Investigation Report of the STS-87 SPARTAN Close Call

Date of Close Call: November 21, 1997

Johnson Space Center

March 2, 1998

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TO: MA/Manager, Space Shuttle Program

FROM: Chairman, STS-87 SPARTAN Close Call Investigation Board

SUBJECT: STS-87 SPARTAN Close Call Investigation Report

Reference Memorandum MA2-97-201, STS-87 SPARTAN Mission Failure

In accordance with your memorandum of December 9, 1997, the Close Call Investigation Board report has been completed and signed by the Board members. Six copies of the report are hereby forwarded to you for distribution and review by organizations responsible for addressing the recommendations. The original report and data collected will be maintained on file by the JSC Occupational Safety Office, Mail Code NA3.

Richard J. Hieb 3/2/98

Richard J. Hieb

Enclosure (six copies)

STS-87 SPARTAN CLOSE CALL
JOHNSON SPACE CENTER

The STS-87 SPARTAN Close Call incident has been investigated and this report containing the facts, findings, and recommendations, is hereby submitted.

CONCURRED BY BOARD MEMBERS:

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AlliedSignal corporation

Neil B. Hutchinson, Member
Science Applications International Corporation

Carl J. Meade, Member
Lockheed Martin Corporation

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Key Personnel Involved In Board Actions or Interviews

Name (Affiliation)	Position	Interviewed
Briscoe, A. Lee (NASA)	Chief, Flight Director Office	Yes
Chawla, Kalpana (NASA)	STS-87 MS1	Yes
Cockrell, Ken (NASA)	CB Crew Selection	Yes
Doi, Takao (NASA)	STS-87 MS3	Yes
Eastabrooks, Earl (USA)	STS-87 Simulation Supervisor	Yes
Embrey, Bernard (NASA)	Engineering, CCTV	No
Frank, Jorge (USA)	STS-87 Rendezvous Trainer	Yes
Gonzales, Lee (USA)	STS-87 Payload Officer	Yes
Harshman, David (USA)	STS-87 Lead RNDZ Officer	Yes
Hartwig, Scott (USA)	USA Training Director	Yes
Kregel, Kevin (NASA)	STS-87 Commander	Yes
Limongelli, John (USA)	STS-87 Lead Trainer	Yes
Lindsey, Steven (NASA)	STS-87 PLT	Yes
Magh, Albert (USA)	STS-87 PDRS Officer	Yes
Marquette, David (NASA)	STS-87 GNC	Yes
Mascaro, Tina (USA)	STS-87 Lead Payload Officer	Yes
Noriega, Carlos (NASA)	CB Training Lead	Yes
Noyes, Chris (USA)	STS-87 RMS Trainer	Yes
Pallesen, Don (NASA)	PDRS Group Lead	Yes
Quenneville, Steve (USA)	PGSC Management	Yes
Reeves, William D. (NASA)	STS-87 Lead Flight Director	Yes
Scott, Winston (NASA)	STS-87 MS2	Yes
Tooley, Craig (GSFC)	STS-87 SPARTAN Lead	Yes
Vora, Nainish (USA)	MOD PDRS Analyst	No
Zeh, John (USA)	STS-87 Payload Trainer	Yes

4. EXECUTIVE SUMMARY

The STS-87 Close Call Investigation Board addressed the SPARTAN spacecraft failure to execute its pirouette maneuver and the failure to re-grapple the SPARTAN following the failure to pirouette. The failure to re-grapple investigation included both the initial tipoff of the SPARTAN by the remote manipulator system (RMS), and the failed rate matching efforts by the orbiter following the tip-off. Not included in the investigation were the separation, rendezvous, and EVA capture.

STS-87 was a 16 day flight with six crew members. The primary payloads were the United States Microgravity Payload (USMP) and the SPARTAN-201 satellite. Additionally, there was a planned Extra-Vehicular Activity (EVA). SPARTAN-201 had flown three times before (STS-56, 64 and 69) without problems except for some difficulty in berthing, due to tight clearances within the release/engage mechanism (REM). Other SPARTAN missions had been flown on the shuttle (STS-63, 72, and 77) with different scientific instruments and payload objectives. The original flight plan was to deploy the SPARTAN on flight day 2 and retrieve it two days later. Due to problems with an independent cooperative satellite (SOHO), the SPARTAN deploy was rescheduled to flight day 3 (November 21, 1997).

On flight day 3, a new flight plan was uplinked and executed by the crew. The final command required to prepare SPARTAN for deployed operations was a crew input via the Payload and General Support Computer (PGSC.) This input was not received by the spacecraft. Lack of telemetry and onboard verification procedures left this condition undetected by MCC and the flight crew. The Board's conclusion based on all the evidence available is that the crew inadvertently omitted the SPARTAN Standby step. SPARTAN was grappled with the Remote Manipulator System (RMS), removed from the Release/Engage Mechanism (REM), and released per the flight plan. The missed command step resulted in the failure of the SPARTAN to execute an expected preprogrammed maneuver ("pirouette") about 2.5 minutes after deploy.

In accordance with the flight rules, and with MCC's concurrence, the crew attempted to re-grapple the SPARTAN satellite. In the process, the RMS operator executed a premature capture, followed by a release in close proximity to SPARTAN, while continuing to drive the RMS towards the grapple fixture. At some point very close to the time the release command was sent, analysis indicates the RMS End Effector snare wires contacted the grapple fixture pin and induced rotational and translational rates into the SPARTAN. A few seconds later, the RMS operator elected to back away rather than attempt capture.

The induced rotational rates (about 2 degrees per second) were judged too large for trying an immediate RMS re-grapple, and the crew attempted to match rotational rates with the SPARTAN spacecraft using the orbiter. Due to its inertial characteristics, lack of an engaged attitude control system, and the tip-off rates, SPARTAN began a 3 axis rotation which made it essentially impossible for the orbiter to match consistently. However, the CDR judged that the rates were low enough that the task was possible. The flight control team established a propellant use limit that protected the remainder of the flight objectives, including retrieval of the SPARTAN satellite. MCC called off the rate matching attempts when that limit was reached. The crew then executed two separation maneuvers, the second to correct residuals from the first. Post flight analysis has indicated there existed an unknown risk of re-contact with SPARTAN caused by substantial attitude control maneuver cross-coupling into translations.

During this rate matching attempt, additional rotational rates were imparted to the SPARTAN by inadvertent RCS jet plume impingement. These were of sufficient magnitude (> 3.8 degrees per second) to cause the SPARTAN to invoke its Minimum Reserve Shutdown mode which, over several orbits, reduced the rates to approximately zero.

A re-rendezvous was planned and executed two days later. The SPARTAN was captured by two EVA crew members and stowed in the REM with the help of the RMS. Re-deployment of SPARTAN was considered later in the mission; however, Space Shuttle Program management concluded insufficient Orbiter RCS propellant remained to guarantee retrieval of the spacecraft.

Principal recommendations of the Board include:

(1) Apply Cockpit Resource Management (CRM) techniques for critical on-orbit activities such as deploys and other RMS operations.

(2) Improve the crew interface to the PGSC/SPARTAN software.

(3) Improve payload training accountability.

(4) Improve assessment and thoroughness of crew member retention of critical training objectives.

(5) Develop and implement a final SPARTAN "Ready for Deploy" verification.

(6) Revisit safety analyses to assess expanding or removing SPARTAN 1-hour constraint.

(7) Re-examine the objectives mix in RMS training; must increase the fail-to-capture element.

(8) Improve range-to-grapple information available to the RMS operator.

(9) Establish rate matching flying techniques, procedures, and Flight Rules and then train to them.

5. METHOD OF INVESTIGATION

The STS-87 SPARTAN Close Call Incident Investigation Board conducted its investigation through collection and evaluation of relevant video and audio media; observation of relevant hardware; review of relevant Flight Data File, Mission Rules, training records, training plans, and real-time uplink message documentation; demonstrations of relevant software and hardware; interviews with members of the flight crew, the training team, and the mission control team, including the SPARTAN customer; and special tests and analyses established by the Board.

A fault tree approach was developed to insure all potential causal paths were investigated. (See Volume II, Section K).

Relevant flight materials were impounded after STS-87 landing until copies could be made or special tests performed to confirm or eliminate potential causes.

Specific tests were authorized for the purpose of acquiring relevant data, including tests of the SPARTAN spacecraft using the flight PGSC hardware and software, KSC tests of the Remote Manipulator System to compare with pre-flight test results, and special tests of the CCTV camera and recording systems. (See Volume II, Section F.)

The Board conducted interviews and received technical briefings at JSC during the weeks of December 9, 1997 and January 12, 1998. Board members investigating various detailed elements of the fault tree conducted independent interviews with relevant parties. Parties interviewed by the Board are listed in Volume I, Section 3.

Data review, analyses and reports were performed by members of the STS-87 flight control team, the STS-87 training team, the SPARTAN customer, The JSC Engineering and Space and Life Sciences Directorates, and the KSC vehicle and payload preparation team. These were presented or provided to the board in appropriate form. (See Volume II.)

6. NARRATIVE DESCRIPTION OF CLOSE CALL

6.1 Background

The STS-87 mission was launched November 19, 1997, and included as its primary payloads the United States Microgravity Payload 4 (USMP-4) and SPARTAN 201-4. There were several secondary payloads, DTOs, DSOs and Risk Mitigation experiments. Additionally, there was planned Extra-Vehicular Activity (EVA). There were six crew members, two of whom had previous flight experience.

The STS-87 crew was assigned approximately nine months prior to launch. The commander (CDR) established an initial distribution of mission tasks. The training organization applied training requirements based on the training catalogue and the specific task assignments to each crew member. All training requirements were met and demonstrated to the extent possible in the available simulation facilities. The crew, the Flight control Team and the training organization all felt the training to be adequate and successful, with all elements well prepared to execute the flight.

Launch was on time on November 19, 1997. On launch day, information of problems with the SOHO satellite (already in orbit), which was an integral part of the solar investigations planned for SPARTAN, caused the flight control team to delay SPARTAN operations from flight day 2 (FD2) to flight day 3 (FD3). This caused a swap of FD3 and FD2, and, taking into account some crew circadian shifting, resulted in FD3 being about an hour shorter between wakeup and SPARTAN deploy than was the case on FD2.

During the RMS checkout period, both the prime RMS operator (MS1) and the backup RMS operator (PLT) exercised the RMS to get a feel for the unloaded arm characteristics. MS1 felt that the RMS was more dynamic that in the simulators.

The crew managed their tasks through the use of the flight plan as the master controlling document, with specific procedures in other documents (e.g., Payload Ops checklist, Rendezvous Checklist, PDRS checklist) executed by various crew members. The CDR's normal process was to check off each line item in the flight plan by calling for verification from the crew member who was responsible for it.

The crew woke up FD3 on time. The FD3 flight plan procedures were uplinked when the K-Band coverage was available after crew wakeup. This made the procedures arrival onboard slightly late and the MCC verbally directed two of the early SPARTAN procedures to be executed by the crew in order to not fall behind the timeline. Although not required, the crew reported the completion of various steps, including SPARTAN steps, up until the time of an LOS period. The SPARTAN Standby step should have occurred, per the timeline, during the LOS period. When the downlink was re-acquired, there was no report from the crew of the Standby step and the MCC did not ask. After receiving the FD3 flight plan uplink, the CDR at some point surveyed the crew as to status of flight plan activities, received a blanket confirmation of "all that SPARTAN stuff," and checked off all SPARTAN steps as a block, including the Standby step. Neither the crew nor the MCC has direct insight into the SPARTAN spacecraft, so there was no independent confirmation. The next steps completed were those associated with RMS grappling, positioning and releasing the SPARTAN and are discussed below.

6.2 Close Call Description

All elements of the flight plan were going well and on time. There were no indications of any problems up until the SPARTAN was deployed. The MCC gave a go for SPARTAN deploy on time and the spacecraft was deployed using the RMS. The SPARTAN spacecraft then failed to initiate a programmed pirouette maneuver approximately 2.5 minutes after release.

The crew, following coordination with the Mission Control Center, attempted to re-grapple the SPARTAN spacecraft with the RMS. During the attempted re-grapple, a tip-off force was imparted to the spacecraft by contact with the End Effector snare wires, resulting in multi-axis rotational rates of the SPARTAN on the order of 2 degrees per second.

The crew attempted, with MCC concurrence, to match orbiter rates with the SPARTAN for approximately one hour so the RMS operator could attempt re-grapple. During this time additional rates were imparted to the SPARTAN spacecraft by orbiter RCS jet impingement that triggered its Minimum Reserve Shutdown (MRS) mode. The automatic activities performed by the spacecraft in MRS made it impossible to recover its mission, but also resulted in reducing the rates to near zero over the next few orbits. The rate matching attempt was unsuccessful and the effort was terminated when propellant was reduced to MCC-determined minimum levels. These minimum levels constituted the propellant required to complete the primary mission objectives, including a subsequent re-rendezvous with SPARTAN.

Two separation maneuvers were accomplished and a re-rendezvous planning effort was undertaken. After a rendezvous two days later, the SPARTAN was captured by two EVA crew members and re-berthed, with the aid of the RMS to push the SPARTAN into its latches.

7. DATA ANALYSIS

7.1 SPARTAN Failure to Pirouette

The SPARTAN crew interface software is loaded in an onboard Payload and General Support Computer (PGSC) which is connected to the SPARTAN spacecraft via orbiter wiring. Use of this software with SPARTAN, up to and including the pre-deploy Status check and all other interfaces exercised once it was re-berthed, demonstrated proper operation, including log file entries for every transaction. This was further confirmed post-landing with a special test at KSC by the SPARTAN customer. No problems were found with the PGSC, the SPARTAN software, or the orbiter wiring.

There is no telemetry available from SPARTAN while berthed, and so there was no opportunity for ground confirmation of spacecraft status. Verbal confirmation of SPARTAN initialization steps with MCC was not required, though occasionally done. By chance, the time for execution of the Standby procedure step was during an LOS period and there was no opportunity for a real-time verbal report from the crew. At the subsequent AOS there was no report of those steps and in accordance with pre-mission planning, the MCC did not ask the crew for a confirmation.

In interviews with the crew, the responsible crew member (MS1) felt that the Standby command had been sent, and the CDR's onboard flight plan showed a check mark by the step indicating that he thought it had been performed. The crew did recall, however, that the Standby step, along with several others, was confirmed in a block rather than as individual steps. ("All of that SPARTAN stuff is complete.")

In summary, analysis of the data relative to the failure of the SPARTAN spacecraft to execute the pirouette maneuver clearly indicates that neither the PGSC display that contains the STANDBY command was called up by the crew, nor was the STANDBY command issued from the PGSC. This is based on review of the special log file (spc.log) that records all transactions between the SPARTAN software program in the PGSC and the SPARTAN spacecraft, in which there was no record of either of the relevant transactions.

7.2 Failure to Re-grapple SPARTAN

7.2.1 RMS Motion Analysis

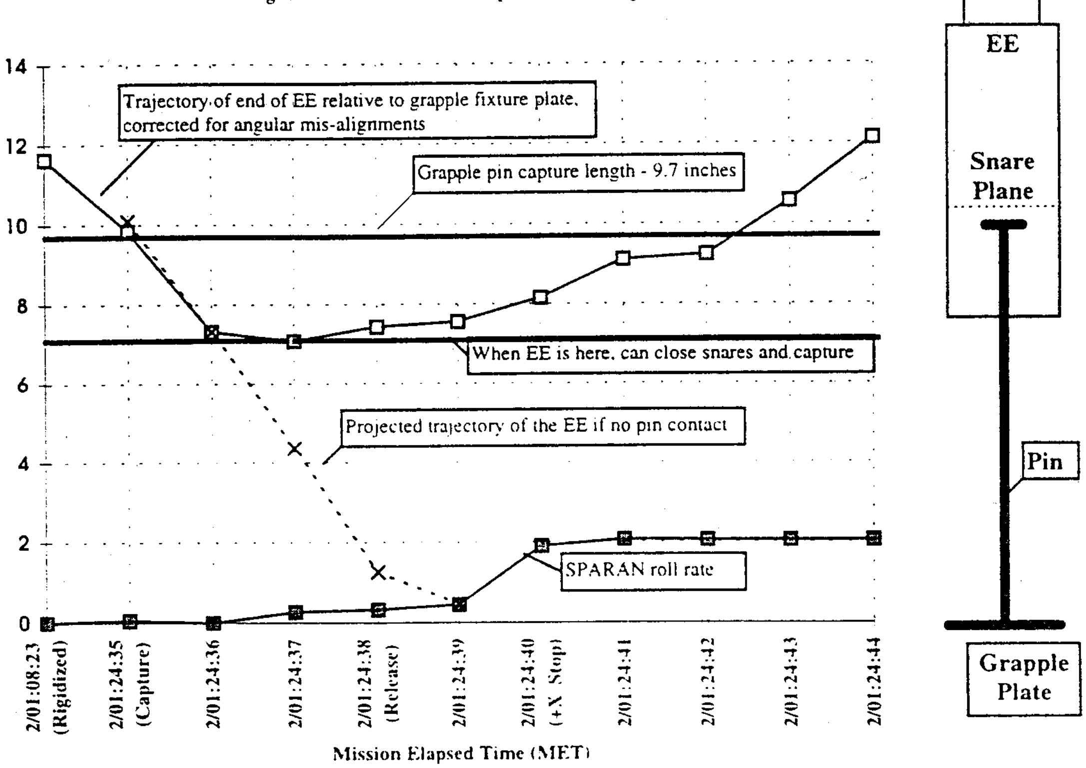
Upon SPARTAN release, the RMS was retracted about 2 feet and then an additional 2 feet (about 56 inches total movement) as the crew awaited the expected SPARTAN pirouette. Once it became apparent that the pirouette was not going to occur, the crew indicated they were going to re-grapple the SPARTAN per the flight rules. The MCC concurred with this action. During this period, there was a small amount of relative motion between the orbiter and the SPARTAN. The CDR wanted to improve the relative position between the grapple fixture and the End Effector (EE) prior to moving the RMS. This required a few small thruster firings. Once this alignment was complete, the RMS operator began movement of the EE towards the grapple fixture.

During this time there were instances of EE camera "blooming" and washout of the CCTV monitor image. A review of recorded EE camera video confirmed blooming, or an overexposed scene, existed for much of the time between initial grapple and the recapture attempt; however, the scene returned to nominal shortly after the RMS began moving towards SPARTAN for re-grapple. The crew reported that a much degraded EE camera view was seen in real time, as compared with that seen later in playback by themselves, the MCC, and this Board. This subject will be addressed in more detail later.

Analysis of the data relative to the failure to re-grapple SPARTAN indicates that the Capture command was erroneously executed before the RMS EE was within the capture envelope. This was confirmed by the RMS operator (MS1). Upon recognition that the command was issued too soon for the capture, MS1 executed the Release command about 3 seconds later. During this time, the EE continued towards the grapple pin at approximately 0.2 fps. This was in contrast to the prescribed response for an early capture command, which is to stop translation and back away before issuing the release command. This procedural deviation was explained by MS1 as due to her belief that the EE was well outside of the capture envelope throughout the inadvertent capture/release sequence.

The Board's review of both the "out-the-window" view as seen from CCTV camera D and the EE camera view indicate the EE was very close to, if not over the grapple pin during the inadvertent Capture/Release sequence. Timing and photo-grammetric analyses (see below) indicate that the snare wires were not fully released (it normally takes about a second) before the EE came within the capture envelope. The SPARTAN rate data retrieved from its tape recorder indicate that the tip-off occurred at about the time of the Release command. The photo-grammetric analysis suggests that the tip of the pin was at the snare wire plane at about the same time. Further, the photo-grammetry indicates that the EE approached no closer to the grapple plate than at the time of tip-off, even though the RMS was continuing to be commanded toward the SPARTAN for several additional seconds. Hence, the board concludes that the snare wires pushed the SPARTAN away as well as inducing rotation. (Reference Volume II, Appendix I.)

Figure 7-1 Photo-Grammetry of Video Images



At the time the capture command was issued, the EE was in motion toward the SPARTAN at about 0.2 ft/sec and this continued for about 5 seconds thereafter (about 12 inches). The resultant trajectory of the RMS is described here in the orbiter X, Y, Z coordinate system, though the SPARTAN was not aligned with that coordinate system. Thus, in the X direction there was about 11 inches of movement aft, in the Y direction there was motion to the left (as viewed from the EE camera) about 5 inches and then back to the right about 5 inches. In the Z direction, there was movement up about 6 inches. There were no RHC inputs during this time.

During the subsequent 5-7 second period when the EE forward motion was stopped, there were still no RHC inputs but the THC commanded Y and Z motions (again expressed in orbiter coordinates) continued right and up, respectively, though erratically. The total distance moved was about 7 inches right and 10 inches up for a vector distance of about 12.2 inches. Since the tip-off had occurred earlier and there was no indication in the SPARTAN rate data of multiple contacts after the initial ones, this movement essentially tracked the rotation of the SPARTAN. The tip-off rate of ~1.9 degrees/second would manifest itself as a movement of the grapple fixture tip of about 14 inches over the ten second period between the time the Release command was issued and the time backaway was initiated, which is roughly consistent with the 12.2 inches of EE lateral movement.

About 5 seconds after stopping forward motion, the RMS operator input a small THC -X command and at 7 seconds backed the EE straight away from the SPARTAN at about 0.2 ft/sec for about 10 seconds.

Thus, in summary, it is clear that the Capture command was premature. The Release command was initiated with the pin very close to the snare wire plane, and the EE continued to move for about 3 more seconds (approximately 6 inches) after release. This provides three possibilities by which rates might have been imparted to the SPARTAN, depending on the grapple pin location relative to the exact time of retracting the snares.

(1) <u>The snares fully retracted before the pin was within the capture envelope</u>. In this case any induced rates had to be caused by the pin being contacted by the inside of the EE or the end of the EE impacting one of the cams of the grapple fixture near the base of the pin. Since there was lateral and vertical movement during the 5-7 seconds before backaway, it is possible. However, the size of the grapple target horizontal bar did not ever come close to filling the CCTV image and therefore it is very unlikely that the EE got close enough to the cams to have made contact. This leaves the potential that the pin was impacted by the inside of the EE. The inside diameter of the EE is about 8 inches so the 12+ inches that was moved in the lateral and vertical directions could have been enough and in the direction to induce the observed rotation. However, the observed rotation began at about the time of the Release command and the video of the EE camera did not show sufficient misalignment for contact with the inside of the EE to be possible.

(2) The snares were still retracting when the pin came in the capture range and the pin was caught between one of the cables and the inside diameter of the EE. The stiffness of the snare cable under this condition is unknown and how much force it can exert is also unknown. Had the pin been caught between a snare cable and the EE the Board believes that as the EE was withdrawn the button on the end of the pin would have caused a small translation of the SPARTAN towards the EE retraction direction, as well as additional rotation rates. Furthermore, the EE would have gotten much closer to the grapple plate. Video analysis indicates this did not occur. In addition, this case would probably have resulted in several rates being imparted to the SPARTAN over a short period of time. SPARTAN rate data show essentially a single force input over a 3-4 second period, with about 80% of the rate change in the last second. Photo-grammetric analysis also shows the distance between the EE and the grapple plate increasing after the Release command.

(3) The snare wire itself, either in the capture position or during the release, (or both) imparted the rotational rates to the SPARTAN through the grapple pin. The photography of the EE and the SPARTAN recorded data suggest this to have been the case. Photo-grammetric analysis places the end of the grapple pin at or very near the plane of the snare wires at the time SPARTAN rate data indicate tip-off occurred. Further supporting this hypothesis is the fact that subsequent motion of the EE roughly matches the induced rotation rate in direction and magnitude, suggesting that the arm operator was reacting to grapple target motion prior to backaway. Moreover, the analysis of the video of the grapple target indicates that the EE was never any closer to the target than at the point of initial tip-off, despite continued RMS motion toward SPARTAN.

The Board's conclusion is that the third case represents the most likely explanation of how rates were imparted to SPARTAN.

7.2.2 RMS Handling Qualities

Analysis of the RMS THC telemetry indicates excessive activity during the re-grapple attempt, relative to training and similar flights, including reaching the hard-stops several times. The THC activity of the level seen would have been a factor in the unloaded arm dynamics resulting in a "jerky" trajectory of the EE. Attempted reproductions of this in the SES produced a video with similar EE motion relative to SPARTAN but was inconclusive with respect to the inflight experience. The SES is tuned to give the most representative performance for operations within the normal operating envelopes (both loaded and unloaded).

During the Board review, it was noted that a modification to the RMS flight software had been made in OI-23 (STS-65) that would result in software commanded motion even with no THC or RHC inputs. This is the result of a software routine, called Position and Orientation Hold Submode (POHS), that had been developed and installed to correct for unwanted motion of the RMS due to small biases in the RMS tachometer. It had been noticed that the EE drifted from commanded direction during slow maneuvers and that made berthing of large payloads difficult. This function is more significant at low rates because the tachometer bias is a larger percentage of the command at low rates. At higher rates, such as observed in the STS-87 case, the POHS effects are negligible since the joints are already moving at their limits and the POHS add-ins are scaled back. The Board concluded that POHS has no relevant bearing on this case.

7.2.3 Visual Cues

A special CCTV test was conducted at KSC to evaluate the monitors and the camcorders. All checked out normally. There was no attempt to recreate the in-cabin sun shafting or other lighting effects because of the difficulty of accurately reconstructing the cabin zero-g configuration with respect to crew position, floating objects, etc. What was demonstrated was that the recorded data represented what was imaged on the monitor, irrespective of other glare effects. It is noteworthy that the crew did not attempt to put the EE camera view on CCTV monitor 1.

A JSC PLAID lab analysis of the solar pointing attitude at the time indicates that the sun was not directly shafting on the CCTV monitors. This does not, however, account for any sunlight reflected from other surfaces, including the crew's shirts, checklist pages, or objects floating in the cabin. In viewing the in-cabin video, the CCTV monitors were generally blocked by crew members so no conclusions could be drawn.

7.3 Rate Matching Attempt

The crew and the flight control team made a qualitative assessment of the SPARTAN rates (purely visual, as there was no telemetry from SPARTAN) and after about one revolution of the SPARTAN satellite, the CDR began attempting to match rates. The crew did not make a quantitative assessment of the rates as they are taught to do in rendezvous training. About 15 minutes after the tip-off, the MCC had established the initial rates to be about 2 degrees per second, but that fact was not conveyed to the crew. About 18 minutes after tip-off, the K-band went into blockage and the MCC lost visual insight.

The orbiter guidance and navigation data indicated substantial rates on occasion (a momentary rate in one axis of up to 3 degrees per second), although rates were generally in the region of 1 degree per second per axis or less. There are no mission rule rate limitations for orbiter rate matching, and the rates attained were well within the orbiter structural capabilities.

The multi-axis nature of the SPARTAN rotation did not allow the orbiter to isolate a single axis to match and the attempt was terminated some 40 minutes after initiation when the propellant limits were reached. Maximum pre-flight training for rate matching was an order of magnitude less than the inflight SPARTAN rotation and more or less limited to single axis rotations.

Analysis of orbiter digital autopilot (DAP) modes indicates many mode changes during this period, including several non-standard configurations. For example, the DAP was used with two or three axes in free drift at one point, which is a difficult configuration in which to maintain precise attitudes and rates. Many maneuver initiations and terminations were accompanied by heavy THC usage to maintain acceptable orbiter/SPARTAN relative positioning.

Post flight assessments in the SES have shown that there is a re-contact issue due to large attitude maneuvers cross-coupling into translations and vice-versa. With one exception (pure yaw), the process of trying to match rates with the SPARTAN is essentially one of flying a circular path around the SPARTAN while maintaining the SPARTAN at a point over the payload bay in reach of the RMS. This involves translating around a circle with a radius of about 40 feet, and rotating the vehicle to keep the bay pointed at the SPARTAN. To maintain a circular trajectory, the orbiter must also translate towards and tangential to the SPARTAN. The cross-coupling of translation and rotation jet firings also make this very difficult to control. For example, in the negative pitch direction, the required aft translation corrections couple into more negative pitch and further, when rotational rates are reduced or eliminated, the existing translation rates can in some cases be converted into a closing rate. The larger the flyaround rate, and the more abrupt the change in rotation rate, the more pronounced this closing effect may become. (More details are in Volume II, Appendix I.) This SES assessment was cursory and if it is to be fully understood, more study will be required to fully characterize the relative motion between the orbiter and a free-flying object such that placards can be developed.

7.4 Fault Tree Analysis Overall Summary

The fault tree analysis (Volume II, Section K), in addition to the above, evaluated the adequacy of the training, the procedures, the ground team and flight crew execution, the inter- and intra-team communications, and the relevant orbiter and payload hardware and software. The evaluations are summarized here:

Training: Scheduled training hours were consistent with previous successful missions. There have been no substantial training catalog changes in payload, RMS or rendezvous operation in several years. Training team members stated before and after the mission that this crew's performance in simulations was well within family and in many cases above average. The crew's lack of understanding of SPARTAN systems and specifically their lack of knowledge of MCC's insight into a berthed SPARTAN was a contributing element to the missed standby command.

Procedures: SPARTAN 201 Procedures were unchanged from the previous mission of that spacecraft. Prior to that flight (between STS-64 and 69), however, an additional procedure was added to the checklist which was placed between the status check and the standby step. The Status Check was the last SPARTAN procedure performed pre-deploy on STS-87. Although the Flight Plan is the governing document, and SPARTAN procedures are executed as "subroutines," it should be noted that the only apparent organization to the Payload Ops checklist was to place the procedures in order of performance where feasible. From a crew perspective this is reasonable, as the checklist can then be easily left open to the "next" step. The Standby procedure, as a result of the change prior to STS-69, was inconsistent with this structure.

Execution: The ground team execution relevant to deploy and RMS re-grapple was per training, procedures, and flight rules. It should be noted the flight day 3 flight plan uplink was later than desirable due to lack of Ku-Band antenna availability, a circumstance that occurs occasionally in flight. As indicated above in sections 7.1 and 7.2, the flight crew did not execute the SPARTAN Standby command, and did not follow the prescribed response procedure for a failed capture. The re-grapple attempt resulted in RMS End Effector induced rates on the SPARTAN and a subsequent unsuccessful rate matching attempt, during which regard for re-contact possibilities due to substantially out-of-the-envelope attitude maneuvering was not addressed by either the MCC or the crew.

Communications: There were miscommunications within the crew with respect to onboard flight plan step execution and misunderstandings by the crew of what insight the MCC had into the

SPARTAN spacecraft systems (i.e., the meaning of "go for deploy".) Communications inside the MCC and with the crew during the rate matching attempt were sparse.

Software and Hardware: In flight and post flight testing of the SPARTAN spacecraft. SPARTAN PGSC and interface wiring, RMS and RMS controls, and CCTV/Monitor systems and sub-systems revealed no problems.

8. FINDINGS, CAUSES, OBSERVATIONS, AND RECOMMENDATIONS

8.1 FINDING

SPARTAN failed to execute the pirouette maneuver.

8.1.1 CAUSES

Primary Cause:

The SPARTAN spacecraft was not correctly initialized for release because the flight crew inadvertently omitted the Standby step.

The command transaction to call up the PGSC display containing the Standby command, and the SPARTAN Standby command transaction itself were not in the SPARTAN software log file. This conclusively shows the Standby command was not executed by the crew. The Standby command is necessary to transition the SPARTAN spacecraft software to the mode that looks for the RMS de-rigidize/rigidize/de-rigidize function to initiate the free-flyer sequencer. Without the standby command, the SPARTAN spacecraft software will not react to the RMS de-rigidize/rigidize/de-rigidize events.

The PGSC software was used again once the SPARTAN was re-captured and berthed and was tested and verified at KSC post-landing as part of the board investigation. In all these cases, the software worked as designed and intended.

Contributing causes:

(1) The sole responsibility of the crew for verifying SPARTAN readiness for deploy was not effectively communicated during preflight training. Some members of the crew erroneously thought the MCC had insight to SPARTAN and would catch any errors in predeploy configuration.

The lack of MCC direct insight was known to the SPARTAN [customer] team, the Payload Officer, and MS2 crewman who had previous SPARTAN mission experience. MS1, who had prime SPARTAN responsibility, and the CDR believed MCC had insight into

SPARTAN while berthed. Some simulation activities unintentionally reinforced their misconception of this MCC insight. MS3 (the backup for SPARTAN operations) was not significantly involved in the SPARTAN deploy. MS2 had SPARTAN deploy experience, but was not involved with SPARTAN on this flight. There was limited discussion by the STS-87 crew with previous SPARTAN crews concerning a second person to verify the SPARTAN procedural steps; rather, communication focused on the berthing task, which is known to be difficult.

(2) Rigorous Cockpit Resource Management (CRM) as applied in other critical phases of a mission was not applied to SPARTAN operations. There was no plan or procedure to verify that all necessary steps had been accomplished in a positive manner or by independent means prior to deploy.

CRM principles as applied to Ascent, Entry, Rendezvous, and EVA were not applied to SPARTAN operations. Task distribution is initially established by the commander and modified/adjusted based on the payload and other mission constraints over the training and flight preparation period. Training personnel knew that the crew was not using a command/verify technique for pre-deploy activities, but this approach varies by crew and is considered discretionary. One flight crew involved with a previous SPARTAN flight invoked a rigorous CRM plan largely because they were aware of no MCC insight to SPARTAN. Other crews invoked varying degrees of CRM. In fact, MS2 did not use a command/verify technique in his SPARTAN operations on his previous flight.

Air-to-ground reporting of SPARTAN Payload Ops Checklist items was not required. Communication protocol with MCC was informal, with courtesy calls on SPARTAN activation as time permitted. As with many payloads, the general practice with SPARTAN from the MCC perspective is negative reporting. If the crew does not report a problem and the MCC has no reason to believe a step was missed, they will assume that it was done. This [false, in this case] assumption led the MCC and the crew to assume the SPARTAN had been properly initialized and the sequencer program would execute its maneuvers and other sequences as planned. This false assumption affected future decisions of both the crew and MCC.

MS1 did not use positive check-marks on the Payload Ops Checklist or flight plan to verify that SPARTAN steps were completed. There was no second crew member observing/verifying SPARTAN PGSC entries. The CDR normally required individual flight plan procedure verification, but there was ambiguous communication between CDR and MS1 with respect to completion of a series of Payload Ops SPARTAN Checklist procedures, including the Standby command, which, although checked off on the Flight Plan by the CDR, were confirmed as a block.

Potential causes:

(1) The SPARTAN crew interfaces are not "user friendly", and provide ambiguous feedback on critical functions in some cases.

SPARTAN is not easy to operate, notwithstanding previous successes; SPARTAN control interfaces can be very misleading, e.g. "pulse" commands which flash "ON" for one second, and then return to "OFF." The crew interface to the SPARTAN via the PGSC did not provide the crew with a readily accessible status of the commands previously sent or the condition of the SPARTAN. Some commands were displayed after being sent, some only flashed on, and others were not displayed at all. The net effect was to create an interface that made detection of inadvertent operator errors difficult.

(2) There is no clear accountability for SPARTAN systems training. Training roles and responsibility between the Shuttle Program and SPARTAN payload customer were poorly defined and not understood by those required to execute it.

The crew received very little formal SPARTAN spacecraft training. The Payload Integration Plan (PIP) is ambiguous with respect to the responsibilities for SPARTAN spacecraft training.

There was a two-hour desktop class given by JSC payload training personnel on the PGSC setup and execution of the FDF procedures. It did not address SPARTAN systems. Moreover, the JSC payload training team did not have detailed knowledge of the SPARTAN command functions. The trainers at JSC clearly felt that specific SPARTAN systems training was the responsibility of the Payload customer.

MS1 obtained most of her SPARTAN systems knowledge from a one-hour familiarization course conducted by the SPARTAN Mission Manager, a casual meeting with SPARTAN representatives, and reading the Cargo System Manual (CSM), which was developed by the JSC Operations Division Payloads Branch. The CSM makes no direct mention of the fact that the ground is without insight into the satellite. The GSFC SPARTAN briefing material is equally vague with respect to ground insight.

(3) The flow of the Flight Data File (FDF) for SPARTAN preparation for deploy was misleading.

The Payload Operations checklist is arranged as a series of isolated procedures, like software subroutines, that are called from the Flight Plan. The P/L Ops Checklist was sequential up to but not including the Standby command. Normally, at completion of the final step in a checklist procedure, the crew returns to the Flight Plan. There is a "proceed with deploy ops" callout following the SPARTAN Status check which is confusing (there is no "deploy ops" procedure and SPARTAN is not ready for deploy at the end of this procedure). Thus the phrase "proceed with deploy ops" is a meaningless step that confused the normal process which is to return to the Flight Plan and proceed to the next procedure called for in that document. It should be noted MS1 stated this wording did not confuse her and was aware another step (the STANDBY command) was needed to configure the spacecraft properly.

SPARTAN 201 Procedures were unchanged from the previous mission of that spacecraft (STS-69). Between STS-64 and STS-69, however, an additional procedure (SPARTAN RE-INITIALIZATION) was added to the checklist. This new procedure was placed between the Status Check and the Standby procedures. On STS-87, the Status Check was the last SPARTAN procedure the crew performed pre-deploy; the Standby step was inadvertently omitted. Although the Flight Plan is the governing document, and SPARTAN procedures are executed as "subroutines," it should be noted that the only apparent organization to the Payload Ops checklist was to place the procedures in order of performance where feasible. From a crew perspective this is reasonable, as the checklist can then be easily left open to the "next" step. The Standby procedure, as a result of the change prior to STS-69, was inconsistent with this structure.

8.1.2 OBSERVATIONS

(1) The limited significance of the MCC "go for deploy" of SPARTAN was not understood by the flight crew.

Since the SPARTAN spacecraft does not provide any telemetry as to its state of readiness. the MCC "go for deploy" call only meant that the orbiter and ground systems were ready to support SPARTAN deployment. The MCC "go for deploy" call may have reinforced the crew's belief that the SPARTAN was ready to release based on independent observations.

(2) The SPARTAN deploy was delayed to FD3. Flight Plan updates were somewhat late in getting onboard.

Flight plan updates are often sent up well into the post-sleep period, and on the day of the incident two SPARTAN procedures were read up to MS1 because of flight plan uplink delays. (The Standby command was not one of those procedures.) The FD3 flight plan uplink was delayed because of lack of Ku-band availability; however, there were no changes in the flight plan to the sequence of deploy activities. Prior to the FD3 flight plan update, there was no SPARTAN deploy sequence available to the crew because it was in the old FD2 plan that had been taped over the previous day when the deploy was delayed from FD2 to FD 3.

The FD3 flight plan update was onboard at MET 1/21:33. The SPARTAN Status check was called down as complete at 1/23:07. about 1.5 hours later. The SPARTAN Standby step was scheduled at 1/23:15. by chance during an LOS period, and was not called down at the next AOS.

MS1 thought it "strange" and "awkward" that MCC calls asked her to do things without a flight plan, which was used as the controlling document for all crew activities. The MCC may not have been aware that the FD2 flight plan pages, which were the only place onboard that had the flight plan callouts for the SPARTAN deploy sequence, had been taped over the previous day by the flight crew. This is a standard procedure for most crews when new flight plan pages are sent up, but may not have been well understood by everyone in the MCC.

(3) The JSC payload trainer knew the basic laptop commands and the interface to SPARTAN, but may not have fully understood the ramifications of those commands (or, at a minimum, communicated those ramifications to the crew).

There were two training personnel involved in STS-87 SPARTAN training; one was the Payload Training Supervisor and the other was the Payload Instructor. MS1 felt that there was little SPARTAN spacecraft systems knowledge resident in the JSC Payload Training organization, and frequently sought information elsewhere. This was in part due to her perception of the inexperience of the assigned Payload Instructor.

(4) There is no independent means to verify SPARTAN as a whole is ready for deploy, including ACS updates.

Following the FD3 failure to recapture SPARTAN, the flight crew downlinked the "spc.log" text file to the MCC. This text file records all communication between the PGSC and the SPARTAN spacecraft. Examination of the text file showed the absence of the STANDBY command and allowed the flight team to understand the current SPARTAN systems configuration. Examination of the spc.log file by the flight crew or the MCC could have allowed verification of proper predeploy configuration.

8.1.3 RECOMMENDATIONS

The Board's recommendations are divided into principal and secondary categories. Principal recommendations should be addressed prior to the next applicable flight; secondary recommendations should be addressed as soon as practical.

8.1.3.1 Principal Recommendations

(1) Apply Cockpit Resource Management (CRM) techniques for critical on-orbit activity such as deploys.

This could include techniques such as command/response procedure checking, read/verify numerical entries, or "watch me do it". All these techniques have potential applicability. In this case, both SPARTAN initialization and RMS operations would be defined as "critical."

(2) Improve the crew interface to the PGSC/SPARTAN software.

The PGSC SPARTAN software should be improved to provide the crew an interface that clearly communicates the current status of the SPARTAN readiness for deploy and provides positive feedback of crew entries and easy assessment of SPARTAN status. The existing interface is not acceptable.

While SPARTAN is addressed here specifically, this recommendation should apply to all shuttle (and space station) payloads. It must be recognized that even if all crew members have previous flight experience, the payloads may be new to them and the amount of training they will get on any one of those payloads is relatively small. Hence, it is very much in the best interests of all payloads that they do everything they reasonably can to make their interfaces as operator friendly as possible. This will minimize training requirements and increase the likelihood of their own success as well as total mission success.

(3) Improve payload training accountability.

Establish clear roles and responsibilities for crew training for external customer-provided payloads in the Payload Integration Plan. Establish clear and specific training objectives, in concert with the payload customer.

(4) Improve payload training thoroughness and crew member retention of critical training objectives.

To insure that payload training can be accomplished effectively, strengthen JSC training knowledge for primary payloads, particularly where control interfaces are involved. The flight crew erroneously thought the MCC had telemetry insight into the SPARTAN predeployment configuration and would detect a configuration error. Although JSC training personnel stated to the Board that this fact was properly communicated to the flight crew during preflight training, the crew obviously did not remember it.

(5) Develop and implement a final SPARTAN "Ready for Deploy" verification.

Develop a positive means to verify the SPARTAN spacecraft has been properly configured for flight.

8.1.3.2 Secondary Recommendations

(1) Make "Go for Deploy" terminology more rigorous and verify its precise meaning in the training plan.

Both the crew and the MCC must have a clear and complete understanding of what each "go" means and what it does not.

(2) Include late flight plan updates as an objective in the training plan.

Simulations are often misleading on this point since they typically simulate only snapshots of the mission. Flight plan updates are part of the crew overhead that is not apparent during most ground based training. Crew members should not find MCC calls "strange" or "awkward," particularly when they are typical of every mission.

8.2 FINDING

The re-grapple attempt failed due to SPARTAN rotational rates.

8.2.1 CAUSES

Primary Cause:

The RMS End Effector snare wires impacted the SPARTAN grapple fixture and induced rotational rates into the SPARTAN due to operator error.

CRM processes for RMS operations involved the PLT as the backup RMS operator. His focus was on display manipulation during grapple, so his eyes were not outside on the satellite or attentive to MS1's arm operation. The CDR was making the proximity calls to MS1. MS3 was in charge of camera operations and was trying to adjust the EE camera iris to improve the view during most of the re-grapple attempt.

MS1 was concerned with arm dynamics and EE camera lack of contrast and "blooming". EE camera "blooming" made the view on the CCTV monitor difficult or impossible to use and at times disturbed MS1's trained scan pattern. MS1 maintained an internal scan pattern which provided no other cues besides the EE camera. Despite the crew's post-flight assertion that the monitor presentation of the EE camera view was "nearly unusable," the approach was continued. There was no attempt to change the EE camera to another monitor or to stop the approach and regroup.

The initial approach trajectory from about 10 feet out was abnormally fast, with the THC X at maximum rates several times, and several significant periods of activity in Y and Z. The approach slowed to the normally trained 0.2 feet/second only during the final few seconds. This may have aggravated MS1's reported "jerkiness" of the unloaded arm performance. Training personnel reported that this was completely unprecedented in MS1's pre-flight RMS performance. Crews are trained not to move the arm too slowly, as this provides an opportunity for bias errors to build up, but crews are also trained to move at steady, medium rates to minimize dynamic effects. Post-flight, MS1 commented that there was no feeling of being particularly rushed or that rates used were unusually high, although there was awareness of the 1 hour SPARTAN constraint and the upcoming "difficult" berthing task.

Upon nearing the grapple fixture, a Capture command was issued prematurely. MS1 indicated that the early capture command was a "mistake," which was immediately realized. Three seconds later, the Release command was issued. MS1 did not follow the trained procedure to back away before release, since "I thought I was well clear of the pin." Post flight photo-grammetric analysis indicates the end of the EE was approximately 1-2 inches from the pin (snare wire plane 3.6-4.6 inches from the pin) when the premature capture was initiated. Examination of CCTV camera D video, which is very similar to the out-the-window view, indicates the EE proximity to the pin was misjudged. The response to the missed capture was not consistent with the documented and trained response procedures.

Not only was there no back away after the missed capture, but translation continued toward the spacecraft. Post flight photo-grammetric analysis, however, indicates the tip of the grapple pin was inside of the EE and had reached the snare wire plane at the time of the Release command. The continuation of the RMS EE toward the SPARTAN grapple fixture after the premature capture/release commands resulted in snare wire contact with the grapple fixture pin and induced translational and rotational rates into the SPARTAN.

MS1 did stop +X translations about 3 seconds after the release command, concurrently with the CDR's perception out the window that the EE was over the pin, within grapple range ("I stopped simultaneously with CDR's verbal to capture"). Although both the CDR (visually out the window) and MS1 (from the EE camera view) felt the EE to be over the pin when the CDR cued MS1 to capture and she stopped translating, post-flight photo-grammetric analysis shows otherwise. Instead, the snare wire tip-off induced a translation that kept the pin from ever entering capture range. The CDR view is significantly degraded by the fact that the deploy/re-grapple attitude is not orthogonal with respect to the cockpit, although in post flight interviews the CDR expressed confidence that he could adequately assess the EE/target separation. MS1 did not attempt a second capture because the pin was not aligned inside the target circle.

During the next 6 seconds, MS1 continued to command vertical and lateral motion of the EE via the THC, though there were no RHC inputs. However, the pin remained out of alignment as seen on the EE camera image, and MS1 elected to back away in order to re-align and try again. In post-mission interviews, MS1 indicated that the EE was out of the grapple envelope as indicated by attitude errors with respect to the grapple target, and she wanted to correct the misalignment. The reason the pin remained out of alignment appears to be the SPARTAN translation/rotation caused by the tip-off.

In interviews with RMS training, RMS systems, and flight crew personnel, the board discovered that there are different points of view on the advisability of initiating capture if the EE is over the pin but out of alignment. The lead RMS trainer indicated that he trained MS1 to attempt capture in this case since a back away could result in a tip-off; MS1 interpreted the training to back away and realign. A cursory survey of previously flown RMS operators is divided. RMS systems personnel support the RMS training technique of attempting capture irrespective of alignment for free-flyers. In any event, in this case attempting a second capture before backing away would have likely been unsuccessful, since the SPARTAN tip-off rotation was keeping the pin at the edge or just outside of the capture range.

Based on information from the SPARTAN tape data review, RMS telemetry, analysis of the photographic data and observation of the recorded video, the contact was a single one that lasted 3-4 seconds, with most of the force imparted in the last second, and appeared to occur approximately at or just after the moment of snare release.

<u>Contributing Causes:</u>

(1) The crew and MCC believed they were under a time constraint to re-grapple and re-berth the SPARTAN in order to have a chance to save the SPARTAN mission.

The SPARTAN spacecraft contains a software sequencer that performs certain functions within a pre-defined period. This sequencer is initialized by the Standby command to await a switch action (called D1) that is activated by the RMS EE when it de-rigidizes, rigidizes and finally de-rigidizes for the SPARTAN deployment. The sequencer contains a maneuver, called a pirouette, which is executed post-deploy to confirm to the crew that the SPARTAN is operating properly. This pirouette is supposed to occur 2 minutes 33 seconds after the D1 signal. The flight rules require that the crew re-grapple the SPARTAN and replace it in the bay if the pirouette does not occur.

There is also a timer, triggered by the same D1 signal, that will enable the firing of a pyrotechnic valve that permanently isolates the Attitude Control System 60 minutes after D1 if the SPARTAN is re-grappled and the RMS rigidizes the capture mechanism. This valve will also fire if the Minimum Reserve Sequence (MRS) is invoked. This isolation safes SPARTAN for entry/landing and of course precludes any further SPARTAN activity on the mission. In order to prevent this from happening, the SPARTAN must be recaptured and berthed and the PGSC software must be used to reset the SPARTAN sequencer prior to 60 minutes elapsing from D1.

The failure of the SPARTAN to execute its pirouette maneuver and the belief that the SPARTAN 60 minute timer had started at D1 established significant pressure on the crew to re-grapple and re-berth SPARTAN as soon as possible. The crew, especially MS1, also expected the berthing task to be difficult and time consuming (based on the experience of previous crews), and they were anxious to reserve the maximum time to accomplish it.

(2) The SPARTAN deploy position was not optimum for re-grapple lighting conditions. The intermittent reflections of sunlight and the EE spotlight into the EE camera and the reported "washout" effect on CCTV monitor 2 effectively caused periodic loss of the CCTV monitor image of the grapple target.

Past mission successes and lack of post mission crew "gripes" on degraded EE views post-deploy may have led to a false sense of security in this area. There was no pre-flight planning for degraded lighting conditions or for analyzing the EE camera selection. The attitude for SPARTAN release (consequently the position of the grapple pin) is determined by solar pointing, Therefore, the relative position of the EE/SPARTAN and the sun are fixed regardless of the arm configuration. Apparently, the original SPARTAN flight techniques set up these agreements years ago based on certain trades and were never changed. In post mission interviews the SPARTAN customer indicated that SPARTAN could be released in other orientations so long as they are able to plan for it pre-mission.

There was an RMS "lessons learned" notebook kept in the astronaut office support group that had considerable insight into "blooming" and its effect on arm operations from previously flown crew members. Prior Shuttle crews have reported difficulties with "blooming" cameras, quirks with the RMS, and other operationally pertinent information. This crew did not know about the notebook.

Pre- and Post-deploy, camera "blooming", or an overexposed scene, was noted onboard but there was no immediate attempt to correct for it, in light of the impending separation maneuver. When re-grapple became necessary, MS3 took the camera to a "partial manual" mode and attempted to solve the problem with iris adjustments. However, automatic gain control was still active, reducing his ability to control the image. In post-mission questioning, he did not seem to be aware of the "full manual" mode of camera operation, sometimes called "manual/manual", which might have improved the results. MS3 indicated he did not recall having been trained to address the blooming phenomena. However the CCTV trainers stated he had at least one training session that simulated blooming situations. MS3 did not attempt to switch the EE camera to monitor 1 during the re-grapple.

Later the MCC requested a dump of the EE video and the crew reported the downlink video replayed through monitor 1 after the incident did not represent what they saw on monitor 2 in real time. Video playback during and after the flight indicated the "blooming" was reasonably corrected during most of the final portions of the re-grapple attempt. However, MS1 maintains that monitor 2 was still nearly unusable during the actual re-grapple activities.

Data from a special test at KSC indicates that the video recorders faithfully reproduce what is displayed on the monitors, and that performance of the two monitors is essentially identical. The Board considered the possibility that sunlight incident on the monitor could have caused loss of contrast, but attitude analysis and in-cabin video shows no direct sun on the monitors. The crew's perception that the monitor 2 scene was mostly unusable during the re-grapple attempt remains unexplained.

(3) Contingency RMS training does not emphasize missed capture responses; SPARTAN berthing was strongly emphasized.

Missed capture training is not a formal part of the flight-specific training flow, but rather a target of opportunity whenever the student missed a grapple in the SES or SMS simulator. Neither the SES nor SMS is a good trainer for "missed grapple" cases. When a fail-to-capture occurred following a Capture command, verbal instructor inputs were made to back off with snares closed, then command Release when the EE was clearly away from pin. The RMS operator generally did not actually perform the steps. However, the actual "stop and re-group" process may have been practiced by MS1 only once. The training instructor recalled "5-10" cases of misses during the entire training period; MS1 only recalls one time. This discrepancy may be partially explained by the fact that in most cases the procedures for re-grapple were reviewed or discussed, but not necessarily performed, due to limited simulator fidelity for this scenario.

The integrated simulations did include a scenario (no SPARTAN pirouette) similar to actual flight that was successfully accomplished.

MS1 had several extra RMS sessions at her own request, but the distribution of those hours appear to have been allocated to heavily favor SPARTAN reberth in single joint mode as well as normal SPARTAN reberthing, instead of re-grapple under expected lighting conditions.

Potential Causes:

(1) Many crew members do not use the End Effector overlay.

The End Effector overlay is designed to aid the crew in establishing range to the grapple fixture target and the window in which capture is assured. The tendency to not use the overlay is due to some history of low confidence in the accuracy of the overlay and a concern that there may be a case where the overlay is not available. It also may be due to the overlay not remaining flush with the monitor, parallax errors, and some slight loss of resolution on the monitor. MS1 did not use the grapple fixture overlay in training or flight. It should be noted that two independent observers (CDR, MS1) felt the grapple pin was in the grapple envelope when the RMS was stopped during the re-grapple attempt. Photogrammetric analysis indicates that it was not.

(2) The SPARTAN deploy position was optimized for single joint deploy and to minimize plume effects during the separation maneuver, and therefore was not optimum for "out-the-window" orthogonal viewing.

This is typical of many RMS-deployable spacecraft. There are multiple requirements which conflict:

- Use a single position for nominal and single joint deploy to minimize pre-mission analysis requirements.

- Use a deploy position which is centered over the payload bay to minimize plume effects during the separation maneuver.

- Use a deploy attitude which is orthogonal with respect to the crew to optimize for visual observation of the interface between the spacecraft and the EE.

In planning for STS-87, as well as many other missions, the first two requirements have received priority, effectively precluding the last. In discussions with the crew, training and systems personnel, the Board noted a significant difference in philosophy for optimization of the deploy configuration.

SPARTAN personnel stated they could accommodate any deploy attitude as long as they had a-priori knowledge of it.

(3) Lighting conditions are poorly simulated.

None of the current simulators have high fidelity lighting models, including "blooming", shadowing, or reflections. The RMS trainers try to have periodic demonstrations of the possible lighting conditions using the MDF in B9A, but it is difficult to set up and is infrequently done. The CCTV training syllabus includes standalone Full Fuselage Trainer (FFT) training on the cameras and includes illustrations of "blooming". This usually occurs early in the flight training period, however. MS3 does not recall having had this training session, or any formal instruction on how to cope with "blooming".

(4) CCTV camera controls are not adequately trained or exercised in an integrated fashion with the RMS.

The crew did not train during integrated simulations on how to handle camera "blooming". Much of the detailed RMS operations training is done by primary arm operators alone and does not include another person practicing adjusting the camera settings while the RMS is being operated. This is a consequence of minimal lighting fidelity in the SMS model, where integrated training typically takes place. The MDF is sometimes used to give the crew a feel for the real lighting conditions, but that training is limited and not generally integrated.

The camera controls training done in the FFT does include iris control and exercises with "blooming", but is standalone.

(5) The RMS unloaded dynamics during the re-grapple attempt seemed to MS-1 to be very different (more uncommanded movement/oscillations) from training.

MS1 described the unloaded arm dynamics as being very different from training. The flight day 1 RMS checkout exercises did not include closed loop flying tasks and were not sufficient preparation for the unloaded dynamics experienced on day 3 when executing the free-flying track and capture. The flight day 3 re-grapple attempt had "more arm dynamics than day one operations." In contrast, MS1 felt the loaded arm dynamics were reminiscent of those experienced in the SES.

At the request of the Board, a special test was performed in the SES with flight RHC/THC inputs. RMS trainers indicated that past crews have always said the SES is a very good match to their flight experience, both loaded and unloaded. A video was made and qualitatively compared to the flight video. The video comparison was not conclusive.

8.2.2 OBSERVATIONS

(1) The preflight assessment of the crew's knowledge base and skills indicated the crew was ready to fly, and the number of hours trained per discipline is consistent with other flights with RMS grappling of SPARTAN payloads.

The primary RMS operator (MS1) had been through the RMS training and had passed qualification testing in the MDF and the SES prior to being selected for STS-87. The backup RMS operator (PLT) had not previously been through RMS training and qualification but did so during the training period. The comparison of training hours and facility allocation is comparable to several other flights involving RMS grappling operations, including STS-64 and STS-69, the previous two SPARTAN-201 flights. Throughout the training flow MS1 continued to refine her RMS skills, with particular emphasis on SPARTAN berthing, which was reputed to be difficult due to very tight tolerances. Several extra berthing exercises were requested by MS1 and performed during the training period.

(2) MS1 did not perform the THC/RHC "feel checks" during CEIT pre-flight at KSC.

The SMS, MDF, and SES hand controllers are generally much less stiff than the flight vehicle controllers. However, MS1 indicated that a good feel was obtained of the THC/RHC during the on-orbit RMS checkout and payload bay survey.

(3) The crew reported significant aft flight deck monitor washout.

The crew reported significant CCTV monitor 2 washout during the re-grapple attempt that is not captured in the flight video recording and could not be substantiated in the post-flight evaluations.

(4) The STS-87 crew were clearly of the opinion that SPARTAN berthing was a difficult task which, along with the 60 minute SPARTAN time limit, led to a sense of urgency to re-grapple.

Modifications after STS-64 resulted in significant improvement in the time required for berthing the SPARTAN. STS-69 berthing time was reportedly improved by a factor of about four, but the STS-87 crew were still concerned about what they might experience. Regardless, the flight crew perception was that SPARTAN berthing would be difficult. In fact, MS1 spent most of her discretionary time training for "single joint" SPARTAN berthing. The SPARTAN/REM interface still has tight tolerances. This kind of interface should be avoided in the future, and fixed if practical in this case. If the 60 minute constraint is relieved, the berthing issue may be sufficiently mitigated for SPARTAN.

(5) There is not a clear agreement among the crew, training and the flight control team on the issue of "Capture when over pin regardless of alignment."

For free-flying payloads, a decision should be made whether the standard approach is to always attempt capture if the EE is over the pin, regardless of alignment, or if the operator should back off and re-align before going back for capture. The chosen technique should be rigorously trained.

8.2.3 RECOMMENDATIONS

8.2.3.1 Principal Recommendations

(1) Revisit Cockpit Resource Management (CRM) for RMS operations.

Consider having R2 visually back up R1, rather than focusing on CRT displays of digital data. On several occasions the chain of events could have been broken by simply stopping activities and reevaluating. Watching for, and reevaluation of, off-nominal situations should be reinforced as an operational philosophy during crew training, particularly when CRM issues are being discussed.

(2) Revisit safety analyses to assess expanding or removing SPARTAN 1-hour constraint.

The one hour constraint may not be required. Any such constraints can lead to realtime accommodations that are not well thought out and could ultimately cause unnecessary direct and/or indirect adverse effects.

(3) Re-examine the objectives mix in RMS training; must increase fail-to-capture element.

This is at least the third flight which has involved a premature capture command, although STS-87 is the first time an adverse situation resulted. There must be a formal training element on this subject and crews should be required to perform the procedures rather than an instructor "walking" them through it.

(4) Improve range-to-grapple information available to RMS operator.

The RMS operator is an integral part of a closed loop control system designed to drive the EE to a particular envelope in the vicinity of the grapple fixture and complete capture. A necessary element of that control feedback is range to the grapple fixture. The means of doing that today are camera views, CCTV monitor overlays, and direct out-the-window views. These can be less than optimum for various reasons and improvements appear warranted and should be pursued. Examples include electronic overlays, a laser range finder, and improved EE cameras, as well as a larger planning emphasis towards orthogonal views of the grapple fixture and optimum lighting conditions.

8.2.3.1 Secondary Recommendations

(1) Consider optimizing deploy RMS position for re-grapple instead of single joint deploy.

Grapple operations should be optimized to maximize the probability of success. It is the Board's view that orthogonality and plume minimization should take precedence over the desire to limit analysis to a single deploy configuration. Conflicting requirements which are payload related must be analyzed with a clear understanding of the implicit risk to mission success when orthogonality requirements are relaxed.

(2) Formalize lessons learned notebooks in training flow.

Lessons learned from crew experience should be immediately evaluated and embedded in RMS training and operations, rather than being kept in a little used and poorly maintained notebook in a different organization. Any such notebooks should be maintained by the training organization and be under formal configuration control.

(3) Increase emphasis on camera operations in training.

Develop an RMS simulation where cameras are degraded, requiring an integrated CCTV/RMS response. Increase FFT camera training to include all operational functionality and ensure crew proficiency through simulations.

(4) Improve lighting models in crew training.

Lighting effects are not simulated well, and the differences seen in flight can be disconcerting during critical activities. In particular, "blooming" and shadowing should be addressed. With the increasing capability of simulation hardware and software, the cost/benefit analysis related to simulation upgrades in this area should be revisited.

(5) RMS check-out (PLB survey) should include a standard closed-loop flying task to better appreciate unloaded RMS dynamics.

RMS flight training is recognized to be a syntheses of flying several different simulators, each with different characteristics. Although it is not believed to be a significant factor in this case, the Board believes that there would be value in establishing and executing a standard "closed loop" RMS control task during RMS checkout that would expose the first time operator to any potential idiosyncrasies or characteristics of the real RMS in the real environment that may not be simulated well in the ground simulators. Following crew return after each RMS flight, a post-flight handling qualities simulation in the SES replicating the standard control task should be performed to validate the simulators.

8.3 FINDING

The orbiter/crew was placed at unknown risk of recontact with SPARTAN by rate matching activities.

8.3.1 CAUSES

Primary Cause:

The effort to match rates was undertaken without a sufficient feasibility assessment.

Neither the CDR nor MCC worried about "out of envelope" rate matching maneuvers. The MCC allowed the crew to attempt any degree of rate matching necessary because the CDR "had the best seat in the house." The only constraint expressed during the mission or in Board interviews with respect to safety was that it was left to the CDR in real time. The SPARTAN rates were an order of magnitude beyond training and previous flight experience in rate matching. The CDR did not get a quantitative assessment of the SPARTAN rate before attempting to match it. The MCC, after computing the rates and realizing the attempt was probably futile (about 15 minutes into the 40 minute attempt), did not inform the CDR of their opinion. Several non-standard DAP configurations were used, including having two axes in free drift simultaneously, which presents a very difficult piloting task. In addition, orbiter translation and rotational thruster firings cross couple significantly, resulting in unpredictable combined vehicle dynamics at high rates. Closing rates which could not have been nulled by the crew could not be ruled out by the information and experience base available at the time, either in the MCC or onboard.

As an example, when negative pitch rate matching is attempted, aft and upward translation corrections are required to keep the target near the end effector. The aft thruster firings cross couple into negative pitch, requiring even greater aft and upward translation corrections. This can rapidly spiral into even greater rates, which in fact happened during STS-87, where negative pitch rates of about 3 degrees per second were reached for a short time. Then, when the crew decides that they want to terminate the rate matching effort, they likely will select attitude hold. This converts the upward and aft translation corrections into a closing rate between the payload and the orbiter of approximately one foot/second for every three degrees/second rotation rate. At a distance where the target is in reach of the end effector, the time until impact is on the order of thirty seconds.

Approximately fifty hand controller deflections in the smaller DAP or twenty in the larger DAP are required to null that closing rate. On STS-87, it does not appear that there was ever any danger of re-contact, but there is no evidence that these issues were considered prior to entering the rate matching activities. The Board believes that occurrence of any other orbiter anomaly (such as a jet driver failure) while the crew is engaged in such an intense piloting task could pose serious safety issues.

As a note, postflight attempts to fly the orbiter to match the inflight actual SPARTAN rates by the CDR and several other crew persons were unsuccessful.

<u>Contributing Causes:</u>

(1) There was an apparent 60 minute time constraint to save the SPARTAN mission.

As indicated in section 8.2, contributing cause (1), the SPARTAN timer was believed by the crew and the MCC to be active and would, when the 60 minutes elapsed, effectively terminate any chance to recover the mission.

(2) SPARTAN rates were not quantitatively assessed by the crew before initiating the rate matching.

It is possible, although by no means certain, that the crew would have elected to discuss options with the MCC or choose not to attempt rate matching if they had measured the rotation rate of the SPARTAN. The initial rate was an order of magnitude larger than anything they had trained to match. Their initial, non-quantitative visual assessment was that the task was 'doable.' The MCC had a quantitative assessment 10-15 minutes into the attempt but did not communicate it to the crew or discuss terminating the rate matching activities because of it. The crew, after observing that the initial SPARTAN rate, which appeared well behaved (single axis and stable), had cross-coupled into multiple axes (essentially resulting in a tumbling spacecraft), continued the rate matching attempt.

(3) The orbiter probably does not have the capability to match multi-axis rates at the level seen on this mission.

Preliminary SES testing suggests that multi-axis rates of the magnitude seen on STS-87 are beyond the capability of the crew/orbiter to match for any appreciable amount of time.

(4) The crew was not trained in multi-axis rate matching beyond about 0.2 degrees per second in a single axis. Crew training for attempted grapple of a high-rate tumbling spacecraft is inadequate for this situation and no mission constraints have been established.

The maximum rates seen in training for RMS track and capture was 1 degree/second. Rate matching with orbiter fly-arounds was limited to 0.2 degrees/second, an order of magnitude less than seen on STS-87. Essentially no training was performed with targets with multi-axis rates (i.e. tumbling). Individually or as a team, they never saw in training anything tumbling as fast as SPARTAN. There was no training to even recognize high rates, let alone match them; however, there was limited training to make rate estimations as part of the rendezvous training flow.

There was virtually no training for combinations of RMS and vehicle rate matching. Very little CDR/MS1 integrated orbiter/arm tumbling target capture training was accomplished - each trained separately, and to much lower rates. Crew training for attempted grapple of a spacecraft tumbling at moderate to high rates is inadequate.

(5) The SPARTAN multi-axis rates were unpredictable due to cross coupling.

Because the SPARTAN had no attitude control system engaged, the initial rate imparted by contact with the RMS steadily coupled into other axes, resulting in a changing picture that was essentially random to the crew. Thus, any limited success in rate matching at a given instant was short-lived, as the axis of rotation continually changed.

8.3.2 OBSERVATIONS

(1) Pluming by orbiter thrusters could have exacerbated EVA retrieval.

Given that RMS capture was deemed impossible, the only backup available was EVA retrieve. The lengthy period of rate matching, with orbiter rate excursions about virtually every axis, left a large window of opportunity for plume impingement on the SPARTAN. Post mission analysis of SPARTAN rate gyro data indicates that the crew was successful in avoiding pluming the SPARTAN for most of the period of rate matching, but that over several seconds near the end of the attempt, the SPARTAN rate was driven to nearly double the initial value by a pluming event. This could have made the task of EVA retrieval significantly more difficult. As it turned out, this additional rate caused the SPARTAN to enter Minimum Reserve Sequence (MRS), a mode which then reduced the rate to less than 0.1 degrees/second by the time the re-rendezvous was complete two days later.

(2) **Intense rate matching activity contributed to the incorrect separation maneuver.**

The CDR indicated, in retrospect, that he did not ensure that conditions (target stable over the payload bay) were correct for initiation of the separation sequence. Given the intense and lengthy period of unsuccessful rate matching activity, it is likely that the crew was exhausted and did not fully focus on the separation task. This resulted in an additional burn being required to successfully separate from the SPARTAN.

(3) **The MRS system was designed to kick off at 3.8 degrees/second, based on the limit of Spartan rate gyro saturation, rather than a more practical limitation of combined orbiter and RMS rate matching ability. Rates of up to 3.8 degrees per second are well beyond the capability of the orbiter to recover.**

The SPARTAN was plumed by the orbiter during the rate matching attempt, inducing rates that exceeded the 3.8 degrees/second Minimum Reserve Shutdown (MRS) engage limit. MRS, utilizing magnetic dampers, was able to reduce the SPARTAN rotational rates over the next several orbits. This limit was selected due to hardware limitations in measuring rates beyond 3.8 degrees/second, rather than by analyzing the capability of the orbiter/RMS system for rate matching/grapple.

8.3.3 PRINCIPAL RECOMMENDATION

(1) **Establish rate matching flying techniques, procedures, and Flight Rules and then train to them.**

There should be general techniques, constraints and rules developed for rate matching. In addition, for each potential situation, groundrules that might be unique to that particular free-flyer should be evaluated and planned for pre-flight, with subsequent integrated training. Consider providing this information to payload designers.

8.4 GENERAL OBSERVATIONS

8.4.1 There were a number of factors that the Board felt might have played a role in the close call, but no evidence was found to support these views. Still, there was belief among the Board members that the operations community should continue to assess these factors to ensure that no causal relationship existed that was overlooked by the Board. These factors included the following:

(1) Crew assignment at L-9 months, the experience mix of the crew, and English fluency.

The STS-87 crew received comparable training relative to previous crews for a flight of this complexity, and the assessment of their performance in simulations was within the normal range. Regular reviews were conducted with the commander, the CB training lead, Training Division management and the STS-87 flight director to assure any concerns were addressed. There were no issues.

(2) A generally junior and inexperienced staff of training personnel, driven by significant attrition.

Although many interviewees expressed concern over the relatively inexperienced nature of the average training personnel, the STS-87 training team was composed of certified, generally senior, training team members.

9. LIST OF TERMS AND ACRONYMS

9.1 Terms

Primary Cause - The major anomalous event immediately preceding a mishap in the absence of which the mishap would not have occurred.

Contributing Cause - A factor, event, or circumstance which led, directly or indirectly, to the primary cause, or which contributed to the severity of the mishap.

Potential Cause - A factor, event, or circumstance which could have been a contributing cause of a similar mishap, but in the investigated case causal relationship was not proven.

Finding - A conclusion based on facts established during the investigation by the investigating authority.

Observation - A factor, event, circumstance deserving comment, but not found to be a contributing or potential cause of the mishap being investigated.

9.2 Acronyms and Abbreviations

SPARTAN	
PGSC	Portable General S Computer
RMS	Remote Manipulator System
EE	End Effector

9.1 Acronyms and Abbreviations

A/G	Air to Ground
ACS	Attitude and Control System
AOS	Acquisition of Signal
C/L	Checklist
CCTV	Closed-Circuit Television
CDR	Commander
CEIT	Crew Equipment Integration/Interface Test
CRM	Cockpit Resource Management
CRT	Cathode Ray Tube
CSM	Cargo System Manual
DSO	Detailed Science Objective
DTO	Detailed Test Objective
EE	End Effector
EVA	Extravehicular Activity
FD	Flight Day
FDF	Flight Data File
FFT	Full Fuselage Trainer
GSFC	Goddard Space Flight Center
KSC	Kennedy Space Center
LOS	Loss of Signal
MCC	Mission Control Center
MDF	Manipulator Development Facility
MET	Mission Elapse Time
MLA	Monochrome Lens Assembly
MRS	Minimum Reserve Shutdown
MS	Mission Specialist
P/L	Payload
PDRS	Payload Deployment and Retrieval System
PGSC	Portable General Support Computer
PIP	Payload Integration Plan
PLAID	Panel Layout Automated Interactive Design
PLT	Pilot
REM	Release/Engage Mechanism
RHC	Remote Hand Controller
RMS	Remote Manipulator System
RNDZ	Rendezvous
SES	Shuttle Engineering Simulator
SMS	Shuttle Mission Simulator
SOHO	Solar and Heliospheric Observatory
THC	Translational Hand Controller
USMP	United States Microgravity Payload

10. MINORITY REPORT

NONE