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RCS Analysis of the Reinforced Carbon-Carbon Tee-Seals as Potential "Flight Day 2" Candidates in Support of the Columbia Accident Investigation

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Abstract

During the Columbia Shuttle investigation, AFRL tried to identify a piece of on-orbit debris that originated from the Orbiter during its second day in space. This "Flight Day Two (FD2)" object was detected by UHF radar and tracked for three days before falling out of orbit. Extensive RCS measurements performed by AFRL and corresponding ballistic analysis by USAF Space Command narrowed the potential candidates down to just two possible classes of objects; (1) a section of Reinforced Carbon-Carbon (RCC) leading edge panel acreage, and (2) a section of RCC "Tee-seals".

During the investigation, AFRL was asked to estimate the UHF RCS of various whole and fragmentary Tee-seals originating between panel segment #6 and #11 on the Shuttle Orbiter left wing, in order to compare with the on-orbit UHF RCS observations. Since actual Orbiter Tee-seal hardware, either whole or fractured, from the left wing area were not available, we predicted UHF RCS on various virtual Tee-seal fragment geometries to confirm or eliminate the Tee-seal as a candidate for the FD2 object. In this paper, we summarize our RCS predictions which conclusively show that a whole or partial RCC Tee-seal could not be the FD2 object. This left the RCC panel acreage as the only known object that satisfies both the on-orbit observed ballistic and UHF RCS data, a confirming piece of evidence in the Columbia investigation.

1. Introduction

Radar Cross Section (RCS) predictions of six Reinforced Carbon-Carbon Tee-seals from the Space Shuttle Columbia were needed to help determine if any of these Tee-seals, or a portion of it, could have been the space object designated "2003-003B" detected on flight day 2 by ground based UHF tracking radars. (This object is more commonly referred to as the "Flight Day 2" object). This space object was detected in orbit on January 17th, 18th, and 19th, 2003, by the Pave Paws UHF Phased array tracking radar at Cape Cod and Beale Air Force Base. For more details on the background of "2003-003B", please refer to[1]. The Tee-seals located on the left wing section are suspected to have been hit by a piece of dislodged foam from the booster during take-off. Damaged Tee-seals may have allowed heat penetration through the Tee-seal opening and weakened the thermal protection system during the reentry stage. Since the precise location of the edge or Tee-seal damage is not known and the actual parts were not recovered, NASA requested AFRL to study six Tee-seals on the left wing based on their CAD models. They will be denoted as Tee-seal 006, 007, 008, 009, 010, and 011 here.

There are many ways that a Tee-seal (or Tee-seal fragment) could have theoretically broken away from the shuttle. We assumed several such "broken Tee-seal scenarios" and produced RCS predictions for those scenarios to see if any of the predicted RCS correlates to the RCS collected by the tracking radar. If the RCS for one of the scenarios compared well with the collected data, the information may suggest that a Tee-seal or Tee-seal fragment *may be a candidat*e for the space object "2003-003B". If none of the predicted RCS matched the collected data, we may rule out these Tee-seals as possible candidates for the space object "2003-003B". According to the assessment in[1], for an object to be a potential "2003-003B" candidate, its circular polarization (CP) UHF RCS has to *equal or exceed* $-1 dBsm \pm 1.3\ dB$ over some angular range at the radar frequency of 433 MHz.

Subsequent sections of the paper are organized as follows. In Section 2, global RCS of the six Tee-seal are computed for four possible scenarios: the whole Tee-seal and three Tee-seal fragments. Since the broken Tee-seal may exhibit resonant behavior at certain fragment lengths, we calculated 38 possible fractional scenarios for Tee-seal

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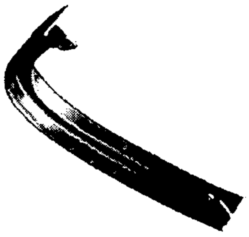
009 by increasing the length of the Tee-seal fragment by one inch increments. In Section 3, we compared the predicted RCS of a non-flight worthy Tee-seal 21 to that measured at the AFRL Advanced Compact Range. This comparison was done to provide a baseline validation for the measurement and prediction data (from the CARLOS code developed by The Boeing Company) on the Tee-seal geometry class. Finally, we conclude our findings in Section 4.

2. Global Radar Cross Sections

Six Tee-seals of different lengths and similar shapes were studied. In Figure 1 and Figure 2, one of the Tee-seals and its mesh are shown, respectively. The lengths for Tee-seal 006, 007, 008, 009, 010, and 011, are 53, 59, 69, 62, 60, and 59 inch long, respectively, with widths from five to six inches. At 433 MHz, the wavelength is 27.28 inches which means the length of the Tee-seals is approximately 2 wavelengths. Due to space limitations, we present numerical predictions only for Tee-seal 009 in this paper, however, similar computations were done for all six Tee-seals.



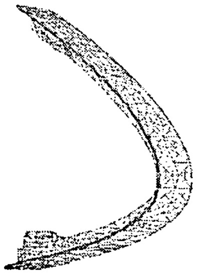


Figure 1. Tee-seal 009 (*left*) and Figure 2. A triangular mesh of Tee-seal 009 (*right*)

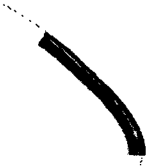


Figure 3. Scenario 2 (*left*), Figure 4 - Scenario 3 (*center*), and Figure 5 – Scenario 4 (*right*)

Since we don't know how the Tee-seals broke away from the shuttle (if they did), we assume the following four scenarios. Scenario 1 is when the Tee-seals broke away in whole as shown in Figure 1. In Scenario 2, the Tee-seals broke from the top of the flange to the apex (see Figure 3). In Scenario 3, the Tee-seals broke from the bottom of the flange to the apex (see Figure 4). In Scenario 4, the Tee-seals broke to form a 20 (Tee-seal 006 and 007) or 30 (Tee-seals 008, 009, 010, and 011) inch long segment including the flange (see Figure 5).

Furthermore, since the orientation of the whole or partial Tee-seal floating in space is unknown, we computed the global RCS values of each of the scenarios to find the maximum possible RCS value. Using the spherical coordinate system, we generated global RCS data by computing the azimuthal pattern (ϕ varying from 0 to 360 degrees) for each theta angle and increasing the θ angle in one-degree steps (θ varying from 0 to 180 degrees). In Figure 6, we plotted the global RCS for Tee-seal 009. The maximum value of each plot indicates the highest possible RCS value for that particular Tee-seal and particular scenario. The minimum of the "peaks" from all pattern cuts is also listed below each figure. The minimum and maximum peak values define the range of peak RCS as the Tee-seal spins in all directions. Figure 7 shows that the maximum RCS from all the Tee-seals and all the scenarios is −3.08 *dBsm*. This value comes from Tee-seal 008, the largest Tee-seal, at its full length (Scenario 1). Since the maximum RCS is less than −2.3 *dBsm*, these six Tee-seals are very *unlikely* candidates for "2003-003B".

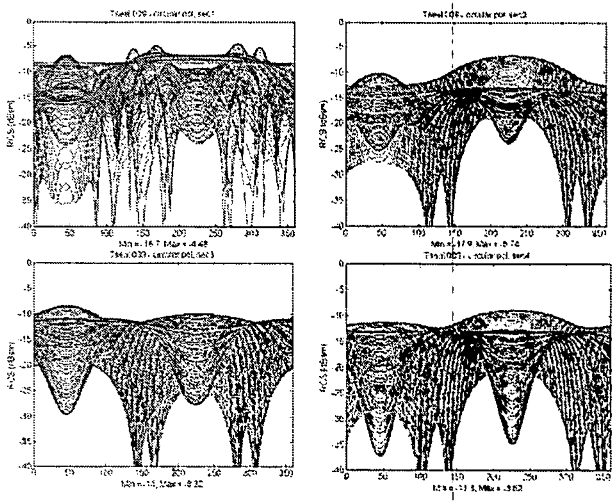


Figure 6. Global RCS of Tee-seal 009

Even though the initial study with the four scenarios suggests that Tee-seals are not candidates, it is possible that at certain resonant lengths, the RCS could be higher than the maximum RCS for the four scenarios. We decided to focus on Tee-seal 009 for this study. Tee-seal 009 is approximately 62.36 inches long. Each flange portion is approximately 8 inches long. We only considered the portion of the seal without the flanges. This flangeless segment was cut into 38 sections of increasing lengths. The first section is approximately 8.66 inches long. The other sections were cut into 1 inch increments. For example, the second section was 8.66+1.018 = 9.678 inches long, the third section was

8.66+ 2×1.018 = 10.696 inches long, etc. The last section (number 38) is the whole flangeless portion of the Tee-seal (see Figure 8 and Figure 9). We provide a schematic drawing of the 38 sections of Tee-seal 009 in Figure 10.

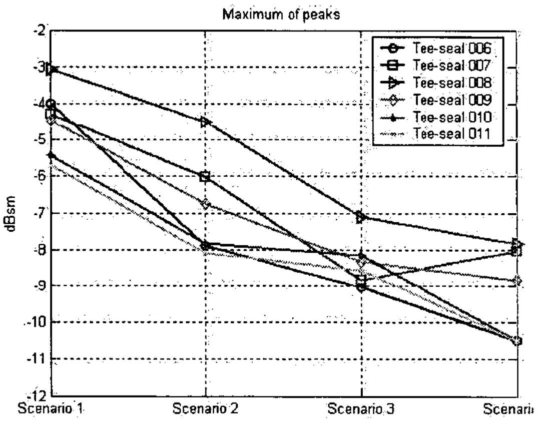


Figure 7. Maximum peaks for different Tee-seals. The highest RCS occurs for Scenario 1 of Tee-seal 008 at -3.08 dBsm

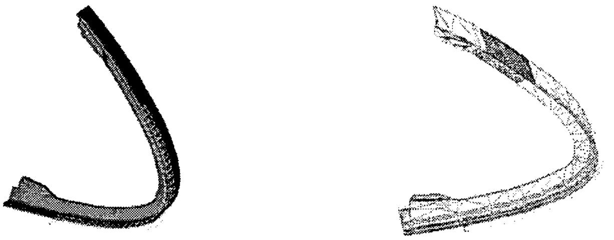


Figure 8. 1-inch incremental cuts of Tee-seal 009 (*left*) and Figure 9 - First fragment of Tee-seal 009 (*right*)

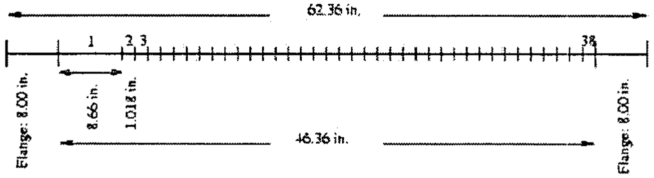


Figure 10. Schematic cuts. The flanges are cut off. The first section is 8.66 inch long. Each consecutive section is 1.108 inch longer than the preceding one. For example, the second section is of length 9.678 inches and the third section is of length 11.174 inches.

Next, we computed the global RCS of the 38 sections at 10 degree increments in the theta direction ($\theta = 10^0$, $20^0, \ldots, 170^0$). For each pattern cut, we determined the maximum. Thus, there are 17 such maxima for each section. By taking the largest and smallest of these 17 numbers, we can establish an upper bound and a lower bound for the largest possible RCS of each section. In Figure 11, we plot the bounds as a function of section number. Notice that the longest section has the highest RCS. There are sections of the seal that reflect the resonance phenomenon such as section 3 (~11.96 inches in length) and section 16 (~25.14 inches in length).

Other Tee-seals exhibit the same behavior with the largest section having the highest RCS and some intermediate sections falling into the resonance regions. From this part of the study, we conclude that the highest RCS for each Tee-seal occurs when the Tee-seal is in its full length. In other words, ***no matter how you cut the Tee-seal, its RCS is going to be lower than the Tee-seal in its full length.*** This again suggests that the highest RCS of all Tee-seals or any Tee-seal fragment is "−3.08 dBsm" indicating that these Tee-seals are not likely candidates for the FD2 object.

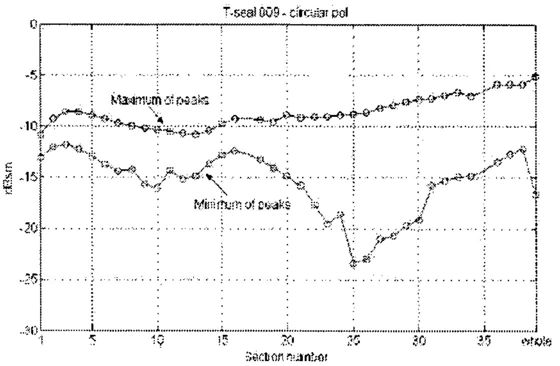


Figure 10. Global maximum and minimum of peaks of Tee-seals 009. Note that the highest RCS occurs when the whole Tee-seals 009 is considered.

3. Predictions and Measurements

To establish computational electromagnetics as a viable approach for this study and to validate our measurement processes, we compared the CARLOS predictions to the Advance Compact Range (ACR) Measurements on Tee-Seal 21. NASA-JSC had sent AFRL a non-flight worthy Tee-Seal from station 21 that is part of the leading edge of the Space Shuttle because of its availability, even though station 21 is not a candidate location of the debris strike in the STS-107 investigation. To generate a geometry file exactly the same as the geometry that was measured, we used a laser scanning technique on the physical Tee-seal 21 (see Figure 12) geometry.

The scanned geometry has such high level of detail that it includes details of "bumps" and embossing on the inside of the Tee-seal. This particular non-flight worthy Tee-seal sample we received from NASA and measured at the ACR has a cutout at the upper right corner of the geometry as shown in Figure 12. We predicted Tee-seal 21 in the same three mounting positions as in the measurement setup. Figure 13 shows the Side mount that was 8 degrees from the plumb. Figure 14 shows the Vertical mount that was 7.3 degrees from the plumb. Although the Horizontal mount was level (see Figure 15), the "front" may not be precisely aligned to zero azimuth.

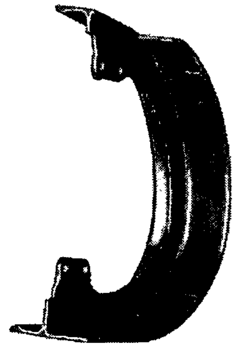
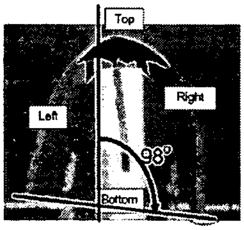


Figure 12. Laser scanned Tee-seal 21 for predictions (approximate 500,000 flat facets)



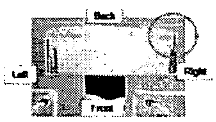


Figure 13. Side mount (*left*), Figure 14 - Vertical mount (*center*), and Figure 15 - Horizontal mount(*right*)

Figure 16 shows that the prediction and the measurement data have excellent agreement in magnitude for the horizontal mount case. Initially, we were concerned that the Reinforced Carbon Carbon Tee-seal may not be a perfect conductor as assumed in the computer model. This concern was dismissed once we obtained such excellent agreement with the measurement. Figure 17 shows the comparison for the Vertical mount case. Again, the agreement is excellent. Figure 18 shows the comparison for the Side mount case. The small discrepancy in the 60 ±° region can be attributed to the alignment difference between the measurement set up and the prediction model. Since it is very difficult to physically align the Tee-seal when the inside ridge of the Tee-seal is supported at only two points by a piece of foam, the Tee-seal can be slightly off the plane defined by the plumb and the bottom line (see Figure 13). Overall, the agreement between the predictions and measurements is excellent allowing us to validate the computational methodology with measurements and have high confidence in our conclusions from section two.

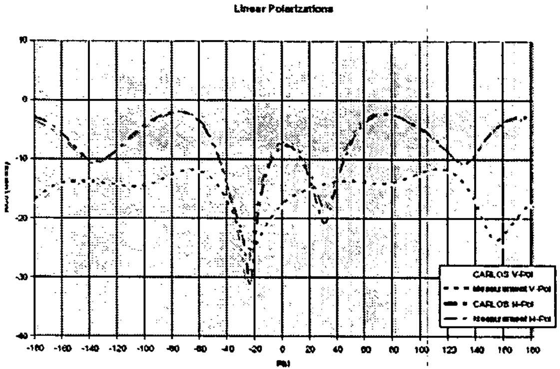


Figure 16. Predictions vs. Measurements –horizontal mount

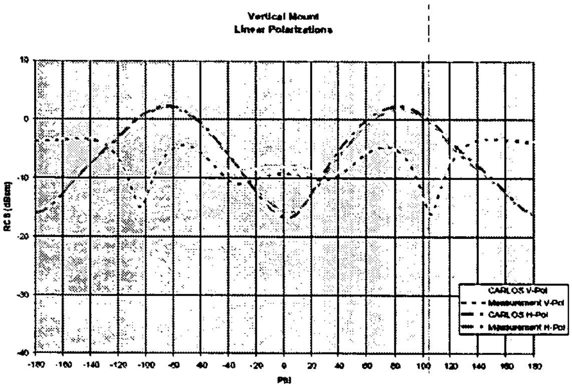


Figure 17. Predictions vs. Measurements –vertical mount

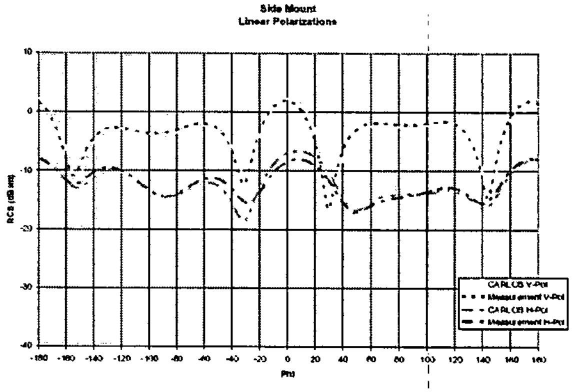


Figure 18. Predictions vs. Measurements –side mount

4. Conclusions

In this paper, we presented a thorough study of the RCS characteristics of Tee-Seals #6 through #11 on the left wing of the Space Shuttle Columbia. We systematically "cut up" a Tee-seal and computed its RCS for Tee-seal #9 starting with the region beyond the flange and adding one inch at a time until the entire Tee-seal was re-created. The results of this assessment allow us to conclude that: (1) at 433 MHz, in no case is the peak

RCS of a partial Tee-seal as large as the RCS of a whole Tee-seal; (2) no combinations of angles and Tee-seal piece sizes produce a Tee-seal candidate whose RCS meets the −1 *dBsm* minimum within the ±1.3 *dB* uncertainty; and (3) even Tee-seal #21 has a predicted CP RCS less the −1 *dBsm* peak value within the limit of measurement uncertainty.

To validate the predictions and measurement data on the Tee-seal, AFRL laser scanned Tee-seal #21 provided by NASA-JSC and compared linear RCS measurements to CARLOS predictions. The resulting data were in outstanding agreement, providing our team a high level of trust in our measurement efforts and predictions calculations for this effort.

The overall conclusion of this study is that, within measurement uncertainties on orbit, AFRL now believes that Tee seals number 6, 7, 8, 9, 10, or 11 are *not viable candidates* for the FD2 object based on our extensive evaluation of both whole tee-seals as well as fragmentary tee seal predictions.

Acknowledgements

The authors would like to thank Mr. David Henn of Lockheed Fort Worth for his help in the initial geometry preparation. Mr. Henn is the ACAD geometry package developer. ACAD was used to generate the surface meshes for this study. His assistance on how to generate surface meshes with the greatest geometry fidelity while minimizing the number of facets significantly improved the throughput of the computation. Because of his help, we were able to explore many scenarios to provide enough data points to conclude our study. For this, we are very grateful. The authors would also like to thank Mr. John Putnam of the Boeing Company for his help on CARLOS, especially on overcoming some geometry input challenges. In addition, we thank Mr. William Griffin of Mission Research Corporation for collecting the Tee-seal 21 geometry via laser radar. Without this geometry, we would not be able to compute Tee-seal 21 and validate our approach for this study. Finally, we appreciate the DoD High Performance Computing Modernization Program (HPCMP) resources made available to us at the ASC and ARL Major Shared Resource Centers. Without the HPC resources, this study would not have been possible.

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