Volume II
Appendix D.20
Bolt Catcher Debris Analysis

This appendix contains – reproduced at smaller than normal size – the study of radar returns from past Space Shuttle launches to determine whether the Solid Rocket Booster bolt catchers may have failed during the flight of STS-107. The report concluded that there was the possibility that one of the debris items seen on radar during that flight could have been part of a bolt catcher.

This appendix has no recommendations, but the Board did make recommendations related to the bolt catcher issue in Volume I. The conclusions drawn in this report do not necessarily reflect the conclusions of the Board; when there is a conflict, the statements in Volume I of the Columbia Accident Investigation Board Report take precedence.

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APPENDIX D.20

Bolt Catcher Debris Analysis

Launching into the Future
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25 June 2003

Department of the Air Force
45th Space Wing
Patrick Air Force Base, FL 32925

ATTN: 45th Range Management Squadron (45 RMS/RMSS)

SUBJECT: CONTRACT F08650-00-C-0005: **TECHNICAL NOTE – BOLT CATCHER DEBRIS ANALYSIS FOR SHUTTLE STS-107 (CDR A205)**

The attached Technical Note presents an analysis of the STS-107 vehicle debris detected by Eastern Range radar following Solid Rocket Booster separation. The analysis was specifically conducted to determine if any debris detected following Solid Rocket Booster separation was characteristic of an External Tank Bolt Catcher.

If additional information is required, please contact Michael Ignacek at (321) 494-9740.

Original signed by

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Technical Note 25 June 2003

BOLT CATCHER DEBRIS ANALYSIS FOR SHUTTLE STS-107

Chuck Cook, Karen Beauchamp, Michael VonNiederhausern

An analysis of debris detected following Solid Rocket Booster separation indicates that one debris item, Item #33, is a good candidate to be an External Tank Bolt Catcher. Peak amplitudes of the debris returns are consistent with those of an External Tank Bolt Catcher. Range Time Intensity data from previous missions indicate that debris items have been detected at or near Solid Rocket Booster separation on 19 past missions. Seven items from five missions exhibit strong similarities to Item #33.

INTRODUCTION

Shuttle STS-107 was launched from Space Launch Complex (SLC) 39A, located at the Kennedy Space Center (KSC), on 16 January 2003. During the ascent phase of this launch, the Orbiter Vehicle, Columbia, was impacted by debris emitted from the External Tank (ET) at approximately T+81 seconds (s). At the request of Mr. William H. Haase, National Aeronautics and Space Administration (NASA) Shuttle Flight Safety Manager, CSR Systems Analysis performed a debris analysis of radar data, optical video, and optical film images collected during the launch.

The analysis was conducted in two parts. The original report, distributed on 14 February 2003 [ref. 1], consisted of analysis of debris detected at T+30 s, T+81 s (near the time of known impact), and from T+150 s to T+230 s. The time frame around Solid Rocket Booster (SRB) separation is typically characterized by abundant plume effects and expulsion of solid fuel debris and was, therefore, not analyzed in the original report. At the request of Mr. Haase, the time period from T+110 s to T+140 s was analyzed for debris, and the results were distributed in a revision to the original report on 4 April 2003 [ref. 2].

This technical note was prepared for the United States Air Force 45th Space Wing by the Systems Analysis Department of Computer Sciences Raytheon (CSR), under contract F08650-00-C-0005, and constitutes a delivery under CDR A205.

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Additionally, 12 samples of selected material from the Orbiter/ET were tested to determine their individual reflectivity coefficients. By using the test material reflectivity values and the maximum Radar Cross Section (RCS) of the detected debris, an approximate size of each of the sample materials relative to each of the detected debris items was determined in the revised report. RCS measurements of an ET Bolt Catcher were not conducted in time to include in the publication of the revised report. At the request of Mr. N. Wayne Hale, Jr., NASA Shuttle Launch Integration Manager, an analysis of debris detected following SRB separation was conducted to determine if any of the debris items were characteristic of an ET Bolt Catcher.

The Eastern Range (ER) radar that supported STS-107 were:

- Radar 1.16 at Cape Canaveral Air Force Station (CCAFS), FL
- Radar 0.14 at Patrick Air Force Base (PAFB), FL
- Radar 19.17 at KSC, FL
- Radar 19.14 at KSC, FL
- Radar 28.14 at Jonathan Dickinson Missile Tracking Annex (JDMTA), FL
- NASA Radar 86.18 at the Wallops Flight Facility, VA
- NASA Radar 86.16R at the Wallops Flight Facility, VA

Only Radar 19.14, Radar 0.14, and Radar 28.14 have the capability to record Full Range Video (FRV) of the track, which may provide an indication of debris presence.

METHODOLOGY

The radar suitable for detection of low RCS particle separations is the C-band FPQ-14 radar (0.14, 19.14, and 28.14). The primary indicator of debris is found in the radar's FRV tape recording. This recording contains returns across the radar's pulse repetition interval (PRI). The FRV tape recording of the radar receiver output is converted at the Data Playback and Digitizing Equipment (DPDE) facility at CCAFS into Range Time Intensity (RTI) charts for documentation of debris separations. The RTI charts are time-tagged with an Inter-Range Instrumentation Group (IRIG) timing format that allows for accurate time correlation.

The time of debris detection, as obtained from the RTI charts, is isolated and then digitized for detailed analysis. Once the data has been digitized, the radar receiver calibration data is used to fit the amplitude data, DPDE counts, to Signal-to-Noise (S/N) values. The radar equation is applied using the specific Radio Frequency Loop Gain (RFLG) value of the radar to get RCS. The data is then plotted in three dimensions (time, relative range, and RCS) to provide a 'picture' of the debris characteristics. It is from these plots that the debris RCS can be estimated. Additionally, the plots reveal the range separation rate relative to the vehicle and the debris flight characteristics (i.e., floating, tumbling, rotating).

Detected debris items from the three-dimensional RTI plots were evaluated as possible candidates for an ET Bolt Catcher. Previous reports [ref. 1 and ref. 2] provided analysis of debris based on the time block when it was first observed. The earlier analyses indicated that the majority of the debris detected from T+150 s to T+230 s was near enough to the noise floor to prevent reasonable estimation of the shape or size. Additionally, it is assumed that if a Bolt Catcher were to detach from the ET and forward bolt assembly, such separation would occur at or near the time of SRB separation. Therefore, the debris detected from T+150 s to T+230 s was eliminated from consideration.

Previous analysis indicated that the debris items detected from T+110 s to T+140 s were largely near the radar noise floor, and a determination of the items' shape and/or size was not possible. Only one debris item, detected by Radar 28.14, had a significant return, and is considered the only possible candidate for an ET Bolt Catcher.

The RCS of an ET Bolt Catcher was determined in tests conducted by the Air Force Research Laboratories (AFRL) at Wright Patterson Air Force Base (WPAFB) [ref. 3]. Data from the candidate debris item was analyzed to determine if it was characteristic of ET Bolt Catcher signal returns as determined by WPAFB. If separation was destructive to a Bolt Catcher, the objects' radar signatures could be greatly different than that of an intact Bolt Catcher. This analysis does not account for a severely damaged Bolt Catcher.

ANALYSIS

Each SRB is attached to the ET with one forward separation bolt enclosed in a forward separation bolt assembly (Fig. 1). At SRB separation, approximately two minutes into flight, the forward separation bolts are broken into halves by explosive charges at each end of the bolts. The SRB half of the bolt is captured in the SRB forward skirt (Fig. 2) and stays with the SRB throughout the remainder of its flight. The ET half of the forward separation bolt is forced into the Bolt Catcher/ET portion of the separation bolt assembly (Fig. 2), which remains attached to the ET and is jettisoned into the Indian Ocean.

Fig. 1 and Fig. 2 have been supplied at the courtesy of Mr. Roger Elliott of United Space Alliance via e-mail on 21 June 2003.

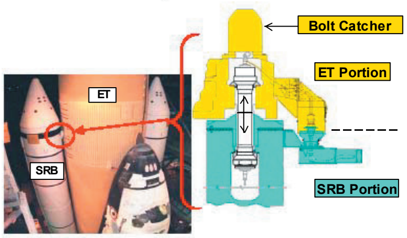

Fig.1. Forward Bolt Assembly and Attachment

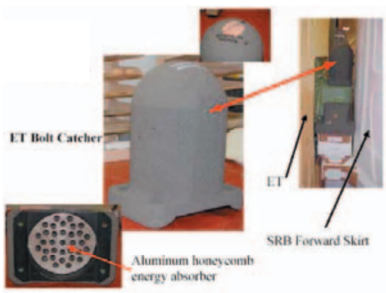

Fig. 2. ET Bolt Catcher

An ET Bolt Catcher is composed of an aluminum casing, covered with a Super Light Ablative (SLA) coating. In the opening at the base of a Bolt Catcher, a honeycombed aluminum disk exists to absorb the explosive energy of the bolt as it separates the SRB from the ET (Fig. 2). Bolt Catcher dimensions are shown in Fig. 3.

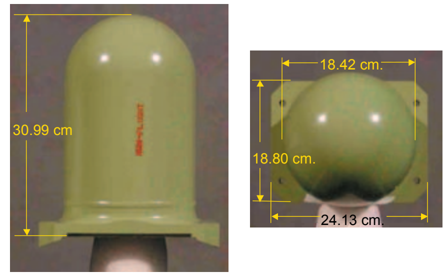

Fig. 3. ET Bolt Catcher Dimensions

A Bolt Catcher's radar return signature characteristics, as well as its mean and maximum RCS, were established in controlled testing at the AFRL, WPAFB. The testing was conducted within the ER radar operating parameters of 5690 MHz frequency and linear vertical polarization. These signatures and measurements were used as an approximation of the signal that may be returned from a Bolt Catcher if captured by the ER tracking radar. Fig. 4 and Fig. 5 present the results of the AFRL C-Band tests. Note that all measurements done at the AFRL were taken from a Bolt Catcher without SLA coating. All comparisons made in this report use these numbers. Although no RCS information is available for a Bolt Catcher with an SLA coating, the maximum RCS magnitudes are not expected to be significantly different from that of an uncovered Bolt Catcher due to the thickness of the coating (1.52 cm) relative to the radar's wavelength (λ), which is 5.27 cm or 0.29λ, and the low radar reflectivity of SLA. A 230-cm^2 plate with SLA coating has an RCS of -32 dBsm vice 3.9 dBsm for a similarly sized metal plate without SLA coating [ref. 4].

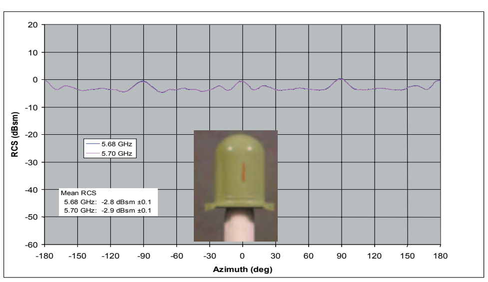

Fig. 4. ET Bolt Catcher, Vertical Mount, Vertical Polarization, C-Band

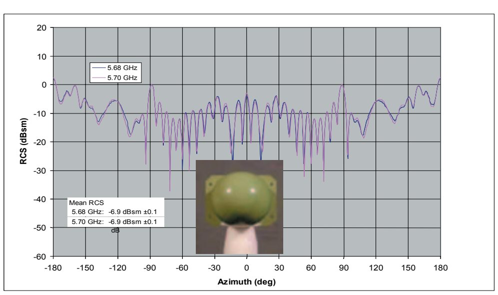

Fig. 5. ET Bolt Catcher, Horizontal Mount, Vertical Polarization, C-Band

The command for SRB separation was issued at T+127 s. Radar 0.14 detected no items around the time of SRB separation, Radar 19.14 detected five items, and Radar 28.14 detected one item. The maximum RCS of the detected items during that time ranged from -15 dBsm to +1 dBsm.

Examination of the RTI charts for Radar 19.14 and Radar 28.14 shows a large cloud of debris particles after SRB separation with some distinct particles discernable from the cloud (Fig. 6 and Fig. 7). The possibility exists that more debris was present than was detected, as the separating SRB and/or its plume may have masked signals from separating objects.

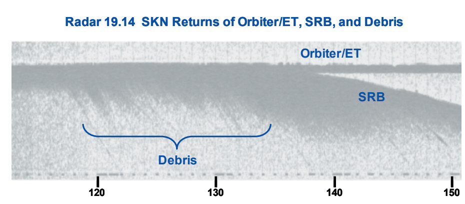

Fig. 6. Radar 19.14 RTI, T+113 s – T+150 s

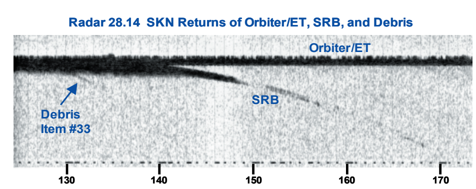

Fig. 7. Radar 28.14 RTI, T+125 s – T+173 s

The digitized data from T+110 s to T+140 s was analyzed in an attempt to determine the basic shape (e.g., flat plate, cone, cylinder, sphere) of the debris. Radar signatures were examined for all objects. For all but a single item, Item #33, the signal returns from the debris could not effectively be distinguished from the radar noise and thus prevented reasonable estimation of the shape. Based on the signal specular analysis, the majority of the debris is assumed to be irregular in shape. As a result, all debris items during this time period were excluded as possible Bolt Catcher candidates, with the exception of debris Item #33. The speculars from Item #33 were well defined, and a detailed analysis of debris Item #33 is provided in the following section.

Debris Item #33

Debris Item #33 (Fig. 8) is first observed at T+128 s, one second after the SRB separation command was issued. The item has a range separation rate of 520 m/s (with a 120 m/s uncertainty), and is visible for two seconds. The signal return of this item is significantly stronger than any of the debris detected by any radar from SRB separation through the remainder of the mission, indicating a larger or a more highly reflective item than any of the other detected debris items. An RTI contour plot depicting debris Item #33 separating from the Orbiter/ET stack is shown in Fig. 8.

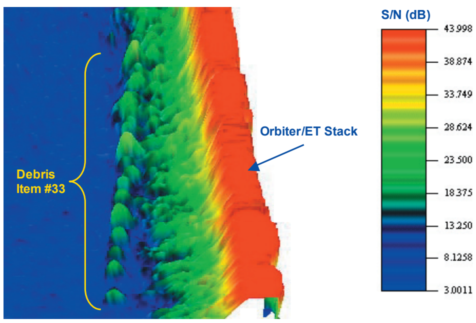

Fig. 8. Item #33 RTI Contour Plot

Item #33 radar signatures are shown in Fig. 9. Analysis of the peaks in this figure suggests a tumble rate of at least 310 degrees per second. At this rate, the 160-PRF of the observing radar limits the speculars to a maximum resolution of 1 point for every 2 degrees. The low resolution of the signature data limits the information that can be extracted from this data. Comparison of the radar spectrals with the Bolt Catcher RCS data gathered at the AFRL (Fig. 4 and Fig. 5) does not eliminate Item #33 as a candidate for a Bolt Catcher, but the low resolution of the signature prevents positive identification. Although the radar signature analysis to determine the shape is inconclusive, the signature peak magnitudes provide information of the maximum RCS of the item, which can be translated into approximate sizes for selected shapes.

Radar 28.14 has a 3-dB beamwidth of 0.38 degrees. As the debris item is moving out of the main radar beam, the debris can be expected to fall out of range for reasonable estimation of true RCS when it exceeds the half-beamwidth point. This is consistent with the signature data; the debris item begins to pass out of the high gain region of the radar beam at T+129.8 s, at which point the item has moved approximately the distance of the radar's half beamwidth. Item #33 spectral data after T+129.8 s was not used in this analysis.

Analysis of the speculars shows that the RCS peak amplitudes of Item #33 returns are consistent with the peak amplitudes for the nose, broadside, and base of an ET Bolt Catcher as determined by measurements at WPAFB (Fig. 4 and Fig. 5). All peak RCS amplitudes for Item #33 are within the uncertainty values established in Revision 1 of the original Technical Report [ref. 2] to be matched to the RCS of the individual facets of a Bolt Catcher; nose, broadside, and base. The AFRL tests indicate that the rounded nose of a Bolt Catcher has a maximum RCS of -3.2±0.1 dBsm. The broadside and the end of a Bolt Catcher have a maximum RCS of -0.3±0.1 and 2.4±0.1 dBsm, respectively. The peak speculars measured at Radar 28.14 ranged from -2 to 2 dBsm with a 3-dBsm uncertainty.

If Item #33 were a metallic cylinder, its theoretical dimensions would be similar to the dimensions of an ET Bolt Catcher. The peak specular amplitudes indicate that the item has a maximum reflective surface of 170±60 cm^2. This reflective area would be produced by a cylinder with a 20±9 cm diameter and a length of 32±9 cm. These tolerances on the Item #33 dimension estimates make it well within the possibility to be the dimensions of an ET Bolt Catcher.

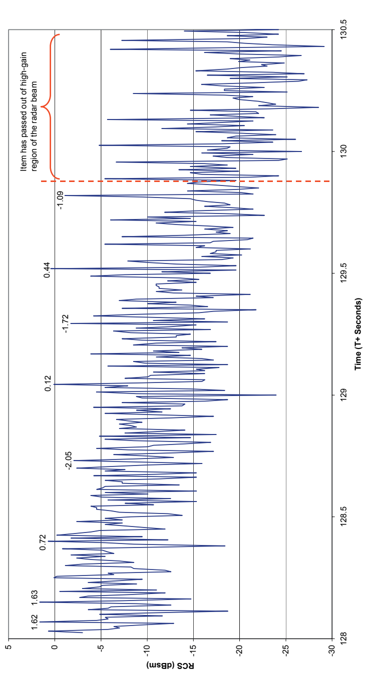

Fig. 9. Item #33 Spectral Plot

Debris Item #33 was evaluated to determine if it could be any other part of the Forward Separation Bolt assembly (Table 1). The ET Bolt Catcher attachment bolts, Bolt Catcher honeycomb particle, and ET separation bolt were eliminated as possible candidates, since none of these items would produce a return of Item #33's magnitude.

Table 1. Forward Separation Bolt Assembly Parts

ITEM	MATERIAL	SIZE (cm)
Bolt Catcher Attachment Bolt	A-286 CRES	0.953 diameter x 6.35 long
Bolt Catcher Honeycomb Particle	AL-5052 Metallic Dust	Typically less than 0.08 diameter x 0.08 long
ET Separation Bolt	4340 Steel	7.62 diameter x 29.21 long

The Item #33 maximum RCS was compared to the maximum RCS that would be returned by a Booster Separation Motor (BSM) aft cover [ref. 4]. The maximum RCS of Item #33 is 1.7±3 dBsm, and the maximum RCS of the BSM aft cover is -9.5±1 dBsm. The much greater RCS of Item #33 eliminates the possibility that it is a BSM aft cover.

Radar 19.14 Debris

The only radar other than Radar 28.14 that detected debris around SRB separation was Radar 19.14. An evaluation of Radar 19.14's debris items was conducted to determine if any of the debris detected could have been any of the forward bolt assembly parts listed in Table 1. The theoretical maximum RCS of a Bolt Catcher attachment bolt is -26 dBsm. At SRB separation, the RCS detection sensitivity for Radar 19.14 was -29 dBsm, so the radar should have been capable of detecting Bolt Catcher attachment bolts if they separated from the Bolt Catcher. Radar 19.14 detected five debris items in close proximity to SRB separation. The maximum RCS of the detected items ranged from -15 dBsm to -13 dBsm. The RCSs of these debris items are too large to be an attachment bolt.

The typical estimated size of a honeycomb particle is too small to be detected by the radar and would have been undetected if present.

The theoretical maximum RCS of the ET separation bolt is -4 dBsm. The maximum RCS of debris items detected by Radar 19.14 (-15 dBsm to -13 dBsm) did not exceed -4 dBsm, so it is possible that one of these items could be an off-aspect return from the bolt. As stated in previous reports [ref. 1 and ref. 2], the signal returns from the debris could not effectively be distinguished from the radar noise and, based on the signal specular analysis, it is assumed that the debris was irregular in shape. As a result, none of these debris items are considered a candidate for the ET separation bolt in the event it separated from the forward separation bolt assembly.

Historical Review

CSR Systems Analysis reviewed 48 previous Shuttle missions for which RTI charts are available, dating back to November 1994. On 19 of these missions, a debris item was detected at a time similar to that of Item #33, specifically, at or near the time of SRB separation. Additionally, on five of these 19 missions, the debris items exhibit a very strong similarity to Item #33 in that they were singular, distinct items, and had similar returns. These five missions were F1642 (STS-110), F1076 (STS-105), F4289 (STS-100), A4651 (STS-95), and A3839 (STS-90). It cannot be determined if these items are identical to Item #33, since all data required to perform a complete analysis may not exist.

CONCLUSIONS

Debris Item #33 was determined to be the only possible candidate for an ET Bolt Catcher. Analysis of speculars from the item shows that the peak amplitudes of the returns are characteristic of the peak amplitudes for the nose, broadside, and bottom of an ET Bolt Catcher as determined by RCS measurements by the AFRL at WPAFB. Additionally, the peak return observed by Radar 28.14 would, theoretically, be indicative of a metal cylinder with similar dimensions of an ET Bolt Catcher.

Full characterization of the signature pattern could not be accomplished due to PRF limitations, and the exact shape of the debris item could not be determined. As a result, this analysis cannot definitely determine if this item is, or is not, an ET Bolt Catcher. However, due to the detection of the item in close proximity to SRB separation, the similar peak amplitudes, and similar theoretical size, this item is considered a reasonable candidate to be an ET Bolt Catcher.

Debris Item #33 was evaluated to determine if it could be any part of the Forward Separation Bolt assembly (Table 1). The ET Bolt Catcher attachment bolts, Bolt Catcher honeycomb particle, and ET separation bolt were eliminated as possible candidates, since none of these items would produce a return of the magnitude observed by Radar 28.14. Additionally, the signal returns from Item #33 were determined to be too large to be a Booster Separation Motor (BSM) aft cover.

RTI data from previous missions indicate that debris items have been detected at or near SRB separation on 19 past missions. Seven items from five missions exhibit strong similarities to Item #33.

ABBREVIATIONS AND ACRONYMS

λ	Wavelength
45 RMS	45th Range Management Squadron
AFRL	Air Force Research Laboratories
AL	Aluminum
BSM	Booster Separation Motor
CCAFS	Cape Canaveral Air Force Station
CRES	Corrosion Resistant Steel
CSR	Computer Science Raytheon
cm	centimeters
dB	decibels
dBsm	Decibels per square meter
DPDE	Data Playback and Digitizing Equipment
ER	Eastern Range
ET	External Tank
FRV	Full Range Video
GHz	Gigahertz
IRIG	Inter-Range Instrumentation Group
JDMTA	Jonathan Dickinson Missile Tracking Annex
KSC	Kennedy Space Center
m/s	Meters per second
MHz	Megahertz
NASA	National Aeronautics and Space Administration
PAFB	Patrick Air Force Base
PRF	Pulse Repetition Frequency
RCS	Radar Cross Section
ref.	Reference
RFLG	Radio Frequency Loop Gain
RTI	Range Time Intensity
s	second
S/N	Signal-to-Noise
SKN	Skin
SLA	Super Light Ablative
SLC	Space Launch Complex
SRB	Solid Rocket Booster
WPAFB	Wright Patterson Air Force Base

REFERENCES

1. CSR Technical Report – Debris Analysis Report for Operation F1120, Shuttle STS-107, 16 January 2003. 14 February 2003.

2. CSR Technical Report – Debris Analysis Report for Operation F1120, Shuttle STS-107, 16 January 2003, Revision 1. 4 April 2003.

3. *RCS Assessment of STS-107 Debris Candidates*, Air Force Research Laboratory, Sensors Directorate, Brian M. Kent, Dan A. Turner, 14 March 2003.

4. Report No. CSR 321-9012, *ETR Radar Support of the STS-27 Tile Damage Investigation*. A.E. Hoffmann-Heyden, 3 February 1989

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