NATIONAL TRANSPORTATION SAFETY BOARD
Office of Research and Engineering
Vehicle Recorder Division
Washington, DC 20594

GROUP CHAIRMAN'S FACTUAL REPORT OF INVESTIGATION

Electronic Recording Devices and Flight Data Factual Report

DCA15MA019

By
Sean Payne

NATIONAL TRANSPORTATION SAFETY BOARD
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June 24, 2015

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1. EVENT SUMMARY

Location:	Koehn Dry Lake, California
Date:	October 31. 2014
Vehicle:	Model 339 SpaceShipTwo
Registration:	N339SS
Operator:	Scaled Composites
NTSB Number:	DCA15MA019

2. RECORDER GROUP

A data group was convened during the on-scene portion of the investigation at the Scaled Composites facility in Mojave, CA. The members of the group were:

Chairman:	Sean Payne Mechanical Engineer National Transportation Safety Board (NTSB)
Member:	Michelle Murray Deputy Division Manager Federal Aviation Administration (FAA) Office of Commercial Space Transportation
Member:	Jason DiVenere Liaison Engineer Scaled Composites
Member:	Cedric Gould Propulsion Engineer Scaled Composites
Member:	Wes Persall Avionics Flight Test Engineer Virgin Galactic

3. SUMMARY

On October 31, 2014, about 1007 Pacific daylight time, a Scaled Composites SpaceShipTwo (SS2) reusable suborbital rocket, N339SS, experienced an in-flight anomaly during a rocket-powered flight test, resulting in loss of control of the vehicle. SS2 broke up into multiple pieces and impacted terrain over a 5-mile area near Koehn Dry Lake, California. One test pilot (the copilot) was fatally injured, and the other test pilot was seriously injured. SS2 had launched from the WhiteKnightTwo (WK2) carrier aircraft, N348MS, about 12 seconds before the loss of control. SS2 was destroyed, and WK2 made an uneventful landing. Scaled Composites was operating SS2 under an experimental permit issued by the Federal Aviation Administration's (FAA) Office of Commercial Space Transportation under the provisions of 14 *Code of Federal Regulations* (CFR) Part 437.

4. DETAILS OF RECORDER INVESTIGATION

4.1. Recorders/Files Received

The National Transportation Safety Board's Vehicle Recorder Division received the following electronic devices:

Recorder Manufacturer/Model:	**Scaled/Aitech Rocket Motor Controller (RMC)**
Recorder Serial Number:	**1003**
Recorder Manufacturer/Model:	**Pressurization System Controller (PSC) Data Logger**
Recorder Serial Number:	**B3P5NS1002**
Recorder Manufacturer/Model:	**Apple – iPhone**
Recorder Serial Number:	**N/A**
Recorder Manufacturer/Model:	**Silicon Drive Compact Flash Card (CF) – Card 1**
Recorder Serial Number:	**N/A**
Recorder Manufacturer/Model:	**Silicon Drive Compact Flash Card (CF) – Card 2**
Recorder Serial Number:	**N/A**
Recorder Manufacturer/Model:	**Solid State Hard Drive – "SS AFT Cam"**
Recorder Serial Number:	**CVCV2504035R240CGN**
Recorder Manufacturer/Model:	**Solid State Hard Drive – "SS Boom Cam"**
Recorder Serial Number:	**S12RNEACC92348V**
Recorder Manufacturer/Model:	**Protec Compact Flash (CF) Card – SODAS CF Card**
Recorder Serial Number:	**ACI07103101**
Recorder Manufacturer/Model:	**SS2 SODAS Telemetry Data File**
Filename:	**TestPointExport_PF04_L-10_END_NTSB_20141105_export_304_16_57_30.CSV**

4.2. Recorders/Files Received

4.2.1. Scaled/Aitech Rocket Motor Controller (RMC)

The Rocket Motor Controller (RMC) monitors and controls SpaceShipTwo's rocket motor propulsion system. It continuously monitors the health status of the rocket motor by reading pressure and temperature sensors, discrete signals such as cockpit switch positions and valve states, and continuity of control circuits. It reads these inputs at a rate of up to 1000 times per second. It also continuously checks its own internal state of health.

When the pilot activates the "Arm" and "Fire" switches, if the RMC has determined that all the input parameters are nominal, it will start the ignition sequence and fire the rocket motor. It does this by operating valves and energizing igniter circuits at prescribed times in a programmed sequence. During this time, the RMC continues to monitor all of its inputs, and determines if the motor is operating safely. If the motor exceeds operating limitations or a sensor fault is detected (or the pilot commands an abort) it executes an emergency shutdown sequence. Otherwise, the RMC allows the motor to continue firing until the preset burn has completed or a normal shutdown is commanded, and then executes a normal shutdown sequence.

The RMC records all sensor inputs, all command outputs, RMC internal health status, and its current software state to nonvolatile memory. This is done at a rate of 100 Hz during non-critical operations, and at 1000 Hz from the time the motor is armed, through motor firing and for 5 minutes after shutdown. The RMC is shown in the condition it was removed from the wreckage in Figure 1.

Figure 1. The RMC as recovered from wreckage site # 2[1].

[1] A index of wreckage site locations and their descriptions can be found in the Vehicle Recovery Group Factual Report, which can be found in the public docket for this accident.

4.2.2. Pressurization System Controller (PSC)

The Pressurization System Controller (PSC) controls SpaceShipTwo's helium pressurization system. The PSC functions independently of the RMC and regulates the pressure of the Main Oxidizer Tank (MOT) using high pressure helium. The metering of the helium pressure is used to deliver liquid nitrous oxide to the injector at high pressure as well as act as a diluent to the nitrous oxide vapor in the Main Oxidizer Tank (MOT). The PSC meters the helium to pressurize the MOT (b) (4) Upon ignition, the PSC will hold the tank pressure up (b) (4) psi as long as there is sufficient pressure in the helium tank, after which time the MOT pressure will decrease for the remainder of the burn.

When operating, the PSC has both a STANDBY and an ACTIVE mode. The PSC is commanded into the ACTIVE mode by way of a pilot actuated switch. When in the ACTIVE mode, the PSC regulates pressure in the MOT to the target pressure. The PSC is enabled only during the later portion of climb to release altitude at "L minus 4"[2] as to not deplete the limited supply of helium onboard. This portion of operation is referred to as "Pre-Pressurization" mode, or "Pre-Press". The drop in pressure of the MOT naturally occurs as a result of the falling helium temperature during the climb to the drop altitude of approximately 50,000 feet.

Once the Main Oxidizer Valve (MOV) is commanded "open" (during Fire command), the PSC continues to regulate tank pressure close (b) (4) psi in ACTIVE state.

The PSC has the ability to monitor its own fault status and alert the crew of functionality issues. The PSC will shut itself down and enter a FAULTED state for situations of out of range tank pressures, a defined pressure difference limit between transducers, or the recording of unrealistic pressure values. When the PSC enters a FAULTED state, a Crew Alerting System (CAS) message of PSC FAULT will appear on the Multi-Function Display (MFD) while the PSC STATUS field turns red. The faults can only be reset if the fault condition no longer exists and the PSC power is cycled.

Figure 2 shows a picture of the PSC data logger, a component of the PSC system, which was recovered from the wreckage.

[2] L minus 4 – A condition of flight 4 minutes prior to release, in which a pre-release checklist is executed.

Figure 2. The pressurization system controller data logger.

4.2.3. Apple – iPhone

The Apple iPhone is a touchscreen smartphone capable of voice calls, text messaging, email, photo/video recording, and many other functions depending on the specific application(s) loaded. Data is stored on non-volatile memory and may include call logs, text messaging logs, photos, videos, and location information. The amount and types of data stored varies based on the device's software version and configuration.

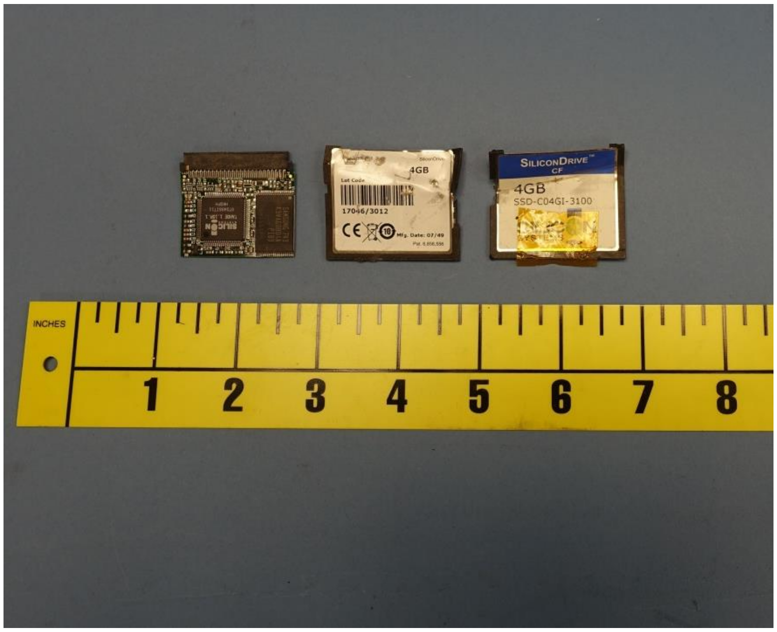
The iPhone recovered from the wreckage was determined to be associated with the co-pilot.

4.2.4. Silicon Drive Compact Flash (CF) Card - Card 1

This compact flash card was found near the co-pilot's seat below the MFD in wreckage site 4[3]. It is likely this CF card is associated with one of the MFDs. The compact flash card used in the MFD stores executable software programs and configuration files for the associated unit. The data stored on this card was determined to have minimal value to the investigation.

[3] For a detailed record of wreckage site locations, see the Vehicle Recovery Group Factual Report which can be found in the public docket for this accident.

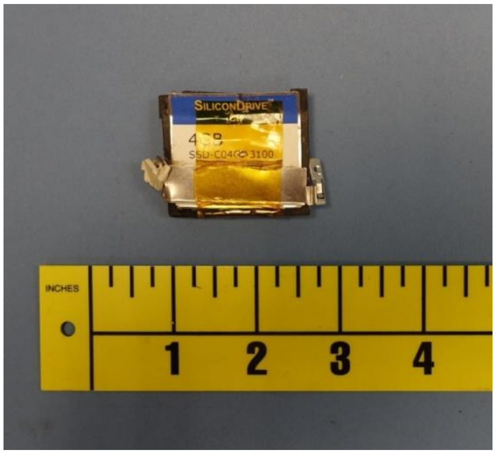
Figure 3. A Silicon Drive CF card located near the pilot's seat at wreckage site 4.



4.2.5. Silicon Drive Compact Flash (CF) Card– Card 2

This compact flash card was found near wreckage site 4. It was determined to be from either one of the Multifunction Displays (MFD) or a Data Acquisition Unit (DAU). The compact flash cards used in both units store executable software programs and configuration files for their associated units. The data stored on this card was determined to have minimal value to the investigation.

Figure 4. A Silicon Drive compact flash card found near wreckage site 4.



4.2.6. Solid State Hard Drive – "SS AFT Cam"

This solid state hard drive was part of a camera system onboard SpaceShipTwo. The onboard camera system consists of a collection of Imperx Bobcat color digital cameras that are set to record the test flight for engineering review and public media purposes. The onboard camera locations for both WhiteKnightTwo and SpaceShipTwo are documented on page 14 of the External Imagery Factual Report, which can be found in the public docket for this accident. Certain cameras record to both a solid state hard drive and are streamed to the ground via SS2's telemetry system. This particular hard drive was determined to be from the "Aft Cam", officially referenced in the onboard camera documentation as the "Ext. Plume Cam Rear View Bobcat". This particular camera was not streamed to the ground via the SS2 telemetry system and the only location of its recorded contents are within the "SS Aft Cam" solid state hard drive documented here.

The hard drive is a 256 GB[4] Samsung Solid State Drive (SSD) and is attached to an adapter bracket for use with a SoundDevices PIX240i camera control unit.

Figure 5. The "SS AFT CAM" Hard Drive as Recovered from the SS2 Wreckage.

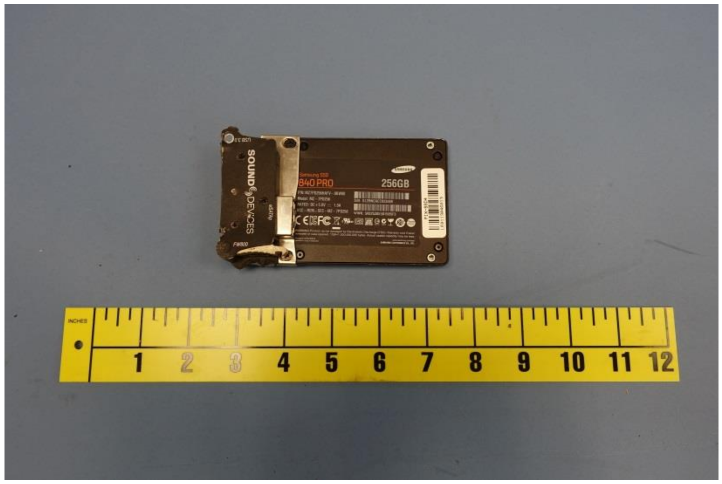
4.2.7. Solid State Hard Drive – "SS Boom Cam"

This hard drive was determined to be associated with the recording from the "Ext. Boom Cam Forward View Bobcat" camera, which was mounted to the left boom of SS2. This camera is documented in detail in the External Imagery Factual Report, which is found in the public docket for this accident. The imagery from this camera was streamed to the ground via the SS2 onboard telemetry system, and a low resolution copy was recorded on the telemetry ground station hardware, found in the Scaled Composites control room at Mojave Air and Space Port (KMHV), Mojave, CA. This hard drive contains a high definition (1920 x 1080) at 23.976 frames per second (fps) recording of the same video file which is discussed in the External Imagery Factual Report.

The hard drive is a 256 GB Samsung Solid State Drive (SSD) and is attached to an adapter bracket for use with a SoundDevices PIX240i camera control unit.

[4] GB - Gigabyte

Figure 6. The "SS Boom Cam" Hard Drive and the Associated PIX Chassis Connector.



4.2.8. Symvionics IADS Instrumentation System Data Files

The Strap On Data Acquisition System (SODAS) captures critical flight and vehicle performance data and uses the spacecraft's telemetry system to stream information to a ground station. The data is displayed during a test event and simulator event in the Melvill Center (Mission Control Room) at Mojave Airport in building 78. Within the mission control room there are multiple data workstations where test engineers monitor various sets of parameters during the test event using Symvionics IADS instrumentation software. The flight data from the telemetry feed is recorded on a computer in mission control, which is captured for both live and post event analysis. Included in the telemetry feed is a downlink for two onboard camera feeds, which is discussed in detail in the Cockpit Image Factual Report as well as the External Imagery Factual Report. Both reports can be found as stand-alone docket items in the public docket for this investigation.

4.2.9. SS2 Strap On Data Acquisition System (SODAS) Compact Flash Card

The SODAS serves as onboard data acquisition, and works in conjunction with the telemetry system to both record and transmit data to the Melvill Center. The data card recovered and discussed in this section was extracted from the SODAS chassis, which was installed in the accident vehicle.

The SODAS is used to collect, record, and transmit data and video. The system is designed to be highly configurable for flight test monitoring and analysis. The system is designed from a COTS[5] unit made by Curtiss Wright Controls (previously ACRA Controls and referred to as such). The system installed on board SS2 consists of three instrumentation chassis, two were located in the cabin and one located in the left wing (aft wing bay). Each chassis is connected via a 422 data link, with the master chassis located in the cabin. The master chassis combines data from each source and packages it into a PCM format for transmission over a telemetry signal. The master chassis has a compact flash slot in which higher rate data is recorded and stored (this is the CF card referred to in this section and recovered from the vehicle wreckage). The

[5] COTS – Commercial off the shelf

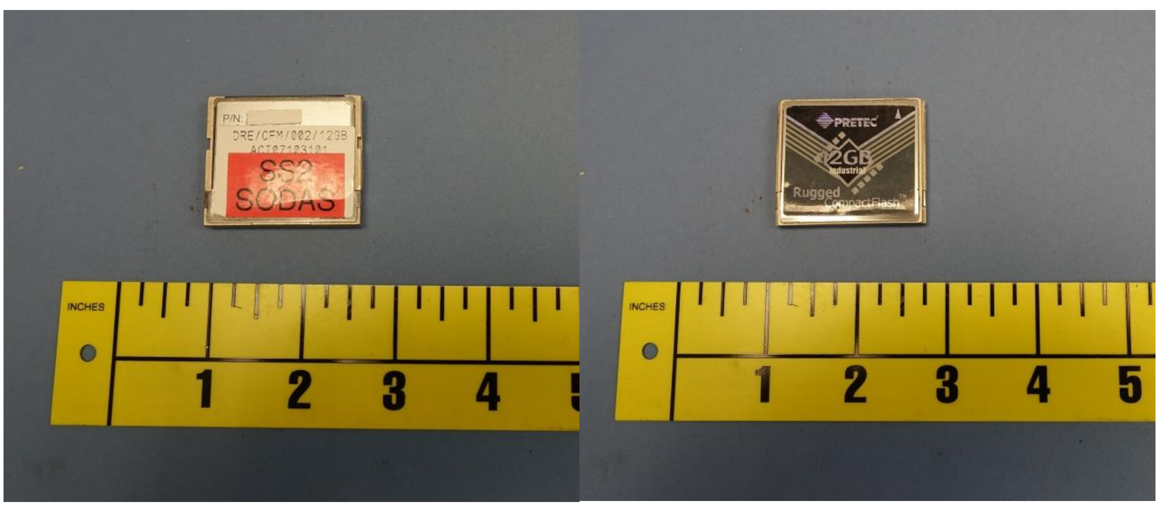
CF card installed in the master chassis was hardened for instances where the card may experience harsh environments. The CF card records a “hard copy” of all onboard flight data parameters at various rates of up to 1,000 Hz. The card contains the only onboard record of the flight data at the described maximum sample rate.

Each ACRA chassis consists of unique modules which converted analog data from thermocouples, accelerometers, pressure transducers and strain gauges into a digital format for telemetry transport and storage on the CF card. Each signal type requires a unique module to perform the A to D conversions in the correct manner. An Ethernet bus monitor module records all DAU data sent to MFD and has an additional port to record CAS message events. The SODAS has its own dedicated power source and GPS antenna for time stamping of data. The SODAS was the only means of recording and telemetering complete data records for analysis and real-time monitoring. The ACRA chassis sent data to a 10W transmitter which relayed the data and video to the Melville Center (Mission Control) for real-time monitoring.

The telemetered video described in the Cockpit Image Recorder and External Imagery Factual reports is also sent through the ACRA chassis video module for insertion into the data stream. The onboard camera control units (PIX) that record high quality video were upstream of the ACRA system, provide an lower resolution output for telemetry purposes.

The SODAS is located in the back of the cabin on a metallic shelf system.

Figure 7. The front and back of the SODAS CF Card.



4.3. Data Recovery

The following sections summarize the data recovery methods used for the electronic devices and files contained within this report.

4.3.1. Scaled/Aitech Rocket Motor Controller (RMC)

The device was removed from the wreckage in one piece. The device exhibited heavy crush damage to the externally attached PCB[6] board area on the top end of the device. Upon arrival at the laboratory, the area of crush damage was removed and the

[6] PCB – Printed Circuit Board.

top panel was opened. An internal inspection revealed that minor crush damage was evident to each of the five internal component cards on the PCB side of the device (Figure 8). Working with Scaled Composites and the manufacturer of the internal cards, Aitech Defense Systems, the component card of interest (CP901) was identified and removed from the device (Figure 9). An inspection of the CP901 card revealed the crush damage had displaced numerous pins on the side of the board opposite the slot connector and that a screw and resistor had been displaced (Figure 10).

On December 18, 2014, the card was brought by an NTSB specialist to Aitech Defense Systems in Chatsworth, California for further inspection and read out. Upon arrival at Aitech Defense Systems, the card was inspected for damage by a production specialist. It was confirmed that the board contained damaged pins in the JP3 and JP4 region of the card and the subsequent displaced resistor was identified. A rework order was created and the damage was repaired by an Aitech laboratory specialist. The card was then put through an impedance test to verify that the card could safely be powered on a test board. The card passed the impedance test with only slight deficiencies noted and it was determined to be a low risk of data loss to apply power to the card in a test board. Power was applied to the card on a test board (Figure 11) and the card was unable to boot. It could not be ascertained why the card would not function properly in the test board.

The memory chip containing critical data was identified on the card as U66 and was removed from the board by an Aitech laboratory specialist. The chip was then placed on a CP901 test card. The CP901 test card was then placed in a laboratory chassis and was read out normally.

Ten data logs in .log format were retrieved from the accident chip. Of these 10 log files, four logs, “non_crit_4a.log”, “non_crit_4b.log”, “critical_5a.log” and “critical_5b.log” were determined to be written during the accident flight and of interest to the investigation. The “non-crit_4” files were determined to contain data starting at the time of RMC power up during pre-flight activities, through SS2’s climb to altitude and a portion of release. This data contained 113 rocket motor and RMC related parameters at a rate of 100 Hz. The “non-crit_4” log ends at an indicated time of 17:07:20.055 UTC. The “critical_5” log files were determined to contain accident data from the time of arming of the rocket motor at 17:07:20.061[7] UTC until vehicle break up and loss of signal at 17:07:33.248 UTC. The parameters recovered from the “critical_5” log files were recorded at 1,000 Hz. The .log files were converted to .CSV format using an executable software program within Matlab.

CSV formatted data converted from the “critical_5” log recovered from the RMC is included in this report as Attachment 1. A translated parameter list defining recovered RMC parameter names and their relationship to recovered flight data is included in this report as Attachment 2. Both attachments can be found in the public docket for this investigation.

[7] Does not account for time offset information discussed in Section 4.5.1. RMC Time Correlation.

Figure 8. Crush damage exhibited to the five internal data cards.

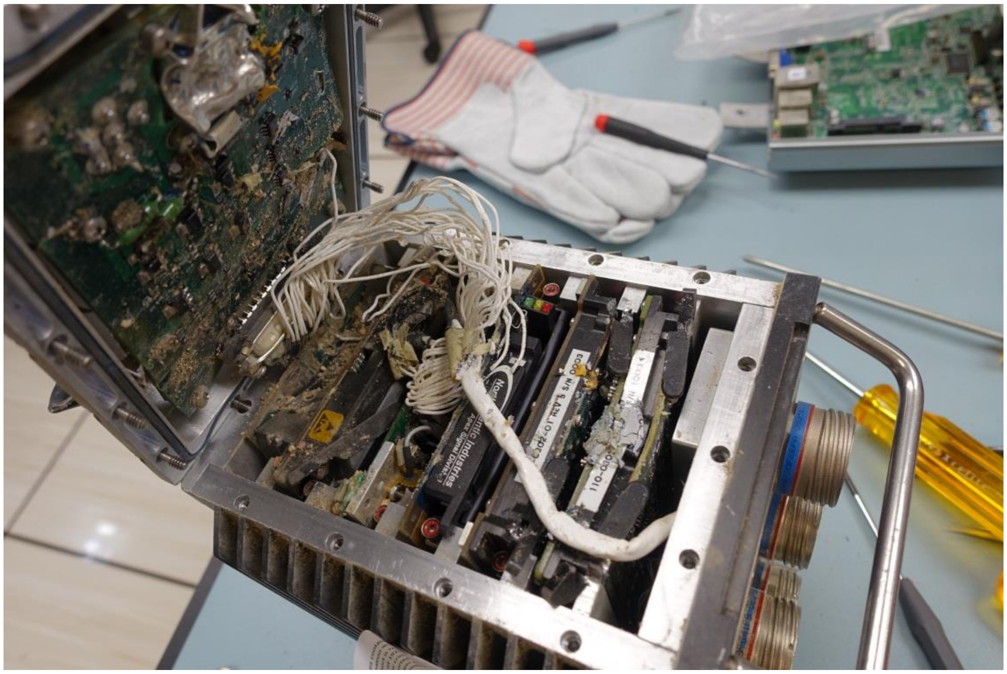


Figure 9. The CP901 card removed from the device.

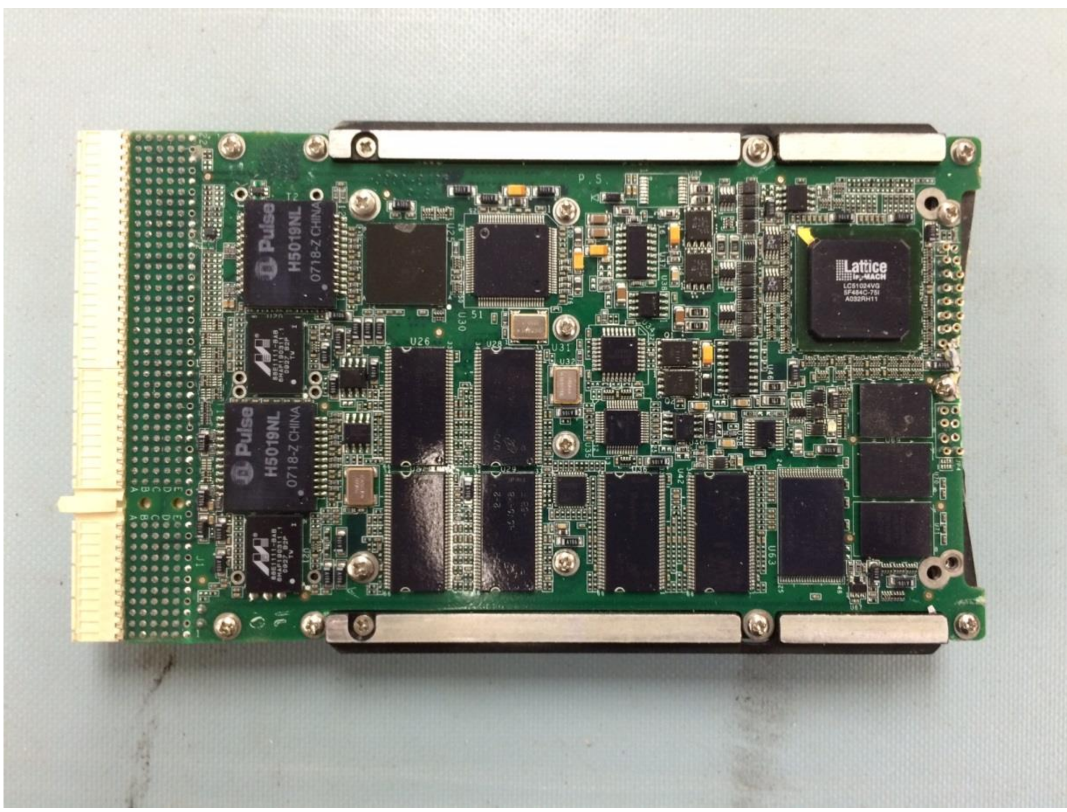


Figure 10 Damaged pins and resistor on the side of the CP901 board opposite the pin connector.

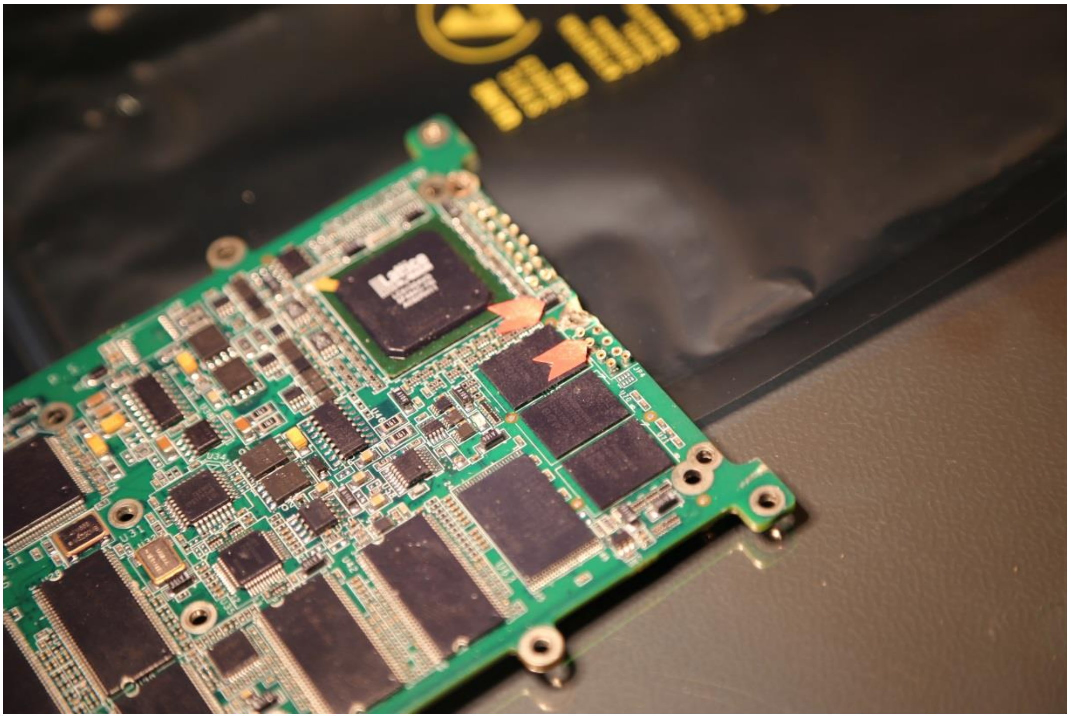


Figure 11. Power applied to the test card with the accident board installed.

4.3.2. Pressurization System Controller (PSC) Data Logger

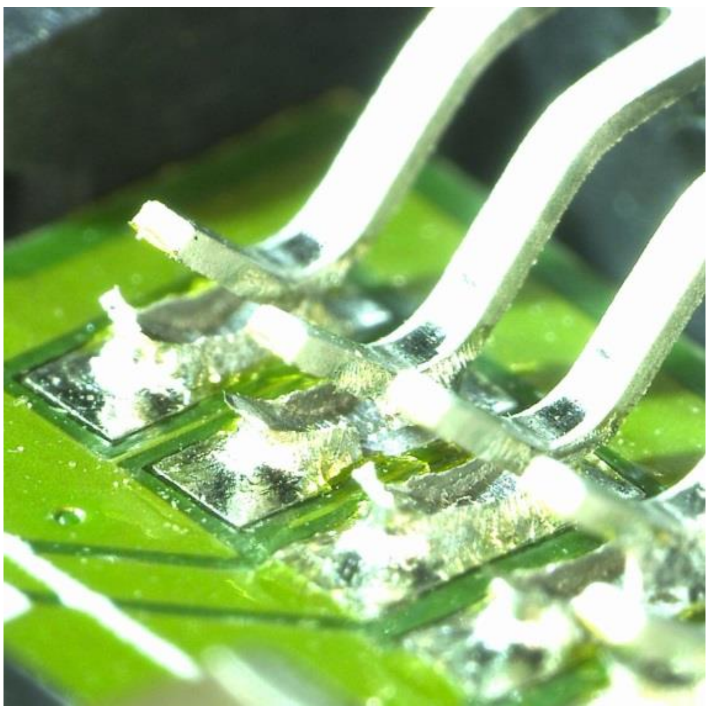
The device arrived with minor damage and structural deformation to the outer metal casing. The device's metal casing was removed for an inspection of its internal components. Minor structural deformation of the device's external connectors in relation to its main board was noted (Figure 12). Some minor structural deformation of the device's hard drive casing area was noted. The hard drive was removed from the device (Figure 13). The hard drive's plastic casing was removed for an internal inspection of the hard drive's components. The internal inspection revealed that four of the hard drive's SATA[8] pins were lifted from their respective solder pads (Figure 14). The four lifted pins were repaired under a microscope with a soldering iron, and the hard drive was read out normally using a SATA forensic write blocker[9]. The readout revealed a PSC data log in a .SQLite[10] format.

Figure 12. The PSC data logger with the external casing removed.

[8] SATA – Serial ATA – a computer bus interface for connecting mass storage devices.
[9] Forensic Write Blocker – a computer hard disk controller made for purpose of gaining read-only access to a hard drive without the risk of electronically damaging or manipulating the drive's contents.
[10] SQLlite – A relational database management system contained in a C programming library.

Figure 13. The PSC data logger's solid state drive in the condition it was extracted from the device.

Figure 14. A stereoscopic image of the 4 lifted SATA pins on the solid state hard drive prior to repair at the NTSB laboratory.



4.3.3. Apple iPhone

Upon arrival at the NTSB laboratory, a precursory inspection of the iPhone's internal components revealed that the device's internal memory was damaged beyond repair.

The device's internal memory was unable to be placed in a surrogate device for readout.

4.3.4. Silicon Drive Compact Flash Card Card 1, Card 2 & Solid State Hard Drive "SS Aft Cam"

These items were sent to the Integrated Electronics Center (IEEC) at State University of New York (SUNY) - Binghamton for evaluation and possible recovery. According to the report, card 1 had a fine crack along the surface of the U3 chip but overall, the device had a "fair to good" likelihood of data retrieval. A readout in the NTSB lab using a forensic write blocker was unable to access the card's internal memory. No further readout attempts were made.

Evaluation of Compact Flash card 2 revealed that all three internal chips were cracked and broken wire bonds were found using C-SAM[11] and X-Ray microscopy. The report listed the likelihood of data retrieval as "poor". No further attempts were made to read the card at the NTSB laboratory.

Evaluation of the solid state hard drive "SS Aft Cam" revealed that the majority of the device's internal memory chips that comprise the solid state hard drive were cracked, in some cases through the respective chip's silicon die. The report listed an overwhelming majority of the internal chips as having a "poor" likelihood of recovery. No further recovery work at the NTSB laboratory was performed.

The IEEC report is listed as Attachment 3 to this report and can be found in the public docket for this accident.

4.3.5. Solid State Hard Drive – "SS Boom Cam"

The hard drive was removed from the SoundDevices PIX hard drive chassis adapter and inspected internally for damage. The hard drive appeared to be in an undamaged condition and was prepped for an initial readout attempt. The unit was connected to a PC via a forensic write blocker and the drive's contents were inspected.

The hard drive revealed a UDF[12] file structure that contained 19 .mov[13] files roughly 6.25 GB in size each. The first filename in the sequence did not contain an appended sequential letter and was named B_001_004.mov. The subsequent files were named B_001_004X.mov, with X being a letter A through R applied to the file sequence in series. The video files were recorded in sequential 5 minute segments using the Apple ProRes 422 compression scheme[14]. The video files began with the aircraft sitting on the runway at KMHV prior to PF04 and were captured from SS2's left boom. Files preceding B_001_004R.mov played normally using a PC. The last complete file, B_001_004Q.mov, contained a 5 minute recording of SS2 being carried by WK2 at a high altitude. Using the known history of flight, it was calculated that file B_001_004Q.mov ended at approximately 17:05:18 UTC. The next file in the file series,

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[11] C-SAM – Confocal Scanning Acoustic Microscope
[12] UDF – Universal Disk Format – An open vendor-neutral file system for computer data storage.
[13] .mov – A filename extenstion for the QuickTime multimedia format.
[14] Apple ProRes 422 – a lossy compression format selectively used in high definition .mov files.

B_001_004R.mov, was unplayable and metadata showed the file size on disk was 0 KB[15].

A hard drive image file[16] in ISO[17] format was created from the SS Boom Cam 256 GB hard drive. The ISO file was read in a HEX editor[18] and forensically searched for the known signatures of .mov files recorded using Apple ProRes 422 compression. The searched revealed a variety of possible locations the unplayable data from file B_001_004R.mov could potentially be located. Each disk location was searched until the missing video data was found. Two separate portions of the missing file were located in different areas of the hard drive and saved.

The two recovered portions of the missing file were pieced together using a non-linear video editor[19]. A working .mov file of the same quality of the original recording (1920 x 1080 pixels of resolution and 23.976 fps) was output along with a series of still images exported for each frame of the recording.

4.3.6. Symvionics I.A.D.S Instrumentation System Data Files

The group relied on Scaled engineers to use IADS to generate configuration files to construct a customized parameter list that could be used to export SS2 and WK2 data in comma separated format (CSV). In collaboration with the different investigative groups, the most relevant parameters to meet investigative needs were identified for further examination. Additional parameters were later added as work progressed from the on-scene portion of the investigation. The parameter names from the identified relevant parameters were subsequently translated from their working names within the Symvionics IADS instrumentation software to unique and easily identifiable “translated” parameter names by Scaled and Virgin engineers. Attachment 4 to this report is the Master Flight Data Parameter Translation list, which can be found in the public docket for this accident.

The telemetry stream recorded most parameters at various rates up to 1,000 Hz, however, the requested exports of the parameters identified in the master parameter list were requested to be output at a rate of 50 Hz. 50 Hz was used as the selected rate for considerations related to file size manageability and the compatibility of working with the data in .CSV format in other software programs.

The group used the master parameter list to export data out of the IADS system into CSV format for multiple data sets. The data sets output from IADS also included previous powered flights (PF), in which the vehicle underwent a test flight that included a rocket motor burn flight profile. The accident flight occurred at what was referred to as “Powered Flight 04”, or PF04, with previous powered test flights starting within the program as “Powered Flight 01” (PF01). The time range of interest for most of the data sets started 10 minutes prior to pylon release, commonly referred to as “Launch minus 10” or “L-10”, indicating the vehicle was 10 minutes from WK2 pylon release.

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[15] KB – kilobyte – 1024 bytes.
[16] Hard drive image file – A bit for bit binary record of a computer hard drive.
[17] .ISO – A disk image of an ISO 9660 file system.
[18] HEX editor – A binary file editor that allows for manipulation of the fundamental binary data that constitutes a computer file.
[19] Non-linear Video Editor – A software program and allows electronic non-destructive editing of video source material.

The two initial exports of PF04 data were based off of the telemetered data that included forecast winds aloft data programed into the IADS system to calculate solutions for flight data parameters computed by the onboard Inertial Navigation System (INS). Since SS2 did not have a supersonic air data system, the vehicle relies on the SS2 INS system which does not account for winds aloft data onboard the vehicle. As the vehicle transitions beyond Mach 0.8, the MFD's airspeed and altitude data displays begin displaying data synthesized from SS2's INS. The data is part of the telemetered data stream and initially arrives at the ground station uncorrected. Since vehicle breakup occurred within the transonic[20] portion of flight, the vehicle's internal flight data systems had transitioned to data generated by the INS system which did not utilize forecast or real time winds aloft data. This presented the potential for INS derived parameters to be inaccurate based upon the differences between forecast winds and actual winds aloft soundings (weather balloons) taken on the day of the accident. At the time of processing of this data, corrected winds aloft data from the soundings were unable to be accounted for due to a technical error within Symvionics IADS. The two data exports initially requested covered the following portions of PF04:

1. PF04 Ground Checks[21] (with forecast winds in derived parameters)
2. PF04 L - 10 min through LOS[22] (with forecast winds in derived parameters)

When the data from the SODAS compact flash card data became available for PF04, data sets were processed exclusively with the CF card data, which allowed processing of winds aloft data collected by "soundings" (weather balloons). As a result, only the processed SODAS CF card data was used in this report.

4.3.7. Strap On Data Acquisition System (SODAS) Compact Flash Card

The SODAS Compact flash card contained a complete, onboard, electronic file record of the flight data that was streamed to the ground by the SODAS instrumentation system. The CF card was noted to have slight displacement damage in its external packaging (Figure 7). Upon arrival at the NTSB vehicle recorder laboratory, it was X-rayed using the lab's GE Phoenix Nanomex X-ray inspection device. An internal inspection using the X-ray device revealed unlikelihood of internal damage to the compact flash card's contents, and the device was read out normally using a compact flash card forensic write blocker. A 12 GB image file of the device's internal memory was retained using PC software.

The 12 GB image file was sent electronically to Scaled Composites for processing through the Symvionics IADS instrumentation system. Flight data was reprocessed using the corrected winds aloft data from the balloon soundings. Flight data for PF04 L

[20] Transonic flight regime – A flight condition in which a range of velocities of airflow exist flowing around different portions of an air vehicle or airfoil, that are concurrently below, at or above the speed of sound. The transonic region generally occurs in the range of Mach 0.8 and 1.0 (600-768 mph) at sea level.
[21] PF04 Ground Checks – Preflight checks for PF04 which took place between 15:42:00 and 15:57:00 UTC.
[22] L.O.S. – Loss of Signal – The time of loss of the streamed telemetry data 17:07:33.020 UTC.

minus 10[23] through LOS were reprocessed and output specifically from this image file. Previous flight data for PF02 and PF03 were processed using CF card data from previous SODAS CF card downloads.

1. PF02 L -10 min through SS2 release, feather unlock, feather, and feather relock and up to nitrous dump

2. PF03 L -10 min through SS2 release, feather unlock, feather, and feather relock

3. PF04 L - 10 min through LOS (with actual winds in derived parameters)

The exported SODAS CF card data for PF04 exhibited a +1.98 second offset to the originally examined telemetry system data set (discussed above in section 4.3.8.) The likely source of this offset is covered in detail in section 4.5.8. of this report.

All data used from the SDOAS CF card were collected and compiled into the Master Test Point Data from Compact Flash Card Flight Data File which is included in this report as Attachment 5.

4.4. Data Description

The following sections summarize the data recovered from and included in this report.

4.4.1. Scaled/Aitech Rocket Motor Controller (RMC)

The RMC contained data sampled at up to 1,000 Hz, and was reviewed to determine if the rocket motor experienced any anomalies prior to or during operation. Specifically, pressure values in the oxidizer tank, the oxidizer injector plenum, and the combustion chamber were examined. A review by the propulsion systems group revealed that pressures climbed normally and stabilized at expected values until the loss of signal occurred. Additionally, the Propulsion Group Chairman's Factual Report reviewed RMC data to determine if the unit operated as programmed, and executed commands in the expected order. The Propulsion System Group Factual Report states, "A review of RMC discrete parameters confirmed that the RMC commanded all launch steps in the proper order as programmed. The RMC commanded abort between T+11.28 and T+11.30 seconds[24] The abort was due to the PT-M3, a CTN seal health, pressure sensor reading of less than -200 PSIA for more than 25 milliseconds."

Select parameters recorded to the RMC were compared to the same parameters recorded by the SODAS system for uniformity. A comparison revealed that the rocket motor operated nominally, and recorded parameters common to both the RMC and SODAS data set were in agreement. Attachment 2 describes the RMC Parameter Translation List and shows the correlation of parameter names between the two data

[23] "L minus 10" – A condition of flight 10 minutes prior to release, in which a pre-release checklist is executed.
[24] T=0 is defined from the SS2_RMC_carrier_separated discrete.

sets. Time correlation between the two data sets is discussed in detail in Section 4.5.1. of this report.

4.4.2. Pressurization System Controller (PSC) Data Logger

A readout of the recovered PSC data log revealed the likelihood that the PSC data logging hard drive had become full sometime during the accident flight. Recorded data shows a discontinuity in the recorded values for multiple parameters throughout the recovered recording. Values that were read out appeared nominal. Values for two pressure parameters show the PSC maintaining levels just below its set target pressure. The pressure data then forms a discontinuity near the time of firing.

A PSC data report prepared by Scaled states that since the .SQL type database had become full, the data logger could not simultaneously log pressure data and manage its own database. This resulted in the data logging manager deleting rows of old PSC flight data and replacing freed space with current data. A review of the data by Scaled suggested that a "significant number of database table rows [had] been deleted ~10,000." Forensic reconstruction of the PSC database was discussed, but not undertaken by the Vehicle Recorder Laboratory of the NTSB.

Scaled's PSC Data Report is included in this report as Attachment 6.

4.4.3. Solid State Hard Drive – "SS Boom Cam"

The recovered video files from this hard drive, particularly file B_001_004R.mov, are discussed in the External Imagery Factual Report which can be found in the public docket for this accident.

4.4.4. SS2 Strap On Data Acquisition System (SODAS) Compact Flash Card

Processing through IADS yielded high rate flight data for the accident flight. As discussed in section 4.3.9., the data log was down-sampled in a .CSV file at an output rate of 50 Hz after processing through IADS.

4.5. Time Correlation

This section describes any time correlation performed for the data included in this report.

4.5.1. Scaled/Aitech Rocket Motor Controller (RMC)

The RMC's internal clock is not synchronized with any time source or any other system. The RMC time is set by an engineer prior to takeoff that performs a manual time correlation by setting the RMC's clock to an IRIG time display. Comparing values from the Critical_5 RMC Data Log and the Master Test Point Data from Compact Flash Card Flight Data File post-accident permitted a comparison of timing information between the two sets of data. Discretes for the following parameters found in the RMC data were compared to the associated recorded data from the PF04 Master Flight Data from Compact Flash Card file (Attachment 5). The results of the comparison are shown below in Table 1.

Table 1: RMC to SODAS Discrete Comparison for Timing Information.

RMC Parameter Name	DAS Associated Parameter Name	Δ Time
SV_A1_Fire_Pilot_Open	SS2_RMC_ SV_A1_Fire_Pilot_Open	0.221 sec.
SV_A2_Arm_Pilot_Open	SS2_RMC_ SV_A2_Arm_Pilot_Open	0.234 sec.
SV_A1_Open_MOV_to_BOV_PSC_CMD	SS2_RMC_ SV_A1_Open_MOV_to_BOV_PSC_CMD	0.238 sec.

When comparing the discrete parameters, the time offset was found to be non-linear. The average time offset (Δ Time) was calculated. When averaged, the time offset resulted in 0.231 seconds. The RMC data in the Critical_5 RMC Data Log was offset by -0.231 seconds to bring the two data sets into alignment. The time offset does not include a 20 millisecond (0.020 sec.) debounce included in the RMC's logic during motor firing.

4.5.2. Solid State Hard Drive – "SS Boom Cam"

The time correlation solutions for the recovered video files from this device are discussed in detail in the External Imagery Factual Report which can be found in the public docket for this investigation.

4.5.3. SS2 Strap On Data Acquisition System (SODAS) Compact Flash Card

Upon processing of the compact flash card data, the resultant timing information exhibited a +1.98 second offset in comparison to the original telemetry system file discussed above in section 4.5.8. The timing discrepancy was eventually attributed to a GPS time card installed in the SODAS chassis and the device's inability to account for leap seconds after the date of a specific firmware load to the GPS card. Records indicate the GPS card was loaded with a revision sometime before the year 2008. Since that time, an international record of leap seconds indicates that a second was added to Universal Coordinated Time on January 1, 2009 and also on July 1, 2012. Since the firmware was loaded prior to 2008, it would not have accounted for the two leap seconds added to the calendar following the original firmware revision.

The SODAS timing data was subsequently offset by -1.98 seconds to bring the data in alignment with the streamed telemetry data file.

5. PLOTS AND CORRESPONDING TABULAR DATA

The plots described below display data obtained from the SODAS compact flash card at a rate of 50 Hz.

Flight Controls and Vehicle Performance

Figure 15 displays select vehicle performance parameters along with flight control input positions for the portion of the recording from approximately "L minus 10" minutes through loss of signal. Ten minutes prior to vehicle release is shown as a vertical line on the plot at 16:57:19 UTC. Stick roll, stick pitch and rudder pedal position are shown sweeping, in a manner consistent with a flight control system check. The left and right feather lock state is shown as transitioning between locked, unlocked and back to a locked state. The plot shows flight control movement around 17:04:00 UTC, consistent with flight control damper checks that should occur during “L minus 4” checks. Additionally, the plot shows the stick being moved to a forward position just prior to carrier separation, which occurred at 17:07:19.100, and is demarcated with a vertical line. The plot’s resolution shows a visible change in feather lock state at some point after carrier separation until the loss of signal occurs at 17:07:33.020 UTC.

Figure 16 is an expanded resolution plot of the same parameters displayed in Figure 15. The plot covers a total of 17 seconds between 17:07:17 and 17:07:34 UTC, the time interval around carrier separation (WK2 release) and loss of signal. The plot shows carrier separation occurring at 17:07:19.100 UTC and the vehicle’s parameters continuing in a dynamic, yet nominal state. The times for the rocket motor armed discrete (17:07:20.280 UTC) and rocket motor fired (17:07:21.620 UTC) are demarcated as vertical lines at their associated times. Airspeed is shown increasing after rocket motor ignition along with a reverse in trend of the recorded altitude data as the pitch is shown increasing at a point described later in the accident flight.

Flight control movements are displayed and the vehicle remains mostly steady in pitch and roll until around 17:07:28.800 UTC, when the first indication of an unlocked feather condition manifests as the left and right feather unlock pressure switches show a true value. At 17:07:29.500 UTC, 0.700 seconds later, the left and right Feather Lock State shows a transition occurring, reaching an unlocked state at 17:07:31.100 UTC. At this time, data shows the recorded pitch becoming positive, until it reaches a maximum value of around 85 degrees at 17:07:32.680 UTC. Near the end of the recording a large variation in roll was also recorded. Recorded data lasts until the loss of signal occurs at 17:07:33.020 UTC.

Feather System and Vehicle Performance

Figure 17 displays relevant feather-related parameters in relation to basic vehicle performance data. Data shows values for various feather-related parameters changing as expected during a time period consistent with the “L minus 10” checks. Near the end of the recording, data shows airspeed and Mach number increasing rapidly until the left and right Feather Lock States indicates a transition occurring to an unlocked state at 17:07:31.100 UTC. Loss of signal occurs shortly thereafter.

Figure 18 is an expanded resolution plot of the same parameters displayed in Figure 17. The plot covers a total of 17 seconds between 17:07:17 and 17:07:34 UTC, the time interval bounded by carrier separation and loss of signal. Data shows airspeed and Mach number climbing rapidly as the vehicle slowly reverses an altitude loss trend after carrier separation. Left and Right Feather Unlock Pressure switches are shown as true at 17:07:28.800 UTC, and Feather Lock State shows Unlocked by 17:07:31.100 UTC. Shortly afterward, Left and Right Feather Actuator Down Pressures climb until Right Feather Actuator Down Pressure reaches a maximum value at 17:07:32.440 UTC. In the same time interval, Feather Position increases until maximum feather actuator down pressure is achieved and then performs erratically until signal loss.

Figure 19 is an expanded resolution plot of the same parameters displayed in Figures 17 and 18. The time interval is just over 2 seconds total, from 17:07:31 UTC until loss of signal at 17:07: 33.020 UTC.

Electrical System

Figure 20 displays various SpaceShipTwo electrical system related parameters. The plotted time interval begins at 16:57:00 UTC and covers the “L minus 10” checks through carrier separation and loss of signal. Mach number, and altitude are also plotted for reference. The plotted parameters show the electrical system functioning nominally throughout the recording.

Figure 21 is an expanded resolution plot of the same parameters displayed in Figure 20. The plot covers a total of 17 seconds between 17:07:17 and 17:07:34 UTC, the time interval around carrier separation and loss of signal. Data shows the electrical system functioning nominally throughout the plotted time interval.

Rocket Motor Performance

Figure 22 contains selected rocket motor performance parameters obtained via the SODAS compact flash card. The plot covers a total of 17 seconds between 17:07:17 and 17:07:34 UTC, the time interval bounded by carrier separation and loss of signal. The plot focuses on pressure values in the oxidizer tank, oxidizer injector plenum, and the combustion chamber (Case Throat Nozzle region – CTN). The plot shows the pressure rising nominally from the time of rocket motor ignition (17:07:21.620 UTC) until loss of signal. Additionally, the plot shows Main Oxidizer Valve actuation pressure (MOV) and Backup Oxidizer Valve actuation pressure (BOV). Pressure is seen increasing in the MOV actuator nominally from the time of rocket motor ignition. Both parameters drop to near zero pressure readings near the end of the recording.

A CTN seal health parameter, PT_M3_MOV_CTN_Seal, is also plotted in this figure. Data shows pressure dropping rapidly just prior to loss of signal and about 40 milliseconds prior to a recorded abort parameter, “RMC_burn_aborted”, going true in the moments immediately preceding loss of signal.

Figure 23 is a hyper-expanded resolution plot showing approximately the last second of recorded data. The plot begins at 17:07:32 UTC and ends with signal loss at at 17:07:33.020 UTC. Data shows a pressure value associated with a CTN seal health parameter, PT_M3_MOV_CTN_Seal, dropping below -200 psi at 17:07:32.840 UTC. Approximately 40 milliseconds later, data shows “RMC_burn_aborted” indicating “true” just prior to loss of signal. For additional information on the triggering of the abort command, reference the Propulsion Group Chairman’s Factual Report, section 5.2, which can be found in the public docket for this accident.

An opaque red oval denotes an area of data instability of plotted rocket engine parameters. Referencing the timing information found in the External Imagery Factual Report, this area of data instability occurred during the vehicle break up sequence. At this moment, it was likely that rocket motor instrumentation equipment and associated wiring harnesses were being disrupted from nominal operation. This could have caused data readings for those parameters to become unreliable.

Cabin Environment

Figure 24 contains cabin pressure and cabin environment related parameters. The plotted time interval begins at 16:57:00 UTC and covers the L minus 10 checks through carrier separation and loss of signal. All parameters appear nominal until the last moments of the recording when there is an indicated drop in cabin pressure and temperature around the time other parameters were indicating that the vehicle had begun to experience a large positive g-force. Signal was lost at 17:07:33.020 UTC.

Figure 25 contains cabin pressure and cabin environment related parameters. The plot covers a total of 17 seconds between 17:07:17 and 17:07:34 UTC, the time interval around carrier separation and loss of signal. All parameters appear nominal until the last moments of the recording when there is an indicated drop in cabin pressure and temperature around the time other parameters were indicating that the vehicle had begun to experience a large positive g-force. Signal was lost at 17:07:33.020 UTC.

6. TABLE OF ATTACHMENTS

Table 2 lists the name and attachment numbers discussed in this report.

Table 2. List of Attachments.

Attachment Number	Name
1	Critical_5 RMC Data Log
2	RMC Parameter Translation List
3	Integrated Electronics Center (IECC) Report
4	Master Flight Data Parameter Translation list
5	PF04 Master Flight Data from Compact Flash Card
6	Scaled PSC Data Report
7	PF04 Ground Check Flight Data

Figure 15. Flight Controls and Select Vehicle Performance Parameters - L – 10 through Loss of Signal.

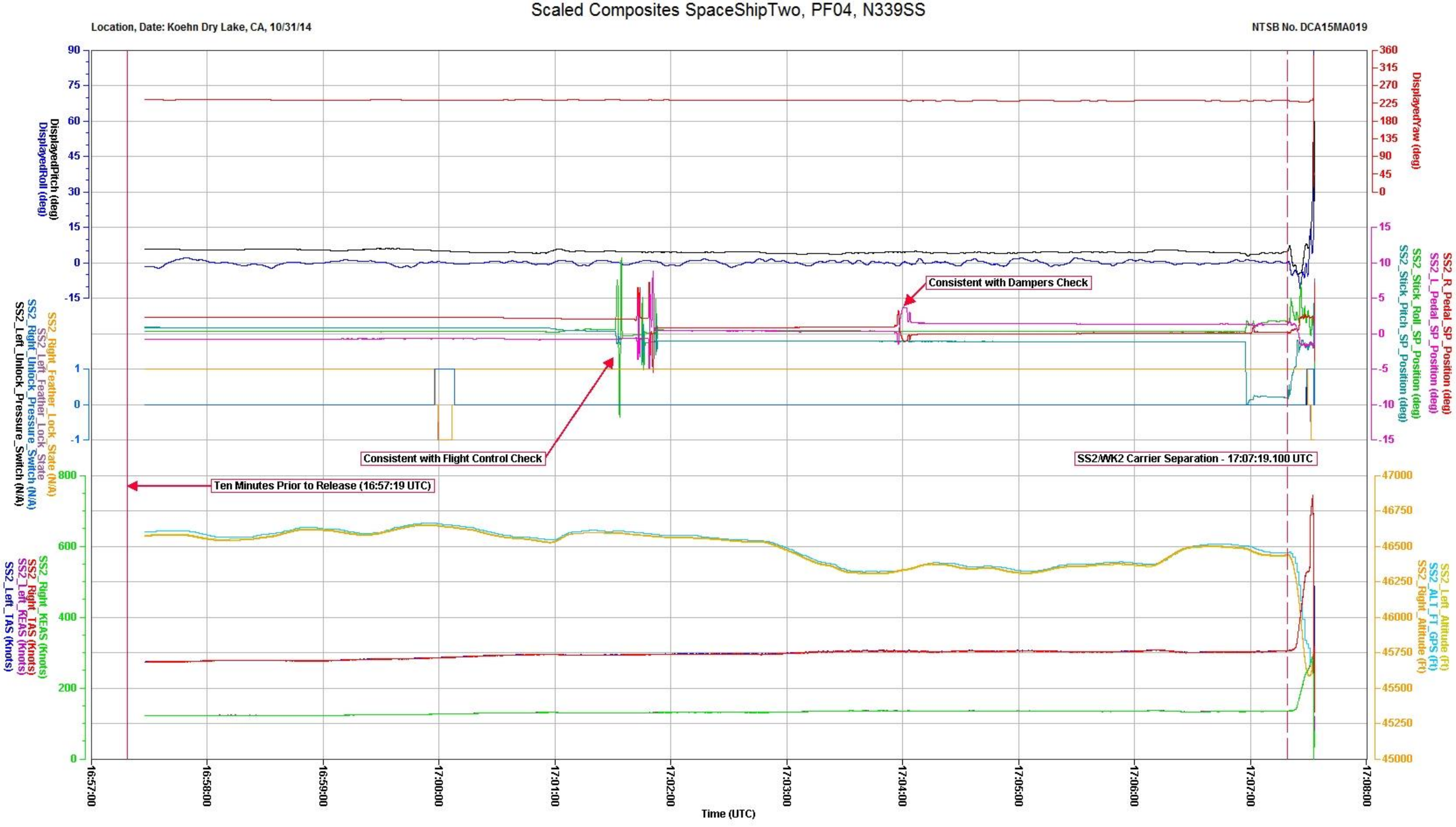

Figure 16. Flight Controls and Select Vehicle Performance Parameters - Carrier Separation through Loss of Signal

Scaled Composites SpaceShipTwo, PF04, N339SS

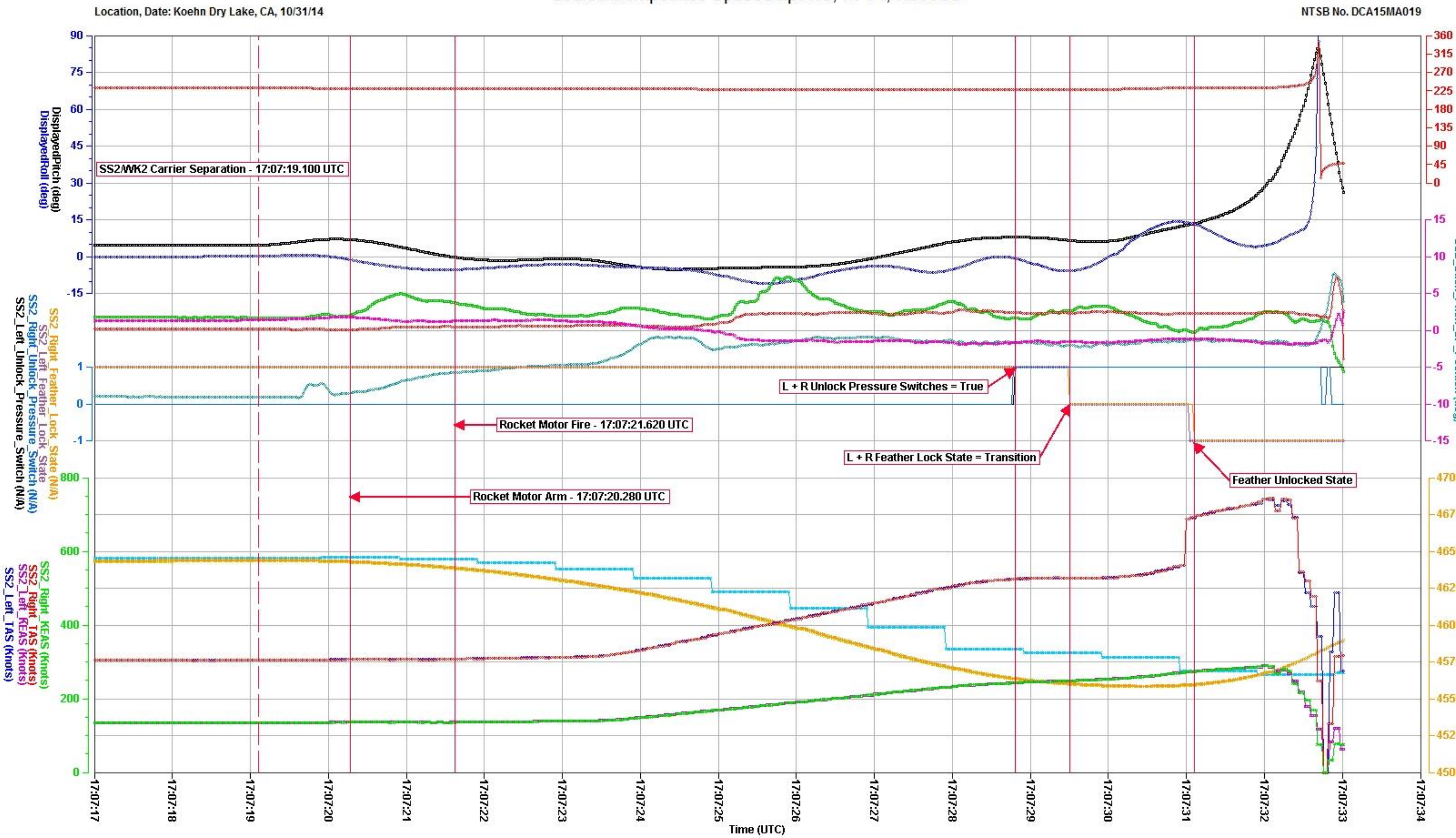

Figure 17. Feather System and Selected Vehicle Performance Parameters – L – 10 through Loss of Signal

Scaled Composites SpaceShipTwo, PF04, N339SS

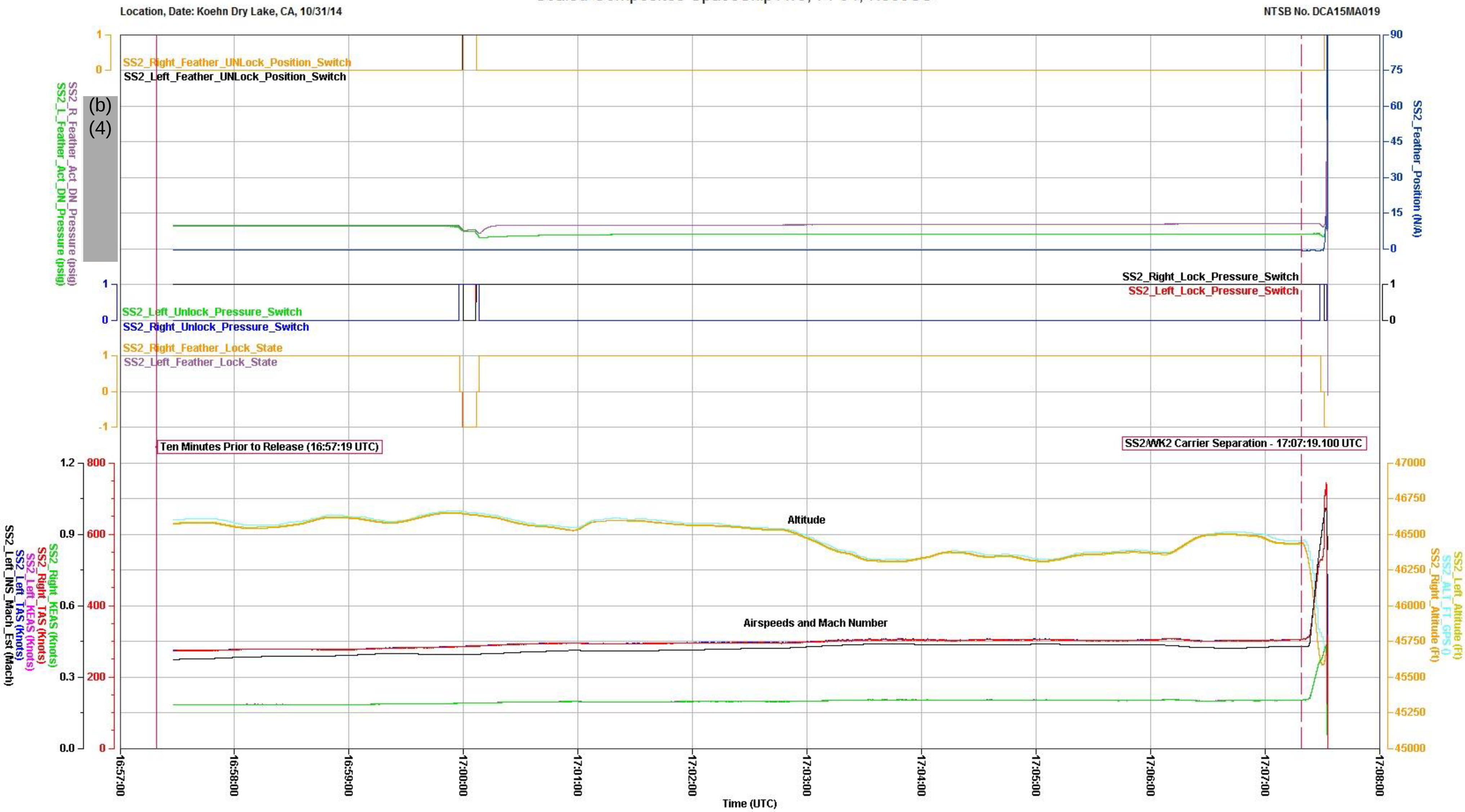

Figure 18. Feather System and Selected Vehicle Performance Parameters – Carrier Separation through Loss of Signal

Scaled Composites SpaceShipTwo, PF04, N339SS

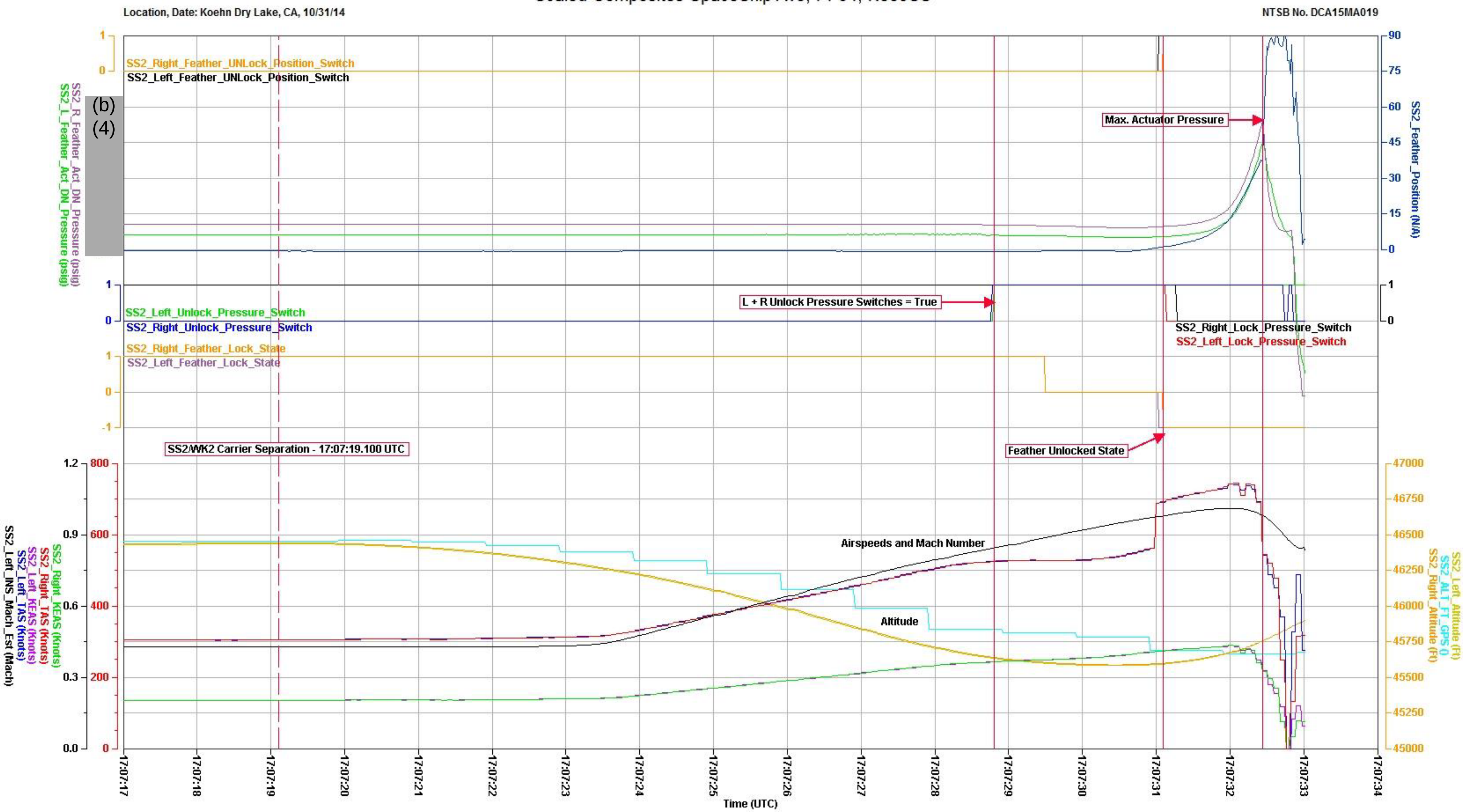

Figure 19. Feather System and Selected Vehicle Performance Parameters – Final Portion of Signal

Scaled Composites SpaceShipTwo, PF04, N339SS

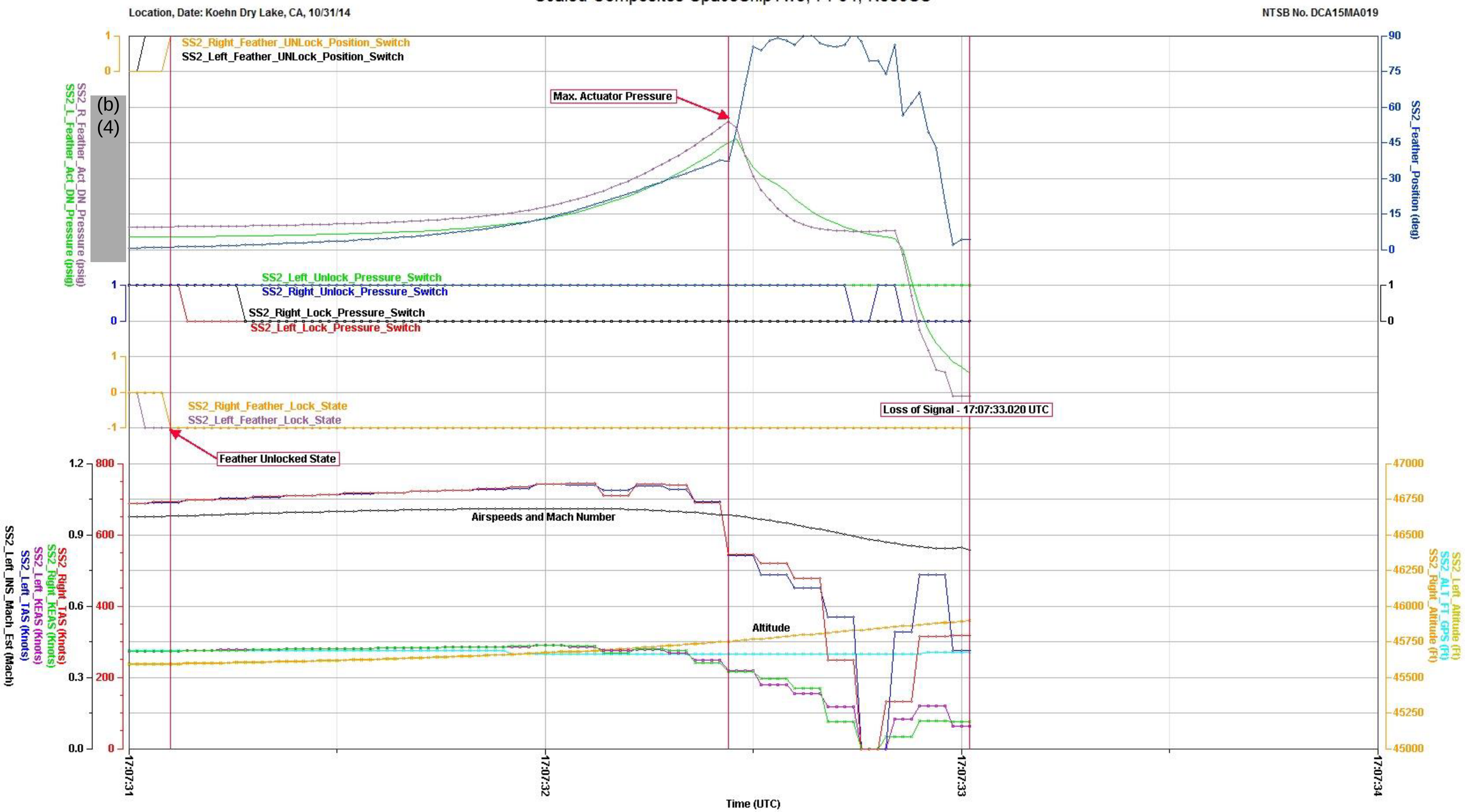

Figure 20. Electrical System – L – 10 through Loss of Signal

Scaled Composites SpaceShipTwo, PF04, N339SS

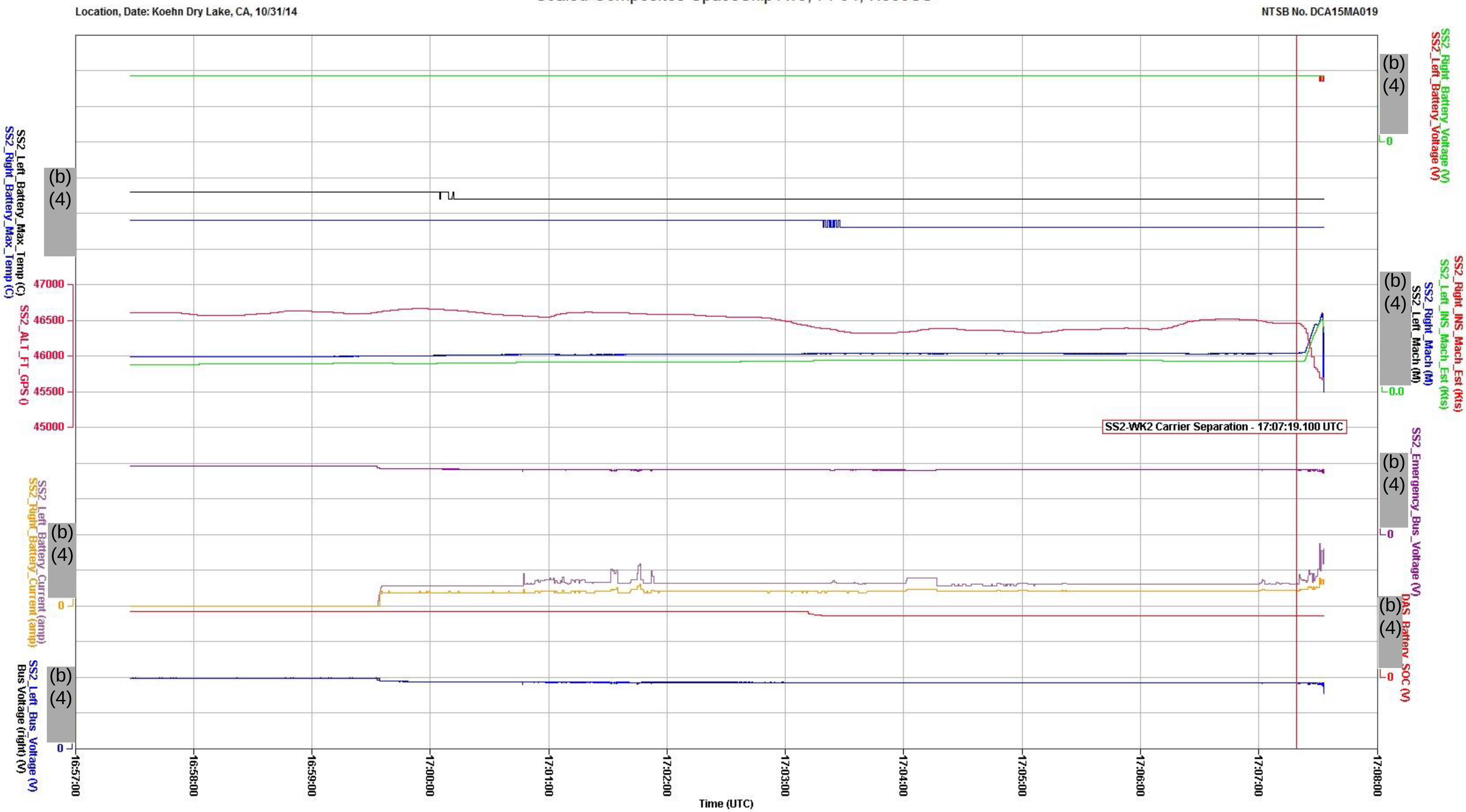

Figure 21. Electrical System – Carrier Separation through Loss of Signal

Scaled Composites SpaceShipTwo, PF04, N339SS

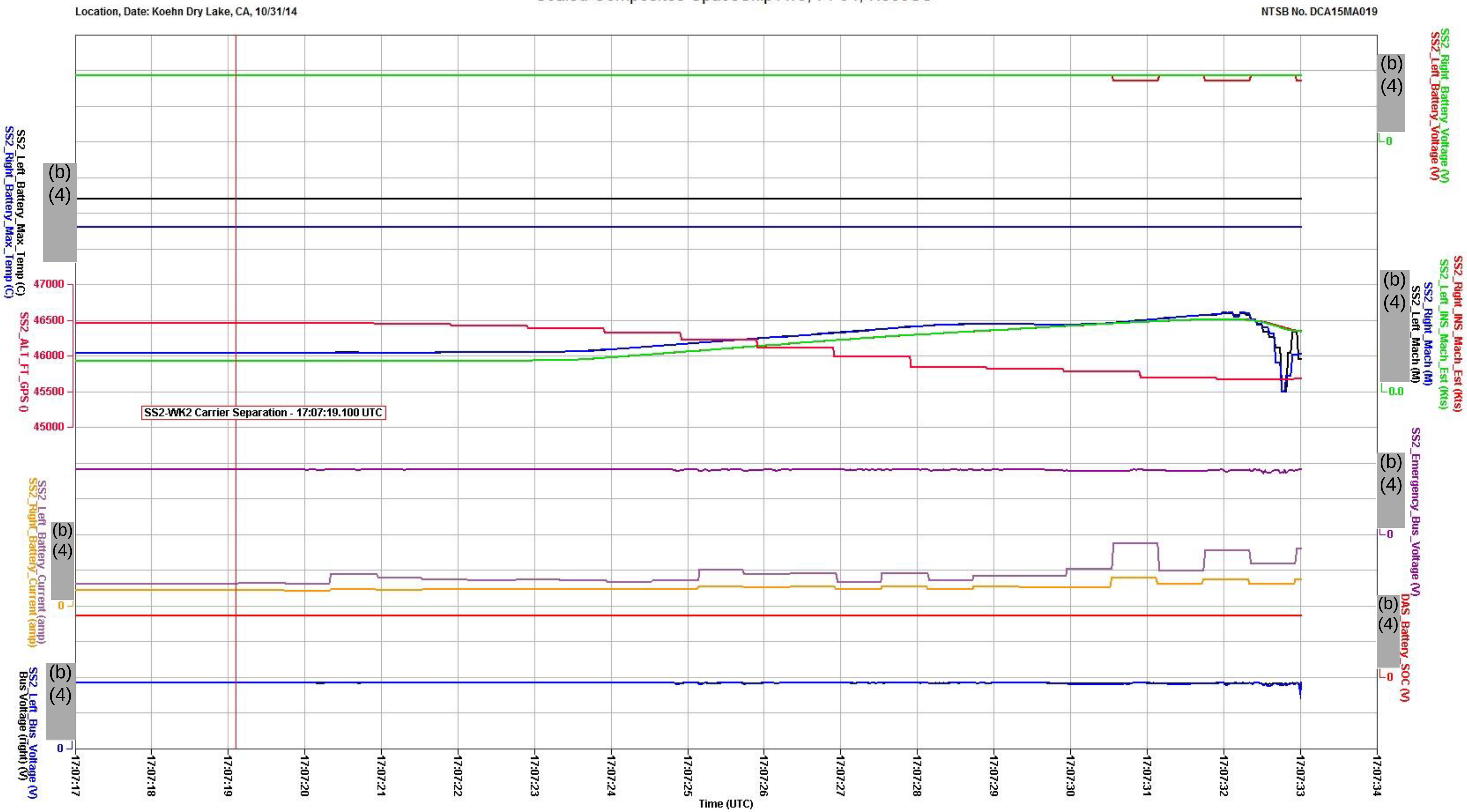

Figure 22. SODAS RMC Data – Select Rocket Motor Discretes and Pressures – Carrier Separation through Loss of Signal

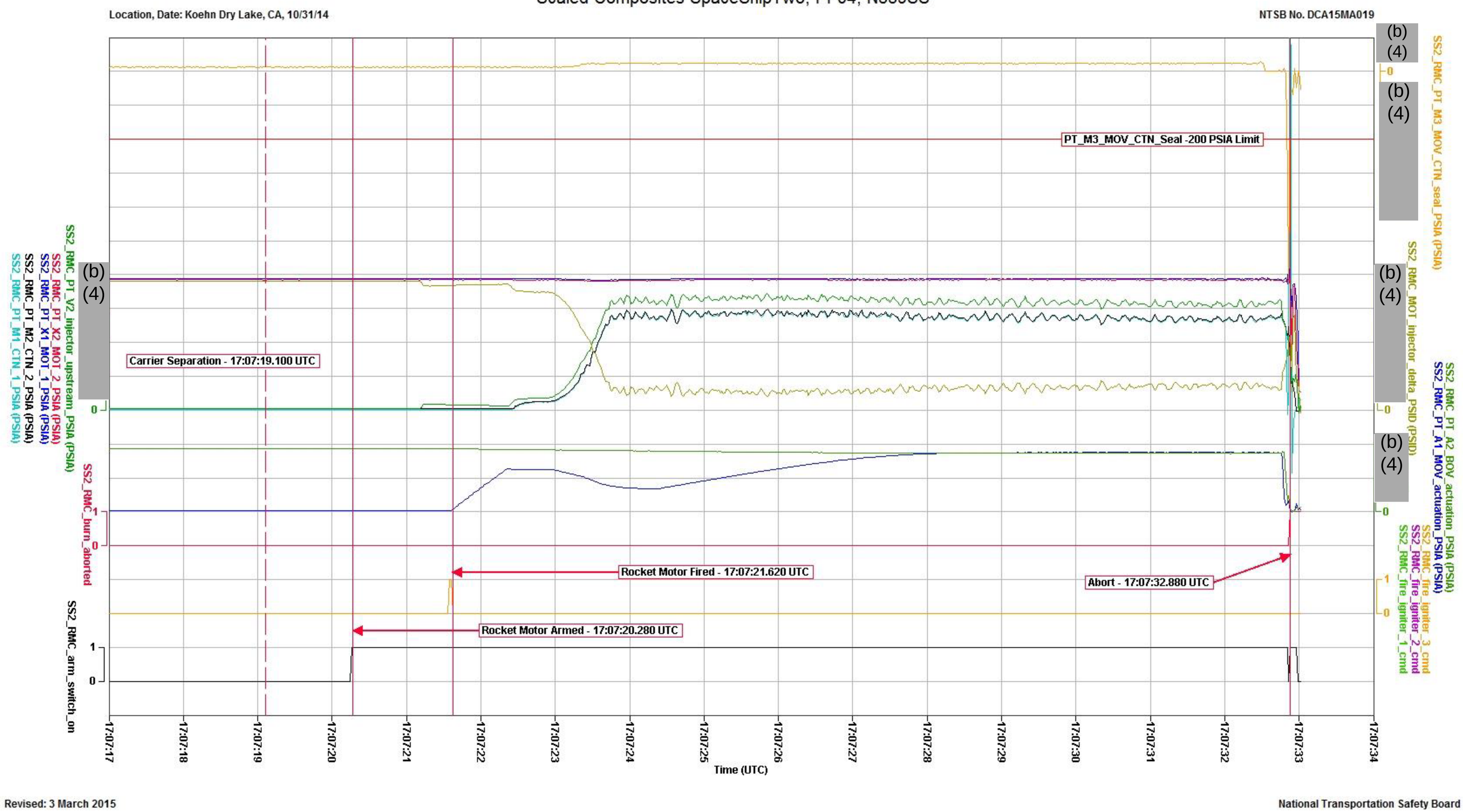

Figure 23. SODAS RMC Data – Select Rocket Motor Discretes and Pressures – Carrier Separation through Loss of Signal

Scaled Composites SpaceShipTwo, PF04, N339SS

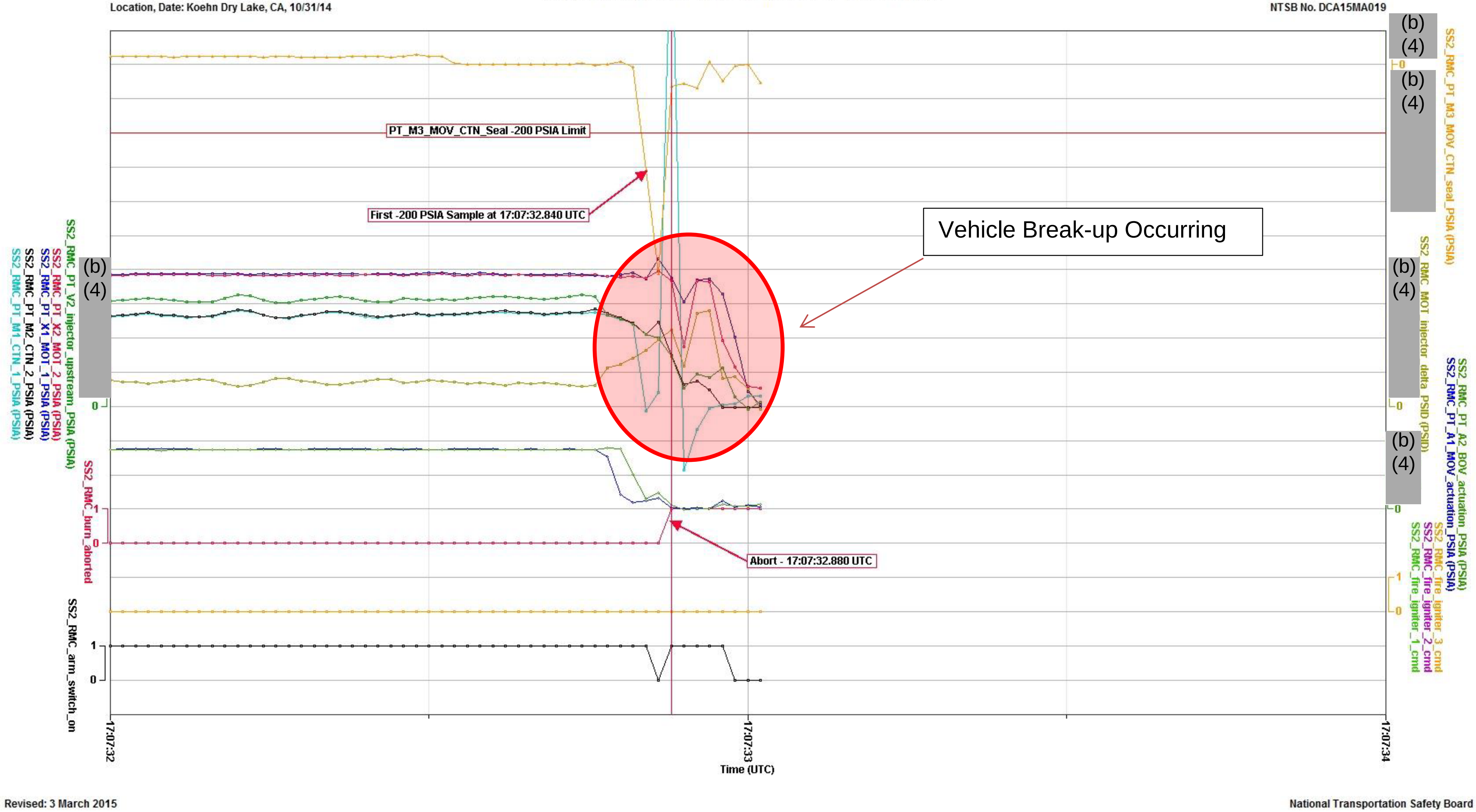

Figure 24. Cabin Environment Related Parameters – L – 10 through Loss of Signal

Scaled Composites SpaceShipTwo, PF04, N339SS

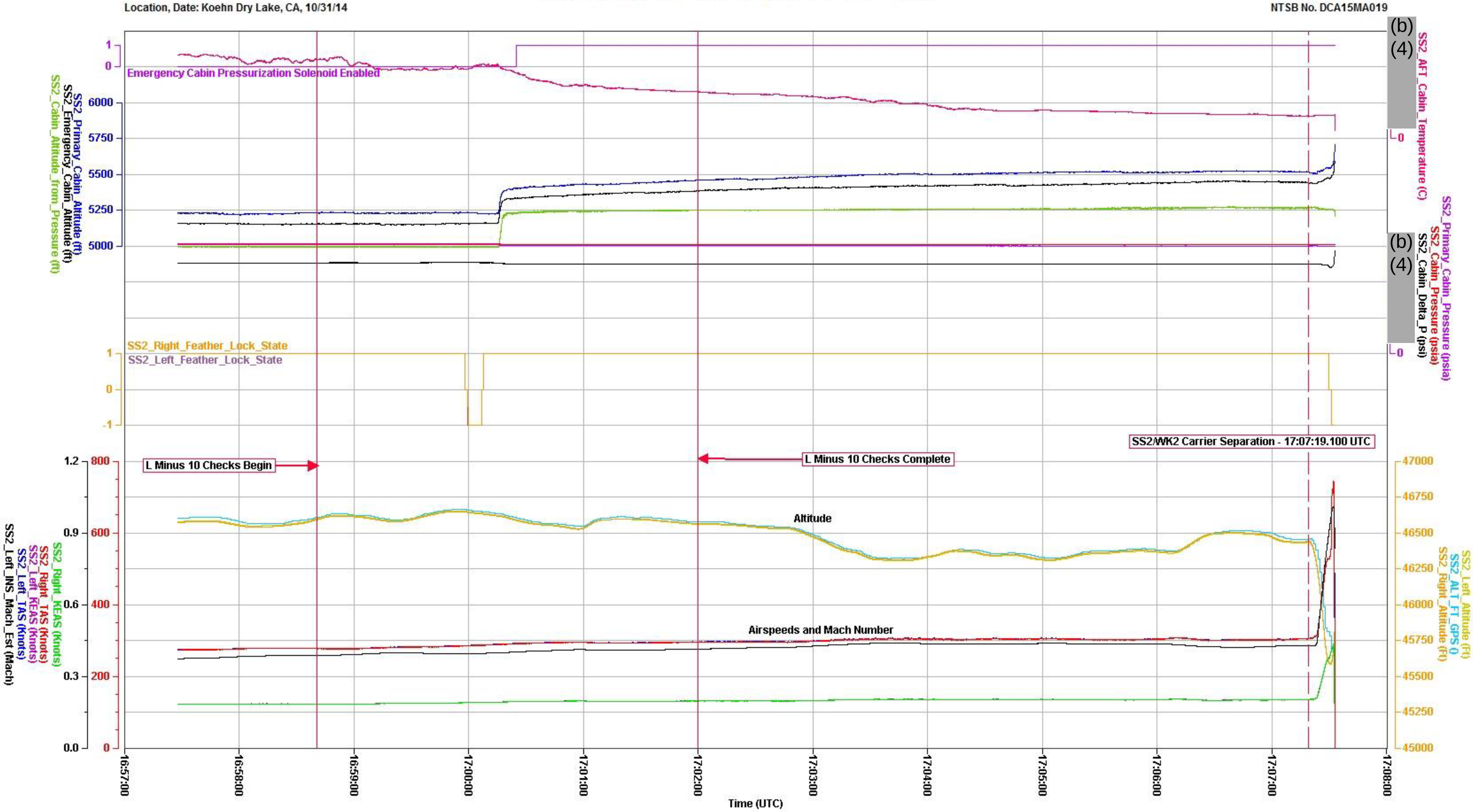

Figure 25. Cabin Environment Related Parameters – Carrier Separation through Loss of Signal

Scaled Composites SpaceShipTwo, PF04, N339SS