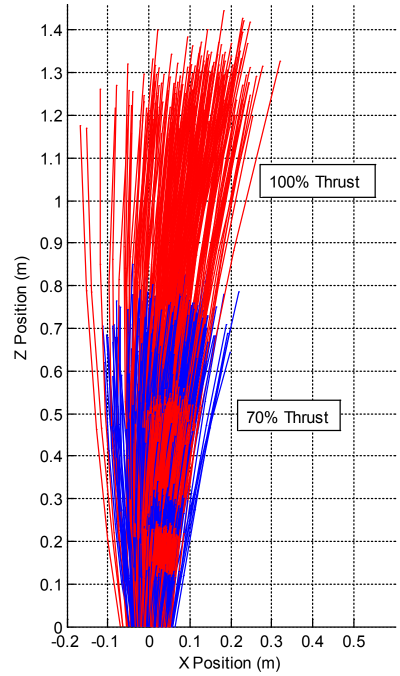


Figure 4.3: D/S profiles from 0.5 to 0.9s after umbilical cut event

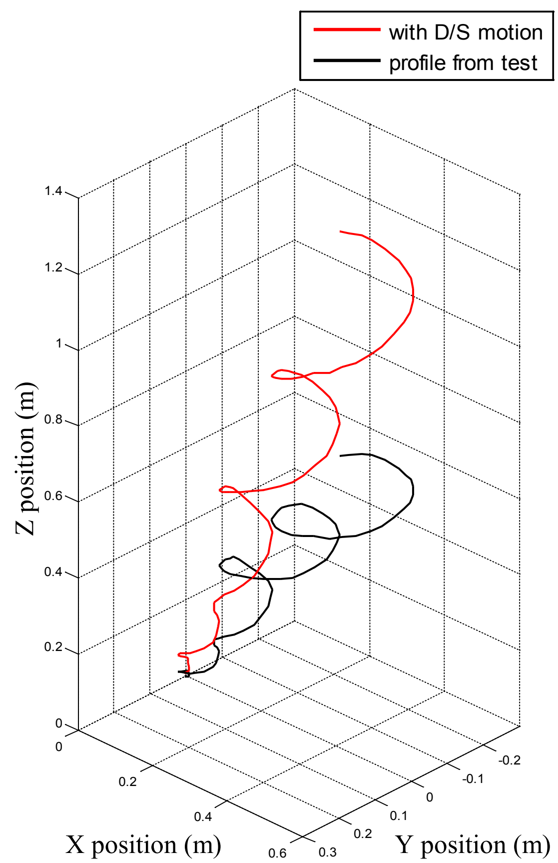


Figure 4.4: Typical profile of umbilical cable motion for pre and post descent stage motion superimposition

occur. With the assumption that there is an equal probability of the drifting in any direction, the probability for recontact is equal to the percent of a full circle that the hardware represents when looking down on the rover deck from above. This is best understood in the example envelope shown in figure 4.6.

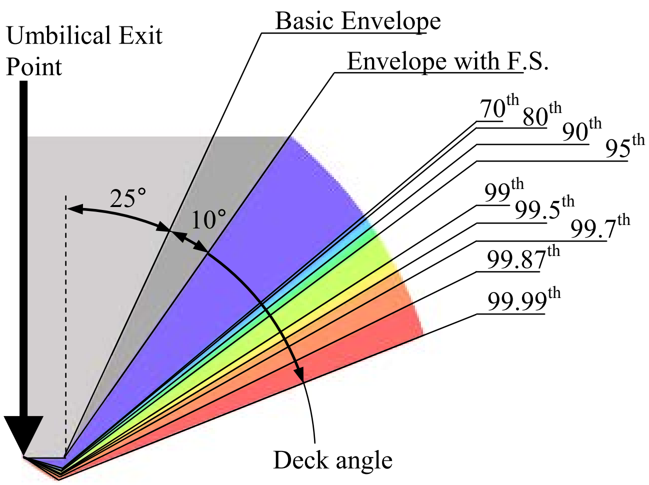


Figure 4.5: Umbilical separation envelope with rover deck angles included (to scale)

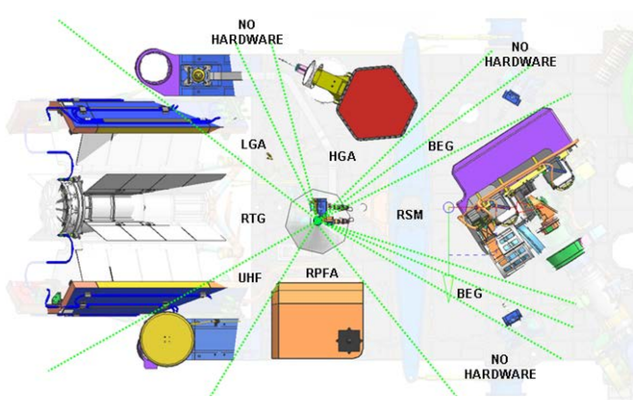


Figure 4.6: Overhead view of rover deck.

In the overhead view of the rover deck shown in figure 4.6, hardware within the example envelope is shown in full color, while that not at risk of recontact is shown in phantom. It can be seen that for this particular separation envelope (an example only), the UHF represents ~30° (the "interference angle") of the 360° of potential motion of the descent stage (the "drift circle").

The amount of interference of the UHF with the umbilical envelopes for various deck angles can be seen in the figure 4.7. It can be seen that the amount of interference changes for difference deck angles. As a result, the percent chance for recontact (taken from the interference angle) was calculated for each deck angle percentile, and the maximum taken as the real chance for recontact. It should be noted that the interference angle was increased by 30° in all cases to account for the unwinding nature of the cable (it does not swing in a perfectly straight line path because it untwists as it swings away).

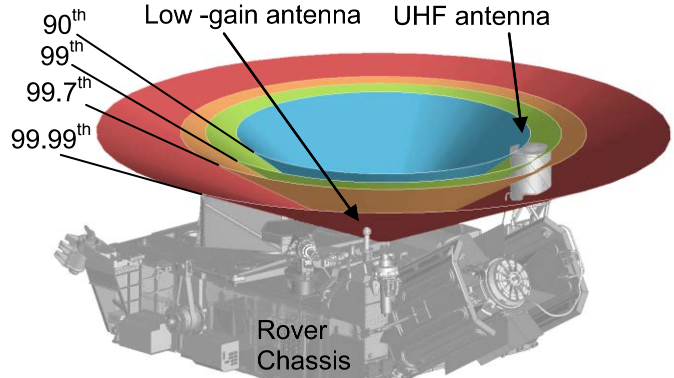


Figure 4.7: Umbilical envelope interference with UHF antenna

The interference angle of the UHF for different deck angle percentiles can be seen in the table 4.2. Also in this table is what percent of the of the drift circle the interference angle represents. The maximum recontact probability was 1.2%.

Deck angle (°)	Deck Percentile	UHF Interference angle (°)	Drift Percent (%)	Recontact probability (%)
15	70	0	0	0
15.6	80	0	0	0
16.9	90	42	12	**1.2**
18.3	95	45	13	0.6
22.2	99	46	13	0.1
23.8	99.5	46	13	0.1
25.6	99.7	46	13	<0.1
28.81	99.87	46	13	<0.1
33.4	99.99	46	13	<0.1

Table 4.2: Recontact Probability for various deck angles

5. CONCLUSIONS

The helical cable packing and deployment design selected for Mars Science Laboratory's umbilical proved to be challenging to implement despites its benefits. The packaging and deployment technique can store a long length of cable in a relatively small volume while maintaining compliance with the minimum bend radius requirement for the cable being deployed. And while the packing technique could be implemented without the used of break-ties, they were needed in this design due to the vibratory environment and the retraction required for the cable. The cable was time consuming to pack not only because of the nuances of maintaining consistency in the twisting of the cable, but also due to the final number of break-ties required.

The break-ties used created a series of load spikes in the deployment signature. The load spikes during the deployment of the initial three coils of umbilical saw almost no average increase between the different temperature trials. The cold deployment of the umbilical showed increased load required for cable extraction in the region where no break ties were used. This increase in cable drag was superimposed on the loads required to rupture the last set of break-ties and as such, these loads saw significant increase when compared to their ambient counterparts.

Although these umbilical extraction loads contained momentary spikes of relative high magnitude, these spikes were short enough in duration to not affect the deployment sequence. Neither the deployment time of the rover, nor the motion of the descent stage were predicted to be adversely affected by these umbilical deployment loads.

In addition to deployment tests, a series of umbilical separations tests were conducted in order to determine the possibility of cable recontact with the rover after being cut. In these separation tests and subsequent data processing, it was determined that there was a statistically significant chance for reconctact. The umbilical was found to have no greater than a 1.2% chance for recontact with the Ultra-High Frequency antenna. The assumptions made in the development of this probability were considered to be conservative. A large factor of safety was included in the test data and specific variables, including descent stage acceleration, time to umbilical release, and initial umbilical angle were set to their most conservative values. The actual probability of recontact, if the probabilities these variables were incorporated, would be lower than the reported 1.2%, which was meant to be a bounding number.

Despite the challenges resulting from the helical nature of this cable deployment system, the device successfully deployed the cable in all deployment tests to date. Despite the difficulty of packing the system and designing the slack management system, the helical cable deployment concept worked extremely well considering the requirements for this mission. And although the separation of the twisted cable from the rover did not lend itself to analytical predictions, testing showed that the torsional strain aided in the motion away from the rover. For future iterations of this system, designs improvements or requirements adjustments which reduce the number of break-ties required and improve the ease of packing should be considered first to decrease the time required to reset the system.

6. Acknowledgements

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