

Video Analysis for Surveillance of Spacecraft Parachute Systems

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The Commercial Crew Program (CCP) has established a surveillance methodology to ensure the reliability of spacecraft parachute systems. The implemented methodology relies on an interconnected framework consisting of imagery analysis, hardware inspections, and vehicle data analysis. Imagery analysis serves as a foundation for these core activities which provide a robust approach to the surveillance of spacecraft parachute systems. As the surveillance framework has been developed, the role of imagery has become more prominent, and therefore imagery requirements have changed. To complete photogrammetric analysis, careful consideration must be made to the role of imagery, required data, imagery requirements, the analysis process, and mission planning. The role of imagery will drive the required data, which will in turn drive imagery requirements. Imagery requirements are likely to drive mission planning through consideration to camera selection and placement. If onboard imagery is required, the camera and data system must be implemented prior to launch. If external imagery is required, the photography package must be implemented such that it can be positioned for a return and free of potential debris fields. For these reasons, an integrated approach must be used to build an imagery package around the required analysis with careful coordination with mission planners.

I. Nomenclature

CCP	=	Commercial Crew Program
CDT	=	Cluster Development Test (series)
CPAS	=	Capsule Parachute Assembly System
CQT	=	Cluster Qualification Test (series)
CRS	=	Cargo Resupply Service
DPG	=	Dugway Proving Ground
EDL	=	Entry, Descent, and Landing
EM-1	=	Exploration Mission-1 (later Artemis-1)
IFA	=	In Flight Anomaly
ISS	=	International Space Station

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IV&V	=	Independent Verification and Validation
JSC	=	Johnson Space Center
KSC	=	Kennedy Space Center
NASA	=	National Aeronautics and Space Administration
PAA	=	Product Assurance Action
PIG	=	Parachute Integration Group
SCIFLI	=	Scientifically Calibrated In-Flight Imagery
SRC	=	Sample Return Capsule
TRaTS	=	Telescience Research and Technology Support

II. Introduction

Parachutes are complex and flexible aerodynamic structures that must deploy and perform in a chaotic and turbulent wake environment. The complexity of parachute deployment and inflation has made them notoriously difficult to predict. Parachute systems are also a critical flight system for crewed spacecraft with NASA's Orion, SpaceX's Dragon2, and Boeing's Starliner all relying on parachutes to stabilize and slow the capsules for a safe landing. In recent years, due to the criticality of the parachute systems, the CCP has established a methodology for modern parachute surveillance.¹ The framework of CCP's parachute surveillance, shown in Figure 1, can be described as a reliability triangle consisting of hardware inspections and Product Assurance Actions (PAAs), trajectory analysis, and imagery analysis. The role of hardware inspections and PAAs are discussed by Morris in reference 1. Trajectory analysis allows for the monitoring of parachute performance such as terminal rate of descent² and peak loading.³ Video and photogrammetric analysis has grown to become a foundational third tenet of the CCP parachute surveillance triangle; a part equal in criticality with hardware inspections and trajectory analysis to provide understanding of system performance and behavior.

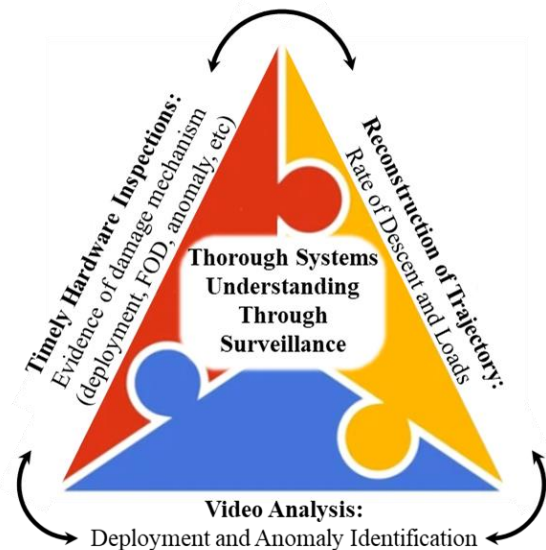


Figure 1. CCP framework for parachute system reliability and surveillance.

III. Engineering Need for Data

A. Reliability Triangle Overview

One important consideration in video analysis is the need for a comprehensive understanding of the flight trajectory. Figure 2 illustrates that the thorough understanding of a parachute system is dependent on vehicle data, imagery, and hardware inspections. Each side of the triangle is important but has differing areas of focus or specialty. For example, simulations and flight data are best suited to understanding inflation loads and rate of descent. Deployment happens in a chaotic, turbulent environment, and is not modeled in current state of the art simulations. Therefore, the deployment must be understood empirically, where video is the primary instrumentation source for analysis. The hardware inspections complement this understanding by providing material evidence and understanding of damage.

In the parachute post-flight surveillance framework, shown in Figure 2, each side of the triangle has a corresponding series of bubbles leading into the center of the figure. The words in each of these bubbles further augments the unique nature of each function. For example, the hardware bubbles illustrate the fact that the inspections are uniquely suited to understanding material residue, evidence of friction or abrasion, and damage locations and sizes. The video analysis bubbles illustrate that video is better suited to gaining a coarse understanding of the flight by identifying anomalies, identifying Foreign Object Debris (FOD), constructing deployment timelines, and analyzing the dynamics of the chaotic deployment.

The bubbles further illustrate that there is a natural progression to the development of the parachute engineer's understanding. Initial subjective observations are formed immediately after flight, and this subjective understanding evolves as analysis continues to a more objective understanding as quantifiable values are assigned to the hardware

and video products. Ultimately, this quantifiable information is used to form a hypothesis about the nature of the parachute inflation or any observed anomalies.

The dependent nature of each side of the triangle is best seen after a hypothesis is formed. A hypothesis formed from a video observation would be tested or checked against the available trajectory data and hardware evidence until a conclusion is made. In this way, the available evidence can support a conclusion stronger than the sum of individual observations.

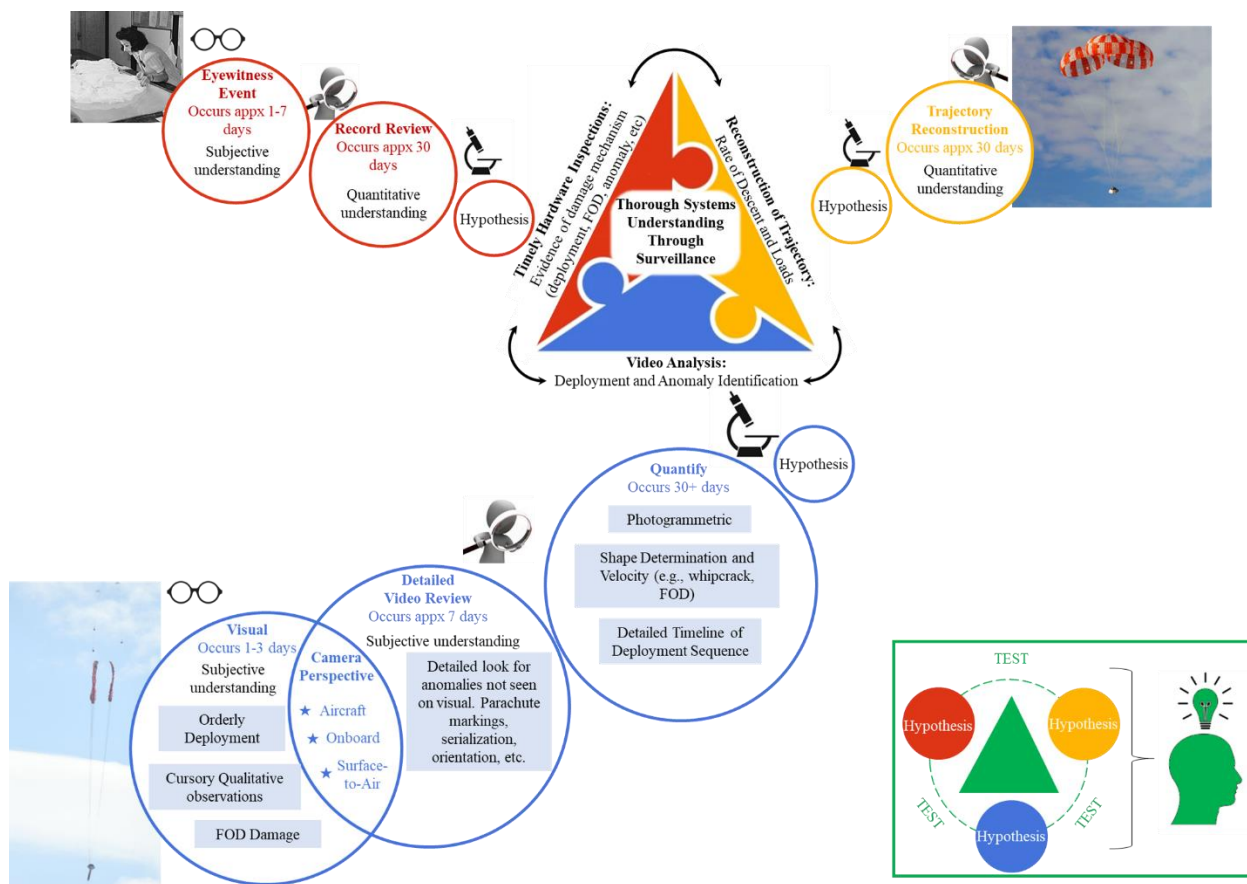


Figure 2. CCP model for post-flight surveillance of crewed spacecraft parachute systems.

B. Role of Imagery in Risk Mitigation

To ensure the safety of crewed spacecraft parachute systems, the CCP created the Parachute Integration Group (PIG) from personnel across multiple NASA centers to complete critical Independent Verification and Validation (IV&V). The PIG is tasked with certifying and surveilling crewed spacecraft parachute systems. To accomplish this, the PIG leverages subject matter experts in all aspects of parachute systems to mitigate risks on hardware prior to flight and to verify performance and/or identify risks following a flight. This process represents a closed cycle that was shown in the previous figure.

When assessing system performance for a given mission, it is important to consider what data can be provided from each component of the reliability model. Hardware inspections provide data on the condition of hardware following a mission. Vehicle and loads data directly inform performance metrics such as flight constraints or model accuracies. Imagery provides a data source that can be considered a combination of the two.

Imagery provides a direct data source on the hardware behavior. While the detail is less than that of hardware inspections, imagery provides temporal data for the hardware. Unlike PAA's and inspections which happen before and after a mission, imagery provides a direct data set on the hardware during system operation. This is important as inspections can only identify if anomalous hardware damage occurred; they cannot identify when it occurred. Imagery

has a unique ability to identify anomalous hardware behavior during a mission. Imagery can therefore be leveraged to monitor system behavior at level which would not be possible with inspections alone.

Imagery also contributes to the understanding of system performance. While imagery cannot provide the loads measurements or vehicle dynamics like vehicle data, imagery is able to contribute information on the process of inflation and canopy or cluster behavior. In the absence of riser level load measurements, imagery of canopy geometry can provide a source of canopy level inflation data.

While these contributions from imagery greatly impact the understanding of system reliability, the most important area of contribution may be by informing on the unexpected. For crewed spacecraft recovery systems, engineers are tasked with monitoring known risks while identifying new risks. Obvious risks are generally discovered during highly instrumented test and certification campaigns while lower-likelihood risks may not be identified until mission operations. The CCP PIG has found imagery to be of paramount importance for the identification and monitoring of these new and more elusive risks.

Traditionally, vehicle data from missions will be of lesser quality than that of a test campaign, due to the difficulty of instrumenting a functional spacecraft versus a test vehicle. With the reduction of quality in vehicle and loads data from a flight vehicle, models and simulations become locked when a system enters service for crewed operations. For flight surveillance, vehicle data therefore is largely a reactive data source. It informs if a system performed within operational constraints and within expected performance parameters. Vehicle data will struggle to identify anomalous behavior if a constraint or a check against a model does not exist for the anomaly in question. If only vehicle data and hardware inspections are available, a gap in surveillance exists for when and how previously unobserved anomalous behavior occurred.

Imagery can help close this gap in the understanding of a system's performance as it can be monitored for both hardware and performance concerns either with or without past behavior in mind. To an extent, imagery represents a comprehensive dataset of the entire system; it captures components of every side of system functionality. In doing so, it is in a unique position to identify unknown risks.

For these reasons, imagery has been found to be a critical data source for mitigating risk associated with parachute systems to ensure system reliability. As such, CCP has expended substantial resources, both in engineering hours and monetarily, to optimize imaging for system risk mitigation.

C. CPAS False Confluence Investigation

An example involving all three sides of the reliability triangle comes from the Orion parachute system. The Capsule Parachute Assembly System (CPAS) Cluster Qualification Test (CQT) drop test program was documented by Evans in Ref. 4. The intent was to certify the system by testing the final design. However, imagery analysis identified a false confluence of suspension lines on one of the main parachutes during the fifth (CQT-4-5) of eight planned tests. A close examination of imagery from earlier tests showed false confluence events had occurred previously, as shown in Figure 3. The earlier events went unnoticed because they were of lower severity and duration than that experienced on CQT-4-5.

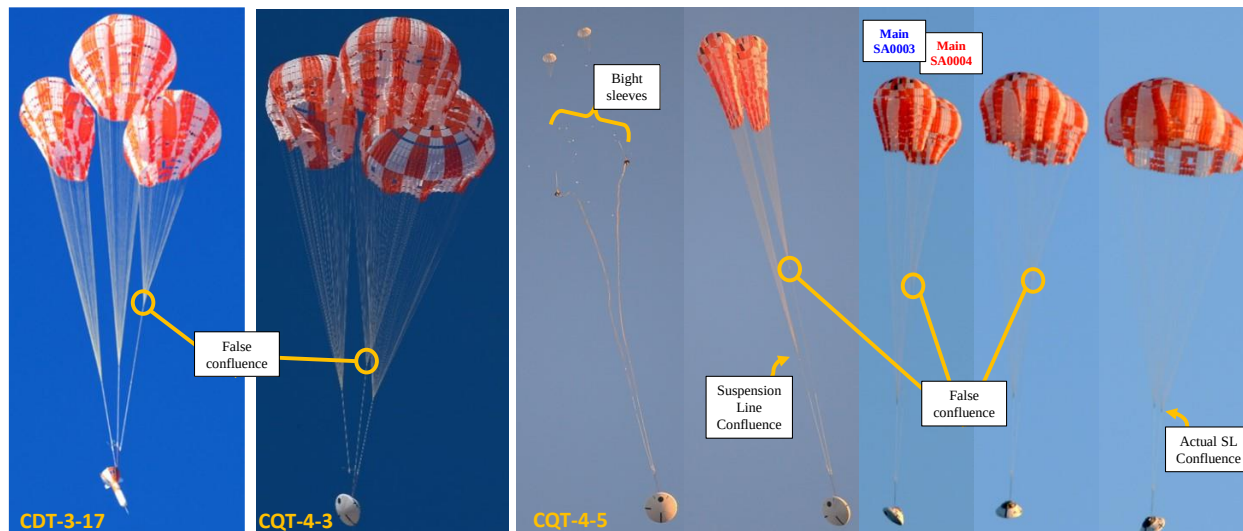


Figure 3. False confluence events on CPAS Orion tests.

In all cases, the false confluence eventually “broke” to release the suspension lines to their typical convergence angles. Should the confluence occur high enough on the suspension lines, the restriction to the inlet size might reduce the parachute drag or even prevent the parachute from inflating. This effect is less prominent in early reefed stages. On CQT-4-5, Main SA0004 was the dominant canopy from early on, despite having a false confluence. The riser loads data in Figure 4 showed a sudden loss of drag by about 40% on SA0004 during the disreef to full open. This signature was confirmed in the cluster load derived from the IMU accelerometer, which matches the sum of the riser measurements. Synchronizing the data to surface-to-air video showed that the load readings were a response to the false confluence breaking, the suspension lines briefly going slack and oscillating, then quickly becoming taut and re-loading. The whole sequence occurred in about 200 milliseconds.

The investigation quickly focused on the bight sleeves: rectangular pieces of Spectra cloth which were loosely wrapped around the suspension lines to prevent interactions with other hardware during deployment. The bight sleeves are not fastened to the suspension lines in any way, so they were expected to quickly be liberated upon parachute deployment. The high-resolution imagery on CQT-4-5 allowed for observing the majority of the bight sleeves in the air, though some remained affixed to the suspension lines, even “riding up” from their original stowed positions. This had the potential to “strangle” a parachute.

As explained in Ref. 5, the bight sleeves were originally designed to prevent suspension line damages of the type seen on CDT-3-5 and were introduced starting with CDT-3-9. A typical bight sleeve installation is shown in Figure 5. In the original configuration, each bight sleeve overlapped itself by about 2 inches. The suspension line design was changed to a tighter weave in order to increase strength and reduce system mass. This reduced the cross section of the lines and reduced the bundle diameter such that the same size bight sleeves now overlapped by about 4 inches. Despite the low-friction nature of Spectra, this increased overlap allowed for bight sleeves to “bind” around the suspension lines, perhaps exacerbated by bending the sleeves and the high-pressure packing process. This change was introduced on CDT-3-17, which had a minor false confluence as previously shown.

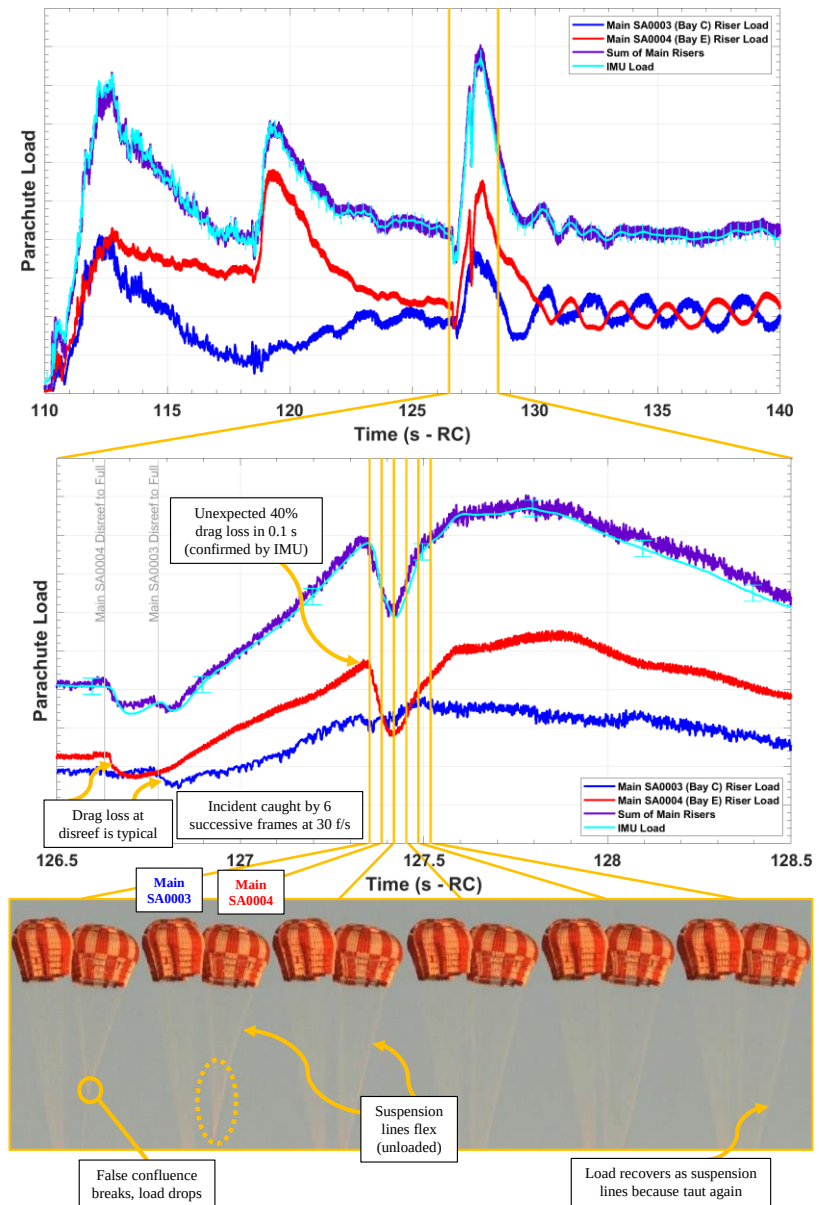


Figure 4. Riser load response for false confluence breaking on CQT-4-5 correlated with visual evidence.



Figure 5. CPAS bight sleeve wrapped around suspension lines with overlap (left) and stowed (right).

The CPAS program quickly decided in March of 2018 to remove the bight sleeves from the design altogether as they were doing more harm than good. This involved changing no less than fifteen drawings and four procedures. However, parachutes had already been packed for CQT-4-6 and Exploration Mission (EM)-1. One of the mains on CQT-4-6 did exhibit some brief binding events.

The final design was only tested on the final two qualification tests for a total of five individual deployments. All three main parachutes on CQT-4-7 used the new design without bight sleeves. Nevertheless, imagery analysis determined one parachute experienced a brief false confluence which was investigated and attributed to self-twist within the canopy's suspension lines that was introduced during packing. One of the three main parachutes on CQT-4-8 had been packed earlier with bight sleeves for environmental testing. None of the parachutes on CQT-4-8 exhibited any binding events. There was no further investigation with the end of the drop test program.

The relatively low risk to the parachute system was accepted for the unmanned EM-1, which was later designated Artemis-1⁶, launching four and a half years after the parachutes were packed with the old design. The still images from a chase helicopter on Artemis-1 are of high enough resolution to see at least two bight sleeves, resulting in minor and temporary false confluences, disappearing somewhere during the first inflation stage. The air crew and photographers had developed their skills over course of the CPAS and CCP test programs.

This example shows that even though extensive testing, hardware inspections, and data are vital, the false confluence was only identified, evaluated, and eliminated through imagery.

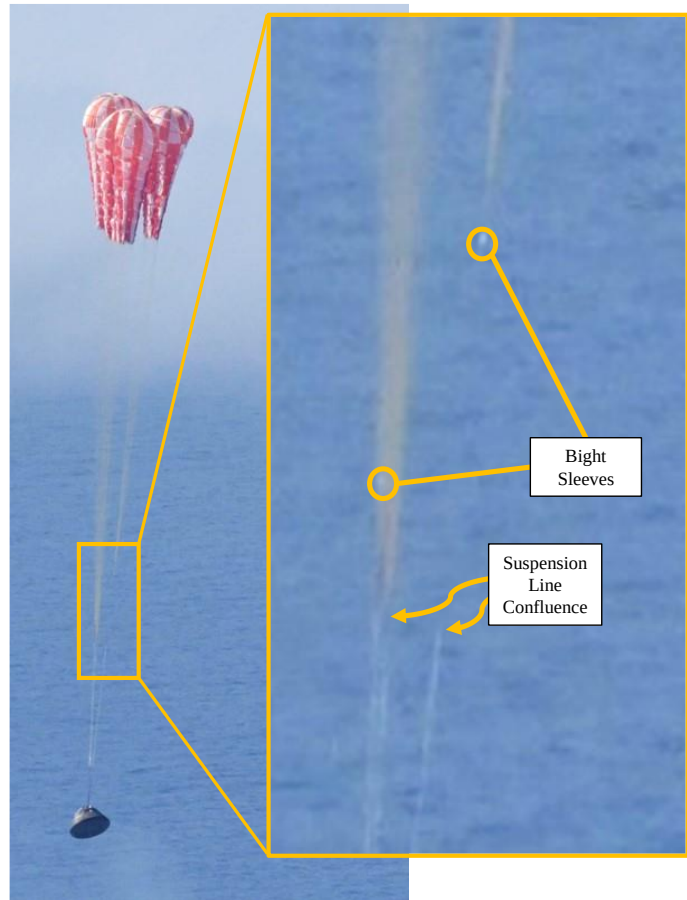


Figure 6. Artemis-1 (formerly EM-1) exhibits a false confluence without a fix determined several years earlier (NASA/James Blair).

IV. Imagery Requirements

The processes of using imagery in flight surveillance is difficult to define and dependent on the duration of the surveillance plan. In general, imagery requirements are dependent on an engineering cycle. In this cycle, engineering need drives the engineering use of imagery, and the engineering use of imagery drives imagery requirements. As the understanding of a system increases, the engineering need will evolve. For a short-term surveillance plan, or a singular mission, a single engineering cycle may be sufficient. For long term surveillance, however, the PIG has found a single cycle is insufficient. In many cases, when it comes to parachute imagery analysis, when one question is answered, another is asked leading to continuous cycle for long term imagery surveillance. As such the starting point for

preparing an imagery surveillance plan can be difficult to define. The PIG has found the best practice is to begin with defining the required type of imagery.

A. Imagery Types

When defining imagery requirements, the first determination that must be made is the required type of imagery. For this paper three general types will be considered: 1) Onboard, 2) Aerial, and 3) Surface Based. Within each category one will find many options such as wavelength (visual or infrared), resolution, framerate, lens size, etc. While the fine options can optimize a specific camera, to capture surveillance objects, the camera must be in the correct position to gather imagery.

Onboard imagery has the major benefit of being close to the parachute system with low perspective skewing. By nature of being on the vehicle, onboard imagery will be far closer to the system than either an aerial asset or surface-based asset. The proximity of the camera allows for high resolution images of an inflating canopy. While onboard imagery has high upsides, it also has high downsides. Due to the nature of being on board the spacecraft, both the camera and storage system must fly the entire mission. By carrying the camera, a mission incurs extra transportation cost from the additional mass. A program also incurs development cost as the camera must be designed, qualified, and installed in the spacecraft. These extra costs will tend to reduce the quality of the onboard camera from the theoretical maximum.

Aerial assets have the major benefit of having the ability to gather side views of a deploying and inflating parachute. These views are useful towards investigating orderly deployment, line sail, inflation times, and debris. By being at altitude, aerial assets can also be above weather that can hinder surface assets. The downsides of aerial assets are that capable platforms and camera packages are limited. The asset must also be flown to the landing location. These restrictions raise the cost of the asset. Additionally, the resolution is limited by the standoff distance of the platform. Careful planning must be carried out to protect an airborne platform from potential debris fields during reentry and parachute system operation. Both the CCP and Artemis program rely heavily on both the Scientifically Calibrated In-Flight Imagery (SCIFLI) team which leverages the NASA WB-57 aircraft and the Kennedy Space Center's (KSC) Telescience Research and Technology Support (TRaTS) team which leverages helicopters to safely obtain aerial coverage of returning spacecraft.⁷

Surface based assets have the advantage of not being size or platform limited. In general, the only camera requirement is that a mount exists and can be deployed to the location of interest. For water landings such as with Artemis and Dragon2 returns, this means placing the mount on a recovery vessel. For a ground landing, such as with CST-100, camera placement is dependent on vehicle accessibility to the landing zone. In both landing methodologies, imaging systems can be positioned to allow the collection of high-quality imagery. The downside is a surface-based asset can experience substantial perspective skewing. Like an aerial asset, consideration must also be made to protect the surface asset from debris fields. Unlike an aerial asset, a surface asset can leverage a planned recovery vehicle. In the event of a water landing, cameras can be placed on the recovery vessels already in the vicinity of the return. Both the CCP and Artemis program rely heavily on the TRaTS team who specialize in placing and operating high quality imaging platforms in difficult locations to obtain surfaced based imagery.

The available assets will be highly dependent on the mission profile. On interplanetary missions for example, onboard cameras will likely provide the only potential imaging source. For returns to Earth however, all three types will likely be available. For Earth returns, an imagery package containing elements from all three types has proven to be highly successful for the PIG. An example of this concept is the assets deployed for the Artemis-1 mission that is described in Figure 7.

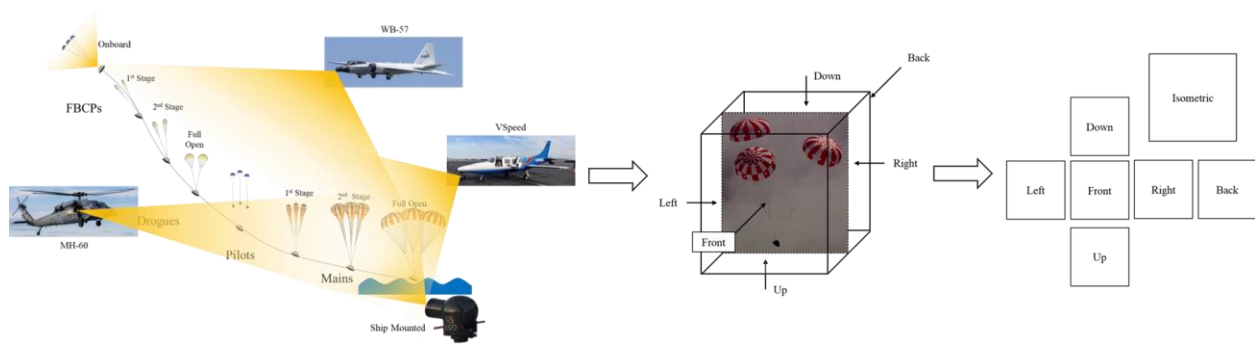


Figure 7. Concept of operations for Artemis-1 imagery collection.

B. Image Quality

The Artemis-1 mission provides an excellent example of a successfully implemented imagery plan, as developed by Lockheed Martin and NASA. Because Artemis-1 was a precursor to human flight, there were many aspects of the mission requiring visual documentation. The needs for Entry, Descent, and Landing (EDL) were balanced with other phases via a large matrix of system requirements. Each area of interest was associated with a lead program, a list of driving subsystem requirements, customers, additional stakeholders, an analysis justification, and assumptions. The parachute requirements were further broken down by event specifying the start and stop conditions, parachute feature location, required spatial resolution at the location, and rationale. The required object size at a particular distance from the camera was used to compute the necessary specifications for each camera.

Selection of cameras systems must take into account several factors as enumerated in Ref. 8: fixed field of view vs. tracking, resolution, fixed focus vs. zoom lens, lighting, and integration time. The next consideration is data retrieval, storage, and dissemination. For cameras onboard the spacecraft, desired image resolution and estimated event speeds were used to determine maximum frame rates for each event phase based on the total onboard data storage quota.

The imagery plan was evaluated by customers using pre-visualization. Some predicted views are shown to compare favorably with the actual recorded images in Figure 8. Analysis of the overall imagery performance was used to develop a list of imagery improvements to be incorporated on Artemis-2.

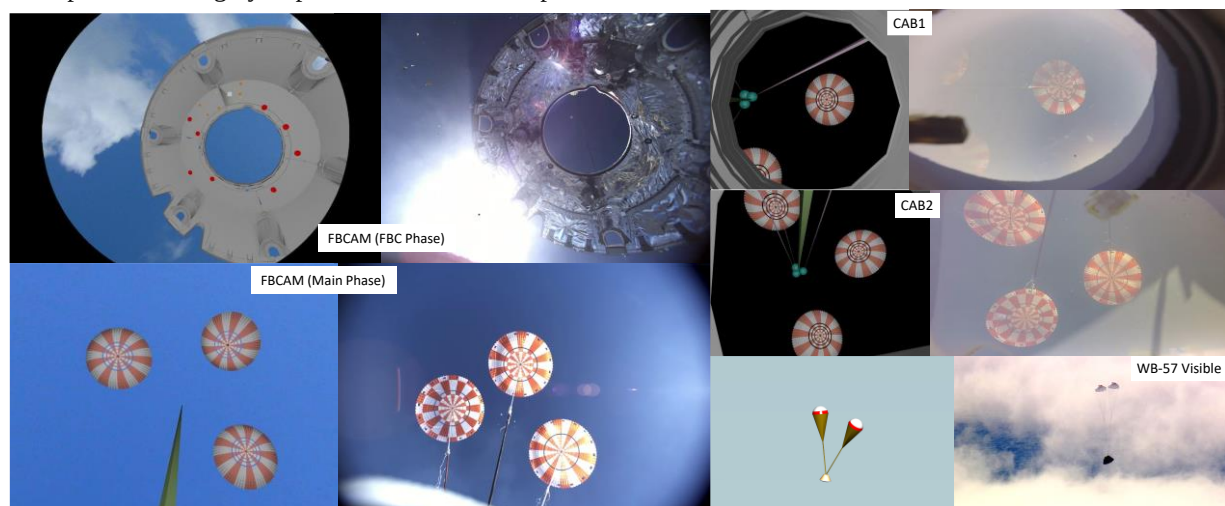


Figure 8. Selected Artemis-1 pre-visualization compared with as-flown imagery.

C. Number Of Cameras

Three of the key features when building an imagery package are: 1) overlap in coverage, 2) redundancy in coverage, and 3) unique viewing angles. A review of the Artemis-1 image quality and summary provides insight into how these three components were essential to the successful imaging of the Artemis-1 parachute system.

When reviewing Figure 7, it can be seen that the different assets were operating at different altitudes for their respective observations. As the capsule descended under the parachutes, this careful stationing of the imagery

platforms allowed for a smooth transition from one asset to the next. The overlap in coverage was crucial to the collection of a dataset without gaps in coverage.

Redundancy of camera platforms also played a critical role in gathering imagery for Artemis-1. Image quality for any given camera will be dependent on camera functionality, atmospheric conditions, and the operator's ability to track and focus on the parachute system. Imaging a vehicle's return can be a rather difficult, and frustrating task. When operating external cameras, the operators are in a race to acquire, zoom, and focus on a rapidly descending object. In the case of arial cameras, the camera is also moving rapidly relative to the vehicle. The result of the operational difficulties is no single camera should be relied upon or expected to perform perfectly. As such, for a guarantee in coverage, camera redundancy must be accounted for when planning a mission. The image quality summary for Artemis-1 is shown in Table 1 and provides a real-world argument for camera redundancy. On Artemis-1, at any given point, there were at least three imagery sources available with at least two having high-quality coverage. When reviewing the table, it is clear the best imagery sources varied substantially during the parachute deployment and descent sequences.

Table 1. Artemis-1 Image Quality Summary

		FBCP/FBC Phase	Drogue Phase	Pilot Phase	Main Phase	Steady State & Landing
WB-57 Dynamite	Visible	Grainy; Inflated FBCPs out of frame	Good	Washed out by ocean reflection	Good; some 1 st stage out of frame	Good until obscured by cloud layer
	MWIR	Good, FBCPs in frame	Grainy, High Contrast	Soft focus	Soft focus	Soft focus
Helo A	GSS	Not acquired	Not acquired until just before release	Excellent	Excellent	Excellent
VSPEED	Visible	Not acquired	Not acquired	Not acquired	Not acquired	Excellent
Ship	GSS DeckCam	Not acquired	Not acquired	Not acquired	Not acquired	Excellent below cloud layer
Orion Onboard	CAB1 Window	Glare, FBCPs in-frame	Glare, mostly in-frame	Glare, in-frame after inflation	Glare, mostly in-frame	Glare, partially out-of-frame
	CAB2 Window	Out-of-frame	Glare, mostly in-frame	2/3 inflations in-view	Good (less glare)	Good (less glare)
	FB1 Bay D	Parachutes not visible under FBC	Good, somewhat washed out	2/3 inflations in-view	Good, somewhat washed out	Good, somewhat washed out
	FB2 Bay A	Parachutes not visible under FBC	Good mortar view, mostly in-frame	Good mortar & inflation of 1/3	Mostly in-frame after inflation	1/3 often out-of-frame

For the final component, unique viewing angles, the PIG has experienced success when three unique viewing angles are available for any given point in a parachute system sequence. The desire for three unique viewing angles stems from two different objectives. The first objective is the ability to determine the proximity of FOD relative to the parachute system and the second is for complete coverage of the canopies.

One of the primary areas of analysis completed by the PIG's analysis team is to identify FOD and determine the risk it poses to the parachutes. The ability to complete this analysis is heavily dependent on the amount of unique viewing angles available. If only a single view is available, no estimate of the FOD's location can be made and therefore the size or shape cannot be estimated. If two views are available, a crude approximation of the FOD's proximity to the parachutes can be made, but it will be inaccurate and potentially highly subjective. When three viewing angles are present, the FOD's proximity to the parachute system can be estimated with confidence. This allows engineers to assess the debris and the risk it poses to the parachute system.

A second reason for three unique viewing angles is for comprehensive imagery of the parachute system. To complete analysis of a mission, it is desirable to be able to see every side of every parachute. This allows for an analyst to identify flight damage as well as understand inflation and cluster behavior. For small canopies, one or two viewing angles may be sufficient for complete coverage. For main canopies however, their size results in a substantial amount of a cluster being blocked from view in any single viewing angle. It has been found that while three viewing angles cannot provide complete coverage, three viewing angles provides minimal imagery blind spots for a main parachute cluster.

The importance of multiple viewing angles may be best highlighted by Figure 9 which breaks down the six potential viewing perspectives by unfolding a virtual cube around a capsule and a parachute system.

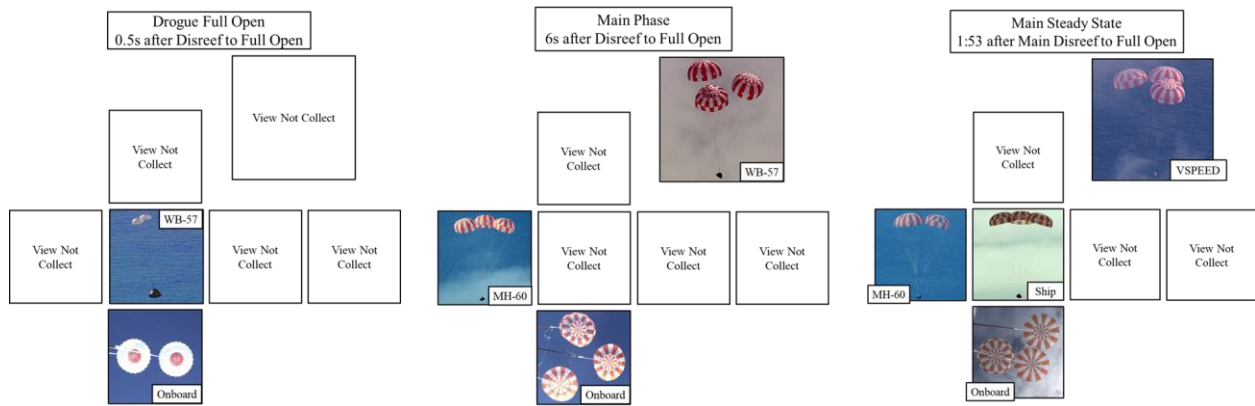


Figure 9. Views of the Artemis-1 parachute system.

The quality of the final integrated imagery product and its ability to inform engineering assessments will be dependent on careful mission specific planning and considerations. The high-level engineering considerations for the Artemis-1 mission and to CCP missions has been outlined in this paper. A review of Table 1 in conjunction with Figure 9 can be used to approximate the success of collecting imagery for the Artemis-1 mission. When viewed in conjunction, it is apparent that the careful planning of imagery assets for overlapping coverage and redundancy allowed for capturing high quality imagery for the majority of the parachute system's operation. Unfortunately, it is also apparent that there were gaps in the coverage. The Artemis-1 integrated imagery product is consistent with the integrated imagery products obtained on CCP missions.

V. Analysis Process

A comprehensive review of imagery can be a complex and time-consuming process. The time required is directly proportional to the amount and quality of imagery collected. Presently, the only method of completing analysis is through the brute force of experienced parachute analysts. While an analyst can leverage software while reviewing imagery, a substitute does not exist for an experienced analyst to review each individual frame of imagery. When multiple cameras are used, this can become a rather extensive task. The CCP program has been in an operational phase long enough that it has witnessed technological growth in camera resolution and camera framerate. As both have increased, the workload for analysts has increased proportionally. This workload and the analyst's workflow must be carefully considered and rolled into operational program schedules.

One of the primary difficulties for the PIG is supporting launch and recovery cadence. Over the last few years, the CCP has experienced an increasing launch cadence. This cadence has driven a need to a rapid, yet comprehensive analysis cycle. To optimize the analysis and reporting of results, the analysis team within the PIG breaks analysis into two phases; an initial high level rapid review followed by an increasingly detailed iterative review.

A. Phase I: Rapid

The necessity for a rapid imagery review has arisen because of launch, on orbit, and recovery cadence. It has become a frequent occurrence for there to be a short period of time between a parachute system demand and a critical flight review. It is desirable to understand a mission's parachute demand prior to mission reviews whenever possible, but a comprehensive review can be time consuming. In order to inform decisions quickly after a system demand, the PIG has implemented a rapid review process that occurs within ~24 hours of a parachute system demand.

During the rapid review, an analyst reviews the best available imagery of each phase of the parachute system. The imagery is typically reviewed at a real-time or 50% of real-time speed. The goal of the rapid review is to quickly identify major and obvious In-Flight Anomalies (IFAs) and begin the reporting and investigative process. In general, the rapid review will identify obvious areas of concern or interest and provide decision makers with information necessary to delay or proceed with an imminent operation.

B. Phase II: Iterative

Following the initial rapid review of a mission, analysis progresses to iterative and detailed analysis cycle. The analyst will review the imagery iteratively with progressing detail while working with their hardware counterparts to build a comprehensive understanding of a mission.

The iterative review starts with an analyst completing an imagery event timeline. This timeline will eventually be used to synchronize imagery analysis with the trajectory analysis. An imagery timeline serves two objectives. First, an imagery timeline can typically be created before the vehicle trajectory data is available. This allows for a rapid understanding and check of major system events. Secondly, the imagery timeline can be used to validate vehicle data by comparing the imagery timeline with the vehicle acceleration data. To create the imagery timeline, the analyst will review most, if not all, of the available imagery at a reduced speed of approximately 25% real-time and events of interest, such as disreef event, on a frame-by-frame basis. While completing the imagery timeline, the analyst will also begin to identify subtle areas of intrigue; observations that will be marked and noted for further analysis.

Once the imagery timeline is completed, the marked areas of interest serve as the starting point for the next iteration of the analysis. At this point, an analyst will review all imagery zoomed in and frame-by-frame. The engineer's goal is to identify, investigate, and interrogate details at the pixel level within imagery to determine if anomalous behavior occurred. It is at this point that imagery analysis begins to enter the process shown in Figure 2 and discussed in Section III-A.

As the iterative phase progresses, imagery analysts will work with hardware teams, vehicle data, and subject matter experts to build an understanding of observations. As observations are pursued, they are chased around the reliability surveillance framework shown in Figure 1 and Figure 2. During this iterative process, some observations will be resolved as nominal or expected while some are marked for further analysis. The resolved items will be noted for future reference and the items marked for additional analysis will be pursued at a lower, or more precise level. This process will continue until it cannot be taken any further. The goal is to identify root cause of all observations, but it is unfortunately, not always possible with the resources and dataset available.

VI. History of Imagery in Parachute Surveillance

A. Apollo 15

The use of imagery to ensure parachute reliability is not a new concept. NASA was using imagery as early as the Apollo missions to both monitor parachute behavior and inform anomaly investigations. Evidence of this fact can be seen in the investigation of the Apollo 15 main parachute failure that occurred on August 7, 1971. After substantial testing and qualifying of the Apollo parachute system, the ninth crewed Apollo mission experienced a main failure during the terminal descent phase after returning from the moon. Imagery played a critical role in investigating the IFA.⁹

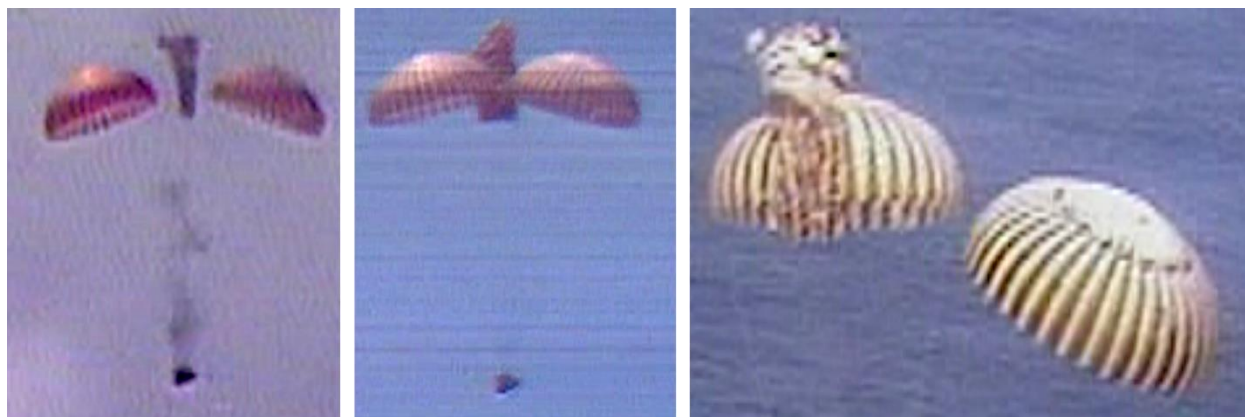


Figure 10. Failure of Main parachute during Apollo-15 terminal descent.

Following the anomaly, Apollo engineers' initial efforts were focused on gathering spacecraft data, imagery, and hardware inspections; a methodology which was an early precursor to the surveillance and reliability framework in use by the PIG today.⁹ Imagery was found to be particularly useful to the initial investigation as engineers used

photographic and television coverage to determine that the forward heat shield was near the spacecraft when main failure occurred. From the available imagery, engineers were able to determine the following:

1. Three (of six) risers on the failed main were loaded
2. Two of the damaged riser lines appeared to be full-length
3. Approximately two thirds of the suspension lines were missing on the failed main
4. No significant canopy damage was apparent

The root cause of the failure was eventually determined to be a burning of monomethyl hydrazine which caused a degradation of the riser and suspension lines.⁹ Without the photogrammetric analysis, the root cause of the main failure may have been difficult to isolate.

B. CPAS CDT-2

The investigation of the failure of the CPAS Cluster Development Test (CDT)-2 in 2008 was described by Machín and Evans in Ref. 10. Surface-to-air imagery played a key role in evaluating the overall scenario: dynamics of the vehicle separation, the difficulty of the tightly-reefed programmer parachute to inflate in a turbulent wake, and the severing of the attachment lines, sending the capsule into an unrecoverable freefall.

Imagery provided an even more in-depth analysis of the system which has not been published to date. Despite the high velocity impact of the test vehicle, recordings of the vehicle accelerations, attitudes, and rates were recovered from the simple, yet hardened avionics “data bricks.” The attitude readings were recorded as Euler angles and were therefore ambiguous when approaching a pitch of ± 90 degrees. NASA/JSC engineer P. Cuthbert was able to correlate video frames with a CAD model to determine the time history of the PTV. Selected images of this analysis are shown in Figure 11.

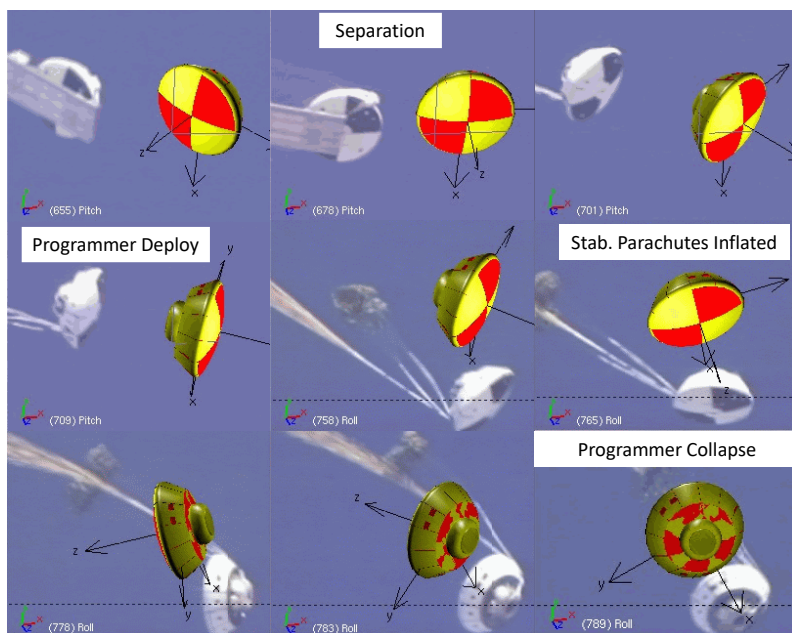


Figure 11. Correlation of PTV vehicle attitude using KTM imagery for CDT-2 failure analysis.

C. SpaceX CRS-15

Collins *et al.* note in *Lessons Learned During SpaceX Crew Dragon Main Parachute Development and Testing* that the understanding of the SpaceX main parachutes during development was negatively affected by a lack of imagery.¹¹ Specifically, during the CRS-15 mission, the Dragon parachute system experienced an anomaly in the main parachute system that resulted in “widespread damage throughout 2 of the parachutes.”¹¹ Collins *et al.* state “there was no footage of the vehicle descent to confirm any off-nominal parachute behavior.”¹¹

The lack of imagery appears to have directly impacted the investigation of the anomaly. Collins *et al.* note “without video coverage of the event, the investigation initially focused on the recovered parachutes.”¹¹ Engineers were required to work backwards from hardware inspections to determine the failure origin point. Engineers also had to infer the timing and the mechanics of the failure’s propagation from the vehicle acceleration data. Unfortunately, the vehicle IMU did not provide any data at an individual canopy level; the IMU only provided cluster level data.

Had imagery been acquired for the CRS-15 parachute failure, it could have provided data at a canopy level. Imagery would have had the potential to directly inform the failure origin point, failure timing, and failure propagation.

D. Interplanetary Missions

Interplanetary missions involving parachute failures cannot easily be investigated when telemetry and/or video is lost. Even successful parachute landings are difficult to evaluate due to limited information. Some recent technological

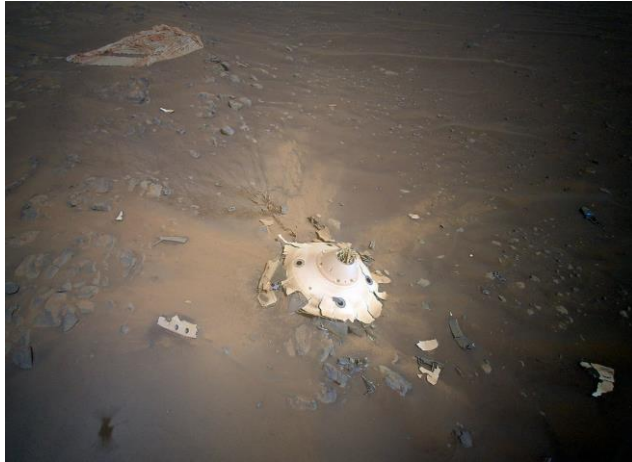


Figure 12. Perseverance backshell and parachute as seen from Ingenuity Mars Helicopter (NASA/JPL-Caltech).

advances have gathered some relevant information of Mars EDL systems. The High Resolution Imaging Experiment (HiRISE) camera on the Mars Reconnaissance Orbiter was powerful enough to obtain images of inflated parachutes in flight for the Phoenix Mars Lander,¹² Mars Science Laboratory (Curiosity),¹³ and Mars 2020 (Perseverance)¹⁴ missions from Mars orbit. In 2015 HiRISE located the Beagle 2 Mars Lander, which had been lost in 2003. The imagery from orbit confirmed that the Beagle 2 parachutes had deployed for a soft touchdown because the solar arrays on the lander were partially deployed.¹⁵ The Perseverance mission was the first Mars EDL to include an upward-looking camera, which was useful both to observe parachute performance and to generate an inspirational message.¹⁶ The Ingenuity Mars Helicopter was even able to locate the landed Perseverance parachute and backshell for a brief inspection (Figure 12).¹⁷

Sample return missions provide a more direct learning opportunity for EDL systems due to the possibility of video observation and hardware recovery, completing the reliability framework. The Genesis Sample Return Capsule (SRC) was intended to be recovered by helicopter in mid-air under a parafoil main parachute, but instead crashed into the Utah desert at the Dugway Proving Ground (DPG) on September 8, 2004. Long distance video was able to observe that neither the drogue nor main parachute ever deployed. An investigation concluded that the fault was due to a G-switch in the SRC avionics.¹⁸ Root causes included failure to “Test as You Fly.”¹⁹ Despite the high impact velocity, the non-deployed drogue provided data for material degradation effects in space.²⁰ Unfortunately, some standard pre-flight seam and joint tests which would have provided comparison data were not performed due to the “Faster, Better, Cheaper” philosophy at the time.

The Genesis design was inherited from the Stardust mission, which although launched in 1999—two years before Genesis—was not scheduled to land until 2006.²¹ The G-switch underwent a flawed modification for Genesis but the original design functioned properly. The Stardust SRC was successfully decelerated by a drogue and main parachute at DPG on January 15, 2006. The pre-dawn landing limited visual observations to infrared video and delayed recovery as high winds pushed the SRC northward from the expected ground track and the SRC found via radio beacon.²² The Stardust entry was reconstructed from radar and wind measurements by Desai and Qualls,²³ and parachute performance was reconstructed by Witkowski and Kandis.²⁴ Despite the high winds, both the drogue and main parachutes for Stardust were recovered. Having spent eight years in a packed state and seven years in deep space these parachutes could provide data for material degradation factors. For example, there was a concern about the aging degradation for the Mars Science Laboratory parachute, which remained in a pack state for about three years due to delays.²⁵ In this case, two sides of the reliability framework were present, but the visible spectrum imagery of the recovery system was traded for spectral imagery observations from a NASA DC-8. This was necessary for validating a hypersonic reentry model for what was then the fastest man-made object to traverse the atmosphere.²⁶

The OSIRIS-REx sample return capsule landed under a main parachute at DPG during daylight hours on September 24, 2023. Although the SRC was successfully recovered undamaged, live video did not show drogue deployment at the expected altitude. Subsequent video analysis and hardware inspection allowed for a fairly rapid investigation of the anomaly.²⁷ The likely cause was mis-connected wires due to different definition of the word “main” by different competencies. The pyrotechnic community uses “main” to indicate the first event (i.e. drogue mortar fire) while parachute personnel expect it to refer to the final recovery parachute. The signal intended to activate the drogue mortar was instead routed to cut away the non-deployed drogue parachute. Later the drogue cut-away signal instead activated the drogue mortar. The severed drogue immediately separated without inflating and the main parachute deployed. Despite the high dynamic pressure, the main parachute survived and completed the mission. The OSIRIS-REx main parachute was recovered (Figure 13) and inspected but the drogue was lost.



Figure 13. OSIRIS-REx sample return capsule with recovered main parachute (NASA/Keegan Barber).

The Japan Aerospace Exploration Agency (JAXA) successfully recovered SRCs for both the Hayabusa^{28,29} and Hayabusa2³⁰ missions in Woomera, Australia in 2010 and 2020, respectively. Both used the same fundamental EDL design, though it was noted that the parachute deployment trigger signal equipment was improved between missions.³¹ The night landings and large standoff conditions diminished opportunities to view the parachutes, yet NASA airborne assets were able to perform spectral analysis of the thermal protection system performance.^{32,33} Each recovery was assisted by the use of laser-reflective material in the main parachute and radio beacons. In both cases the main parachutes remained attached to the SRCs and were therefore recovered.

VII. Conclusions

The reliability of parachute systems is critical to the success and safety of NASA missions. In support of the Commercial Crew Program, NASA’s Parachute Integration Group has established a robust surveillance framework to ensure spacecraft parachute system reliability. For this framework to be successful, a strong programmatic commitment to imagery collection is required. As one of the three core tenets within the surveillance framework, imagery has been found to be a critical data source that serves as a foundation for NASA’s understanding of spacecraft parachute performance. The NASA Parachute Integration Group considers the collection and analysis of high-quality imagery to be mandatory for evaluating parachute system performance and identifying In-Flight Anomalies. The criticality of imagery demands that careful consideration be made to build an imagery package that is sufficient to inform post flight analysis and ongoing surveillance activities. This process must be completed with careful coordination with mission planners and mission operations.

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